FINAL PROJECT REPORT – ESPIRITU SANTO

RFQ Number: RFTGA 2012/2863

AAM Project Number: 20076A

Project Name: Acquisition of LiDAR and Imagery Derived Products for Vanuatu

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1.0 Introduction

AAM was engaged by Geoscience Australia to collect topographic and bathymetric data required to assess key vulnerabilities and risks, formulate adaptation strategies and plan, in addition to mainstreaming adaptation into decision making along the Vanuatu coast.

Acquisition began on 7th October 2012, however the onset of the wet season in Vanuatu meant that the remaining survey was delayed and was completed between 10th and 23rd May 2013.

AAM deployed its Optech ALTM Pegasus (October) and ALS 60 (May) instruments for this project. This sensors are capable of detecting multiple returns, with a minimum of 4 potential returns for each outbound laser pulse as well as recording the intensity of each return.

The planned point density for the survey was an average density of 3.0pts/m^2 for the topographic LiDAR capture.

The vertical accuracy for this data set is +/-0.30m, and the horizontal accuracy is +/-0.80m. This data is presented in terms of ITRF2008 UTM zones 58. The vertical data is presented in terms of ITRF2008 Ellipsoidal and MSL (2012).

Sections 2 through to 4 refer to the Topographic element of this project. The Bathymetric data capture is addressed in Section 7.0 of this report.

DATA IN THIS FINAL REPORT RELATES TO THE ESPIRITU SANTO DATASET.

This *Espiritu Santo Project Report* addresses the following topics as specified in the contract:

1. how each of the contract specifications has been met,
2. a statement of consistency with any specified standards,
3. results of independent accuracy tests,
4. metadata statements
5. extra-ordinary issues that may have affected the nature or delivery of the project
6. other project information of note.

2.0 Contract Specifications Confirmed

2.1 Category of Elevation Capture and Laser Flight Settings

The survey undertaken was ICSM Category 1:

- Absolute vertical accuracy: 1 sigma 0.30m or better in areas of open, flat terrain.
- Absolute horizontal accuracy: 1 sigma 0.80m or better in areas of open, flat terrain.

The category of elevation is assigned based on LiDAR system specifications and settings used for project acquisition. The following Table shows the LiDAR system settings used for acquisition.

Laser Flight Settings		
Description	Espiritu Santo	Units
Sensor ID	Optech ALTM Pegasus / ALS60	
Flying Height	700 / 700	m
Swath Overlap	30 / 27.5	%
Swath Width	509 / 496	m
Half Scan Angle	20 / 20	Degrees
Scan Frequency	40 / 40	Hz
Maximum Number of Returns	4 / 4	
Footprint Size	0.14 / 0.14	m
Pulse Rate Frequency	250 / 122.6	KHz
Estimated Horizontal Accuracy	0.8 / 0.8	m
Estimated Vertical Accuracy	0.3 / 0.3	m
Average Point Spacing	0.32	Pts/m^2
Average Density of Ground Strikes	7.34	Pts/m^2

The Figure below displays the LiDAR system accuracy specifications as presented by Optech for the ALTM Pegasus.

Parameter	Specification
Operational envelope [1,2,3,4]	150-5000 m AGL, nominal
Laser wavelength	1064 nm
Horizontal accuracy [2]	1/5,500 x altitude, 1 σ
Elevation accuracy [2]	<5-20 cm, 1 σ
Effective laser repetition rate	Programmable, 100-500 kHz
Position and orientation system	POS AV™ AP50 (OEM)
Scan width (FOV)	Programmable, 0-75°
Scan frequency [5]	Programmable, 0-140 Hz (effective)
Sensor scan product	800 maximum
Beam divergence	0.25 mrad (1/e)
Roll compensation	Programmable, ±37° (FOV dependent)
Vertical target separation distance	<0.7 m
Range capture	Up to 4 range measurements, including 1st, 2nd, 3rd, and last returns
Intensity capture	Up to 4 intensity returns for each pulse, including last (12 bit)
Image capture	5 MP interline camera (standard); 60 MP full frame (optional)
Full waveform capture	12-bit Optech IWD-2 Intelligent Waveform Digitizer (optional)
Data storage	Removable solid state disk SSD (SATA II)
Power requirements	28 V, 800 W, 30 A
Dimensions and weight	Sensor: 630 x 540 x 450 mm; 65 kg; Control rack: 650 x 590 x 490 mm; 46 kg
Operating temperature	-10°C to +35°C
Relative humidity	0-95% non-condensing

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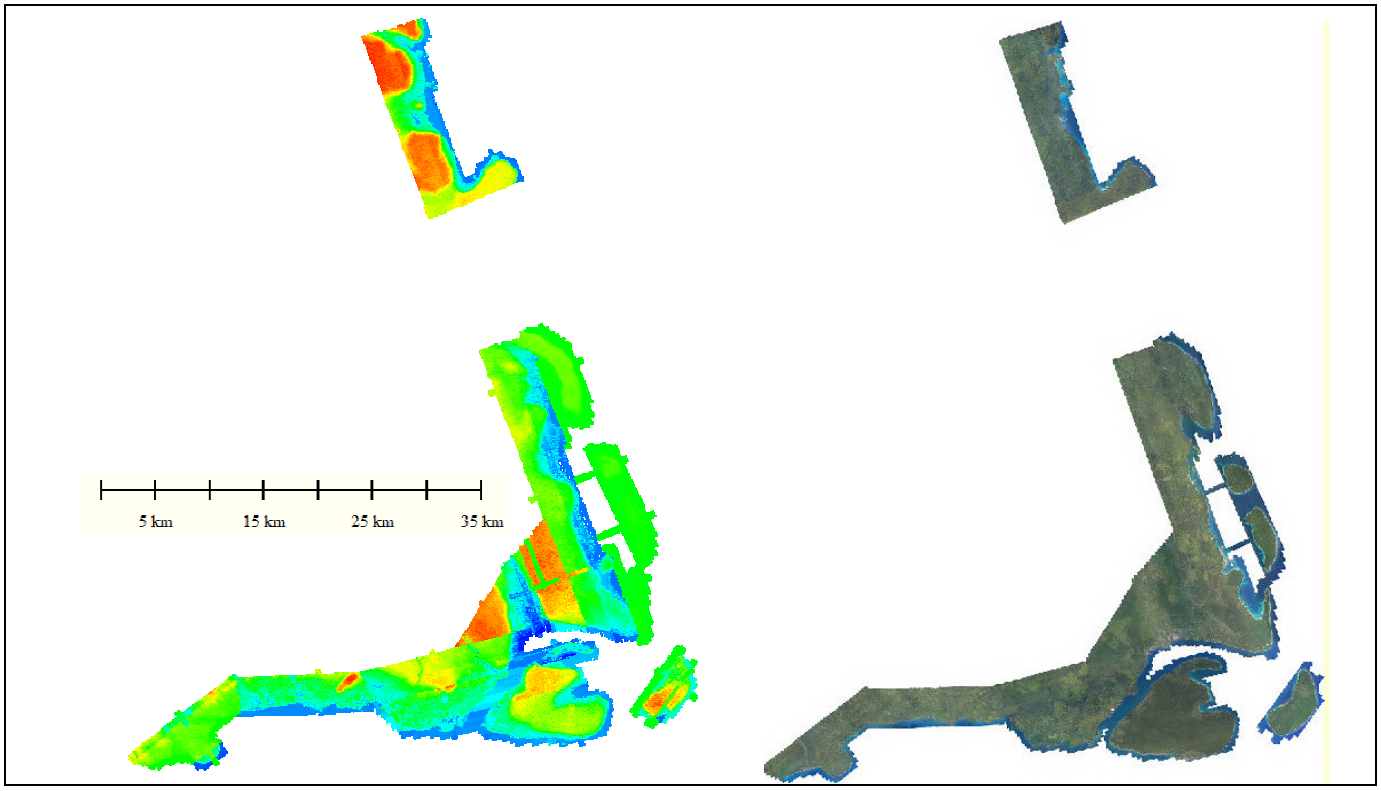
2.2 Topographic Coverage

The area of interest on Espiritu Santo covers an area of approximately 488sqkm.



Espiritu Santo Topographic Overview – LiDAR Elevation Data and Imagery Data

2.3 Horizontal Datum

The survey was coordinated in terms of ITRF2008.

2.4 Vertical Datum

For data presented in ITRF2008 all elevation data has been presented in Mean Sea Level (MSL) 2012. Ellipsoidal data has also been presented.

In order to verify the accuracy of the EGM2008 model or any adjustment to the vertical heights, a number of tidal stations were recovered across the Vanuatu Island chain in order to establish the height difference between the 1'x1' EGM2008 model and local Mean Sea Level.

Examination of existing tidal records revealed that the tidal regime is primarily semi-diurnal with a diurnal inequality evident. This results in a tidal regime that has two highs and two low waters a day but one of these cycles will be a higher high and low water.

During processing of all the GPS benchmarks, orthometric heights were calculated using the 1'x1' EGM2008 mark. As a result it was possible to calculate the ellipsoid to geoid (MSL) value for these points. These points were then compared with the derived values.

The below table demonstrates the relationship between EGM2008 and MSL for all of the tide gauge sites across the three islands of Efate, Espiritu Santo and Malekula.

MSL heights on wharf survey marks							
Wharf Control Point (tide gauge connected)		Phase 1 Resolved Heights (GPS only)			Phase 2 Adopted Heights (Tide gauge)		
Island	ID	Ellipsoid Height (GRS80)	Geoid Separation (EGM2008)	Orthometric height (EGM2008l)	MSL (measured)	Ellipsoid Height (GRS80)	Geoid Separation (corrected)
		(A)	(B)	(C)	(D)	(E)	(F)
Efate	povi	66.872	63.585	3.287	**2.550**	66.872	64.322
	emua	68.067	65.624	2.443	**1.642**	68.067	66.425
Malekula	lili	66.077	63.756	2.321	**1.294**	66.077	64.783
Santo	saw1	67.635	64.855	2.780	**1.750**	67.635	65.885
	saw2	67.573	64.854	2.719	**1.688**	67.573	65.885

In order to validate the MSL values calculated through the use of short period observations a comparison was made of the reading of Port Vila against longer period observations held by the South Pacific Sea Level Climate Monitoring Project (SCSLCMP). As all other island MSL values were in close agreement with Port Vila MSL, it was felt that this comparison validates all of the results as shown below.

Comparison with Annual MSL Values	Mean Sea Level (m)	Observed Mean Sea Level (m)	Difference
2010	0.899	0.904	+0.005
2011	0.919		-0.015
2012 (to Oct)	0.905		+0.001
2010-2012	0.908		-0.004

The results obtained are a good indicator of the differences between the EGM2008 and local orthometric height datum and should be used to correct the data. It is assessed that the MSL values are correct to +/-0.004m with only average differences of 0.05m seen during the period of observations and analysis.

Station	Ellipsoidal Height	EGM 2008 Geoid-Ellipsoid Separation Value	Calculated Separation Value based on MSL	Difference between EGM 2008 and Observed MSL Separation Values
PoVi	66.872	63.585	**64.322**	**-0.737**
Emua	68.067	65.624	**66.425**	**-0.801**
LiLi	66.077	63.756	**64.783**	**-1.027**
saw1	67.635	64.855	**65.885**	**-1.030**
saw2	67.573	64.854	**65.885**	**-1.031**

2.5 Map Projection

The survey data is presented in terms of ITRF2008 UTM zone 58.

2.6 Survey Control

The primary survey control point (GPS Base stations) was established at Luganville Airport on Espiritu Santo.

The central base stations were coordinated using AUSPOS (24 hour periods, multiple days) and checked against a number of surrounding State Survey Control Points.

All reference and check point surveys were coordinated relative to the nearest base station. All base station, reference points, and check points were coordinated against local survey marks.

Summary of the datum used throughout the project is below:

Horizontal:
The horizontal datum was established directly from AUSPOS for each base station. The Base stations accuracies were subsequently checked by control survey from established coordinated survey marks.

Vertical:
Ellipsoid - Established directly from AUSPOS as per the horizontal datum.
MSL - Each base station, reference point survey, and check point survey was linked to surrounding MSL marks, thereby providing them a "local " MSL datum in their immediate vicinity

2.7 Data Tiling and File naming

Data is provided in tiles 1km by 1km to the following filenaming convention:

Intensity and RGB Imagery

Naming Convention for LiDAR intensity or other forms of imagery: *ProjectNameYYYY-INT-GSD_xxxyyyy_zz_wwww_hhhh.ecw*		
ProjectName	*EfateLidar*	A meaningful description of the total survey area of interest. Do not use "_" as part of the Project Name
YYYY	*2012*	Year of survey
INT/RGB	*-INT*	Intensity image file identifier. Use RGB for 3 band natural colour imagery or RGBI for 4 band infrared
GSD	*-002*	Ground sampling distance or resolution of image in metres.
xxxyyyy	*_4806558 (480,000mE) (6558,000mN)*	Easting and northing value (whole kilometre) of the south- west corner of the tile. A single "_" must be used to separate the remaining file name components.
zz	*_56*	UTM zone of the file
wwww	*_0020*	Width of the **dataset or tile** in whole kilometres
hhhh	*_0050*	Height of **dataset or tile** in whole kilometres
For example: EfateLidar2009-INT-002_4806558_56_0020_0050.ecw		

Unclassified LiDAR

Naming Convention for LiDAR point clouds: *ProjectNameYYYY-UNC-DAT-SWT_xxxyyyy_zz_wwww_hhhh.las*		
ProjectName	*EfateLidar*	A meaningful description of the total survey area of interest. Do not use "_" as part of the Project Name
YYYY	*2012*	Year of survey
UNC	*-UNC*	Unclassified point cloud. Fully calibrated and adjusted to specified datum
DAT	*-ELL*	Ellipsoidal heights (PNG94)
SWT	*-1..n*	Swath number (1 file per swath)
xxxyyyy	*_4806558 (480,000mE) (6558,000mN)*	Easting and northing value (whole kilometre) of the south- west corner of the tile. A single "_" must be used to separate the remaining file name components.
zz	*_56*	UTM zone of the file
wwww	*_0002*	Width of the tile in whole kilometres
hhhh	*_0002*	Height of the tile in whole kilometres
For example: EfateLidar2009-RAW-ELL-001_4806558_56_0002_0002.las		

Classified LiDAR

Naming Convention for LiDAR point clouds: *ProjectNameYYYY-CL-DAT_xxxyyyy_zz_wwww_hhhh.las*		
ProjectName	*EfateLidar*	A meaningful description of the total survey area of interest. Do not use "_" as part of the Project Name
YYYY	*2012*	Year of survey
CL	*-C2*	classification level.
DAT	*-ELL or MSL*	Specified vertical datums. Ellipsoidal (ELL) or Orthometric (MSL)
xxxyyyy	*_4806558 (480,000mE) (6558,000mN)*	Easting and northing value (whole kilometre) of the south- west corner of the tile. A single "_" must be used to separate the remaining file name components.
zz	*_56*	UTM zone of the file
wwww	*_0002*	Width of the tile in whole kilometres
hhhh	*_0002*	Height of the tile in whole kilometres
For example: EfateLidar2009-C3-MSL_4806558_56_0002_0002.las		

ESRI Grids

Naming Convention for tiled UTM ESRI GRIDS: *txxxyyyyssppp* *(in addition to folder structure above with UTM GRIDS stored in separate folders, with all projection information defined.)*		
t = surface type.	*e*	Surface type • s – digital Surface model (DSM) • e – digital Elevation model (DEM) • f - canopy Foliage model (CFM) • c - Canopy elevation model (CHM) • h – Hydro digital elevation model (DEMH) • b – Bathymetry • m – Bathymetry and terrain elevations • t – Derived terrain variables (add as necessary)
xxxyyyy	*6458595* (645,000mE) (8,595,000mN)	• Easting and northing value (whole kilometre) of the south- west corner of the tile.
ss	*01*	Tile size (km) (square tile) • 01 – one kilometre • 02 – two kilometre • 05 - five kilometre • 10 – 10 kilometre • _5 (represents half a kilometre)
ppp	*001*	Ground sampling distance (GSD) or pixel size • 0_5 - half a metre • 001 – one metres • 002 – two metres etc
For Example: e645859501001		

Naming Convention for Mosaic (UTM) ESRI GRIDS: *txxxxxxxyyppp* *(in addition to folder structure above with UTM GRIDS stored in separate folders, will all projection information defined.)*		
t = surface type.	*e*	Surface type • s – digital Surface model (DSM) • e – digital Elevation model (DEM) • f - canopy Foliage model (CFM) • c - Canopy elevation model (CHM) • h – Hydro digital elevation model (DEMH) • b – Bathymetry • m – Bathymetry and terrain elevations • t – Derived terrain variables (add as necessary)
xxxxxxx	*efate*	A meaningful description of the total survey area and or sensor, dataset version etc.
yy	*12*	Year of Survey
ppp	*010*	Ground sampling distance (GSD) or pixel size in metres (UTM) UTM • 0_5 - half a metre • 001 – one metres • 002 – two metres etc
For Example: eEfate07010		

Naming Convention for all other UTM files: *ProjectNameYYYY-SSSS-PPPP-GSD_xxxyyyy_zz_wwww_hhhh.asc*		
ProjectName	*EfateLidar*	A meaningful description of the total survey area of interest. Do not use "_" as part of the Project Name
YYYY	*2012*	Year of survey
SSSS-PPPP	*-DEM-GRID*	Surface type. • DSM • DEM • HDEM • CHM • CFM • Bathymetry (BAT) • Mixed (MIX). Bathymetry and terrain elevations • TTT (Other terrain variables e.g. slope (SLP). Add as necessary. Product type • Mass points (MASS) • Breaklines (BRK) • TIN (TIN) • GRID (GRID) • Contours (CON) • Cross Sections (CROSS) • Imagery (BIL, TIF, IMG, ECW etc) • Other Use additional field width and more characters if required.
GSD	*-010*	Ground sampling distance or resolution of product where appropriate. Where GSD is not required producers can extend the surface type and product description field.
xxxyyyy	*_4806558* *(480,000mE)* *(6558,000mN)*	Easting and northing value (whole kilometre) of the south- west corner of the tile. A single "_" must be used to separate the remaining file name components.
zz	*_56*	UTM zone of the file
wwww	*_0020*	Width of the dataset or tile in whole kilometres
hhhh	*_0050*	Height of dataset or tile in whole kilometres
ext		File extension according to format conventions • LAS • xyz ascii format for easting, northing, elevation, intensity • asc – ESRI ascii GRID format • shp • dxf etc
For example:	*EfateLidar2009-DEM-GRID-010_4806558_56_0020_0050.asc*	

Primary LiDAR Point Cloud Data

The LAS files have been provided to ASPRS V1.2 Standards.
LAS file point classifications levels are formatted to comply with ASPRS Standard LiDAR Point Classes.

1	Unclassified
2	Ground
3	Low Vegetation (<1m)
4	Medium Vegetation (>1m – 2m)
5	High Vegetation (>2m)
6	Building
7	Low Point (noise)
8	Model Key-point (mass point)
9	Water
10	Reserved for ASPRS Definition

All returns and intensity has been retained. Overlap data has been retained. LAS files retain all relevant capture data including: point source ID and all flight path, sensor, GPS and processing system data. Refer to Section 2.7 data tiling and file naming for data tiling and file naming specifications.

2.8 Digital Elevation Model (DEM)

ArcGIS Terrains were created from ground classified LIDAR data. One metre ESRI ArcGIS binary grids were derived using a customised ArcGIS macro.

2.9 Digital Surface Model (DSM)

ArcGIS surfaces were created from non-ground classified LIDAR data. One metre ESRI ArcGIS binary grids were derived using a customised ArcGIS macro.

2.10 Canopy Elevation Model (CEM)

A canopy elevation model was produced as two metre ESRI ArcGIS binary grids using ArcGIS with the following methodology:

- All ground surface derived using natural neighbours interpolation [G] *(Floating Point)*
- First return vegetation surface derived using natural neighbours interpolation [V1] *(Floating Point)*
- Height in metres above ground of first vegetation returns [V1] - [G] = [H] *(Floating Point)*
- Mask of all vegetation ALS returns with 1m buffer, reclassified to 0 outside mask and NoData inside [M] *(Integer)*
- Mosaic of canopy height surface and vegetation mask [H] + [M] = CEM *(Floating Point)*

2.11 Foliage Cover Model (FCM)

A foliage cover model was produced as 10 metre ESRI ArcGIS binary grids using ArcGIS with the following methodology:

- Count of all vegetation returns per 10m cell [V] *(Integer)*
- Count of total ALS returns per 10m cell [A] *(Integer)*
- Proportion of all vegetation to total ALS returns expressed as a percentage ([V] / [A]) * 100 = FCM *(Floating Point)*

2.12 Contours

Contours were generated in ESRI Shape file format with 0.5m and 5m intervals.

2.13 Bathymetric Datasets

Please refer to Section 7.0, Bathymetric LiDAR Survey.

2.14 Imagery

Imagery has been generated in ECW and TIFF format to the capture extents. Please see details of camera specifications below:

DiMAC cameras bring high-quality imagery to a medium format

- Patented true Forward Motion Compensation technology provides crisp, blur-free imagery (fly lower, faster and longer)
- Temperature stabilization
- Rigorous geometric and radiometric calibration
- Wide choice of lenses
- 1-year comprehensive manufacturer's warranty with 24/7 support

ALTM Multi-Sensor Integration Package

- Custom-engineered multi-sensor mount
- Fully integrated lidar and photo mission planning capability
- Fully integrated sensor control and monitoring capability
- All required interconnect cables
- Full calibration report with lidar/camera boresight values
- Planning, operations, and data-processing training

Parameter	Specification
Camera Module (CM)	
Area sensor	60 MP full-frame CCD 8,984 x 6,732 pixels (effective) 6 µm x 6 µm pixels 53.9 x 40.4 mm (effective)
True Forward Motion Compensation (FMC)	Solid-state electro-mechanical
Lenses	50 mm /70 mm /120 mm /210 mm
Shutter	Electro-mechanical iris mechanism 1/125 to 1/500 sec., f-stops: 4, 5.6, 8, 11, 16
Filter	Standard size RGB and IRC interchangeable filters
Image output	8 or 16 bits per channel 24-bit RGB: 180 MB 48-bit RGB: 360 MB
Capture rate	2.5 sec.
Resolution (GSD)	2 cm to 1 m / <1 inch to 3.3 feet
IT Cube (ITC)	
Control & acquisition computers	PC/104 RoHS-compliant small form-factor embedded computers with minimum: Intel® Core™ Duo LV2400 CPU, 1-GB RAM 4-GB flash disk local storage IEEE 1394 Firewire interface
Removable storage units	500-GB pressurized hard drives - 8,000 images typically
Dimensions (H x W x D)	250 x 250 x 250 mm / 10 x 10 x 10 in
Weight	15 kg / 33 lbs
Input voltage (DC)	24-28 V
Current draw	5 A
Software	
DiOPS	Real-time camera operations and configuration management
CaptureOne	Image development

2.15 Project Plan

Prior to data capture commencement, a Project Plan was submitted to and approved by Geoscience Australia. This Project Plan details work breakdown structure, agreed data capture plans, project milestones and delivery schedules, progress reporting schedules.

2.16 Pre-survey Quality Assurance Plan

Prior to the commencement of aerial LiDAR data capture, AAM prepared and submitted to Geoscience Australia a Quality Assurance Plan that conformed to an identified management system and generally complies with ISO 9001. The Plan addressed the organisation and management of the project, work procedures, environmental considerations, safety and risk control and test procedures.

The Plan also detailed the procedures to be used in verifying that the deliverables meet the required specification including:

- the procedures and methodologies to be used to verify that the deliverables meet the required specifications.
- Details of proposed calibration checks and methodology to be used to establish both reference stations and ground test sites.

2.17 Post-survey Spatial Accuracy Report

Following successful capture of the aerial data a Post Survey Spatial Accurracy report was submitted and approved by Geoscience Australia.

Observed flight runs were provided in ESRI shape file format.

All reference and check points used to verify accuracy were provided in ESRI shape file format.

For analysis of ground comparisons refer to Section 3.0. Accuracy Assessment.

2.18 GPS Base Station Data

GPS data for all occupations of base-stations has been supplied in RINEX format (Receiver Independent Exchange Format

2.19 GPS Base Station Data

The seamless dataset has been generated using techniques set out in AAMs plan for generation of seamless dataset (see Section 8.0) and complies with specification.

3.0 Accuracy Assessment

Accuracy assessment was undertaken in two phases. Initially a post-survey reference site assessment was conducted to analyse the overall accuracy of the transformed lidar ground strikes relative to MSL. Additional check points were then collected to independently assess the accuracy of the classified data according to different land cover types.

The independent ground survey was not undertaken in an appropriate method to allow for classification accuracy assessment of landcover classes in the form of an error matrix. The survey did however, allow for a detailed assessment of vertical accuracy across different land cover classes. ID photos were only collected for each survey site and not individual points.

3.1 Project Design Accuracy

Project specifications and technical processes were designed to achieve data accuracies as follows:

Project Design Accuracy			
	Measured Point	**Derived Point**	**Basis of Estimation**
Vertical data Horizontal data Test points	 < 0.13m 0.05m	0.15m	Project Design System specifications Survey methodology used

Notes On Expected Accuracy

- Values shown represent standard error (68% confidence level or 1 sigma), in metres.
- “Derived points” are those interpolated from a terrain model.
- “Measured points” are those observed directly.
- Accuracy estimates for terrain modelling refer to the terrain definition on clear ground. Ground definition in vegetated terrain may contain localized areas with systematic errors or outliers which fall outside this accuracy estimate.
- Laser strikes have been classified into “ground” and “non-ground”, based upon algorithms tailored for major terrain/vegetation combinations existing in the project area. The definition of the ground may be less accurate in isolated pockets of dissimilar terrain/vegetation combinations.

3.2 Reference Site Analysis

Test points were distributed in 7 groups across the Espiritu Santo Island and located on open clear ground. Comparison of the field test points with elevations interpolated from measured data are summarised in the table below.

Before

	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6	Site 7	Average
Average dz	-0.010	0.079	0.112	0.076	-0.076	0.11	0.231	0.075
Minimum dz	-0.042	0.029	0.078	0.060	-0.135	0.072	0.163	0.032
Maximum dz	0.021	0.104	0.170	0.090	-0.005	0.141	0.279	0.114
Average magnitude	0.016	0.079	0.112	0.076	0.076	0.11	0.231	0.100
Root mean square	0.019	0.081	0.114	0.076	0.084	0.111	0.233	0.103
Std deviation	0.016	0.019	0.017	0.009	0.036	0.015	0.031	0.020

After

	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6	Site 7	Average
Average dz	-0.090	-0.001	0.032	-0.004	-0.156	0.03	0.151	-0.005
Minimum dz	-0.122	-0.051	-0.002	-0.020	-0.215	-0.008	0.083	-0.048
Maximum dz	-0.059	0.024	0.090	0.010	-0.085	0.061	0.199	0.034
Average magnitude	0.090	0.013	0.032	0.008	0.156	0.031	0.151	0.069
Root mean square	0.092	0.018	0.037	0.010	0.160	0.034	0.154	0.072
Std deviation	0.016	0.019	0.017	0.009	0.036	0.015	0.031	0.020

3.3 Check Point Analysis

For the purposes of independent accuracy assessment check point measurements were taken throughout the project area. Check points were collected for each land cover type across the project extent. The Table below shows the number of check points for each class.

Area	Landcover Class	No of Points
Espiritu Santo	grass (~0.1 - 0.3m high)	29
	grass (~0.02m high)	60
	under wooded trees (~10-20m high)	45
	grass (~1.5m high)	19
	under trees (~5-10m high)	18
	thick bush	5
	grass (~0.02 - 0.30m high)	45
	grass (up to 0.3m high)	11
	grass (~0.01m high)	69
	grass /shrubs (~0.3 - 1.0m high)	11
	under trees (~10 - 20m high)	5
	forest tree cover (~10-20m high)	52
	grass (~0.05 - 0.1m high)	21
	grass (~0.2m high)	19
	grass (up to 1.0m high)	17
	under high wooded trees (up to 30m high)	11
	under palm trees (up to 30m high)	28
	grass (~0.2m - 1.0m high)	7
	shrubs / bushes	33

Comparison of the field check points with elevations interpolated from the LiDAR and DEM data resulted in the accuracies shown in the following tables for the landcover classes:

Vertical Accuracy – LiDAR Data					
Area	**Landcover Class**	**No of Points**	**Mean Difference (m)**	**Std Deviation (m)**	**RMS (m)**
	grass (~0.1 - 0.3m high)	29	+0.247	0.030	0.248
	grass (~0.02m high)	60	+0.023	0.135	0.136
	under wooded trees (~10-20m high)	45	+0.227	0.072	0.238
	grass (~1.5m high)	19	+0.700	0.140	0.713
	under trees (~5-10m high)	18	+0.141	0.098	0.170
	thick bush	5	+0.204	0.054	0.210
	grass (~0.02 - 0.30m high)	47	-0.130	0.060	0.142
	grass (up to 0.3m high)	11	-0.147	0.046	0.154
	grass (~0.01m high)	69	-0.001	0.021	0.021
	grass /shrubs (~0.3 - 1.0m high)	11	+0.559	0.209	0.593
	under trees (~10 - 20m high)	5	0.024	0.029	0.035
	forest tree cover (~10-20m high)	52	+0.118	0.098	0.153

	grass (~0.05 - 0.1m high)	21	+0.135	0.064	0.148
	grass (~0.2m high)	19	+0.081	0.063	0.101
	grass (up to 1.0m high)	17	+0.178	0.109	0.207
	under high wooded trees (up to 30m high)	11	-0.037	0.224	0.217
	under palm trees (up to 30m high)	28	-0.003	0.043	0.043
	grass (~0.2m - 1.0m high)	7	+0.070	0.030	0.075
	shrubs / bushes	33	+0.232	0.205	0.307

Vertical Accuracy Comparison with Data Specification – LiDAR Data						
Area	**Landcover Class**	**Within ±0.30m**	**Outside ±0.30m**	**Total**	**% Within ±0.30m**	**% Outside ±0.30m**
	grass (~0.1 - 0.3m high)	28	1	29	96.55	3.45
	grass (~0.02m high)	60	0	60	100.00	0.00
	under wooded trees (~10-20m high)	38	7	45	84.44	15.56
	grass (~1.5m high)	0	19	19	0.00	100.00
	under trees (~5-10m high)	17	2	18	94.44	11.11
	thick bush	5	0	5	100.00	0.00
	grass (~0.02 - 0.30m high)	45	0	45	100.00	0.00
	grass (up to 0.3m high)	11	0	11	100.00	0.00
	grass (~0.01m high)	69	0	69	100.00	0.00
	grass /shrubs (~0.3 - 1.0m high)	1	10	11	9.09	90.91
	under trees (~10 - 20m high)	5	0	5	100.00	0.00
	forest tree cover (~10-20m high)	50	2	52	96.15	3.85
	grass (~0.05 - 0.1m high)	21	0	21	100.00	0.00
	grass (~0.2m high)	19	0	19	100.00	0.00
	grass (up to 1.0m high)	13	4	17	76.47	23.53
	under high wooded trees (up to 30m high)	9	2	11	81.82	18.18
	under palm trees (up to 30m high)	28	0	28	100.00	0.00
	grass (~0.2m - 1.0m high)	7	0	7	100.00	0.00
	shrubs / bushes	25	8	33	75.76	24.24

4.0 Metadata

A complete metadata statement consistent with the current ANZLIC standard has been provided for each data product supplied. Metadata documents have been provided in Adobe Reader (.pdf) format. Further for every file in each data product, an .xml document with a complete metadata statement consistent with the current ANZLIC standard has been provided.

4.1 General Capture Specifications

MetaData Elements	
Characteristic	**Description**
Device Name	ALS60
IMU Used	uIRS 200Hz
Acquisition Start Date	07/10/2012
Acquisition End Date	23/05/2013
Number of Runs	216
Number of Cross Runs	21
Flight Direction	Variable
Flying Height (AGL)	700m
Half Scan Angle	20
Swath Width	496
Sidelap	27.5%
Average Point Spacing	0.50
Laser Pulse Rate	122.6KHZ
Laser Pulse Mode	Single
Laser return Types	1st, 2nd, 3rd and Last
Laser Intensity	Supplied on all returns
Laser footprint size	0.14m
DEM output pixel size	1m
DSM output pixel size	1m
CHM output pixel size	2m
FCM output pixel size	10m
Horizontal Datum	ITRF2008
Vertical Datum	ITRF2008 MSL (2012),
Map Projection	UTM zones 58
System Calibration Certification	20th June 2012

4.2 Source Data

Source Data				
Item	**Source**	**Description**	**Ref No**	**Date**
Laser System	AAM	ALS60	20076A	07/10/12-23/05/13
GPS Base Data	AAM	Static GPS	20076A	07/10/12-23/05/13
Base Stn Coords	AAM	Total Station	20076A	07/10/12-23/05/13
Field Survey Data	AAM	RTK & Total Station	20076A	07/10/12-23/05/13

4.3 Reference Systems

	Horizontal	Vertical
Datum	ITRF2008	MSL
Projection	UTM Zone 58	N/A
Geoid Model	N/A	Tide Gauge Calculated
Santo Primary Base (Airport)	Efate Airport 738029.598E 8284336.503N	Santo Airport 42.791 RL
SAW1	Luganville Wharf 734894.896E 8283453.280N	Luganville Wharf 1.750 RL
SAW2	Luganville Wharf 734914.353E 8283466.199N	Luganville Wharf 1.686 RL

4.4 Limitations of Data

The definition of the ground under trees and over wetland areas may be less accurate.

5.0 Extraordinary Issues

There have been no extraordinary issues associated with this project.

6.0 Other Project Information of Note

6.1 ANZLIC Metadata Statement

To be generated from NEDF/ANZLIC metadata tool

7.0 Bathymetric LiDAR Survey

7.1 Executive Summary

Overview

The Laser Airborne Depth Survey (LADS) for GeoScience Australia commenced on the 10th October 2012 and data gathering operations were completed on the 26th November 2012. The survey was conducted by Pelydryn Limited using a HawkEye IIb Bathymetric LiDAR sensor, fitted to a NOMAD provided by AAM Pty Ltd.

NOMAD Aircraft used for flying operations in Vanuatu.

Weather conditions during the preliminary phases of the survey were good with little or no impact on preparatory field operations. As the aircraft arrived on site and began airborne acquisition, the weather deteriorated significantly with heavy rainfall experienced in showers or for prolonged periods. This had several impacts on operations, low lying cloud and rainfall prevented operations due to operational limitations and safety considerations.

