USA – FLORIDA

Broward County

NOAA

Data Acquisition and Processing Report
Horizontal and Vertical Control Report
& Separates Report
to accompany
Descriptive Reports
H12116 – H12118

Surveyed by Fugro LADS, Incorporated
2009

OPR-H328-KRL-09
October 28, 2009

U.S. DEPARTMENT OF COMMERCE
NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
NATIONAL OCEAN SERVICE

Data Acquisition and Processing Report

Type of Survey Hydrographic Lidar

Project No. OPR-H328-KRL-09

Time frame July – August 2008

LOCALITY

State Florida

General Locality Broward County

2009

HYDROGRAPHER
MARK SINCLAIR

CHIEF OF PARTY
SCOTT RAMSAY

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DATE

NOAA FORM 77-28 (11-72)

U.S. DEPARTMENT OF COMMERCE
NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION

REGISTRY No.

H12116 – H12118

HYDROGRAPHIC TITLE SHEET

State Florida

General Locality Broward County

Scale 1:10,000 **Date of Survey** July 12 – August 24, 2008

Instructions dated June 17, 2009 **Project No** OPR-H328-KRL-09

Vessel Fugro LADS Aircraft, call sign VH-LCL

Hydrographer M.J. Sinclair **Chief of Party** S.R. Ramsay

Surveyed by J.G. Guilford, D.J. Stubbing, J.K. Young, W.T. Newsham, B.A. Weidman, K.J. Oberhofer, C.N. Waite, R.B. Touchstone, V. Sicari

Soundings by Laser Airborne Depth Sounder

Graphic record scaled by B.A. Weidman

Graphic record checked by S.R. Ramsay, J.G. Guilford **Automated Plot** N/A

Soundings in Meters at MLLW

REMARKS

Requisition / Purchase Req. # NCNJ3000-9-15915

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Sub-Contractors Baxley Ocean Visions, Inc., 5018 Harrison Street, Hollywood, FL 33021
Coastal Planning and Engineering, Inc., 2481 NW Boca Raton Blvd., Boca Raton, FL 33431
Quester Tangent Corp., 6582 Bryn Road, Saanichton, British Columbia V8M 1X6, Canada

Times All times are recorded in UTC.

Datum and Projection NAD83, UTM (N) Zone 17

Purpose The purpose of this survey is to provide NOAA with modern, accurate hydrographic survey data with which to update the nautical charts of the assigned area. This project was initially conducted by Tenix LADS, Inc., under contract to Baxley Ocean Visions, Inc., for Coastal Planning and Engineering, Inc. and Broward County. The survey has been re-processed and deliverables prepared in accordance with NOS specifications, for use by NOAA.

Acronyms A complete list of all acronyms used throughout this report is provided at Appendix I of the Separates Report.

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A. EQUIPMENT

The LADS Mk II hydrographic survey system comprises two main subsystems. The Airborne System (AS) is used to acquire raw bathymetric data, real-time Global Positioning System (GPS) data, downward-looking video and digital imagery. The Ground System (GS) is used to plan operations, calculate depth values from the raw data, apply post-processed kinematic GPS (KGPS) positioning, apply tidal corrections, provide tools to allow the collected data to be evaluated and export digital data for the compilation of final survey deliverables. These two subsystems are complemented by other tools required for quality control activities; in particular, contouring, 3-D visualization and georeferenced imagery review. Third party software is also used for product compilation, image creation and survey management, namely CARIS and Terramodel. The general data flow between the subsystems and tools is illustrated in Figure 1.

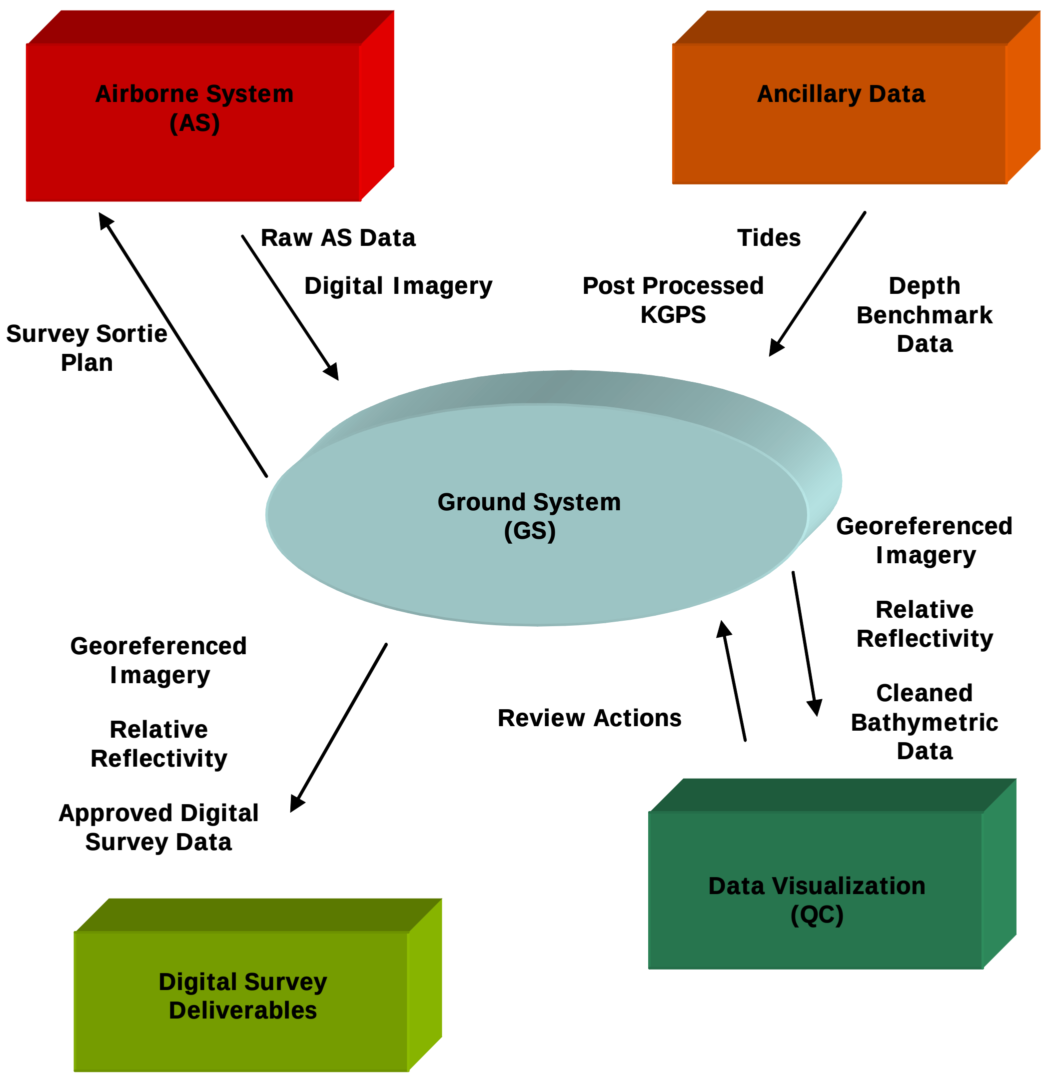


Figure 1 – General data flow within LADS Mk II

A.1 AIRBORNE SYSTEM

A laser, scanner, optical system, photo-multiplier tube and conditioning electronics collect the raw sounding signal. These items are mounted on a stabilized platform that is controlled via servo systems, using information from an Attitude and Heading Reference System (AHRS) mounted on the platform. Aircraft position information is obtained using GPS. Figure 2 illustrates the major components of the AS.

Three computers, linked via an FDDI optic fiber network, control and monitor the AS operations. These computers are:

a. The System Control Computer (SCC) for operator interface, logging and overall system coordination.

b. The Navigation System and Support (NSS) computer for position monitoring and control.

c. The Laser Control and Acquisition (LCA) computer for control of the scanner and laser and digitization of raw sounding data. The LCA also synchronizes overall AS timing.

AS system time is synchronized with GPS time, and all data acquired for logging is appropriately time-stamped at the point of acquisition, then passed to the SCC to be written to Digital Linear Tape (DLT).

Ancillary equipment includes:

- A video camera and VCR to display and record the view below the aircraft and a forward-looking video camera for real-time operator awareness.
- A Redlake MegaPlus II ES 2020 digital camera used to capture georeferenced imagery below the aircraft.
- Systems for temperature control of equipment.
- VHF transceiver and aircraft intercom.
- Satellite phone.

The operator interface allows the operator to monitor the quality of sounding, position and other data in order to set appropriate system parameters and control the sequence of sortie operations.

Detailed descriptions of the main AS components and their functions are given under the headings below. Each of these components was checked by the LADS Technical Department on trials flights conducted during March 2007, in order to achieve the requirements of the LADS Mk II Performance Verification Certificate (provided at Appendix III).

- Sounding Equipment
- Positioning Equipment
- Sortie Control
- Ancillary Equipment
- Operator Interface

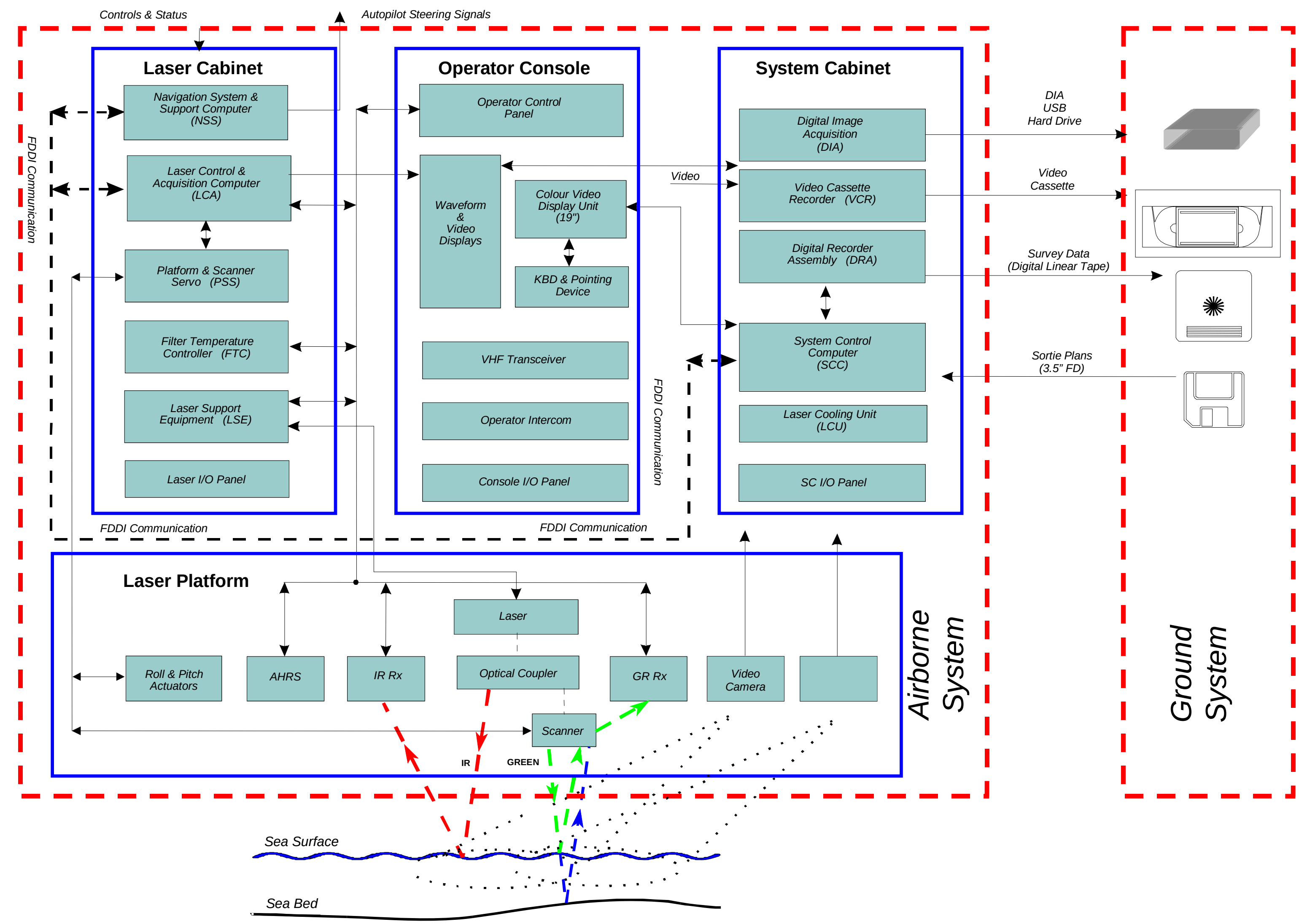


Figure 2 – AS Functional Block Diagram

A.1.1 Sounding Equipment

Soundings in the LADS Mk II system are obtained by the transmission of laser pulses via a scanning system aboard the aircraft and by detecting return signals from land, the sea surface, the water body and the seabed. The transmitting and receiving components are housed on a stabilized platform that compensates for aircraft pitch and roll. The return signals are electronically amplified and conditioned prior to being digitized and logged.

The primary sounding components of the AS are:

- Laser. An Nd: YAG laser producing IR energy at a wavelength of 1064nm at 990 pulses per second, of which 900 pulses are used for sounding purposes.
- Optical Coupler. The optical coupler is used to split the IR beam. Part of the IR beam is transmitted vertically to nadir on the sea surface. The other part of the split beam is frequency-doubled to produce green laser pulses of wavelength 532nm. The green pulses are transmitted onto the mirror of the scanner.
- Scanning System. The scanning mirror is oscillated in both the major (across track) and minor (along track) axes. The required scan pattern is generated by controlling software. All possible patterns are listed in the Sounding Patterns section.
- Optical Receivers. The IR and green return signals are detected by two separate receivers. The IR return from the surface of the sea is used to establish a height datum. The IR receiver is a solid-state detector producing an electronic signal from the IR return. The green return comprises energy returned from the surface, water column and seabed, and is used to determine water depth (refer to Figure 3 and Figure 4). The green return is transmitted via the scanner into a photomultiplier tube. The electronic outputs of the two return signals are electronically mixed prior to digitization.
- AHRS. The AHRS is a laser gyro inertial navigation system providing platform attitude information to the platform servo system that in turn, maintains platform stabilization. The AHRS also reports platform attitude to the LCA computer and provides height data.
- LCA computer. This controls the laser and scanner operations and digitizes (8 bits at 500MHz) appropriate sections of the composite electronic red / green return signal along with platform attitude data and other system parameters. This digital information is passed to the SCC where it is logged to DLT.
- Waveform Display. This Cathode Ray Tube (CRT) display presents the operator with real-time sounding waveforms and is used by the operator to check data quality during acquisition.

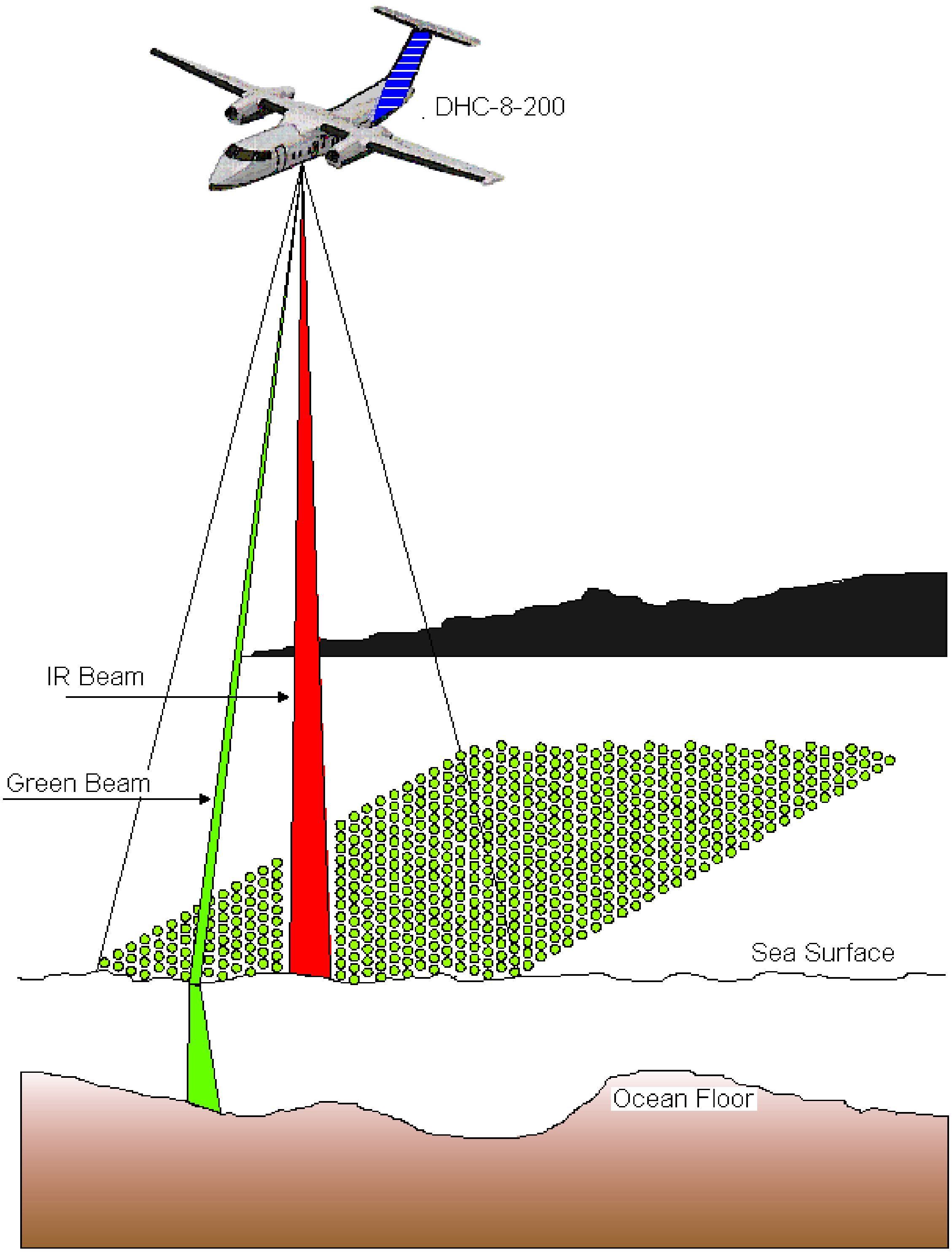


Figure 3 – The Laser Scan

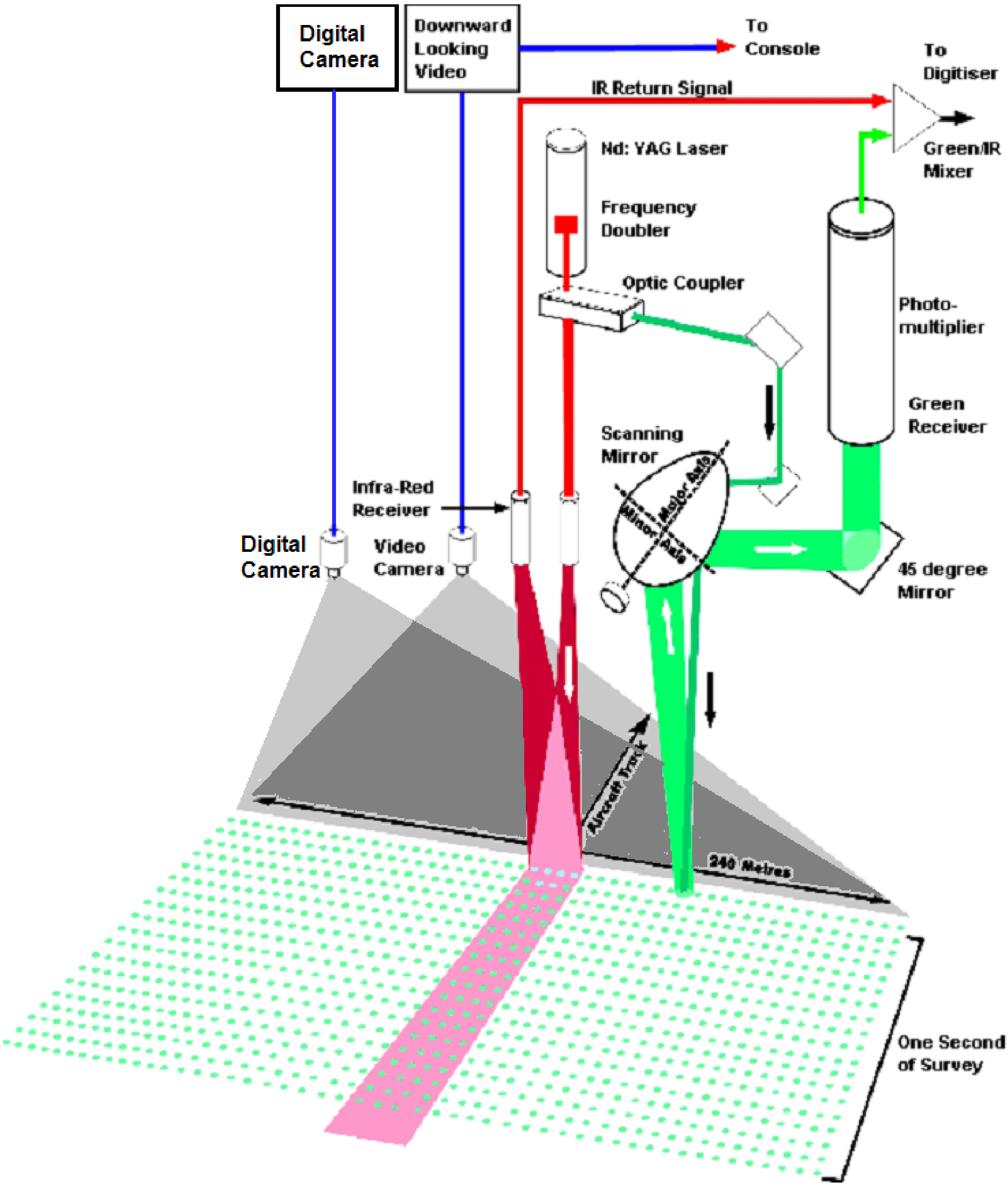


Figure 4 – The AS Scanner, Laser and Receivers

A.1.2 Positioning Equipment

The center of the scanning mirror is the survey reference point on the aircraft. The GPS antenna is positioned relative to this point, as described in Section C.

The signal from the GPS antenna is split and fed to two independent GPS receivers. One is used for real-time aircraft position fixing and track keeping, and the second is used to record GPS data for calculating post-processed KGPS positions. An Ashtech GG24 single-frequency GPS receiver is used to provide real-time positioning of the aircraft. An Ashtech Z12 dual-frequency GPS receiver is used to independently log and compute post-processed positions.

The output of the real-time GPS receiver is fed to the NSS to:

- Fix aircraft position and determine ground speed.
- Calculate aircraft cross-track error and automatically maintain track along survey lines.
- Provide pilot display information.
- Establish and maintain system UTC time.

The NSS passes the received GPS and derived information to the SCC for logging.

A.1.3 Sortie Control

A sortie plan is generated on a floppy disk on the GS to transfer survey information to the AS. The sortie plan contains spheroidal, grid and magnetic variation parameters and a list of survey objectives including the line number, start and end coordinates, and coordinates for navigation position checks. During the course of the sortie, the airborne operator amends the sequence of survey objectives and aircraft altitude to suit environmental conditions and amends the scan pattern parameters for the survey lines to suit survey specifications.

The SCC controls the sequence of survey operations by:

- Planning all required flight paths and communicating these to the NSS.
- Transmitting required parameters for scan patterns, aircraft altitude, etc. to the LCA.
- Initiating the starting and stopping of system operations, via commands sent to the LCA and NSS at specific waypoints on the run-in and run-out of survey lines.

The operator may abort and restart the sortie operations and re-order the sequence of objectives at any time. Scan patterns can be amended on all lines except the executing objective. A display of the planned survey line and received GPS data is situated in the cockpit and used to advise the pilots of required aircraft configurations. The display provides an indication of cross-track error with required and actual values for altitude and ground speed.

Aircraft positioning during survey acquisition is under automatic control of the NSS, via the aircraft autopilot. Aircraft turns are under pilot control assisted by the display. Aircraft altitude and speed are under pilot control, and communication between the operator and pilots is via the aircraft intercom system.

The management of survey objectives execution can be impacted by both low cloud coverage and high ground in the survey area. LADS Mk II is able to operate at different survey heights, irrespective of scan pattern, so that adequate aircraft clearances can be maintained above high terrain or below low cloud ceilings as required. Survey altitudes at 200ft increments are available from 1,200 to 2,200ft (366 to 671m). Altitudes must be constant for the duration of a survey line but may be varied from line to line by the AS operator during the course of a sortie.

During daytime operations a narrow-band green filter is used to filter out other light frequencies from the photomultiplier tube. This filter has a slight attenuating effect on the laser returns, which reduces the maximum depth performance. This filter can be removed once the ambient sunlight levels drop, which results in improved performance at night.

Glassy sea conditions may result in very strong IR surface returns that can saturate the IR receiver, causing a loss of surface datum. The AS monitors the IR surface return performance and advises the operator if IR saturation occurs. The operator can activate an IR attenuator that provides correct IR surface return amplitudes to be fed to the IR receiver. Should sea surface conditions change, which may result in lower IR return amplitudes, the AS informs the operator to deactivate the IR attenuator.

