FINAL PROJECT REPORT - EFATE

RFQ Number: RFTGA 2012/2863

AAM Project Number: 20076A

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

Account Manager: Brett O'Hagan

Project Manager: Martin Tunwell

Document Control			
Process Stage	Who	Role	When
Draft V1 Prepared by	Martin Tunwell	Project Manager, AAM	Mar2013
Final Version 1	Martin Tunwell	Project Manager, AAM	Mar2013
Final Version 2	Martin Tunwell	Project Manager, AAM	May2013

Table of Contents

1.0 Introduction 3
2.0 Contract Specifications Confirmed 4
2.1 Category of Elevation Capture and Laser Flight Settings 4
2.2 Topographic Coverage 5
2.3 Horizontal Datum 5
2.4 Vertical Datum 5
2.5 Map Projection 7
2.6 Survey Control 7
2.7 Data Tiling and File naming 8
2.8 Digital Elevation Model (DEM) 12
2.9 Digital Surface Model (DSM) 12
2.10 Canopy Elevation Model (CEM) 12
2.11 Foliage Cover Model (FCM) 12
2.12 Contours 12
2.13 Bathymetric Datasets 12
2.14 Imagery 13
2.15 Project Plan 13
2.16 Pre-survey Quality Assurance Plan 13
2.17 Post-survey Spatial Accuracy Report 14
2.18 GPS Base Station Data 14
2.19 GPS Base Station Data 14
3.0 Accuracy Assessment 15
3.1 Project Design Accuracy 15
3.2 Reference Site Analysis 15
3.3 Check Point Analysis 17
4.0 Metadata 19
4.1 General Capture Specifications 19
4.2 Source Data 19
4.3 Reference Systems 20
4.4 Limitations of Data 20
5.0 Extraordinary Issues 20
6.0 Other Project Information of Note 20
6.1 ANZLIC Metadata Statement 20
7.0 Bathymetric LiDAR Survey 21
7.1 Executive Summary 21
7.2 Narrative 23
7.3 Geodesy 25
7.4 Data Processing 38
7.5 Spatial Accuracy 43
7.6 Survey Analysis 46
7.6 Conclusion 62
8.0 Seamless Products Plan 63
9.0 Spatial Accuracy Report 64

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 was undertaken between September 11th and November 26th 2012. Rain, low cloud and other weather related challenges were faced in this aerial LiDAR survey.

AAM deployed its Optech ALTM Pegasus for this project. This sensor is 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 58/59. 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 EFATE DATASET. FURTHER FINAL REPORTS WILL BE PRODUCED FOR ESPIRITO SANTO ONCE DATA HAS BEEN CAPTURED.

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

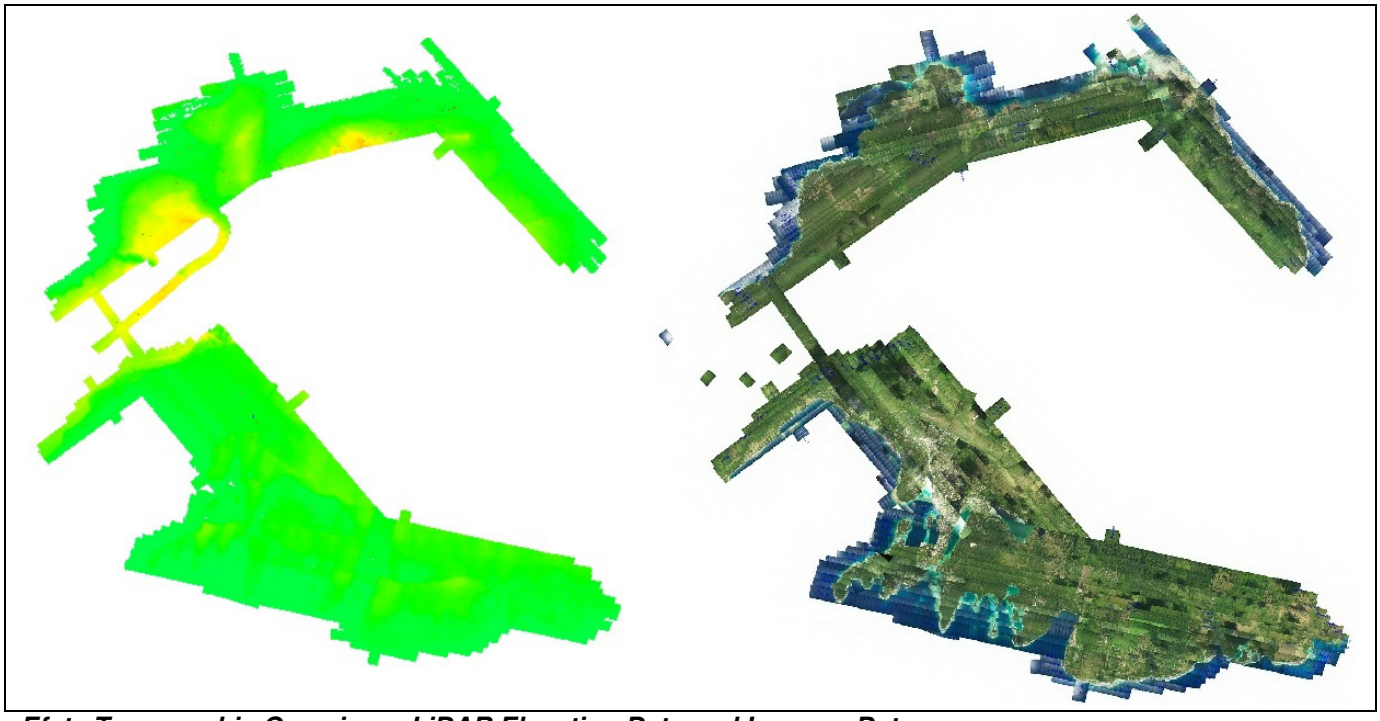
The Figure below displays the LiDAR system accuracy specifications as presented by Optech for the ALTM Pegasus.

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

Copyright Optech CA

2.2 Topographic Coverage

The area of interest on Efate covers an area of approximately 268sqkm.



Efate 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**

2.5 Map Projection

The survey data is presented in terms of ITRF2008 UTM zone 59.

2.6 Survey Control

The primary survey control point (GPS Base stations) was established at Port Villa on Efate.

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. In total 887 field survey points were collected across the Malekula lidar capture area.

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 8 groups across the Efate 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 Adjustment									
	Site								
	TIP1_MSL_121116	TIP2_MSL_121116	TIP3_MSL_121116	TIP4_MSL_121116	TIP5_MSL_121116	TIP6_MSL_121116	TIP7_MSL_121116	TIP8_MSL_121116	OVERALL
Average dz	0.583	0.504	0.576	0.651	0.639	0.724	0.678	0.616	0.621
Minimum dz	0.508	0.451	0.565	0.606	0.573	0.705	0.632	0.531	0.451
Maximum dz	0.673	0.558	0.592	0.725	0.670	0.767	0.862	0.787	0.862
Average magnitude	0.583	0.504	0.576	0.651	0.639	0.724	0.678	0.616	0.621
Root mean square	0.584	0.504	0.576	0.652	0.639	0.725	0.681	0.618	0.622
Std deviation	0.040	0.016	0.011	0.033	0.021	0.014	0.062	0.055	0.032
Average Dz Applied	-0.621								

After Adjustment									
	Site								
	TIP1_MSL_121116	TIP2_MSL_121116	TIP3_MSL_121116	TIP4_MSL_121116	TIP5_MSL_121116	TIP6_MSL_121116	TIP7_MSL_121116	TIP8_MSL_121116	OVERALL
Average dz	-0.041	-0.114	-0.044	0.031	0.019	0.104	0.058	-0.001	0.002
Minimum dz	-0.258	-0.169	-0.055	-0.014	-0.047	0.085	0.012	-0.089	-0.258
Maximum dz	0.053	-0.030	-0.028	0.105	0.050	0.147	0.242	0.224	0.242
Average magnitude	0.047	0.114	0.044	0.034	0.025	0.104	0.058	0.047	0.059
Root mean square	0.063	0.116	0.045	0.045	0.028	0.105	0.083	0.061	0.068
Std deviation	0.048	0.019	0.011	0.033	0.021	0.014	0.062	0.061	0.034
Average Residual Dz	0.002								

Land surveyed test points were assessed for accuracy before being used in the test point analysis and those shown to be outliers or inaccurate were excluded from the calculation. Points excluded are detailed in the below table.

Test Point Sites	Total Number of Test Points	Total Number of Test Points Used	Number of Excluded Test Points	Reason for Test Point Exclusion
TIP1	64	63	1	Sitting approximately 0.15m higher than all the other test points
TIP2	106	104	2	Sitting slightly lower than all the other test points
TIP3	7	7	0	-
TIP4	39	39	0	-
TIP5	29	29	0	-
TIP6	33	33	0	-
TIP7	11	11	0	-
TIP8	73	72	1	Sitting slightly lower than all the other test points

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
Efate_TIP1	Grass	47
	Grass Under Trees	36
Efate_TIP2	Grass Under Wooded Trees (10-12m)	11
	Shrubs(5m) Under Trees(10m)	8
Efate_TIP3	Grass/Bushes (1-5m)	21
	Low Shrubs/Grass Cover (0.5-1m)	78
Efate_TIP4	Grass Under Wooded Trees (10-12m)	10
	High Grass (1-2m)	24
	Sand Under Palms (4-10m)	27
Efate_TIP5	Grass (0.5-1m)	11
	Grass Under Trees (5m)	23
	Shrubs (2m)	18
	Shrubs(5m) Under Trees(10m)	13
	Trees (15m)	7
Efate_TIP6	Grass	32
	Grass (0.5-1m)	18
	Grass Under Wooded Trees (10-12m)	38
	High Grass (1-2m)	12
Efate_TIP7	Grass (0.5-1m)	38
	High Grass (1-2m)	36
Efate_TIP8	Grass	22
	Low Shrubs/Grass Cover (0.5-1m)	28

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:

Area	Removed Offset Value	Landcover Class	No of Points	Mean Difference (m)	Std Deviation (m)	RMS (m)
Efate_TIP1	-0.0388	Grass	47	0.017	0.033	0.037
		Grass Under Trees	36	-0.005	0.035	0.035
Efate_TIP2	-0.1158	Grass Under Wooded Trees (10-12m)	11	0.120	0.128	0.171
		Shrubs(5m) Under Trees(10m)	8	0.128	0.109	0.164
Efate_TIP3	0.0437	Grass/Bushes (1-5m)	20	0.197	0.128	0.233
		Low Shrubs/Grass Cover (0.5-1m)	78	0.074	0.111	0.133
Efate_TIP4	-0.0314	Grass Under Wooded Trees (10-12m)	10	0.041	0.096	0.100
		High Grass (1-2m)	23	0.235	0.136	0.270
		Sand Under Palms (4-10m)	27	-0.003	0.043	0.042
Efate_TIP5	-0.0212	Grass (0.5-1m)	11	0.06	0.023	0.064

		Grass Under Trees (5m)	23	-0.013	0.052	0.052
		Shrubs (2m)	17	0.207	0.048	0.212
		Shrubs(5m) Under Trees(10m)	13	0.068	0.084	0.105
		Trees (15m)	7	0.046	0.035	0.056
Efate_TIP6	-0.1044	Grass	32	0.005	0.014	0.015
		Grass (0.5-1m)	18	0.073	0.049	0.087
		Grass Under Wooded Trees (10-12m)	37	0.145	0.183	0.150
		High Grass (1-2m)	12	0.389	0.129	0.409
Efate_TIP7	-0.0401	Grass (0.5-1m)	38	0.214	0.095	0.233
		High Grass (1-2m)	36	0.138	0.097	0.168
Efate_TIP8	0.0114	Grass	22	0.024	0.023	0.033
		Low Shrubs/Grass Cover (0.5-1m)	28	0.076	0.069	0.102

Landcover Class	Within ±0.30m	Outside ±0.30m	No of Points	% Within ±0.30m	% Outside ±0.30m
Grass	101	0	101	100.00	0.00
Grass Under Trees	36	0	36	100.00	0.00
Grass Under Wooded Trees (10-12m)	55	2	57	96.49	3.51
Shrubs(5m) Under Trees(10m)	21	0	21	100.00	0.00
Grass/Bushes (1-5m)	14	6	20	70.00	30.00
Low Shrubs/Grass Cover (0.5-1m)	102	4	106	96.23	3.77
High Grass (1-2m)	52	19	71	73.24	26.76
Sand Under Palms (4-10m)	27	0	27	100.00	0.00
Grass (0.5-1m)	57	10	67	85.07	14.93
Grass Under Trees (5m)	23	0	23	100.00	0.00
Shrubs (2m)	17	0	17	100.00	0.00
Trees (15m)	7	0	7	100.00	0.00

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	Optech ALTM Pegasus
IMU Used	SAGEM FMU
Acquisition Start Date	11/09/2012
Acquisition End Date	26/11/2012
Number of Runs	101
Number of Cross Runs	7
Flight Direction	Variable
Flying Height (AGL)	700m
Half Scan Angle	20
Swath Width	509
Sidelap	30%
Average Point Spacing	0.32
Laser Pulse Rate	250KHZ
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 59
System Calibration Certification	20th June 2012

4.2 Source Data

Source Data				
Item	**Source**	**Description**	**Ref No**	**Date**
Laser System	AAM	ALTM-Pegasus	20076A	11/09/12-26/11/12
GPS Base Data	AAM	Static GPS	20076A	11/09/12-26/11/12
Base Stn Coords	AAM	Total Station	20076A	11/09/12-26/11/12
Field Survey Data	AAM	RTK & Total Station	20076A	11/09/12-26/11/12

4.3 Reference Systems

	Horizontal	Vertical
Datum	ITRF2008	MSL
Projection	UTM Zone 59	N/A
Geoid Model	N/A	Tide Gauge Calculated
Villa Primary Base (Airport)	Efate Airport 215602.397E 8040986.833N	Efate Airport 17.594 RL
Wharf 1 (POVI)	Port Villa Wharf 213718.036 8034663.940N	Port Villa Wharf 2.550 RL
Wharf 2 (Emua)	Emua Wharf 222519.661E 8059165.356N	Emua Wharf 1.642 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.