The rainfall experienced also caused significant run off of sediments into the coastal area and the resultant turbidity impacted on the quality of the data. The local orographic weather effects sometimes meant that flights could be continued at one end of the island, whilst raining at the other.

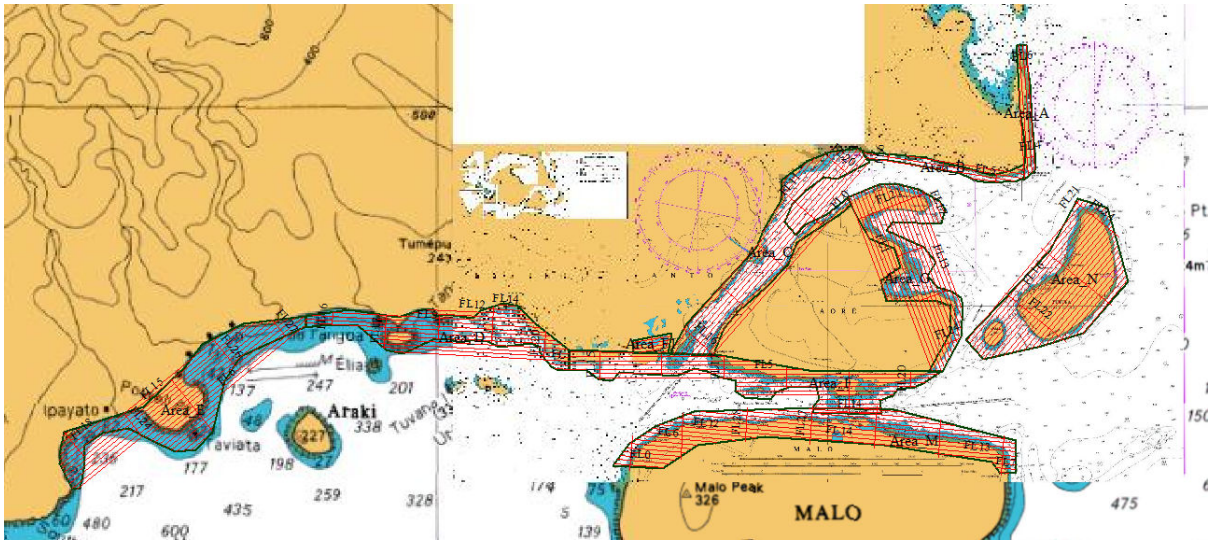
In any case the flying programme was extended as a result of the short sorties undertaken whilst trying to progress operations between weather fronts. Sun glint was also a problem as it meant that operations could only be flown before 10am and after 2pm meaning the amount of daylight was also limited.

As a result of the weather conditions there were occasions where sorties took place during the time where sun glint was a factor and if necessary lines were reflown to capture data.

Shipping and fishing activity had no impact on acquisition operations. The large numbers of vessels encountered in Port Vila Bay were manually removed from the dataset during data processing.

Survey Areas

In Espiritu Santo the allocated survey areas were divided into 10 blocks



Survey Area Overview Espiritu Santo

Areas and line directions were chosen in order to achieve a balance between data collection and turns whilst flying.

The HawkEye IIb system was mounted on board an AAM provided NOMAD aircraft. This aircraft is well suited to Bathymetric LiDAR work, offering a stable platform and allowing the operator full access to the system in flight. The sensor installation was approved by a licensed Aircraft Engineer and all aircraft operations complied with Civil Aviation Safety Authorities (CASA) regulations at all times.

Occupational Health and Safety controls were established in the Project Safety Management Plan and were adhered to throughout survey operations. There were no reportable incidents and no injuries to personnel, damage to property or the environment during survey operations.

Survey Data

Prior to the start of flight operations, a number of preliminary activities were undertaken in preparation for the survey. Ground and Sea Control Areas (GCA and SCA) were established by Pelydryn and AAM Pty Ltd. The system arrived in Efate, factory calibrated (having been installed and test flown in Australia) requiring only field calibrations to allow operations to commence.

The survey area lay from 200m inland out to the 40m contour or the limits of the shapefile provided by the Client. No additional flying was undertaken outside of these polygons. Bathymetric, topographic, position, attitude and imagery data was collected simultaneously and logged using the Operator Console software.

Offline data processing was conducted using Coastal Survey Studio (Version 2.3.0.11), CARIS HIPS (Version 7.1 SP 2 HF 6) and Fledermaus (Version 7.3.2a). All of the systems generally performed well, though the large volumes of topographic data acquired did impact on the offline data processing speed particularly when processing in the extreme shallow water on the coastal fringe where the bathymetric and topographic data overlapped.

The area surveyed varied considerably. The topography consisted of areas of open grassland, coconut plantations, heavy forest and urban areas. The bathymetry was characterised by shallow reef plates fringing the coastline with steep drops and coral outcrops lying offshore. Sandy beaches and rocky outcrops interspersed these areas. Where possible lines along the Low Tide Line were flown at low water and high water to allow capture across the area where waves were breaking.

Mobilisation and Acceptance Tests were completed in Brisbane and calibration flights were undertaken in Efate and are fully detailed in the Mobilisation Report (see **Error! Reference source not found.**).

Geodetics

Online positioning was provided by an Applanix POSAV. A Post Processed Kinematic (PPK) solution was utilised and applied to derive a full 3D navigation solution using Applanix POSMMS (v5.4). This uses position and attitude data logged whilst online, RINEX data from a local base station and rapid ephemeris data to derive a final navigation solution. This tightly coupled navigation solution was later applied to the raw waveform data in Coastal Survey Studio. All data is reported in the ITRF 2008 Reference frame as the AUSPOS Processing Service was used to provide base station data co-ordinates.

Dynamic and Static validation of the navigation solution were undertaken daily and as part of the initial calibration flights. Further details can be found in the Mobilisation Report (see **Error! Reference source not found.**).

Tidal Data

The Statement of Requirement required all data to be produced on the ellipsoid and reduced to Mean Sea Level for orthometric heighting based on EGM 2008. It was therefore necessary to undertake observations to establish Mean Sea Level at various sites on Efate, Malekula and Espiritu Santo. Existing tidal stations were recovered at Port Vila, Efate and at Luganville, Espiritu Santo. Two new stations were established temporarily at Emua, Efate and Lits Lits Jetty, Malekula. Mean Sea Levels were derived and compared against existing datum values and EGM 2008 heights to derive corrections to reduce ellipsoidal heights to MSL. Full details of these observations are in the Tidal Report.

Seabed Features and Contacts

No specific wreck investigations were required by the contract.

Conclusion

Following extensive surveying and analysis of cleaned data in accordance with Pelydryn's stated acceptance criteria, it is assessed that the requirement to detect all depths shoaler than 40m has been met. Data gaps do exist in the reef structures and on the seabed where no data was obtained for which there are a number of reasons:

a. In shallow waters, the system's capability to detect both the sea surface and seabed return is highly sensitive to other factors such as glint, breaking waves, contrast and slope. This is discussed more fully at Section 3.6
b. Turbidity – the high rainfall experienced led to significant reductions in water clarity due to run-off from shore.

The sea areas surveyed and encompassed within the limits provided with this report are surveyed to IHO Order 1B. Topographic data collected by Pelydryn meets the requirements laid down in Section 11 (General Topographic LiDAR Specifications) of the Statement of Requirement.

7.2 Narrative

The system was mobilised to Brisbane on 21st September 2012. Following a delay due to customs issues and aircraft availability the system was installed in the aircraft on 18th October 2012. After local liaison was completed, data gathering commenced on 31st October 2012.

Survey Activity Summary

Days on Task	Mobilisation	Surveying	Weather	Maintenance	Transit	Breakdown	Standby
50	4	21.3	9.95	9	3	0.75	2

Table 1: Survey Activity Summary

A Daily Narrative highlighting key milestones and events during the survey is detailed below. For further detailed daily reports see the relevant Daily Progress Reports (delivered daily during operations) and attached at Annex B.

September 2012	
Date	
27 Sep	System 002 Arrives Brisbane – Held up in Customs due to licensing issues
28 Sep	Field Equipment shipped from UK to Vanuatu

October 2012	
08 Oct	Field Team depart UK for Vanuatu
09 Oct	System 002 released from Customs in Brisbane. Field Equipment Arrives in Vanuatu
10 Oct	Field Team Arrive Efate, Vanuatu
11 Oct	Field Reconnaissance to identify GPS Sites and Tide Station Locations
12 Oct	Team 2 Depart UK for Brisbane Field Team continue Preparations for field survey work
13 Oct	Establish Tide Station at Port Vila
14 Oct	Establish Tide Station at Emua. Team 2 Arrive Brisbane
15 Oct	Mobilise Vessel Carry out Sea Control Area Survey
16 Oct	Complete Sea Control Area Survey, demobilise Vessel
17 Oct	Standby – Weather – Delayed departure to establish Tide station on Malekula
18 Oct	Field Team Establish Tide Station Malekula, Team 2 Install System into Aircraft
19 Oct	Field Team – Tide Station Observations Malekula Team 2 Calibration Flights on Gold Coast
20 Oct	Aircraft in Maintenance
21 Oct	Field Team Recover Tide Station at Emua (Tide Gauge destroyed) Aircraft in Maintenance
22 Oct	Field Team Establish Tide Station on Espiritu Santo Aircraft in Maintenance
23 Oct	Field Team Field Observations on Santo Aircraft in Maintenance
24 Oct	Field Team Field Observations on Santo Aircraft in Maintenance
25 Oct	Field Team Recover Tide Gauge from Malekula Aircraft in Maintenance
26 Oct	Aircraft in Maintenance
27 Oct	Aircraft in Maintenance
28 Oct	Team 2 Arrive Vanuatu – Continue Preparations for Flying Operations
29 Oct	Continue Preparations for Flying Operations Conducted Second Tidegauge Comparison in Port Vila
30 Oct	Continue Preparations for Flying Operations
31 Oct	A/C Arrives from Brisbane, Meetings with ATC, Completed Calibration Flight

November 2012	
01 Nov	Survey (2hrs)
02 Nov	Survey (4hrs)
03 Nov	Survey (1.5hrs)
04 Nov	Survey (2.5hrs)
05 Nov	Survey (5hrs)
06 Nov	Standby – Planning Reflights
07 Nov	Survey (3hrs)
08 Nov	Survey (3hrs)
09 Nov	Standby – Pilot Illness
10 Nov	Standby – Pilot Illness
11 Nov	Survey (7hrs)
12 Nov	Survey (0.5hrs)
13 Nov	Data Processing
14 Nov	Deploy to Espiritu Santo for Survey
15 Nov	Survey (0.5hrs)
16 Nov	Survey (2hrs)
17 Nov	Standby Weather
18 Nov	Survey (2.25hrs)
19 Nov	Survey (2.5hrs)
20 Nov	Survey (2.5hrs)
21 Nov	Survey (5hrs)
22 Nov	Standby Weather
23 Nov	Survey (3.5hrs)
24 Nov	Survey (3.1hrs)
25 Nov	Standby Weather
26 Nov	Survey Operations Completed in Vanuatu

7.3 Geodesy

Horizontal Datum, Spheroid, Projection and Grid Details

All control is referred to ITRF 2008 datum and GRS 80 spheroid, UTM Zone 58 (S) Projection.

Geodetic Reference System	
Reference Frame/Datum	ITRF 2008
Spheroid	GRS 80
Semi- Major Axis	6378137.00
Inverse Flattening	298.257222101

Projection System Espiritu Santo	
Projection	Transverse Mercator
Grid Details	UTM Grid Zone 58 South
Central Meridian (CM)	165° 00’ 00” E
Latitude of Origin	000° 00’ 00”N
False Easting	500,000.000
False Northing	10000000
Scale Factor on CM	0.9996

Datum, Spheroid and Projection Details

Horizontal and Vertical Positioning

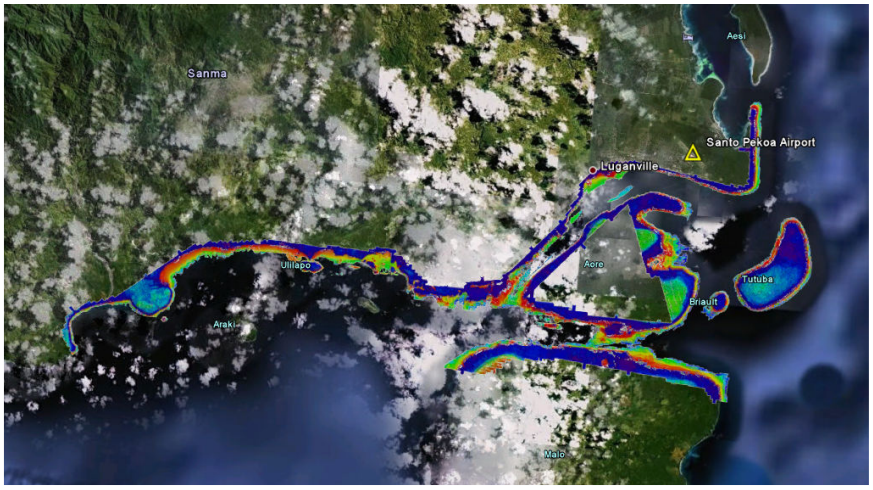
Positional control for the aircraft and installed survey system was provided by the integrated Applanix POS AV 410 Inertial Measurement Unit which is part of the Hawkeye IIb system. The survey was conducted on the WGS84 (ITRF 2008) datum with all outputs being related to the ellipsoid.

POS AV uses an IMU and GNSS receiver as its primary navigation sensors during flight. The embedded software runs an inertial algorithm that calculates velocity, angular movement and heading to derive an inertial position. At the same time a Kalman filter compares this position with the one provided by the GNSS receiver. The output inertial position is adjusted by this filter to remove the inertial errors that can build up. During flight operations the output position has a horizontal accuracy of between 1-3m and a vertical accuracy of 0.5-1.0m. In order to improve the horizontal and vertical accuracy of the navigation solution, Pelydryn post processes the recorded position and orientation solution to derive accuracies better than 0.1m in all planes.

In order to gain the most accurate position and orientation solution, Pelydryn made use of a series of previously co-ordinated GPS Base stations (positions were observed by AAM) and precise ephemeris to post process the aircraft navigation sensor data in Applanix’s POSPAC MMS (Version 5.4) to produce a post processed navigation solution. Base Station observables were observed daily from two previously established co-ordinated Stations as detailed in the **Error! Reference source not found.**below table:

Figure 1 Base Station Name	**Figure 2**	**Figure 3**
Figure 4 **Figure 5 Santo Pekoa Airport**	**Figure 6 Latitude** **Figure 7** **Figure 8 Longitude** **Figure 9** **Figure 10 Altitude**	**Figure 11 15° 30’ 26.08043” S** **Figure 12** **Figure 13 167° 13’08.09278” E** **Figure 14** **Figure 15 108.530m**

Base Station Co-Ordinates



Position of GNSS Base Station - Espiritu Santo.

Short baseline algorithms were used within PosPAC MMS to allow a single base station solution to be used. This algorithm is automatically selected within the software when the first and last 5 minutes of the mission are within 20 km of the selected base station and ensures the navigation files for this project area were within the accuracy specification. Each SBET file was reviewed to provide an error check. The POSPAC MMS Accuracy Reports from each sortie is provided in**Error! Reference source not found.**.

Geodetic Observations

As part of the survey, Pelydryn undertook a number of geodetic observations to establish GPS Benchmarks adjacent to the tidal stations. Observations were undertaken using a Trimble R8 GNSS Receiver. All data was processed using the AUSPOS Processing service using final ephemeris and the control networks were adjusted by AAM using Leica Geo Office to derive final co-ordinates.

Station	Horizontal Accuracy (m)	Vertical Accuracy (m)	WGS84 Latitude	WGS84 Longitude	Ellipsoidal Height (m)	UTM Easting 59/58	UTM Northing 59/58	Orthometric Height (m) (EGM 2008)
POVI	0.006	0.004	17° 41' 59.79798" S	168° 18' 00.78807	66.850	213718.036	8034663.941	3.265
EMUA	0.006	0.004	17° 32' 12.04392" S	168° 23' 10.87230" E	68.067	222519.660	8059165.356	2.441
LITS	0.006	0.004	16° 06' 45.21392" S	167° 26' 37.25042" E	66.077	761373.858	8217066.306	2.321
SAW1	0.006	0.004	15° 30' 55.85469" S	167° 11' 23.25304" E	67.635	734894.896	8283453.280	2.780
SAW2	0.006	0.004	15° 30' 55.42801" S	167° 11' 23.90112" E	67.573	734914.349	8283466.201	2.726

Non Adjusted Co-ordinates of All Stations Observed by Pelydryn.

Positioning Checks

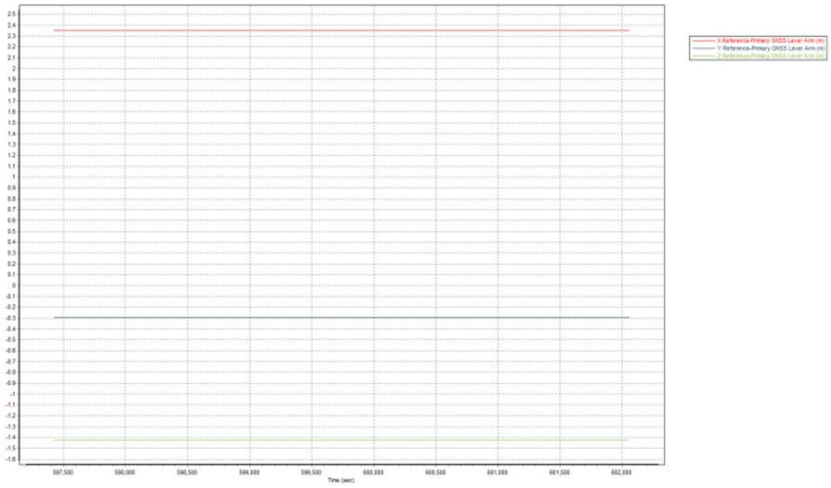
Lever Arms

Following installation of the system into the aircraft, the Primary GNSS Antenna to IMU Reference Position (on top of IMU) Offsets are measured and input into the POSAV Controller software. On completion of the calibration flight the GPS lever arms are recalculated during post processing of the navigation data. The refined values are input into the controller software and checked each day on start up by the system operator. Following input of the post processed values no changes were observed during the course of the survey.

	Reference to IMU Lever Arms (m)	Reference to Primary GNSS Lever Arms (m)
X	-0.080	2.353
Y	-0.015	-0.297
Z	-0.126	-1.423

Lever Arm Values

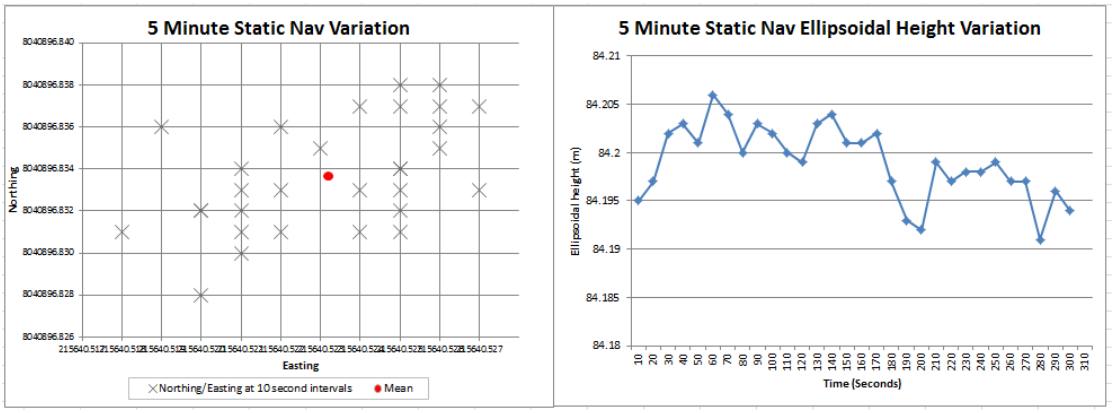
On a daily basis as part of the Quality Control on the navigation data the Lever Arms were checked to see if there was any drift in their values which would indicate movement of the system. **Error! Reference source not found.** illustrates the values during the first sortie; a straight line in all 3 values shows there has been no changes in the lever arms used indicating that the converged values for the offsets are correct.



Lever Arms Checks in POSPAC MMS

Static Navigation Check

A Static Position Check was carried out on completion of each day's flying. The POSAV System in the HawkEye IIb is set by the operator to record data for 5 minutes after each flight whilst the aircraft is stationary. This data was analysed daily after processing and used to check that the POS AV is performing as expected with no noticeable instability in the observed horizontal and vertical positioning. The variation in the Northing, Easting and Ellipsoidal Height data at the end of each mission is assessed and used to give a gross error check.



Typical Static Navigation Check Results

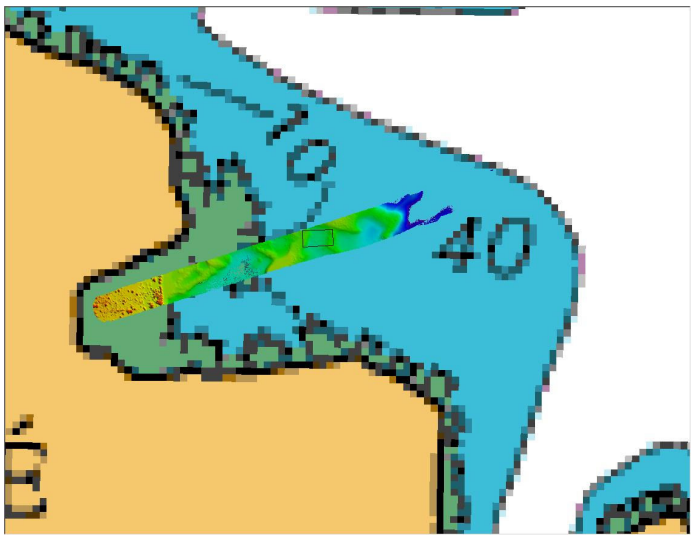
Statistical Summary			
Mean	215640.52	8040896.83	84.20
Standard Deviation	0.003	0.003	0.004
Min Value	215640.518	8040896.828	84.191
Max Value	215640.527	8040896.838	84.206
No of Samples	30	30	30

Example Results from Analysis of Static Validation.

System Repeatability Check

Espiritu Santo

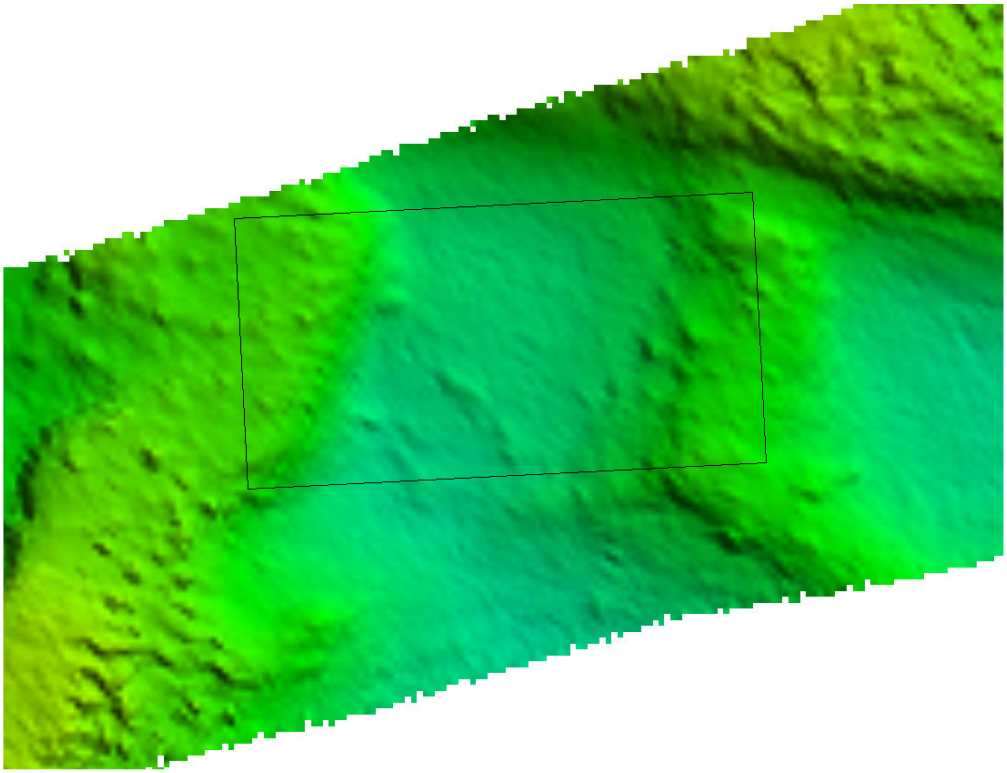
Following Mobilisation to Espiritu Santo an area of Aore was selected for a daily check. This was overflown daily to allow a check to be conducted on the system's operation during flying operations. Following data processing, a surface comparison was conducted in CARIS and TerraSolid to analyse the quality of the data.



Dynamic Navigation Check Area with flat and sloping seabed highlighted (black boxes).

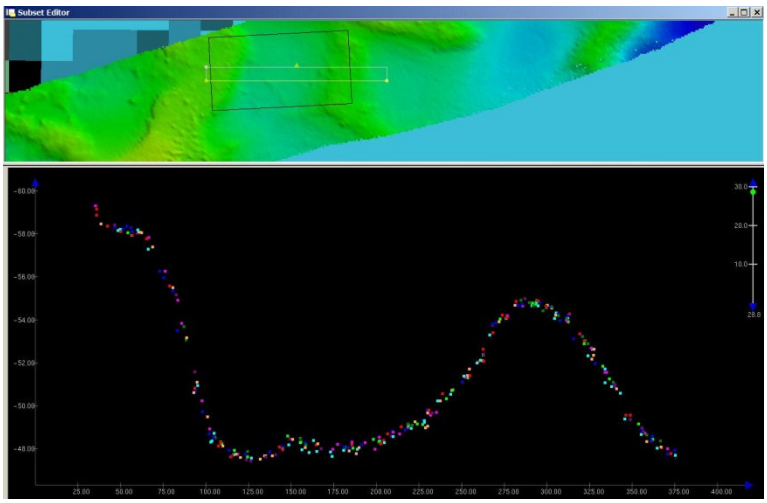
The following lines were flown during the course of the survey over this patch:

Santo_SCA_HD_2012-319_20121114_211545_SCA_Santo_FL003_7157506_Flightline 0_HD_exported
Santo_SCA_HD_2012-319_20121114_234726_SCA_Santo_FL000_5930661_Flightline 0_HD_exported
Santo_SCA_HD_2012-319_20121116_213838_SCA_Santo_FL000_5692007_Flightline 0_HD_exported
Santo_SCA_HD_2012-319_20121117_191411_SCA_Santo_FL001_4885402_Flightline 0_HD_exported
Santo_SCA_HD_2012-319_20121117_195946_SCA_Santo_FL000_9680776_Flightline 0_HD_exported
Santo_SCA_HD_2012-319_20121118_184221_SCA_Santo_FL002_0822779_Flightline 0_HD_exported
Santo_SCA_HD_2012-319_20121119_024800_SCA_Santo_FL001_7523117_Flightline 0_HD_exported
Santo_SCA_HD_2012-319_20121119_043643_SCA_Santo_FL000_2256233_Flightline 0_HD_exported
Santo_SCA_HD_2012-319_20121120_031606_SCA_Santo_FL001_7069002_Flightline 0_HD_exported
Santo_SCA_HD_2012-319_20121120_055501_SCA_Santo_FL000_9414349_Flightline 0_HD_exported
Santo_SCA_HD_2012-319_20121121_184220_SCA_Santo_FL001_8496963_Flightline 0_HD_exported
Santo_SCA_HD_2012-319_20121121_234758_SCA_Santo_FL000_1888790_Flightline 0_HD_exported
Santo_SCA_HD_2012-319_20121122_022949_SCA_Santo_FL002_1123386_Flightline 0_HD_exported
Santo_SCA_HD_2012-319_20121122_043642_SCA_Santo_FL000_6808984_Flightline 0_HD_exported
Santo_SCA_HD_2012-319_20121123_211230_SCA_Santo_FL001_4343394_Flightline 0_HD_exported
Santo_SCA_HD_2012-319_20121124_021255_SCA_Santo_FL000_1687978_Flightline 0_HD_exported
Santo_SCA_HD_2012-319_20121124_042033_SCA_Santo_FL001_0675069_Flightline 0_HD_exported



Close up of Santo Verification Area.

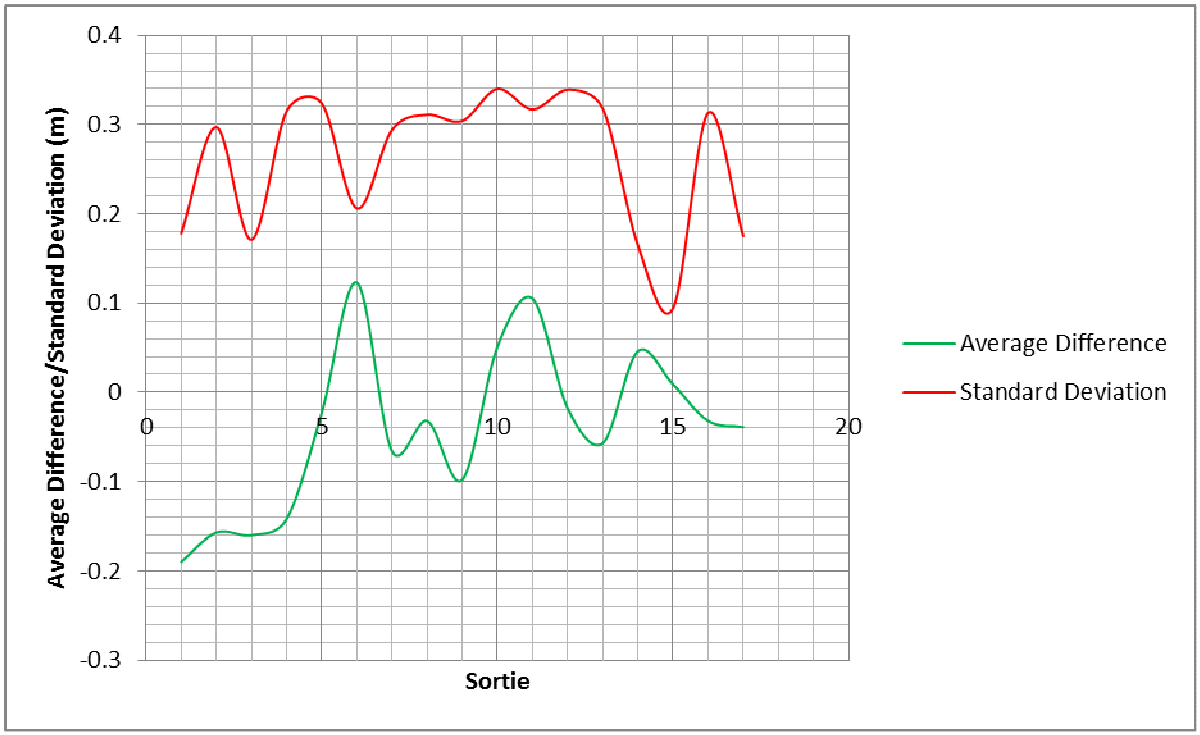
Repeatability Check Location
Long/Lat: 15.56779 E/167.209642 S
Number of returns: 7923
Dimensions: 260/160m



Area 1 Cross Section Santo

Area 1	Average dz	Std Deviation
Date	Metres	
20121114_211545	-0.19	0.178
20121114_234726	-0.157	0.297
20121116_213838	-0.16	0.171
20121117_191411	-0.142	0.315
20121117_195946	-0.023	0.324

20121118_184221	0.123	0.206
20121119_024800	-0.066	0.294
20121119_043643	-0.032	0.311
20121120_031606	-0.098	0.304
20121120_055501	0.051	0.34
20121121_184220	0.105	0.317
20121121_234758	-0.018	0.339
20121122_022949	-0.057	0.318
20121122_043642	0.046	0.165
20121123_211230	0.009	-0.094
20121124_021255	-0.032	0.313
20121124_042033	-0.039	0.175
Average	-0.040	0.143



Statistical Results of Efate Dynamic Repeatability Check.

Analysis of the results show a variation in the average depths of all points within the polygon analysed which falls within the IHO Order 1 Vertical Accuracy Requirements. The random nature of the results indicates no systematic drift in the laser calibration values.

The variations in the Standard Deviation are indicative of slope or general variations in the depth recorded as a result of varying turbidity and the system's ability to resolve the seabed from the waveform when flying over the area from different directions.

Vertical Control and Tidal Data

The data gathering phase of the survey was conducted on the ellipsoid in order to eliminate transformation errors in positioning and LiDAR acquisition. Four Tidal stations were established during the course of the survey on the islands of Efate, Malekula and Espiritu Santo.

Data Acquisition Survey Operations

Introduction

An airborne LiDAR survey was undertaken along the southern coast of Espiritu Santo between Naoreure Point and South Cape to provide bathymetry up to the drying line and to provide an overlap with gathered topographic LIDAR data.

Line spacing was set at 198m with general orientation running parallel to the coast. Crosslines were run across each block to allow checking of the application of the GPS derived tidal reduction.

System

The survey was undertaken using the HawkEye IIb bathymetric LiDAR system. System 002 was used throughout the survey. One minor defect impacted on operations causing some delay to the programme:

a. System Air Conditioning Unit Failures due to loss of gas and controller board failure.

As a result of this, the system tended to overheat and careful monitoring and flight management had to be introduced in order to keep the system in its optimum operating temperature range.
The survey was flown on Flight Case 401. Flight plans were optimised to allow the longest lines possible to reduce the number of turns required. All reflights were conducted on Flight Case 401. Full details of flight plans and flight cases can be found at Section0.

Hawkeye System 002 installed in NOMAD

The HawkEye IIb was calibrated to the aircraft by means of a topographic Ground Calibration Area and a Sea Calibration Area, both in Port Vila. Details of the Calibration are found in the Mobilisation Report. The calibration and validation results indicate that the HawkEye IIb system was operating within specified parameters and achieved the required accuracy for the survey.

