# Cover Sheet

**Title Sheet**

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**A – Equipment**

The Beechcraft King Air 90 (call sign N91S) collected shallow water bathymetry (down to 15 meters), topographic (up to 100 meters) and imagery data during the course of this project. The aircraft was equipped with a SHOALS-1000T Bathymetric and Topographic LiDAR System. The equipment list along with technical specifications and plane descriptions are included in Appendices A and B.

SOUNDING EQUIPMENT

The Beechcraft King Air 90 (call sign N91S) was equipped with a SHOALS-1000T Bathymetric and Topographic LiDAR System. The 1 kHz bathymetric laser (or hydro laser) was used to collect data over the entire survey area. The laser was operated to achieve 3m x 3m spot spacing flying at 300m altitudes at approximately 140 knots. The survey lines were planned with 20% overlap and flown twice – once at low water and once at high water in opposing directions to achieve 200% coverage.

In the LiDAR system, the laser outputs green and infrared beams. The infrared beam is used to detect the water surface and does not penetrate. The green beam penetrates the water and is used to detect the seafloor. The green beam also generates red energy when excited at the air/water interface. This is known as Raman backscatter and can also be used to detect the sea surface. Distances to the sea surface and seafloor are calculated from the times of the laser pulses, using the speed of light in air and water. Background theory on bathymetric LIDAR can be found in the paper, "*Meeting the Accuracy Challenge in Airborne LIDAR Bathymetry*" (Guenther, et al.[1]). This paper can be found in Appendix E.

The topographic data was also collected using the 1 kHz bathymetric laser and was operated to achieve 3m x 3m spot spacing flying at 300m altitude at approximately 140 knots. The survey lines were planned with 20% overlap and flown two times in opposing directions to achieve 200% coverage.

In addition to LiDAR data, a DuncanTech DT4000 digital camera was also used to acquire one 24-bit color photo per second. The camera, mounted in a bracket at the rear of the sensor, captures imagery of the area being flown. The data was then utilized during processing in the GCS and later by way of an orthomosaic for shoreline application.

POSITIONING EQUIPMENT

LiDAR

The aircraft was equipped with an Applanix Position and Orientation System for Airborne Surveys (POS/AV). The Applanix POS/AV 410 measured orientation (roll, pitch and

[1] *"Meeting the Accuracy Challenge in Airborne LIDAR Bathymetry", Gary C. Guenther, A. Grant Cunningham, Paul E. LaRocque, David J. Reid*

heading) as well as position. The system consists of a POS/AV computer with a NovAtel Millennium GPS card, a NovAtel 512 airborne L1/L2 GPS antenna, and an Inertial Measuring Unit (IMU). The IMU is permanently mounted within the SHOALS-1000T sensor. It uses a series of linear accelerometers and angular rate sensors that work in tandem to determine orientation. The orientation information is used in post-processing to determine position of the laser spots. However, analog data from the POS/AV was also used during acquisition to maintain a consistent laser scan pattern.

Data received by the airborne system was continually monitored for data quality during acquisition operations. Display windows showed coverage and other information concerning the system status. In addition, center waveforms at 5Hz were shown. This information allowed the airborne operator to assess the general quality of all data being collected.

Positioning was determined in real time using an OmniStar 3100LM DGPS receiver. An AeroAntenna AT-3065-9 antenna was used to acquire the differential corrections. Two differential receivers were available: the OmniStar 3100LM and a CSI MBX-3S Coast Guard beacon receiver. The OmniStar 3100LM was the primary source of differential corrections for this project.

However, final positions were determined using a post-processed Kinematic GPS solution.

## SOFTWARE

### LiDAR Acquisition

The primary data sets were collected with the SHOALS-1000T Airborne Bathymetric and Topographic LiDAR control and data acquisition system (SCADA) using the 1kHz bathymetric laser (or hydro laser). The Pilots utilize a heads up display (HUD) display connected to the operators rack and is located in the cockpit for line tracking.

The following eight System Monitor display windows are available in the SHOALS-1000T Bathymetric and Topographic Lidar control and data acquisition system (SCADA) for operators to monitor data quality:

1. Main Display: This display summarizes functional information from the other displays.
2. Flightline Display: This displays the settings for the current flightline, entered in the ground control system (GCS) before the mission.
3. Algorithm Display: This displays data for each laser shot from the real-time airborne depth extraction algorithm.
4. Dropout Statistics Display: This displays the dropout statistics for the current flightline. Dropouts are laser shots for which the depth algorithm cannot produce a valid depth. All values are reset to zero when a new line is selected.
5. Laser + Receiver Display: This displays vital information such as energy levels and surface channel status from the laser and receiver that is fundamental to SHOALS-1000T operation.

6. POS/AV Display: This displays useful positioning and orientation statistics from the POS/AV and GPS.
7. Drives Display: This displays the amount of space on two hard drives that has been used to record SHOALS-1000T data in survey state. Data is recorded onto both drives in parallel.
8. Power Supplies Display: This displays the voltages being output by the SHOALS-1000T power supplies, and the temperatures on the power supply boards.

In addition to the system windows listed, the operator also has a Real Time Chart display, Waveform Display, and Video Image windows. The chart display shows color depth soundings and swath coverage. The depths are color-coded numbers representing the depth in meters according to the color scale set by the operator. The waveform display, updated at 5Hz, shows the quality of the depths being collected, and helps to confirm that all four channels are producing good waveforms. The video window shows the digital camera images of the area, and is updated every second.

## LiDAR Processing

All soundings were processed using SHOALS GCS (Ground Control System) 6.01 and converted to CARIS HIPS 5.4. Preliminary Smooth Sheet soundings were exported from HIPS, suppressed using CARIS GIS 4.4a, imported into Microstation SE (V05.07.01.14) and tagged as specified in the NOS Hydrographic Surveys Specifications and Deliverables (version March 2003).

SHOALS GCS Management And Planning Software (MAPS) 6.01 and ESRI ArcMap 9.0 were utilized for general survey planning.

Applanix POSPac 4.2 was utilized for post-processing the dual frequency GPS data sets acquired by the aircraft and the base stations. For every flight mission, a new project was setup in POSPac. The software then extracted the POS data collected on the aircraft into the POSPac project, separating it into component data sets such as IMU, primary GPS, and secondary GPS.