Figure 1: 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. The impact on data quality is discussed more fully in Section 4.
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

The survey area in Efate was divided into 5 main blocks as shown in the graphic below (Figure 2);

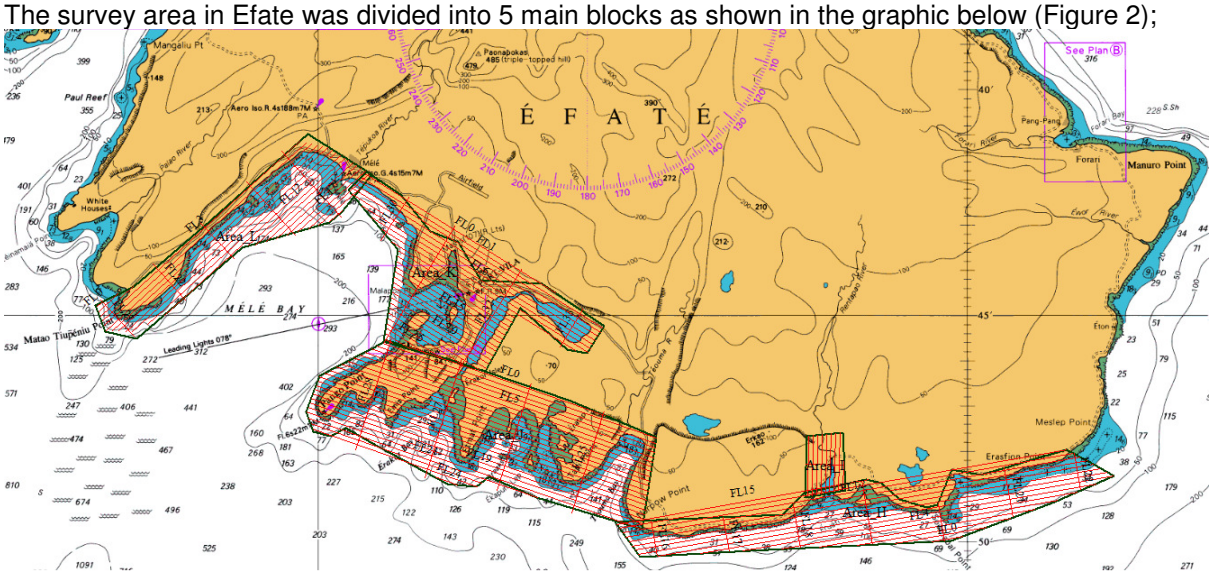


Figure 2: Survey Area Overview Efate

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.

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.

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. An existing tidal station was 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.

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.

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 59 (S) Projection.

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

Projection System EFATE	
Projection	Transverse Mercator
Grid Details	UTM Grid Zone 59 South
Central Meridian (CM)	171° 00’ 00” E
Latitude of Origin	000° 00’ 00”N
False Easting	500,000.000
False Northing	10000000
Scale Factor on CM	0.9996

Table 2: 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 Table 3 below:

Base Station Name		

Bauerfield Airport	**Latitude**	**17° 41' 59.79798" S**
	Longitude	**168° 19'07.76854" E**
	Altitude	**82.696m**

Table 3: Base Station Co-Ordinates

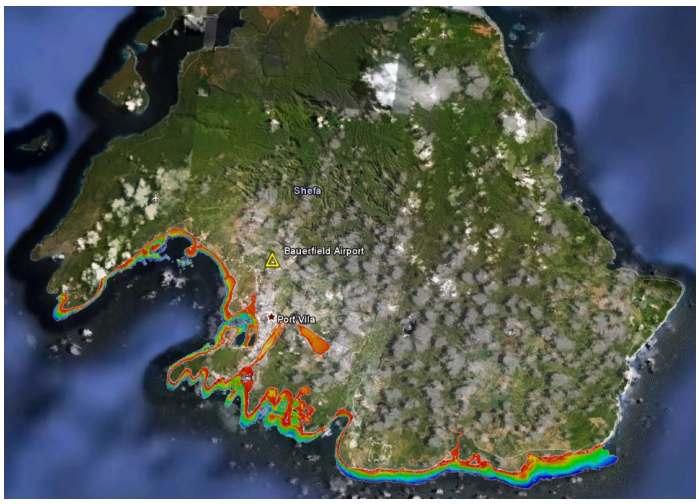


Figure 3: Position of GNSS Base Station Efate.

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.

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

Table 4: 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

Table 5: 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. Figure 4 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.

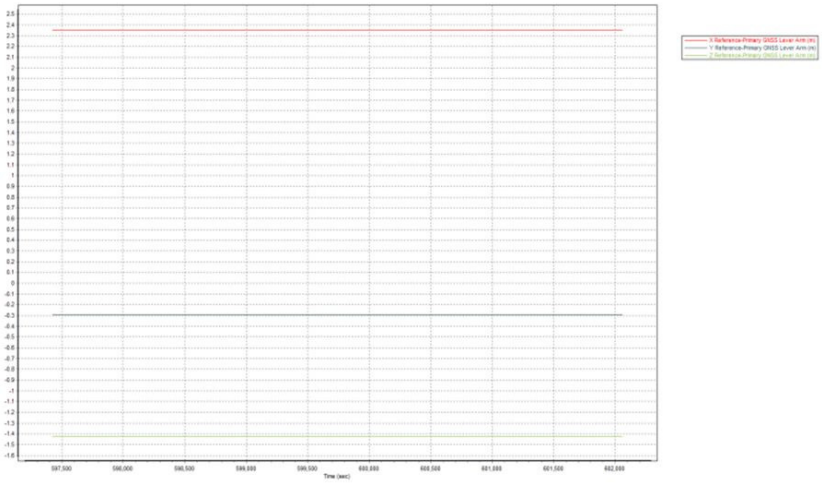


Figure 4: Lever Arms Checks in POSPAC MMS

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. A sample output is in Figure 5, along with a sample comparison in the positions at Table 6.

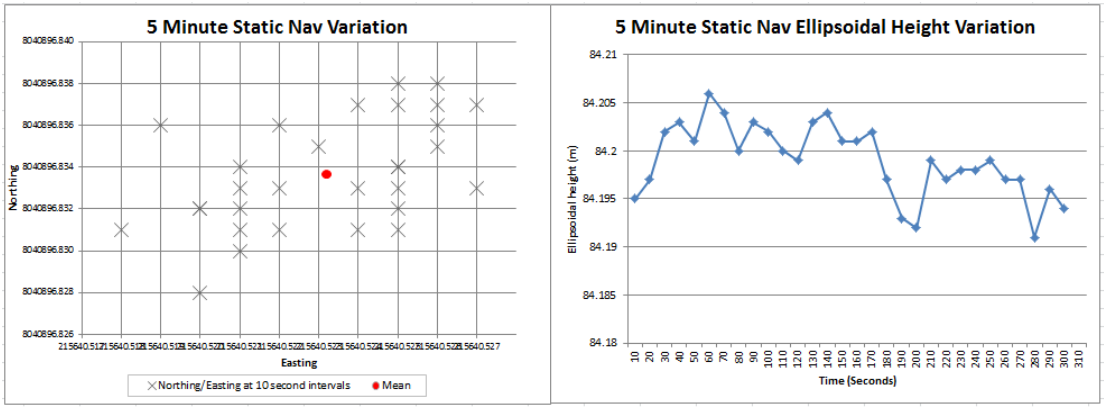


Figure 5: Typical Static Navigation Check Results

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

Table 6: Example Results from Analysis of Static Validation.

System Repeatability Check

Efate

A single area in the approaches to Port Vila Bay was used as a local Sea Control Area during survey operations (see **Figure 6**). As required by normal operating procedures, the Sea Control Area was overflown at the start and end of each flight to check the calibration of the system and ensure that there was no system 'drift' in the calibration values. Data from the calibration flight was used to compile a high resolution surface from the lines flown. Data from each subsequent sortie was processed and checked each day against this surface to ensure that the system was providing consistent results.

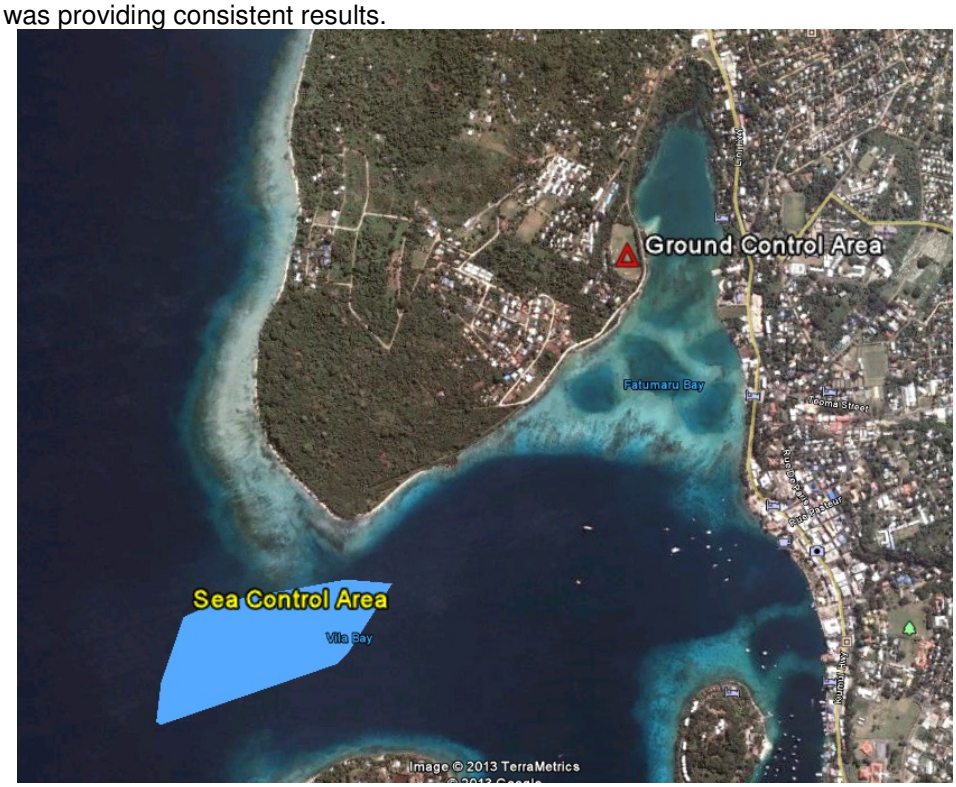


Figure 6: Efate Sea Control Area.

Following data processing, a surface comparison was conducted in CARIS and TerraSolid to analyse the quality of the data.

Examination of the selected area allows the user to see if any drift is developing in the system's calibrations values. Due to the varying conditions experienced with water visibility, the results may vary slightly, but the check provides a continual check on errors and performance.