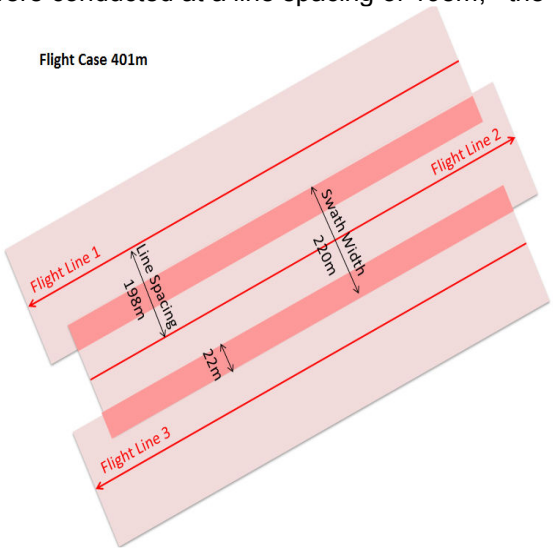
Survey Parameters

LiDAR used	:	HawkEye IIb
Operating frequencies (kHz)	:	1Khz (Bathymetric) 4Khz (topographic)
Horizontal datum	:	ITRF 2008
Spheroid	:	WGS 84 (GRS80)
Projection	:	UTM (S)
Central Meridian and Grid Zone	:	Zone 58
Vertical datum	:	Survey on Ellipsoid
Main Line Spacing (m)	:	198m (FC 401)
Line Direction	:	Varies (Parallel to Coast)
Cross Line Spacing	:	2000m
Cross Line Direction	:	Perpendicular to Coast
Average survey speed (knts)	:	110knts
Average across track % overlap	:	10%
General water depth achieved (m)	:	35-40

Survey Parameters - Vanuatu

Flight Case Parameters

The HawkEye IIB has several flight cases. To achieve 100% coverage, and ensure that the required standards for the survey are achieved, the flight case 401 was used (Figure 13). Main lines for the LiDAR data acquisition were conducted at a line spacing of 198m; the flight altitude was set at 400m with a swath width of 220m.



Flight Attribute	401 Scan Case
Flight Case Name	401
Altitude (m)	400
Speed (m/s)	67-74
Swath Width (m)	220
Lateral Shot Distance (m)	5
Forward Shot distance (m)	4.5
Percentage overlap (%)	10
Line spacing using above overlap (m)	198

Flightcase 401 Details.

Espiritu Santo Survey Configuration

Espiritu Santo Survey Configuration			
Mission Name:	Vanuatu		
Horizontal Datum:	WGS 84	**Vertical Datum:**	Ellipsoidal
Flight case:	401	**Altitude:**	400m
Swath Width:	220m	**Line Spacing:**	198m
Speed:	130-140kts	**Coverage:**	110%
Number of Lines:	193	**Total Line Length:**	1039km

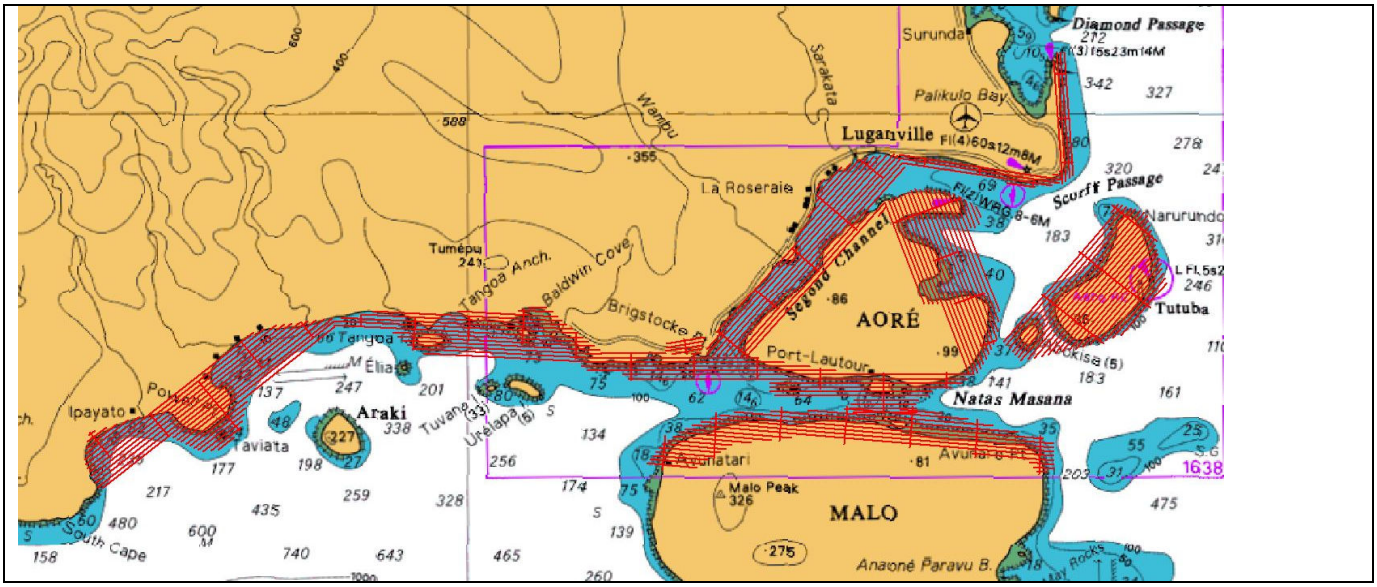


Figure 1: Espiritu Santo Line Planning Information.

Upon completion of the planned first pass lines, data coverage was analysed in the field and reflights were flown to improve coverage where the turbidity, sun glint and white water affected light penetration. Some lines were reflown to improve coverage where the aircraft was off track due to turbulence.

Data Logging Parameters

The flying altitude and flight case establishes the scanner logging parameters and is set during mission planning. Although it is possible to modify it during a flight for each individual flightline, no amendments were made on this project during flight.

Hydro laser

Parameters are set and modified during a flight in the shallow and deep receivers in order to maximise the efficiency of the gain (or monitor signal).

The following parameters can be altered: K, Go and Range Time Correction (see **Error! Reference source not found.**). The K parameter represents the diffuse attenuation coefficient which increases as water clarity decreases. The gain (Go) is used to compensate the damping of light in water.

The laser return data is recorded during a time window (in nanoseconds) that is manually set. The part of the waveform saved is the start of the laser pulse and the response from water surface and bottom. The time between the start of the pulse (TO) and return from the surface is the Range Time Correction.

Area	K shallow	K deep	Go shallow	Go deep
Espiritu Santo	0.1-0.17	0.07-0.14	-2.0- -1.3	-2.0- -1.5

Hydro Laser Minimum and Maximum Parameters

Topo Laser

The operator can set and monitor the Topo laser power during acquisition. Power is generally set to 2500mW during planning. The power can be changed during flight for each individual flightline. Topo power was reduced over highly reflective areas during this project.

Camera Parameters

The operator can set and monitor the exposure time during acquisition. This parameter varied from 0.5-2 in bright days to 3-5 in normal days.

Software

The following software was used during the course of the survey:

System Software:
- AOC Version: 1.07.03

Processing Software:
- CSS: Version 2.03.11
- PosPAC MMS Version: 5.4 SP 1
- CARIS HIPS and SIPS Version: 7.1 Service Pack 2 Hotfix 6
- Fledermaus Version 7.3.2a
- TerraScan Version Version 12

Environmental Impacts on Survey Operation

Meteorological Impacts

Weather had a significant impact on operations due to the high rainfall experienced, with the accompanying low cloud and wind squalls, which prevented or curtailed flight sorties on a regular basis. A number of short re-flights were required due to the aircraft being off track as a result of strong winds and turbulence in the survey area.

On a number of occasions low cloud (below 1200ft) meant surveying operations had to be suspended or the flight sortie moved due to the scattering effect of water droplets in the cloud.

Low Cloud along the coastline.

Sun Glint

Sun glint is a known issue with bathymetric LiDAR and wherever possible line direction is planned to reduce the impact. Sun glint increases the amount of noise in the data which becomes more significant with weak bottom returns from deeper areas combine with areas of high turbidity. It can also impact in shallow water on areas of light seabed. Sun glint was therefore a significant factor when surveying the deeper areas later in the period when the sun angle remained higher than 60 degrees for longer periods during the day. Operations were

conducted in the early and late parts of the day at the inception of operations, but as weather conditions delayed the survey it was necessary to fly between rain showers and this has impacted on data quality on occasions.

Sun Glint along the shallow coastal fringe.

Extreme Shallow Water

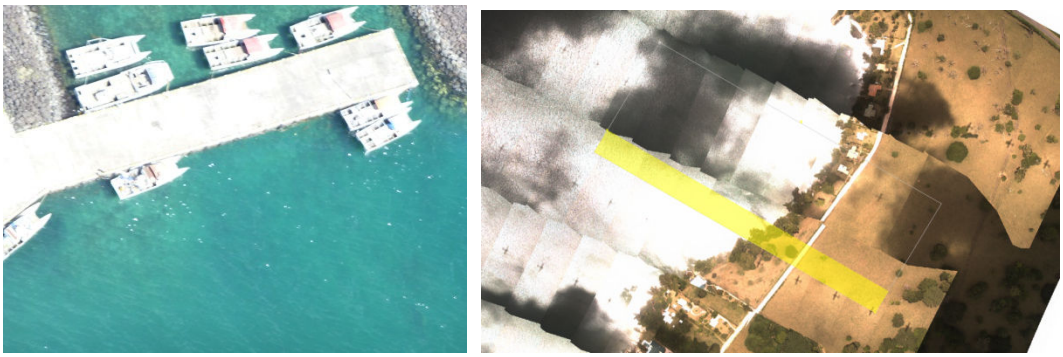
Designed to operate across the land/sea interface, the system generally can detect depths up to 0.5m. In most areas the range of tide allows either a deeper return at a higher state of tide or a topographic detection at low water. The Tidal range experienced in Vanuatu was 1-1.5m during the survey, which meant that the shallow fringing reef plates would be difficult to survey if there was any significant wave action. A number of factors contribute to the detection of a valid return with the laser in extreme shallow water situations:

a. Waveform Discrimination - The shallow water algorithm does not work well in these situations and detection will drift in and out and can cause variation in the depths seen due to the surface and seabed return being so close together on the waveform and the system's ability to discriminate between the two.

Extreme Shallow Water over Coral Reef

b. Slope - Steep changes of slope when we go from shallow too deep along the reef drop offs means the system's operating parameters are changing rapidly between the shallow and deep water algorithms, where there are large slopes this can impact on detection
c. Very Shallow water can cause extreme glint even at low altitude (**Error! Reference source not found.**), the resultant reflections can reduce the quality of the surface and seabed return.

d. Change in Classification – i.e. when going from Land to Sea next to jetties and breakwaters (**Error! Reference source not found.**). The often rapid changes in between land and water as you pass over small islands or manmade structures can lead to a lag in the system's ability to track the seabed temporarily on the leeward side of the feature.



Extreme Shallow Water with topographic features cause problems in seabed tracking and the effects of Sun Glint in shallow water.

e. Seabed Contrast. Very dark patches or black areas (such as dead coral heads) with a surrounding highly contrasting seabed, (very shallow to deep water) can impact on the system's ability to classify the return resulting in data gaps in areas where depths may be expected (**Error! Reference source not found.**). Changes in the colour of the seawater can also impact on the quality of the return.

Contrast and slope changes behind or close to features affect seabed detection.

As a result of these known limitations, lines were flown in opposite directions and at different times of day and states of tide to mitigate most of the effects noted above. Following field cleaning and analysis of the acquired data a number of gaps were found on the coastal fringing reef plate. These areas were reflown in an attempt to infill the gaps seen and provide as complete a dataset as possible.

Turbidity

Turbidity severely impacts on a bathymetric LiDAR's ability to achieve penetration in any depth of water. Typically achieving seabed detections at 2.5 times Secchi disk depth, turbidity can reduce this significantly. Heavy rainfall or coastal works can cause significant sediment run off into local waters. Tidally modified these sediment plumes can drift up and down the coast reducing the ability to detect the seabed. On both islands this became a significant problem and attempts were made to mitigate the effects by flying at different states of tide or flying additional lines.

Examples of Turbidity caused by Surface Water Run-off.

7.4 Data Processing

Field Processing

Pelydryn undertook data cleaning whilst in the field to quality control data and assess density and coverage for reflight purposes. In order to do this it was necessary to process the raw waveforms with post processed navigation to produce LAS files. These files were imported into CARIS, following QC in Coastal Survey Studio, where they were checked for density, coverage and vertical misalignments. Topographic data along with imagery were also checked to allow any flight replanning to be undertaken.

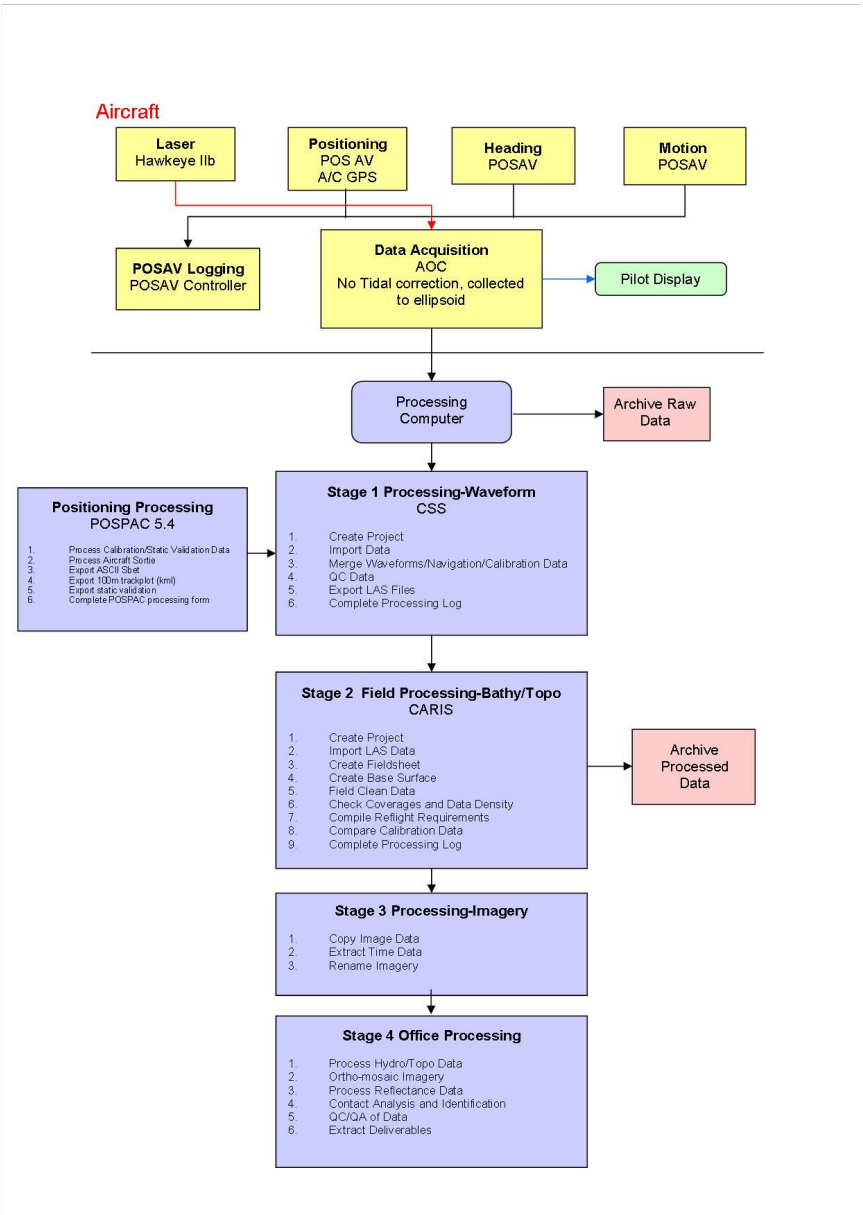
Data Backup and Archiving

On completion of each day's flying, raw navigation and HEII data was saved to a Back-up disc and a Processing disc. Any subsequent field processing of data was carried out only on the data on the Processing disc. The following data was nominally backed up on Portable USB Hard Drives

a. Raw HawkEye Wave Form Data and Imagery.
b. POSAV Trajectory Files.
c. GPS Base Station data.
d. Processed Waveform Data (following merge with post processed navigation data).
e. Smoothed Best Estimate of Trajectory Files (SBET) for use with imagery processing.
f. Time referenced imagery for image mosaicking.
g. LAS Files for Bathymetry, Topography and not Found data outputs form Coastal Survey Studio.
h. Processing Reports and Forms.

Data Processing

Raw aircraft navigation files were processed using PosPAC MMS to produce a post processed navigation solution utilising rapid ephemeris and a ground based GPS Station data which lay within 30km of the area being surveyed. The figure below illustrates the typical workflow for data processing used on this project. Following navigation processing the post processed inertial navigation solution is merged with the raw waveforms to produce a processed waveform in CSS. This waveform is then exported as a LAS File for subsequent data editing in CARIS HIPs. Concurrently the imagery taken during survey is time tagged and renamed to allow an ortho-mosaic to be produced at a later stage.



Processing Workflow for Vanuatu

Navigation Post-Processing

The PosPAC MMS software applies data from the installed Applanix Inertial Measurement Unit (POS AV 410) to produce a Real Time Vehicle Frame (RTVF) navigation solution. Base Station observables (from a co-ordinated station) in the form of RINEX data along with ephemeris data is imported into PosPAC MMS to give a decimetre accuracy solution to the GPS position. PosPAC MMS creates a Smoothed Best Estimate Trajectory (SBET), which combines the Corrected GPS position and the IMU data to produce a navigation solution with centimetric accuracy.

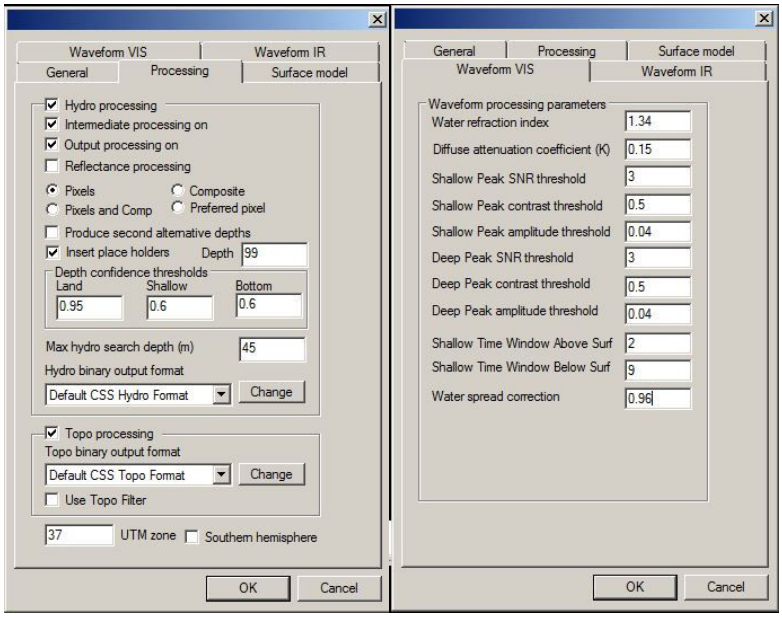
The navigation solution is exported from PosPAC MMS in text file format and used as an input to processing the raw HawkEye IIb files in CSS. It is also exported as an SBET for imagery processing.

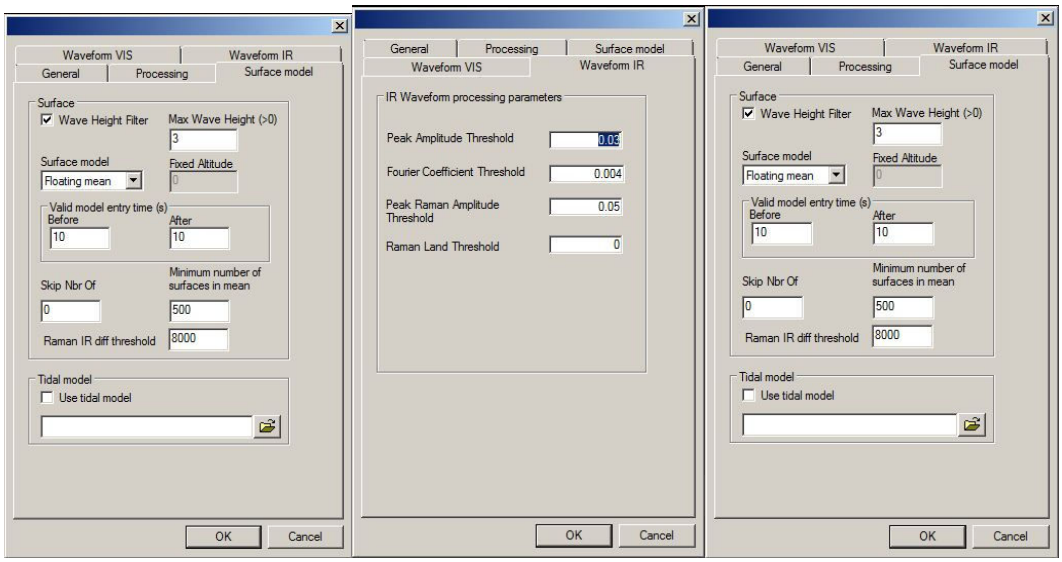
Waveform Processing

Coastal Survey Studio (CSS) is the propriety processing software for processing HawkEye IIb data. It takes inputs in the form of a navigation file, a calibration file and the raw wave forms from the HawkEye IIb. The output from CSS is *.LAS files which can be imported to other processing and visualisation software for subsequent data editing.

CSS processes the wave forms to produce values classified by laser into 'Deep', 'Shallow', 'Land' or 'No Bottom'. These values can be output as Ellipsoidal Heights or depths. Outputs can be set by the processor but currently all data variables are output into the CSS files.

Batch Processing of HawkEye IIb files requires the input of 'confidence' settings and 'k' values by the Processor. These are initially set based on conditions experienced during the survey. Inspection of individual waveforms, especially those which return 'No Bottom' values, is carried out after batch processing to check the automatic interpretation of wave forms. The 'confidence' setting can be adjusted where wave forms show evidence of returns that have not been classified by the automatic processing. The effect of this can be to introduce more 'noise' into the data but also more valid 'Bottom' returns. The Processor will adjust the 'confidence' value and reprocess when it is considered advantageous to the overall survey.





Typical CSS Processing Settings

As part of Pelydryn's Quality Control, each line processed in CSS is visualised to check for coverage, beam width and scan pattern, as well as a gross error check. Once lines are accepted they are exported as LAS files. It is possible to filter the 'no bottom' values at this stage and they can be removed from the processed data set.
LAS files were exported from CSS in the form of Point Latitude, Point Longitude and Height. Three LAS file types were output:

a. LAS_HD – Bathymetric Data
b. LAS_NotFound – All data classified as not valid
c. LAS_TD –Topographic Data.

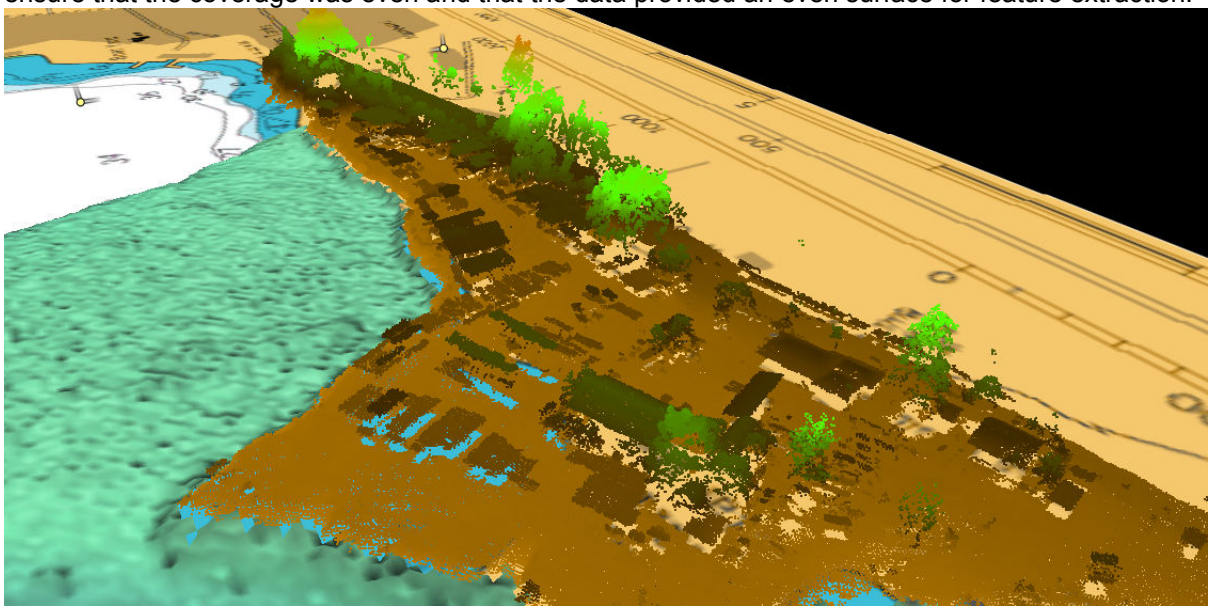
Field Cleaning and Quality Control of Hydro Data

All LAS HD (Hydro) files were imported into CARIS HIPS (Version 7 Service Pack 2 Hotfix 6) to check coverage, data quality and navigation. Pelydryn undertook basic filtering and cleaning to remove outliers, most notably those in the form of 'surface returns 'detected by LiDAR. The following procedure was used to verify the data collected:

a. LAS Files were imported into CARIS HIPS on a day and area basis.
b. The sortie to be processed was loaded with a chart backdrop to remove surface noise and outliers.
c. Once complete a 3m base surface was made and the sortie is checked for separation areas and outliers using the Standard Deviation Surface.
d. Once accepted the data is combined with all other data for that area and a Base Surface for the area is created or updated at 3m and 30m resolution.
e. The data is checked to ensure that there are no discrepancies between lines and any areas of poor coverage or density are noted for reflight.
f. The Field Manager confirms the lines entered agree with the Flight Log, Processing Log and CARIS (This ensures all valid data is included).
g. A check using the Chart is then carried out to identify any new shoals or the extents of coverage achieved. The Density and coverage checks are reviewed and any lines to be reflown or areas for reflight are created.

Field Cleaning and Quality Control of Topo Data

No field cleaning of the topographic LiDAR Data was undertaken. It was however checked on a daily basis to ensure that the coverage was even and that the data provided an even surface for feature extraction.



Point Cloud of Topographic LiDAR viewed in Fledermaus.

Office Processing

Once the survey was complete the data was transferred to the United Kingdom for final data processing. Once backed up, data processing was completed using CARIS HIPS. The following datasets were transferred to AAM for processing and analysis:

a. Unclassified topographic data in LAS file format.
b. All imagery captured.
c. All trajectory files for imagery processing.

Ortho Mosaic Processing

Ortho-mosaics were processed by AAM and have been supplied separately.

CARIS

The raw LAS files were previously imported in to CARIS HIPS using the Conversion Wizard and field cleaned. On arrival in the office, new Base Surfaces were calculated and the swath data was examined with noise and outliers rejected. Data Processing was conducted in three stages:

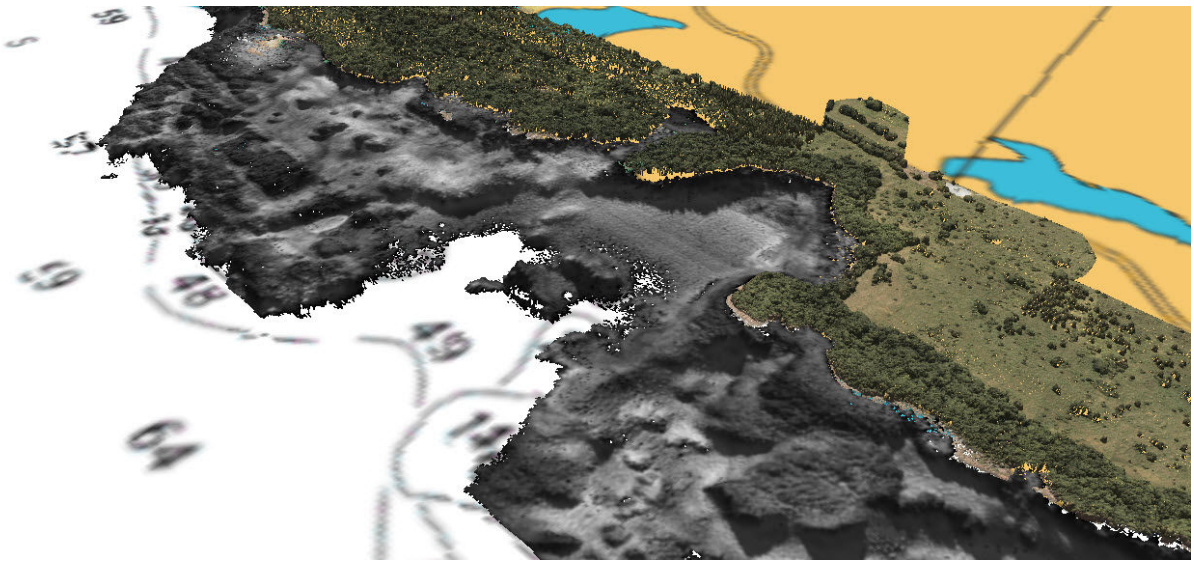
a. Process Bathymetric Data up to the waterline.
b. Process Topographic Data down to the waterline.
c. Process the Coastal overlap using both the Bathymetric and Topographic Data.

Data was processed at a higher resolution than the final deliverable in order to ensure that all outliers were identified and flagged rejected. Base Surfaces at 3m resolution were built with a full set of statistics allowing the generation of Shoal, Deep and Standard Deviation Surfaces, which could be used to identify data for removal. Data was processed in 1km blocks using the three surfaces highlighted above to identify data for rejection. In the coastal overlap, imagery taken at the time of flight was also used to identify features and the location of the breaker line to assist in the removal of data in these areas. All contacts and significant features identified in processing were designated and recorded in the Contact Log.

Reflectance Processing

Reflectance data was a required deliverable for this project and peak amplitude data was extracted from the raw waveforms to allow data processing to take place following the following steps:

1. Following processing of the raw waveforms in CSS the Peak Amplitude of each point was exported in LAS Format in xyza format
2. The exported LAS files were imported into Terrascan
3. The resultant dataset intensity values are adjusted to allow for different incident angles and differences in return strength due to gain and altitude variations
4. The resultant values were scaled for a 0-256 8 Bit colour map and the final contrast adjusted.
5. The resultant data was exported as an ECW and in xyzi format.



Sample Reflectance Data from South Coast Santo (with background Ortho-Imagery.

Data is supplied with this report in both ECW and XYZi at 5m resolution.

Quality Control and Analysis of Data

Following data cleaning the data was quality controlled by a senior member of Pelydryn's staff in order to ensure no spurious data remained. All Quality Control and Analysis of the data was undertaken using Fledermaus. The CARIS HDCS datasets were imported into DMagic (Data preparation tool) and a PFM (3d Visualisation surface)

was built. The resultant surfaces were loaded into Fledermaus where they were checked and if required edited to remove any outliers that had been missed during the processing phase. Once these checks were complete the data was unloaded back to CARIS and final base surfaces were built at the resolution of the final product to allow final checks of the data to be carried out.

Extraction of Data Deliverables

Following QC/QA of all point data all accepted points were exported from CARIS in ASCII format. This data was then imported and merged with both the Reflectance Data and Classification to derive the two final datasets referenced to the ellipsoid.
Once the data was merged it was split into 1km blocks based on UTM Grid Zone 58S of Espiritu Santo using TerraSolid. As part of the QA process this data was reimported into Fledermaus and a surface comparison completed to ensure all data had been exported and merged correctly. Data in xyz format and Shapefiles defining the block accompany this report.

7.5 Spatial Accuracy

Uncertainty Model

Pelydryn has created a Total Propagated Uncertainty Model (TPU) for the HawkEye IIb that gives the uncertainty associated with each sounding, banded into a depth range. The TPU model takes individual sources of uncertainty from the various components of the survey system as well as environmental conditions and combines them into a series of values across depth bands using statistical RMS calculations.
These values are supplemented by the empirical data obtained from the factory and field calibration processes, the static navigation checks, the dynamic navigation checks and the settings selected by the Operator during data gathering operations.
Spatial data can be examined statistically to give an estimate of positional accuracy using the propagation of errors based around a Gaussian distribution. In this case, a linear distribution is considered and the standard deviation can be computed:

$$\sigma = \sqrt{\frac{\Sigma x2}{n - 1}}$$

where: σ is one standard deviation of the linear error
x is denoting the known residual errors of the process
n is denoting the number of residual errors of the process

Figure 2: Calculation of Positional Accuracy

Navigation Solution

The HawkEye IIb is fitted with an Applanix POS AV 410 providing real time precision GNSS and inertial measurement. The accuracy of the POS AV system varies between 0.05m and 2m depending on the method used to obtained corrections. For this project, a post-processed navigation solution utilized POS PAC MMS processing software to give an accuracy of between 0.05m and 0.1m. Restricting aircraft turning rates, banking angles and speed changes further reduced the uncertainty associated with the navigation system. Operators monitored the PDOP of the real time navigation solution and used the Applanix INFUSION processing solution, supplemented where required with additional base stations. Further details of the Applanix POS AV specifications are at http://www.applanix.com/media/downloads/products/specs/POSAV_SPECS.pdf

Base Station

Corrections for the post processed GPS solution are obtained from either permanent reporting stations or base stations installed for the survey. The accuracy of the position of these stations introduces an element of uncertainty into the final position solution obtained. As the Base Station provides information on which corrections to be applied to the raw GPS gathered in the aircraft are based, the corrections can only ever be as good in absolute terms as the accuracy of the position of the base station itself.
During this survey, RINEX Corrections were obtained from stations specifically established for the survey. It is assessed these station accuracies were 0.03m for horizontal and 0.05m for the vertical.

HawkEye IIb System Uncertainty

The following HawkEye IIb system sources of uncertainty are factored in to the TPU model:

- HawkEye IIb Internal Offsets and Latency
- Scanner Position
- Laser Discrimination

Laser Footprint

Lasers are subject to beam divergence, which means that some beam spreading takes place in the air during airborne laser surveys. This gives rise to an altitude-dependant spot size at the sea surface, which is calculated using the design specified divergence for the altitude in use.
Light is spread further in the water column in the form of "Broadening", giving rise to a broader Footprint of the laser on the seafloor. This Footprint on the seabed will be a function of the Spot size and the Broadening, which is itself a function of depth and the water clarity (k).
These two sources of uncertainty are combined to provide the positional uncertainty associated with the laser footprint at the seabed.