The laser is designed to be eye safe in accordance with the following standards:

a. ANSI Z136.1-2000, American National Standard for Safe Use of Lasers

b. IEC 60825-1 (Edition 1.2) International Standard – Safety of Laser Products

c. AS/NZS 2211.1 Supplement 1:1999 Australian / New Zealand Standard Laser Safety

The laser power can be reduced by a further factor of four using a built-in green attenuator. The operator may activate / deactivate the green attenuator at any time.

A.1.4 Ancillary Equipment

A video camera is positioned on the stabilized platform and directed downward at nadir. A calibrated graticule is superimposed on the camera image to provide the operator with a scan width and distance reference. The image, graticule and other relevant system information, including position and time, are presented to the operator and recorded throughout a sortie.

A forward-looking video camera is also provided to assist the AS operator for the purpose of evaluating conditions ahead of the aircraft.

A Digital Imagery system provides georeferenced imagery. This system comprises a Redlake MegaPlus II ES 2020 digital camera, a Matrox 4Sight M frame grabber and a Matrox embedded computer running Windows XP embedded operating systems. Images are taken at one-second intervals with a 1600x1200 resolution and a 2-megapixel interline-transfer camera head and controller. At the end of each sortie, the images are copied to the LADS GS with the use of a removable hard drive.

A.1.5 Operator Interface

The operator monitors and controls system operation from the console. The following key information is provided to monitor system performance:

- Sortie Information. The Sortie ID, spheroid and grid in use and available survey objectives are displayed. Sortie objective information includes the scan pattern set for the objective and estimated time to complete the objective.
- Objective Information. The Objective ID, selected scan pattern, required speed and altitude pertaining to the current objective being executed and objective status, such as time to completion, are presented.
- Waveform Display. This display is a CRT on which displayed is each of the mixed red / green sounding return signals as digitized by the LCA (the traces are overlaid). The operator continually assesses this display to determine data quality.
- Depth Profile. A depth profile determined from nadir soundings is available to the operator with an associated confidence factor. As the algorithm is limited by real-time considerations, these depths and confidences are only indicative.
- Aircraft Position, Speed, Altitude and Cross-Track Error. A number of displays including a copy of the pilot display are available to the operator to determine the aircraft position and performance parameters. Speed and altitude are continually monitored and the pilot is informed of deviations from the desired values.
- GPS Status. The operator is provided with the data from the GPS receiver including number of satellites, satellite altitudes and azimuths, signal to noise ratio (SNR) and which satellites are being used.
- Equipment Status. System status and performance parameters are available to the operator including laser power and temperature, dynamic gain values, AHRS status and scanner performance.

Items controlled by the operator for sortie execution and data acquisition are:

- Sequence of objective execution
- Scan pattern for each objective
- Operating height for each objective
- Depth logging range and topographic height range for each objective
- Dynamic gain limits
- IR and green receiver attenuator positions
- Seabed reflectivity and seabed gradient controls

A.1.6 Depth and Topographic Mode

During normal bathymetric survey mode (Depth Mode), LADS Mk II determines the depth of water with the height datum being determined from the reflected IR laser signal, GPS height and AHRS height. When over land this IR signal is not valid and the height datum is obtained from the GPS and AHRS.

This ancillary height datum allows LADS Mk II to measure topographic heights. The topographic height range is dependent on the depth range in use. In addition, the topographic range may be reduced due to returns from thick foliage, which may prevent laser returns from being received from ground level.

A.1.7 LADS Mk II Aircraft and System Specifications

Aircraft Type	De Havilland Dash 8-200, twin turbo prop, high wing
Aircraft Modifications	Long range tanks, pressurized laser bay window and autopilot interface
Transit Cruise Speed	250kts (maximum 275kts)
Transit Altitude	To 25,000ft
Survey Speed	Dependent on Scan Pattern: Nominal 140-210kts (72-108m per second)
Survey Height	1,200 to 2,200ft (366 to 671m) in 200ft increments
Survey Track-Keeping	+/- 5m (manual or via autopilot coupling)
Survey Endurance	8 hours nominal
Operational Capability	Day / Night Operation
Depth Sounding Rate	900 soundings per second
Swath Width	Dependent on Scan Pattern: 50-288m (independent of aircraft height and water depth)
Scan Pattern	Rectilinear
Sounding Density	Variable: 6x6m, 5x5m, 4x4m, 3x3m, 2.5x2.5m and 2x2m
Soundings per sq km	Dependent on scan pattern. For 4x4m – 75 000/km^2 (assuming 32m overlap)
Soundings per hour	Up to 3 million
Topographic and Depth Range	-50m (topo) to 70m (depth)
Area Coverage	Dependent on scan pattern. For 4x4m – up to 41.5km^2/hour (12.1 sq nm/hr) assuming 32m overlap
Position Fixing	Autonomous GPS and post-processed L1 + L2 dual-frequency KGPS
Recording Media	DLT, VHS Video Tape, USB Hard Drive
Digital Camera	Image Area at 1500ft operating altitude: ~330m x 250m. Image Resolution: >4 pixels/m at an altitude of 1600ft. Digital Image Capture Rate: 1 per second. Digital Image Horizontal Accuracy: +/-5m (95% confidence).

A.1.8 Logging Parameters

A.1.8.1 Position Fixing

The AS obtains a position fix every 0.5 seconds.

A.1.8.2 Navigation Update

While executing a survey line under AS control navigation, correction is passed to the aircraft autopilot every 0.5 seconds.

A.1.8.3 Post-Processed GPS

The GPS airborne and base logging stations log position information from GPS satellites at 0.5 second intervals.

A.1.8.4 Sounding Rates

LADS Mk II obtains depth soundings in a rectilinear pattern where the sounding density is variable (see Table 1) but sounding rate is invariant.

For all sounding patterns, the soundings are grouped into one-second frames made up of 18 scan lines. Each of the 18 scan lines contains 50 laser pulses, of which 48 pulses are used for depth sounding. The outermost laser pulses are not used for depth sounding. This provides an effective sounding rate of 864 soundings per second.

A.1.9 Sounding Patterns

LADS Mk II has variable scan pattern functionality as detailed in the following table. The 4x4 and 4ax4a patterns both provide 4x4m spot density but have different swath width and survey speeds. All patterns are available at each of the operational altitudes (1,200 – 2,200ft in 200ft increments).

Sounding Density (m)	Swath Width (m)	Line Spacing 200% Coverage (m)	Line Spacing 100% Coverage (m)	Survey Speed m/sec (kts)
6x6	288	125	250	108 (210)
5x5	240	100	200	90 (175)
4x4	192	80	160	72 (140)
4ax4a	150	60	120	90 (175)
3x3	100	40	80	77 (150)
2.5x2.5	75	30	60	72 (140)
2x2	50	20	40	72 (140)

Table 1 – Scan Configuration

A.2 GROUND SYSTEM – OVERVIEW

Conversion of raw sounding data from the AS to final depth data is accomplished on a GS (refer to Figure 5). There are four GS's available for operations, as follows:

a. GS Bilbo, comprising a single CPU Compaq (DEC) Alpha Series 4100 Server with 256MB ram, up to 750GB disk space, DLT and Digital Audio Tape (DAT) drives.

b. GS Frodo, consisting of a Compaq Alpha ES40 3-processor Server with 1 GB EEC RAM, 764 GB disk space, DLT drives and magazines, DAT drive, CD-ROM drive and is networked to up to 12 Compaq 1.5 GHz PCs.

c. GS Gandalf, consisting of a Compaq Alpha ES40 3-processor Server with 1 GB EEC RAM, 764 GB disk space, Super DLT (SDLT), DLT, and DAT drives, a CD-ROM drive and is networked to a series of 8 HP Small Form Factor PCs with Windows and Linux (dual boot) that serve as processing terminals for GAP, Fledermaus, CARIS, etc. Gandalf is also networked to an HP 750c DesignJet plotter, printers and QC workstations.

d. GS Katrina, consisting of a Compaq Alpha ES40 3-processor Server with 1 GB EEC RAM, 764 GB disk space, SDLT and DLT drives and magazines, DAT drive, CD-ROM drive and is networked to an HP 800ps DesignJet plotter, printers, and QC workstations.

The GS hydrographic software is a Fugro LADS, Inc. proprietary package written in ADA to operate in a UNIX True-64 (DEC) environment.

The GS provides the facilities for all LADS survey management tasks from initial mission planning through to production of final digital deliverables.

The primary functions are:

- Mission planning. This includes the specification of the total survey area, spheroid and grid, survey sub-areas, line spacing, swath widths, survey lines to cover the sub-area, individual survey lines, depth benchmark areas and lines, crosslines, tidal areas and navigation check points.
- Sortie planning. A sortie plan is the specification of a series of survey objectives to be executed by the AS. Survey lines and navigation check objectives are selected by the operator and written to floppy disk along with grid and spheroidal information.
- Sortie processing. This function calculates sounding depths and positions from the raw sounding data logged by the AS. Depths and positions are associated with various confidence metrics.
- Quality Control. Utilities within the GS for data integrity checks include the Positioning Analysis Software (PAS) for generating static and dynamic GPS check reports and data, navigation position checks, depth benchmark comparisons and crossline comparisons.
- Data validation, checking and approval. Surveyors validate the calculated soundings on a run-by-run basis editing soundings as appropriate. The validated data is checked by a senior surveyor and finally approved by the Field Party Leader.

- Data output. Approved bathymetric data is output to the client in CARIS digital format and S-57 digital format. Relative reflectance data is calculated in and exported from the GS.

In addition, the GS provides facilities for the generation of survey management plots and reports.

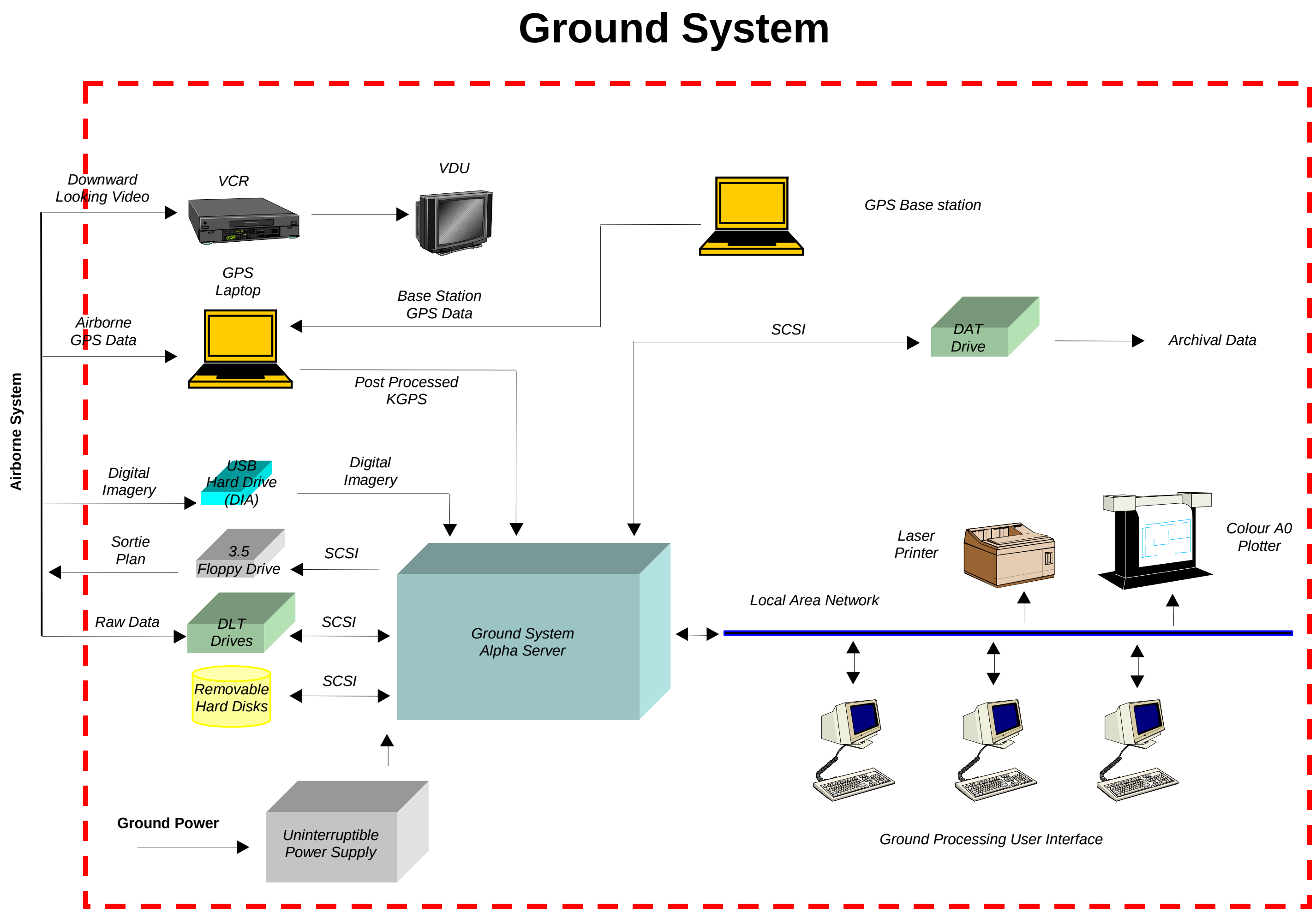


Figure 5 – Block Diagram of the LADS Mk II GS

A.2.1 Mission Planning

At the commencement of a survey, one or more databases are established on the GS. Each database contains spheroid and grid data, tide data and survey objectives.

Sub-areas are defined covering the specific areas to be surveyed. Survey lines are then generated within each sub-area at operator specified line spacing. Other survey lines can be specified by entering start and end coordinates.

A.2.2 Sortie Planning

Prior to each sortie, survey objectives are selected from the appropriate database. The start and end coordinates of the required survey lines are written, together with spheroid and grid data, to a sortie plan on a floppy disk. This plan is read by the AS and used to control sortie operations.

A.2.3 Sortie Processing

Processing parameters are set prior to sortie processing. The post-processed KGPS positions from the local reference station are applied first. Preliminary tides are applied and final verified tides can be reapplied at a later time.

Raw sounding data logged by the AS is automatically processed by the GS to produce depth, position and a series of confidence parameters.

On completion of automatic line processing, operator quality control checks, validation, checking and approval of the sounding data can be conducted.

A.2.4 Data Organization

Data within the GS database is held on a line-by-line basis. Within the survey lines the data is grouped into one-second frames made up of 18 scans of 48 sounding pulses (864 pulses per frame).

A.2.5 Primary and Secondary Soundings

All processed soundings comprise the primary sounding set. Where data set reduction is required, a shoal-biased subset of the primary soundings called secondary soundings is created. Secondary soundings form a shoal-biased subset based on operator selected confidence and secondary selection radius criteria. Only secondary soundings are validated, checked, approved and output. For this survey a secondary sounding reduction radial of 1m has been used, which means all soundings have been hydrographically reviewed and all valid soundings have been provided in the final data set. All incorrect secondary soundings were set to primary during the course of data validation, checking and approval and were excluded from the final dataset.

A.2.6 Automatic Data Processing

Automatic processing is completed in two stages:

1. Sortie Tape Processing (STP).

   STP reads the data on the tape and stores it in the internal GS database for further processing. The data is line-based and consists of raw waveform data, navigation data, platform data, system data, and error and event logs. This process also includes producing a backup of the raw data tape on DAT or DLT.

2. Sortie Run Processing (SRP).

   SRP is the second and major processing phase during which sounding depths and positions are calculated on a line-by-line basis. The process is normally triggered automatically by STP as each line becomes available, but may be invoked later by the operator if reprocessing of lines with different processing parameters is required.

The major processing steps of SRP are:

- Apply post-processed KGPS position data to the raw data and digital images from the downward-looking camera.
- Process the raw waveform to identify surface reflections.
- Process the raw waveform to identify and calculate initial depths. Up to five possible seabed returns can be established per waveform.
- Classify each of the identified seabed return pulses by SNR, agreement with near neighbors and a maximum likelihood estimator.
- Select the most likely seabed return pulse based on the above classification and a shoal weighting function.
- Model the sea surface from the available surface pulses.
- Correct the calculated depths for sea surface datum including tide, slant range, optical propagation and early / late entry. Tidal corrections may be reapplied later if required.
- Calculate position of each sounding on the seabed. This algorithm uses KGPS fixes, aircraft track and speed, antenna offsets, platform attitude (heading, roll and pitch), beam scan angles and sounding depth. Where the GS is unable to determine a depth from the raw data, the sounding is classified as “No Bottom Detected” (NBD).
- Calculate primary confidence indices (0-9) for each non-NBD sounding and all frames where:

  C0 = Subsurface Pulse Confidence (based on SNR)

  C1 = Near Neighbor Confidence

  C2 = Pulse Type Confidence

  C3 = Position Confidence

  C4 = Sea Surface Reference Confidence

C5 = Not Used

C6 = Coverage Confidence (confidence that the swath covered the planned width)

CW = Weighted Primary Confidence

- Store each sounding and associated confidence data in the database.
- Determine the secondary sounding subset (it may be appropriate to have all soundings classified as secondary) and for each secondary sounding, calculate and store secondary confidences:

CS1 = Secondary Neighbor Confidence (near neighbor agreement)

CS2 = Useable Points Confidence

CS3 = Secondary Area Confidence

CSW = Weighted Secondary Confidence

A.2.7 Bottom Object Detection (BOD)

A particular feature in the SRP improves the ability of the LADS Mk II GS to detect small objects on the seabed.

The BOD algorithm proceeds in two phases. Each phase can be independently enabled / disabled and tuned via a series of BOD processing parameters set by the operator prior to SRP.

Phase one of the algorithm is designed to detect objects 2-3m in height, while phase two is only invoked if phase one fails. Phase two is more sensitive and intended to find objects less than 2m in height.

A.2.8 Line Reprocessing and Segmentation

It may be necessary to reprocess the same raw sounding data with different processing parameters. The run identification scheme adopted in LADS Mk II provides a mechanism to manage the reprocessing of survey line data multiple times.

After a line is reprocessed, the required segment can then be set to Accepted, and the remaining data can be set to Anomalous or Rejected, and is subsequently excluded from final data output.

A.3 GROUND SYSTEM – USER INTERFACE

The following displays and their associated operations are the primary tools used for data validation, checking and approval.

A.3.1 Composite Data Display

The Composite Data Display is used for overall assessment of the depths along the line and the general quality of the data. The operator may pan along and zoom into specific areas of the line. The position in Eastings and Northings of the nadir at that point, the distance along track, time of acquisition and frame number of the point under the cross hairs is displayed as the operator pans along the line.

The operator can position cross hairs at the point of interest on this display before invoking more detailed displays. The other displays are initialized at the position of the cross hairs.

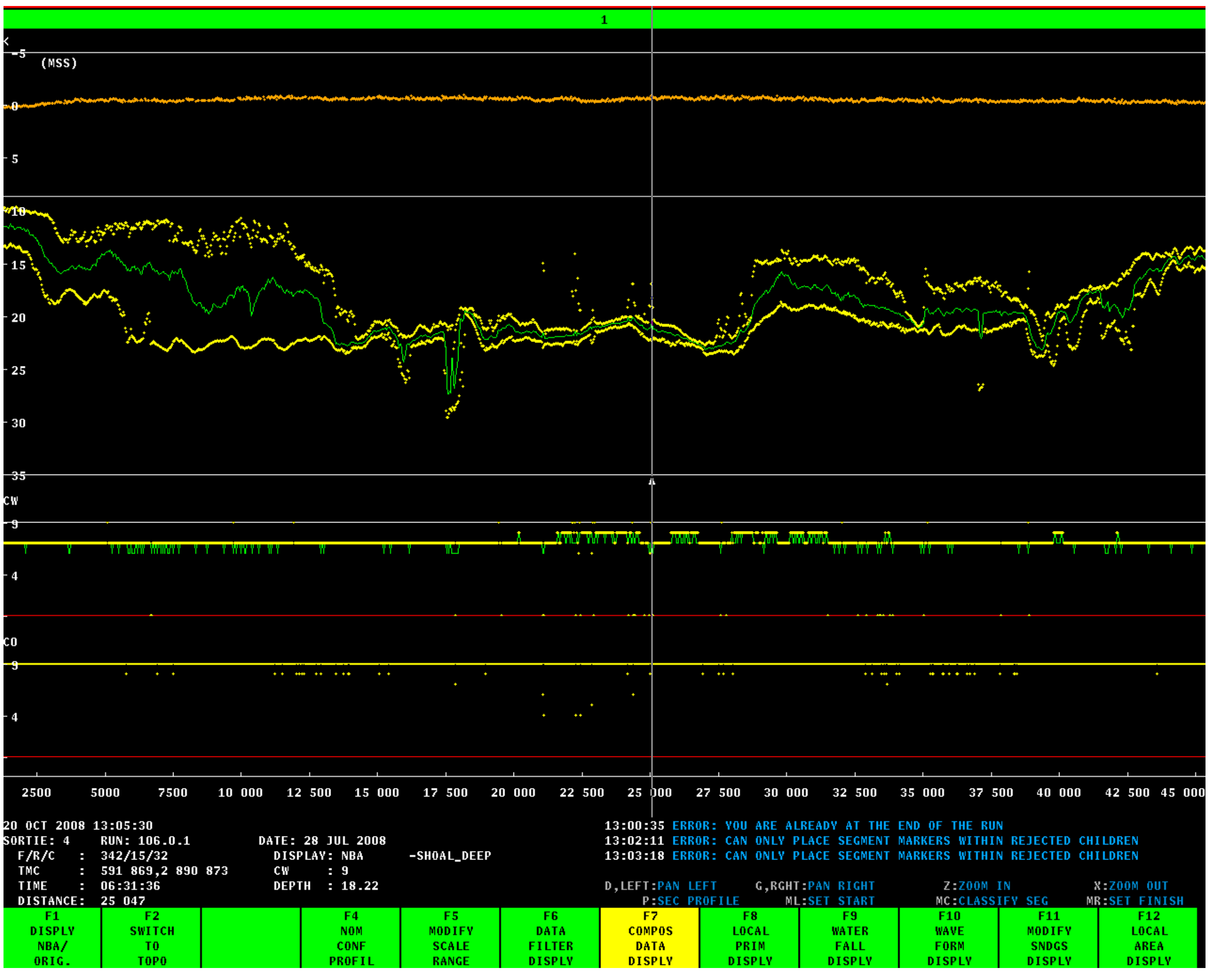


Figure 6 – Composite Data Display

Three profiles, with distance along track on the X axis and depth on the Y axis, are superimposed on this display:

- For each scan the average of all soundings across a scan is graphed as a green line. If the number of NBD soundings in the scan exceeds a specified number (set as a processing parameter), the green line is drawn across the bottom of the display.
- The shoalest secondary sounding in each scan can be displayed as a yellow dot.
- The deepest secondary sounding in each scan can be displayed as a yellow dot.

These profiles enable the operator to rapidly assess where there is a high NBD count and assess where there are areas of noise.

Below the depth profiles, two operator selectable profiles are displayed. Each of these can be one of:

- Any of the primary or secondary confidences.
- Parameters related to the integrity of the height datum.
- Tidal correction and tidal area boundaries.

The Composite Data Display is also used to segment the data into the following line subsets:

- Accepted – data is to be cleaned and exported in the final dataset.
- Anomalous – data is rejected and will not be exported, as more accurate or more complete coverage exists from overlapping survey lines.
- Rejected – data is rejected and the survey line must be reflown to obtain adequate coverage.

A.3.2 Local Primary Display

The Local Primary Display shows the depths of all soundings across the 18 scans conducted during one second of data acquisition. Soundings are arranged logically (not by position) as a row per scan of 48 soundings across the row. A white bar between rows indicates a frame boundary. Primary soundings are green, secondary soundings are yellow and NBD soundings are marked as "NB".

The length of the bar between the integer and decimal values of the depth of each sounding is proportional to the primary (CW) or secondary weighted confidence (CSW) as appropriate.

The operator may scroll forward or backward along the line and position the cursor over soundings for which detailed displays, such as the Waveform Display or Sounding Audit Display, are required.

The survey line identifier, position, time, frame, row, column and confidences are displayed for the sounding at the bottom of the Local Primary Display.