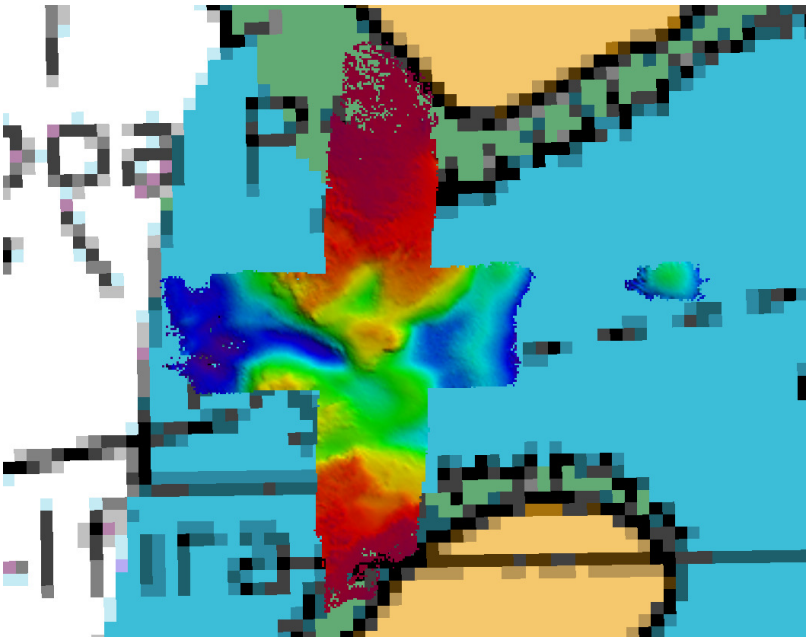


Figure 7: Dynamic Navigation Check Area with flat and sloping seabed highlighted (black boxes).

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

20121031_070401_SCA_FL000_2135990_Flightline 0_HD_exported
20121031_070401_SCA_FL001_0770897_Flightline 1_HD_exported
20121031_200643_SCA_FL000_8031250_Flightline 0_HD_exported
20121031_221305_SCA_FL000_1521347_Flightline 0_HD_exported
20121101_052853_SCA_FL000_3612170_Flightline 0_HD_exported
20121101_070317_SCA_FL000_8633381_Flightline 0_HD_exported
20121101_195912_SCA_FL000_6938993_Flightline 0_HD_exported
20121101_212250_SCA_FL000_0685445_Flightline 0_HD_exported
20121102_193806_SCA_FL000_0070497_Flightline 0_HD_exported
20121102_224741_SCA_FL000_8966338_Flightline 0_HD_exported
20121103_192624_SCA_FL000_8297677_Flightline 0_HD_exported
20121104_192901_SCA_FL000_7444074_Flightline 0_HD_exported
20121104_205124_SCA_FL000_4507278_Flightline 1_HD_exported
20121105_194616_SCA_FL000_1901913_Flightline 0_HD_exported
20121105_235708_SCA_FL000_1210364_Flightline 0_HD_exported
20121107_235540_SCA_FL000_4255500_Flightline 0_HD_exported
20121108_030150_SCA_FL000_1573534_Flightline 0_HD_exported
20121111_025911_SCA_FL000_7445295_Flightline 0_HD_exported
20121111_061502_SCA_FL000_8340708_Flightline 0_HD_exported
20121111_212238_SCA_FL000_1379131_Flightline 0_HD_exported
20121112_000859_SCA_FL000_7267067_Flightline 1_HD_exported
20121113_055545_SCA_FL000_2797631_Flightline 0_HD_exported
20121113_071942_SCA_FL000_7268898_Flightline 0_HD_exported

Table 7: List of Lines flown over Efate Sea Control Area.

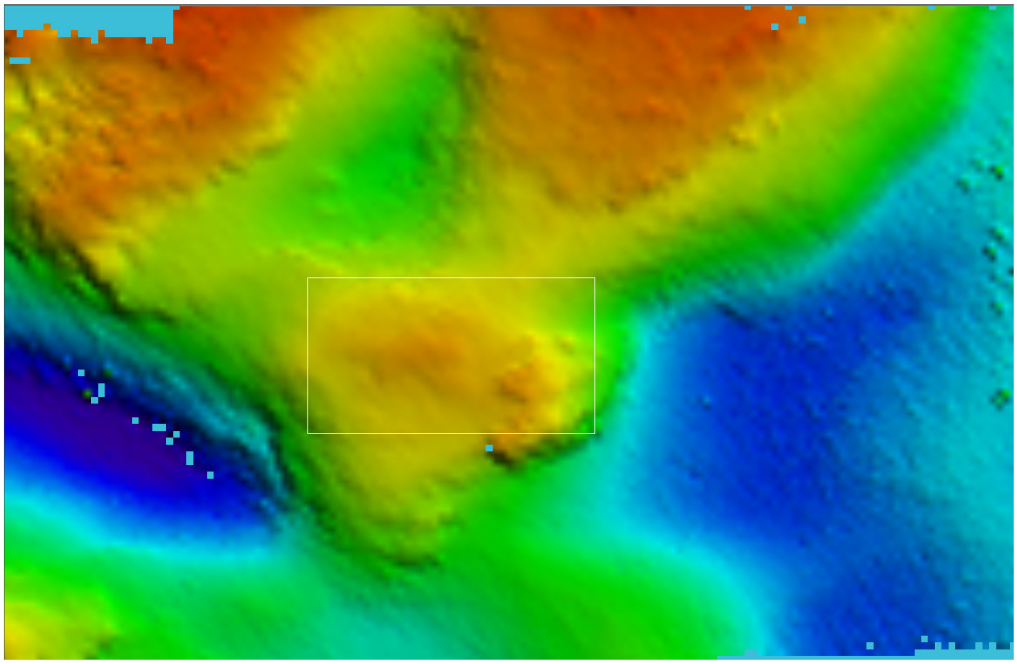


Figure 8: Close up of Efate Verification Area.

Figures 10 illustrates a cross section of the surfaces used for the dynamic checks

Repeatability Check Location
Long/Lat: 17.74043844 E/168.293260 S
Number of returns: 23904
Dimensions: 125/68m

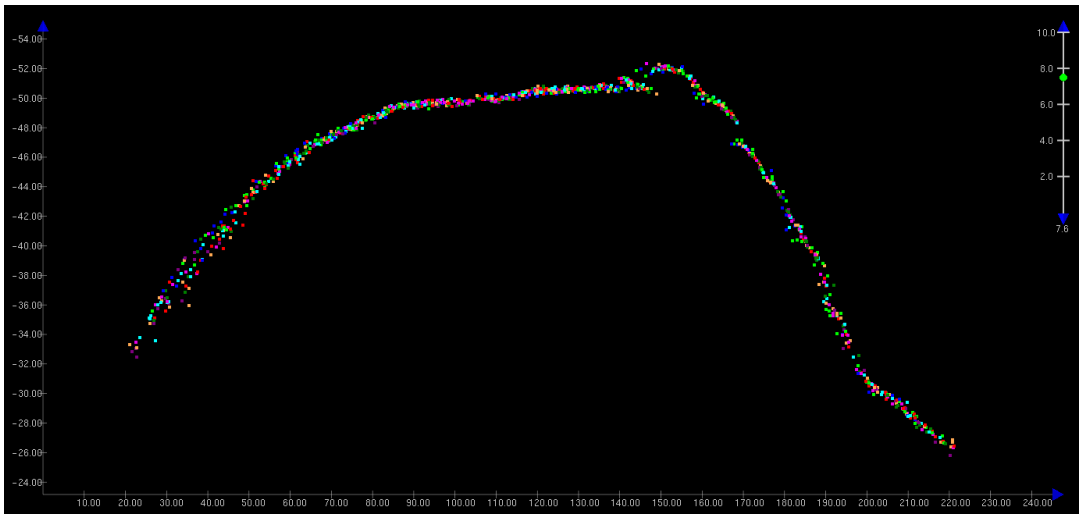


Figure 9: Area 1 Cross Section Efate

Figure 10 and Table 8 shows the statistical analyses of all lines subsequently flown over the Dynamic Check Area.

Area 1	Average dz	Std Deviation
Date	Metres	
20121031_200643	-0.083	0.361
20121031_221305	-0.012	0.33

20121101_052853	-0.068	0.319
20121101_070317	0.023	0.335
20121101_195912	0.018	0.329
20121101_212250	0.052	0.343
20121102_193806	-0.11	0.409
20121102_224741	-0.031	0.46
20121103_192624	0.079	0.354
20121104_192901	-0.051	0.355
20121104_205124	0.092	0.393
20121105_194616	-0.038	0.329
20121105_235708	0.011	0.339
20121107_235540	-0.041	0.368
20121108_030150	-0.016	0.336
20121111_025911	-0.117	0.344
20121111_061502	0.007	0.341
20121111_212238	-0.058	0.33
20121112_000859	-0.046	0.446
20121113_055545	-0.084	0.332
20121113_071942	0.001	0.35
Average	**-0.02247619**	**0.357286**

Table 8: Summary of Repeatability Checks Efate

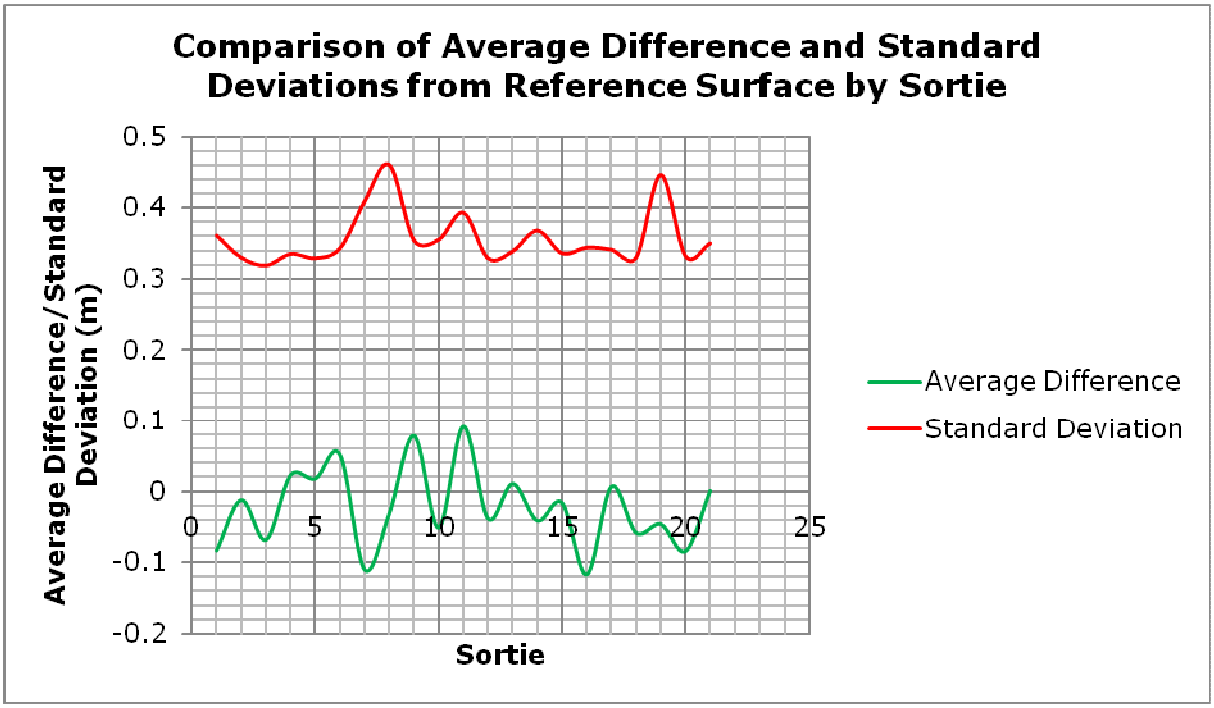


Figure 10: Statistical Results of Efate Dynamic Repeatability Check.

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 coastal fringes of the Southern side of the Island of Efate between Matao Tiupeniu Point and Erasfion Point (Figure 2) 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.

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. The calibration and validation results indicate that the HawkEye IIb system was operating within specified parameters and achieved the required accuracy for the survey.

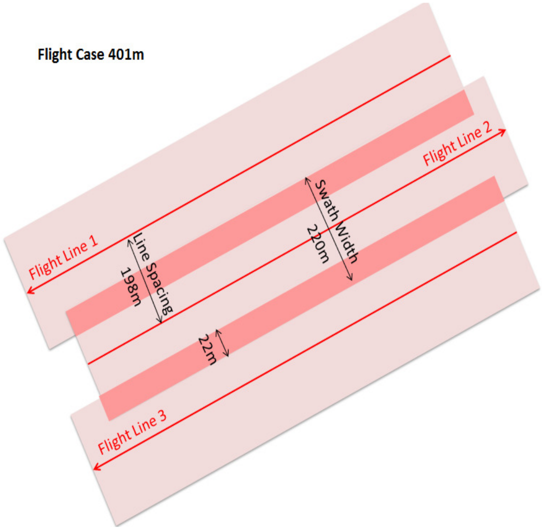
Survey Parameters

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 59/58
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

Table 9: 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 will be 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

Figure 11: Flightcase 401 Details.