Surface Angle of Incidence

As light moves from one medium to another it is subject to refraction. In this case, refraction occurs as the light moves from the air into the water at the sea surface. The amount of refraction can be calculated using Snell's Law (http://www.opticalres.com/lt/illuminationfund.pdf):

$$n_1 \sin\theta_1 = n_2 \sin\theta_2$$

Where

n_1 = the refractive index of Air (1.000292)
n_2 = the refractive index of Salt Water (1.3423)
θ_1 = the angle of incidence of the light with respect to the normal (90 – 10)
θ_2 = the refracted angle with respect to the normal

For the HawkEye IIb laser, the angle of incidence at the sea surface is 20 degrees which means that the refraction is 14 degrees. This is included in the position calculation of the centre of the laser footprint. However, this calculation assumes that the angle of the interface at the surface is horizontal, i.e. there is a flat sea surface. This is not always the case. If the sea surface has small waves or even ripples the actual angle at the sea surface can be different. And it will be different for each laser spot with some spots interfacing with the front of a wave, some interfacing with the top or bottom of a wave and some interfacing with the back of a wave.
Again using Snell's Law, it can be seen that this angle of the sea surface at the point of interaction will give rise to different values of refraction.

When this happens there will be an uncertainty introduced to the horizontal position of the spot centre and also to the vertical value as the light is not now following the predicted path through the water column; it is taking a longer path and will hence give a deeper depth value than if it were following the route for a flat surface. The worst case occurs when the angle of interaction is at its greatest i.e. on the face of a wave.
The Hawkeye IIb is normally operated in sea states below sea state 3 although the actual angle of incidence is input based on conditions observed.

Tidal Observations and Co-Tidal Modelling

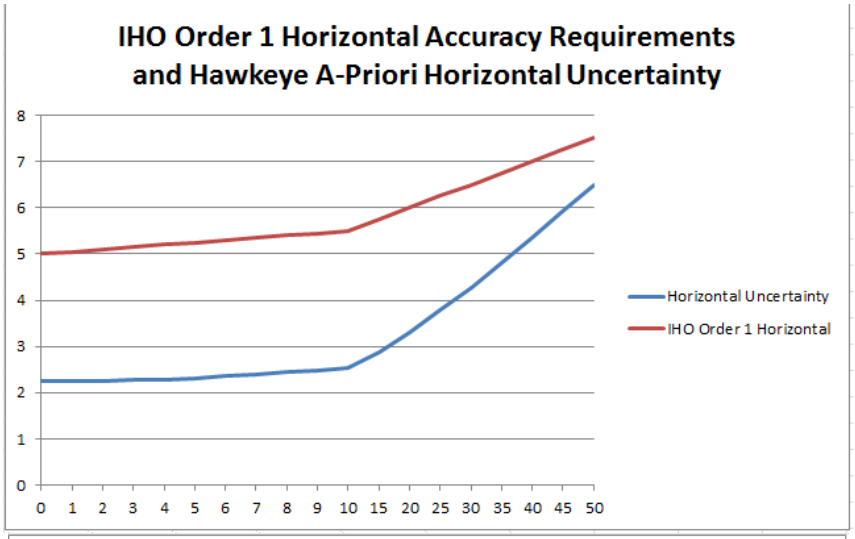
The TPU model also accepts values of uncertainty associated with the observance or tides and the use of co-tidal corrections or separation models. It is assumed that the derived separation model for this survey is accurate to 0.1m

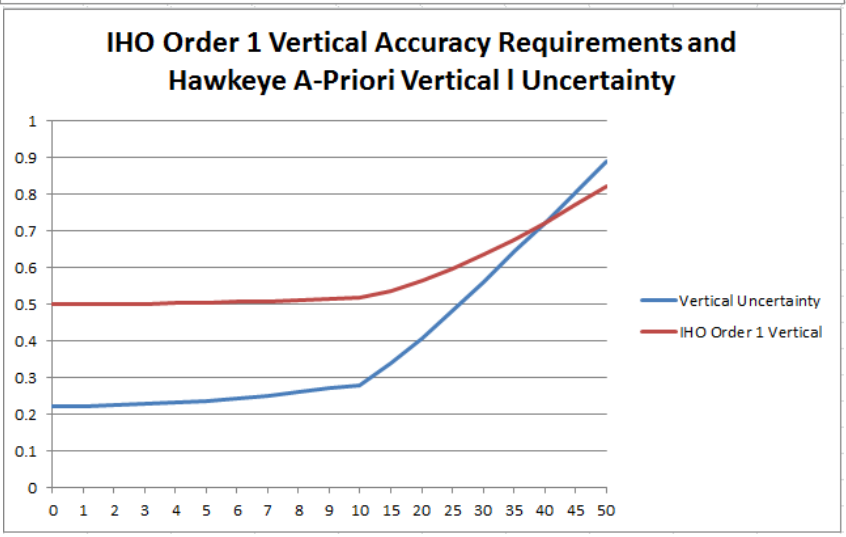
Geoid Model and Transformations

The use of transformation calculations introduces further uncertainty to the final values. The HawkEye IIb operates in WGS84 as a default so any transformations required to meet the required output parameters may introduce uncertainty. This is quantified in the TPU model, but can be considered to be zero when using GRS80.

Empirical Observations

The data from the HawkEye IIb is validated against bathymetric data obtained by MBES and topographic data obtained by terrestrial survey observations or from higher order topographic data. A statistical comparison of the HawkEye IIb data is carried out against this control data and the results are used as an input to the uncertainty model. The accuracy and precision values specified for the higher order data are also input into the model although it should be noted that the resultant uncertainty is worst case and as such the specified requirements are usually exceeded.





Horizontal and Vertical Horizontal Propagated Uncertainty and IHO Order 1 Required accuracies.

Accuracies Required for IHO Order 1

The International Hydrographic Organisation (IHO) has established standards to be met for Order 1 and detailed them in SP44 (5th Edition) as follows for vertical accuracy:

$$\pm\sqrt{a^2 + (b \times d)^2}$$

Where:

a represents that portion of the *uncertainty* that does not vary with depth

b is a coefficient which represents that portion of the *uncertainty* that varies with depth d is the depth

b x d represents that portion of the *uncertainty* that varies with depth

The vertical *uncertainty* at the 95% *confidence level* should be recorded

Horizontal accuracy is defined as 5m +/- 5% of the depth.

As an example for the depths experienced in the survey this equates to the following:

IHO Order 1 Horizontal Accuracy at 5m	5.25m
IHO Order 1 Vertical Accuracy at 5m	0.504m

Accuracies Achieved (95% Confidence)

Following examination of the acquired data it is inferred the following accuracies have been achieved in this survey:

	5m	10m	20m	30m	40m
Horizontal Uncertainty	2.344	2.531	3.173	4.021	4.971
Vertical Uncertainty	0.255	0.285	0.381	0.502	0.634
Order 1 Horizontal Requirements	5.250	5.500	6.000	6.500	7.000

Order 1 Vertical Requirements	**0.504**	**0.516**	**0.596**	**0.634**	**0.721**

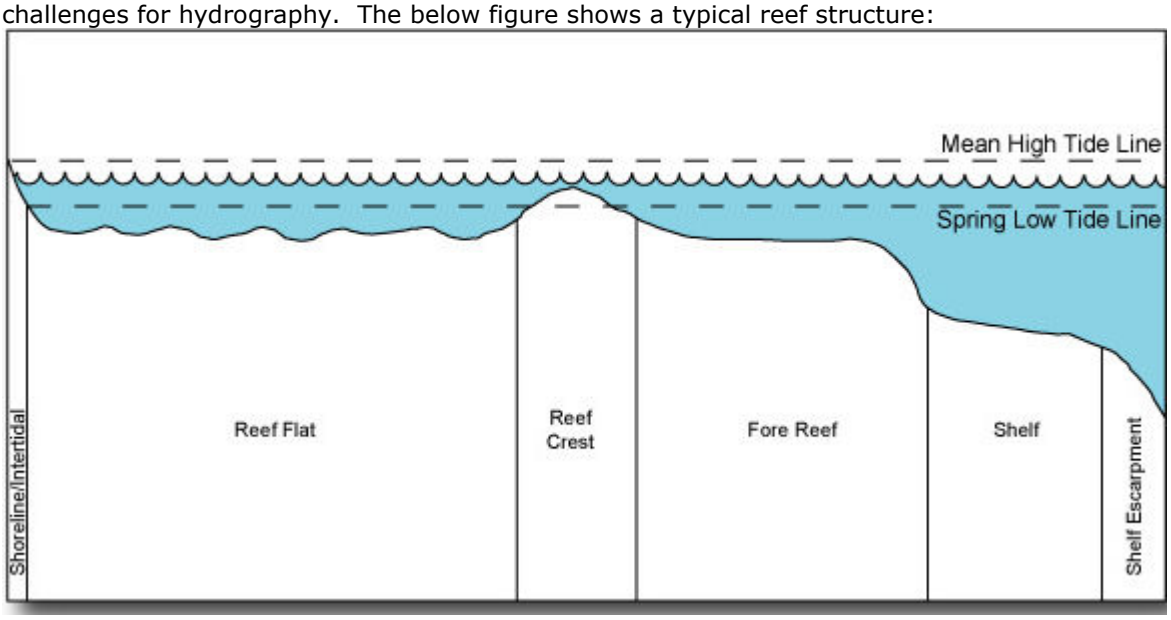
Horizontal and Vertical Accuracies Achieved

7.6 Survey Analysis

At all stages of the acquisition process, Pelydryn has undertaken a comprehensive analysis of the post processed navigational solution and the quality of the acquired bathymetric data. Having conducted Quality Assurance on the post processed navigation data it is assessed that the navigational solution has met the required IHO Horizontal and Vertical Positioning requirements.
Having confirmed the validity of the navigational solution, an analysis of the data coverage and density has been undertaken. The results for the density in the areas have been presented in Section 0. The density achieved utilising the acceptance criteria provided by Geoscience Australia has been exceeded in all areas that the HawkEye IIb System has obtained depth detections. However there are several observations to be made about the coverage and quality of the data that has been supplied.

Data Coverage

Pelydryn were contracted to undertake surveys on the polygons provided in the tender document. The entire extent of these polygons was flown once and it is assessed that the seabed was consistently detected at depths of up to 40m and in some instances in excess of 40m. The reef structures are complicated and provide unique challenges for hydrography. The below figure shows a typical reef structure:

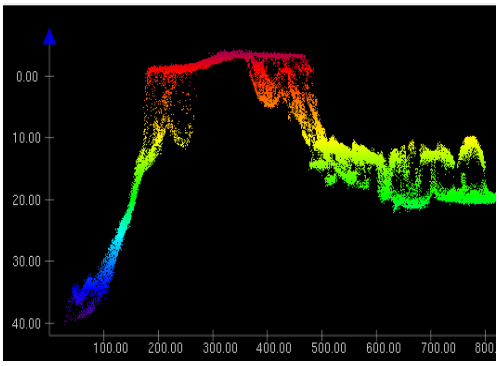


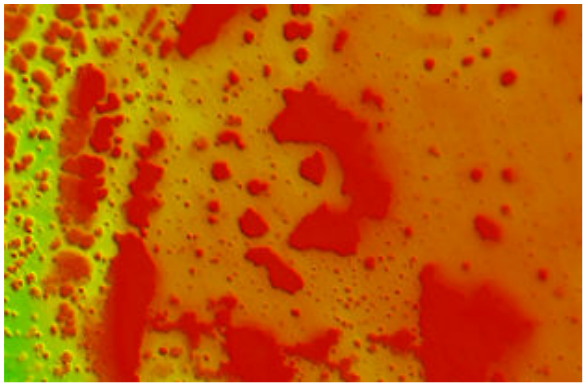
Typical Reef Structures in the Red Sea

The reef flat is often in very shallow water and provides challenges to LiDAR systems because of the shallow depths encountered. Reef Crests are easily visible and often form small offshore islands. As the water gets deeper the fore reef and shelf can extend for significant distances before the reef edge and drop -off is encountered. Alternatively on the seaward side of fringing and patch reefs they can abruptly drop off in a near vertical wall. Within the reef flats and fore reef it is common to find isolated coral heads, gullies and highly irregular seabed due to the breakdown of dead coral to form boulders and new growth on and around it.

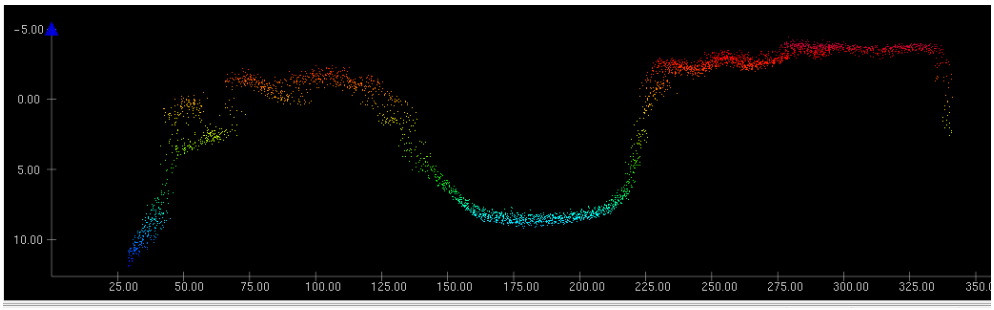
Typical Reef Flat or Fore Reef with isolated Coral Heads

Near Vertical Drop Offs





Typical Steep Sided Gullies



Gently Sloping Fore Reef

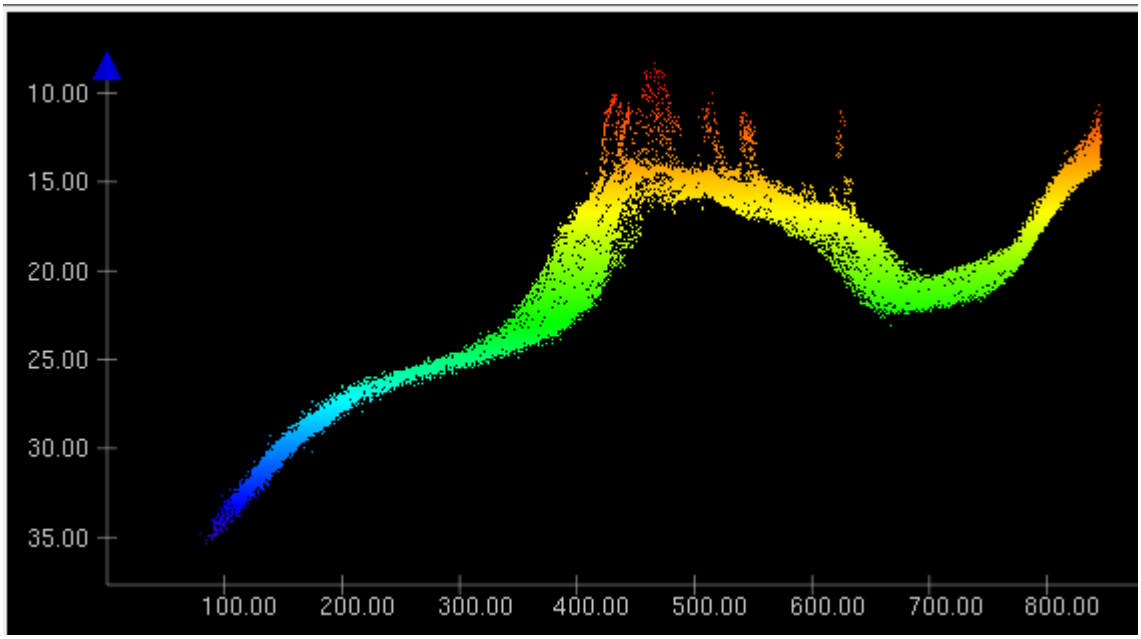


Figure 3: Typical Reef Topography encountered in Coastal Waters

The topography encountered varied significantly and when water clarity issues and steep slopes were encountered this would often reduce the depths observed. As a result reflights were conducted in order to try to extend the coverage with variations in line direction used to try and collect additional data. Where no additional coverage was found on a second flight the areas were designated “no bottom found” where no depths were encountered.

Coverage in Shallow Water

The report has covered the issues of operating the HawkEye IIb System in Shallow Water. Pelydryn undertook extensive reflights in these areas in order to increase both coverage and density; however water clarity, the depth and the contrast of the seabed, has meant that coverage is not 100% in the very shallow regions.

Coverage in Deep Water

The offshore reefs provided a unique challenge to the HawkEye IIb System. Steep sided on the seaward face the reef plate was generally lying between 10m and in excess of 30m deep with isolated coral heads and pinnacles being much shoaler or projecting above the water. Areas of poor coverage were reflown with varying line directions to capture more data as required.

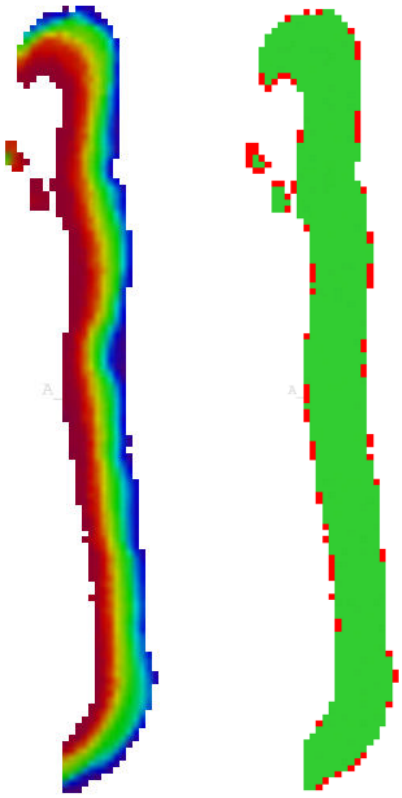
Survey Density

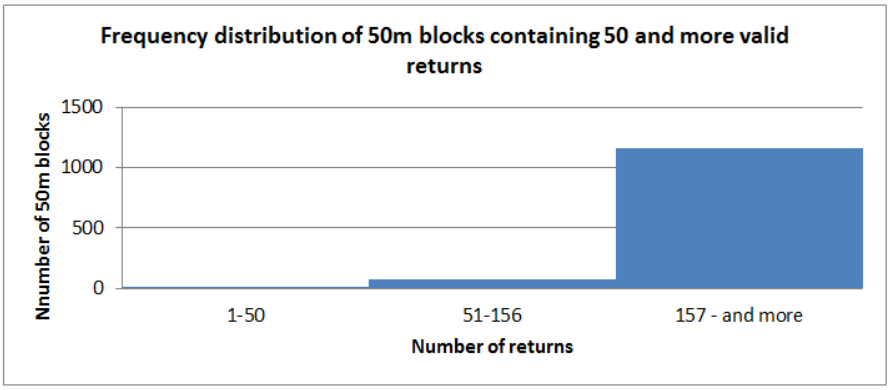
The data collected meets the requirements of the contract and the data acceptance criteria provided by Geoscience Australia. The following density results were achieved on the final processed data:
Following Completion of the data processing the following results were achieved around Espiritu Santo:

Santo Bathymetric Survey Density ***(85% of all 50m x 50m shall contain 50 or more soundings)***	
Area A	93%
Area B	86%
Area C	83%
Area D	91%
Area E	89%
Area F and F1	90%
Area G	91%
Area M	92%
Area N	91%
Total Area	90%