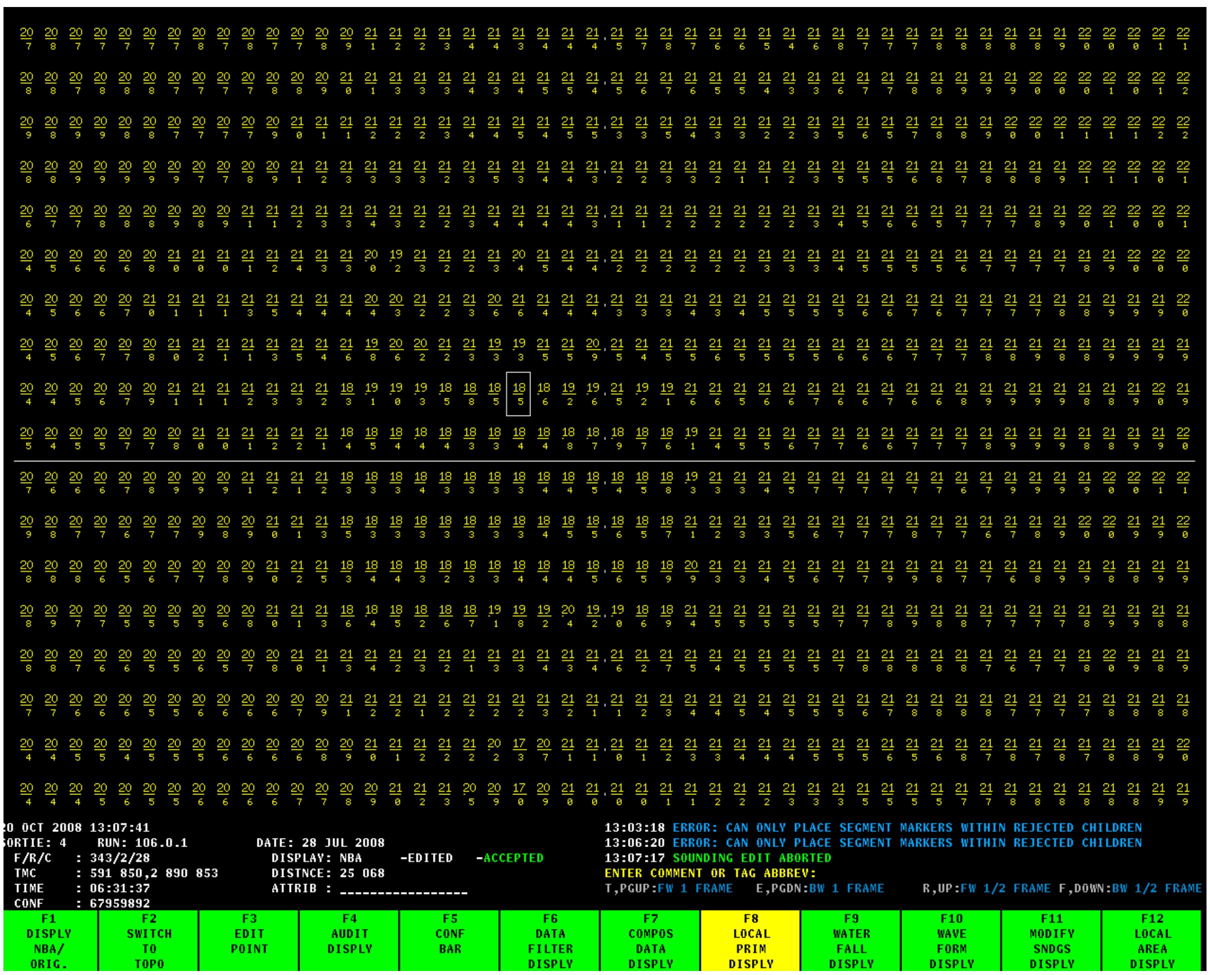


Figure 7 – Local Primary Display

A.3.3 Waveform Display

The Waveform Display shows a matrix of nine sounding waveforms, centered on the nominated sounding. The display is invoked from the Composite Data, Local Primary, Waterfall and Local Area Displays. This display allows an operator to assess the quality of the laser waveform and to resolve or clarify specific sounding values, such as incorrect selection from multiple bottom returns or a false sounding value due to noise in the signal.

Within each waveform window the frame, row, column, gain settings, position, depth, alternate contender depth (such as a BOD) and SNR are presented. A more detailed discussion of the interpretation of waveforms is given in Section B.9.

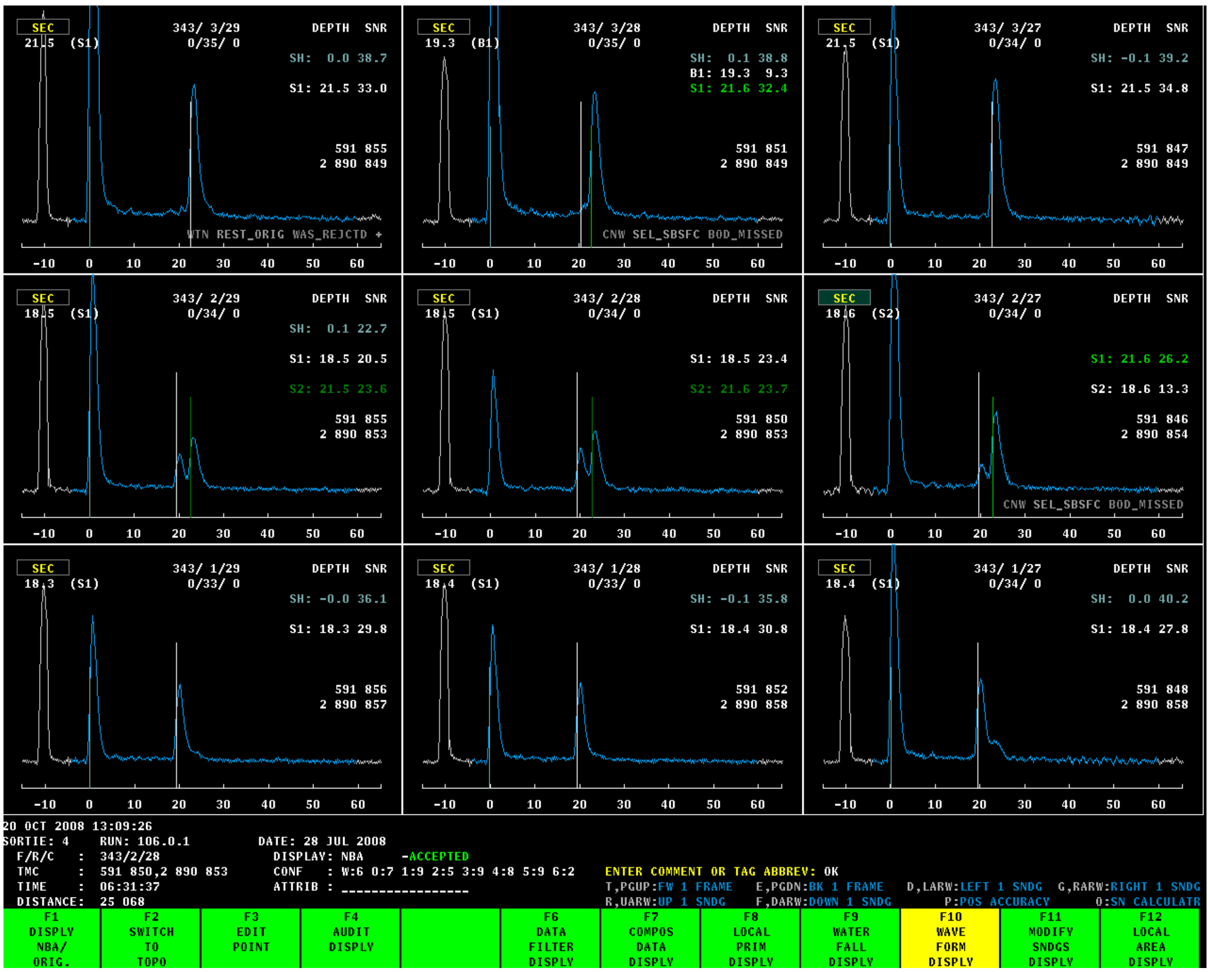


Figure 8 – Waveform Display

A.3.4 Waterfall Display

The Waterfall Display is a pseudo 3-D display constructed from multiple color-coded profiles of the depths across each swath for three frames along a line. Secondary soundings are displayed as yellow dots. The operator may scroll forward or back along a line and select an individual sounding for which to invoke the Waveform Display.

The display allows an operator to gain a general assessment of the shape and nature of the bottom and is particularly good for identifying seafloor objects and spurious noise outliers.

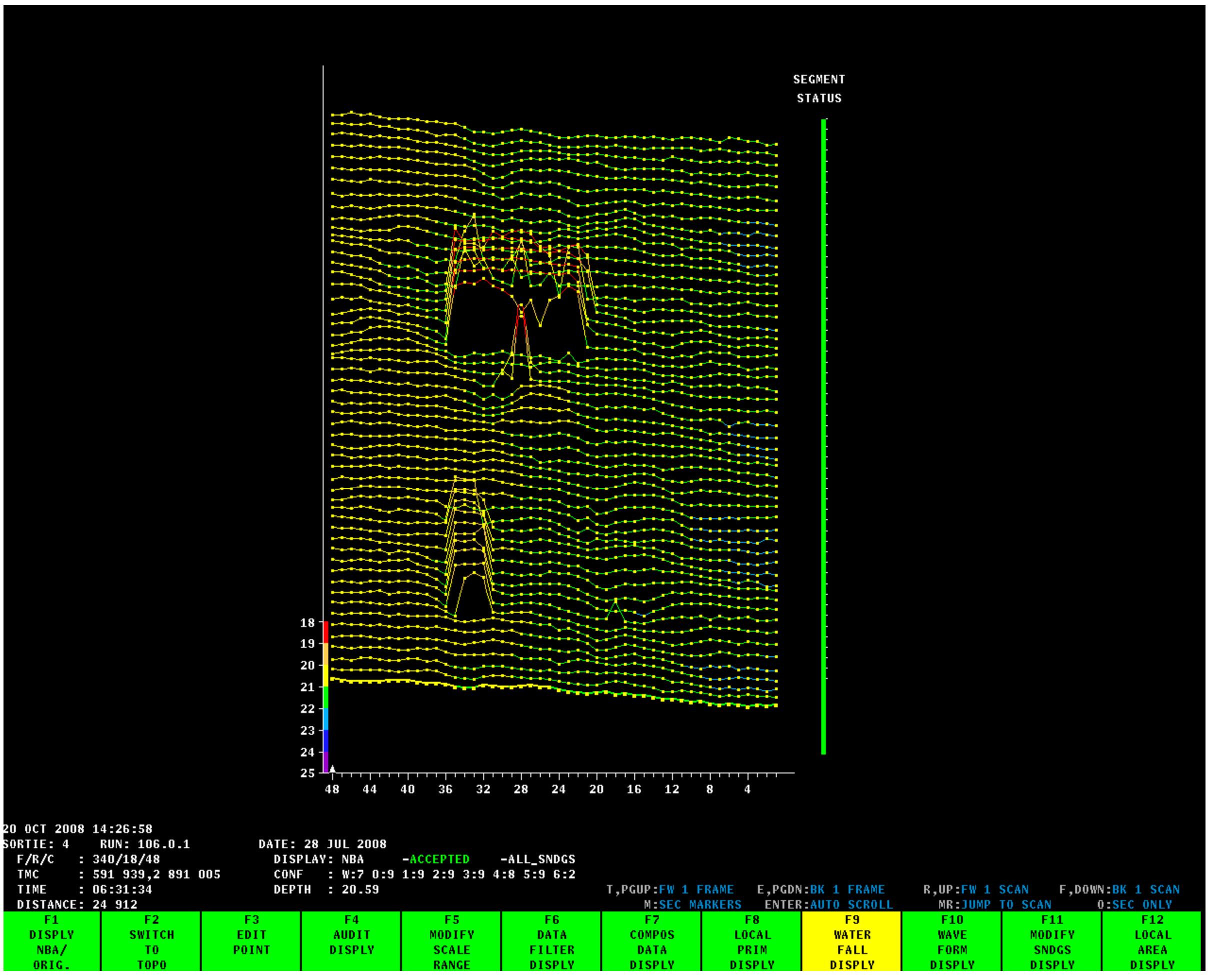


Figure 9 – Waterfall Display

A.3.5 Local Area Display

The primary purpose of the Local Area Display is to check consistency of data across overlapping runs. Facilities provided in this display include coverage and depth variation checks (based on grid cells of nominated size) and TIN contouring.

When this display is invoked, the soundings from the currently selected line and nominated overlapping lines, centered on the current cursor position (as set in the Composite or Primary Displays), are shown. Soundings are presented in their true geographic positions and color-banded by depth.

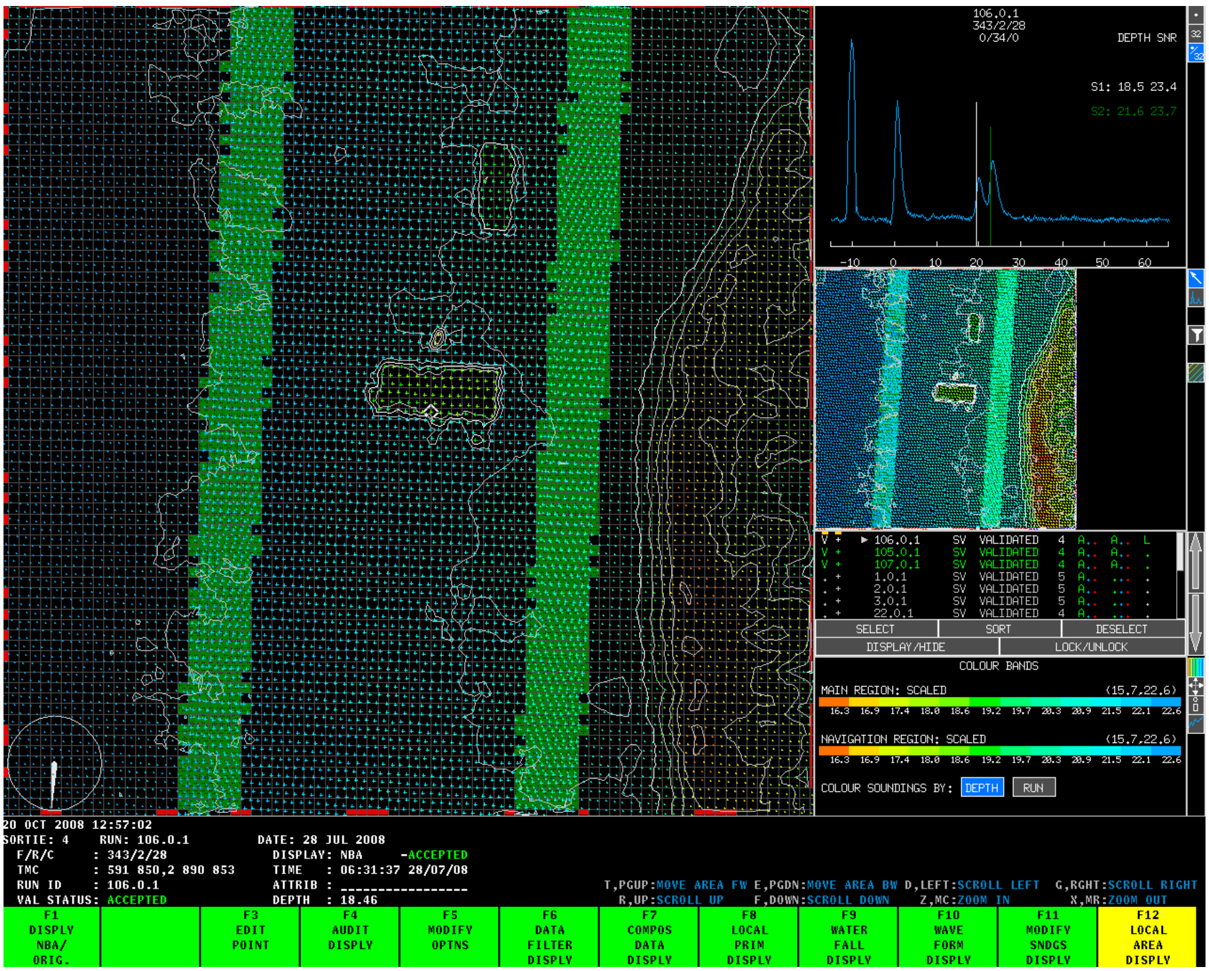


Figure 10 – Local Area Display – Small Scale

The display is divided into five sub-windows, as shown in Figure 11:

a. The working window, on the left, provides a detailed scalable view of a sub-region. The operator may pan, zoom and select soundings in this window. A rectangle within the navigation window shows the position and extent of the area displayed in the working window.

b. The waveform window, positioned in the top right of the display, shows the waveform for the currently selected sounding, highlighted by a white triangle in the working window.

c. The navigation window, positioned middle right in the display, provides a top-level view of the area currently selected.

d. The runs window, directly below the navigation window, lists the overlapping runs along with the status of the line, e.g. Accepted, Anomalous or Rejected.

e. The color band window shows the color band depth ranges for displayed soundings in the navigation and working windows. The soundings can be colored by depth or by line.

The lower region of the screen displays summary information similar to that on the Composite and Primary Displays.

TIN contours of the displayed soundings can be shown in both the navigation and working windows and contour intervals can be amended as required.

For the purposes of coverage and depth variation checks, the operator selects a cell size appropriate to the sounding density. For each cell the system checks coverage criteria. When there is no sounding coverage from any survey line, the cell is colored bright red. When there is coverage from overlapping survey lines, but not the primary line, the cell is displayed black. When there is sounding coverage from both the primary and overlapping lines, the cell is color filled green, olive, brown, or dark red. The color of a cell indicates the degree of variation in the depths of soundings within the cell. Green represents a mean depth variation from the primary survey line sounding of less than 0.5m, olive less than 1.0m and so on. Olive, brown and red cells do not necessarily indicate that there is an erroneous sounding in the dataset. Often these colors simply reflect the sloping nature of the seabed area, or a real feature that is shoaler than the surrounding seabed.

a. – – b. – c. – d. – e.

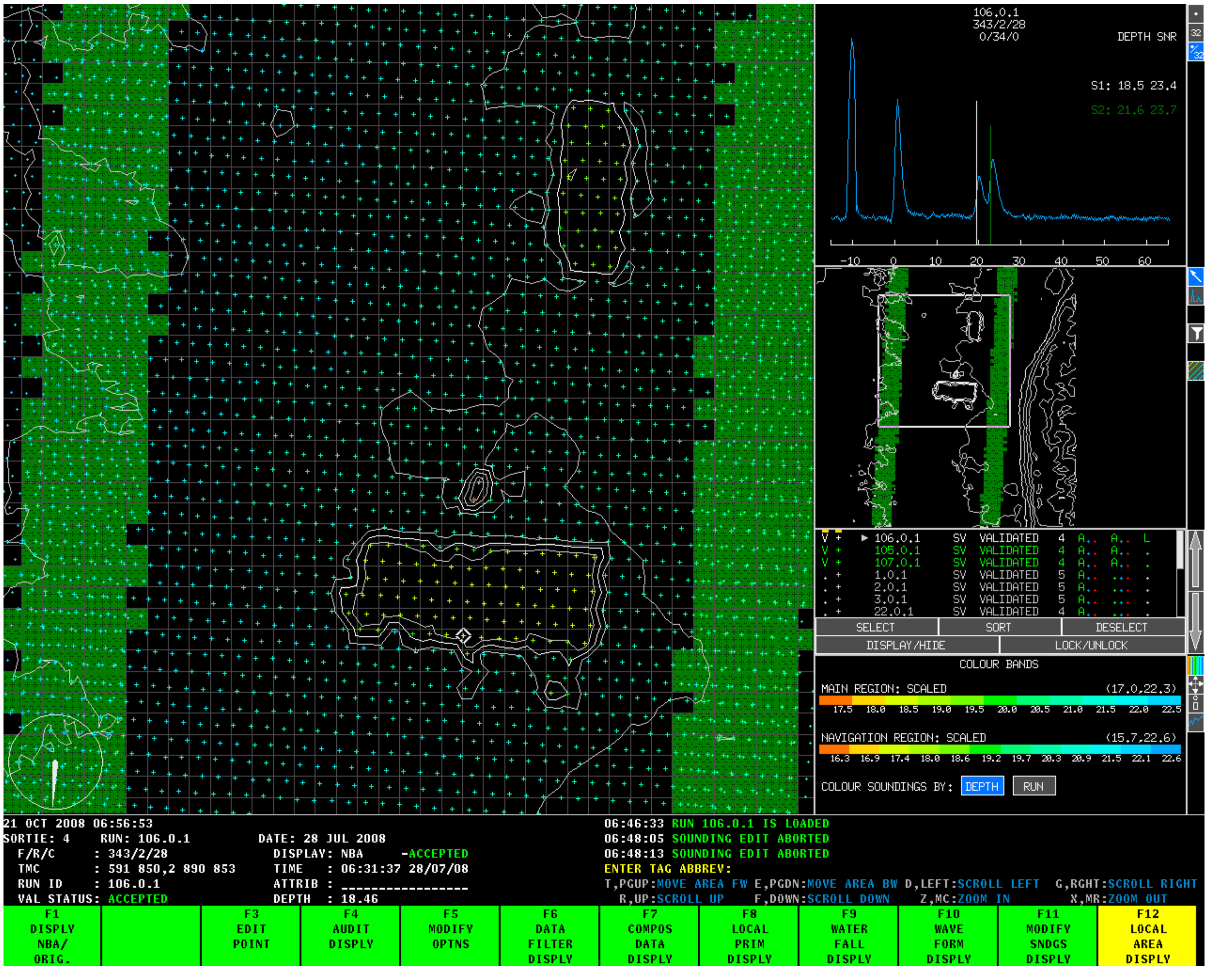


Figure 11 – Local Area Display – Medium Scale

In both the navigation and working window, the soundings are displayed at their geographical positions. As the operator zooms in on the working window, symbols in the working window are replaced by depth values (refer to Figure 12). The sub-region displayed in the working window is represented by a white square in the navigation window.

On selecting a sounding in the working window, the sounding is highlighted with an enclosing diamond and its waveform is shown in the waveform window.

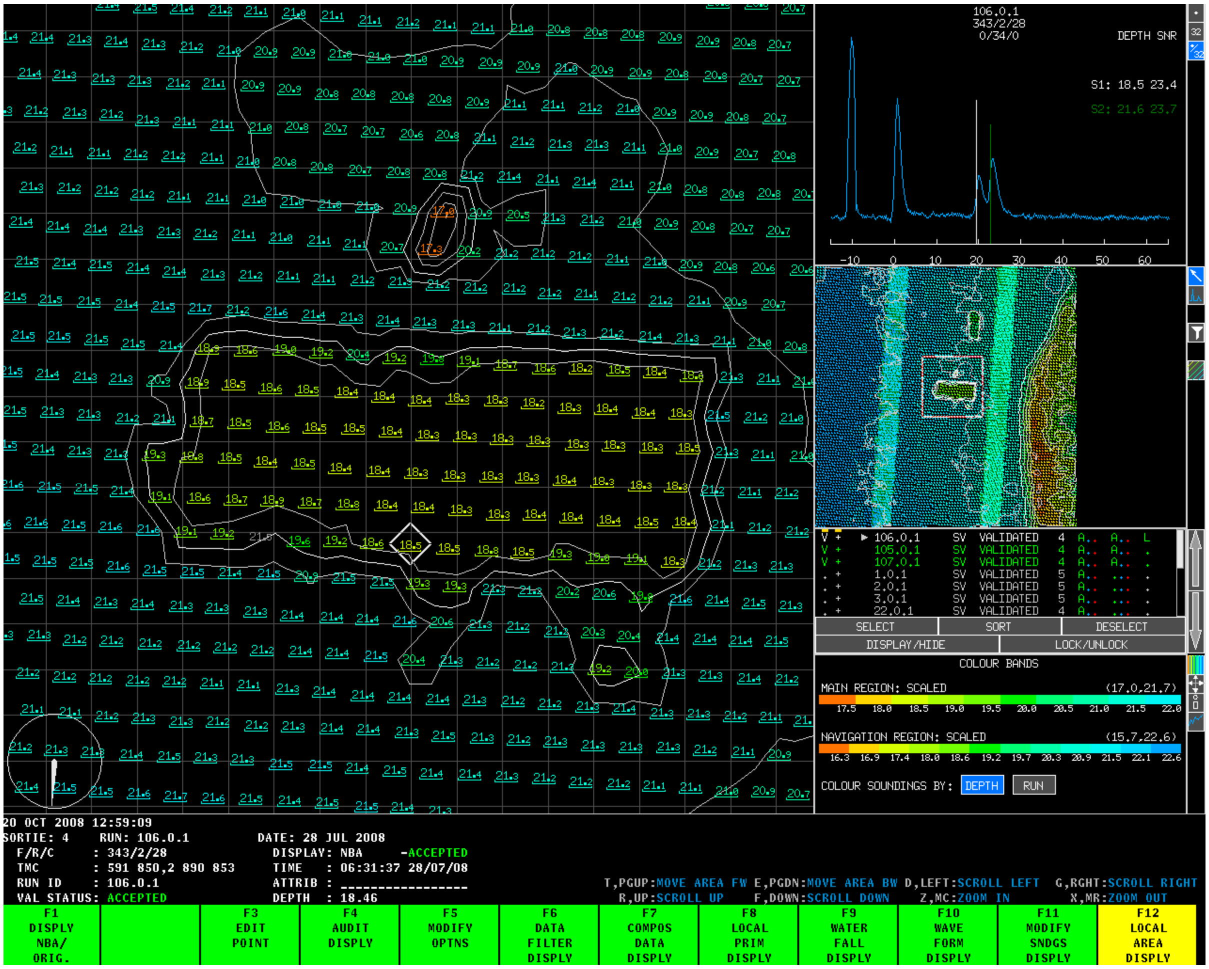


Figure 12 – Local Area Display – Large Scale

A.3.6 GS Digital Image Window

The imagery collected by the downward-looking digital camera in real-time is processed along with the raw data. These images are georeferenced and can be either manually or automatically displayed alongside of the Raw Data Display, the Waveform Display or the Local Area Display. The images are automatically rotated to fit the current display.

These images are displayed in the GS Digital Image Window on the second dual screen monitor. This display is automatically linked to all of the GS displays mentioned previously and the selected sounding is highlighted in the downward-looking image with a yellow circle of 5m diameter.