Using POS GPS—part of the POSPac suite—dual frequency GPS data from the aircraft and ground control base station were converted from their native formats (NovAtel and Ashtech, respectively), to the POS GPS .gpb format. The KGPS data sets were then post-processed using the antenna phase center positions from a GPS receiver located at the NGS benchmark AB2631.

The POSPac module POSProc then used the post-processed KGPS positions to post-process the POS/AV attitude data and refine the inertial solution. The final solution was exported to a sbet.out file, which was then used by SHOALS GCS.

Interactive Visualization Systems, Inc. (IVS) Fledermaus 6.1.5 was used to edit the data auto-processed data in SHOALS GCS.

## B –Quality Control

LIDAR DATA

Data were provisionally processed at the temporary office base in Portsmouth, New Hampshire to determine data coverage. The remaining data were processed in Fugro Pelagos' San Diego office. An overall processing flow is given in Figure 2, below.

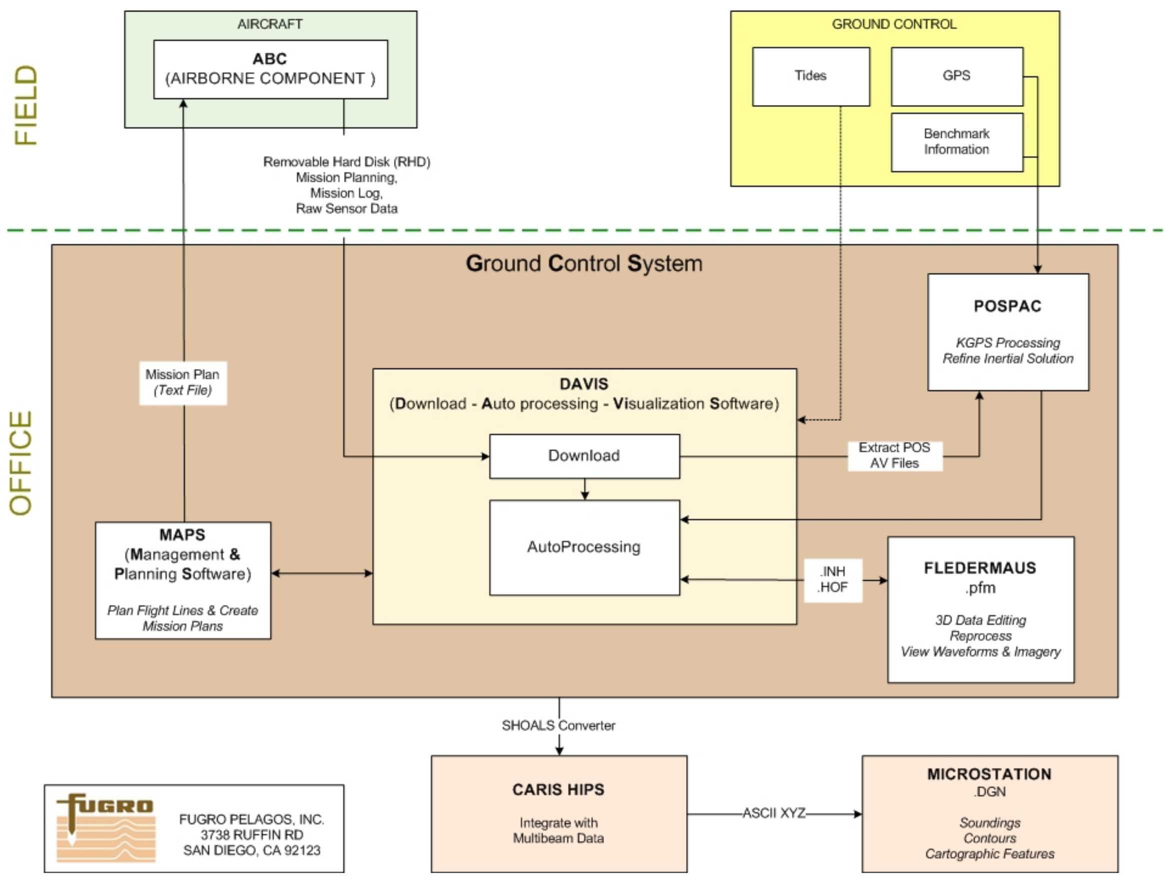



**Figure 1 - Processing Data Flow**

GROUND CONTROL

All data were processed using the Optech SHOALS-1000T Ground Control System (GCS) on Windows XP workstations. The GCS includes links to Applanix POSPac software for GPS and inertial processing, and IVS Fledermaus software for data visualization and 3D editing.

The GCS was used to process the KGPS and inertial solutions (via POSPac), apply environmental parameters, auto-process the LIDAR waveforms, apply the vertical datum offsets and tides, and edit data (via Fledermaus). The processed data was then converted to CARIS HIPS Version 5.4 and an ASCII file for MicroStation exported.

The LIDAR dataset was processed as two datasets, by splitting the data as Hydro data and Topo data. This was done since tides could not be applied to the Topo data. The Hydro data was processed using kinematic positioning (horizontal) and tide data (vertical) while the Topo data was processed using kinematic data for both horizontal and vertical datums. In order to apply kinematic data as the vertical datum, the Ellipsoid to MLLW relationship had to be determined.

The Ellipsoid height at the NGS benchmark AB2631 was determined to be -19.237 meters from the 4 days of GPS observations and the NGS datasheet. The published (NOAA CO-OPS website) height of this benchmark relative to MLLW is 8.879 meters. The Ellipsoid to MLLW at the benchmark can be computed from the above to be 28.116. Therefore if the survey area was only in the vicinity of this benchmark then any data referenced to the Ellipsoid could be corrected to MLLW by simply applying this straight offset. To verify this the sections of the Hydro data was processed with tidal info as well as kinamatic GPS. The differences with the survey area were well within IHO first order accuracies. As a result a straight offset of 28.116 was applied to all Topographic data to reduce it to the MLLW datum.

For every flight mission, a project was set up in Applanix POSPac, version 4.2. POS/AV data downloaded from the air was extracted from DAViS (Download, Auto processing and Visualization Software) into the POSPac project. A copy of the native Ashtech GPS ground control files were also copied to the POSPac project directory. With POSGPS version 4.2, GPS data from the air and ground control base station were converted from the native NovAtel and Ashtech GPS formats respectively, to the POSGPS' .gpb format. The KGPS data was then post-processed using the antenna phase center positions from a GPS receiver located at the NGS benchmark AB2631 as the master control coordinates. A summary of the GPS quality control processing results can be found in Appendix C of the Horizontal and Vertical Control Report.