Densities achieved in Survey Areas around Espiritu Santo

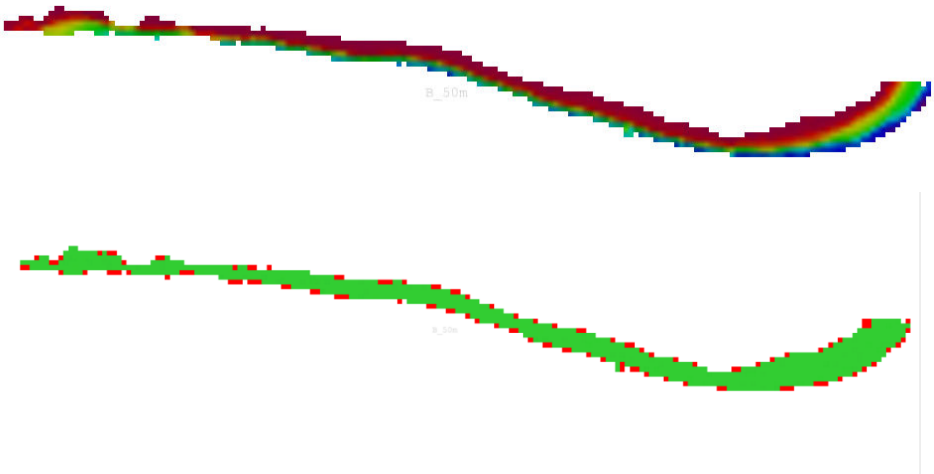
BLOCK A

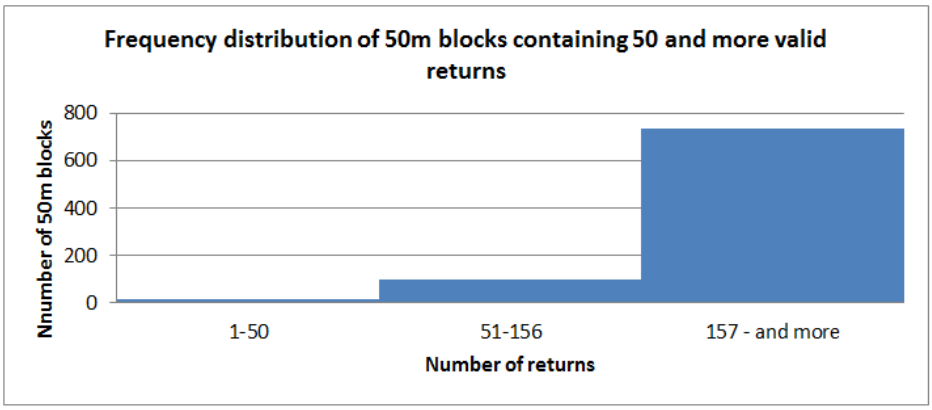




Block A Data Density

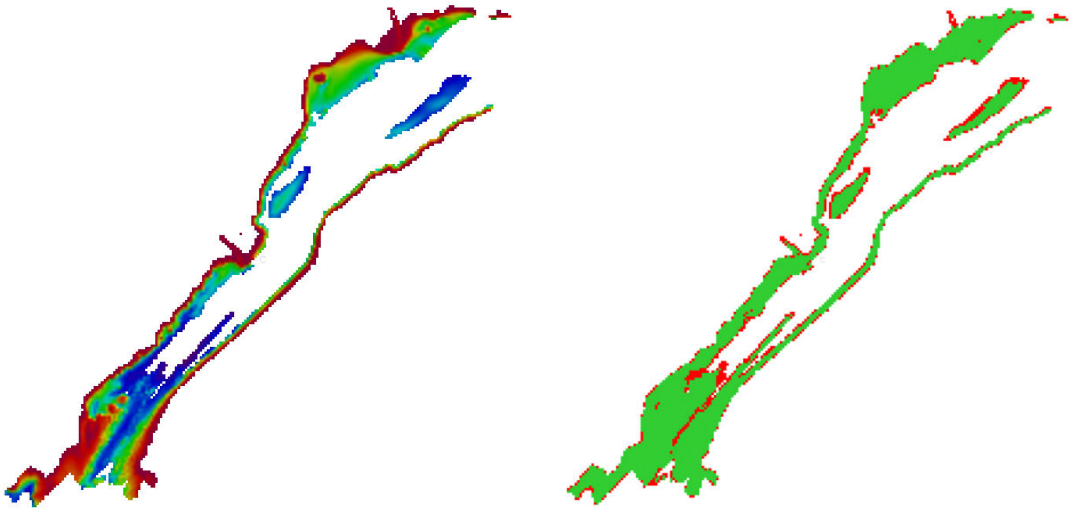
Block B

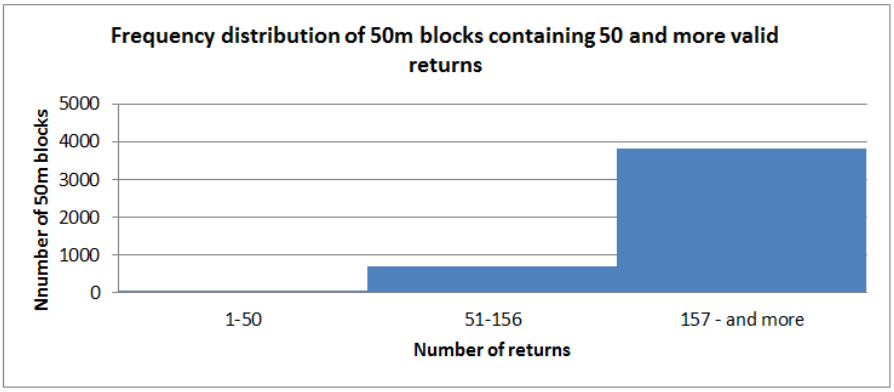




Block B Data Density

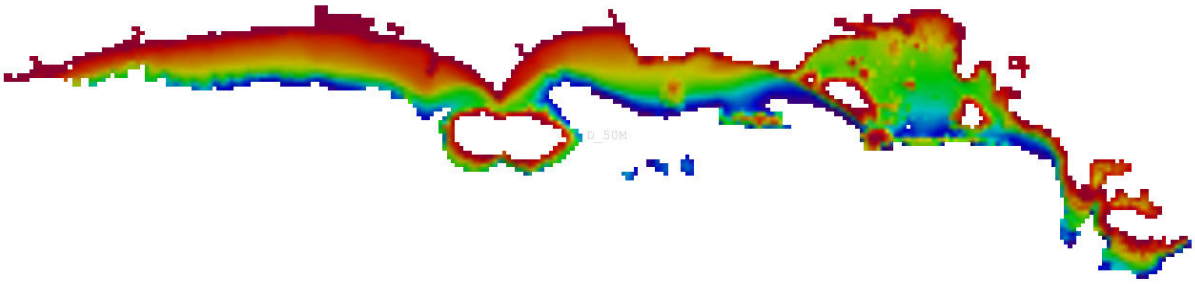
Block C

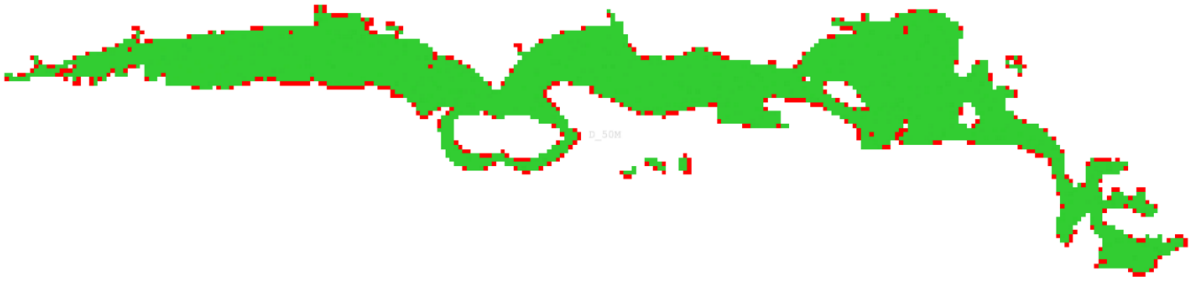


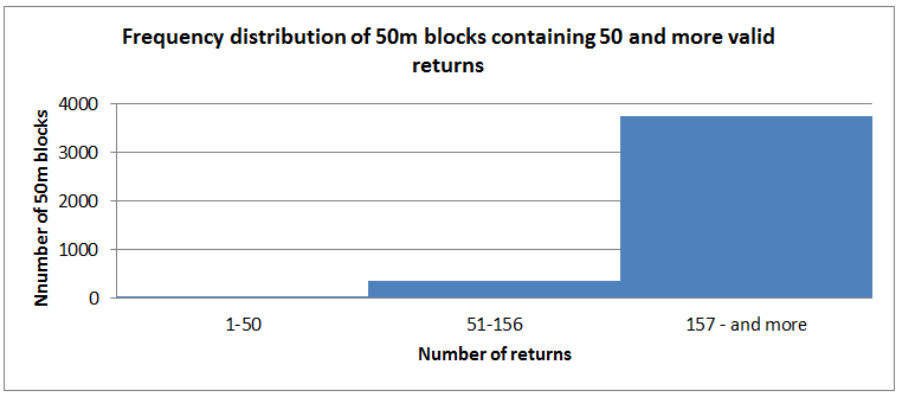


Block C Data Density

Block D

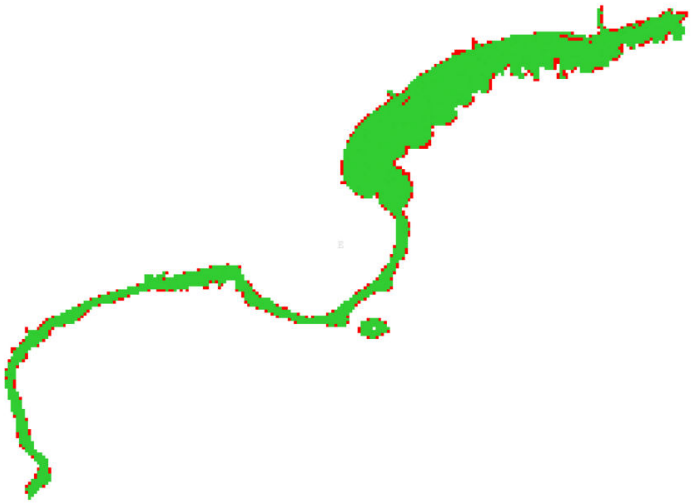


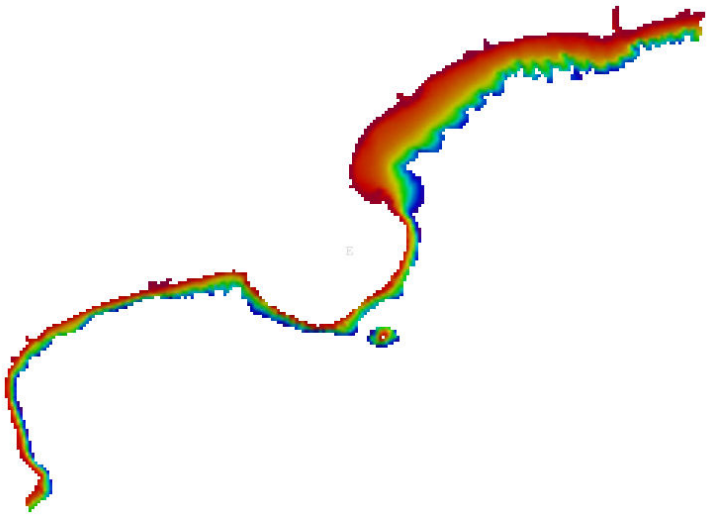


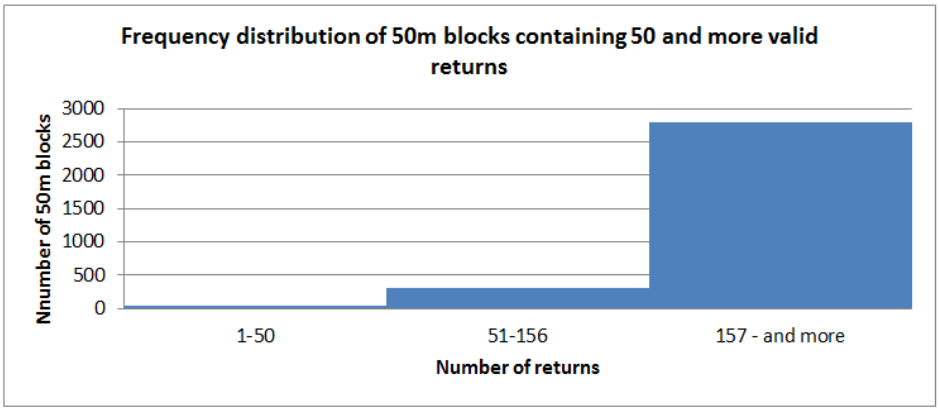


Block D Data Density

Block E

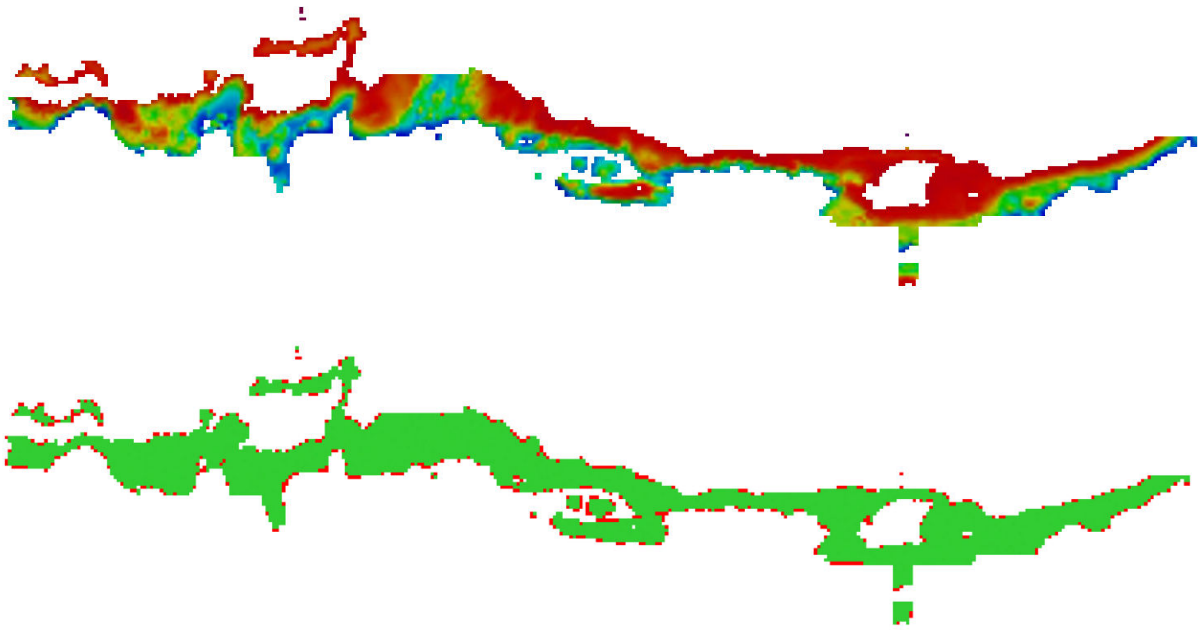


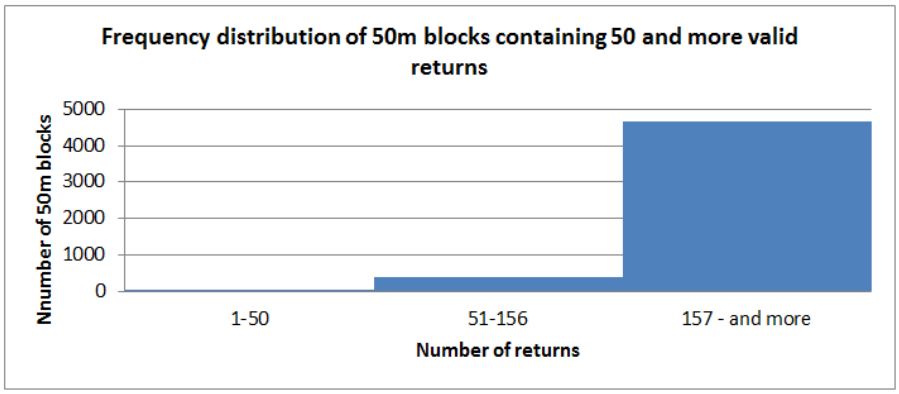




Block E Data Density

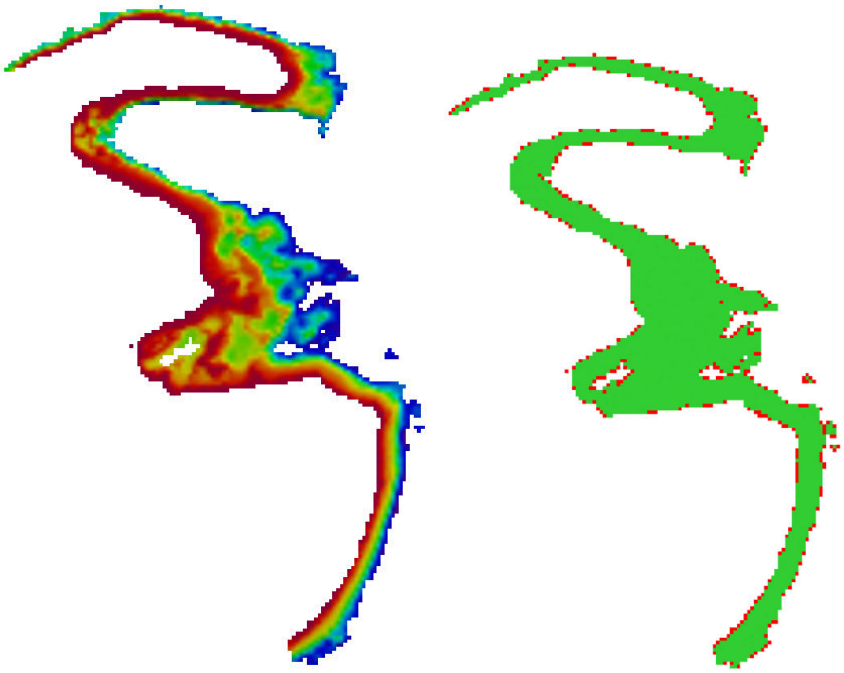
Block F and F1

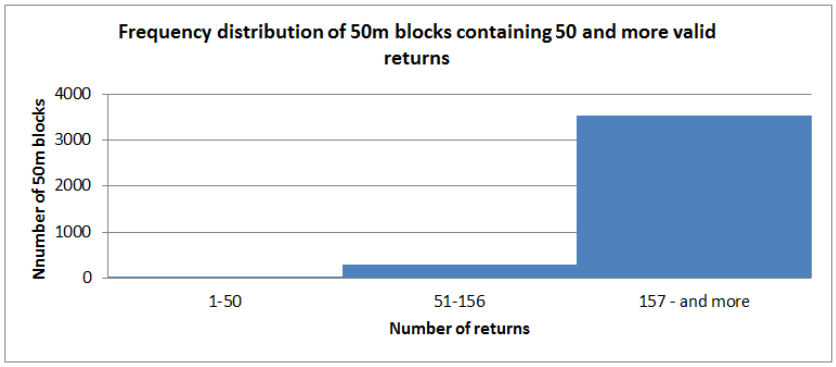




Block F and F1 Data Density

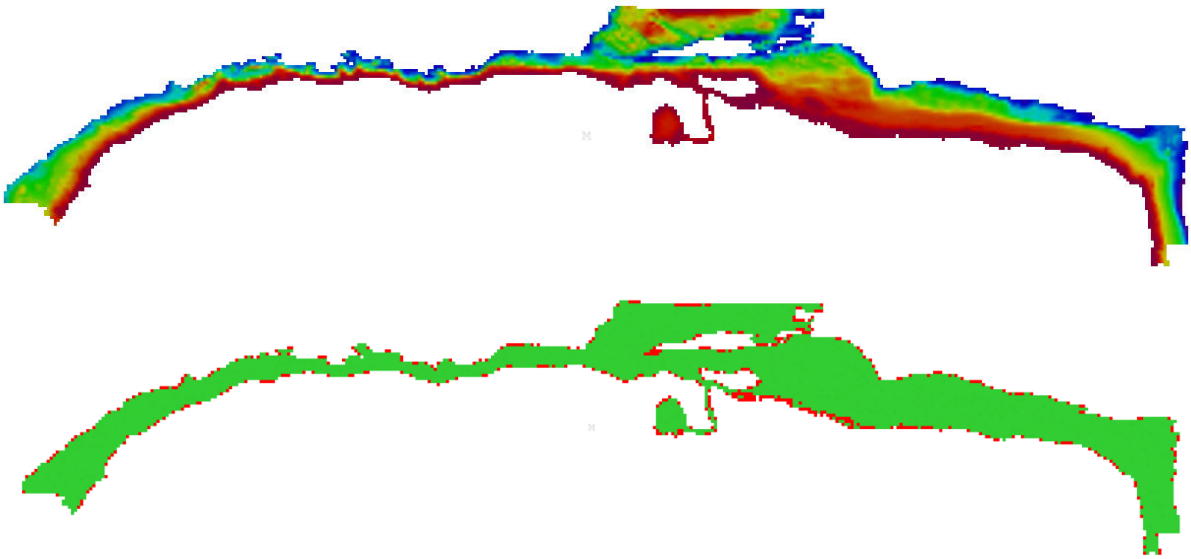
Block G

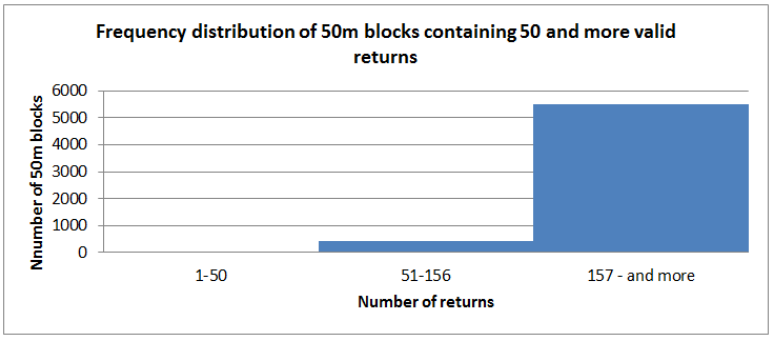




Block G Data Density

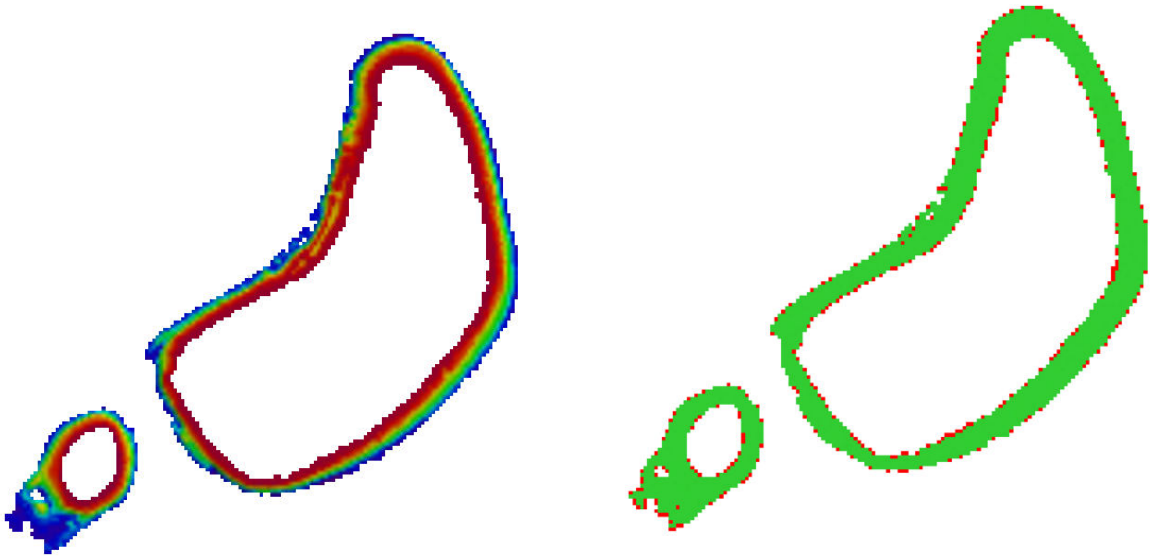
Block M

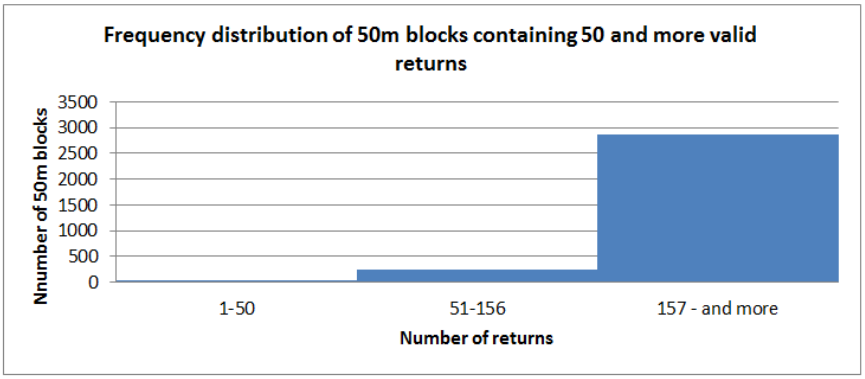




Block M Data Density

Block N





Block N Data Density

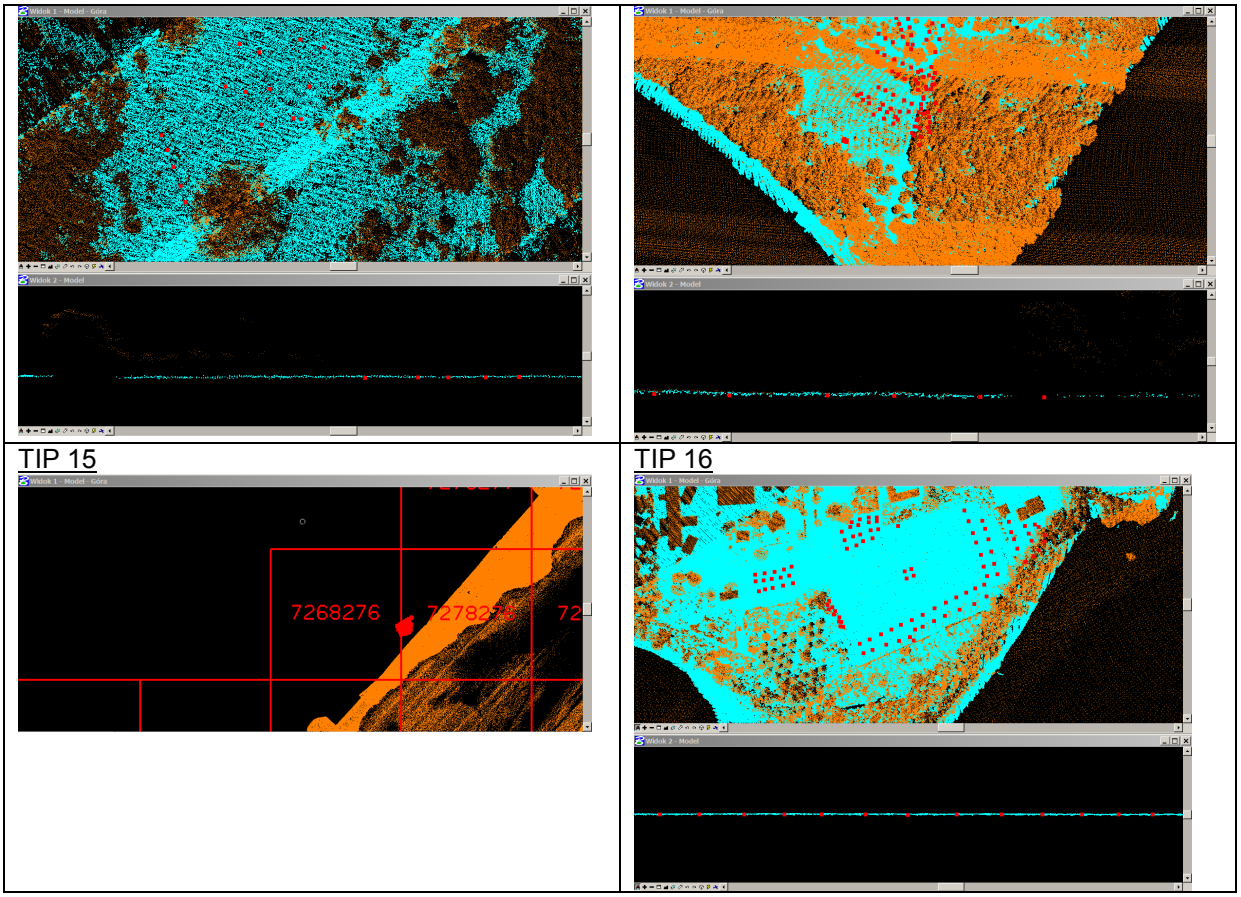
The environmental conditions experienced during the period of the survey, particularly the turbidity that resulted from the cycle of passing weather fronts and suspended sediments, meant that it was not possible to achieve the 100% coverage required in all areas during the period defined for the survey. Repeated coverage with different flightlines, sensor settings, wind conditions, tide heights and sun angle did not improve the seabed definition and where areas were flown twice with no detection it has been marked no bottom found.

Topographic Integration Point Analysis

A number of sites lying adjacent to the area surveyed by the HawkEye IIb were co-ordinated and the surrounding area was surveyed using a Leica Total Station. Following establishment of the control points, a series of measurements were taken using a Leica TS 11 Total Station sited over one of the control points and a Prism in order to derive the shape and elevation of the site, recording x, y, z co-ordinates referenced to the ellipsoid (WGS 84). The Total Station combines a Theodolite to record vertical and horizontal angles, and an Electronic Distance Measurement device, to enable the acquisition of 3-Dimensional coordinate data. Total Stations work by reflecting infra-red laser against a prism. The Total Station requires two operators, one to operate the device and the other to position the prism pole in the required location for surveying. A surveyor walked transects with the prism which was observed and recorded in the controller unit software. All observations were undertaken by AAM Pty and the final adjusted ellipsoidal data was provided to Pelydryn for comparison with acquired data. The data from the observed sites was compared against the topographic data collected from lines which passed over the sites previously surveyed.

The results are presented graphically and in tabular format below. Unfortunately TIP 15 lay too far inshore for the area to be covered by the topographic LiDAR and was discounted in the analysis.

TIP 13	TIP 14



TIP Site Locations on Santo Profile View.

	TIP 13	TIP 14	TIP 15	TIP 16	AVERAGE
Average dz	0.155	0.143	N/A	0.116	0.138
Std Deviation	0.077	0.165	N/A	0.157	0.133

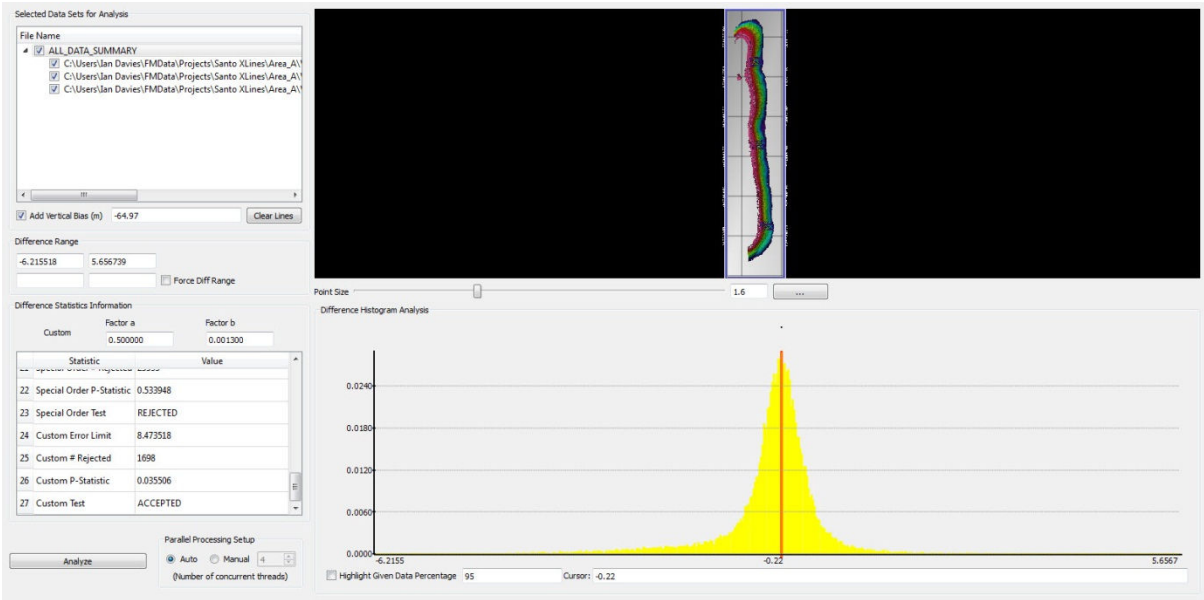
TIP Analysis Results Santo

Analysis of the GNSS and Total Station EODM Observations show good agreement and low residual errors, confirming the correct calibration and derivation of the point altitude from the topographic laser .

Cross-line Comparisons

Cross-lines were run perpendicular to the main sounding lines wherever possible. Analysis of the data quality was performed using the Crosscheck Tool within Fledermaus. At the core of this program is a point versus surface comparison tool, designed to generate difference statistics. The cross-line data was processed in CARIS HIPS, before being exported as an ASCII XYZ file. These XYZ files were then compared against the finalised Fledermaus Shallow Edited Surface. The difference statistics for each cross-line are detailed below, together with sample graphics for each survey Block.

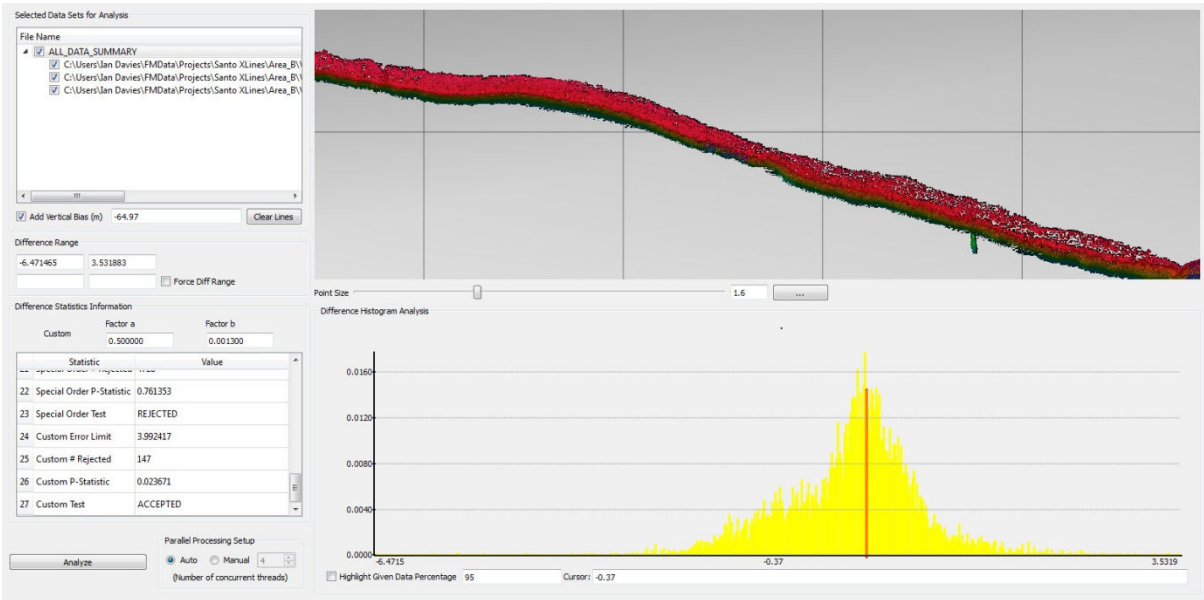
Hydro Crosscheck Results Block A – Espiritu Santo



Area A Statistical Summary			
No Of Points	47823	Order 1 Error Limit	0.5462
Difference Mean	-0.3484	Order 1 Rejected	12697
Difference Median	-0.2461	Order 1 P- Statistic	0.2655
Standard Deviation	0.7642	Order 1 Test	**ACCEPTED**

Crosscheck Results Block A

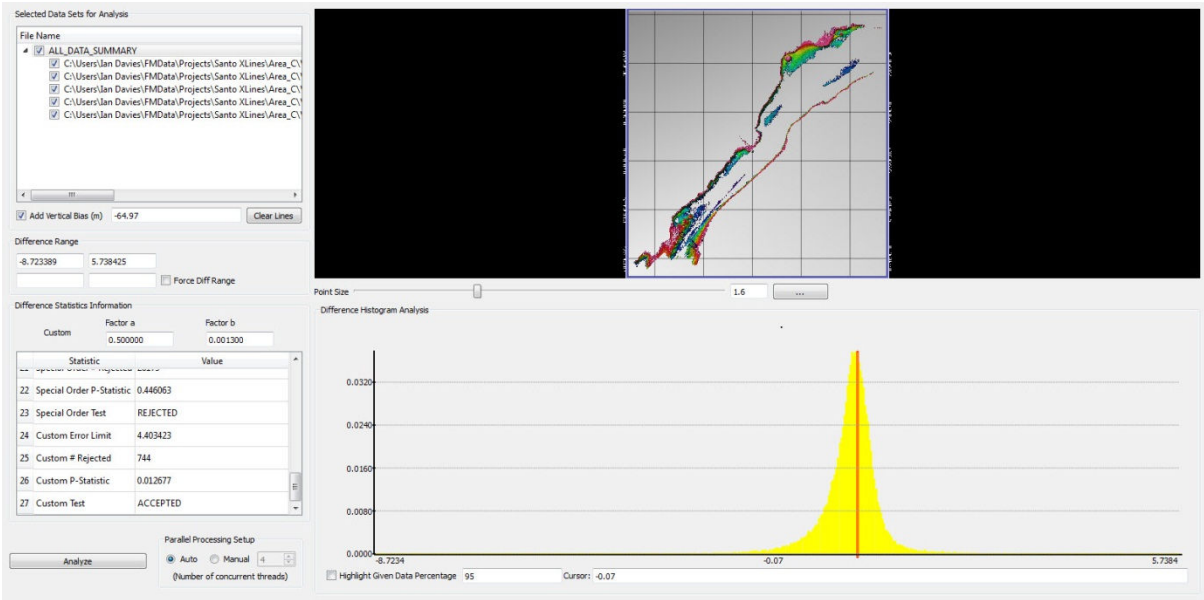
Hydro Crosscheck Results Block B – Espiritu Santo



Area B Statistical Summary			
No Of Points	6210	Order 1 Error Limit	0.5105
Difference Mean	-0.5398	Order 1 Rejected	3302
Difference Median	-0.4504	Order 1 P- Statistic	0.5317
Standard Deviation	0.8490	Order 1 Test	**ACCEPTED**

Crosscheck Results Block B

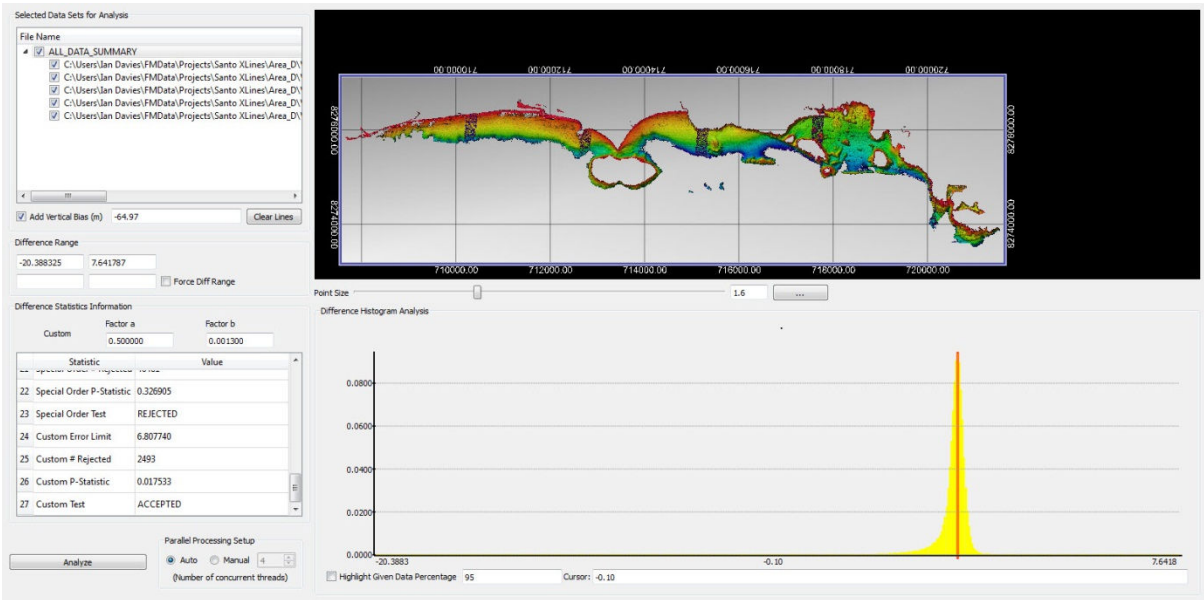
Hydro Crosscheck Results Block C – Espiritu Santo



Area C Statistical Summary			
No Of Points	58689	Order 1 Error Limit	0.5127
Difference Mean	-0.1666	Order 1 Rejected	12248
Difference Median	-0.1200	Order 1 P- Statistic	0.2087
Standard Deviation	0.5467	Order 1 Test	**ACCEPTED**

Crosscheck Results Block C

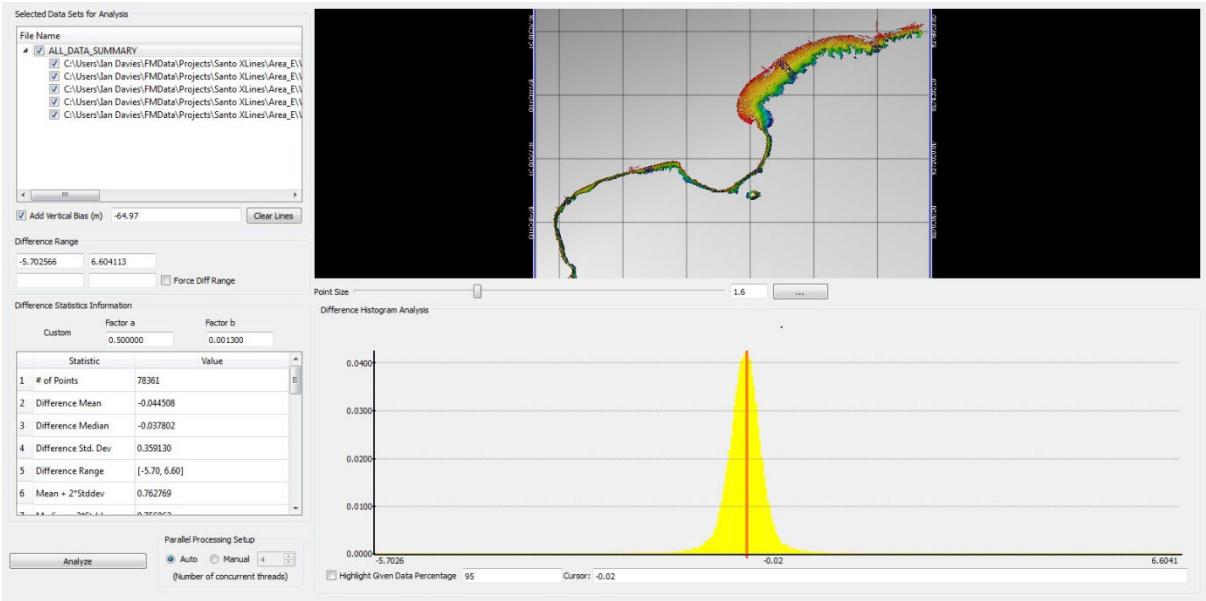
Hydro Crosscheck Results Block D – Espiritu Santo



Area D Statistical Summary			
No Of Points	142185	Order 1 Error Limit	0.5302
Difference Mean	-0.2377	Order 1 Rejected	20418
Difference Median	-0.1141	Order 1 P- Statistic	0.0175
Standard Deviation	0.7231	Order 1 Test	**ACCEPTED**

Crosscheck Results Block D

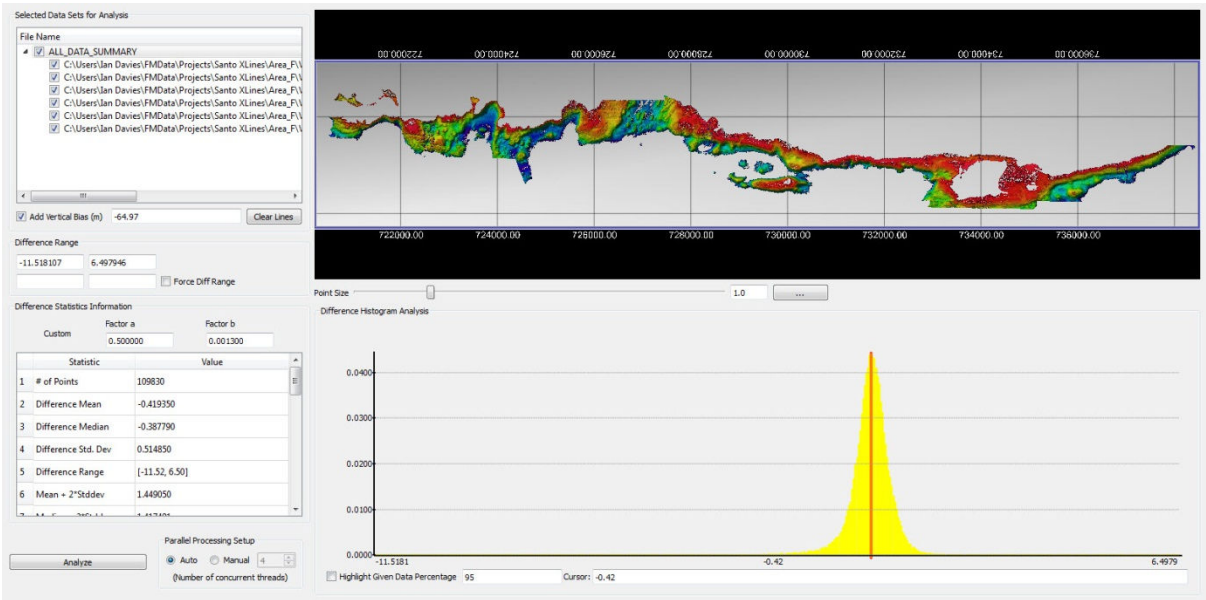
Hydro Crosscheck Results Block E – Espiritu Santo



Area E Statistical Summary			
No Of Points	78361	Order 1 Error Limit	0.5726
Difference Mean	-0.0445	Order 1 Rejected	5387
Difference Median	-0.0378	Order 1 P- Statistic	0.6874
Standard Deviation	0.3591	Order 1 Test	**ACCEPTED**

Crosscheck Results Block E

Hydro Crosscheck Results Block F – Espiritu Santo

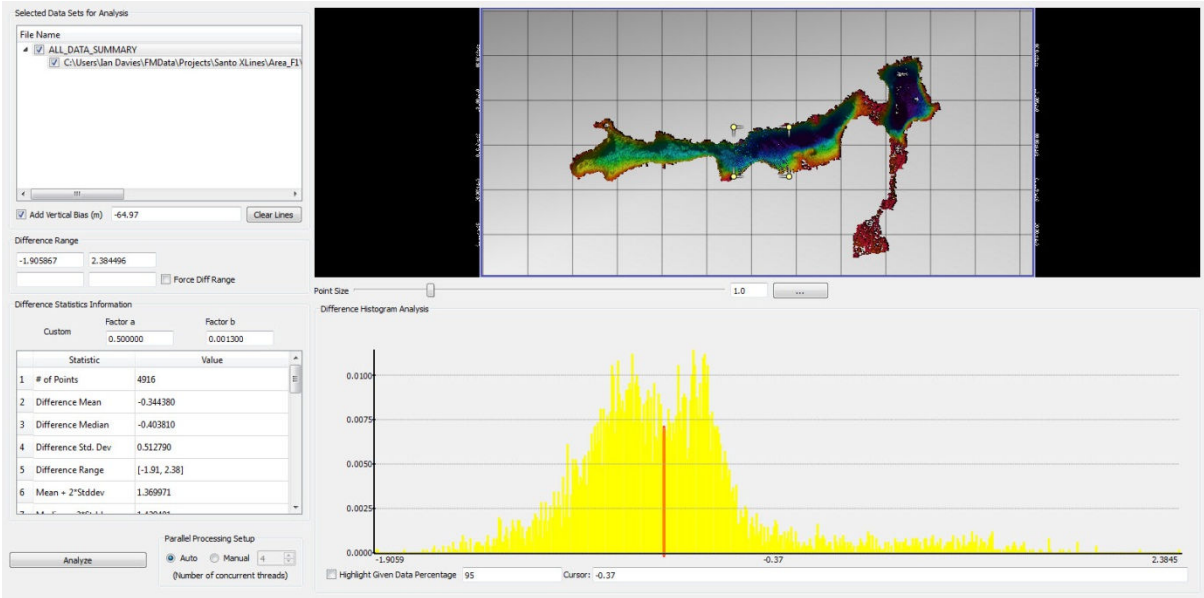


Area F Statistical Summary			
No Of Points	109830	Order 1 Error Limit	0.5278

Difference Mean	-0.4193	Order 1 Rejected	36329
Difference Median	-0.3877	Order 1 P- Statistic	0.3307
Standard Deviation	0.5148	Order 1 Test	**ACCEPTED**