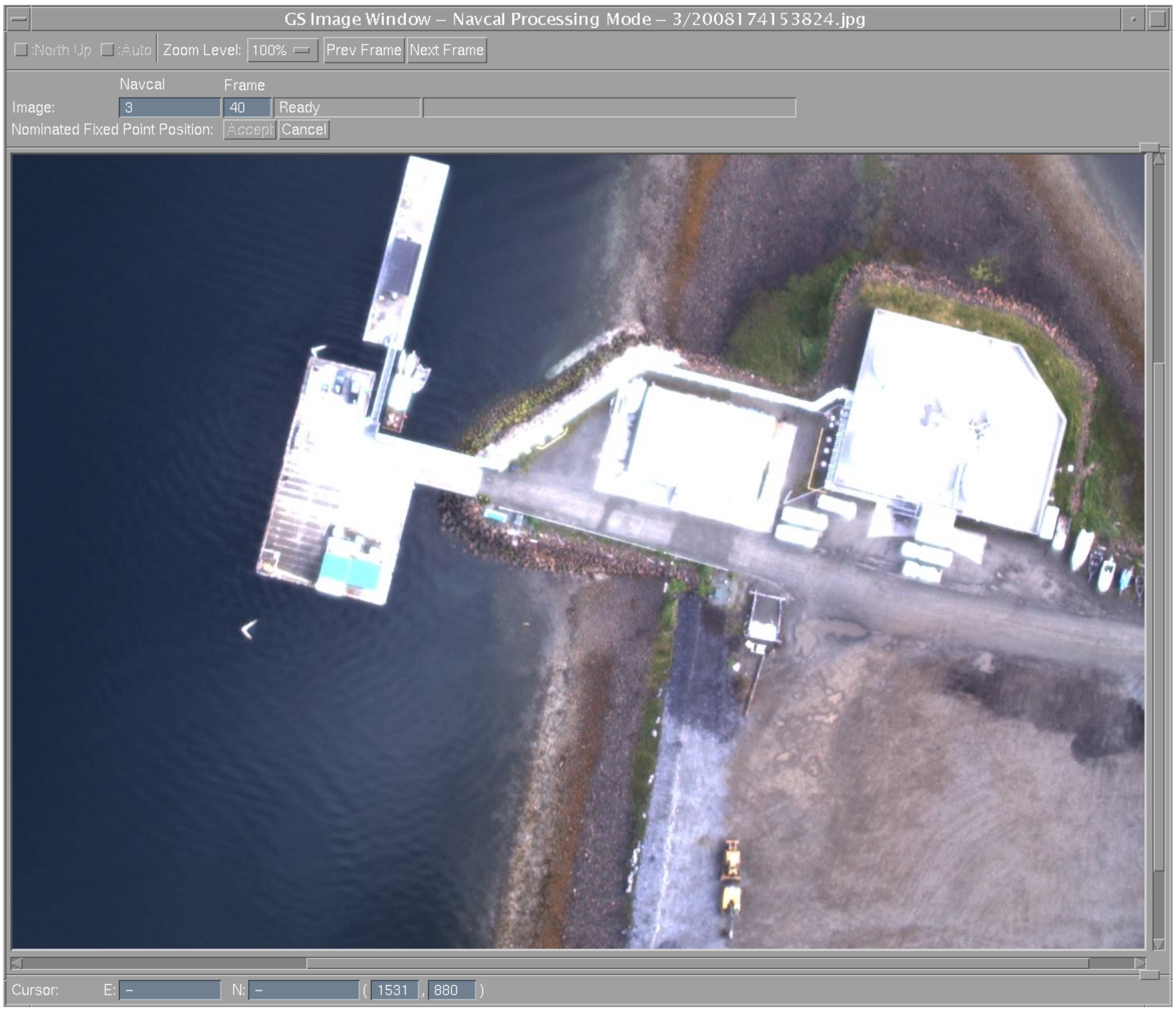


Figure 13 – GS Digital Image Window – Daylight image from Alaska 2008

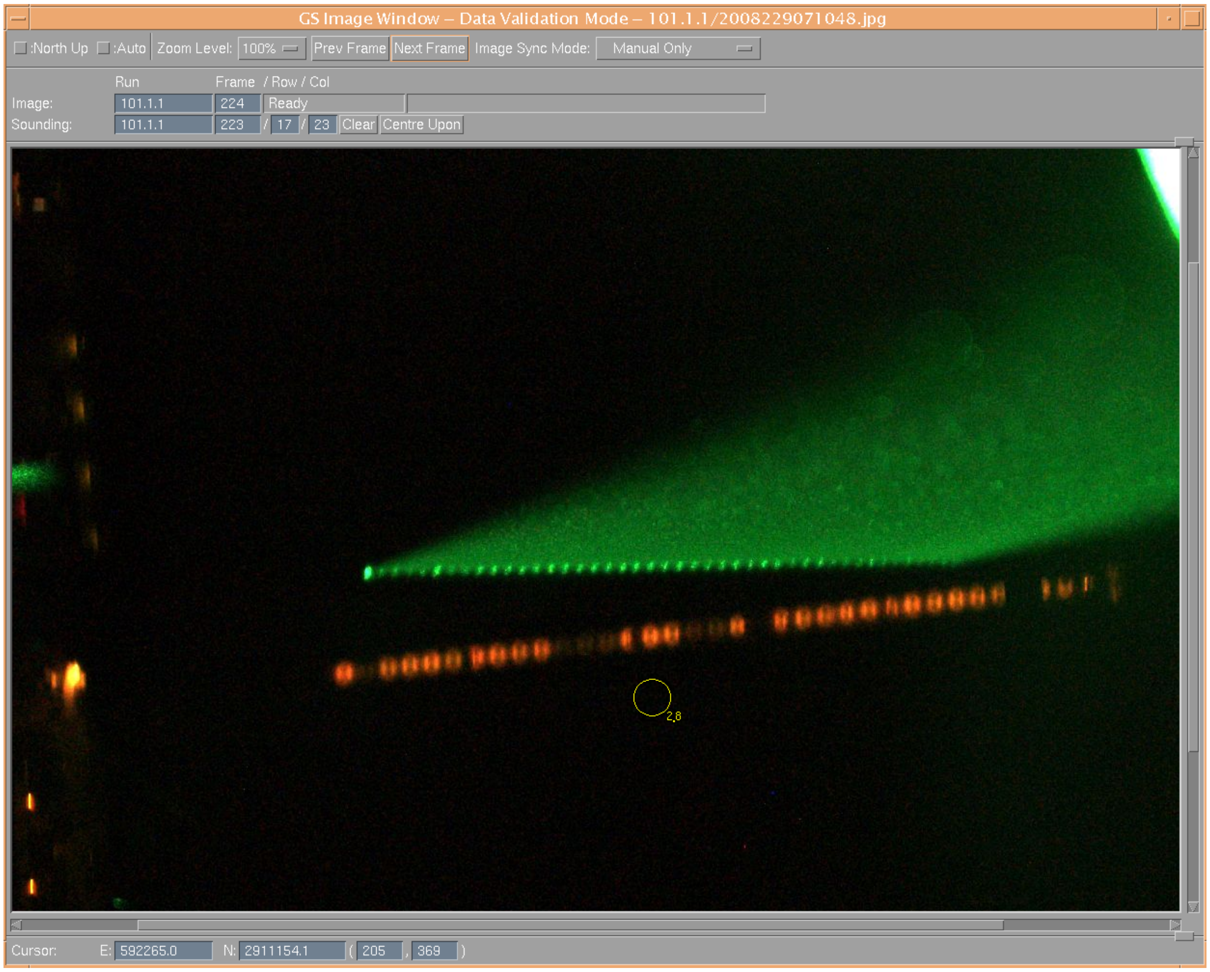


Figure 14 – GS Digital Image Window – Night image from Broward County 2008 (Anglin's Pier)

The GS Digital Image Window enables the operator to easily correlate features such as coastline, islands, islets, drying rocks, rocks awash, shallow rocks, kelp, beacons, buoys, boats, jetties, buildings and trees in the image with the data presented in the different GS displays. The quality of imagery and zoom functionality of the window even enables discernment of biological data artifacts, such as bird strikes and whale returns. Sea lions sunning themselves on drying rocks have also been noted in the imagery.

For night time survey operations digital imagery has limited usefulness. Only areas that are artificially illuminated can be discerned in the imagery and correlated with bathymetric data (refer to Figure 14).

A.3.7 Audit Display

The Audit Display is used to view additional data associated with a single sounding. The display enables an operator to check details such as the aircraft height and heading, platform angles, mirror scan angles and tidal reduction of the sounding (refer to Figure 15).

Figure 15 – Audit Display

A.3.8 Data Filter Display

The Data Filter Display is used to edit numerous points at one time. The display contains two separate windows (refer to Figure 16). The first is representative of the shoalest and deepest soundings per scan, similar to the Composite Data Display. The second window displays numerous filter tabs, each of which is used to set the parameters for the required block edit.

The Data Filter Display essentially enabled the operator to reapply the sortie processing parameters to specific survey lines, or areas of lines, with amended values to reduce the single point editing required to validate, check and approve the data. The filters can highlight specific types of soundings and tags and rapidly set soundings to NB, primary or secondary within different depth ranges and SNR's.

Figure 16 – Data Filter Display

A.4 SOFTWARE VERSIONS

System	Version	Remarks
Fugro LADS AS	AS 9.0.4	Airborne System Software version
GPS Logging AS	5.6.0	Ashtech Data Logger Software
GPS Logging BS	3.22	GrafNav GPS Data Logger Software
GPS Processing	8.10	GrafNav (Precise Differential GPS Navigation Trajectory Software)
Fugro LADS GS	E8.5.10 to E8.7.00	Ground System Software versions
CARIS BASE Editor	2.1.0.0	
CARIS HIPS and SIPS	6.1.1.2	

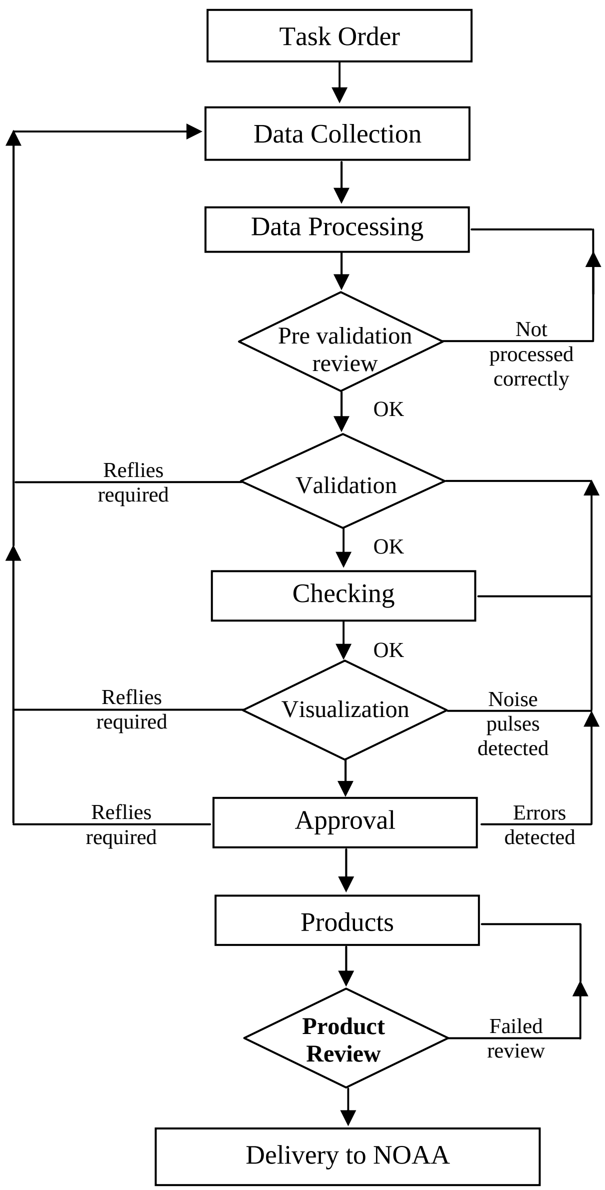
Table 2 – Software versions

B. QUALITY CONTROL

B.1 DATA PROCESSING

Data processing involves the following stages:

- Automatic data processing as described in Section A.2.6
- Survey line acceptance and segmentation by Deputy Project Manager / Project Manager
- Pre-validation of the data by senior surveyors
- Validation of the data by hydrographic surveyors
- Checking of the data by the Deputy Project Manager
- Visualization of the data by a senior surveyor
- Approval of the data by Project Manager



Refer to Section A.3 for the specific GS User Interface displays used to conduct data pre-validation, validation, checking and approval.

B.2 PRE-VALIDATION

Pre-validation is the first interactive step of data processing.

Pre-validation is conducted to confirm that the automatic data processing has been performed correctly and to give guidance for the validation process. The survey data that sufficiently passes quality checks is segmented to Accepted status for validation by hydrographic surveyors. When the required coverage is not obtained, the line is nominated to be reflown. The majority of reflies are created during the in-field pre-validation phase. Some data cleaning is also undertaken during the pre-validation stage, with obvious noise, turbidity and datum shifts removed. The majority of pre-validation will be conducted using filters provided in the Data Filter Display (refer to Section A.3.8).

B.3 VALIDATION

Validation proceeds through the following steps:

1. Examining the depth profile on the Composite Data Display for the correct processing and segmentation of each survey line.
2. Examining the position confidence (C3) profile to verify that adequate positioning accuracy is maintained during the survey line. Additional positioning quality confidences, such as PDOP, number of satellites and correction latency, are examined in profile along the survey line.
3. Examining the coverage confidence (C6) profile to verify that no coverage gaps exist due to the aircraft flying off the predetermined track.
4. Examining the Kalman filter tilt and bias for the line to determine areas that datum shifts have occurred due to excessive aircraft roll, poor sea surface datum or prolonged periods flying over topography.
5. Resolving erroneous soundings after examining outlying data points along the survey line using:

a. The Primary Depth Display

b. The Waterfall Display

c. The Waveform Display

d. The Local Area Display

Validation data editing operations are generally applicable to single depth soundings, but data filters may be applied when pre-validation has missed significant areas of erroneous soundings. The typical single point edits required include the selection of an alternate depth contender, inserting a waveform depth contender where an automatic one does not exist and deletion of the sounding, as appropriate. Tagging of soundings is also an integral part of data validation and is discussed in Section B.8.

B.4 CHECKING

Once a line has been validated it goes through an independent checking phase by the Deputy Project Manager. All soundings edited by the validator are highlighted on the line and the checker ensures the correct edit has been made during validation. Checking also involves identification of residual unedited erroneous soundings missed during data validation and review of the tagged data points.

B.5 DATA VISUALIZATION

All checked data is exported from the GS in a defined ASCII format for spatial presentation and checking. The position, depth, run and other relevant information are extracted from the line-based data for use in the generation of Triangulated Irregular Networks (TINS) and gridded data sets. Both of these are used to produce contour plots, sun-illuminated color-banded images and coverage check plots. Anomalies found in these plots are reported to the Project Manager for remedial action in the GS.

A number of software packages are used to produce these products and create query files to be imported into the GS for sounding interrogation.

B.6 APPROVAL

In the final phase the Project Manager reviews each line from start to finish to ensure that all data edits and tags were made correctly during pre-validation, validation and checking and that no erroneous soundings remain in the final dataset. Each survey line is reviewed primarily in the Local Area Display (refer to Section A.3.5).

B.7 AUDIT TRAIL

The significant filter and single point edit actions in validation, checking and approval are logged on appropriate forms, and the procedures used have been certified as conforming to ISO-9001 Quality Assurance standards. All operator actions are logged by the GS for complete traceability.

B.8 TAGGING OF SOUNDINGS

During data processing on the GS, the operators have the ability to assign S-57 and user-defined tags to gaps and features in the data. These are often used to highlight or define the nature of specific features or seabed areas to minimize investigation duplication during data checking, QC and approval. Some of the seabed / near shore features highlighted by GS tags include wrecks, obstructions, pipelines, breakwaters, beacons, jetties / piers and bridges.

The GS user-defined tag was used to delineate Secondary Exclusion Zone (SEZ) gaps in very shallow water seabed coverage, typically at a 50m interval. A data gap due to the SEZ occurs at the land / sea interface where the waveform return from the seabed is mixed with the waveform return from the sea surface. Neither the seabed nor a drying sounding can be determined so a gap exists in this shallow area. In most cases, these gaps are fully, or partially filled by flying alternate 200% coverage lines at a different tidal state.

B.8.1 Lidar Gap Tagging

The following user-defined tags were used to delineate gaps in the Lidar seabed coverage, typically at a 50m interval:

GB	Bathymetry data gap due to ships / boats.
SEZ	Bathymetry / topography data gap due to the secondary exclusion zone (SEZ).

A data gap due to boats occurs when a vessel is over flown during data collection. Additional lines are planned to cover these gaps, but due to vessels being anchored at the same position throughout the survey period, some gaps may not be filled.

A data gap due to the SEZ occurs in very shallow water, where the waveform return from the seabed is mixed with the waveform return from the sea surface. SEZ gaps are common along most coastlines at the land / sea interface. Neither the seabed nor a drying return can be determined, so a gap exists in this very shallow area.

B.9 LASER WAVEFORMS - NATURE AND INTERPRETATION

The annotated Sounding Waveform Display (refer to Figure 17) contains the following data:

- Graphic of raw laser waveforms showing return from the water surface ① and seabed ② for a matrix of 9 adjacent soundings
- Depth contender showing selected seabed return, in this case a BOD contender ③ and alternate subsurface return contenders ④ if they exist
- The Frame, Row and Column of the active sounding ⑤
- The real-time green receiver gain values for sounding measurement ⑥
- Type of sounding, currently there are up to 5 subsurfaces that can be selected by the GS, a shallow return, two subsurface returns and BOD returns for both subsurfaces ⑦
- Depth values for the possible subsurfaces ⑧ and the SNR for the respective depth values ⑨
- The selected depth and the type of return ⑩
- The status of the sounding, either secondary, primary or NBD ⑪
- Grid coordinates of sounding on the survey spheroid and grid ⑫

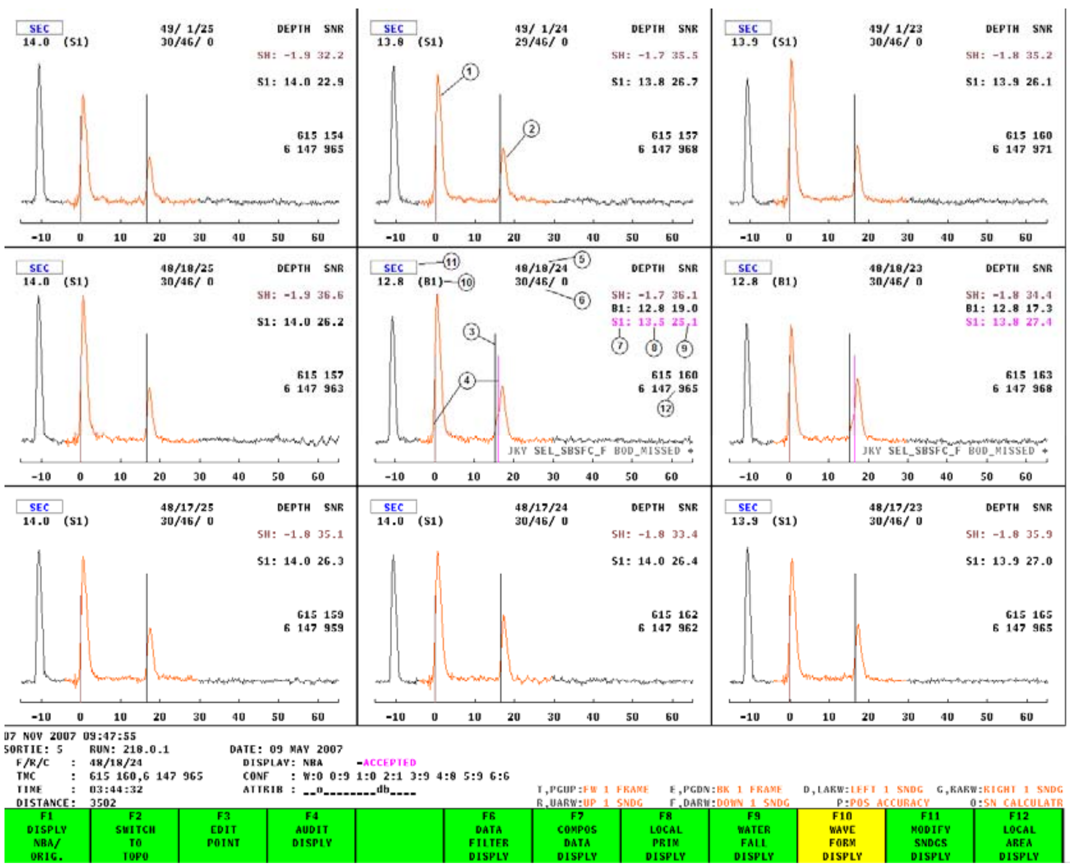


Figure 17 – Annotated Sounding Waveform Display

The raw laser waveform represents the level of energy detected by the green receiver as a function of depth. A surface model, or datum, is then calculated from the infrared, GPS and inertial AHRS heights and filtered green surface returns. The SRP selects up to five possible seabed returns for each waveform based on SNR criteria. If no possible seabed returns are found, the sounding is classified as NBD.

Depths, measured from the surface datum to the 50% point on the leading edge of a seabed return, are calculated for each possible seabed return. These depths are then corrected for the optical path of light through the water and the height of tide.

Where more than one seabed return is found, the most likely is selected based on SNR versus depth criteria. The selected return is indicated on the Waveform Display by a white depth contender bar and the alternate depth contender bars are colored blue. During validation the operator will check these selections and edit as appropriate.

Objects on the seabed will appear on the raw laser waveform before the seabed return. Detection of an object on the seabed will depend on both the density of the scan pattern, gain of the green receiver, backscatter from the water column and the ratio between the level of laser energy reflected from the target and that from the illuminated area of the seabed. The latter is in turn influenced by the size of the target, the depth of water (which affects the area of seabed illuminated) and the reflectance of the target compared with the surrounding seabed.

Backscatter from the water column is received as noise on the raw laser waveform and ultimately limits the maximum gain that can be applied, which influences the maximum depths that can be measured by the system.

B.10 RELATIVE REFLECTIVITY

The reflectivity of the LADS laser pulse is analogous, but different, to both multi-beam backscatter and topographic Lidar intensity. The reflectivity of the LADS laser pulse represents a measure of the amount of energy reflected from the seabed for each individual laser pulse at the wavelength of the laser, 532nm (green / blue).

The basic difference between processing LADS laser waveform for depth and reflectivity is that depth processing focuses on the leading edge of the return waveform, and reflectivity requires the entire return pulse from the seabed to be integrated. The two figures below depict, firstly, the time domain calculation required for depth calculations between the waveform returned from the sea surface and seabed, and secondly, the integration of the waveform to calculate the energy reflected from the seabed.

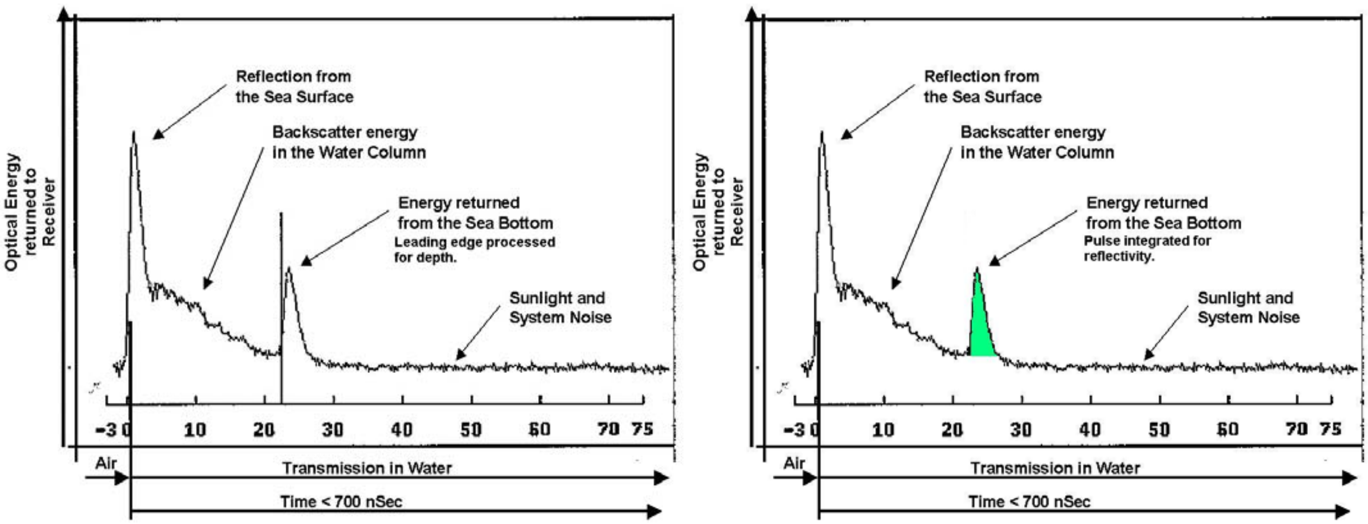


Figure 18 - Time domain calculation required for depth calculations between the waveform returned from the sea surface and seabed, and secondly, the integration of the waveform to calculate the energy reflected from the seabed.