The post-processed GPS positions were then used to process the POS orientation data and refine the inertial solution. The final solution was exported in a sbet.out file, which was then used by the GCS during LiDAR auto processing.

Once data had been downloaded to DAViS, hardware related calibration information was entered into the GCS. A list of the calibration values used can be found in Section C. In addition to the hardware values, some default environmental parameters were also set. Initially, the surface detection method was selected to use the Raman channel. If no Raman pick was found then the Infrared would be used, followed by the Green channel.

Before auto processing in the GCS, the tide zone file and tides (Hydro data) were imported into GCS. Once calibration values were set, environmental parameters selected, tide zones defined and KGPS data processed, the LIDAR data was auto processed using the GCS. The auto processing routine contains a waveform processor to select surface and bottom returns from the bathymetry data, and surfaces from the topographic data. In addition, it contains algorithms to determine position for each laser pulse.

The auto process algorithms obtained inputs from the raw data and calculated a height, position, and confidence for each laser pulse. This process, using the set environmental parameters, also performed a first cut at cleaning the data of poor land/seafloor detections. Questionable soundings were flagged as suspect, with attached warning information.

Data were then imported into a project PFM format file to allow data inspection and editing in Fledermaus.

Data visualization and editing was done using Fledermaus. Fledermaus was used to view a gridded surface of the entire dataset in 3D (Figure 4). Any areas with questionable soundings/elevations were then reviewed using the 3D area-based editor, which displayed each individual sounding in 3D (Figure 5). This was used on smaller subsets of the data. Gross fliers were rejected. Other data of uncertain quality requiring more examination were reviewed with the waveform window, showing shallow and deep channel bottom selections, and IR and Raman surface picks (Figure 6). Other metadata such as confidence and warnings are also incorporated into the viewer. In addition, the camera image associated with the laser pulse was displayed.