Crosscheck Results Block F

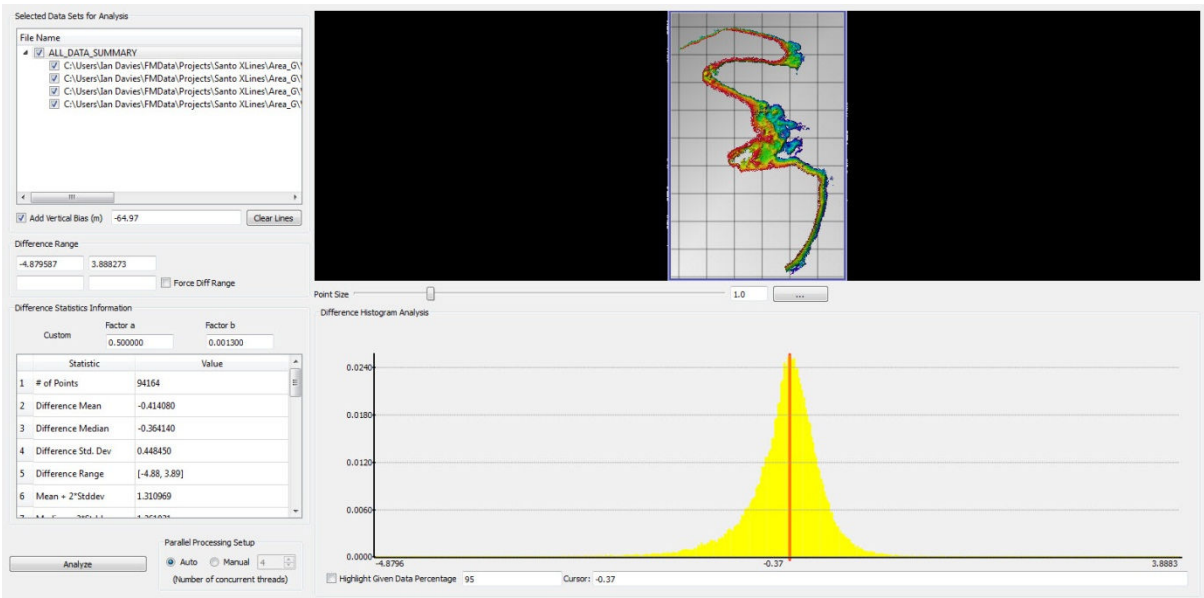
Hydro Crosscheck Results Block F1 – Espiritu Santo



Area F1 Statistical Summary			
No Of Points	4916	Order 1 Error Limit	0.5025
Difference Mean	-0.3443	Order 1 Rejected	2320
Difference Median	-0.4038	Order 1 P- Statistic	0.4719
Standard Deviation	0.5128	Order 1 Test	**ACCEPTED**

Crosscheck Results Block F1

Hydro Crosscheck Results Block G – Espiritu Santo

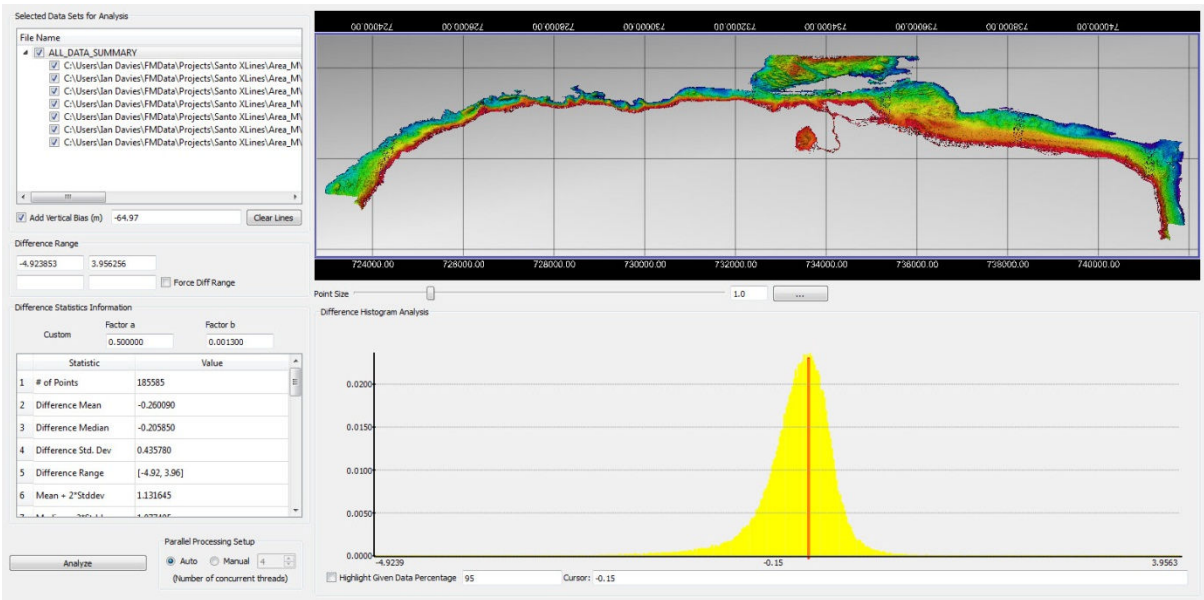


Area G Statistical Summary			
No Of Points	94164	Order 1 Error Limit	0.5375
Difference Mean	-0.4140	Order 1 Rejected	26990

Difference Median	-0.3641	Order 1 P- Statistic	0.2866
Standard Deviation	0.4484	Order 1 Test	**ACCEPTED**

Crosscheck Results Block G

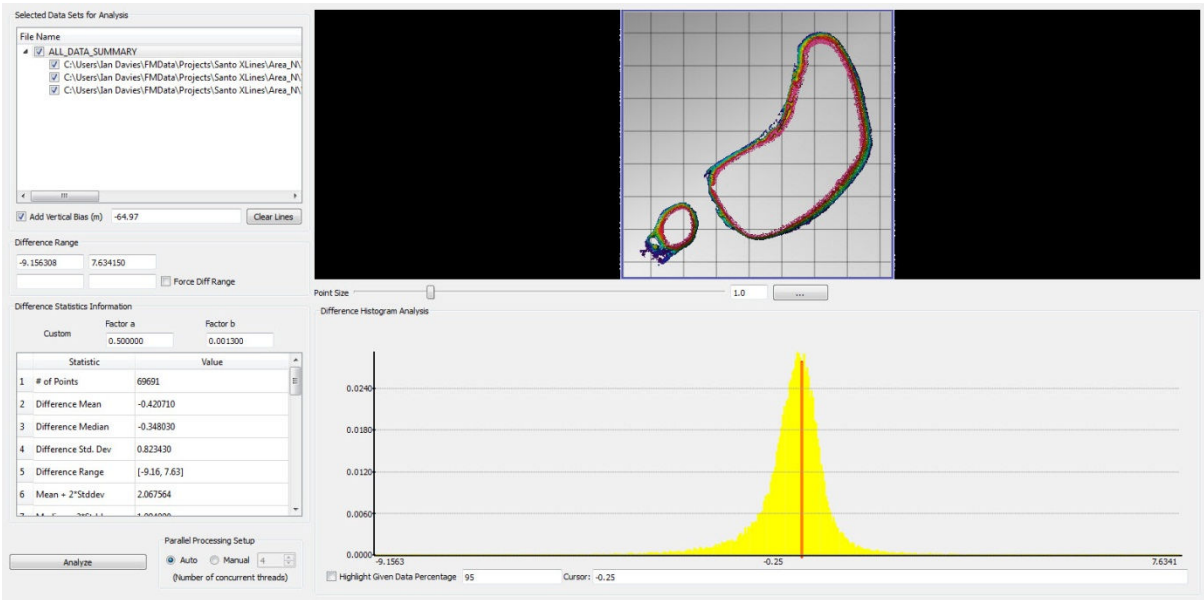
Hydro Crosscheck Results Block M – Espiritu Santo



Area M Statistical Summary			
No Of Points	185585	Order 1 Error Limit	0.5479
Difference Mean	-0.2600	Order 1 Rejected	32447
Difference Median	-0.2058	Order 1 P- Statistic	0.1748
Standard Deviation	0.4357	Order 1 Test	**ACCEPTED**

Crosscheck Results Block M

Hydro Crosscheck Results Block N – Espiritu Santo



Area N Statistical Summary			
No Of Points	69691	Order 1 Error Limit	0.5413
Difference Mean	-0.4207	Order 1 Rejected	16150
Difference Median	-0.3480	Order 1 P- Statistic	0.3867
Standard Deviation	0.8234	Order 1 Test	**ACCEPTED**

Crosscheck Results Block N

The Cross-line Comparison analysis shows that the data has met IHO Order 1 specifications.

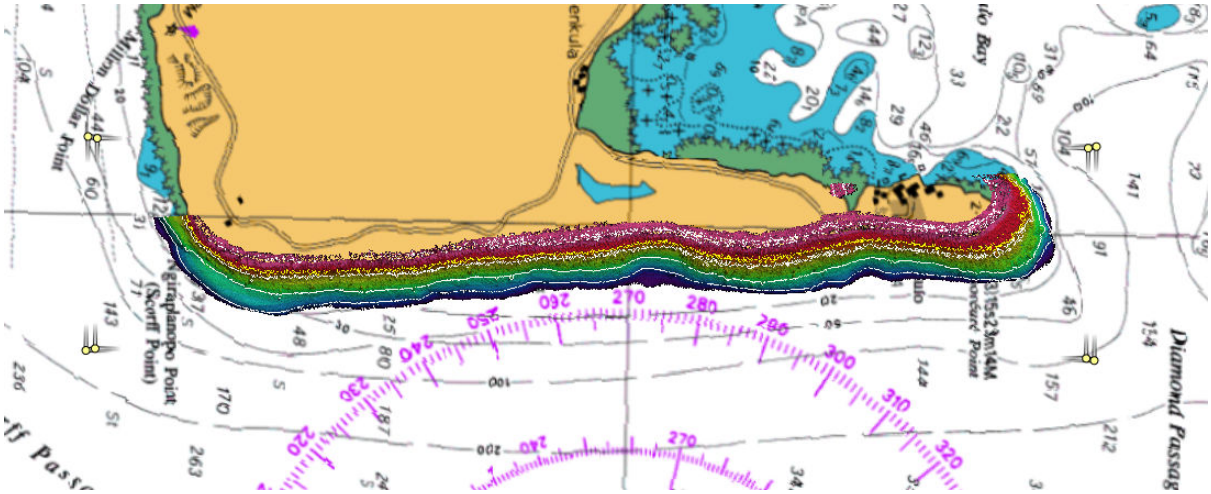
Survey Coverage and Comparison with the Bathymetric Chart

Comparison was made between the survey data and Geotiffs of BA Charts 1575 and 1638. The method used for comparisons was to resample and drape the Geotiff chart over the accepted DTM. As the system works by resampling the lower resolution to the higher resolution (chart to DTM) some distortion can occur. When comparing depths, the centre of gravity of the sounding has been taken as the position to be verified. A check is made to ensure the depth under the sounding footprint is similar and where different the general depth in the area is quoted to allow checking and verification. The advantage of draping and sampling the chart over the DTM with contour plots is to allow the surveyor to quickly see the area he needs to focus on (such as shoals) and any new features helping with the comparison process.

The Areas surveyed are covered by BA Charts 1575 and 1638. The area was last surveyed in 1943 with leadline soundings from the 1800 contributing to the source data of the diagram. As Chart Datum is not fully established in Luganville, the derived level of Chart Datum has been applied to the data in order to carry out a comparison.

Area A

Area A extends from Naoreure Point to Ngiraplanopo Point covering the Eastern seaward Side of Palikulo Bay. Area A is characterised by a small reef plate with a slope of 7 degrees descending to 40m approximately 400m offshore. Comparison with the existing chart shows that the contours on are much closer to shore than currently charted. Complete data coverage has been achieved to the project specification, with consistent depths of 40m (CD) achieved where seabed topography (slope) and water clarity allowed.



Area A gridded at 5m

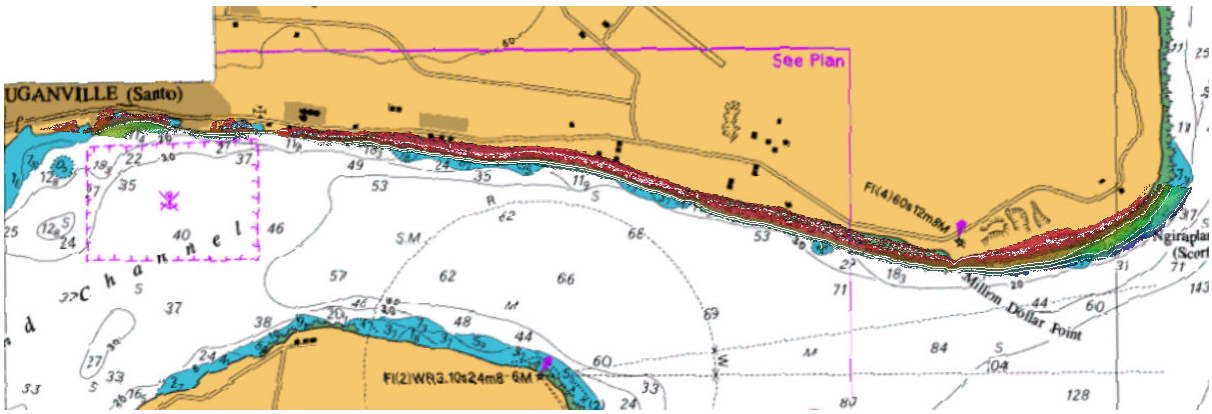
One Hydrographic Note has been submitted with this report relating to an uncharted wreck in the following position

Latitude	Longitude	Least Depth (CD Port	Remarks
15°	167° 15.1948" E	Dries 3.90m	Wreck– H Note 004

Position of Uncharted Wreck

Area B

Area B lies on the North side of the Segond Channel between Ngiraplanopo Point and Luganville. Area A is characterised by a small reef plate with a slope of 7 degrees descending to 40m approximately 400m offshore. Comparison with the existing chart shows that the contours on are much closer to shore than currently charted. Complete data coverage has been achieved to the project specification, with consistent depths of 40m (CD) achieved where seabed topography (slope) and water clarity allowed.



Area B gridded at 5m

One Hydrographic Note has been submitted with this report relating to a charted wreck in the following position

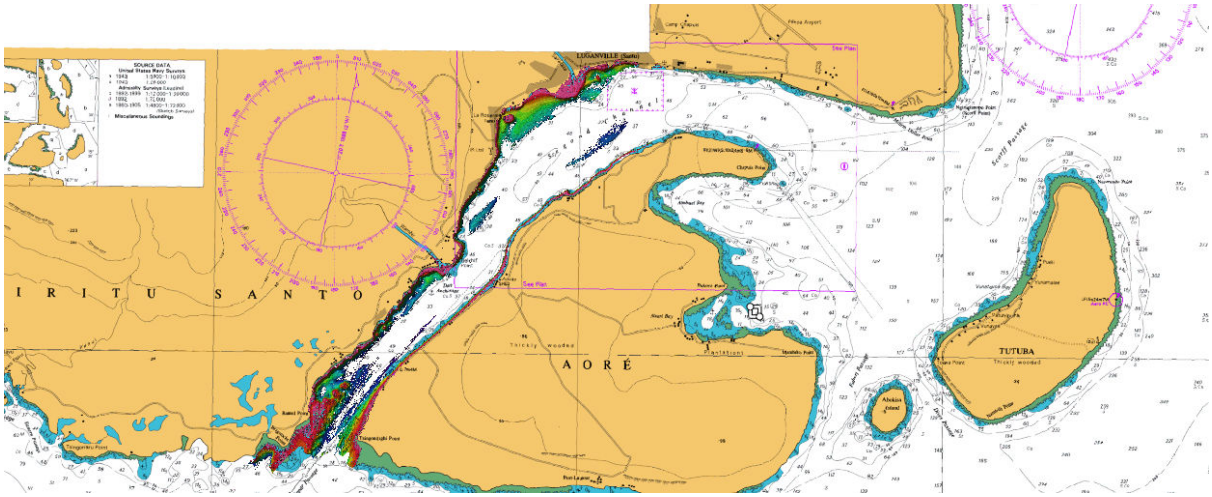
Latitude	Longitude	Least Depth (CD Port	Remarks
15°	167° 14.1017" E	16.89m	Charted Wreck H Note 005

Position of Charted Wreck

Area C

Area C extends from Luganville to the East to Brigstocke Point covering both sides of the Segond Channel between Espiritu Santo and Aore. Comparison of the bathymetric chart reveals complicated seabed topography. Steeply sloping fore reefs can be clearly seen in the eastern side of the channel as the channel turns

South West a number of shoals can be seen within the channel. At the southern entrance to the channel there is a deeply incised channel, which cuts through shallower extensive shallow reef areas on each side. Examination of the contours shows general agreement. Complete data coverage has been achieved to the project specification, with consistent depths of 40m (CD) achieved where seabed topography (slope) and water clarity allowed.



Area C gridded at 5m

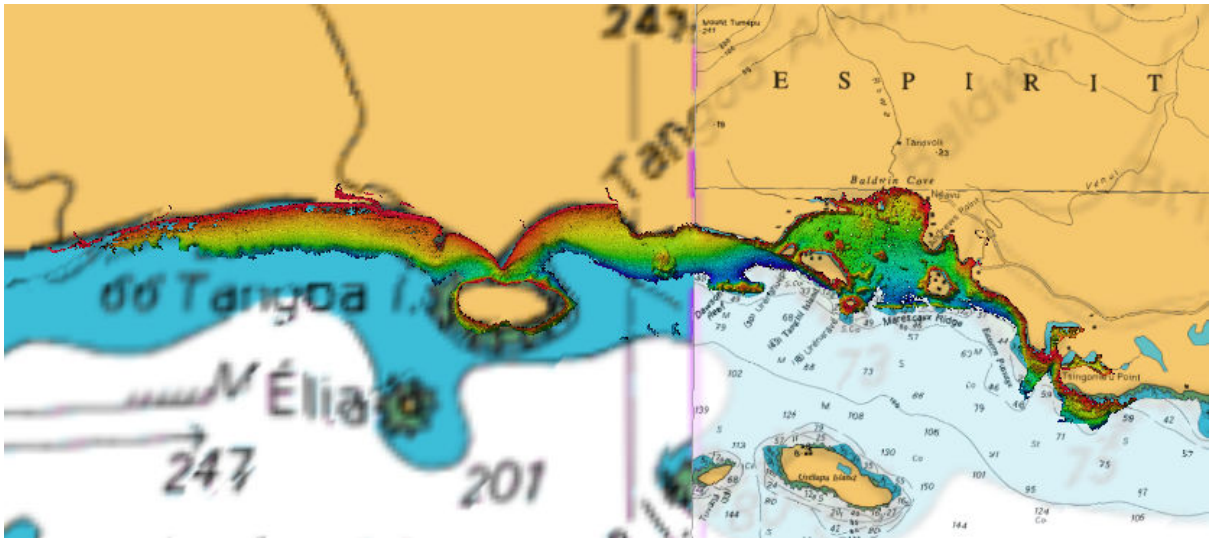
One Hydrographic Note has been submitted with this report relating to uncharted wrecks and pinnacles in the following position

Latitude	Longitude	Least Depth (CD Port	Remarks
15° 31.3893'S	167° 09.6942" E	dries 4.70m	Uncharted Wreck – H Note 006
15° 31.7535'S	167° 09.3170" E	dries 7.33m	Uncharted Wreck – H Note 007
15° 32.6302'S	167° 09.3068" E	0.93m	Uncharted Wreck – H Note 008
15° 31.8017'S	167° 09.3923" E	12.18m	Uncharted Shoal – H Note 009
15° 31.8155'S	167° 09.4790" E	18.17m	Uncharted Shoal – H Note 010

Position of Uncharted Pinnacle

Area D

Area D runs from West of Tangoa Island to Tsingoniaru Point in the East. Area D is characterised by a small fringing reef plate extending along the coast with a number of off lying pinnacles and larger reef structures and islands. Comparison with the existing chart sees a wide gently sloping reef plate in the to the West of Eila. East of Elia the seabed topography becomes more complicated with a more indented coastline fringed by islands and large reef structures running parallel to the shore. Contours show general agreement, although some uncarted features have been seen and are subject to H Note action below. Complete data coverage has been achieved to the project specification, with consistent depths of 40m (CD) achieved where seabed topography (slope) and water clarity allowed.



Area D gridded at 5m

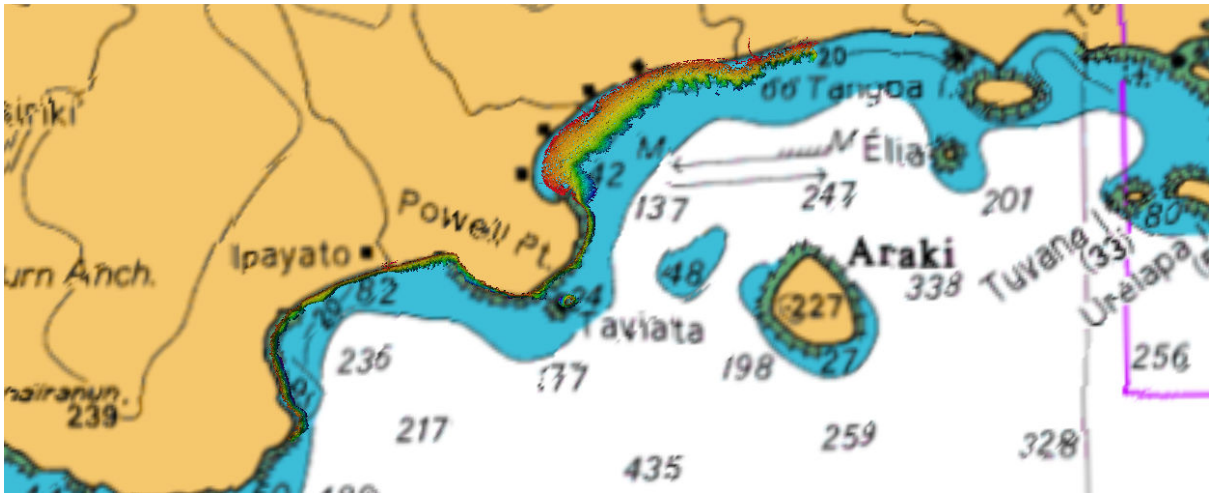
One Hydrographic Note has been submitted with this report relating to uncharted pinnacles in the following position

Latitude	Longitude	Least Depth (CD Port	Remarks
15° 35.0730'S	167° 02.1463" E	2.33m	Uncharted Shoal– H Note
15° 35.3583'S	167° 02.2167" E	Multiple	Uncharted Shoal– H Note
15° 35.4717'S	167° 02.3278" E	27.32m	Uncharted Shoal– H Note
15° 35.6885'S	167° 02.6623" E	25.69m	Uncharted Shoal– H Note

Position of Uncharted Shoals Area D

Area E

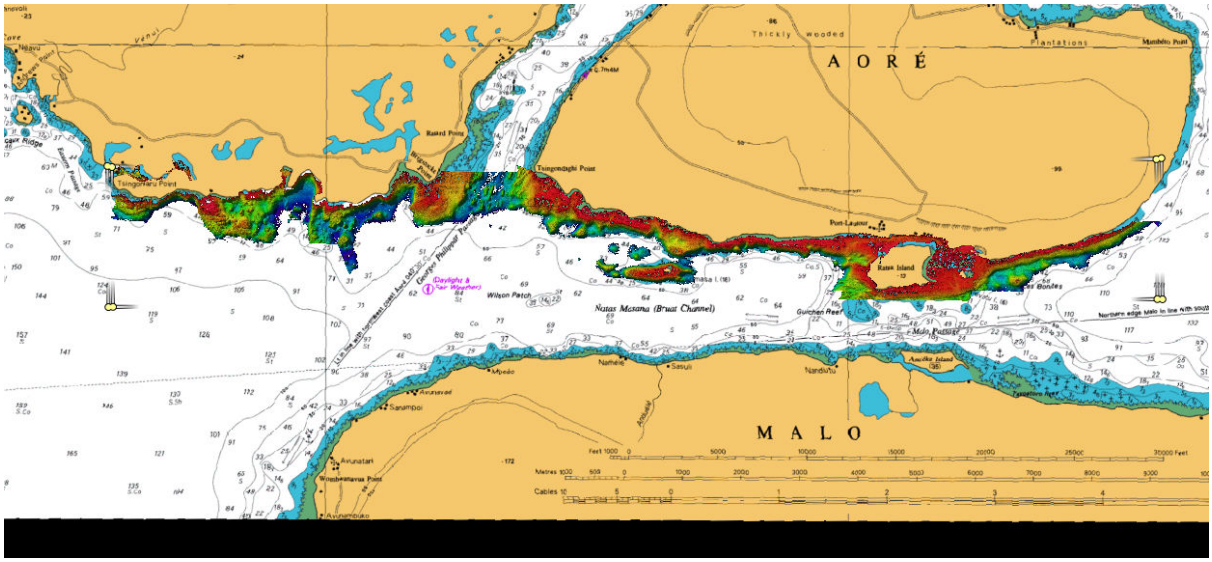
Area E lies between Tangoa Island and South Cape. The area is characterised by a small steep sloping fringing reef plate extending along the coast from Powell Point to South Cape. Examination of the limited charting data in this area indicates the depths and contours lie closer to the coast. The area from Powell Point heading North East is a wider more gently sloping topography. A full comparison is not possible in this area due to the scale of the current charting. Complete data coverage has been achieved to the project specification, with consistent depths of 40m (CD) achieved where seabed topography (slope) and water clarity allowed.



Area E gridded at 5m

Area F

Area F extends along the Southern side of Aore through the Malo Passage and as far west as Tsingoniaru Point on Espiritu Santo. Comparison with the existing chart reveals general agreement with the charted contours. Of note however is the large number uncharted shoals lying between Brigstocke Point and Tsingoniaru Point which suggest the chart in this area is significantly different to that observed. Significant features have been raised in Hydrographic Notes. Complete data coverage has been achieved to the project specification, with consistent depths of 40m (CD) achieved where seabed topography (slope) and water clarity allowed.



Area F gridded at 5m

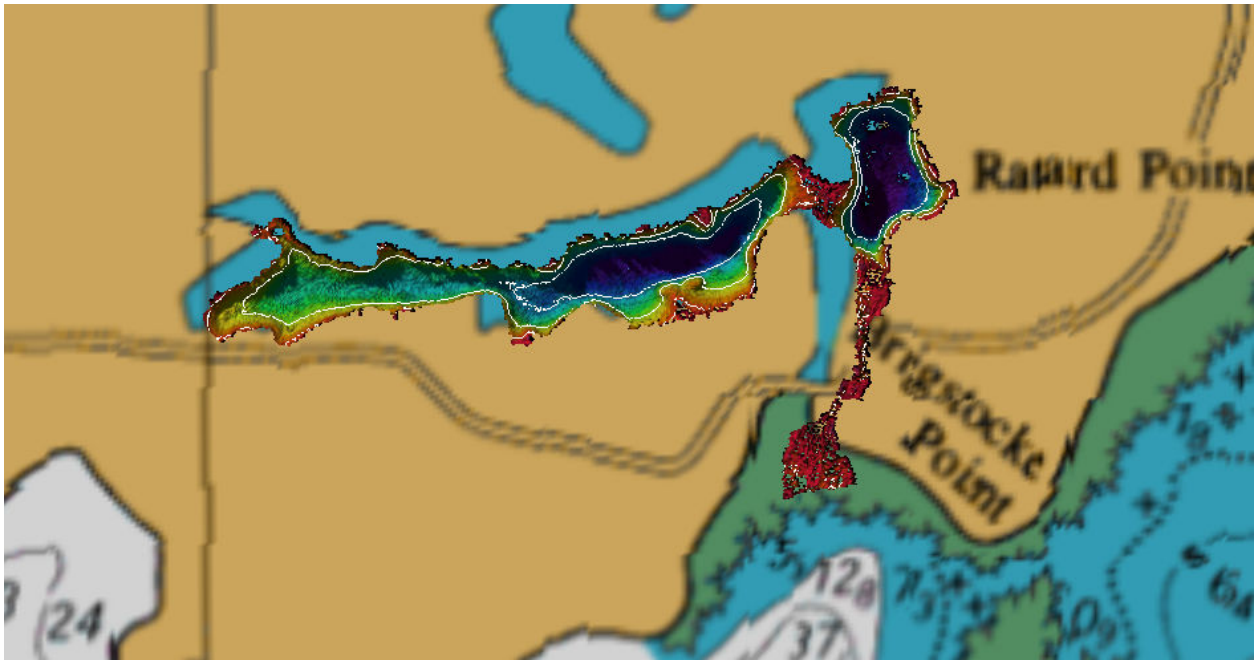
Four Hydrographic Notes have been submitted with this report relating to uncharted pinnacles in the following position

Latitude	Longitude	Least Depth (CD Port	Remarks
15° 36.3127'S	167° 05.9372" E	5.98m	Uncharted Shoal– H Note 015
15° 36.5290'S	167° 05.6178" E	7.93m	Uncharted Shoal – H Note 016
15° 36.4213'S	167° 04.6343" E	2.33m	Uncharted Shoal – H Note 017
15° 36.3231'S	167° 04.1717" E	Multiple	Uncharted Shoal – H Note 018

Position of Uncharted Shoals Area F

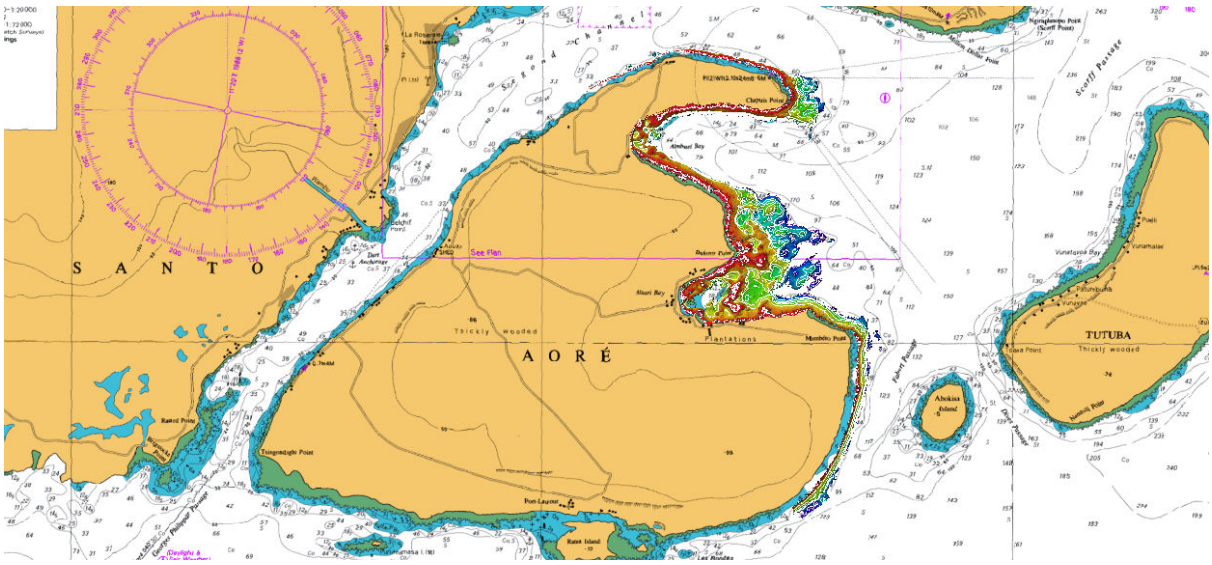
Area F1

Area F1 is a small lagoon connected to the sea close to Brigstocke Point. No Charting information currently exists for this area. Examination of the data reveals the lagoon to have a maximum depth of around 8m. Complete data coverage has been achieved to the project specification, with consistent depths of 40m (CD) achieved where seabed topography (slope) and water clarity allowed.



Area G

Area G lies on the Eastern side of the Isle of Aore running from the Segond channel in the North to the Malo Pasage in the South. Comparison with the existing chart shows general agreement with those charted. Due to water conditions full coverage was not achieved in Aisari Bay. Examination of the bathymetric data revealed a number of uncharted shoal depths which are reported on by Hydrographic Note. Data coverage has been achieved to the project specification, with consistent depths of 40m (CD) achieved where seabed topography (slope) and water clarity allowed.



Area G gridded at 5m

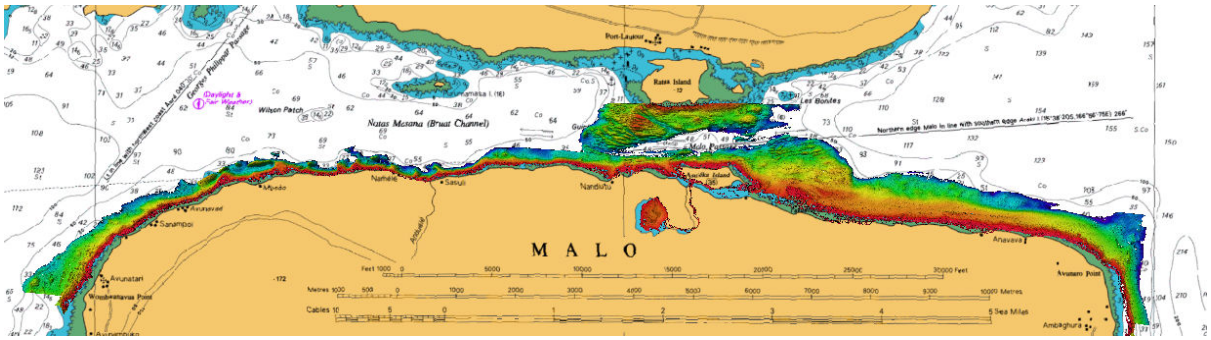
One Hydrographic Note has been submitted with this report relating to uncharted pinnacles in the following position

Latitude	Longitude	Least Depth (CD Port	Remarks
15° 33’ 20” S	167° 12’ 50” E	Multiple	Uncharted Shoal– H Note

Position of Uncharted Shoals

Area M

Area M lies on the North side of the Island of Malo extending from Avunaro point in the East to Wombvanavua Point in the West. The area covers the Malo Passage which shows charted depth in excess of 50m between Asueke and Ratua Islands. The fore reef varies in extent along the coast and examination of the contours shows general agreement with those charted. One shoal depth Complete data coverage has been achieved to the project specification, with consistent depths of 40m (CD) achieved where seabed topography (slope) and water clarity allowed.