Efate Survey Configuration

Efate Survey Configuration

Mission Name: Efate			
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:	120	**Total Line Length:**	921km

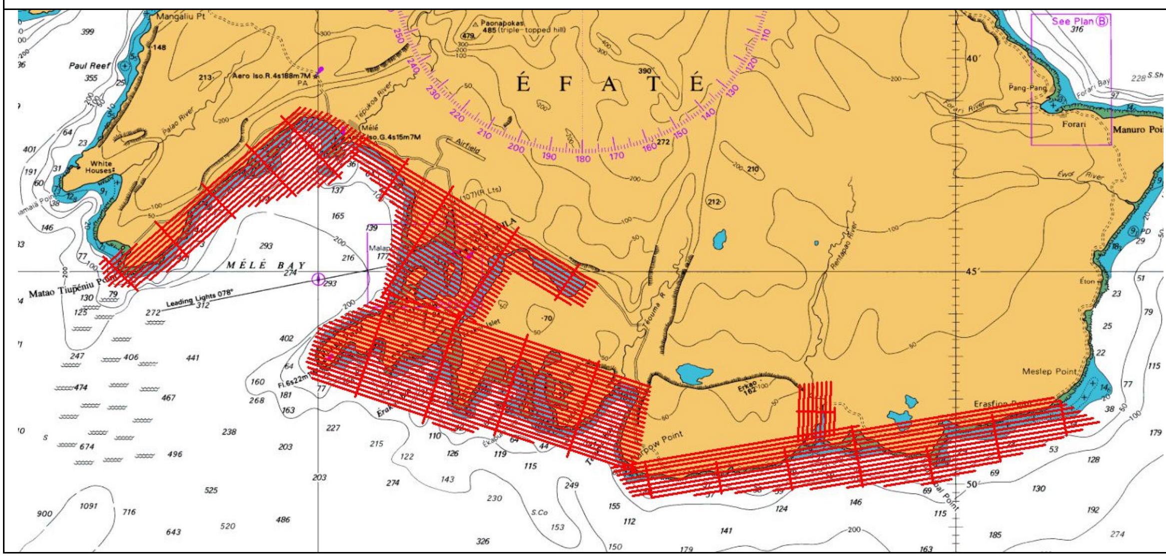


Figure 12: Efate Line Planning Information.

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 Table 10). 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
Efate	0.11-0.21	0.09-0.20	-1.9 - -1.0	-1.9- -1.00

Table 10: 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 Operations

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.

Figure 13: Low Cloud along the coastline.

Sun Glint

Sun glint is a known issue with bathymetric LiDAR and line direction is wherever possible 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.

Figure 14: 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.

Figure 15: 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 (Figure 16), 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 (Figure 16). 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.

Figure 16: 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 (Figure 17). Changes in the colour of the seawater can also impact on the quality of the return.

Figure 17: 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.

Figure 18: 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. **Figure 19** 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.

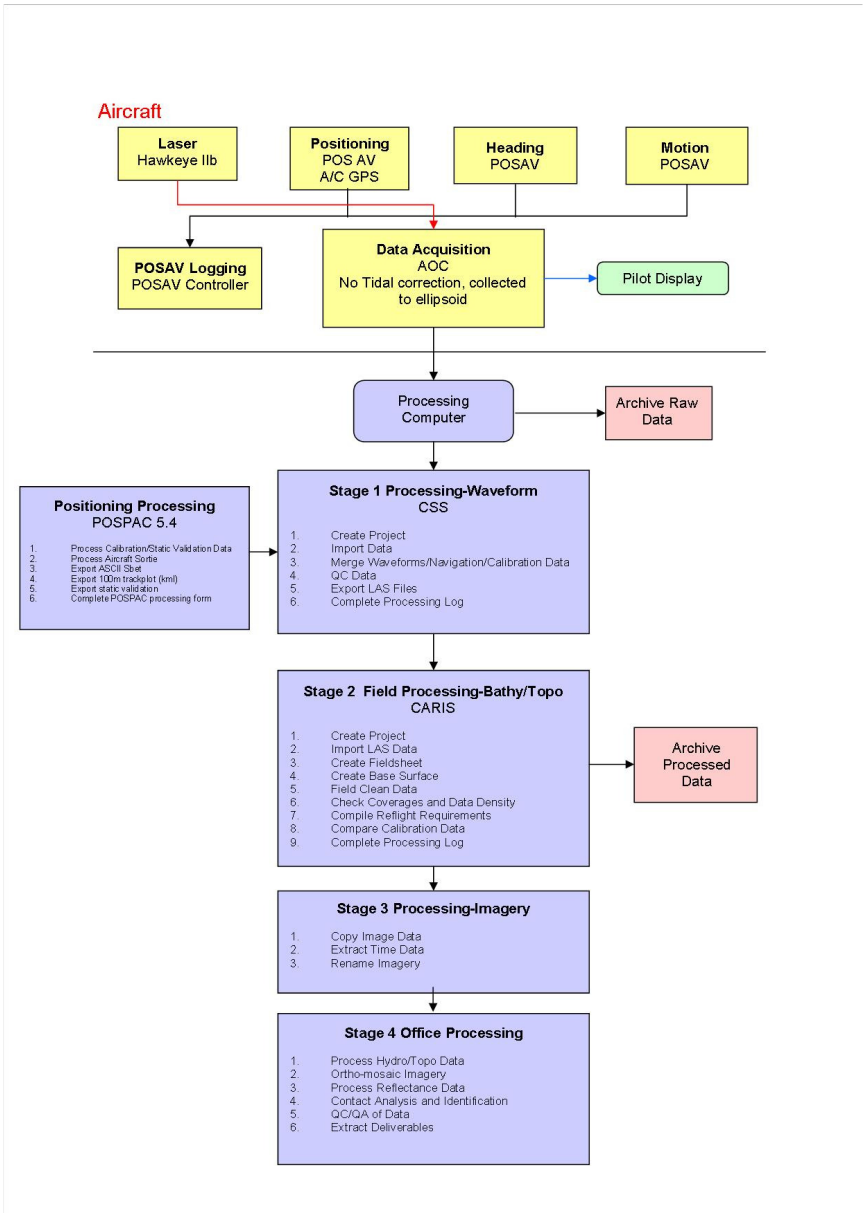


Figure 19: Processing Workflow for Vanuatu

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.
A summary of typical processing parameters is in **Figure 20**.

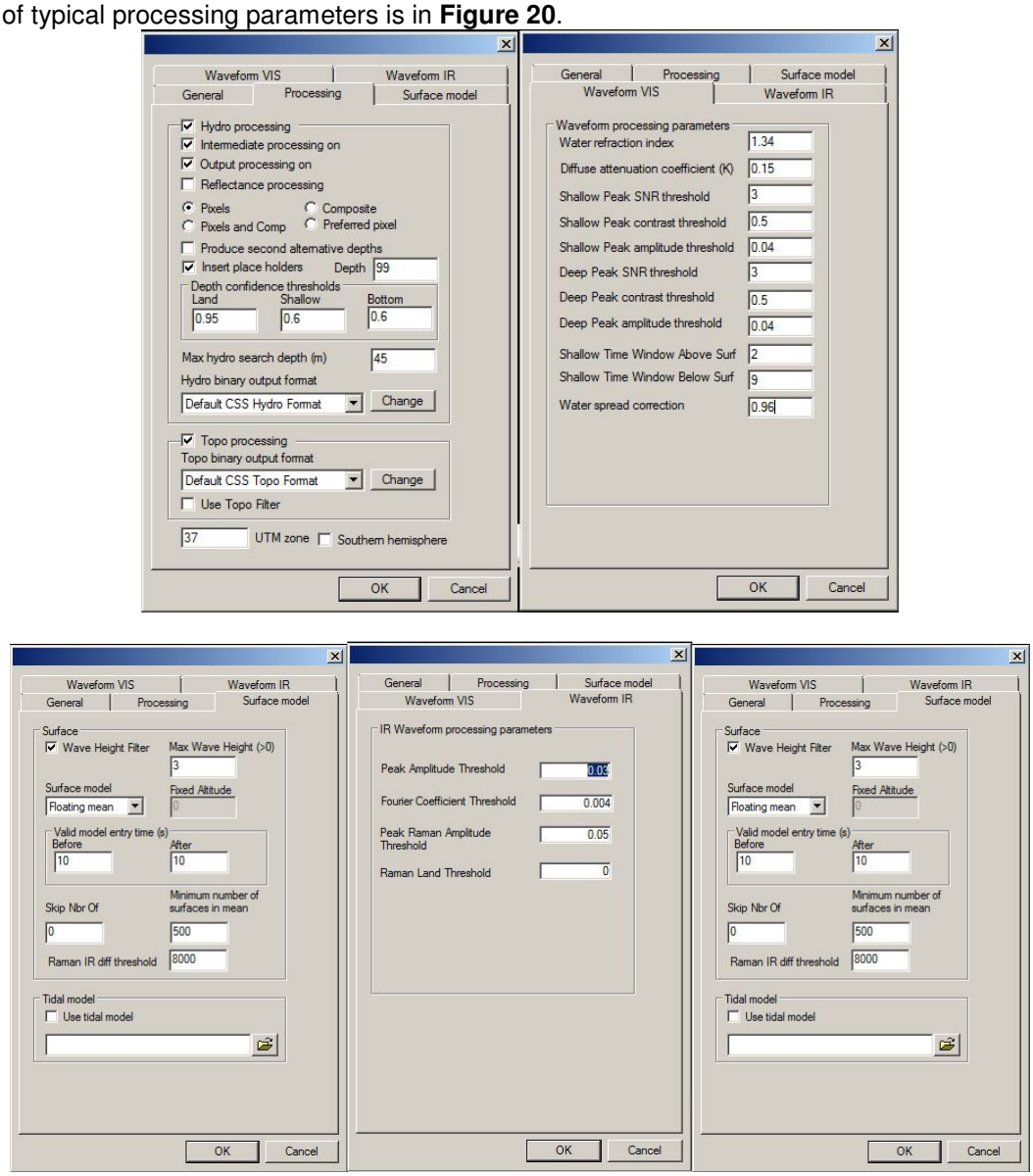


Figure 20: Typical CSS Processing Settings

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.

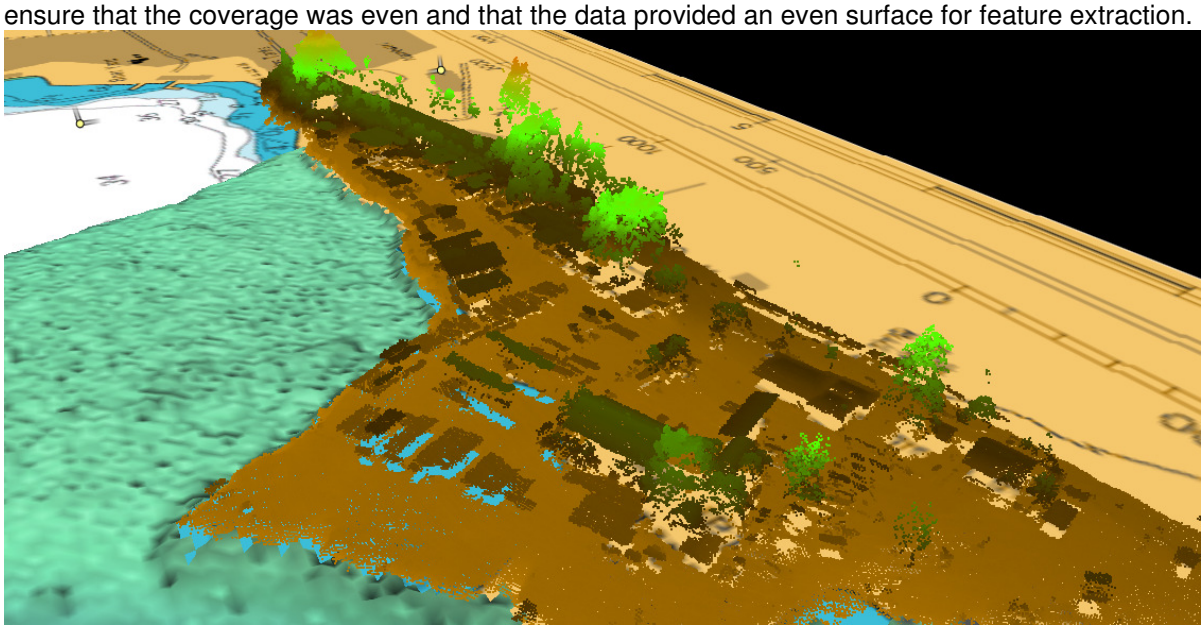


Figure 21: Point Cloud of Topographic LiDAR over Port Vila Port viewed in Fledermaus.