However, prior to determining the reflectivity for each pulse, each sounding is assessed for suitability. Drying soundings and soundings in very shallow water are not processed for reflectivity. Also, within the processing workflow, reflectivity processing is undertaken after the raw data has been processed for depth. Thus, soundings for which valid depths were not approved are also removed from the reflectivity processing. Following this vetting process suitable soundings are processed to produce reflectivity data.

The entire return waveform needs to be compensated for the electronic gain of the receiver system. The gain control algorithms of the LADS system are complex and not described here. However, functionally this step is straight forward with each sounding normalized for the electronic gain that was applied to the photo multiplier tube to which the received laser energy is optically routed.

The gain normalized return waveform is then analyzed to determine the level of returned energy from the seabed. As indicated previously this is just a simple integration of the segment of the waveform reflected from the seabed. The integration of the waveform from the seabed will produce a numerical value. In order to ensure this value accurately and meaningfully maps variation of seabed reflectivity, it must be normalized for several parameters.

Energy is lost from the pulses transmitted from the aircraft. These losses are attributed to several sources, and to produce a robust reflectivity value, they must be compensated for. These energy loss sources include losses through the air, losses at the air / water interface and losses through the water column, as well as any system specific losses such as optical filtering, receiver field of view or polarization. It is assumed no energy is lost through the air.

The actual path length of the pulse through the air and water is a function of the aircraft height, water depth and angle at which each pulse is transmitted from the aircraft. The loss through the water column is a function of turbidity and water depth. Waveforms are analyzed to determine a beam attenuation coefficient that is then used to calculate loss as a function of water depth. The loss at the air / water interface, whilst not varying significantly with incidence angle given the LADS system geometry, could be expected to vary significantly with increased sea state. Additional losses for the LADS system are due to optical components that are used in some circumstances. The loss of energy attributed to these is also calculated.

The reflectivity algorithm determines the relative reflectivity of the sea bottom using a simple energy summation for each sounding. The transmitted energy is recorded during the survey and the received energy can be found by integrating the bottom pulse in the green waveform. The energy losses along the path of the beam are estimated using models of the physical phenomena, such as light scattering through the water column and diffuse reflection from the sea bottom. Finally, the amount of energy absorbed by the sea bottom is calculated and hence the reflectivity can be determined.

energy absorbed = energy transmitted – energy received – path losses

Accounting for losses along the path of the beam is complicated, as the amount of scattering and absorption depends on both the depth and turbidity of the water. The reflectivity algorithm allows for either automatic estimation of turbidity from the backscatter through the water column, or the manual input of a turbidity value.

The algorithm is limited to finding the relative reflectivity of the sea bottom, and does not attempt to classify areas into material types such as rock or sand. This is because many different materials will have the same reflectivity, even if they are a different color (because only green light is used). The reflectance data is a relative measure of reflectance, not an absolute measure. For identifying areas of common material types, additional processing and bottom sampling is necessary.

B.11 QUESTER TANGENT LIDAR SEABED CLASSIFICATION

For this project additional processing of the LADS Relative Reflectivity data was conducted by Quester Tangent. The results of this further processing are presented in the Quester Tangent report at Appendix IV. The Final Report on Lidar Seabed Classification of the Inshore Waters of Broward County, FL and the Quester Tangent data is listed at Appendix II as being provided on the USB hard drive.

B.12 DATABASE MANAGEMENT

B.12.1 Survey Line Identification

The table below lists all of the survey lines flown during the survey and the specific reason for them being conducted:

Sub-Area	Lines	Sounding Density	Line type	Remarks
–	1 – 3	4x4	Cross Lines	Cross line comparison checks.
–	22 – 23	4x4	Additional Coverage Lines	For additional coverage at Port Everglades.
–	50 – 53	4x4	Depth Benchmark Lines	For depth accuracy checks.
1	100 – 117	4x4	Main Survey Lines	100% coverage.
2	200 – 209	4x4	Main Survey Lines	100% coverage.
3	300 – 308	4x4	Main Survey Lines	Flown to obtain 200% coverage in near shore areas.
–	400 – 404	4x4	Additional Coverage Lines	For additional near shore coverage.
–	500 – 501	4x4	Additional Coverage Lines	For additional near shore coverage.

B.12.2 Line Identifier Convention

Line identifiers within the LADS Mk II system uniquely define a specific line and are made up of 4 fields separated with a decimal '.' as follows:

(Items in <> are the generic names for the fields.)

<LineNumber>.<Section>.<Sequence>.<Child>

e.g. 101.1.2.3

Maximum fields are
100000.99.99.99

LineNumber – Range 1...100000
This field uniquely defines the line and is chosen by the operator when defining a line.

Section – Range 0...99
This field denotes the section of the line.

Zero indicates the whole original line. When the line or part of the line is reflown, the section number is incremented. Thus:

- 101.0.x.x is the original line
- 101.1.x.x is the first refly
- 101.2.x.x is the second refly

Sequence – Range 1...99
This field denotes the number of times the logged data for the specific <LineNumber> .<Section> has been processed. Each time a line is processed by the SRP function, the GS allocates a new sequence number for the line. Thus:

- 101.0.1.x is the first processing of the original line
- 101.0.2.x is the second processing of the original line
- 101.1.1.x is the first processing of the first refly
- 101.1.2.x is the second processing of the first refly

Child – Range 1...99
This field denotes the segment (or child section) of a <LineNumber> .<Section>.<Sequence>.

Hydrographic surveyors divide lines into Accepted, Rejected or Anomalous segments during the Line Validation process. These segments are given sequential child numbers. Thus:

- 101.0.1.1 – is the first child (segment) of the first processing of the original line
- 101.1.2.3 – is the third child (segment) of the second processing of the first refly

B.12.3 Processing Parameters

Each survey line is processed with a specific set of processing parameters, with the set used for the line recorded on the Survey Line History Sheet. Full details are recorded in the survey data management folders held by Fugro LADS, Inc.

B.13 ERROR MINIMIZATION AND MODELS

B.13.1 Water Clarity

The greatest contributor to depth performance, seabed coverage and data quality with a bathymetric Lidar system is water clarity. In order to minimize the errors and data gaps attributed to poor water clarity, ongoing analysis of the water column conditions was imperative.

The water clarity at Broward County was managed effectively by using this survey area as an alternate to the large NOAA survey being conducted concurrently over Biscayne Bay, Florida. As the Broward County area was approximately 5 minutes flight time from the

NOAA area, rapid diversion between the surveys during periods of limiting environmental conditions, such as low cloud and glassy seas, resulted in numerous evaluations of water clarity. It was not until the third attempt at data collection in the area that water clarity conditions were deemed adequate for effective coverage. As 80% of the most critical survey lines were flown during this sortie and the flight on the following evening, water clarity was deemed excellent for the survey, and this is represented by bathymetry generally beyond 35m water depth and good quality LADS Relative Reflectivity across the survey extents.

B.13.2 Total Propagated Uncertainty

For this survey area, global horizontal and vertical uncertainties have been assigned based on the defined horizontal and vertical error budget, as stated in the Horizontal and Vertical Control Report. The assigned horizontal uncertainty is 2.51m and the assigned vertical uncertainty is 0.34m.

However, when the calculated BASE Surface grid node standard deviation is greater than the assigned vertical uncertainty, the standard deviation is used as the uncertainty value. This has occurred in areas of high relief, which is common throughout the survey area. In some sloping areas the standard deviation may exceed IHO Order-1 limits. This could be attributed to a 3m grid resolution being used for BASE Surfaces.

B.14 DATA OUTPUT AND DELIVERABLES

Digital data deliverables and graphics BASE Surface and S-57 feature file are output and prepared in accordance with:

- NOS HYDROGRAPHIC SURVEYS. SPECIFICATIIONS AND DELIVERABLES. April 2009.
- HYDROGRAPHIC SURVEY PROJECT INSTRUCTIONS. OPR-H328-KRL-09 of June 17, 2009.

All data is exported in meters as per the above documents.

B.14.1 Bathymetry Dataset Deliverables

Digital datasets delivered are:

- Full resolution dataset
- BASE Surface created in CARIS
- S-57 feature files created in CARIS

Full resolution dataset:
A full resolution dataset is created during export from the GS. The export is in a CARIS compatible format (*.CAF) and includes accepted data. Data is imported into CARIS HIPS in order to create a dataset in HDCS format. Data is delivered in the HDCS format. Data is stored to centimeter precision and is in meters. Soundings are not rounded.

BASE Surface:
The BASE Surface is created using the Uncertainty BASE Surface option in CARIS HIPS using a resolution of 3m.

S-57 feature file:
The S-57 feature file contains features such as rocks, MHW line (both natural and man made coastline), MLLW line, delineation of coverage gaps and cultural features, and has replaced the traditional smooth sheet. All features have been generated and attributed using CARIS BASE Editor software.

MHW and MLLW lines have been interpolated and edited where necessary using CARIS. The BASE Surface has been used as the source for the interpolation of linework.

The MHW line was also quality controlled against publicly available imagery to check for correct interpolation of the data, particularly in areas of where cultural features were present.

Rocks were identified using the measured data and BASE Surface and then flagged in CARIS HIPS. The features were created as S-57 objects and attributed using CARIS BASE Editor.

All S-57 objects created in BASE Editor were exported to an S-57 feature file (*.000) as the final step.

B.14.2 Relative Reflectance Dataset Deliverables

Ext	Data Type	File format
.txt	File containing GS export parameters	TXT
.txt	ASCII Relative Reflectivity, for all soundings in the reflectance dataset	TXT

B.14.3 Quester Tangent Deliverables

Ext	Data Type	File format
.csv	Broward County Classification	Excel CSV
.txt	ASCII Interpolated Broward County Classification	TXT
.txt	ASCII Interpolated Broward County Classification Including Unknown Values	TXT
.pdf	Lidar Classification of Broward County Report	PDF

B.14.4 File Naming

File names for all items output by the GS are constructed as follows:

<RegistryNumber> . <Extension>
where <Extension> is derived from the data type as per the following table:

Ext	Data Type	File format
.txt	File containing GS export parameters	TXT
.caf	LADS Mk II CARIS Output Data	CARIS compatible format
.cbf	LADS Mk II Waveform Data	CARIS compatible format

File names for all items output by CARIS are constructed as follows:

<RegistryNumber> . <Extension>
where <Extension> is derived from the data type as per the following table:

Ext	Data Type	File format
.000	S-57 feature file	.000 Ed 3.1
.hns	CARIS HYDROGRAPHIC NAVIGATION SURFACE	CARIS BASE Surface Format
.xml	CARIS BASE Surface parameters file	XML (Extended Markup Language)

B.14.5 Summary of Digital Deliverables

A directory listing of each digital deliverable is provided at Appendix II.

C. CORRECTIONS TO SOUNDINGS

The optics and electronics for laser transmission and reflected waveform collection for all soundings is done by equipment mounted on a stabilized platform within the aircraft. This platform is stabilized by a servo system, with information provided from the AHRS. This minimizes the motion effect (roll and pitch) of the aircraft. All attitude residuals from the local horizontal are logged by the AS for correctional processing by the GS.

Sounding depths and positions are determined in the GS from the raw laser waveform, aircraft height, platform attitude parameters and GPS, as logged by the AS.

The GS automatically corrects soundings for aircraft height and heading, offsets between sensors, latency, mirror and platform angles, sea surface model errors, refraction of the laser beam at the sea surface, the effects of scattering of the beam in the water column and reduction for tide.

Correct operation of the system is verified by static and dynamic position checks, depth benchmark comparisons, analysis of overlaps from the 100% coverage of the seabed and crossline comparison results.

All laybacks are measured relative to the survey reference position on the aircraft, which is the center of the scanning mirror. The GPS antenna used for position determinations in the AS is located on the upper side of the aircraft fuselage, forward and to the left of the sounding reference position (refer to Figure 19). The signal from this antenna is passed to a splitter, one signal going to the GPS receiver in the Navigation Systems computer of the AS and the other passes to the GPS airborne logger.

Offsets are from the sounding reference point to the GPS antenna with the following axis and sign convention:

- X positive, toward the nose of the aircraft
- Y positive, to the left, facing forward
- Z positive, vertically up

The offsets are:

- X offset: + 1.895m
- Y offset: + 0.43m
- Z offset: + 2.45m

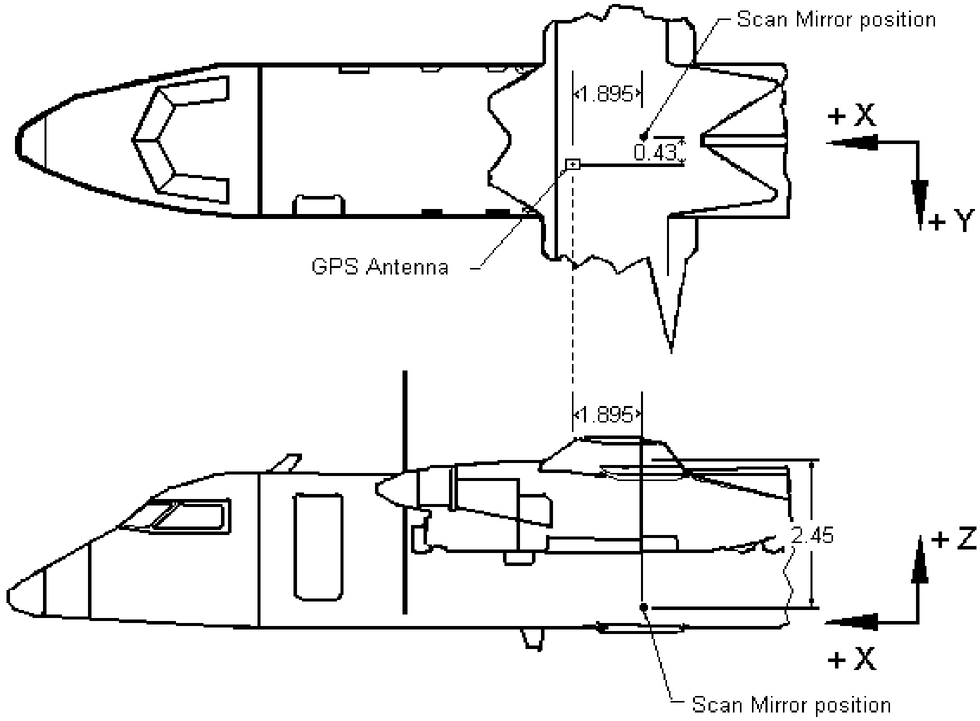


Figure 19 – Laybacks

D. APPROVAL SHEET

LETTER OF APPROVAL – OPR-H328-KRL-09

This report and the accompanying digital data are respectfully submitted.

Field operations contributing to the accomplishment of this survey were conducted under my direct supervision with frequent personal checks of progress and adequacy. This report and the accompanying digital data have been closely reviewed and are considered complete and adequate as per the Hydrographic Survey Project Instructions.

Report	Submission Date
Data Acquisition and Processing Report	October 28, 2009

Mark Sinclair
Hydrographer

Fugro LADS, Incorporated

Date: October 28, 2009

APPENDIX I – LADS MK II GROUND SYSTEM OUTPUT FORMAT SPECIFICATION FOR CARIS

This is a controlled document.

Copy No:
Issue No: 1.00

LADS Mark II

Ground System Output Format Specification for CARIS

Document Number: LADS2A05.001.008

Authorised by: ______________________

Date: 06/05/2003

Amendment Status

As necessary, authorised amendments will be issued to holders of this document. Amendments will take the form of replacement or additional pages.
The amendment status appears at the top right side of each page. For instance, Issue 1.00, where 1 is the Issue and 00 is the Amendment. The next amendment change would appear as 1.01.
Upon receipt, amendment pages are to be inserted in this document and superseded pages removed. For each amendment incorporated, the amendment number, date of incorporation and the signature of the amending officer must be entered in the table below.

Amendment Number	**Date Incorporated**	**Entered By**

List of Effective Pages

Page Number	Issue Status	Page Number	Issue Status
Title Page	1.00		
ii	1.00		
iii	1.00		
iv	1.00		
1	1.00		
2	1.00		
3	1.00		
4	1.00		
5	1.00		
6	1.00		
7	1.00		
8	1.00		
9	1.00		
10	1.00		
11	1.00		
12	1.00		
13	1.00		
14	1.00		
15	1.00		
16	1.00		
17	1.00		
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19	1.00		
20	1.00		
21	1.00		

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1. Introduction

1.1 Purpose

The purpose of this document is to specify the format produced by the **Output CARIS Data Function** of the Laser Airborne Depth Sounder (LADS) Mk II Ground System (GS).

1.2 Scope

The document applies to the results generated by the **Output CARIS Data Function** of the LADS Mk II Ground System.

1.3 Definitions, Acronyms and Abbreviations

1.3.1.1 Definitions

Mission	A mission is defined as a continuous period of operation of the LADS Mk II System, with the objective of conducting a survey of an area of ocean defined by the customer. Individual survey flights are called sorties.
Easting & Northing	The aircraft position is expressed in metres North and East of the false origin on the Universal Transverse Mercator (UTM) Grid. This implies that a change in easting and northing represents a corresponding movement on the earth's surface expressed in metres. Note: The changes in eastings and northings are related to changes in latitude and longitude via complex translation equations.
Julian Day	The numerical day of the year i.e. January 1 is day 1 and February 28 is day 59.
Soundings	Soundings consist of depth information that results from laser events and, position information corresponding to GPS data. The waveform as seen on the displays is a composite of the Green and IR returns. The soundings, numbered 1 to 48 for each scan, are always numbered from the starboard side.
Survey Run	This is the part of the survey objective where depth soundings are taken.
Fairchart	Hardcopy plot of bathymetric survey data. The soundings appearing on the fairchart are the sub-set of soundings that have the field "Fairchart Selected" set to "Y".
No Bottom At (NBA)	These are secondary soundings where the seabed has not been detected by the Ground System, and a NBA depth has been assigned by a Hydrographic Survey Operator. The depth value assigned is the depth which, in the opinion of the Hydrographic Survey Operator has been

swept clear by laser, with depths less than this being detected by the system

1.3.1.2 Acronyms

AS	Airborne System
GS	Ground System
GPS	Global Positioning System
LADS	Laser Airborne Depth Sounder
UTC	Universal Time Coordinated
NBA	No Bottom At
UTM	Universal Transverse Mercator
NBD	No Bottom Detected

1.3.1.3 Abbreviations

Nil

1.4 References

Glossary of LADS Terminology 0006A00005

2. GS Output Format

2.1 Overview

When the **Output CARIS Data Function** is run the results take the form of two files per run:

1 An ASCII file with CAF(CARIS ASCII Format) extension,
2 A Binary file with CBF (CARIS Binary Format) extension.

Each file name has the following structure:

- a 1-12 character prefix (prompted for in the GS),
- followed by an underscore, and then
- 7-14 digits that describe in the following order; the run number (1-4 digits), an underscore, run segment (1-2 digits), an underscore, run sequence (1-2 digits), an underscore and run child (1-2 digits).

The maximum length of the filenames including the extension is 30 characters.

For example, if the operator enters a filename of OTWAY, then for run 1020.0.1.2, the two output files will be called:

“OTWAY_1020_0_1_2.CAF”, and

“OTWAY_1020_0_1_2.CBF”.

A GS tableau option allows for the CAF files to be kept together in a single file or spread over one file per run. In the case of the single file the filename will be of the form “OTWAY.CAF”. Binary files will always be separate.

The structure of an ASCII file is shown in Figure 2-1 below, with the components being described in the following sections.

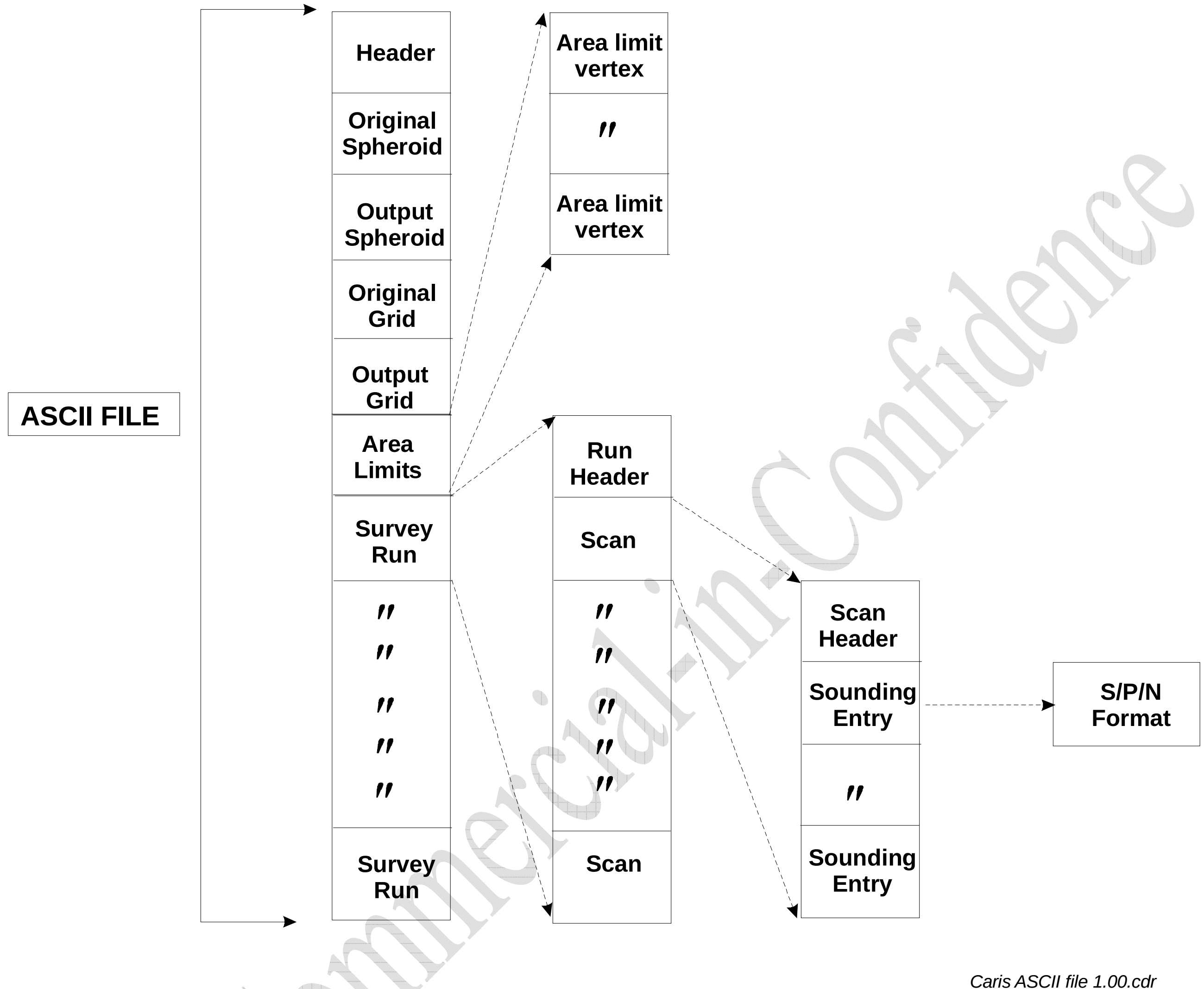

Figure 2-1 Structure of the ASCII file from the Output CARIS Data Function

2.2 Output Information

2.2.1 Header

The information associated with the **Header** output is listed below.

Name	Format	Range	Comments
Header identifier	X(3)	HCA	Header of CARIS ASCII format
Specification Issue	F(5,2)		Issue number of the specification
Mission title	X(40)		
Mission ident number	D(3)	1.. 999	
Time of data output	D(7)		Julian date, formatted as dddyyyy
Data scope	X(1)	S,P,A	S – All secondary soundings, P – All Primary soundings. A – All Primary soundings, including soundings where the sea bed was not found (NBD)
NBA included	X(1)	Y, N	This flag indicates that soundings marked as "No Bottom At" have been included.
Clash Range Radial	D(3)	0 .. 550	Represents the minimum distance in metres between soundings. Soundings contained in the fairchart are identified with the "fairchart selected" flag in the sounding data. If no reduction processing was performed this value will be 0, and the "fairchart selected" flag will be set true for all soundings.
Position transform applied	X(1)	Y, N	This flag indicates that positions used in this data have been transformed to a spheroid or grid different to that used to collect the data. The values for the original and output spheroid/grid are detailed below.

Table 1 Header Output Information

The format of the information associated with the **Header** output is as shown below:

Format
X(3) ∧F(5,2) ∧X(40) ∧D(3) ∧D(7) ∧X(1) ∧X(1) ∧D(3) ∧X(1)←

Table 2 Format of Header Information

2.2.2 Original/Output Spheroid

The information associated with the **Original/Output Spheroid** output is listed below.