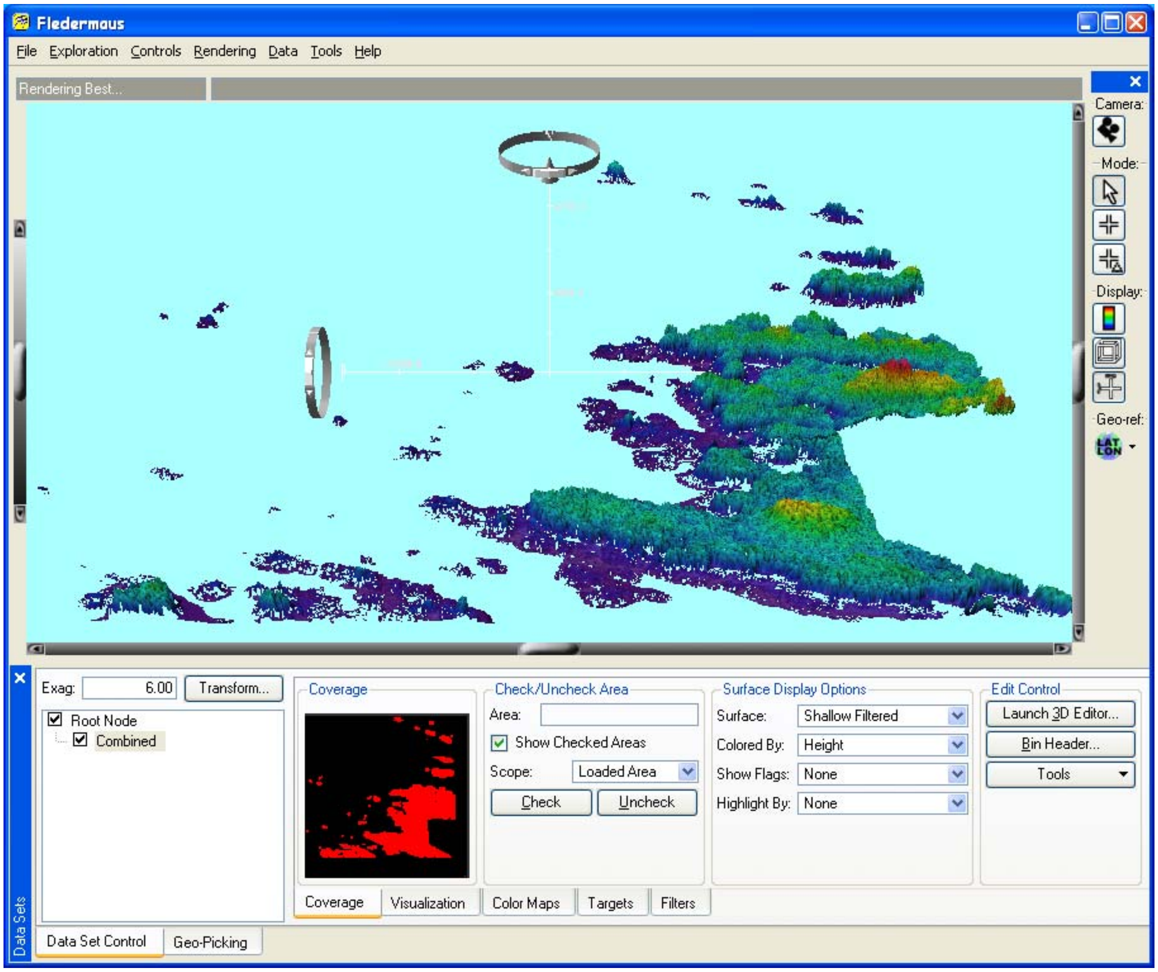



**Figure 2 - Viewing the Dataset Surface in Fledermaus**

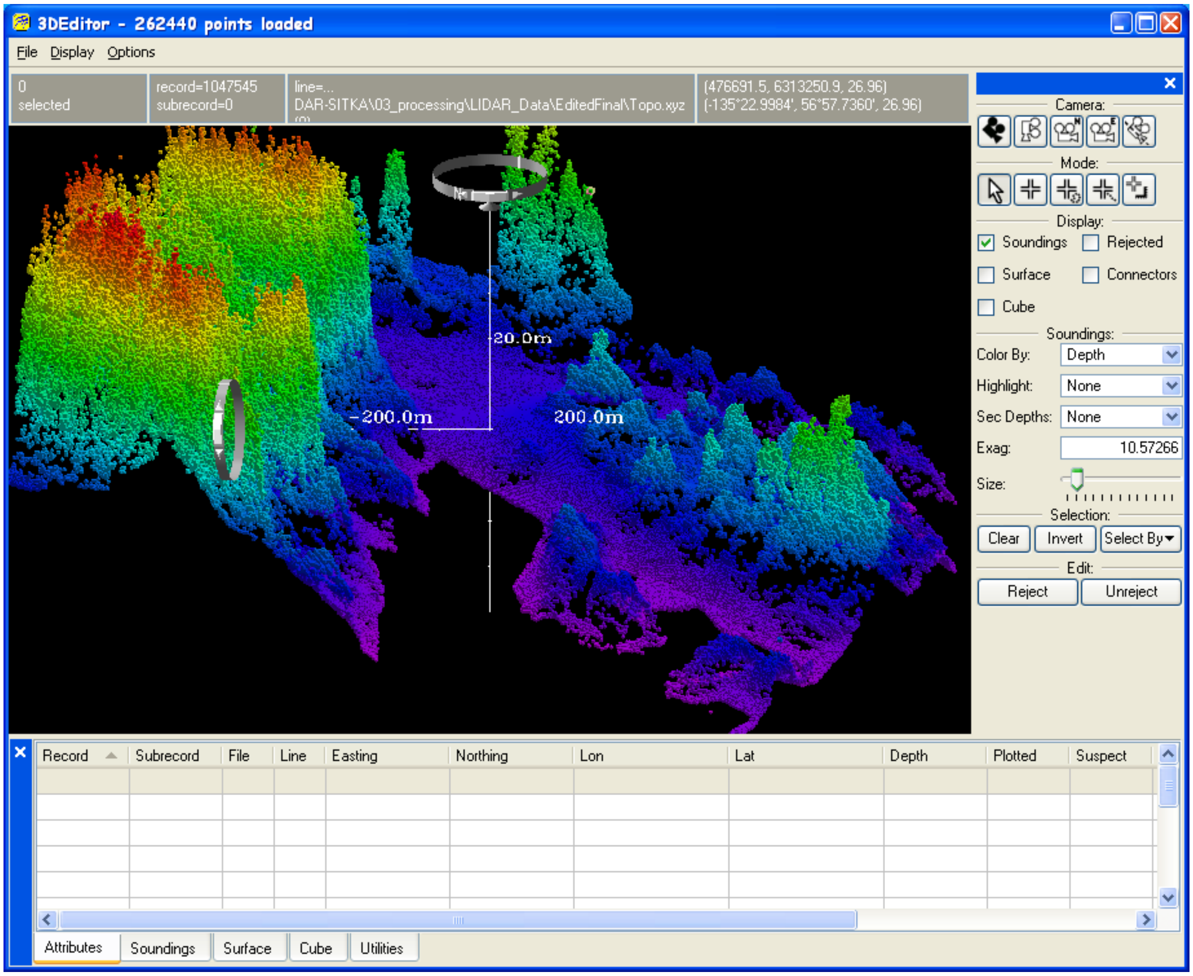



**Figure 3 - Fledermaus 3D Editor**

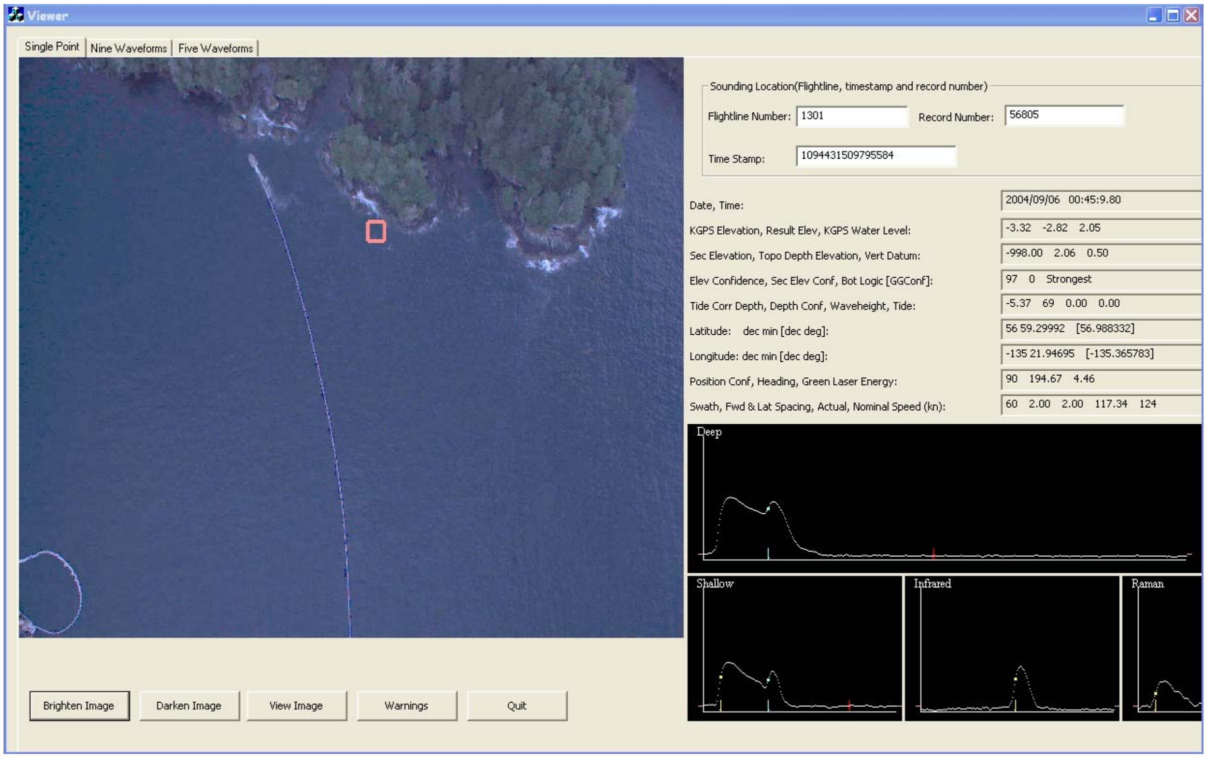



**Figure 4 - Waveform Viewer**

Other SHOALS specific tools, such as depth swapping (for handling second depth returns), were used inside Fledermaus.