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 color map and the final contrast adjusted.
5. The resultant data was exported as an ECW and in xyzi format

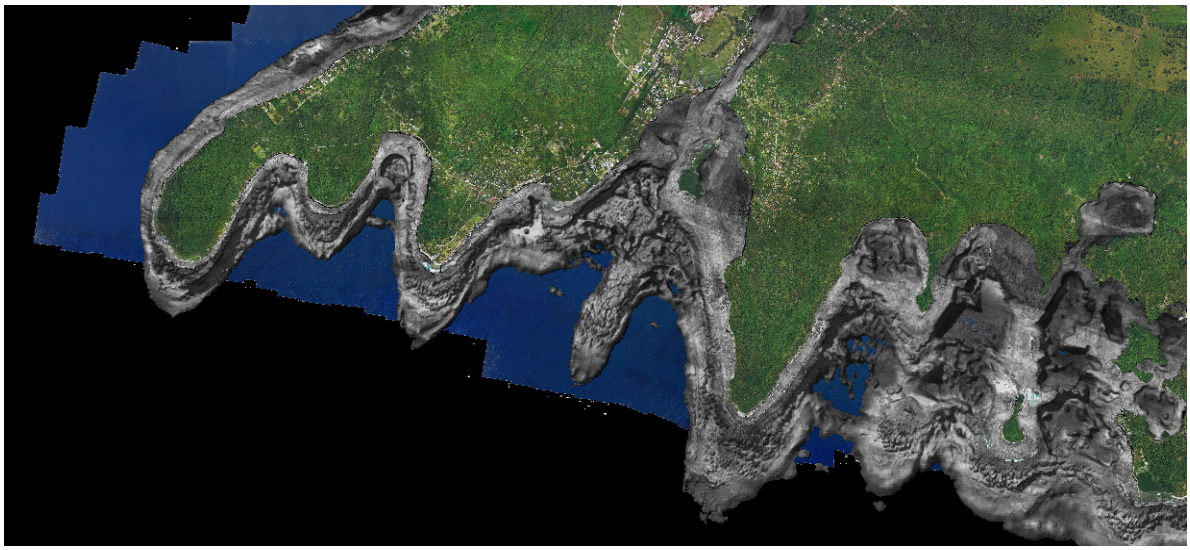


Figure 22: Sample Reflectance Data from South Coast of Efate with background Ortho-Imagery.

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 59S for Efate 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 23: 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.

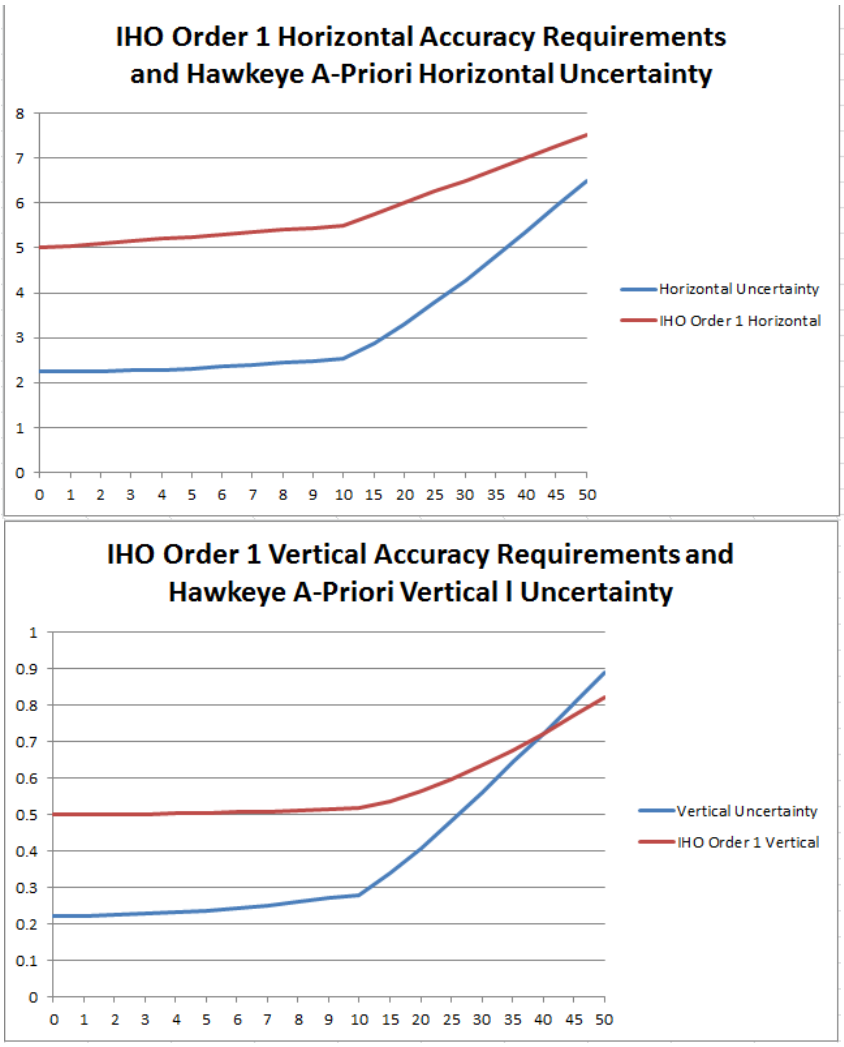


Figure 24: Horizontal and Vertical Horizontal Propagated Uncertainty and IHO Order 1 Required accuracies.

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**

Table 11: 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. Figure 25 below shows a typical reef structure:

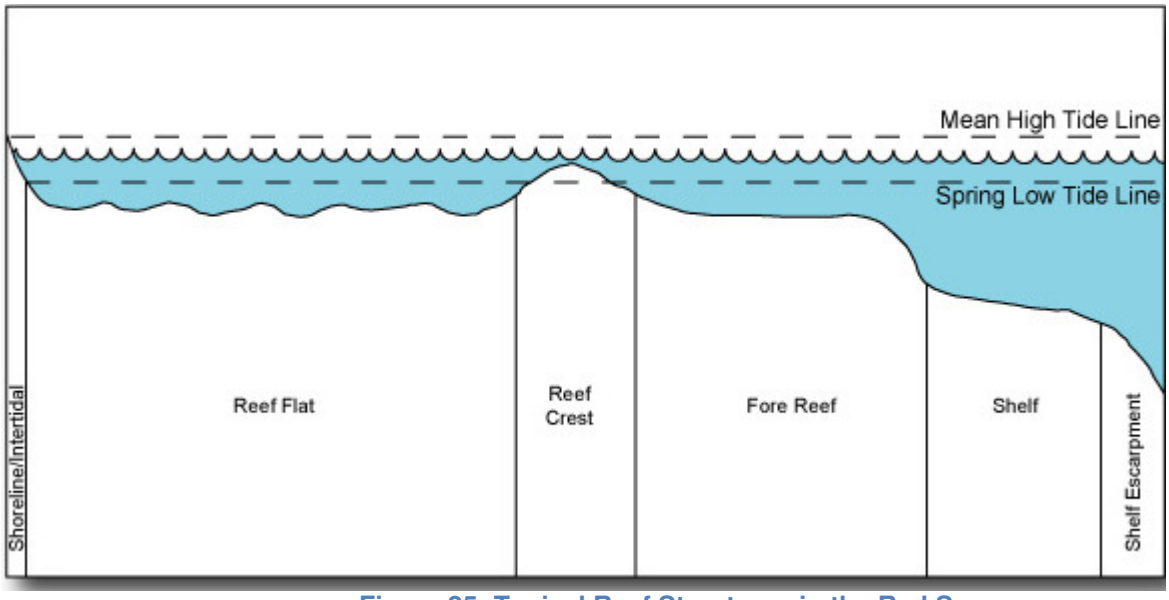
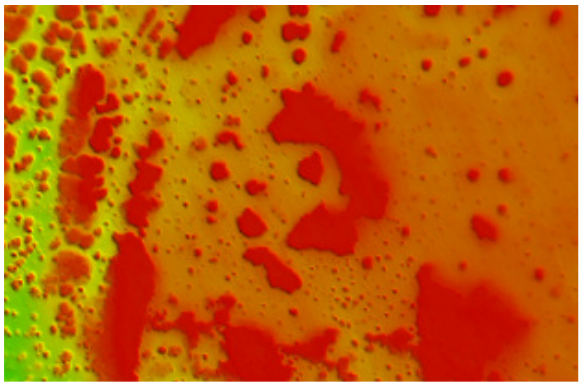


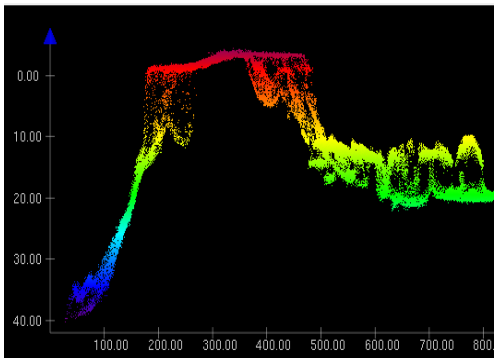
Figure 25: Typical Reef Structures in the Red Sea

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.

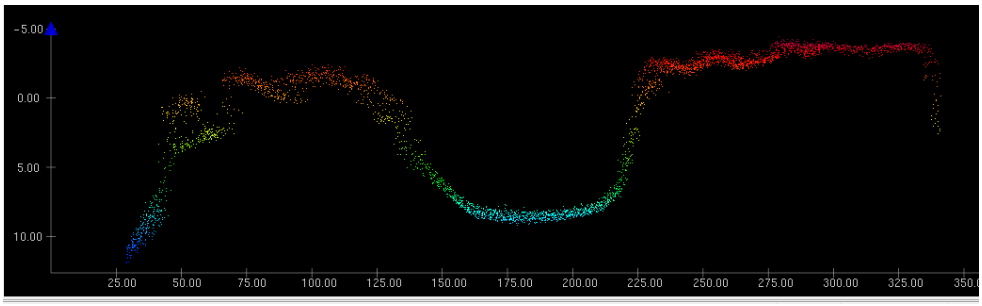
Typical Reef Flat or Fore Reef with isolated Coral Heads



Near Vertical Drop Offs



Typical Steep Sided Gullies



Gently Sloping Fore Reef

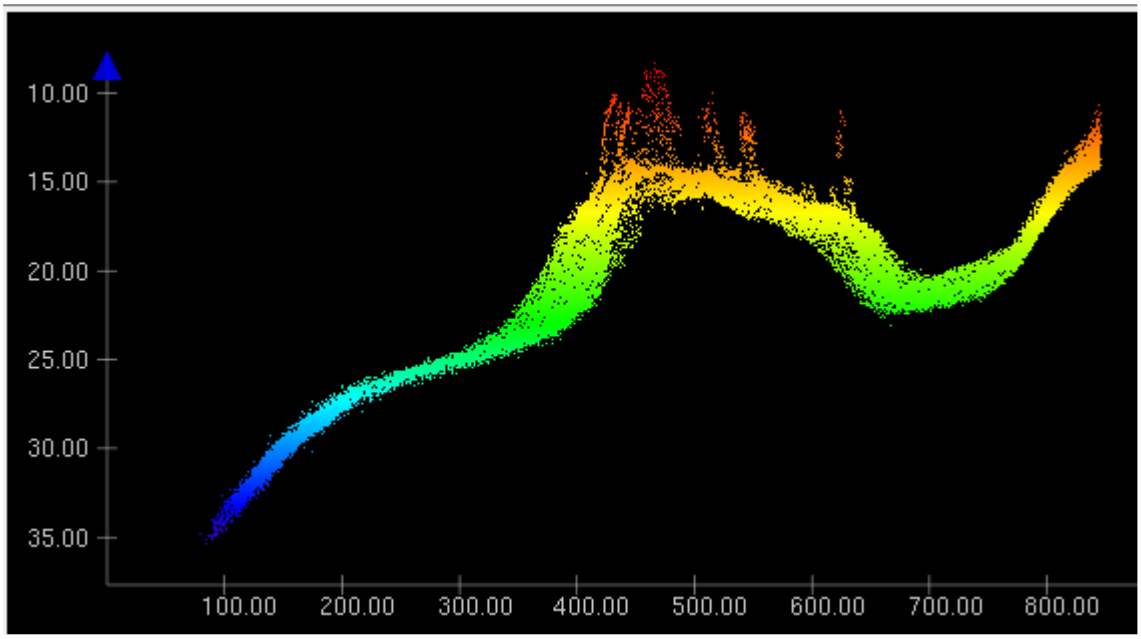


Figure 26: Typical Reef Topography encountered in Coastal Waters

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

Paragraph 0 has documented 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. An example is shown in the image below (Figure 27) between Ifira and Worowloa Point, where the combination of factors previously mentioned has affected the density of data gathered. It however has met the density requirements specified in the SoR.