Area M gridded at 5m

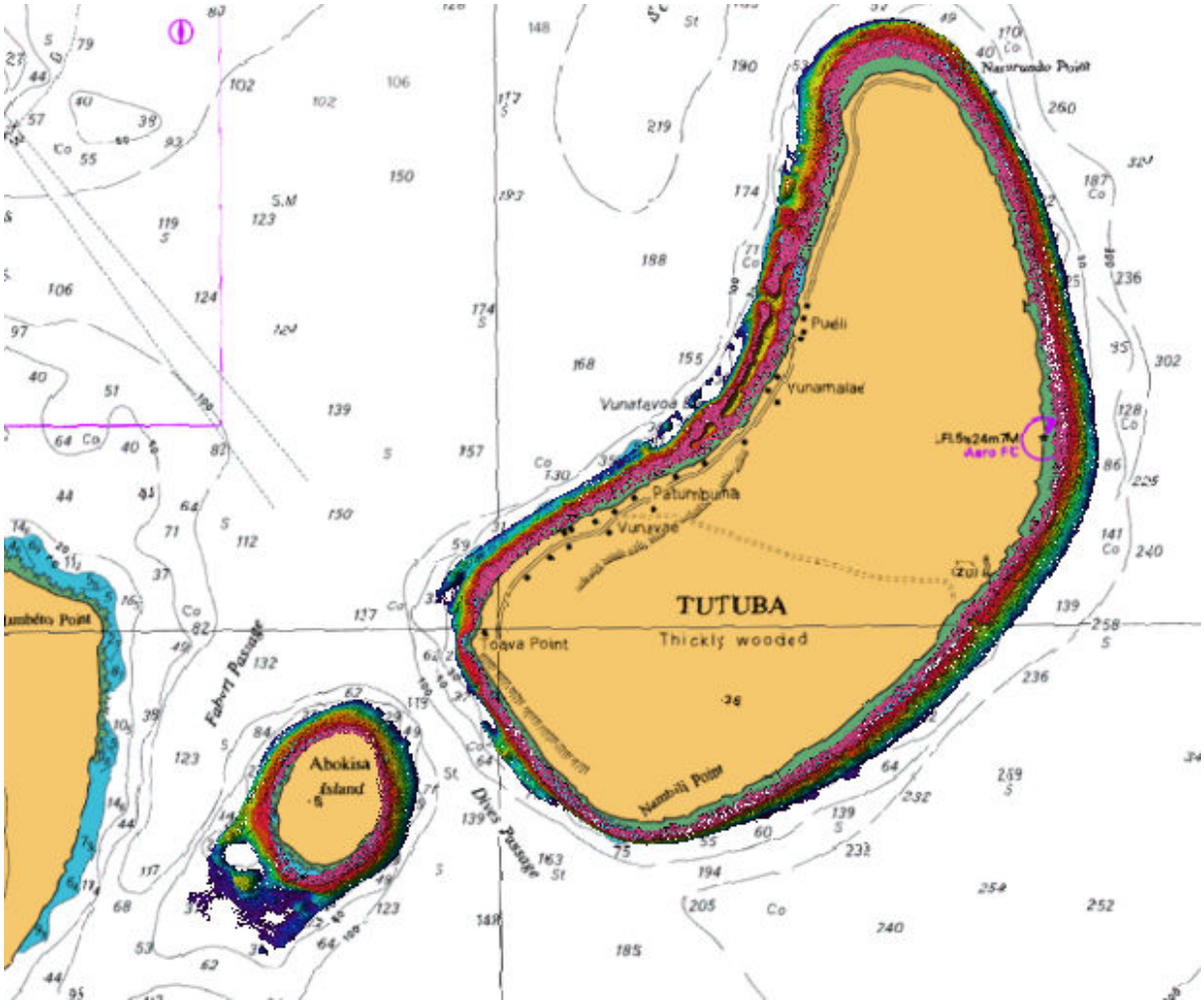
One Hydrographic Note has been submitted with this report relating to uncharted shoals in the following position

Latitude	Longitude	Least Depth (CD Port	Remarks
15°	167° 12.3218" E	7.96m	Uncharted Shoal– H Note

Position of Uncharted Shoal

Area N

Area N covers the coastal fringes of Tutuba and Abokisa Islands. Tutuba has a steeply sloping fore reef with depths descending to 40m+. Examination of the 5m and 10m contours around both islands shows general agreement with a number of areas on the eastern side of Tutuba in particular where the contours lie closer inshore than charted. Due to the slope all other contours appear closer inshore as the depths increase around both islands. No new significant contacts were detected. Complete data coverage has been achieved to the project specification, with consistent depths of 40m (CD) achieved where seabed topography (slope) and water clarity allowed.



Area N gridded at 5m

Wrecks/Contacts/Significant Features

The Field Processor examined all data in CSS initially as point clouds, and then in CARIS HIPS during field cleaning, utilising the 2D view to examine lines and the 3D view to examine areas. During this process the significant contacts or deviations from the adjacent soundings were noted. The plot of Standard Deviation in CARIS was also used to highlight areas of rapid changes in depth relative to the surrounding area.

Any significant features were examined more closely (including reviewing the wave forms from the feature) and a decision made on the probability of the return being valid and where necessary a Hydrographic Note was raised.

7.7 Conclusion

Within the operational limitations of the system, the HawkEye IIb has detected all significant shoals and features to the required 40m depth within the areas surveyed except where seabed slope, extreme shallow water or turbidity have reduced detection capabilities.

8.0 Seamless Products Plan

AAM's plan outlining the technique for creating the SCDEM (composed of both the bathymetric and topographic DEMs) is as follows:

- 1m ESRI grid for topographic coastal data and 5m ESRI grid for bathymetric coastal data have previously been adjusted to common Topographic Integration Points (TIP) which are at Mean Sea Level (2012).
- The topographic DEM has been clipped to the coastline prior to delivery.
- The bathymetric DEM will be clipped 0.5m to the land side of the topographic DEM. This will ensure 100% coverage and no gaps between the bathymetric and topographic data.
- Both bathymetric and topographic DEMs will be merged using the underlying framework of runs and TIP sites. No averaging or smoothing will be performed on the seamless coastal DEM. Using the same TIP sites, independent vertical adjustment will be performed on each dataset meaning that when datasets are merged they fit seamlessly together.

Notes on Expected Accuracy:

- Seamless coastal DEM meets required accuracy in areas of clear open ground. The 'limitations of data' section below outlines potential accuracy degradation in the coastal seamless DEM.
- 1m ESRI grids from topographic coastal data and 5m ESRI grids for bathymetric coastal data, previously adjusted to common surveyed test sites, have been derived from seamless ESRI terrain using Natural Neighbours interpolation method.
- Seamless data accuracy between the bathymetric and topographic datasets is diminished in the tidal areas.

Limitations of Data:

- The definition of ground under trees may be less accurate.

9.0 Spatial Accuracy Report

Introduction

The acceptance of this report by Geoscience Australia is required before point classification and other product derivation is to proceed. The elements of this deliverable are to include

- Observed flight runs are to be provided in ESRI shape file format. The shape file should contain the following attributes: RUN, DATE and TIME for each run.
- All survey control coordinates, site ID and checkpoint comparisons in both EXCEL spreadsheet and ESRI shape file formats.
- Details of system calibration checks.
- Results of relative (flight run) matching and details of any adjustment made.
- Source of primary ellipsoidal control.
- Results of vertical and horizontal accuracy validation.
- Details of ellipsoid to orthometric corrections applied including any final adjustment to MSL supplemental to the standard Geoid correction.
- Relationship of the collected bathymetric LiDAR data to previously collected topographic LiDAR data at TIP sites including ESRI grid representing the differences.
- Digital photographs of all survey and check sites, with the site ID included in the file name. The bearing of the photo direction should also be indicated.

Observed Flight Runs

Observed flight runs are to be provided in ESRI shape file format. The shape file contains the following attributes: RUN, DATE, TIDE HEIGHT and TIME for each run.

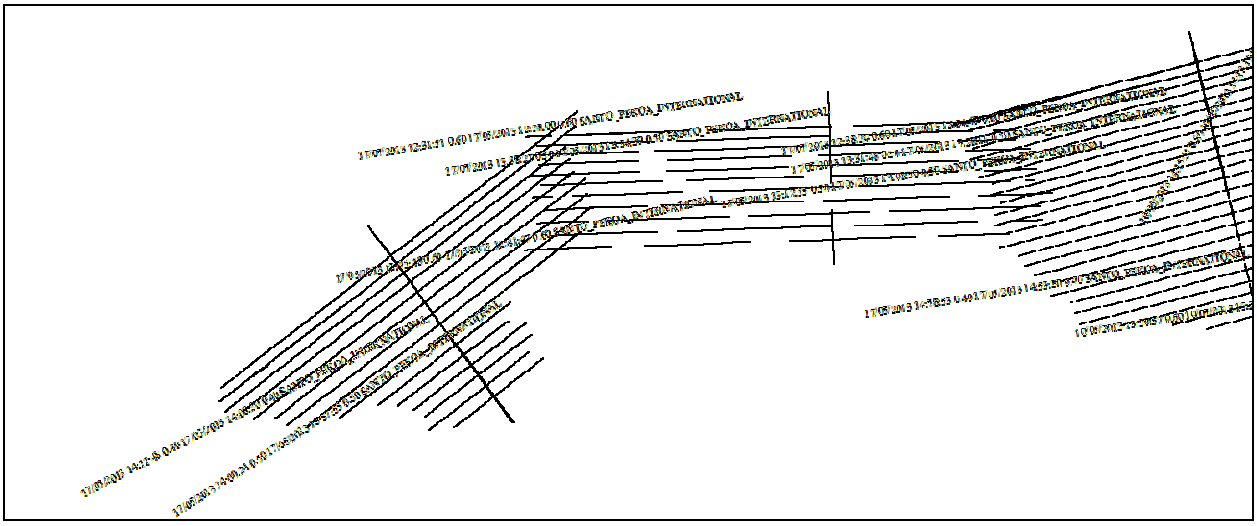


Fig 1.1 – Diagram showing example of observed flight runs for Espiritu Santo provided in ESRI SHP file.

Survey Control Check Points

All survey control and/or check points used to verify accuracy are provided in ESRI shape file format.

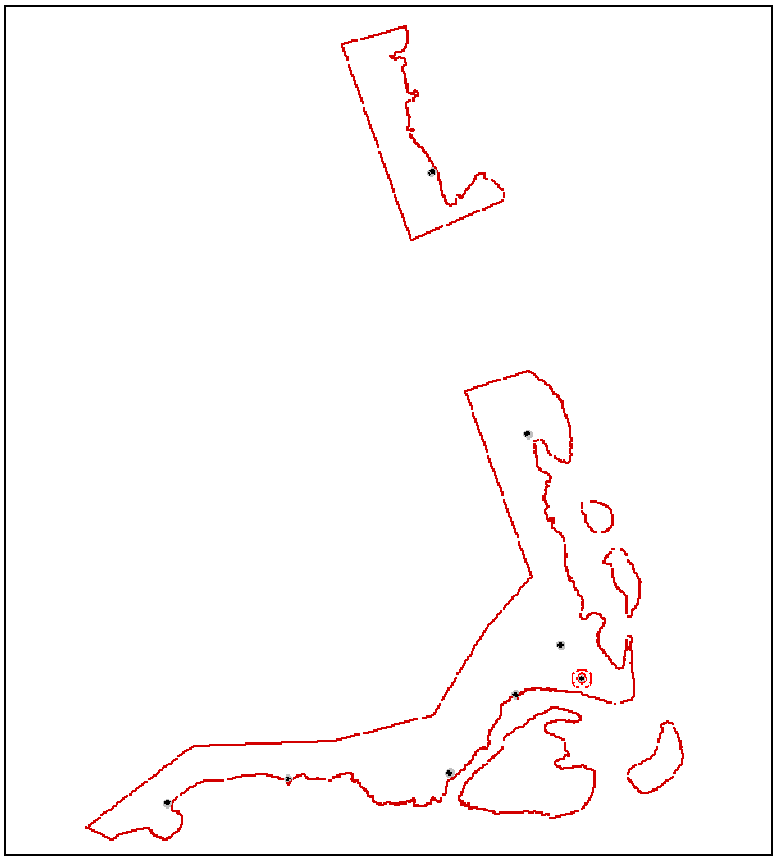


Fig 2.1 – Test Point & Base Station Locations on Espiritu Santo

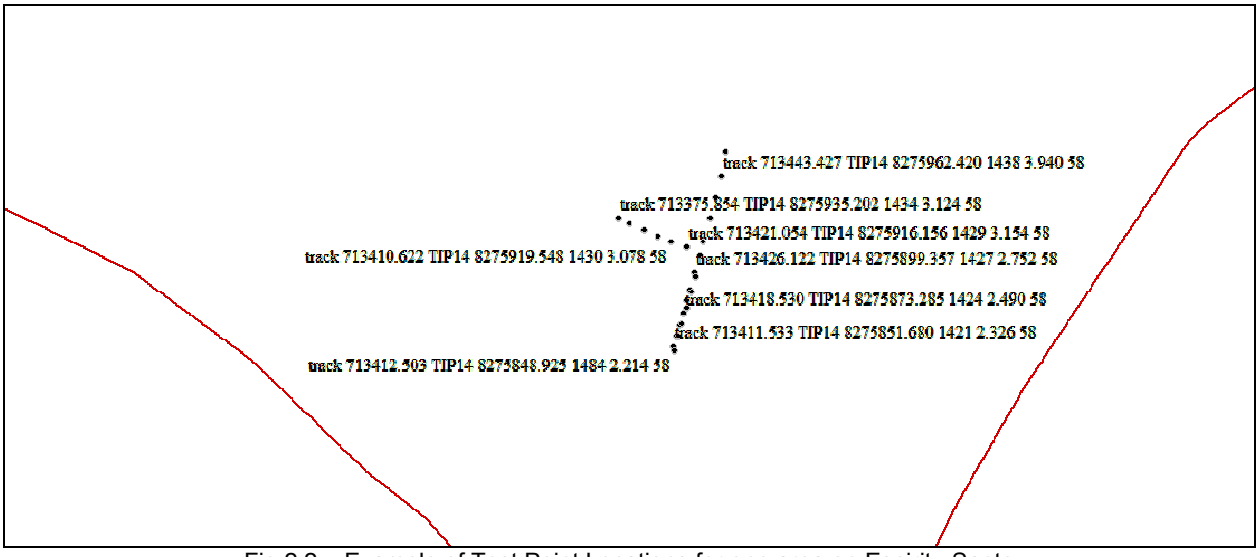


Fig 2.2 – Example of Test Point Locations for one area on Espiritu Santo

Results of Horizontal & Vertical Calibration Checks

Results of horizontal and vertical calibration checks, both relative (flight runs) and absolute (ground truth), including details of any adjustments made.

Base Station Analysis:

The Vanuatu Land Survey Department provided a number of control stations along the coastline adjacent to the mapping polygon.

At the Port Vila (Efate) and Luganville (Santo) International Airports, AAM established Primary and Secondary survey control points to observe base GPS data when the Lidar was being captured. These survey control points are permanent structures for future reference and were tied into ground survey network by static GPS.

After locating the permanent survey control provided by the Land Survey Department, new survey control marks were required at each test point location (TIP).

The coordinates for the permanent survey control points provided by the Land Survey Department were of unknown history. It was decided all primary control marks (permanent) would be measured by long static observations and processed using Geosciences Australia Auspos solution.

In most situations 6 hours of data was observed to generate the primary control coordinates. This process meant that on each island there were a number of primary controls established and used in conjunction with the previously established airport control stations on Efate and Santo.

Each network consists of static baselines observed on each island, connecting the adopted Primary Control Marks and the secondary control marks at each TIP site. Each network was adjusted using Leica Geo Office software.

The network included all observed baselines and primary station coordinates to do the adjustment. Each primary control station was assigned fixed point status and constrained horizontally and vertically according to the Auspos solution report. Horizontal constraint was set to 0.01m and vertical set to 0.05m. These values are 10 times the estimated precision from Auspos.

A network of survey control was adjusted and reported for each island, forming the basis for the acquisition of ground test points. Full details are reported in the Geodetic Survey Report, presented with this report.

LiDAR Point Density Analysis:

For each Island 1km x 1km tiles were selected at random in order to test the point density of the data is within specification. The only specifications used in selecting which tile to test were the tiles had to be full data tiles which had only been covered once. In other words the tiles did not include any cross lines or re-runs. Please see the table below showing the results.

Area	Tile Number	Emitted Ground Point Density per sqM (open clear flat ground)
Santo	e719n8335	6.573
	e725n8322	5.807
	e723n8329	5.329
	e723n8279	8.618
	e734n8301	5.401
	e732n8299	4.833
	e734n8292	5.081
	e736n8287	4.979
	e738n8284	4.948
	e731n8283	9.766
	e726n8276	4.950
	e714n8277	4.900
	e701n8274	7.363
	e734n8276	4.835
	e728n8284	5.177
	e730n8305	9.002
	Average Point Density	6.098

LiDAR Validation Analysis:

The LiDAR data has been checked against validation data on open clear land collected during the land survey. Comparison has been made with several validation areas across Espiritu Santo. The data was then adjusted and re-examined against the validation plots. Below are the tabulated results for Espiritu Santo showing the shifts applied and the comparison after the shifts.

Espiritu Santo Topographic Analysis

Before

	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6	Site 7	Average
Average dz	-0.010	0.079	0.112	0.076	-0.076	0.11	0.231	0.075
Minimum dz	-0.042	0.029	0.078	0.060	-0.135	0.072	0.163	0.032
Maximum dz	0.021	0.104	0.170	0.090	-0.005	0.141	0.279	0.114
Average magnitude	0.016	0.079	0.112	0.076	0.076	0.11	0.231	0.100
Root mean square	0.019	0.081	0.114	0.076	0.084	0.111	0.233	0.103
Std deviation	0.016	0.019	0.017	0.009	0.036	0.015	0.031	0.020

After

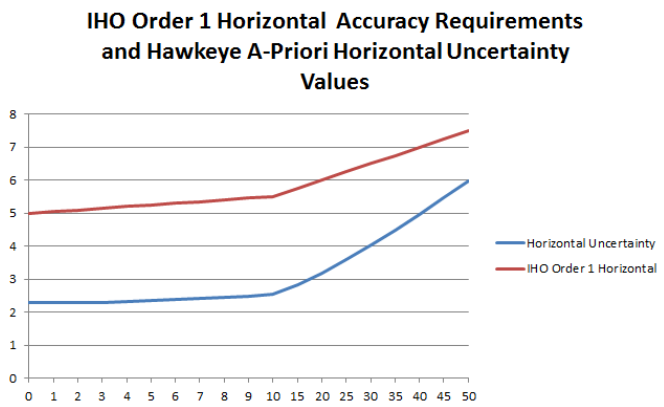
	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6	Site 7	Average
Average dz	-0.090	-0.001	0.032	-0.004	-0.156	0.03	0.151	-0.005
Minimum dz	-0.122	-0.051	-0.002	-0.020	-0.215	-0.008	0.083	-0.048
Maximum dz	-0.059	0.024	0.090	0.010	-0.085	0.061	0.199	0.034
Average magnitude	0.090	0.013	0.032	0.008	0.156	0.031	0.151	0.069
Root mean square	0.092	0.018	0.037	0.010	0.160	0.034	0.154	0.072
Std deviation	0.016	0.019	0.017	0.009	0.036	0.015	0.031	0.020

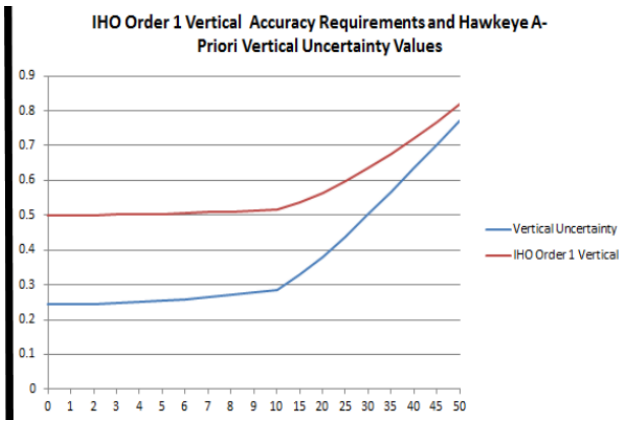
Bathymetric Post Survey Accuracy Report

Please find below the Total Propagated Uncertainty Model for the flight configuration of Hawkeye IIB utilised on the Geoscience Australia Contract G4098 for the bathymetric LiDAR capture over Espiritu Santo.

	5m	10m	20m	30m	40m
Horizontal Uncertainty	2.344	2.531	3.173	4.021	4.971
Vertical Uncertainty	0.255	0.285	0.381	0.502	0.634
Order 1 Horizontal Requirements	5.250	5.500	6.000	6.500	7.000
Order 1 Vertical Requirements	0.504	0.516	0.596	0.634	0.721

Provided by Applanix. Assumes a post-processed DGPS solution using a base station not more than 35km from the survey area
[1] Assumes a latency of 1ms and internal measurements of 2mm
[1] Uses output from POS PAC MMS iterated and verified by tape measure
[1] Assumes AHAB can record the angle to 0.001m
[1] Specification required by Pelydryn. May be better than this
[1] Discrepency between the Control Area and the LiDAR data. This correction may already include errors from the Sea Control Area
[1] Based on the wavelength of light measured at 1ms pulse duration
[1] Spot Position Uncertainty in x/y is made up of the diameter of the footprint on the sea bed, divided by 2 for multi pixelation
[1] The angle of incidence at the sea surface will cause the light to enter the water at a different angle, rather than that assumed when the sea is flat (Snell's Law). Conditions during the survey were very good with sea state remaining around SS1. This is considered to create at worse a 10 degree error in the assumed angle of incidence at the sea surface. Spot Position Uncertainty in z is made up of the difference between the depth assuming the beam has entered the water when flat, and the depth assuming the beam entered the sea when it was at an angle of 10 degrees. This value is the diameter of the footprint divided by 4, which assumes the pixel position is in the middle of a quadrant of the footprint. 'c' is derived using pythagorus (a2 + b2 = c2) where 'a' is the depth if the beam enters when the sea is flat, and 'b' is a quarter of the total footprint. This value is then calculated again for when the sea surface is angled at 10 degrees to the incoming laser beam to give a second value of 'c' (c2). The vertical error is the delta between 'c' and 'c2'.





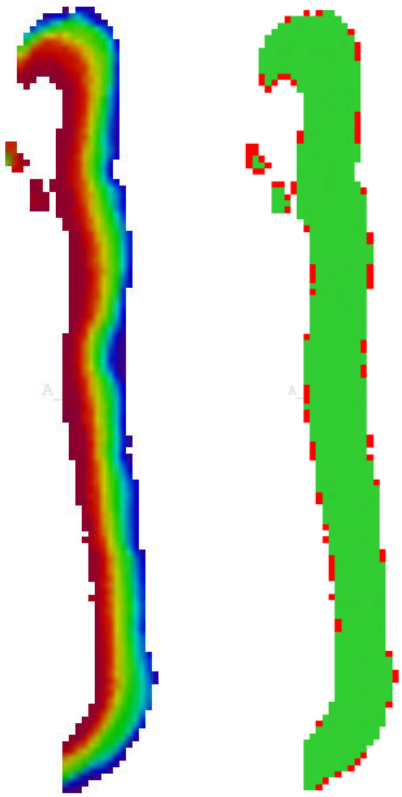
Bathymetric Post Survey Density Report

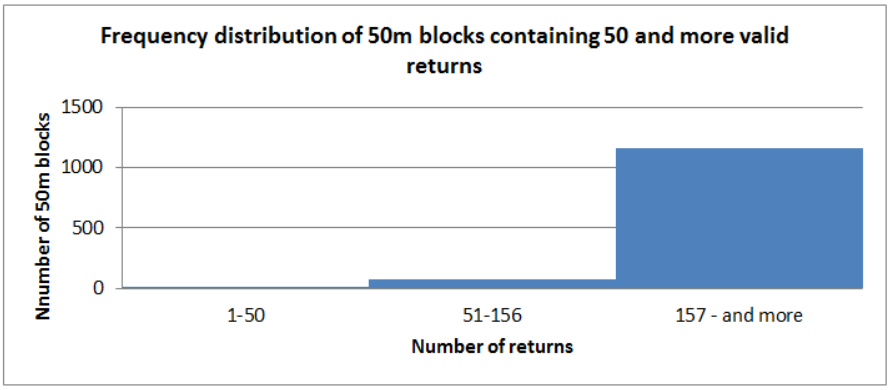
The data collected meets the requirements of the contract and the data acceptance criteria provided by Geoscience Australia. The following density results were achieved on the final processed data:

The following graphics show the data density coverage for each block in Espiritu Santo. The first image in each is data coloured by depth. The second image represents data coloured by density within 50x50m blocks. Green represents blocks with 50 and more returns, and red less than 50 returns. A Histogram plot is also shown for each block showing distribution of data density.

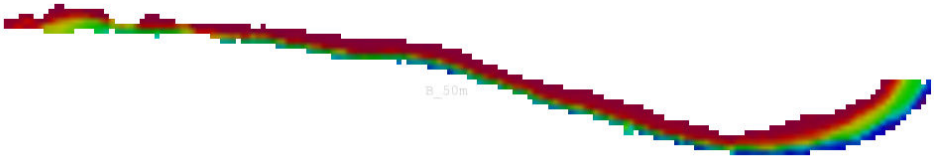
Santo Bathymetric Survey Density *(85% of all 50m x 50m shall contain 50 or more soundings)*	
Area A	93%
Area B	86%
Area C	83%
Area D	91%
Area E	89%
Area F and F1	90%
Area G	91%
Area M	92%
Area N	91%
Total Area	90%

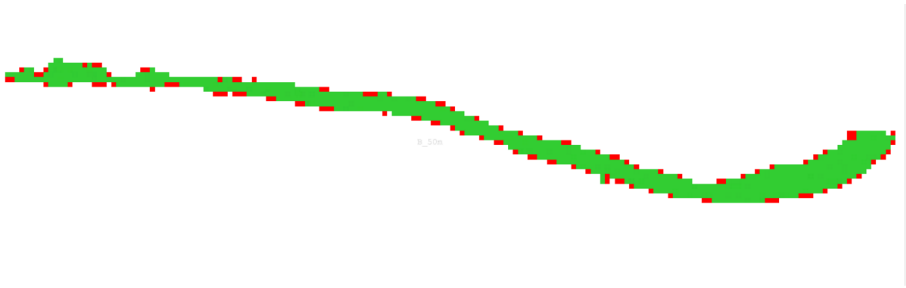
BLOCK A

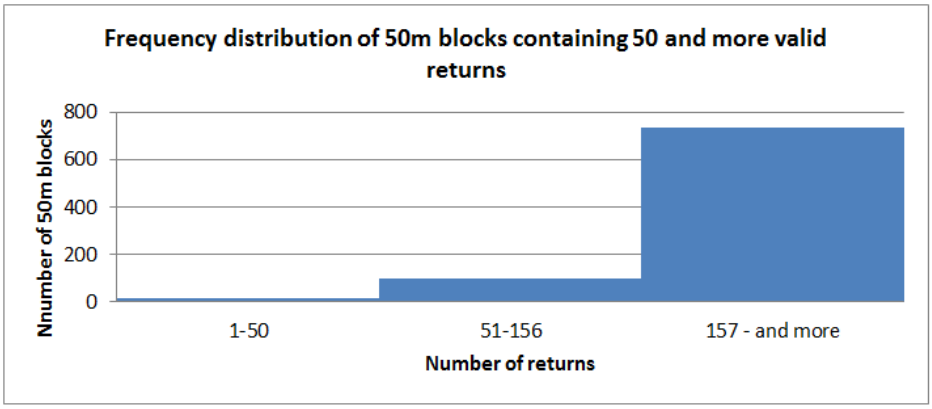



Frequency distribution of 50m blocks containing 50 and more valid returns
Nnumber of 50m blocks
1500
1000
500
0
1-50
51-156
157 - and more
Number of returns

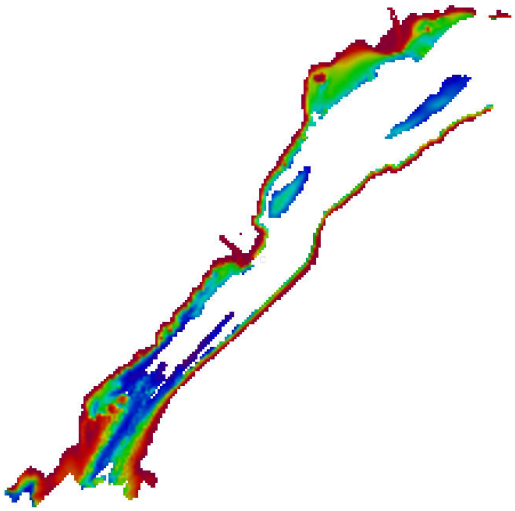
Block B

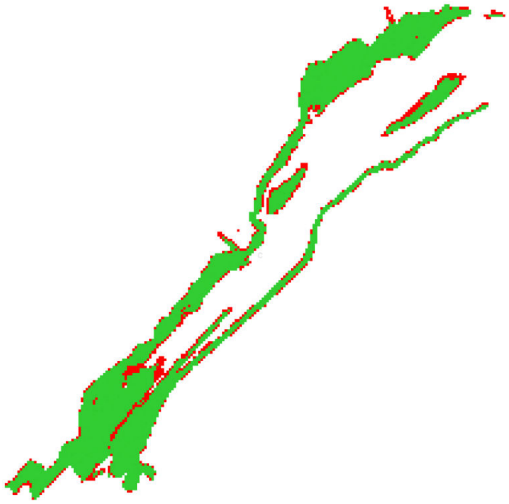


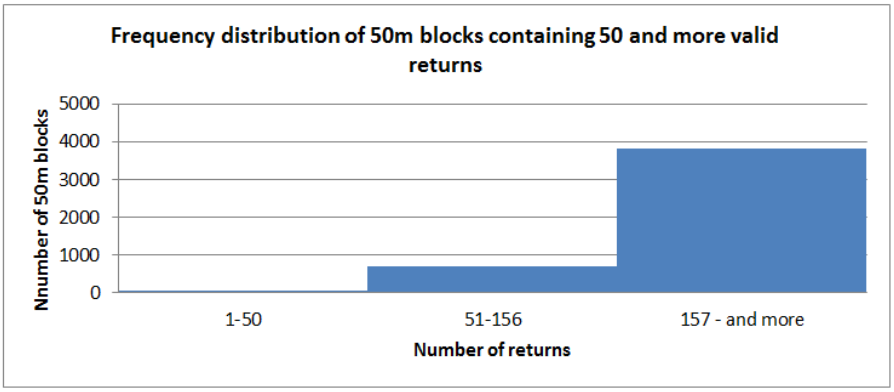



Frequency distribution of 50m blocks containing 50 and more valid returns
Nnumber of 50m blocks
800
600
400
200
0
1-50
51-156
157 - and more
Number of returns

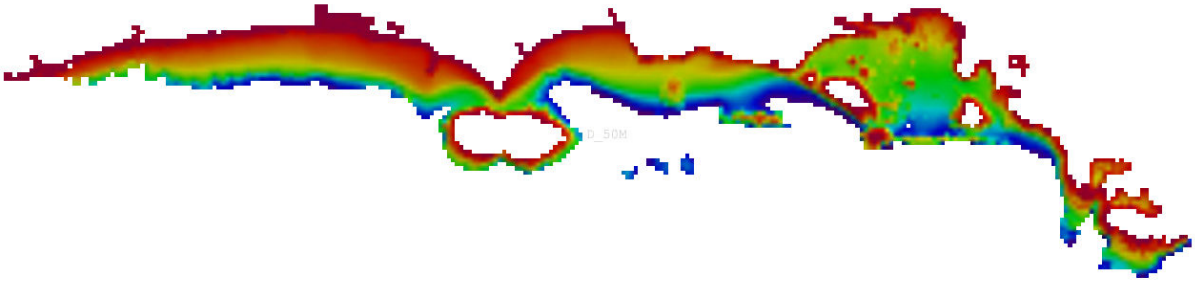
Block C

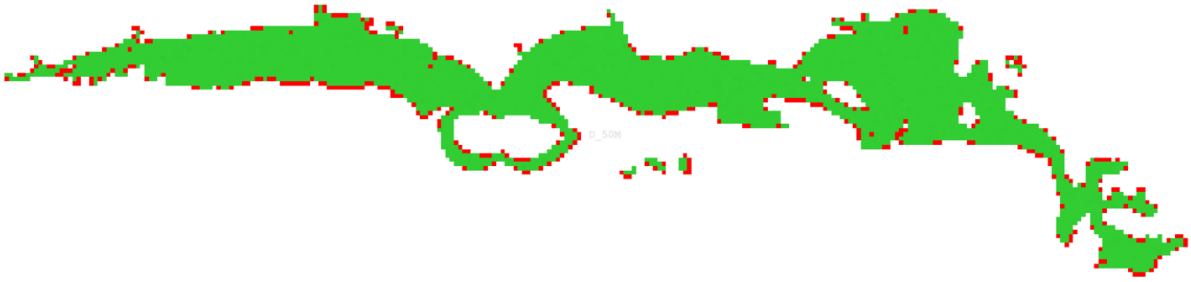


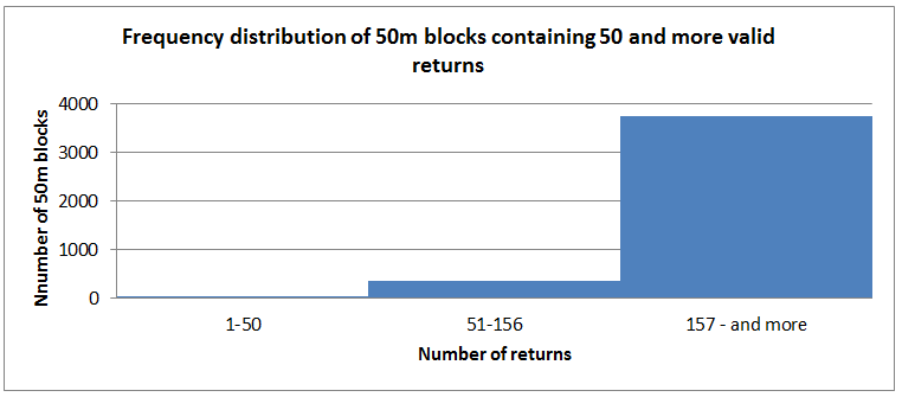




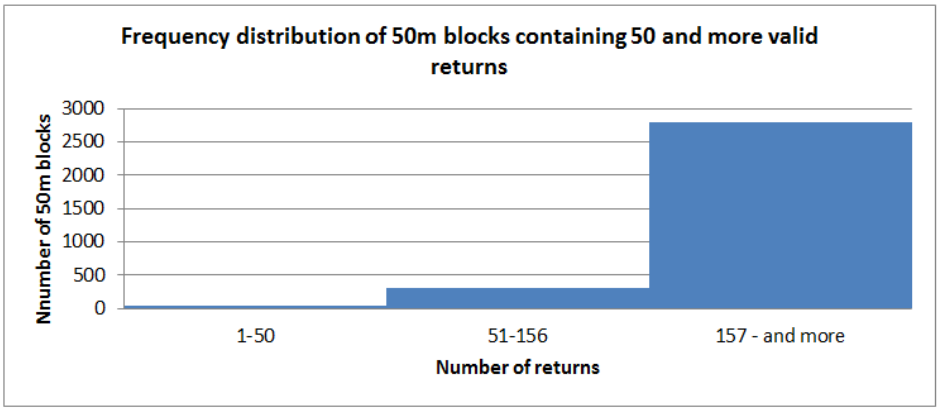
Block D






Frequency distribution of 50m blocks containing 50 and more valid returns
Nnumber of 50m blocks
4000
3000
2000
1000
0
1-50
51-156
157 - and more
Number of returns