Once all editing was completed in Fledermaus, the .HOF files were converted to CARIS HIPS Version 5.4 and exported to ASCII XYZ files. Exported data were in NAD83, with soundings and elevations relative to MLLW in feet. During the importing of this data into Microstation, elevations 2.3 feet above the MHW value were referenced to MHW. The data were transformed to the final charting datum, given in Table 1. Note that while these XYZ files are in meters the smooth sheet is in feet.

**Table 1 - Geodetic Parameters for Charting & Deliverables**

| | |
|---|---|
| Datum | North American Datum 1983 |
| Projection | Geographic |
| Horizontal Units | N/A |
| Vertical Datum | Mean Lower Low Water (MLLW) |
| Vertical Units | Feet |

A statistical analysis of the sounding data was conducted via the CARIS GIS QC Tool. Tie lines were run in the area and were compared with lines acquired from the main-scheme lines where applicable. The Quality Control Reports are in Separate 4.

Sounding data that passed the required quality assurance checks were imported into a CARIS HIPS workfile along with the multibeam soundings and shoal biased. The data were then suppressed using a constant term of 4 and a sounding size of 1.8mm in CARIS GIS using the Suppress Soundings program. Contours were generated in CARIS GIS at intervals specified in Appendix 8 in the NOS Hydrographic Surveys Specifications and Deliverables and were edited in Microstation SE and Microstation 8.1. Final shoal biased soundings and contours were saved and plotted in Microstation SE.

## C - Corrections to Soundings

### TIDES

All sounding data were reduced to MLLW initially using unverified tidal data from the NOAA tide station (ID# 8423898), located in Fort Point, Newcastle Island, NH.

Preliminary tidal data was downloaded from the NOAA CO-OPS website (http://www.co-ops.nos.noaa.gov/data_res.html) approximately 5 hours after each flight. The data was downloaded in UTC time (Eastern Standard Time to UTC was +4 hours) and appended to a cumulative file which was then applied to the data.

On November 3, 2005, the verified tidal data was downloaded from the NOAA CO-OPS website for OPR-A321-KRL-05. On November 20, 2005, using the GCS software, the tide zone file and verified tides were imported into GCS and all LiDAR sounding data were tide corrected. Verified tidal data was used for the Preliminary Smooth Sheet.

### AIRCRAFT ATTITUDE: HEADING, PITCH, AND ROLL

Aircraft heading and dynamic motion were measured by the POS/AV for the OPR-A321-KRL-05 survey. An accelerometer block (the IMU), which measured aircraft attitude, was mounted directly inside the sensor unit within the SHOALS-1000T system. The operational accuracy specifications for this system, as documented by the manufacturer, are as follows:

**Table 2 - POS/AV Specifications**

| POS/AV Accuracy | |
|---|---|
| Pitch and Roll | 0.008° |
| Heading | 0.015° |

### LiDAR SYSTEM CALIBRATION

Careful alignment of the various Hydro subsystem components is performed in the laboratory prior to airborne use (Note: no documented report issued). However, there remain small residual angular offsets that are impossible to measure there with sufficient accuracy, so airborne data is collected for their determination.

The Hydro subsystem calibration is broken into the following groups

1. Angular Calibration
2. Vertical Accuracy
3. Horizontal Accuracy
4. Underwater Vertical Accuracy

The Angular calibrations are carried out by collecting data over a suitable water surface, preferably on a calm day. The data is then analyzed in SHOALS GCS to derive the Angular calibration values. This is done by analyzing small sections of data at a time, such that the applied Angular values cause the water surface to be flat and un-tilted.

The angular calibration values (as obtained above), when applied to the data creates a flat and un-tilted surface. Vertically, however, it could be offset from the absolute elevation. To remove this residual vertical error, the angular calibration is combined in an iterative method with comparisons between the LIDAR derived elevations over a previously surveyed land surface (an airport runway is often used as the land surface). The angular offsets and the vertical offsets of the system are fully determined when any altitude dependence of the elevation differences between the two data sources are removed.

The horizontal accuracy is checked by collecting data over a recognizable manmade feature, such as a large building with well-defined corners. The LIDAR points at the corners of the building are compared to the known coordinates to determine the horizontal accuracy. No horizontal offsets were required for to achieve horizontal position accuracy requirements—the angular calibration values were sufficient to satisfy the requirements.

Finally the underwater vertical offsets are determined by collecting data over a previously surveyed seafloor (derived from multibeam sonar). As with the land-based vertical offset comparisons, the LIDAR data is compared to the multibeam sonar derived surface. A vertical depth offset is then calculated to produce agreement between the LIDAR and the multibeam surfaces.

As with the Hydro subsystem, the down looking cameras internal parameters are determined through laboratory measurements (refer to Appendix C for calibration procedures and results). In addition to the laboratory measurements the camera needs to be bore sighted with the rest of the system. Collecting flightlines with camera imagery over a recognizable feature in four directions does this. A set of camera pointing angles is derived such that the recognizable feature is in the same location regardless of the flight direction.

The ERDAS Image V8.7 software was utilized to create the orthomosaic that was used for the mapping and verifying of shoreline features. The accuracy of the orthomosaic is apparent when viewing photos from reciprocal lines in the orthomosaic, the horizontal alignment of distinct features are well within IHO Order 1 (+5m). The positional accuracy of the orthomosaic was verified by a ground truth method via the Skiff. In areas where it was safe to navigate, the Skiff obtained horizontal positions on rocks that were clearly defined on the orthomosaic and the results were well within the IHO Order 1 specifications.

**Table 3 - SHOALS-1000T Calibration Values**

| SHOALS-1000T (SYSTEM 2) CALIBRATION VALUES July, 2005 | |
|---|---|
| **Angular Calibration (degrees)** | |
| Rcvr_horiz_misalign_angle | -0.018 |
| Rcvr_vert_misalign_angle | +1.299 |
| Imu_sensor_pitch_offset | -1.249 |
| Scan_x_yaw_misalign_angle | -0.600 |
| **Vertical Offsets (meters)** | |
| Bathy_topo_bias_200 | +0.250 |
| Bathy_topo_bias_300 | +0.250 |
| Bathy_topo_bias_400 | +0.250 |
| **Underwater Vertical Offsets (meters)** | |
| Deep_bias_left_200 | -0.507 |
| Deep_bias_right_200 | -0.498 |
| Deep_bias_left_300 | -0.440 |
| Deep_bias_right_300 | -0.412 |
| Deep_bias_left_400 | -0.549 |
| Deep_bias_right_400 | -0.543 |
| Apriori_depth_bias_shallow | -0.190 |
| Apriori_depth_bias_deep | -0.190 |
| **Camera Calibration Values (degrees)** | |
| Camera_boresight_roll | -0.700 |
| Camera_boresight_pitch | +10.72 |
| Camera_boresight_heading | 0.000 |

**D - Approval Sheet**

# Approval Sheet

For

## H11296

Standard field surveying and processing procedures were followed in producing this survey in accordance with the following documents:

> OPR-A321-KRL-05 statement of work and hydrographic manual;
> Fugro Pelagos, Inc. LiDAR Acquisition Procedures;
> Fugro Pelagos, Inc. LiDAR Processing Procedures;

The data were reviewed daily during acquisition and processing.