Name	Format	Range	Comments
Spheroid entry identifier 1	X(2)	C1,D1	C – Original, D – Output.
Spheroid ident text	X(40)		
Spheroid entry identifier 2	X(2)	C2,D2	C – Original, D – Output.
Major semi axis	F(10,2)	6_300_000.0 .. 6_500_000.0	
Minor semi axis	F(10,2)	6_300_000.0 .. 6_500_000.0	
Flattening	F(9,6)	250.0 .. 350.0	
Eccentricity	F(14,12)	0.006 .. 0.0075	
Spheroid entry identifier 3	X(2)	C3,D3	C – Original, D – Output.
GPS X offset	F(8,2)	-1000.0 .. 1000.0	The following "GPS" prefixed fields represent the transformation parameters required to move from the WGS84 spheroid to this spheroid.
GPS Y offset	F(8,2)	-1000.0 .. 1000.0	
GPS Z offset	F(8,2)	-1000.0 .. 1000.0	
GPS X rotation	F(10,5)	-206.0 .. 206.0	Uses the Coordinate Axis Rotation sign convention. (ie. rotations effect the axis). A positive rotation is defined as clockwise when viewed from the origin along the axis. (eg for a given position, a positive rotation about the Z axis will result in the transformed position having a longitude with a smaller value)
GPS Y rotation	F(10,5)	-206.0 .. 206.0	see above
GPS Z rotation	F(10,5)	-206.0 .. 206.0	see above
GPS Scale factor	F(8,5)	-1.0 .. 1.0	

Table 3 Output Information for Original/Output Spheroid

The format of the information associated with the **Original/Output Spheroid** output is as shown below:

Format
X(2) ∧X(40) ←
X(2) ∧F(10,2) ∧F(10,2) ∧F(9,6) ∧F(14,12) ←
X(2)∧F(8,2) ∧F(8,2) ∧F(8,2) ∧ F(10,5) ∧ F(10,5) ∧ F(10,5) ∧F(8,5) ←

Table 4 Format of Original/Output Spheroid Information

2.2.3 Original/Output Grid

The information associated with the **Original/Output Grid** output is listed below.

Name	Format	Range	Comments
Grid Entry Identifier	X(2)	F1,G1	F – Original, G – output
Grid ident text	X(20)		
Latitude of true origin	D(3)	-90 .. 90	
Central meridian longitude	D(4)	-180 .. 180	
Zone identifier	X(2)	1 .. 60, SP	1 .. 60 – UTM Zone identifier. SP – identifies a non-standard (special) zone.
False origin easting	D(8)	-5_000_000 .. 5_000_000	
False origin northing	D(9)	-10_000_000 .. 20_000_000	
Central scale factor	F(7,4)	0.5 .. 1.5	

Table 5 Output Information for Original/Output Grid

The format of the information associated with the **Original/Output Grid** output is as shown below:

Format
X(2) ∧X(20) ∧D(3) ∧D(4) ∧X(2) ∧D(8) ∧D(9) ∧F(7,4) ←

Table 6 Format of Original/Output Grid Information

2.2.4 Area Limits

The information associated with the **Area Limits** output is listed below.
There can be up to 10 vertices defining and area, with these vertices being numbered from 0-9. Lines are only output for vertices that have been defined. i.e. for a rectangle only 4 vertices are output.
The polygon points are ordered in a clockwise fashion, and the polygon is not closed geometrically. The coordinates are relative to the output spheroid and grid systems.

Name	Format	Range	Comments
Area limits identifier 1	X(2)	L0	Entry identifier for polygon point 1
Lat	F(12,8)	-90.0 .. 90.0	
Long	F(13,8)	-180.0 .. 180.0	
Easting	D(8)	-5_000_000 .. 5_000_000	
Northing	D(9)	-10_000_000 .. 20_000_000	
…			
Area limits identifier **n**	X(2)	L[**n**-1]	Entry identifier for polygon point **n**
Lat	F(12,8)	-90.0 .. 90.0	
Long	F(13,8)	-180.0 .. 180.0	
Easting	D(8)	-5_000_000 .. 5_000_000	
Northing	D(9)	-10_000_000 .. 20_000_000	
Where **n** = 1 .. 10			

Table 7 Output Information for Area Limits

The format of the information associated with the **Area Limits** output is as shown below:

Format
X(2) ∧F(12,8) ∧F(13,8) ∧D(8) ∧ D(9) ←

Table 8 Format of Area Limits Output

2.2.5 Run Header

The information associated with the **Run Header** output is listed below.

Name	Format	Range	Comment
Run header identifier	X(2)	R1	
Run identifier	X(14)		The run identifier has a format as follows: Run.section.sequence.child (eg. 100.0.1.1) Where Run = run number Section = section number of main run. Used when a section of the run is reflown. Sequence = identifies the nth flown occurrence of the same run Child = portion of run accepted manually by hydrographic selection
Date flown	D(7)		Julian Date, formatted as dddyyyy
Planned Track	D(3)	0 .. 360	The planned track of the run in degrees, expressed as a grid bearing
Status	X(9)	ACCEPTED, ANOMALOUS or REJECTED	The run status of the child run.

Table 9 Output Information for Run Header

The format of the information associated with the **Run Header** output is as shown below.

Format
X(2) ∧X(14) ∧D(7)∧D(3)∧X(9)←

Table 10 Format of Run Header Output

2.2.6 Scan Header

The information associated with the **Scan Header** output is listed below.

Name	Format	Range	Comment
Scan header identifier	X(2)	W1	
Scan Reference Position lat - output spheroid	F(12,8)	-90.0 .. 90.0	Corresponds to position of sounding at column 24 in the Output Spheroid. Expressed in degrees.
Scan Reference Position long - output spheroid	F(13,8)	-180.0 .. 180.0	Corresponds to position of sounding at column 24 in the Output Spheroid. Expressed in degrees.
Time - year	D(4)	0 .. 9999	
Time – Julian Day	D(3)	1 .. 366	
Time – Hour	D(2)	0 .. 23	
Time – Minute	D(2)	0 .. 59	
Time – Second	D(2)	0 .. 59	
Scan Row Number	D(2)	1 .. 18	The Scan Number can be considered as a time component, ($1/18^{th}$) of a second
Tide Correction	F(6,2)	-20.00 .. 20.00	Represents the tide adjustment made to the observed depth to give the sounding Depth relative to the LAT datum.

Table 11 Output Information for Scan Header

The format of the information associated with the **Scan Header** output is as shown below.

Format
X(2) ∧F(12,8) ∧F(13,8) ∧D(4) ∧D(3) ∧D(2) ∧D(2) ∧D(2) ∧D(2) ∧F(6,2) ←

Table 12 Format of Scan Header Output

2.2.7 Sounding Entry (S, P, N)

The information associated with the **Sounding Entry** output is listed below.

Name	Format	Range	Comments
Sounding identifier	X(1)	S,P,N,X	S - secondary sounding, P - primary sounding, N - NBA sounding, X – NBD sounding.
Selected Depth Position lat - output spheroid	F(12,8)	-90.0 .. 90.0	Expressed in degrees.
Selected Depth Position long - output spheroid	F(13,8)	-180.0 .. 180.0	Expressed in degrees.
Selected Depth Position Easting - output spheroid	D(8)	-5_000_000 .. 5_000_000	
Selected Depth Position Northing - output spheroid	D(9)	-10_000_000 .. 20_000_000	
Contender Depth Position lat - output spheroid	F(12,8)	-90.0 .. 90.0	Expressed in degrees. 0.0 when no contender exists.
Contender Depth Position long - output spheroid	F(13,8)	-180.0 .. 180.0	Expressed in degrees. 0.0 when no contender exists.
Contender Depth Position Easting - output spheroid	D(8)	-5_000_000 .. 5_000_000	0 when no contender exists.
Contender Depth Position Northing	D(9)	-10_000_000 .. 20_000_000	0 when no contender exists.

Name	Format	Range	Comments
- output spheroid			
Frame	D(4)	1..1749	Frame number
Row	D(2)	1..18	Scan number
Column	D(2)	1..48	Sounding number
Selected Depth	F(6,2)	-99.99 .. 99.99	Selected Depth to tide datum (includes tide correction) in metres 99.99 when no depth was detected
Contender Depth	F(6,2)	-99.99 .. 99.99	Contender Depth to tide datum (includes tide correction) in metres 99.99 when no depth was detected
Flag	D(1)	0..255	Validation flag from LADS Ground System (see Table 15 – Validation Flag bit values)
Comment	X(10)		Operator comment
Spare	X(10)		Spare field for future expansion

Table 13 Output Information for Sounding Entry

The format of the information associated with the **Sounding Entry** output is as shown below.

Format
X(1) ∧F(12,8) ∧F(13,8) ∧D(8) ∧D(9) ∧ F(12,8) ∧F(13,8) ∧D(8) ∧D(9) ∧D(4) ∧D(2) ∧D(2) ∧F(6,2) ∧F(6,2) ∧D(1) ∧X(10) ∧X(10)←

Table 14 Format of Sounding Entry Output

Bit 7	Bit 6	Bit 5	Bit 4	Bit 3	Bit 2	Bit 1	Bit 0
spare	Clashed	Converted NBD	Manual Secondary	Swapped Contenders	Significant Contender	Excessive Gradient	Depth Edited

Table 15 – Validation Flag bit values

2.3 ASCII Format Legend

The legend for the symbols used in the format tables is listed below.

Symbol	Description	Comments
X	Text	
D(max_size)	Integer	Max_size represents the maximum number of characters allowed for the integer, including a leading minus sign if appropriate.
F(max_size,aft_digits)	Float	Max_size represents the maximum number of characters allowed for the float, including a leading minus sign if appropriate. Aft_digits represents the number of digits after the decimal point. Eg “ -10.000” would be represented as F(7,3)
^	Field separator	May be comma, space, tab.
←	Line terminator	(may be <CR><LF>, <LF>, <CR>)

Table 16 ASCII Format Legend

2.4 Binary Waveform Format

Raw waveform data is provided in a binary file in the following format.

2.4.1 Header

The information associated with the **Binary File Header** is listed below.

Name	Format	Minimum value	Maximum Value	Comments
Header identifier	ASCII(3)	HCB		Header identifier for Caris Binary file
Specification Issue major issue number	uchar	0	255	1
Specification Issue minor issue number	uchar	0	255	0
Mission Title	ASCII(40)	0	255	A string of 40 ASCII characters as per 2.2.1 Header. String is space padded.
Run Identifier	ushort	1	9 999	LADS run number range 1..9 999
Run Segment	uchar	0	99	LADS run segment number range 0..99
Run Sequence	uchar	0	99	LADS run sequence number range 0..99
Run Child	uchar	0	99	LADS run child number range 0..99

Table 17 Binary File Header

2.4.2 Scan Header

The information associated with the **Binary Scan Header** is listed below.

Name	Format	Minimum value	Maximum Value	Comments
Scan header identifier	ASCII(2)	W1		
Time - year	ushort	0	9999	
Time – Julian Day	ushort	1	366	
Time – Hour	uchar	0	23	
Time – Minute	uchar	0	59	
Time – Second	uchar	0	59	

Table 18 Binary Scan Header

2.4.3 Waveform

The information associated with the **Waveform** is listed below.

Name	Format	Minimum value	Maximum Value	Comments
Waveform identifier	ASCII(2)	WF		Waveform identifier
Frame	ushort	1	1 749	LADS frame number range 1..1 749
Row	uchar	1	18	LADS scan number range 1..18
Column	uchar	1	48	LADS sounding number range 1..48
Selected Depth Index	uchar	0	255	Index into the waveform indicating position of the selected depth
Contend Depth Index	uchar	0	255	Index into the waveform indicating position of the contending depth. 0 indicates no contender
Waveform Sample 1	uchar	0	255	1st sample of the digital waveform
Waveform Sample 2	uchar	0	255	2nd sample of the digital waveform
. . .				
Waveform Sample 120	uchar	0	255	120th sample of the digital waveform

Table 19 Binary Waveform

2.5 Binary Format Legend

The legend for additional symbols used in the format tables is shown below.

Symbol	Description	Minimum value	Maximum Value	Binary Size (bytes)
ASCII	ASCII character	0	255	1
ushort	Unsigned 16 bit Integer	0	65 535	2
uchar	Unsigned 8 bit Integer	0	255	1

Table 20– Binary Format Legend

APPENDIX II – LISTING OF DIGITAL DATA ON THE USB HARD DRIVE

<u>OPR-H328-KRL-09</u>

<USB Drive Letter>:\OPR-H328-KRL-09\Report_Files\

Reference	**Remarks**
Cover	Adobe Acrobat PDF and MS Word 2003
DA&P_Report	Adobe Acrobat PDF and MS Word 2003
DA&P_Report_Appendix_<I-IV>	Adobe Acrobat PDF and MS Word 2003
H&V_Control_Report	Adobe Acrobat PDF and MS Word 2003
H&V_Control_Report_Appendix_<I-VI>	Adobe Acrobat PDF and MS Word 2003
Separates_Report	Adobe Acrobat PDF and MS Word 2003
Separates_Report_Appendix_I	Adobe Acrobat PDF and MS Word 2003
Spine	Adobe Acrobat PDF and MS Word 2003

<USB Drive Letter>:\OPR-H328-KRL-09\Tidal_Data\

Reference	**Remarks**
BOV_observed_tides.xls	.xls file containing observed tides for Broward County supplied by BOV
Sortie_<sortie number>\Sortie_<sortie number>	.xls file containing; a. preliminary tides b. final tides for the tide application for each sortie
Tide_application_reports\TIDE_APPLICATION_REPORT_sortie_<*sortie number*>	.txt file of the Sortie Tide Application Report output from the GS
Tide_monitor_data\Sortie_<*sortie number*>\TIDE_MONITOR_DATA_REPORT_sortie<*sortie number*>_ts<*tide station number*>	.txt file of the TIDE_MONITOR_DATA_REPORT output from the GS

<USB Drive Letter>:\ OPR-H328-KRL-09\LADS_Relative_Reflectance\

Reference	**Remarks**
LADS_Relative_Reflectance\ 09_BRO_RR6.RR1	LADS Mk II Relative Reflectance GS Export
LADS_Relative_Reflectance\ 09_BRO_RR6.PRM	.txt file (Relative Reflectance export parameters)

Note: This data was provided to Quester Tangent on October 27, 2008.

<USB Drive Letter>:\ OPR-H328-KRL-09\Relative_Reflectance\QTC_Deliverables\

Reference	**Remarks**
Lidar_Classification_Broward.pdf	.pdf file (Final Report)
Broward_10cls.csv	.csv file
Broward_10cls_interp.xyz	ASCII .txt file
Broward_10cls_interp_all.xyz	ASCII .txt file

Note: This data was provided by Quester Tangent to Fugro LADS, Inc. as a final deliverable on November 26, 2008.

H12116

<USB Drive Letter>:\OPR-H328-KRL-09\H12116\Report_Files

Reference	Remarks
H12116_Descriptive_Report_Cover	Adobe Acrobat PDF and MS Word 2003
H12116_Descriptive_Report	Adobe Acrobat PDF and MS Word 2003
H12116_Descriptive_Report_Appendix_<I–IV>	Adobe Acrobat PDF and MS Word 2003
H12116_Descriptive_Report_Spine	Adobe Acrobat PDF and MS Word 2003

<USB Drive Letter>:\ OPR-H328-KRL-09\ H12116\BASE_Surface\

Reference	Remarks
H12116_3m_UNC_FINAL.hns	CARIS BASE Surface file
H12116_3m_UNC_FINAL.xml	XML parameters file

<USB Drive Letter>:\ OPR-H328-KRL-09\ H12116\Chart_Comparisons\

Reference	Remarks
H12116_ChartComp.xls	Microsoft Excel 2003
H12116_ChartComp.hob	CARIS.hob file
Screendumps\09_bro_gs_tags_chartcompA… <chart_comparison_number>_<la/wf>.jpg	Screen captures for each chart comparison

<USB Drive Letter>:\ OPR-H328-KRL-09\H12116\Data\

Reference	Remarks
Vessel\H12116.hvf	CARIS vessel file
BRO_SHEET_A.caf	LADS MKII CARIS output
BRO_SHEET_A_<LineNumber>_<Section>_... …<Sequence>_<Child>.cbf	LADS MKII Waveform data
Params.txt	.txt file

H12116 (cont.)

<USB Drive Letter>:\ OPR-H328-KRL-09\H12116\HIPS\

Reference	Remarks
HDCS_Data\H12116\ H12116\<Year-Julian Day>\ <LineNumber>	CARIS HDCS data. Project\Vessel\Day\Line format
Fieldsheets\H12116\H12116\ H12116.<extension>	CARIS fieldsheets files

<USB Drive Letter>:\ OPR-H328-KRL-09\ H12116\Lidar_Coverage\

Reference	Remarks
H12116_Shoal.tif	Geotif file
H12116_Uncertainty.tif	Geotif file

<USB Drive Letter>:\ OPR-H328-KRL-09\H12116\S57_Feature_File\

Reference	Remarks
US512116.000	S-57 feature file

H12117

<USB Drive Letter>:\OPR-H328-KRL-09\H12117\Report_Files

Reference	Remarks
H12117_Descriptive_Report_Cover	Adobe Acrobat PDF and MS Word 2003
H12117_Descriptive_Report	Adobe Acrobat PDF and MS Word 2003
H12117_Descriptive_Report_Appendix_<I–IV>	Adobe Acrobat PDF and MS Word 2003
H12117_Descriptive_Report_Spine	Adobe Acrobat PDF and MS Word 2003

<USB Drive Letter>:\ OPR-H328-KRL-09\ H12117\BASE_Surface\

Reference	Remarks
H12117_3m_UNC_FINAL.hns	CARIS BASE Surface file
H12117_3m_UNC_FINAL.xml	XML parameters file

<USB Drive Letter>:\ OPR-H328-KRL-09\ H12117\Chart_Comparisons\

Reference	Remarks
H12117_ChartComp.xls	Microsoft Excel 2003
H12117_ChartComp.hob	CARIS.hob file
Screendumps\09_bro_gs_tags_chartcompB… <chart_comparison_number>_<la/wf>.jpg	Screen captures for each chart comparison

<USB Drive Letter>:\ OPR-H328-KRL-09\H12117\Data\

Reference	Remarks
Vessel\H12117.hvf	CARIS vessel file
BRO_SHEET_B.caf	LADS MKII CARIS output
BRO_SHEET_B_<LineNumber>_<Section>_... …<Sequence>_<Child>.cbf	LADS MKII Waveform data
Params.txt	.txt file

H12117 (cont.)

<USB Drive Letter>:\ OPR-H328-KRL-09\H12117\HIPS\

Reference	Remarks
HDCS_Data\H12117\ H12117\<Year-Julian Day>\ <LineNumber>	CARIS HDCS data. Project\Vessel\Day\Line format
Fieldsheets\H12117\H12117\ H12117.<extension>	CARIS fieldsheets files

<USB Drive Letter>:\ OPR-H328-KRL-09\ H12117\Lidar_Coverage\

Reference	Remarks
H12117_Shoal.tif	Geotif file
H12117_Uncertainty.tif	Geotif file

<USB Drive Letter>:\ OPR-H328-KRL-09\H12117\S57_Feature_File\

Reference	Remarks
US512117.000	S-57 feature file

H12118

<USB Drive Letter>:\OPR-H328-KRL-09\H12118\Report_Files

Reference	Remarks
H12118_Descriptive_Report_Cover	Adobe Acrobat PDF and MS Word 2003
H12118_Descriptive_Report	Adobe Acrobat PDF and MS Word 2003
H12118_Descriptive_Report_Appendix_<I–IV>	Adobe Acrobat PDF and MS Word 2003
H12118_Descriptive_Report_Spine	Adobe Acrobat PDF and MS Word 2003

<USB Drive Letter>:\ OPR-H328-KRL-09\ H12118\BASE_Surface\

Reference	Remarks
H12118_3m_UNC_FINAL.hns	CARIS BASE Surface file
H12118_3m_UNC_FINAL.xml	XML parameters file

<USB Drive Letter>:\ OPR-H328-KRL-09\ H12118\Chart_Comparisons\

Reference	Remarks
H12118_ChartComp.xls	Microsoft Excel 2003
H12118_ChartComp.hob	CARIS.hob file
Screendumps\09_bro_gs_tags_chartcompD… <chart_comparison_number>_<la/wf>.jpg	Screen captures for each chart comparison

<USB Drive Letter>:\ OPR-H328-KRL-09\H12118\Data\

Reference	Remarks
Vessel\H12118.hvf	CARIS vessel file
BRO_SHEET_C.caf	LADS MKII CARIS output
BRO_SHEET_C_<LineNumber>_<Section>_... …<Sequence>_<Child>.cbf	LADS MKII Waveform data
Params.txt	.txt file

H12118 (cont.)

<USB Drive Letter>:\ OPR-H328-KRL-09\H12118\HIPS\

Reference	Remarks
HDCS_Data\H12118\ H12118\<Year-Julian Day>\ <LineNumber>	CARIS HDCS data. Project\Vessel\Day\Line format
Fieldsheets\H12118\H12118\H12118.<extension>	CARIS fieldsheets files

<USB Drive Letter>:\ OPR-H328-KRL-09\ H12118\Lidar_Coverage\

Reference	Remarks
H12118_Shoal.tif	Geotif file
H12118_Uncertainty.tif	Geotif file

<USB Drive Letter>:\ OPR-H328-KRL-09\H12118\S57_Feature_File\

Reference	Remarks
US512118.000	S-57 feature file

APPENDIX III – LADS MK II PERFORMANCE VERIFICATION CERTIFICATE

Tenix

TenixLADSCorporation

LADS Mk II Performance Verification Certificate

Quality System
Quality Endorsed Company
ISO9001 Lic20702

The LADS Mk II System was flown for system performance verification over Gulf St Vincent, South Australia, Sorties 3 to 10, during March 2007.

A well-surveyed benchmark run was used to verify depth and position, with the latter by using submerged targets at known positions in the benchmark area. The system performance was verified as meeting the requirements of IHO Order 1 depth and horizontal accuracy.

Approving Authority: M. Penley 2 / 8 / 07

Mark Penly, Technical Manager

APPENDIX IV – QUESTER TANGENT FINAL REPORT ON LIDAR SEABED CLASSIFICATION

Quester Tangent

LiDAR CLASSIFICATION

Final Report on LiDAR Seabed Classification of the Inshore Waters of Broward County, Fl

Prepared for Tenix LADS

Issue Date: 25 November 2008

QUESTER TANGENT™
Making Data Intelligent™

DATE	REVISION	DESCRIPTION
25 Nov 08	R00	Original Issue

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EXECUTIVE SUMMARY

The aims of seabed classification are to assemble areas of the sea floor into classes of similar bottom type and to label those classes in terms of their dominant geological or biological characteristics. Quester Tangent has extensive experience in seabed classification with acoustic data and has applied that approach to the information contained in a LiDAR signal. The first part of this aim, segmentation, was done with LiDAR signals acquired during the Tenix LADS survey off Broward County in July and August 2008. This generated a map of optical diversity through assigning groups of LiDAR footprints to seabed classes based on their reflectivity.

The second part, labelling the regions of a segmented map, requires ground truthing, that is, information acquired by some other means. The seabed off Broward County has been surveyed and analysed extensively, so there is no shortage of ground truth. No detailed correlation of QTC classes with ground truth is reported here. Only a qualitative correlation was attempted, using the map published by Walker, Riegl, and Dodge (ref. 1). This comparison gave confidence that the LiDAR classifications are generally sound.

The segmentation reported here is based exclusively on seabed reflectivity at the LiDAR wavelength. A reflectivity image is constructed by the Relative Reflectivity (RR) model developed by Tenix LADS. This model extracts the seabed reflection from the green-laser backscatter, removes the contributions from hydrosols (particles suspended in the water), and corrects for refraction and some other geometric effects to give a seabed reflectivity value for every LiDAR footprint. Each of these values becomes a pixel in the reflectivity image for each survey line. Even though the Tenix files are composites for the entire survey, their data are deconstructed back into the original survey lines for classification. Working with individual survey lines rather than mosaics has several advantages, primarily that the reflectivity data are evenly spaced and that they were recorded with consistent conditions and within a short time period.

To start the classification, each reflectivity image, as surveyed, is divided into sub-images. A series of features is extracted from each of these arrays of pixels. These are concatenated into Full Feature Vectors (FFV), one for each small patch of the seabed in the regions of acceptable quality. An unsupervised classification technique is then used to segment and classify the sets of FFVs. Principal components analysis (PCA) is employed to reduce the dimensionality of the features while retaining a very large portion of the information content. Objective automated clustering is used to group FFVs, and thus seabed patches, into classes. The results of PCA and clustering are captured in a catalogue of seabed types and in class maps for the surveyed area. The optimal number of classes was found to be ten. Ten classes are shown in the maps in this report and appear in the accompanying files.

SEABED CLASSIFICATION WITH SONAR AND LiDAR DATA

Established in 1983, Quester Tangent Corporation (QTC) is a privately owned, Canadian corporation and a designer and manufacturer of software products and hardware systems that allow users to acquire, monitor, validate, and process large amounts of data in either historical or real time. While the application of the technology is ideal for any industry requiring data handling and supervised or unsupervised processing capabilities, the company's two current key markets are marine sciences and transit electronics. To date, Quester Tangent has sales in over 30 countries.

QTC has been active in sediment classification since 1993. QTC VIEW™ hardware systems provide real-time at-sea classifications using the detailed structure of echoes from echo sounders. QTC IMPACT™ software is an Integrated Mapping Processing and Classification Toolkit for processing recorded echoes. QTC IMPACT generates classifications using similar procedures to QTC VIEW, but with more user control and filtering options available because the processing is done after the survey. These products have been widely used for surveys and research in which accuracy, repeatability, and the absence of artifacts are key.

While these products were being developed, multibeam systems became the technology of choice for hydrographic survey worldwide, and sidescan sonars also gained wide acceptance. Neither of Quester Tangent's single beam products QTC VIEW nor QTC IMPACT can be used with multibeam or sidescan data. To classify the seabed with sonar images, a totally new approach was required – one that extracts information not from the details of the vertical echo over time but from the amplitudes, variability, and texture of the backscatter image. The software suites that QTC developed to classify these data are QTC MULTIVIEW™ and QTC SIDEVIEW™.