Block E



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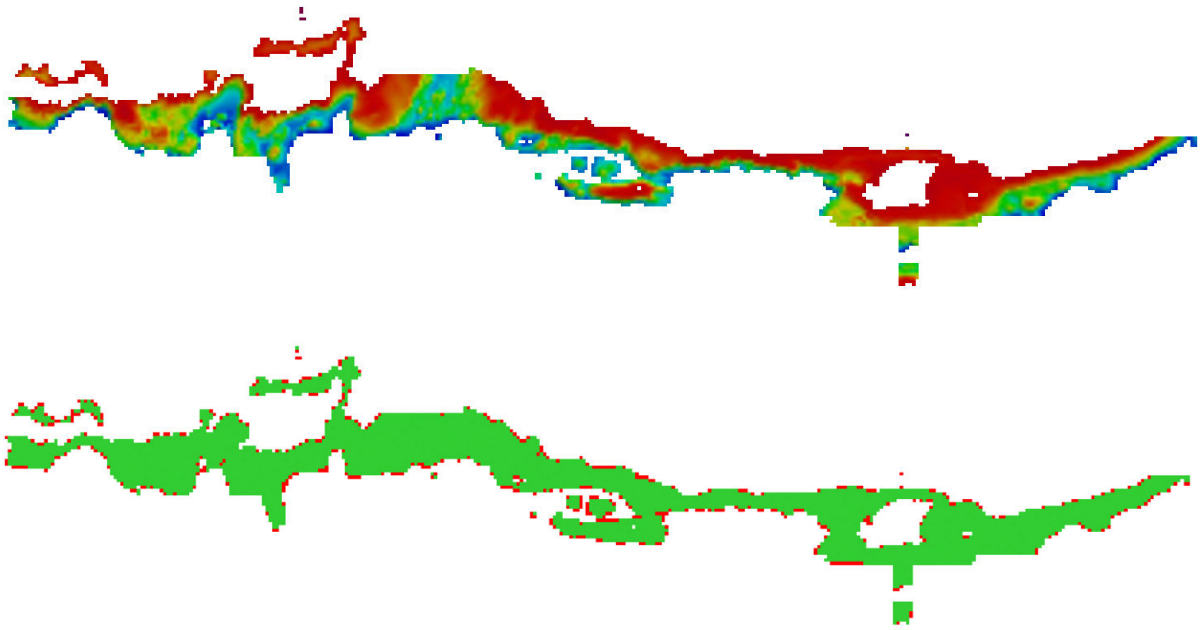
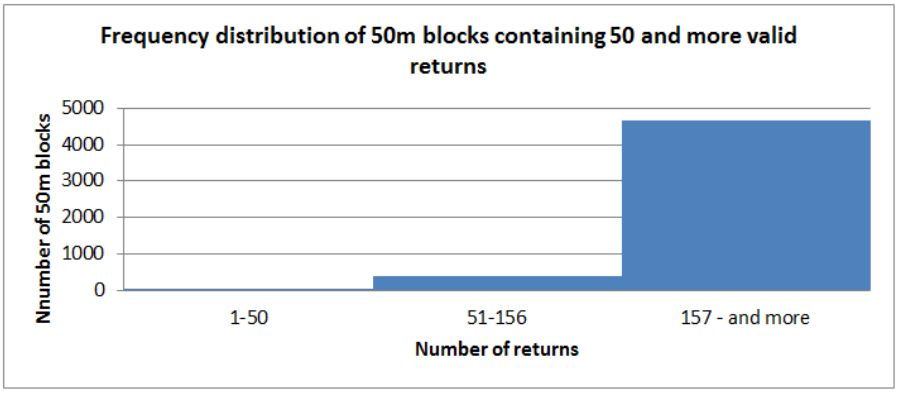
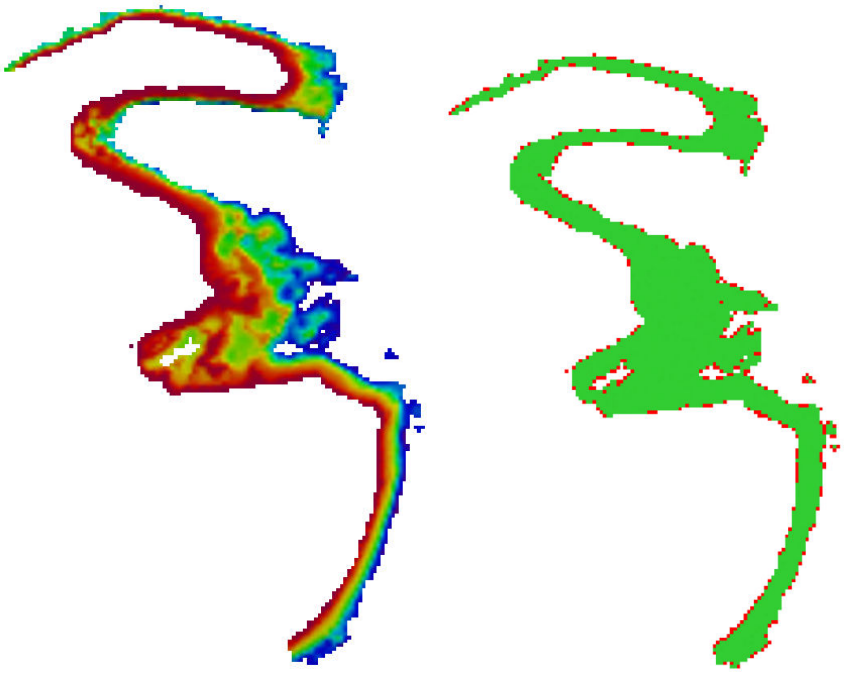
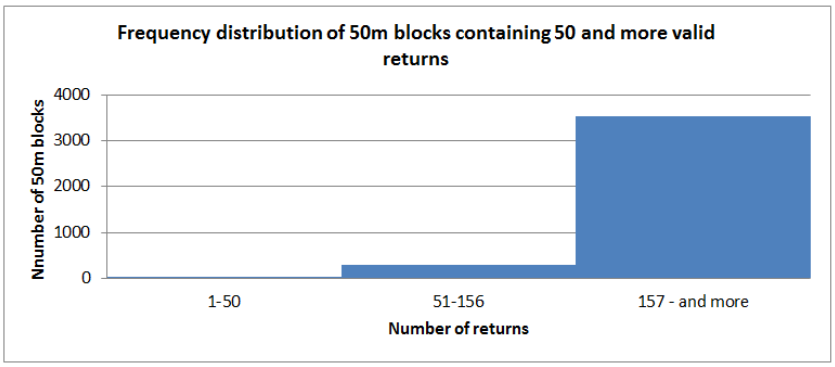


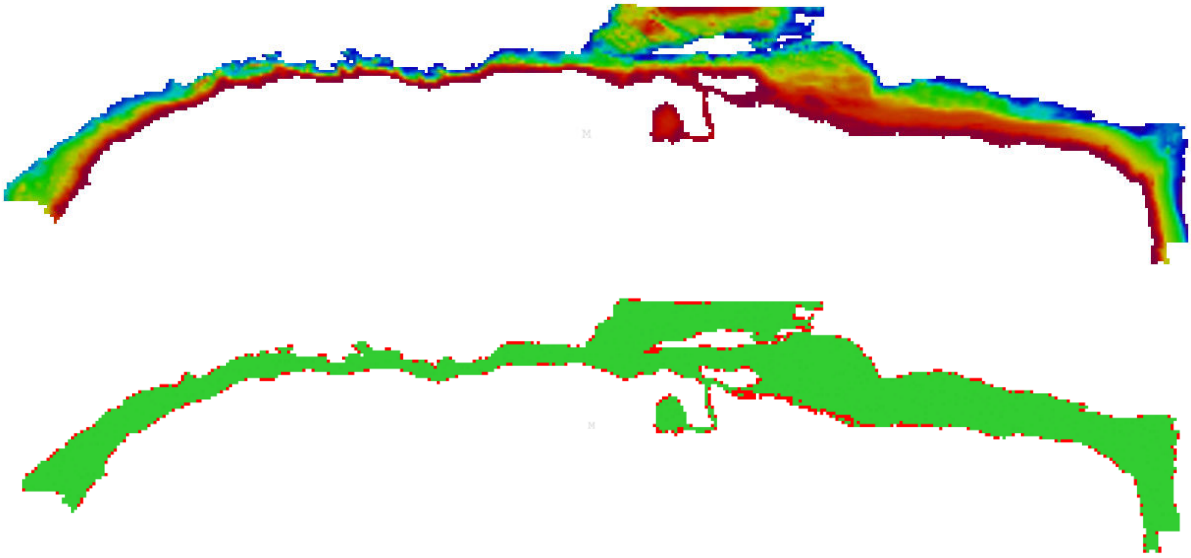


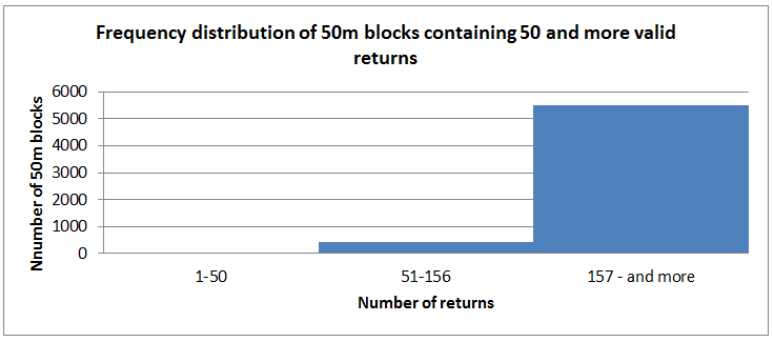
Block G



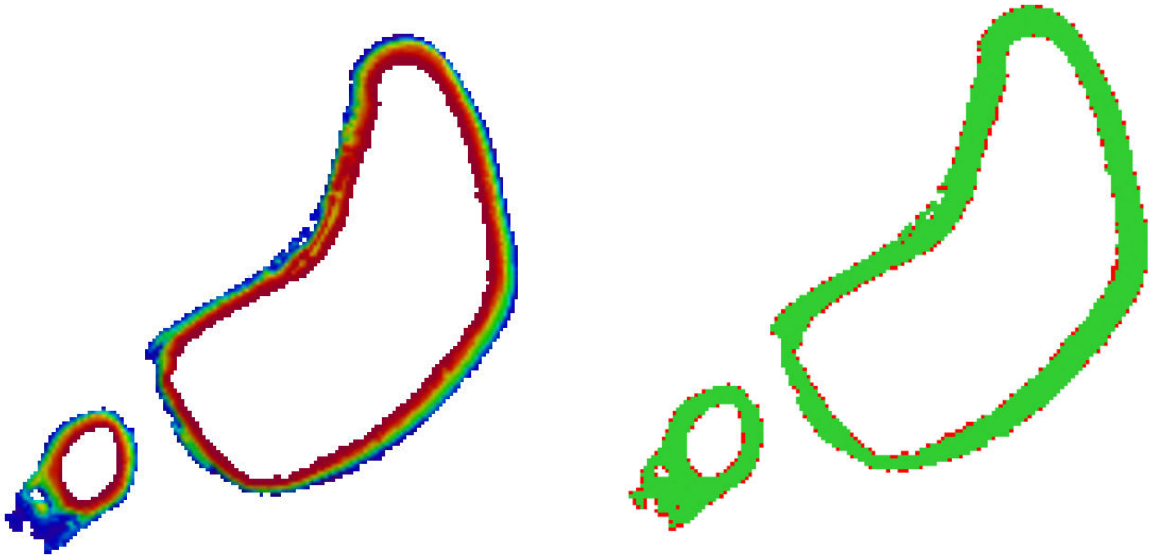


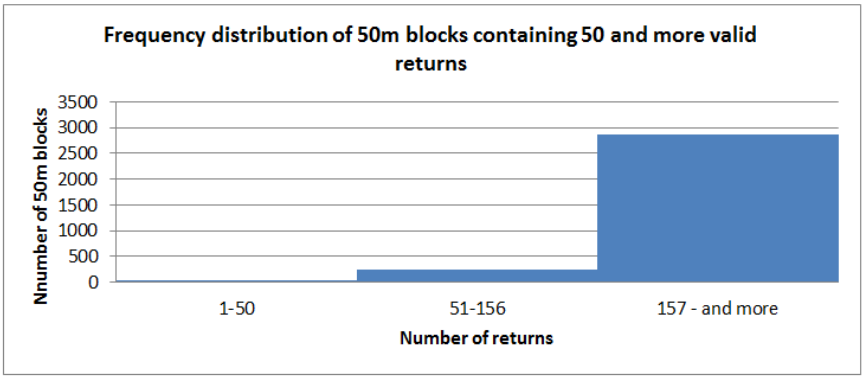
Block M




Frequency distribution of 50m blocks containing 50 and more valid returns
Nnumber of 50m blocks
6000
5000
4000
3000
2000
1000
0
1-50
51-156
157 - and more
Number of returns

Block N




Frequency distribution of 50m blocks containing 50 and more valid returns
Nnumber of 50m blocks
3500
3000
2500
2000
1500
1000
500
0
1-50
51-156
157 - and more
Number of returns

Establishment of MSL from Tide Gauge Observations

MSL Introduction

In order to verify the accuracy of the EGM 2008 model or any adjustments to the vertical heights, the GeoScience Australia RFP directed that a number of tidal stations were to be recovered across the Vanuatu Island chain in order to establish any height differences between the 1'x1' EGM 2008 model and local Mean Sea Level. Following evaluation of the areas to be surveyed the following sites were identified:

- Main Wharf – Port Vila, Efate
- Emua Jetty, Efate
- Lits Lits Jetty, Malekula
- Luganville, Espiritu Santo

A tidal station was to be recovered/established at each site and sufficient observations were undertaken to allow several Mean Sea Level (MSL) observations to be made in order to establish any height differences. Any differences observed would be applied to the acquired topographic and bathymetric survey data in order to provide a seamless Digital Elevation Model.

Tidal Regime

Examination of existing tidal records revealed that the tidal regime is primarily semi-diurnal with a diurnal inequality evident. This results in a tidal regime that has two highs and two low waters a day, but one of these cycles will be a higher high and low water.

Tidal Ranges are generally small with an average range of around 1.0-1.5m.

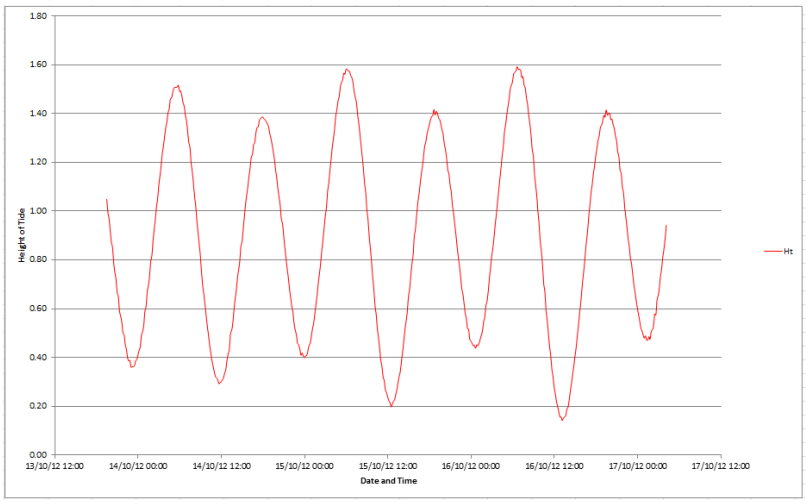


Figure 4.4 - Sample Tidal Curve Showing Tidal Regime

Recovery of Mean Sea Level

Surveyors have traditionally attempted to measure heights relative to MSL, which was thought to be a close approximation to the Geoid, and so it has become standard practice for authorities to evaluate MSL for a selected tide gauge and to relate the datum of all future levelling to this particular plane.

However a number of factors can cause variations in this level on a recurring cycle due to currents, water density changes, atmospheric pressure and winds. To determine a true mean sea-level, measurements must be made over long periods of time in order to average tidal variations. However, no matter how long a period of data is averaged, the true MSL is unattainable because changes are taking place over short and long time scales.

The results in this report are therefore a snapshot of levels based on an arithmetic average using the Low Pass Doodson Filter over 39 hour periods to remove diurnal and higher frequency tidal features.

The following methodology was used to recover/establish tide stations at each of the four locations identified:

- A GPS Benchmark was established adjacent to each tidal station using a minimum of 2 but ideally 6 hours of observations with a Dual Frequency GNSS Receiver. Static points were processed by AAM using the AUSPOS processing facility and the final co-ordinates were derived from a Network Adjustment of all points observed.
- For temporary tide stations a 2m tidepole and tidegauge sensor were co-located at a suitable point on the jetty with the zero of the pole set at a level below the lowest expected tide and as close to LAT as possible.
- The tidepole was levelled to the GPS Benchmark and in the case of Main Wharf in Port Vila to the local benchmark network.
- A 13 hour comparison was undertaken to confirm the correct operation of the gauge and to determine the relationship between the pole and gauge. Readings were taken at least every 30 minutes and at 10 minute intervals 1 hour either side of High and Low Waters.
- For the two temporary tide stations the gauges were left in-situ for periods in excess of 5 days.
- Regular 39hr Mean Sea Level Checks were undertaken to determine the value of MSL related to the ellipsoid.
- The averaged values for MSL at each site was compared with the EGM2008 value to establish the difference between the Geoid model and local Mean Sea Level to determine a revised orthometric height and correction to be applied to all data to adjust it from the ellipsoid to MSL.

Luganville Pier - EspirituSanto

A tidal station was required to support bathymetric and topographic operations on the island of Espiritu Santo. Following deployment to the island, no suitable location was found to establish a temporary tide station. However, a VegaPULS radar sensor had previously been established at one of the piers in Luganville (15° 30.943’ S 167° 11.374’ E), which had been set to approximately tide gauge zero at Port Vila.

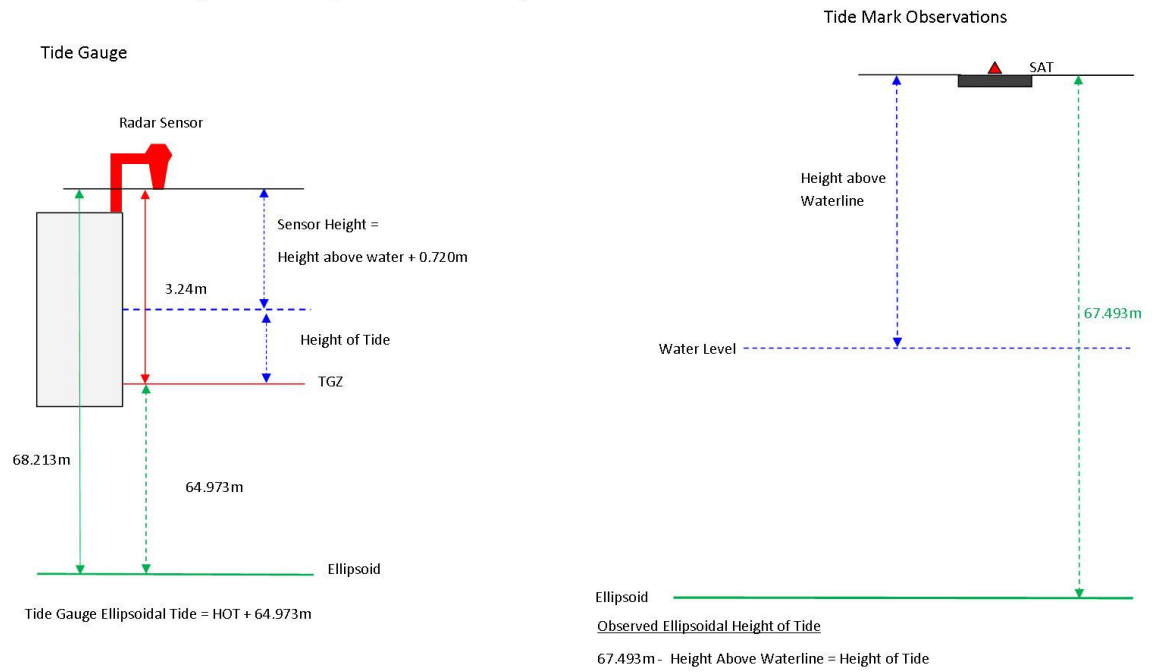
Figure 5 Location of Luganville Tide Station

The decision was taken to establish two GPS Benchmarks (both derived from 6 hour observations) adjacent to the site and using the ellipsoidal heights and measured offsets to the sensor establish an ellipsoidal value for Mean Sea Level.

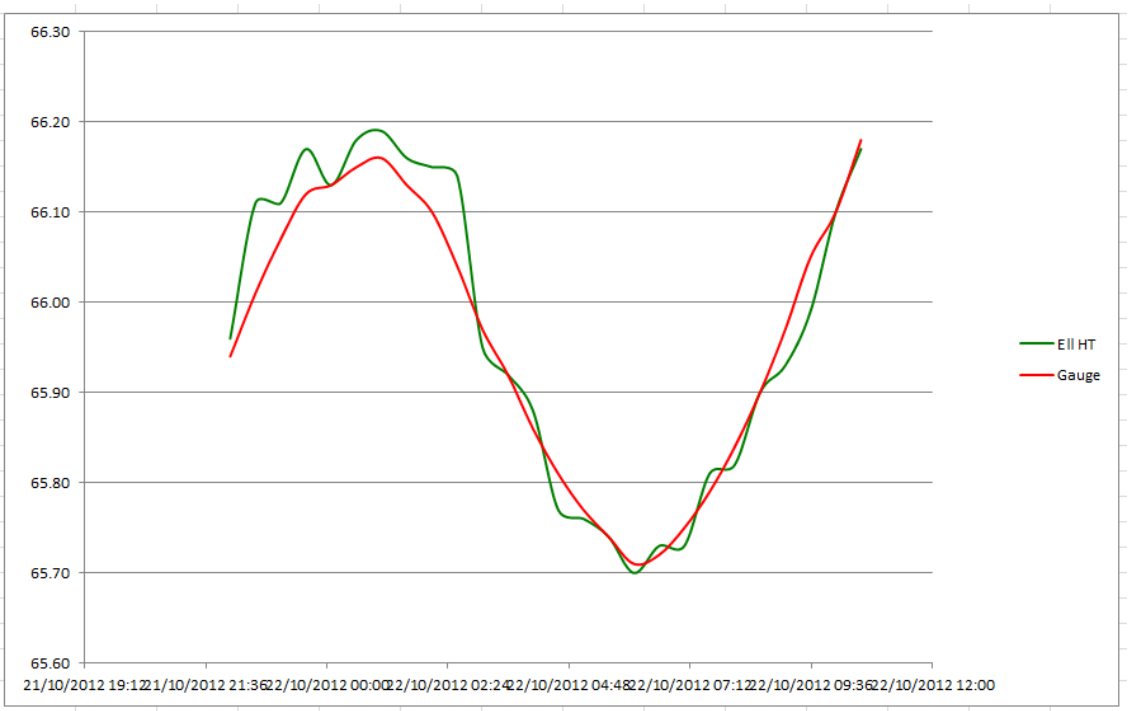
As the value of the tidegauge zero was not precisely defined it was decided to convert all tidal data to the ellipsoid and derive a Mean Sea Level on the ellipsoid. Due to the lack of a suitable point to insert a tidepole, a local mark was made adjacent to the radar gauge sensor and an offset measured to the face of the radar sensor. This mark was then levelled to the two benchmarks which had been established.

Tidal observations were undertaken by measuring from this mark down to the water's surface and subtracting this from the ellipsoidal mark to derive an ellipsoidal tide. In order to derive an ellipsoidal tide reading from the gauge it was first of all necessary to derive the Tide Gauge Zero. This was done by measuring the height of the sensor above the mark in order to establish an ellipsoidal height for the sensor. By adding the Sensor Height to the height above the waterline and the height of tide it was possible to calculate an average height of the sensor above the tide gauge zero. This height was then used to derive an ellipsoidal height reading to establish the local Tide Gauge Zero. Following analysis this was calculated to be 3.24m below the sensor.

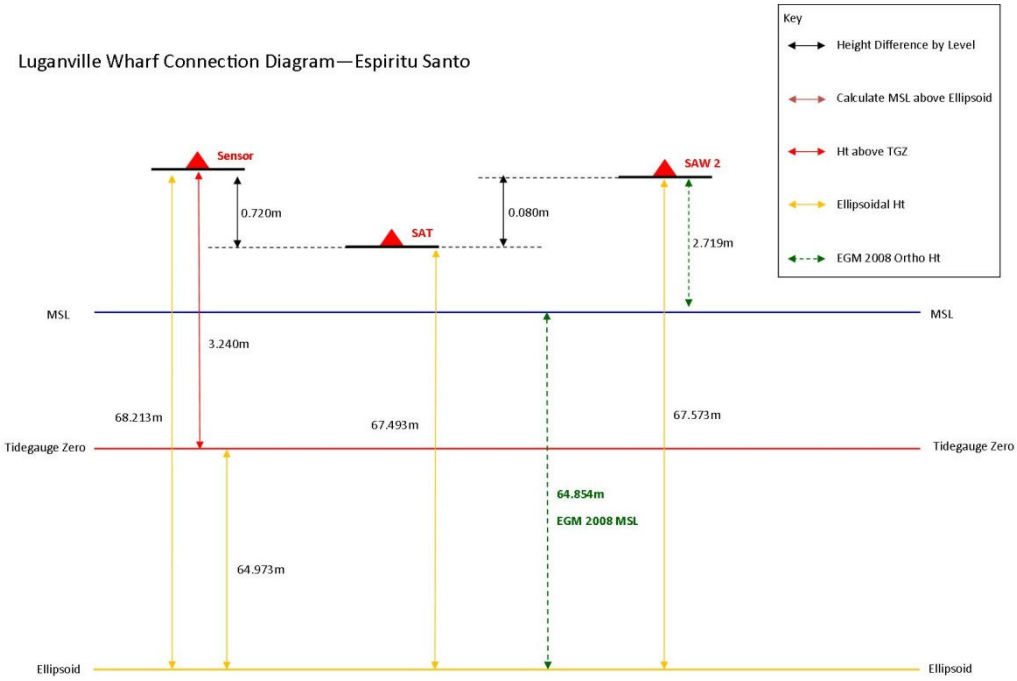
Calculation of Ellipsoidal Height of Tide — Luganville



A 13 hour comparison was conducted between the radar gauge and local mark. Weather conditions were poor at the start with a scend of 0.2m making accurate readings difficult, but as conditions improved the quality of the reading improved with far closer agreement seen.



Following processing of the GPS station the following connections were established:



The gauge is continuously operating and the values are available from the NTF website. Data was downloaded for the period 06 October to 27 November 2012. Tidal Observations were reduced to the ellipsoid based on the sensor height.

Having averaged the values the ellipsoid-geoid separation value was calculated as 65.885m. Mean Sea Level was 0.893m above the zero of the gauge. It is considered the values obtained give a good indication of the Mean Sea Level at Luganville.

Mean Sea Level Comparisons

Comparison with EGM2008 Values

During processing of all of the GPS Benchmarks, orthometric heights were calculated using the 1'x1' EGM 2008 mark. As a result it was possible to calculate the ellipsoid to geoid (MSL) value for these points. These points were then compared with the derived values and the differences established as can be seen in the table below:

Station	Ellipsoidal Height	EGM 2008 Geoid-Ellipsoid Separation Value	Calculated Separation Value based on MSL	Difference between EGM 2008 and Observed MSL Separation Values
saw1	67.635	64.855	**65.885**	**-1.030**
saw2	67.573	64.854	**65.885**	**-1.031**

Comparison with Existing MSL Data

In order to validate the Mean Sea Level Values calculated through the use of Short Period Observations a comparison was made of the readings at Port Vila against longer period observations held by the South Pacific Sea Level Climate Monitoring Project (SCSLCMP). As all of the other island Mean Sea Level values were in close agreement with Port Vila Mean Sea Level, it was felt that this comparison validates all of the results. Several epochs of data were downloaded to allow averages to be calculated from yearly, monthly and year to date values with the following results.

Comparison with Annual MSL Values	Mean Sea Level (m)	Observed Mean Sea Level (m)	Difference
2010	0.899	0.904	+0.005
2011	0.919		-0.015
2012 (to Oct)	0.905		+0.001
2010-2012	0.908		-0.004

A further comparison was done against the monthly values of 2012 (to Oct) with the following results.

Comparison with 2012 Monthly MSL Values	Mean Sea Level (m)	Observed Mean Sea Level (m)	Difference
January	0.952	0.904	-0.048
February	0.883		+0.021
March	0.909		-0.005
April	0.853		+0.051
May	0.878		+0.026
June	0.916		-0.012
July	0.899		+0.005
August	0.933		-0.029
September	0.940		-0.036
October	0.890		+0.014
Sum of 2012	0.906		-0.002

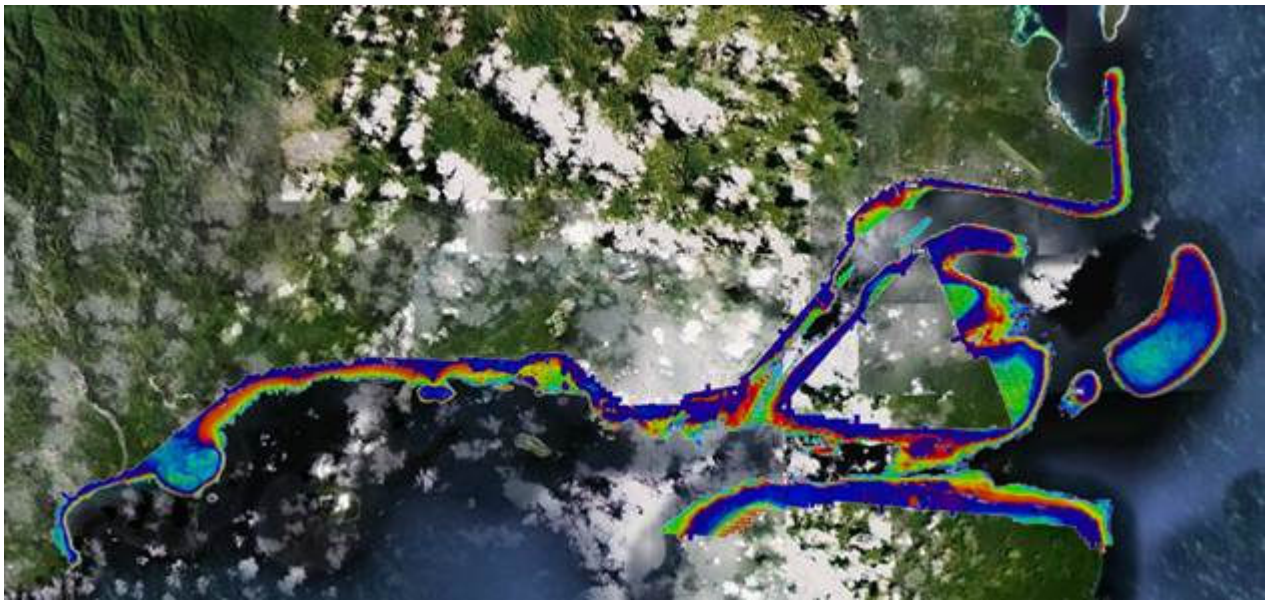
Analysis of this data sees a larger variation in the values on a month by month basis and this is accepted to be a result of seasonal variations in climate. However the values are consistent and show that the calculated Mean Sea Level has been established correctly.

It is assessed that following analysis of the data that the Mean Sea Level Values obtained are accurate to 0.004m when compared to the last 3 years of tidal records at Port Vila. These differences seen are within the likely range of accuracies as stated in The International Oceanographic Commissions Manual on Sea Level Measurement and Interpretation and it is recommended that the values derived are used to reduce ellipsoidal data to MSL.

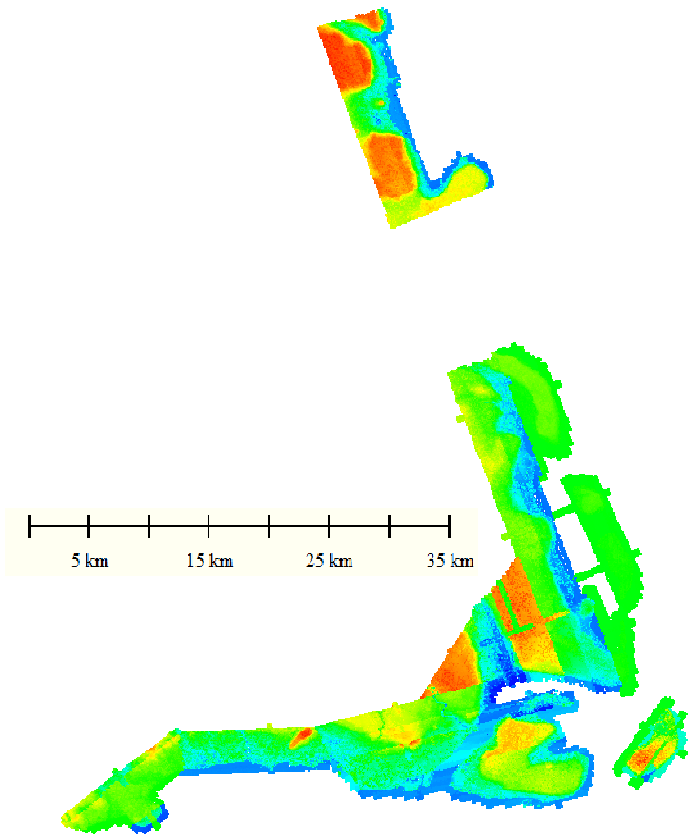
The results obtained are a good indicator of the differences between the EGM 2008 and local orthometric height datum and should be used to correct the data. It is assessed that the MSL values are accurate to +/- 0.004m with only average differences of 0.05m seen during the period of observations and analysis. The insertion of temporary GPS benchmarks at Luganville will allow a local connection to be derived and allow the data from the gauge to be more fully analysed.

Validation Plots for LiDAR

Espiritu Santo Bathymetric LiDAR Capture



Espiritu Santo Topographic Elevation



Geodetic Survey Report

The Geodetic Survey Report is presented as a separate document. The Geodetic Survey Report is presented along with this document in terms of **20076A_Geodetic_Survey_Report_Dec12_Rev01.**