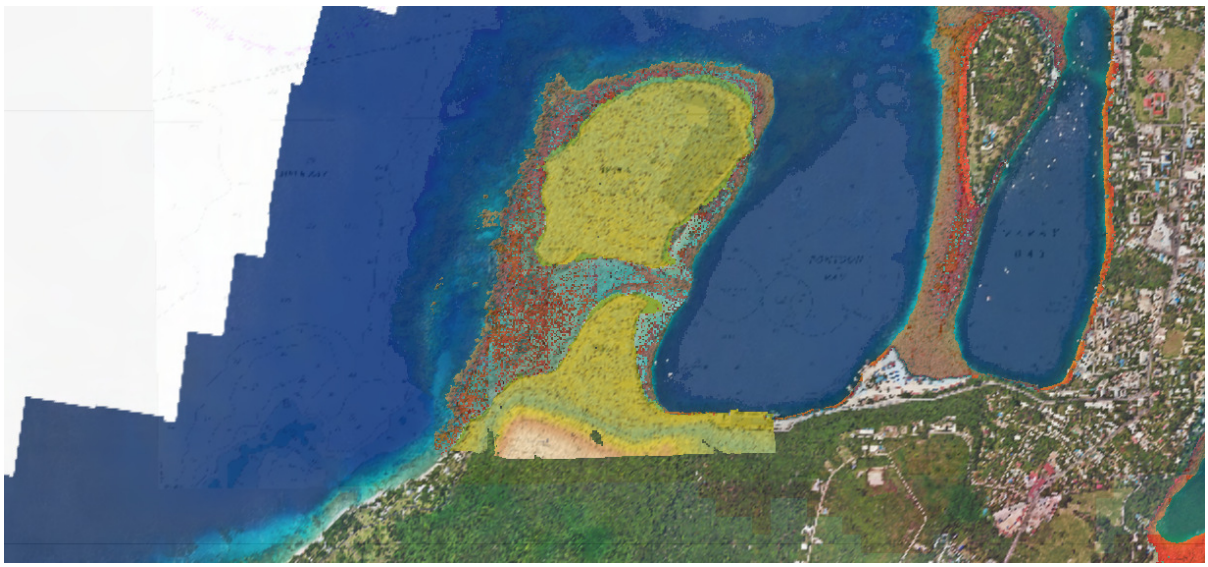


Figure 27: Gaps in Data Coverage seen in Shallow Water (Data at 3m Resolution)

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:

Efate Bathymetric Survey Density ***(85% of all 50m x 50m shall contain 50 or more soundings)***	
Area H	94%
Area I	81%
Area J	93%
Area K	90%
Area L	92%
Total Area	93%

Table 12: Densities achieved in Areas H - L.

The following graphics show the data density coverage for each block in Efate. 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.