It is well known that the statistical characteristics of a sonar backscatter image depend on the bottom type. Even to a novice user, the texture differences between images of rocks, sand, and mud are readily apparent. Differences between silt and clay are less obvious. Statistical processing can capture many of the pertinent details of the interaction between the sound and the bottom and of its vertical relief. Multivariate statistics can then isolate those details that are rich in information about the bottom, producing features that contain the information necessary for accurate and reliable bottom classifications.

Seabed classification can be done visually, mechanically, and remotely. All visual methods (divers, video, photography) and mechanical methods (divers, grab samples, cores, probes) are slow and manually intensive, thus expensive and not suited to survey work over extensive areas. In contrast, remote acoustic methods can cover large areas quickly as there is no need to stop the survey vessel. This is even more so for a LiDAR survey with its very high area coverage rate. Remote sensing of the seabed, however, is segmentation; that is, it divides an area into regions that are reasonably homogenous but does not label them directly as sand or mud, for example. Labels can be determined by analysis of visual or mechanical results, that is, ground truth. The power of remote seabed classification is the ability to apply ground-truth identifications over much larger areas than could realistically be mapped with physical samples; that is, the sediment properties obtained from the point samples can be applied with confidence over entire regions that have been mapped remotely.

This report describes applying these processes to classify LiDAR data. It starts with the Relative Reflectivity (RR) model that Tenix LADS developed to generate a reflectivity value at the green-laser wavelength for each footprint of a LiDAR survey. These are assembled into images, one pixel per footprint. Each image is divided into small squares, 9 pixels on a side. The squares are placed only where the reflectivity values are present and meet quality standards. These reflectivity images are analysed using features that capture amplitude (or reflectivity), its distribution, and its texture. Texture is an important property of images that can be visualised as the roughness and pattern differences between real surfaces, such as glass, wood, and cloth. Texture is a second-order statistic of a matrix, meaning that it is based on relationships between a pixel and its neighbours, that is, order is important. Features are generated by first constructing a Gray-level Co-occurrence Matrix (GLCM).

Reflectivity and texture features are extracted from images from the survey lines. An alternative approach, easier to implement, would have been to combine all the reflectivity values for a survey area into a mosaic, and extract features from it. Class maps produced by analysing mosaics of sonar images almost always have artifacts under the ship track or where lines overlap because accurate compensation for geometrical effects becomes impossible as details like range and grazing angle for a pixel get lost in the mosaicing process. Here, the RR model has already done the image compensation, so that motive for analysing line images, rather than mosaics, does not apply. Two strong reasons for processing data on a line-by-line basis remain. One is that line images are regularly spaced reflectivities, and regularly spaced values are required for textural analysis. Mosaics also consist of evenly-spaced data, but their pixel values are averages of different numbers of the measured reflectivities, with averaging methods such as mean, median, and shine-through. These distort texture, and not uniformly throughout the survey area. The second reason is that overlap regions can be analysed separately. Agreement, or lack of it, among class assignments from the overlapping lines is valuable in assessing the quality of the class map.

Classification of the sea bottom that gave rise to these features is done by an automated clustering method that adapts to the characteristics of the data set. Each cluster represents a bottom type, which can be labelled based on ground truth; for example, photographs, grain-size analysis, or other local data. If the bottom type is known before classification, data from the areas of known sediment type can be used to build a catalogue, which would then be used to classify subsequent or archived data. This is called supervised classification. The first method mentioned, unsupervised classification, forms the data into logical clusters that can then be identified based on ground truth. The effectiveness of unsupervised classification in uncovering practical and valuable information from imagery has been demonstrated in many projects. This clustering technology, with its classification options, forms part of QTC MULTIVIEW, QTC SIDEVIEW, and LiDAR classification as described here.

In summary, image-based seabed classification is the segmentation of seabeds into discrete classes based on the characteristics of backscatter throughout a region. Segmentation is a valid and useful survey tool, even though it does not independently identify geophysical types. Dividing the seabed into classes is useful because seabed characteristics are relatively constant throughout a class and distinct from the characteristics of other classes. Therefore, the amount of ground truth that needs to be collected, visually or mechanically, is dramatically reduced. A small number of samples from each class are adequate to define the entire class. Also, if sampling locations are chosen away from class borders the samples would be known to represent a single class, not a mixture of classes. This further reduces the number of samples that have to be processed. The strategy of identifying classes with a few samples and confidently extrapolating those characteristics throughout a region is both scientifically valid and very cost effective.

Classification Process

Process Flow

Figure 1 illustrates the flow of the two similar classification processes for LiDAR data and for sonar-image data from either a multibeam or a sidescan sonar. The process flow for sonar data is described in more detail in Reference 2. Once the Tenix LADS data are loaded, as described below, the primary quality control is the construction of a mask that sets aside pixels that do not have both reflectivity and depth values. Each pixel in a LiDAR image is a LiDAR footprint. In this survey the footprints were 4 m apart, which is much lower resolution than a sonar image in which pixels can be as small as 15 cm on a side.

All the data for LiDAR classification is from two files prepared by Tenix LADS. These files meet the specifications listed in References 3 & 4. One is the usual CAF file, which contains verified bathymetry. The other is a file of seabed reflectivity for all the LiDAR footprints for which a reflectivity can be calculated. The reflectivity is an 8-bit value, normalised over a day's survey lines. These files can be very large if they are for a full survey area, as they usually are. They contain enough common information to allow the depth and reflectivity from each footprint to be brought together. The QTC load process reorganises these data back into their original survey lines and generates three matrices of the same size for each survey line:

1. a matrix of reflectivity values
2. a matrix of depths
3. a mask, which is a matrix of the same size whose value is zero for each footprint that has both a reflectivity value and a negative depth, least-significant bit set to one if reflectivity is absent, and the next bit set to one if depth is absent.

These matrices have 48 columns, since there are 48 footprints across a LADS scan line. The number of rows equals the number of LADS scan lines in that survey line.

Place Squares

The data matrices are divided into rectangular patches, guided by the mask. Patches are placed only where at least 95% of the mask within a patch is zero. Each patch is thus described by three submatrices: reflectivity values, depth, and mask. After feature generation, PCA and clustering, each patch gives rise to one point in feature space and thus to one classified point on a class map. The location of that point on the map is the position of the centre of

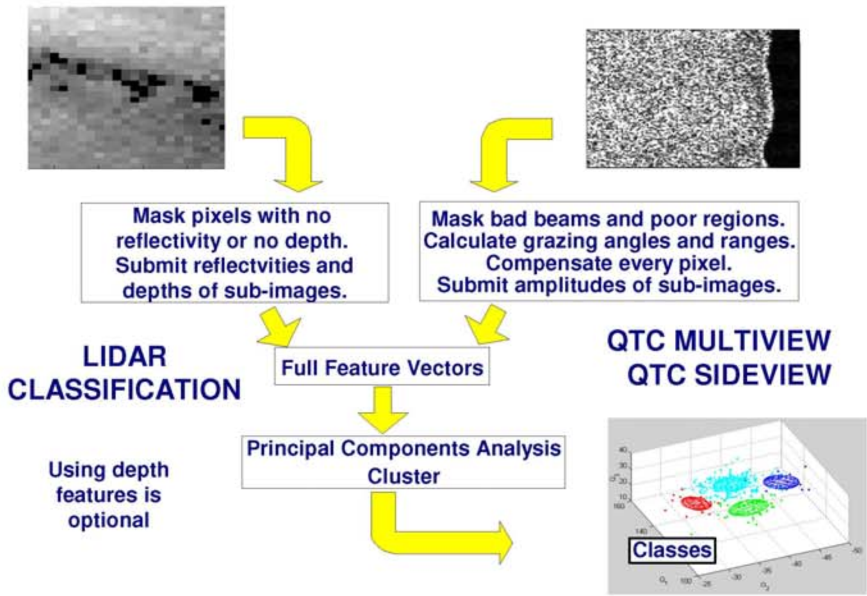

Figure 1. Process flows for seabed classification of images of reflectivity as collected by LiDAR and by sonar systems.

the rectangular patch. The patches are placed in image space, that is, on the image; and the spatial resolution of the class map is the distance between patch centres, in metres or feet. In classifying sonar images, the user has to choose the size of the patches as a compromise between spatial resolution and having too many patches for practical processing. The available lengths of each side are 9, 17, 33, 65, 129, 257, and 513 pixels (that is, $2^n + 1$ for $n = 3$ to 9). Popular choices are 33, 65, or 129 pixels across-track since sonar images often have thousands of pixels in each raster. LiDAR data, by contrast, have only 48 pixels across track, and the same spacing along-track, meaning that the only sensible choice is a square 9 pixels on a side. Patches do not usually overlap, when classifying sonar images, but here the squares overlapped 2 pixels. This allows up to 6 squares across-track.

Squares are not placed over all of each image. LiDAR footprints that have no reflectivity or no depth have an associated non-zero mask value. Squares are placed only on parts of the image that have good data, that is, the mask is mostly zero. The process that places the squares uses only the mask. It assumes a trial position, accepts or rejects it based on the mask segment contained in the square, and then moves to another candidate position. It was found to be too much of a constraint to require that every mask value in the candidate square be zero. Instead, up to 5% can indicate unusable data. Before features are generated, each masked value is replaced by the median of its immediate neighbours. To ensure this median can be calculated, no square can include any 3 x 3 segment all masked.

Generate Features

A large number of features are extracted from the reflectivities in each square patch of each image. The classification process is able to use many features because Principal Components Analysis (PCA), in the next processing step, will select those combinations of features best suited to each data set. For this work with LiDAR reflectivities, the following features were extracted:

Basic Statistics: Mean, standard deviation, skewness, and kurtosis are indicative of the reflection coefficient and interface roughness.

Quantile and Histogram: These measure the distribution of reflectivity at low resolution.

Power Spectra: Fast Fourier Transforms (FFTs) are used to find power spectra, which describe statistical characteristics on many resolution scales.

Ratios based on Power Spectra (Pace): Ratios of log-normalised power in various frequency bands provide good discrimination for classifying images.

Grey-Level Co-occurrence Matrices (Haralick): Grey-Level Co-occurrence Matrices (GLCMs) describe the reflectivity changes over selected distances and directions in the image patch, and are widely used to assess texture. Haralick presented perhaps the first list of texture features that can be derived from a GLCM. They have evocative names such as prominence, contrast, and entropy.

These features have been selected to capture many useful aspects of the data. As the technique was developed for acoustic imagery analysis, the selection of features was frequently examined to determine which features were providing useful discrimination and to determine if any algorithm consistently produced redundant features. One interesting result from these studies was that mean intensity was rarely the sole determining feature in the overall classification process. It is combinations of intensity and texture that seem to drive classifications.

Occasionally, all the reflectivity values in a square were found to be equal, usually because of some artifact. Some features are infinite or undefined if there is zero standard deviation in the matrix. These squares were omitted from further processing.

The reflectivity features were concatenated to make a full feature vector (FFV) for each square. Specifically, 132 features are generated from the reflectivity data, so each of these FFVs has 132 values.

Merge FFVs

Merging FFVs is simply assembly of the FFV files from each survey line into one large matrix. Each row of this matrix holds feature values from one square, and there are 132 columns, one for each feature. The actual operation is trivial. However this step deserves mention because it is here that the process shifts from considering each survey line independently to working with all the lines in a survey area. Note that it is FFVs from all the lines on all the survey days that are merged; no mosaic is ever made.

Also, it is here that the processing shifts from Matlab programs that were written or adapted for LiDAR classification to QTC SIDEVIEW, QTC's commercial classification software for sidescan images. As features were generated, FFV files were written in QTC's internal ffvdb format. This made them accessible to QTC software through QTC's toolkit for LiDAR classification.

Multivariate Statistical Analysis

A major strength of this processing is the incorporation of multivariate statistical techniques, as they permit the use of many features. Experience has shown that some features are important in what might be called the standard classifications: mud, sand, gravel, and so on. Others are important for more specialised classifications such as discriminating among sand/mud mixtures. For any particular data set, PCA selects the features that are most useful for the discrimination task at hand. Features that are close to constant are largely disregarded. Redundancies, that is, correlated features, are also acceptable, but only one remains significant. What is left is a reduced feature set that compactly describes the diversity of the data set. While some features may have little diversity or be tightly correlated when used to describe one set of seabed sediments such as open continental shelf sand and gravel, they may be found to give useful discrimination in other cases, such as on deltaic sediments. Thus, the connection between features and classification adapts to the character of the data set.

For each patch of each image, the features are calculated and then arranged as a row vector of 132 elements. The name given to these rows of features is Full Feature Vectors (FFVs). This information must be optimised or reduced without losing any details of the sediment. The dimension of the FFVs is reduced by principal components analysis to isolate the combinations of features that are responsible for most of the diversity in the data set. In general, the top three combinations capture a very high percentage of the variance, so the rest of the combinations can be disregarded. These top three combinations are called Q-values.

The result of this reduction process is contained in the reduction matrix. Any FFV can be reduced to three Q-values by matrix multiplication. The reduction matrix is part of the catalogue used for supervised classification. New FFVs, derived from any subsequent survey, can be reduced to Q-values in this way as part of the supervised classification process. Alternatively, the multivariate statistical processing can be run on any partial or complete data set to find new information.

Cluster Analysis

The reflectivity character - represented by Q1, Q2, and Q3 - from like seabeds will be similar. When plotted on a three-axis plot, called Q-space, points with similar values, for example from a single seabed type, form a cluster. Dividing a data set into clusters optimally is a statistical problem that has occupied statisticians for decades and is still being studied today. An automated cluster engine (ACE), developed at Quester Tangent to satisfy the need for a reproducible objective division into clusters, was used for this work. Unlike most other methods, it requires no user input at all. ACE identifies the optimal number of clusters and the division of points into those clusters. This result is optimal in the sense that it is a minimisation of a cost function closely related to the Bayes Information Content (BIC) of the data set which, loosely speaking, is a measure of the irreducible information in an image or data set.

ACE makes many independent attempts, called iterations, to divide a data set into any number of clusters in the range that the user specifies. The results from each attempt are a list of assignments of which point belongs to which class and the associated BIC score for that division of the data points. The best division into a particular number of clusters is the one with the lowest score for that number. The best overall division is the lowest overall BIC score, so this tells us the optimal number of clusters into which the data set should theoretically be divided.

Using ACE requires only patience. It uses both Monte Carlo and simulated annealing techniques to seek the global minimum of the BIC cost function. Usually a satisfactory result is produced by an overnight run.

Classification

The result from ACE is a statistically optimal division of all the records into a number of classes, where ACE also recommends that number. Armed with that result, it is straightforward to make both a final classification file and a catalogue that can be used to classify new data.

The final classification result is an ASCII file listing positions and class assignments of each square. Each square on an image leads to one line in an output file. Quester Tangent's usually lists these final class assignments in so-called seabed files, in which the columns include date, time, longitude, latitude, depth, Q1, Q2, Q3, the class assignment, and two percentages that indicate the quality of the assignment. For the Broward survey a more compact form was used, of which a small sample appears in Table 1.

Interpolation

This comma-separated file is ready to be read into any GIS. However caution is needed. The positions are irregularly spaced, because they are some of the LiDAR footprints. To work with these classes, including making maps, they need to be interpolated to a regular grid. **Only a very few GIS interpolate class assignments properly, and even with these the process requires care**. Class assignments cannot be treated as if they were samples of a continuous variable. For example, if a grid point is surrounded by data points assigned to classes 2 and 4, it would be wrong to assign that grid point to class 3, which might be a typical interpolation result rounded to an integer. The reason is that the class numbering system is arbitrary, and class 3 is, in general, not related at all to classes 2 and 4. The correct assignment is the mode of all the points around the grid point, thus either 2 or 4 depending on which one occurred the more often. To increase accuracy, do not just count occurrences close to each grid point, but instead weight each occurrence depending on distance from the grid point. This amounts to creating a histogram of classes in the vicinity of each grid point – the class assignment is the class scoring highest in that histogram.

961492.26,	710806.27,	07,	-21.35,	20080728
961584.66,	710799.40,	04,	-23.04,	20080728
961388.83,	710719.10,	02,	-19.68,	20080728
961481.92,	710711.27,	09,	-21.70,	20080728
961571.93,	710705.59,	04,	-23.14,	20080728
961385.27,	710624.70,	07,	-20.06,	20080728
961478.82,	710617.45,	02,	-21.57,	20080728

Table 1. Some lines from the final output csv file containing a class assignment (column 3) for each square of each survey line. Columns 1, 2, and 4 are the easting, northing, and depth of the centre pixel of the square that gave rise to that row. Column 5 is the date on which those pixels were surveyed.

961483.54297 666301.12 UNKNOWN
961483.54297 666351.12 UNKNOWN
961483.54297 666401.12 7
961483.54297 666451.12 7
961483.54297 666501.12 7
961483.54297 666551.12 7
961483.54297 666601.12 7

Table 2. A selection from an xyz file showing classes interpolated to grid points with a spacing of 50 feet. These were generated with a search radius of 300 feet. Five of these points were assigned to class 7. Points in the rectangular grid located more than 300 feet from any classified survey point have no class assignment, hence "UNKNOWN".

Because very few commercial GIS suites do categorical interpolation, Quester Tangent developed a small package, CLassification and MApping Software (QTC CLAMS) to do just that. CLAMS interpolated the Broward data set with a grid spacing of 50 feet, which amounts to 1167560 points. Seven of those 1167560 lines are shown in Table 2. In this small sample, the easting is held constant while the northing increments are 50 feet. Because the survey covers only about a third of the rectangular grid, about two-thirds of the grid points have no class assignment. Specifically, the search radius in CLAMS was set to 300 feet. A histogram was assembled for each grid point, with class numbers weighted inversely by the square of the distance. The class scoring highest in the histogram was assigned to that grid point. If the histogram was empty, because there was no classified point within 300 feet, no class was assigned. The top two lines in Table 2 are for unassigned grid points, while the other five grid points were assigned to class 7.

Classifying LiDAR Data

Introduction

The previous section of this report describes the methods Quester Tangent uses to classify seabed sediments with LiDAR data. This section contains specifics of the LiDAR survey of Broward County and its classification.

Tenix Survey in Broward County

Tenix LADS Corporation surveyed the entire offshore waters of Broward County, Florida, with the LADS Mk II LiDAR system on 28 and 29 July and 7 and 16 August 2008. The bulk of the survey was done in the first two days. Since the Tenix method for calculating relative reflectivity, RR, can be affected by changes in water conditions, it is best to acquire most of the survey data in a short time during which the water conditions are unlikely to change much.

Statistics on the number of LiDAR transmissions and the number of footprints were derived from the Tenix RR and CAF files as a by-product of loading the data for classification. These files contain only data that survived quality control. There may have been other survey lines, or portions of survey lines, that were set aside during quality control. The number of LiDAR transmissions that were present in these final files is given, for each survey day, in Table 3. The two consecutive days in July contributed 96.5% of those transmissions. Furthermore, examining maps of the lines covered each day showed that the August surveys covered very little area that had been omitted from the July surveys.

Sounding was conducted using 4 x 4 m laser spot spacing, which has a swath width of 192 m. Line spacing

	Swaths	
July 28	142786	74.6%
July 29	42018	21.9%
Aug 7	34	0.1%
Aug 16	6536	3.4%

Table 3. Number of LiDAR swaths on each survey day, counting only those that passed quality control measures. Each swath can produce data from up to 48 footprints.

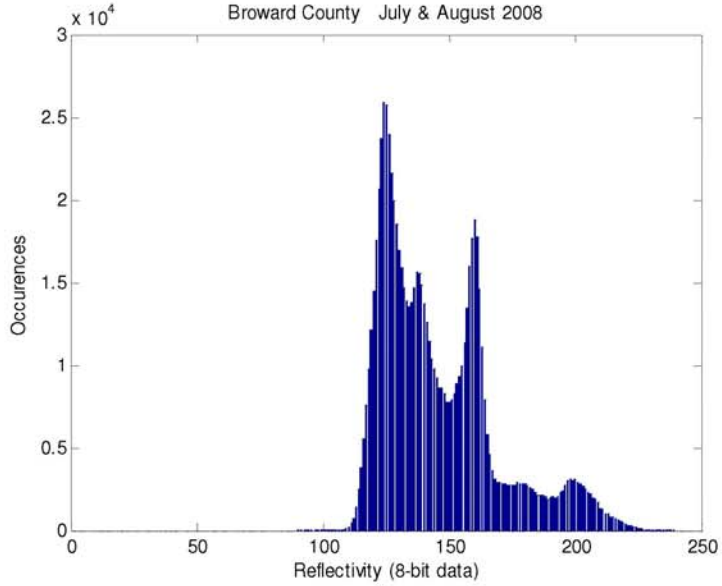

Figure 2. Histogram of all the reflectivity values from the Broward survey, as derived by the Tenix RR model

was 170 m for the major survey lines, giving a little more than 100% coverage. The survey area extended from onshore out to the maximum depth that could be measured, which was 56 m. Depths as large as these can be measured only in water of high optical transmissivity, which is another favourable condition for seabed classification.

Data for Classification

It is important that the data used for classification be well distributed through their dynamic range. The quality of the classification would be degraded if most of the reflectivity values were crammed into a small fraction of their 8-bit dynamic range. Figure 2, a histogram of all the Broward seabed reflectivities, shows that this is not a problem – that the reflectivity values cover about half of the allowed dynamic range.

A large fraction of the LiDAR footprints have both depth and reflectivity, which allows them to be used for classification. Footprints with only one of these are likely flawed in some way, and therefore are not used. For example a bottom pick incongruent with its neighbours may be from some water-column object, in which case its reflectivity is not representative of the sediment and should not be used for classification. The number of footprints with depth and reflectivity, or only one, or neither, is given in Table 4.

In choosing the data set for classification, two options were available. One was to use all the data that Tenix supplied in the CAF and RR files. The second was to use primarily the two main survey days, with perhaps some of the August data. The advantage of this choice is that the water conditions would have changed little during the 30 h or so between starting to survey on 28 July and finishing on 29 July, and consistent water conditions are beneficial for LiDAR seabed classification. This argument was deemed persuasive, and so some of the August lines were set aside from classification. The lines that were classified are listed in Table 5.

Place Squares

The loading process described above organised the reflectivity and depth data into matrices organised by swath

	Depth and reflectivity	Depth, no reflectivity	Reflectivity, no depth	No reflectivity or depth
Number of footprints	8198487	706949	76399	204117
Fraction of footprints	89.3%	7.7%	0.8%	2.2%

Table 4. Beam footprints with acceptable depths and reflectivities from the Broward survey.

Date Line number	Mean depth (m)	Number of squares	Date Line number	Mean depth (m)	Number of squares
28 July 2008			**29 July 2008**		
08_10BRO_RR6100	8.3	6738	08_10BRO_RR6022	17.1	3
08_10BRO_RR6101	9.7	7661	08_10BRO_RR6110	34.5	4253
08_10BRO_RR6102	11.0	8073	08_10BRO_RR6112	41.4	2784
08_10BRO_RR6103	12.9	8448	08_10BRO_RR6301	3.2	823
08_10BRO_RR6104	15.3	9234	08_10BRO_RR6302	4.4	1725
08_10BRO_RR6105	17.7	9480	08_10BRO_RR6303	5.4	2246
08_10BRO_RR6106	19.1	9191	08_10BRO_RR6304	6.2	2991
08_10BRO_RR6107	20.2	9126	08_10BRO_RR6305	6.7	3141
08_10BRO_RR6108	22.2	9420	08_10BRO_RR6306	6.4	3177
08_10BRO_RR6109	25.3	9210	08_10BRO_RR6307	7.0	3931
08_10BRO_RR6110	24.9	4692	08_10BRO_RR6308	7.7	4149
08_10BRO_RR6111	35.6	6114			
08_10BRO_RR6201	7.4	5711	**16 Aug 2008**		
08_10BRO_RR6202	7.2	5038	08_10BRO_RR6205	6.1	1508
08_10BRO_RR6203	7.5	2810	08_10BRO_RR6206	6.1	531
08_10BRO_RR6204	6.5	2572	08_10BRO_RR6207	5.3	286

Table 5. Composition of the data set that was classified.

and column. A matrix, or array, organised this way is simply an image of bottom reflectivity as it might have been recorded on the aircraft during the survey. The depth data can be thought of similarly. To classify the seabed, these two arrays are divided into square patches. The reflectivity and depth arrays in each square are the raw material for the 132 features.

In sonar classification, it is natural to divide the image into port and starboard sides. Because the programs used in this work are based on QTC's existing software, this division was done here as well, even though this makes less sense with LiDAR data. Columns 1-24 were designated port, and 25-48 as starboard. The squares into which the image was divided were 9 pixels on a side. To fit three squares into 24 columns, they were allowed to overlap by up to two pixels. Squares were placed from the aircraft track outward. To port, for example, they are in columns 17-25, then 10-18,and then 3-11 if all data are valid. Masked data sometimes push the squares out to column 1, or forbade three squares being placed. Alongtrack, the placement algorithm for sonar images treated the image in strips. It attempted to place squares on rasters 1-9, and then on rasters 8:16, and so on, again allowing an overlap of 2. Thus in a region of good data the distances between the centres of the squares were 7 pixels in both directions, which is 28 m since the footprints were 4 m apart. The total number of squares placed on all the 30 survey lines listed in Table 5 was 145610.