This report has been reviewed and approved. All records are forwarded for final review and processing to the Chief, Atlantic Hydrographic Branch.

Approved and forwarded,

Dushan Arumugam, Fugro Pelagos, Inc.
Lead Hydrographer
Fugro Pelagos, Inc. Survey Party

# Appendix A – Equipment List and Software Versions

## LiDAR Equipment

**Table A1 – LiDAR Equipment Used**

| System | Manufacturer | Model | Serial No. |
|---|---|---|---|
| SHOALS-1000T | Optech | SHOALS-1000T | System 2.0 |
| Digital Camera | DuncanTech | DuncanTech DT4000 | 534 |
| POS/AV | Applanix | Firmware Model 410 | 609 |
| POS/AV | Applanix | IMU | Internal |
| GPS Antenna | AeroAntenna | AT 2775 | 5070 |
| AeroAntenna | Aero | AT-3065-9 | 5848 |
| OmniStar | Fugro | 3100LM | Internal |
| Radio Beacon | CSI Inc. | CSI-MBX-3 | Internal |
| Ground Control | Lieca | Leica 1230 | 453406 |
| Ground Control | Lieca | AX1202 | 5110009 |
| Ground Control | Lieca | Leica 1230 | 457176 |
| Ground Control | Lieca | AX1202 | 3460081 |

## LiDAR Software

GCS V 6.01
IVS Fledermaus 6.1.5
CARIS HIPS/SIPS V 5.4 (w/ Service Pack 2)
Microstation SE V 05.07.01.14
Microstation V 08.01.02.15
POSPac 4.2
ESRI ArcMap V9.0
ERDAS IMAGINE V8.7

## Appendix B – Acquisition Vehicle Descriptions

### LiDAR

The Beechcraft King Air 90 (Figure B1) was modified with a camera door in the AFT starboard side floor, in which the SHOALS-1000T Bathymetric and Topographic LiDAR System could be mounted. Technical specifications for the plane can be found in Table B2 below. The aircraft was mobilized at Dynamic Aviation in Bridgewater, Virginia. The airborne component of the SHOALS-1000T consists of three separate modules. The lasers and camera are housed in a single package that was bolted to a flange above the aircraft camera door (Figure B2). An equipment rack, containing the system cooler and power supplies, was installed aft of the laser (Figure B3). The operators console was attached to the seat rails foreword of the power supply. The console was installed so the operator was facing forward (Figure B4). All hardware was located on the starboard side of the aircraft. Equipment installation required about 2 hours.

The only offset measurement required during system mobilization is from the POS/AV Inertial Measurement Unit (IMU) to the POS/AV GPS antenna. The IMU is completely enclosed within the laser housing. The offsets from the IMU to a common measuring point (CMP) on the outside of the housing are known.

Offsets were measured using a total station. An arbitrary base line was established along the port side of the aircraft. Ranges and bearings were measured from the total station to the CMP on the top of the laser housing (Figure B6). Additional measurements where made to the sides and top of the housing to determine its orientation. A final measurement was made to the center of the POS/AV GPS antenna (Figure B5). The IMU to POS/AV GPS offsets are calculated using the known IMU to CMP offsets. A summary of the offset measurements can be found in (Table 1) below.

**Table B1 - Aircraft Offsets**

| OFFSET | X | Y | Z |
|---|---|---|---|
| IMU to CMP | 0.073 | -0.230 | -0.415 |
| CMP to POS/AV GPS Antenna | 1.300 | -0.155 | -0.855 |
| IMU to POS/AV GPS Antenna | 1.373 | -0.385 | -1.270 |

The offsets from the IMU to the POS/AV GPS antenna are entered in to the POS/AV console prior to survey.

**Table B2 - Beechcraft King Air (N91S)**

| Airplane | Beechcraft King Air |
|---|---|
| Official Number | N91S |
| Owner | Dynamic Aviation |
| Wing Span | 47 ft 10.5 in |
| Length | 35 ft 6 in |
| Gross Weight | 9,650 lbs |
| Typical Empty Weight | 5,150 lbs |
| Survey Mode Duration | ~4-5 hours |
| Engine | PT6A-20 (Jet) |