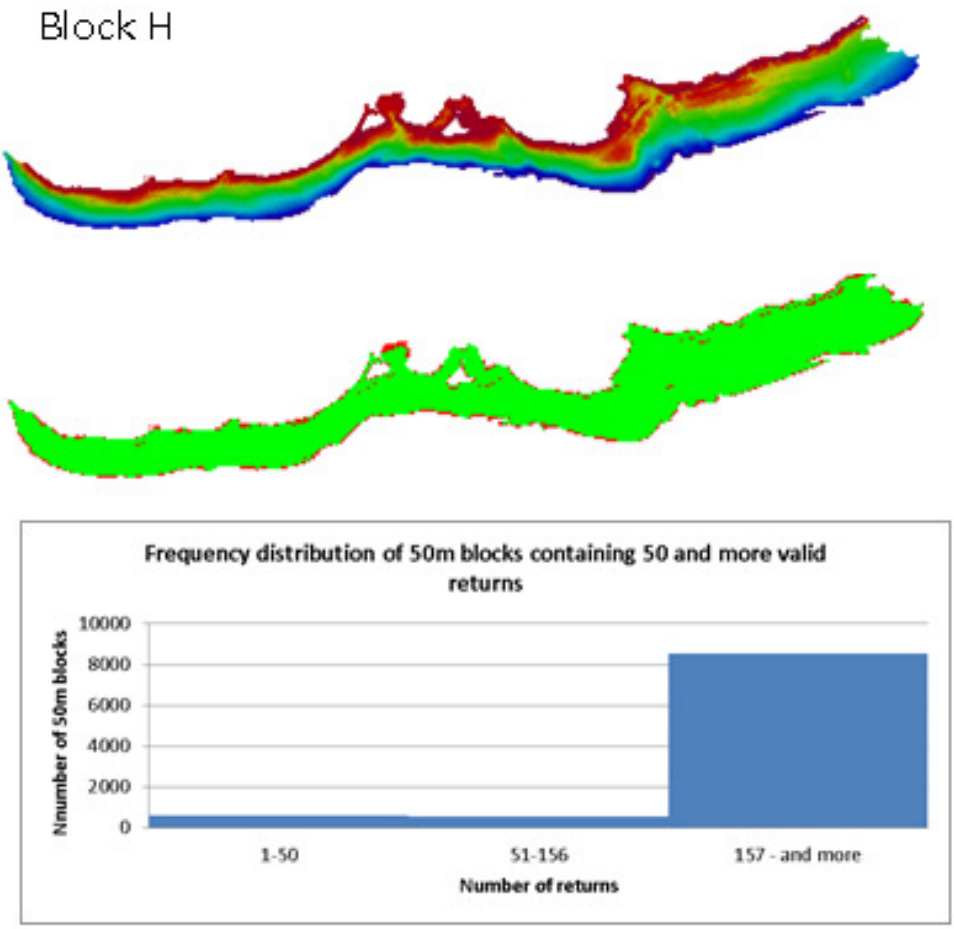


Figure 28: Block H Data Density

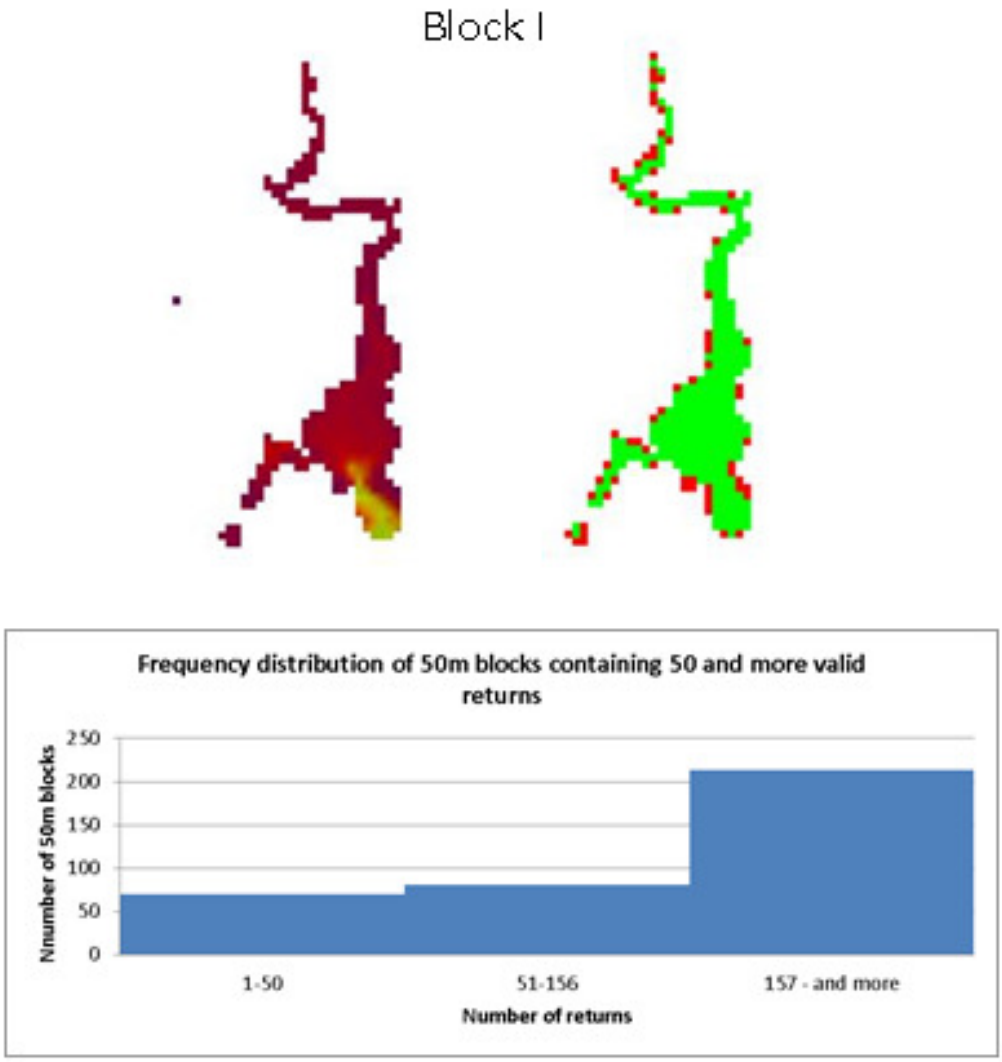


Figure 29: Block I Data Density

Figure 30: Block J Data Density

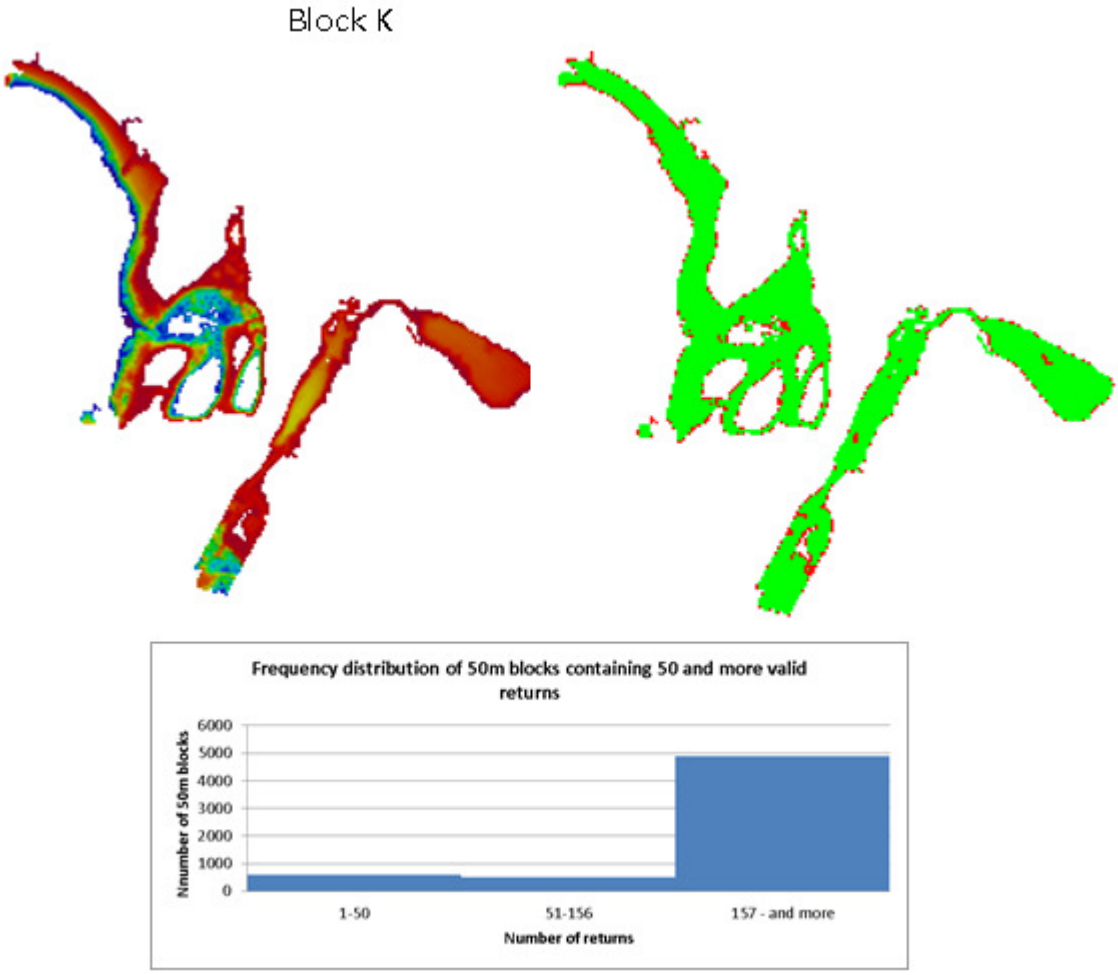


Figure 31: Block K Data Density

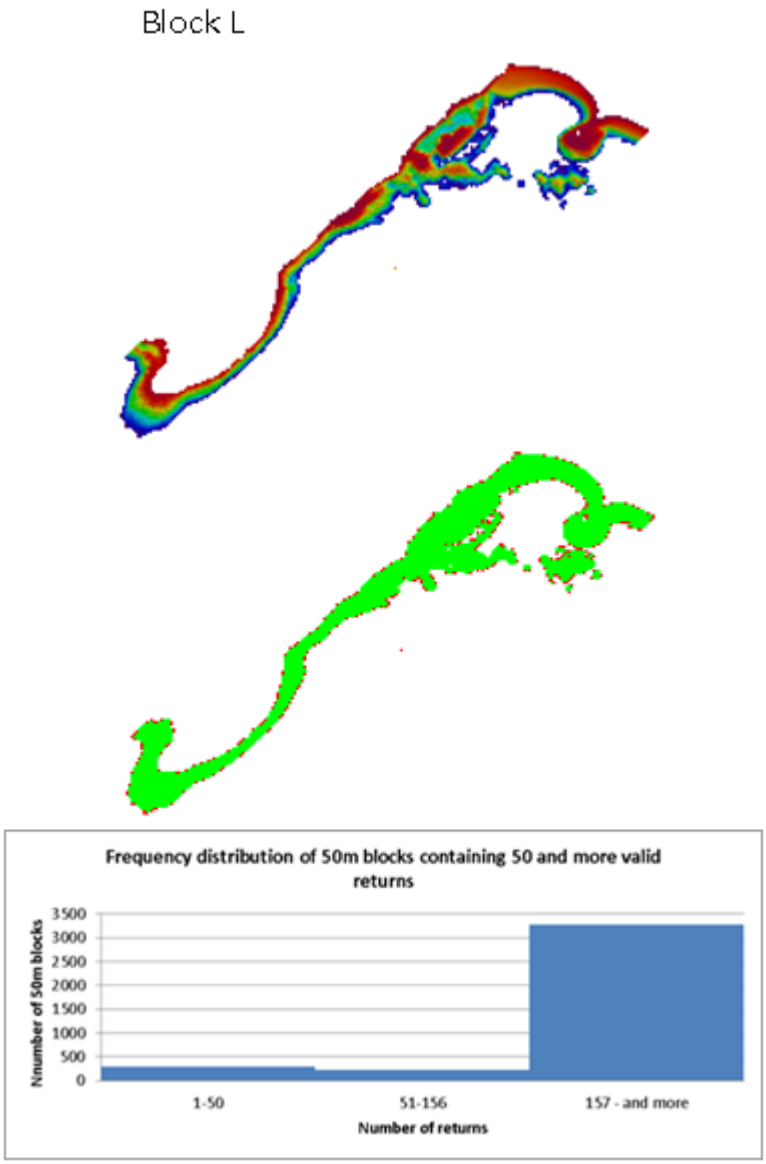


Figure 32: Block L Data Density

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. Area I did not meet the 85% criteria, however this was up a small river where conditions were not optimal and this was accepted.

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 sites were located in the locations highlighted in the graphic below:

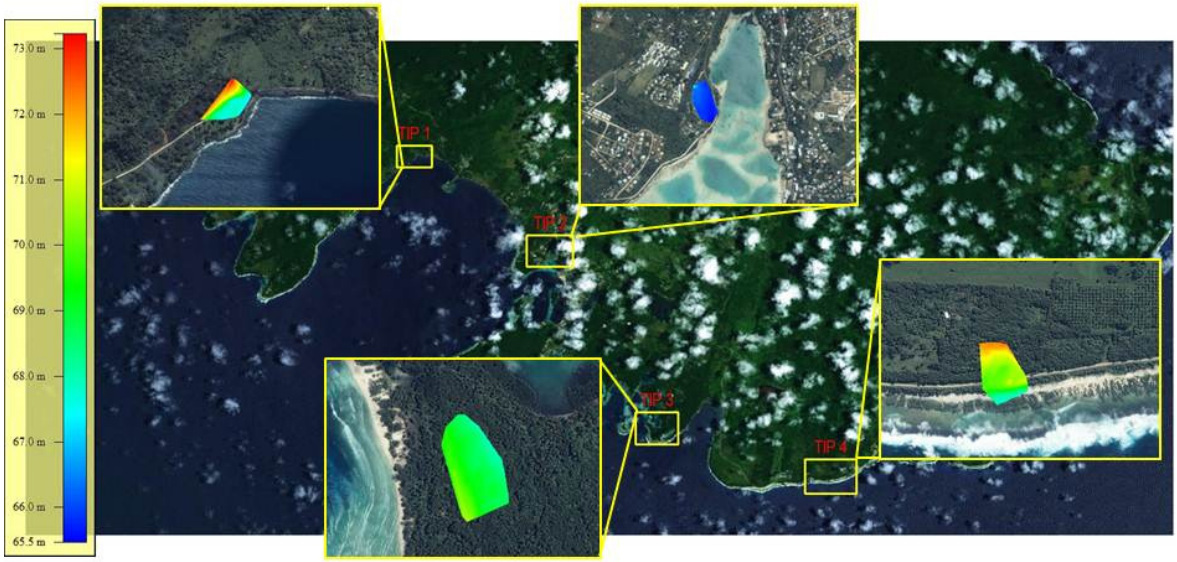
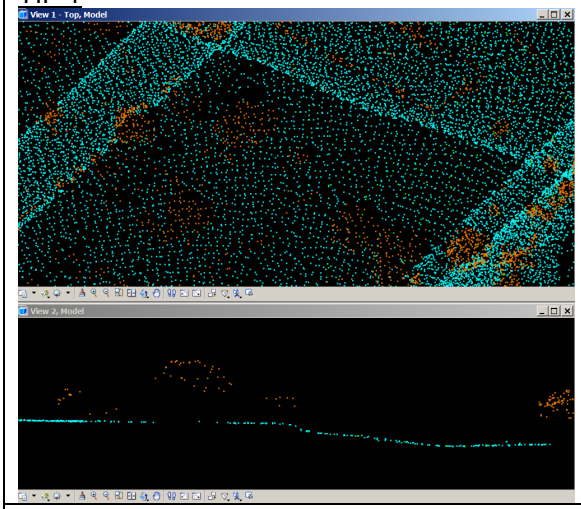
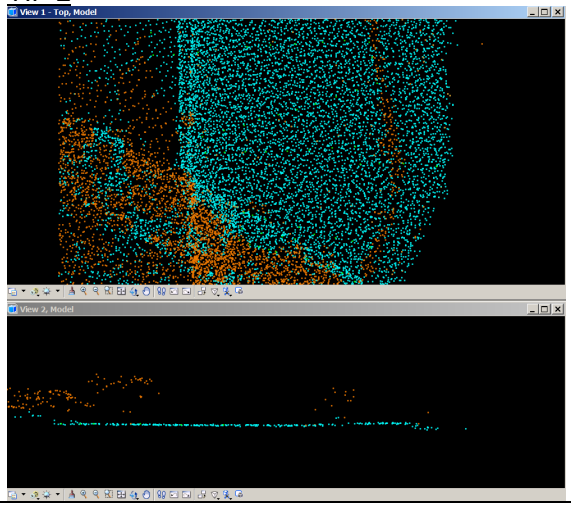


Figure 33: TIP Site Locations on Efate.

The data from the observed sites was compared against the topographic data collected from lines which passed over the sites previously surveyed. Results of this analysis are displayed in Table 13:

TIP 1 	TIP 2 
TIP 3	TIP 4

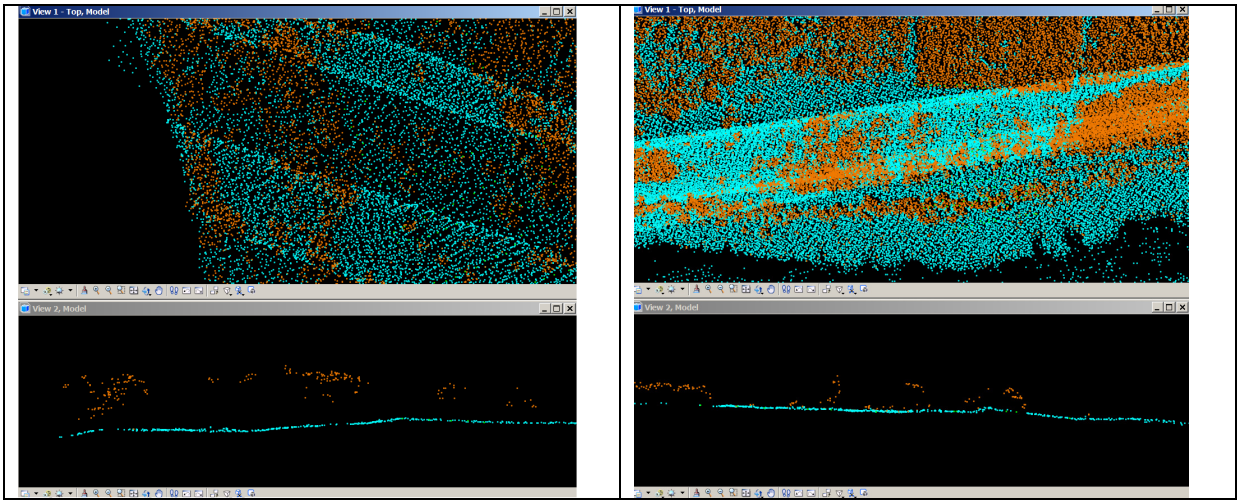


Figure 34: TIP Site Locations on Efate Profile View.

Efate	TIP 1	TIP 2	TIP 3	TIP 4	Average
Average dz	-0.033	0.051	0.097	-0.005	0.0275
Std deviation	0.103	0.317	0.263	0.139	0.2055

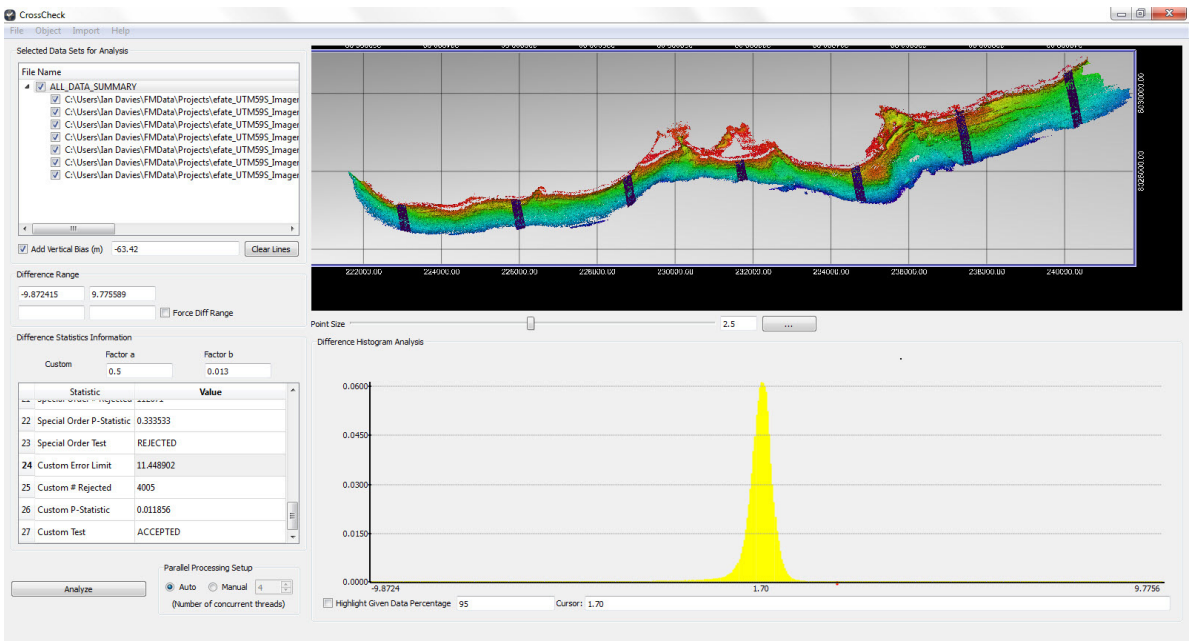
Table 13: TIP Analysis Results Efate

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.