Generate and Merge Features

Generating features is a straightforward process with no user inputs. The only unusual aspect, one that arose because of the character of LiDAR reflectivity data, is that in 39 squares all the pixels had the same reflectivity. Features cannot be calculated for a square if the reflectivity has zero standard deviation. These squares were set aside. Merging is the process of concatenating the FFV files for each survey line in which squares had been placed to give a merged FFV for each bay. This was done in QTC SIDEVIEW, while all previous classification steps were done in Matlab. Of the 145610 squares, 39 were set aside, leaving 145027 records to be classified.

Reducing Dimensionality and Clustering

Reducing the number of dimensions from 132 in the FFVs to three was done with principal components analysis (PCA). The resulting three principal components are called Q values. PCA gives a matrix of feature weights. The first three columns of the weights matrix are kept as the reduction matrix for the data set being

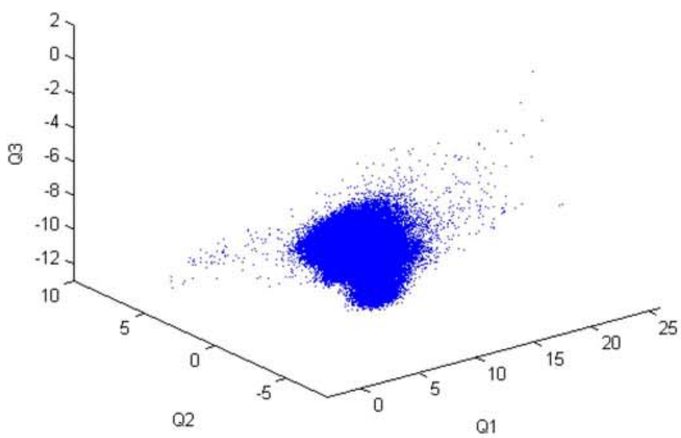

Figure 3. The 145027 Broward records plotted in feature (Q) space before they are divided into classes.

classified. Any FFV can be reduced from its 132 elements to three Q co-ordinates by multiplication by a reduction matrix. Figure 3 is feature (Q) space with one point for each of the 145027 records. The axes in this plot are the principal components. Associated with each point is a location, a time, a survey line, and so on; enough data for the points to be plotted in geographic space at this stage or after clustering.

ACE has the task of dividing these points into their natural clusters. This is unsupervised classification, because no prior knowledge or assumptions about the seabed are used. Supervised classification and discriminant analysis can both be involved in QTC classification, but neither was used in this work.

Figure 4 has the ACE cluster results for the Broward survey. Each dot is an individual attempt at clustering that started with the original data, uninfluenced by any other result. Ideally the lower red line, which connects the best results for each candidate number of clusters has a well-defined minimum at the optimal number of clusters for that data set. When this is so, there is no ambiguity about choosing the best number of clusters. If the minimum is less clear, it is necessary to choose a result. Ties and near-ties are normally broken in favour of the smaller number of clusters. (It is possible to derive a criterion for the statistical significance of the difference between near ties, but usually this is not necessary.) In particular, it is rare for the class maps of near ties to differ much. In a series of class maps with increasing numbers of classes, it is often true that the major classes stay in nearly the same places as minor classes are added. In this case, we take the optimal number of clusters, or classes, to be ten, because the score for ten classes is a near tie with the score for fifteen. The number of records assigned to each class and the color with which the class is plotted in the class maps are given in Table 6.

This optimal ACE result includes a list of the class to which each image square is assigned. The final step in seabed classification is therefore at hand – just transferring these assignments into a file that also has the position of each square. These can be so-called seabed files, the usual complete Sideview final result, or a trimmed version. Both are comma-separated ASCII files. A trimmed ASCII file (csv) is supplied as a final result of this work, with columns as in Table 1.

Class assignments

Figure 5 (on the last page of the report) is, one might say, an interlude before turning to class maps. It was made by applying the catalogue of variables that classify the entire data set to a part of one survey line. This is not a normal part of the classification process, but was done here to illustrate the results. Shown is a high-quality part of the survey, in which the squares cover the entire reflectivity image. It can be seen how the classes related to the amplitude and texture of the reflectivity image.

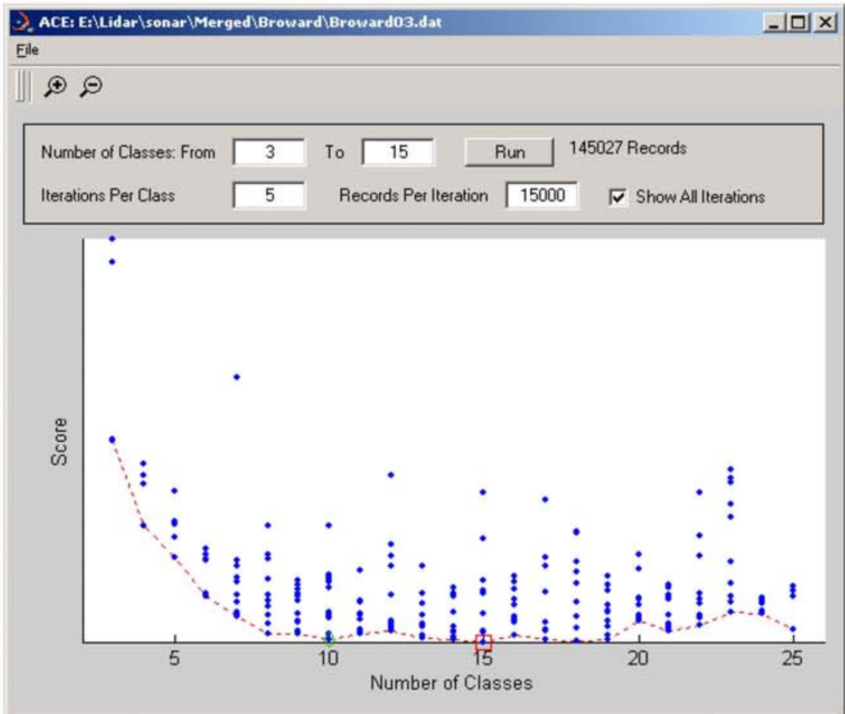

Figure 4. Plot of ACE clustering results for the Broward survey. Each dot is an individual run from a random starting position in the multidimensional space of cluster solutions. The optimal result for each candidate number of clusters has the lowest score; these are connected by the dotted line. A box surrounds the overall optimal result.

Understanding Figure 5 is hampered by not knowing how similar the classes are to each other. It is arbitrary whether the cyan and green classes, for example, are neighbours in Q space and thus similar, or at opposite ends of the feature space and thus very dissimilar. Similarity colors were developed as an aide to keeping track of the relationships between classes. The concept is that each class has a color assigned based on the position of its cluster centre in Q space. The Q1 coordinate determines the amount of red, Q2 green, and Q3 blue. With similarity colors, classes of similar shades are known to be similar in the character of their reflectivity, and this can ease understanding of class maps.

Plots of the points in the csv file could, of course, be made, but are often misleading. With such a high density of points, the points plotted later overwrite the earlier ones, and this can distort the presentation of classes. Instead, we proceed to interpolation.

Interpolation

Interpolating the class assignments to a regularly spaced array of grid points is required to use this seabed classification in a GIS, or even to make maps that are not distorted by overwriting. The spacing between the centres of squares, that is, between classified records, is 28 m in areas fully covered by squares and not overlapped by any other survey line. The grid spacing was chosen to be 50 US survey feet, thus about half the average spacing between field points. The search radius for interpolation was 200 feet, which ensures that several field points are considered in assigning a class to each grid point while avoiding inappropriate extrapolation at edges. These interpolated files are also provided as deliverables, in formats as described above with Table 2 as the example.

Feature and class complexity were calculated on the same grid and with the same search radius. Seabed complexity has been found to be a useful habitat indicator for some species. Specifically, these complexity indices are calculated around the same grid points that were used for interpolation. For each grid point in turn, the feature (Q) values and class assignments for all the points within the chosen search radius are compiled. The feature complexity index is the square root of the trace of the covariance matrix of feature values, and the class complexity

1 (5669)	2 (16717)
3 (13707)	4 (9002)
5 (22969)	6 (835)
7 (55447)	8 (4222)
9 (2239)	10 (14220)

Table 6. Number of records (that is, squares) assigned to each of the ten classes, shown in parentheses, and the colors with which the classes are plotted in the next section of this report.

index is the number of classes around the grid point minus one divided by the total number of classes minus one. They are usually plotted with zero represented as black up to white as the highest observed value. For most data sets, these plots tend to be generally dark because the highest values occur only infrequently.

CLASS MAPS

Broward County inshore waters

All the positions in these maps and in the associated files are relative to NAD83, projected onto the Florida State Plane Coordinate System East, in US survey feet.

Figure 6 is the class map for LiDAR classification of the seabed of the inshore waters off Broward County, and Figure 7 is a zoom into the area around the dredged channel. Shown are interpolated classes from the process described above. Figures 8 and 9 show feature and class complexity respectively.

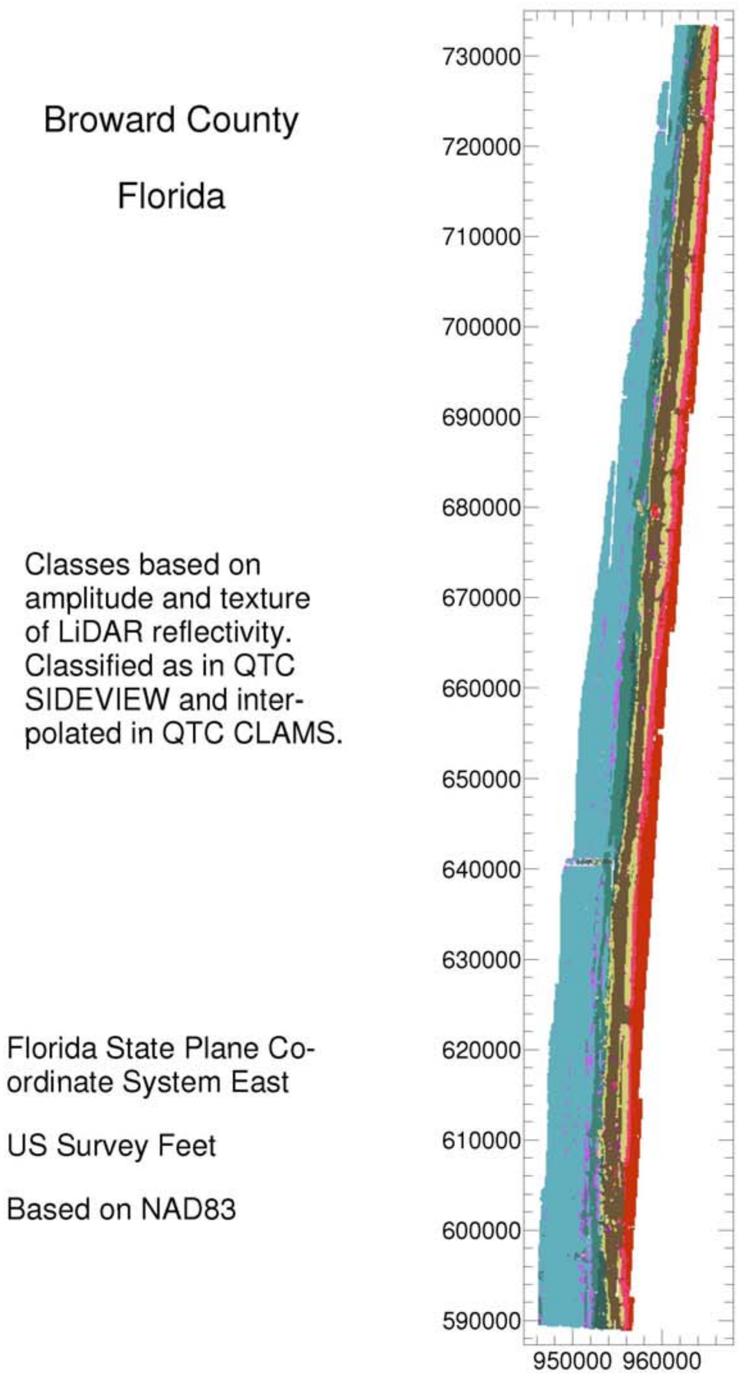

Figure 6. Interpolated class map of the seabed off Broward County. Ten classes are shown in similarity colors with a grid spacing of 50 US survey feet

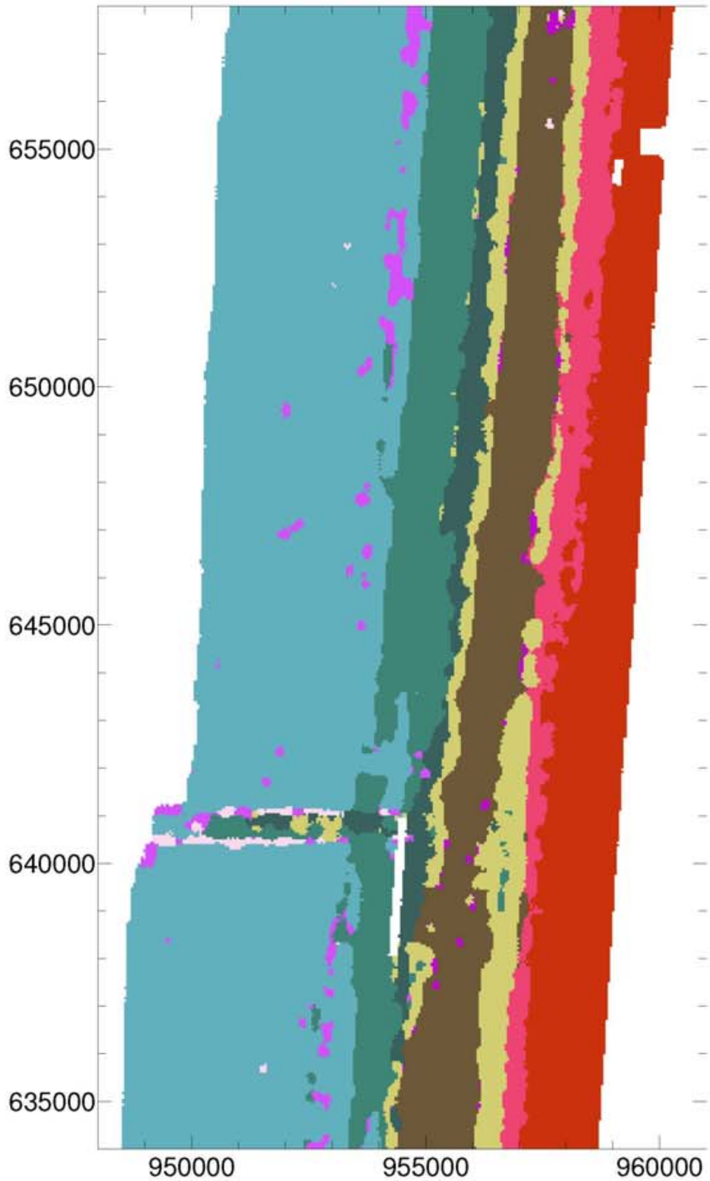

Figure 7. A portion of Figure 6, showing classes in the dredged channel and in the outlying reef structure.

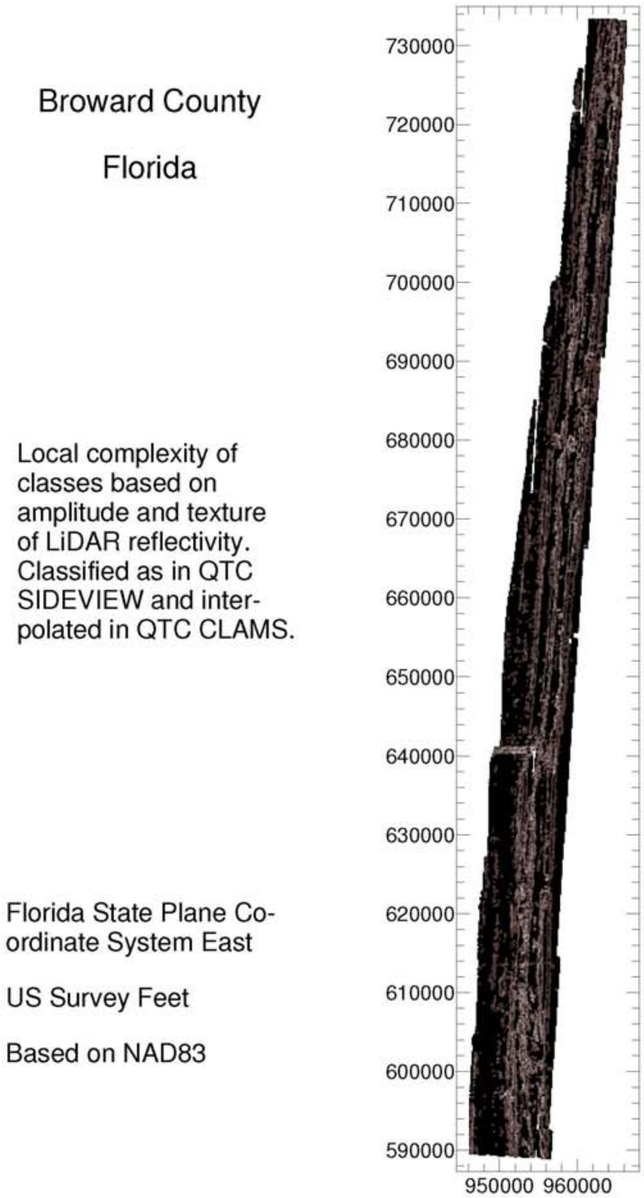

Figure 9. Local complexity of the ten classes of this data set, plotted in gray scale. Homogeneous areas are shown black.

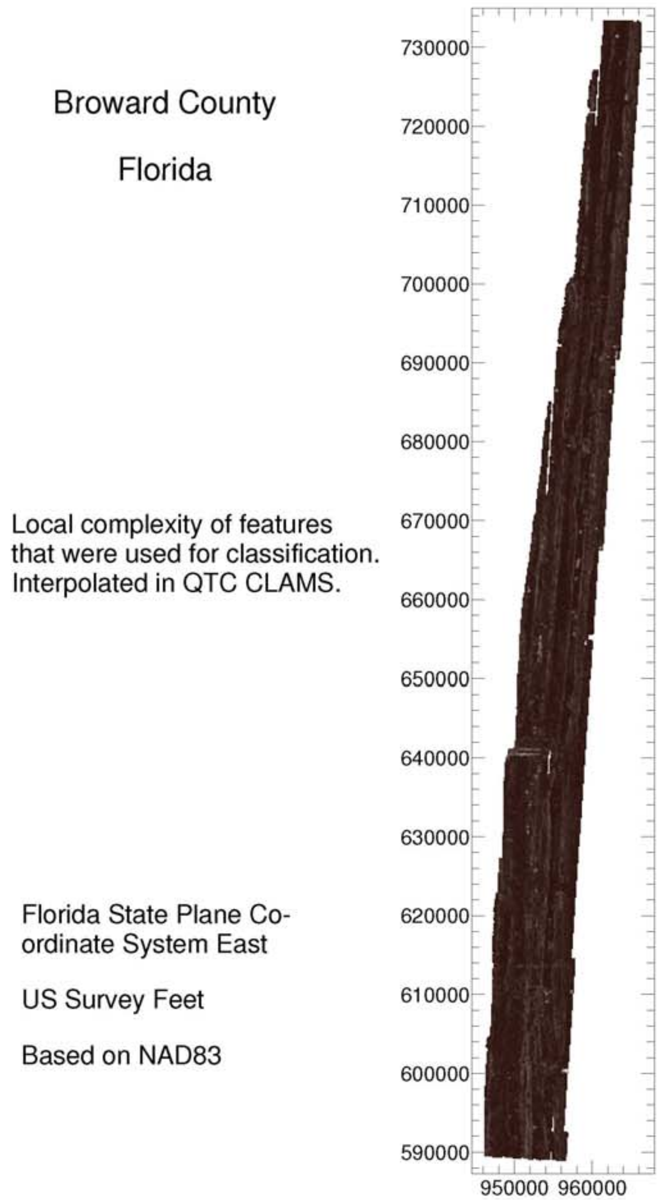

Figure 8. Local complexity of the features that were used to classify this data set, plotted in gray scale. Homogeneous areas are shown black.

CONCLUSIONS

This report describes a process to classify the seabed using reflectivity as measured by a Tenix LADS LiDAR system. It is based heavily on Quester Tangent's established methods for classifying sonar images. Each 9 x 9 subimage of each survey line, provided it meets quality standards, has been assigned to one of ten classes. This is the first part of remote classification, and is often called segmentation. It is the division of a survey area into regions that are reasonably homogeneous and reasonably distinct from each other, based on the LiDAR reflectivity alone. It is not possible to label these regions, with labels such as sand or reef, based on LiDAR data alone.

The second part of classification, labelling the regions of a segmented map, requires ground truthing, that is, information acquired by some other means. The seabed off Broward County has been surveyed and analysed extensively, so there is no shortage of ground truth. No detailed correlation of QTC classes with ground truth is reported here. Only a qualitative correlation was attempted, using the map published by Walker, Riegl, and Dodge (ref. 1). The bounds of this work did not include any correlation, so even the qualitative results are not reported here. However, this comparison did give confidence that these LiDAR classes are generally sound.

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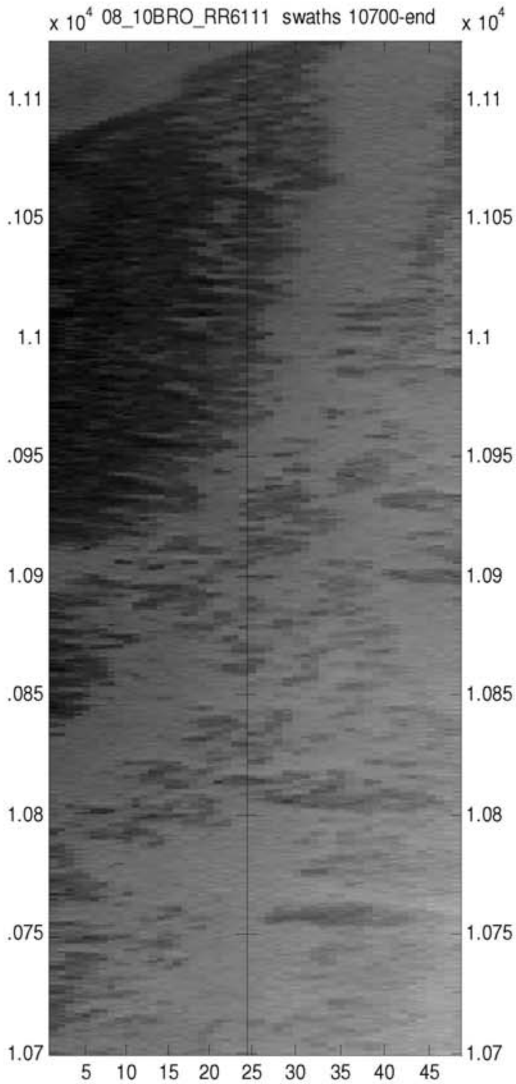

Figure 5a. Seabed reflectivity of the last 425 swathes of line 08-10BRO_RR6111, surveyed on 28 July 2008. Each pixel is a laser footprint. The y-axis is swath number, x-axis is footprint number, 1 to 48, with an artificial division between port and starboard after footprint 24.

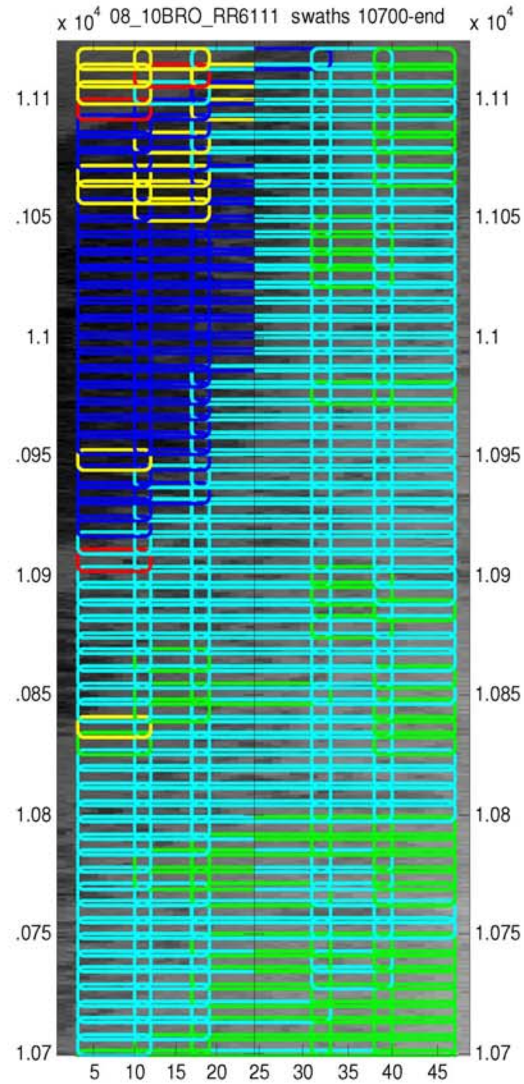

Figure 5b. Squares overlaid on the image of Figure 5a, and colored according to the class assigned to each. They appear as rounded rectangles, but are nine pixels on each side. They overlap their neighbors by two pixels, but this is not shown across the center line. Classes (and colors) are assigned to entire data sets, not to individual survey lines. These classes were assigned by applying the catalogue for the entire survey to this line.