**Figure B1 - Beechcraft King Air (N91S)**


**Figure B2 - Lasers and camera**

**Figure B3 - System cooler and power supplies**

**Figure B4 - Operators console**


**Figure B5 - NovAtel GPS Antenna and Aero DGPS Antenna locations**

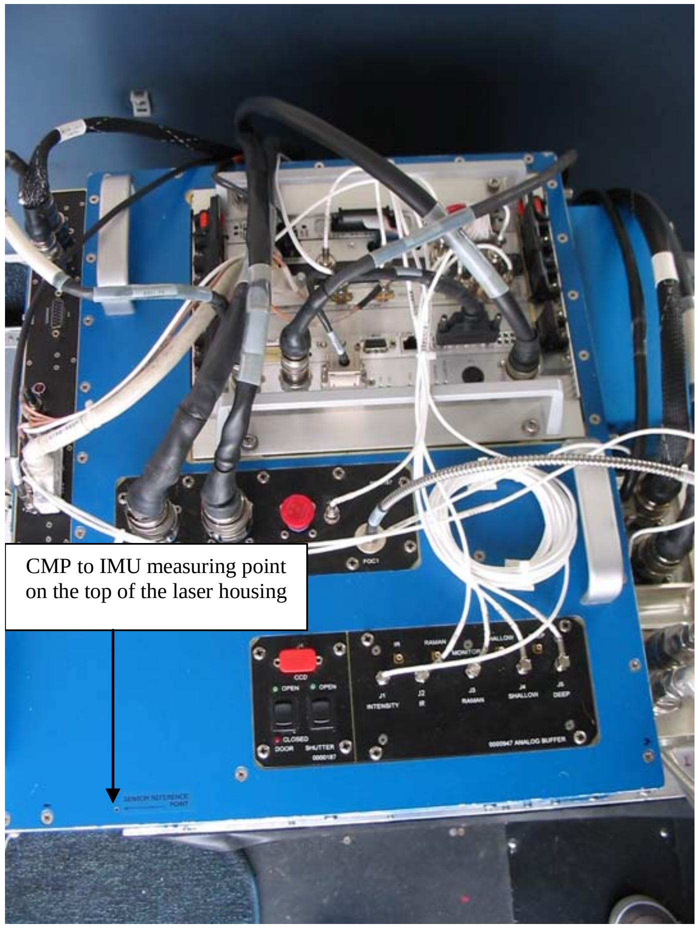



**Figure B6 - CMP to IMU measuring point**

# Appendix C – Calibration Reports

2003-08-31

## CHARTS DIGITAL CAMERA CALIBRATION DESCRIPTION

In order to confirm the correspondence of the camera to the SHOALS-1000 system, a few factors must be addressed. The first is the Interior Orientation (IO) of the camera. The second is the boresight angles. The third is the issue of coordinate frames. The fourth is the use of GPS to locate the camera perspective center. The fifth is the use of the average altitude.

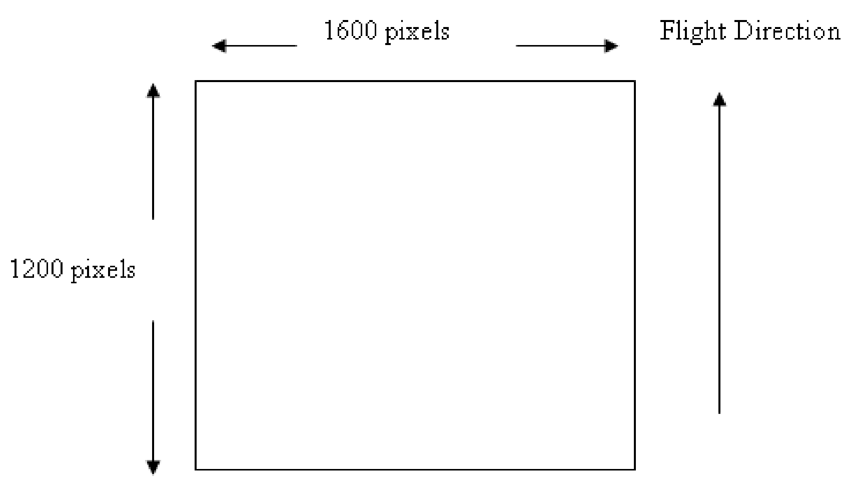
## 1 INTERIOR ORIENTATION OF DIGITAL CAMERAS

### 1.1 Introduction

There are several parameters which characterize the interior calibration of a digital camera. These parameters can be first determined in a ground test field calibration but the required accuracy is usually not achieved. Subsequently, airborne data over a test field at an altitude of ~ 700 meters is used to derive the IO parameters.

The camera system must be flown several times over a target field which has several identifiable targets. The image overlap must be 60 –70% in the forward direction and 20-40% in the lateral direction. After the images are acquired they must be viewed with a software package (like PCI Geomatics OrthoEngine) which can be used to measure the pixel locations of the targets in the images. Applanix has software packages called POSEO and POSCAL which can be used to derive the Interior Orientation of the camera as well as the boresight angles between the camera optical axis and the IMU reference plane

The orientation of the CCD in the camera is such that the short axis is in the flight direction:



## 1.2 Focal Length

The first important number is the calibrated focal length. The camera lens has a nominal focal length of 16 mm. The final more accurate value will have to be derived from airborne data. The scale of the image on the ground is determined by the focal length so it must be known to a high precision.

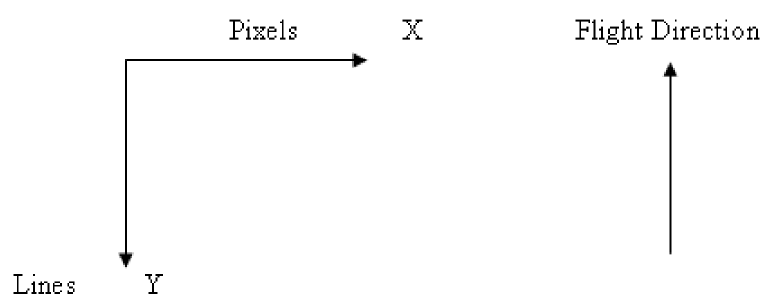
f = 16.065 mm

This is recorded on the System Parameters file along with other basic data as:

```
digital_camera: 534
lateral_pixels: 1600
forward_pixels: 1200
pixel_size: 7.4
focal_length: 16.065
```

## 1.3 Principal Point

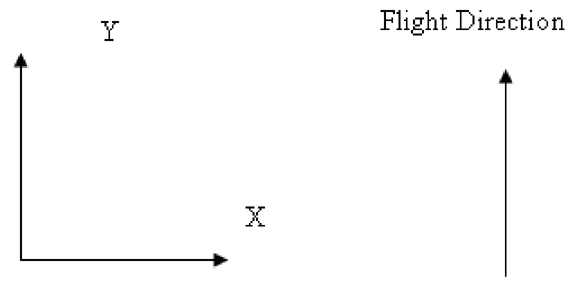
The principal point is defined as the intersection of the optical axis with the CCD plane. The number is usually given in one of two different conventions. Typically, the location of a point on a CCD is given in terms of pixels and lines from the upper left corner of the CCD. The axes are defined in the following way, where the (0,0) point is the upper left corner of the upper left pixel:




For the delivered CCD the **factory** location of the Principal Point will be nominally at the center of the CCD:

X = 800 pixels
Y = 600 lines

Another way of locating the Principal Point is by reference to the center of the CCD. This 1600x 1200 device has its center at X = 800 and Y = 600. For imaging, the axes are defined with the Y axis being positive in the upward direction, as shown below:




The airborne data will be used to derive a more accurate Principal Point location. Referenced to the center of the CCD the **final** Principal Point will be given as:

X_OFFSET = 30.11 pixels

Y_OFFSET = -11.68 pixels

These values are recorded onto the System Parameter file as:

```
principal_point_offsets: 30.11, -11.68
```

Note that some Aerial Triangulation (AT) software requires that the dimensions of the offsets be given in mm. If this is the case, the pixel values above must be multiplied by 0.0074 mm, since the pixel size is 7.4 microns.

## 1.4 Radial Distortion

The focal length is closely coupled to the radial distortion of the optical lenses. In fact it is quite common that the final focal length is chosen for the mean value of the radial distortion. The distortion of the lens can be given as a table of values or as a series of coefficients, which correct for the radial shift of an object in the image plane. For example a delivered camera had the following as its radial distortion table:

| Radius(mm) | Distortion (mm) |
|---|---|
| 2.0 | 0.001 |
| 4.0 | 0.003 |
| 6.0 | 0.006 |
| 8.0 | 0.012 |
| 10.0 | 0.018 |
| 12.0 | 0.025 |
| 14.0 | 0.031 |
| 16.0 | 0.032 |
| 18.0 | 0.023 |

| | |
|---|---|
| 20.0 | 0.000 |
| 22.0 | -0.046 |

Another way of defining the distortion is through a series of coefficients which describe the same curve. There are variances as to how many coefficients are used. In this example we show the values for a 8 coefficient description. The equation for this model is:

$$\text{Shift (mm)} = K0 + K1(R) + K2(R^2) + K3(R^3) + K4(R^4) + K5(R^5) + K6(R^6) + K7(R^7),$$

where R is the distance from the center of the CCD in mm. The derived coefficients for the above table are:

| | |
|---|---|
| K0 | 3.14180 E -03 |
| K1 | -3.20167 E -03 |
| K2 | 1.38125 E -03 |
| K3 | -2.33337 E -04 |
| K4 | 2.46806 E -05 |
| K5 | -1.37561 E -06 |
| K6 | 3.67647 E -08 |
| K7 | -4.10320 E -10 |

The calculated values for the CHARTS camera (SN 534) are as written on the System Parameters file:

radial_distortion_K0: 0.0
radial_distortion_K1: 0.000687854
radial_distortion_K2: -0.00000575118
radial_distortion_K3: 0.0000000432508
radial_distortion_K4: -0.0000000000187
radial_distortion_K5: 0.0
radial_distortion_K6: 0.0
radial_distortion_K7: 0.0

# 2 Boresight Angles

Despite the efforts to align the camera with the laser system in the laboratory, there will still be offset angles which are required. These boresight angles are the three attitude angles between the IMU frame and the optical axis of the camera. They will be fixed offsets, as long as the Scanner or the camera are not disturbed in the Sensor Structure. If either one is removed and re-installed the boresight angles must be rederived from airborne data.

The boresight angles for the system can be derived from data taken at high altitude. For example, known Ground Control Points (GCPs) can be overflown in opposite directions. The relative shift on the ground can then be used with the altitude to adjust the boresight angles. This was done with some preliminary CHARTS data and the boresight angles were as follows:

```
camera_boresight_roll: -0.10
camera_boresight_pitch: 12.00
camera_boresight_heading: 0.0
```

where the first is the boresight roll angle between the optical axis and the IMU reference plane; the second is the boresight pitch angle; and the last is the boresight heading angle. These angles are all in degrees.

Note that a more sophisticated algorithm for the boresighting of the camera is being considered. However, the angles above resulted in an accuracy of under 3 meters.

These three boresight angles must be used as inputs to the algorithm to derive the best angles from the IMU roll, pitch and heading angles.. These angles are displayed and they are changeable on the Utilities/Show Camera Parameters Panel of the GCS.

Note that these angles can be changed anytime, and the georeferenced positions on the image will change WITHOUT having to reprocess any data.

# 3 Coordinate Frame

The attitude angles reported by the IMU are in the local level frame of the IMU. The roll is the rotation about the forward flight X axis of the IMU (positive roll is right wing down); the pitch is the rotation about the cross flight Y axis (positive pitch is nose up); and the heading is the rotation about the vertical Z axis (positive heading is clockwise from North; Z is pointing down.)

The Camera boresight angles are added to the measured Roll, Pitch and Heading angles of the IMU. These result in the angles used to calculate the position of the pixel on the ground.

# 4 Camera Lever Arm

The GPS trajectory of the processing is chosen to be centered at the IMU center for the CHARTS system. To arrive at the GPS location of the camera perspective center, we must then apply lever arms which describe the shift in location from the IMU to the camera center.

These camera lever arms are required as inputs to the calculation. These dimensional values will not change since the SHOALS-1000 system and the camera will always be mounted in the sensor structure in the same way. Even if one or the other of the systems is removed and re-installed in the structure the offset distances will not change significantly. (By contrast, the boresight angles will definitely have to be recalculated since these must be known very accurately).

Using the usual definition of axes where X is forward, Y is to the right, and Z is down, the camera lever arms are:

X: -0.364 m
Y: 0.060 m
Z: 0.131 m.

These are recorded on the System Parameters file as:

```
posref_camera_lever_arm: -0.364, 0.06, 0.131
```

where in the case of CHARTS the posref is the location of the IMU.

## 5 ALTITUDE

The derived angles of the projection of the camera image onto the ground are just that: angles. They do not in themselves contain enough information to derive the locations of pixels on the surface.

The extra dimension required is the height of the camera above the ground. For this we use the average altitude of the system which in turn is derived from the average slant range of the laser. Note that over a flat water surface the average slant range is a good indication of the altitude. However, over rough terrain the average altitude derived by the system will not necessarily be very accurate for the height of the camera at the instant the image is taken. This is another reason the georeferencing of the camera pixels is not as accurate as other aerial survey systems.

CameraCalibrationValues 09/09/2005

```
[DIGITAL_CAMERA_SECTION]

digital_camera:534
lateral_pixels: 1600
forward_pixels: 1200
pixel_size: 7.4
focal_length: 16.065
radial_distortion_K0: 0.0
radial_distortion_K1: 0.000687854
radial_distortion_K2: -0.00000575118
radial_distortion_K3: 0.0000000432508
radial_distortion_K4: -0.0000000000187
radial_distortion_K5: 0.0
radial_distortion_K6: 0.0
radial_distortion_K7: 0.0
principal_point_offsets: 30.11, -11.68
camera_boresight_roll: -0.70
camera_boresight_pitch: 10.72
camera_boresight_heading: 0.0
camera_trig_delay: 0.00
posref_camera_lever_arm: -0.364, 0.06, 0.131
```

# Appendix D – Background theory on bathymetric LiDAR