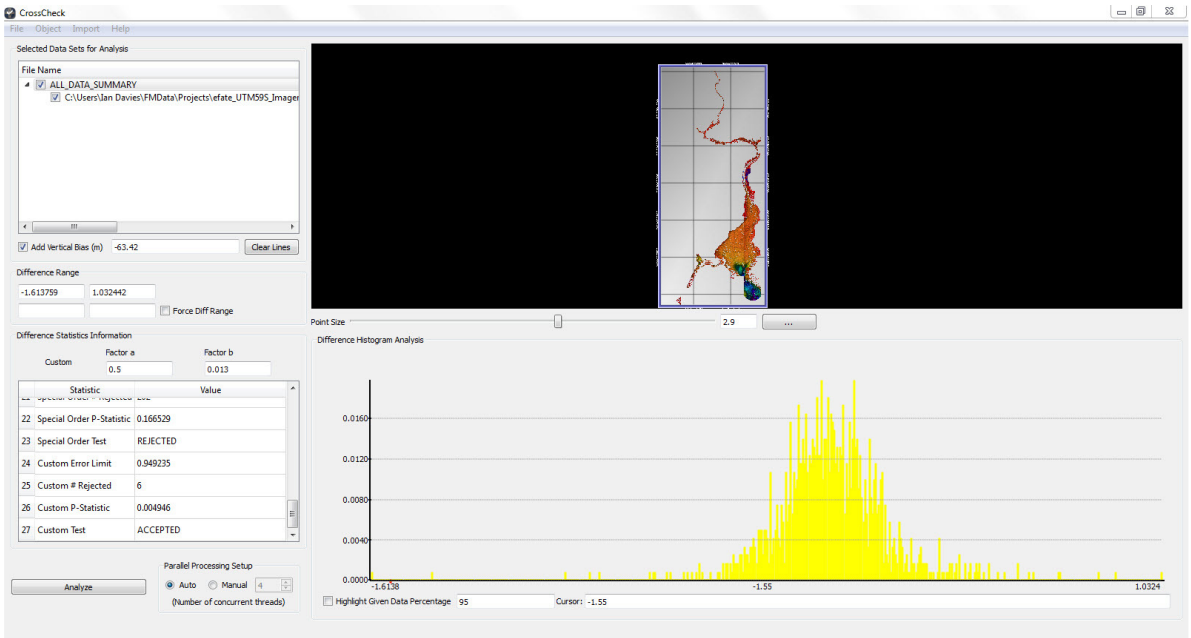
Hydro Crosscheck Results Block H



Area H Statistical Summary			
No Of Points	337811	Order 1 Error Limit	0.5817
Difference Mean	-0.2506	Order 1 Rejected	4005
Difference Median	-0.1722	Order 1 P- Statistic	0.0118
Standard Deviation	0.6107	Order 1 Test	**ACCEPTED**

Figure 35: Crosscheck Results Block H

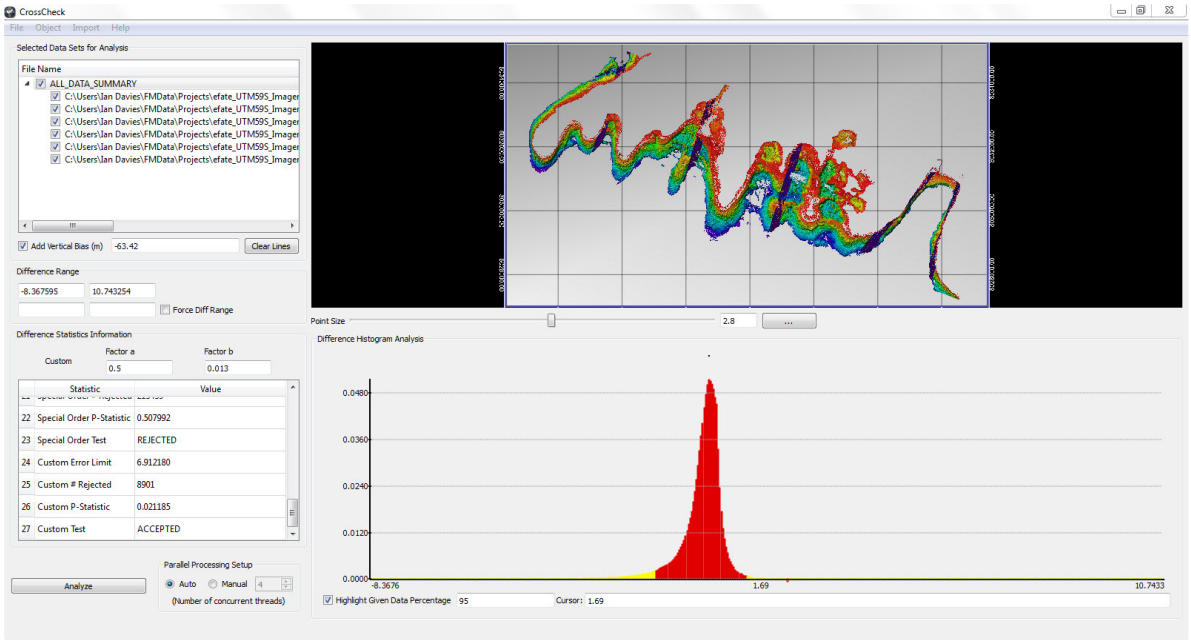
Hydro Crosscheck Results Block I



Area I Statistical Summary			
No Of Points	1213	Order 1 Error Limit	0.5004
Difference Mean	-0.0739	Order 1 Rejected	6
Difference Median	-0.0802	Order 1 P- Statistic	0.0049
Standard Deviation	0.197	Order 1 Test	**ACCEPTED**

Figure 36: Crosscheck Results Block I

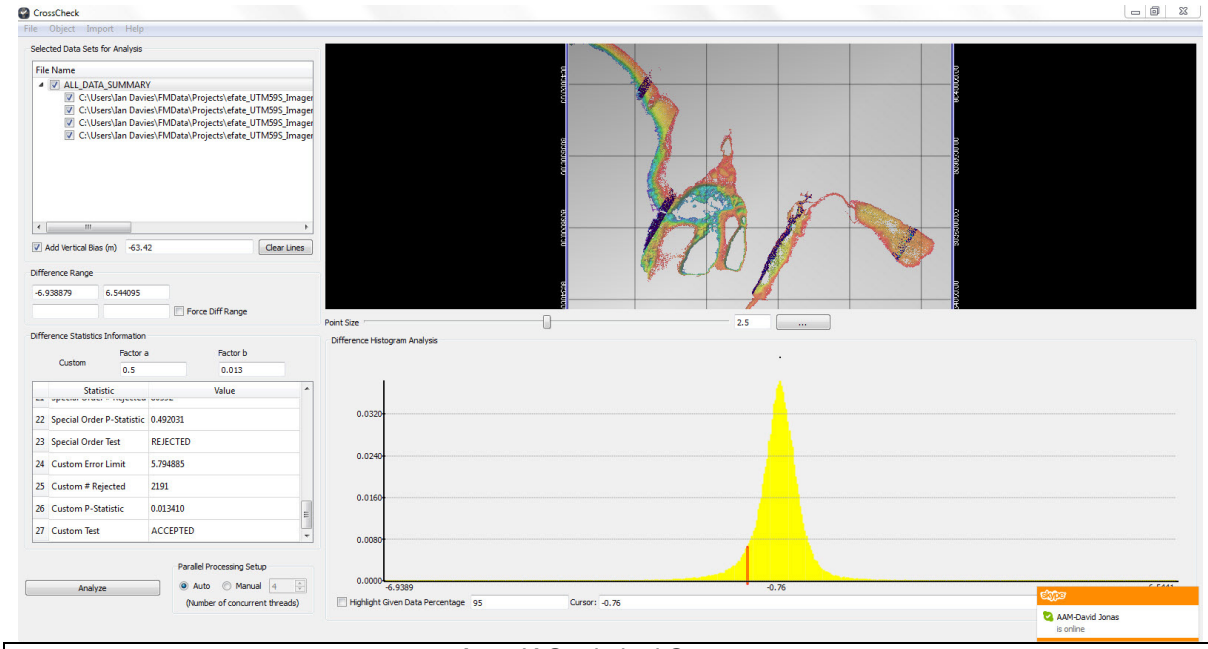
Hydro Crosscheck Results Block J



Area J Statistical Summary			
No Of Points	420162	Order 1 Error Limit	0.5311
Difference Mean	-0.3635	Order 1 Rejected	8901
Difference Median	-0.2588	Order 1 P- Statistic	0.0211
Standard Deviation	0.5564	Order 1 Test	**ACCEPTED**

Figure 37: Crosscheck Results Block J

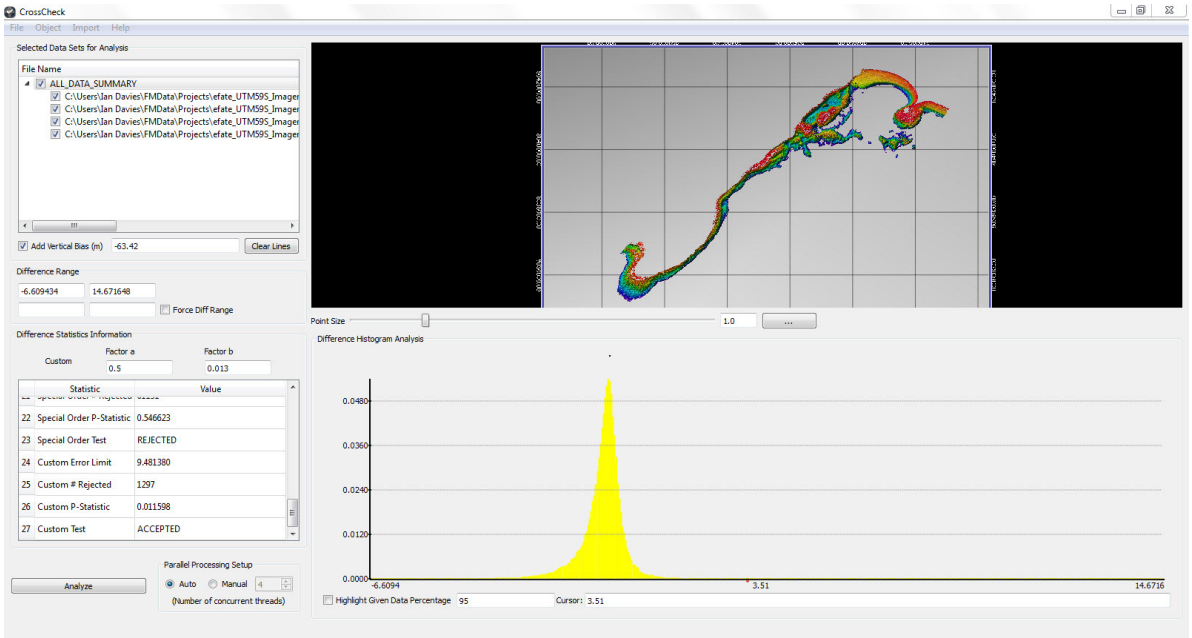
Hydro Crosscheck Results Block K



Area K Statistical Summary			
No Of Points	163388	Order 1 Error Limit	0.5220
Difference Mean	-0.2372	Order 1 Rejected	2191
Difference Median	-0.2122	Order 1 P- Statistic	0.0134
Standard Deviation	0.4650	Order 1 Test	**ACCEPTED**

Figure 38: Crosscheck Results Block K

Hydro Crosscheck Results Block L



Area L Statistical Summary			
No Of Points	111834	Order 1 Error Limit	0.5573
Difference Mean	-0.3721	Order 1 Rejected	1297
Difference Median	-0.1722	Order 1 P- Statistic	0.0115
Standard Deviation	0.2868	Order 1 Test	**ACCEPTED**

Figure 39: Crosscheck Results Block L

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 1570, 1494, 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.

Area H

Lying between Erasfion and Narpow Point on the southern side of Efate the area has depths ranging from drying heights to 45+m when referred to Chart Datum at Port Vila. Area H is characterised by a narrow reef plate lying close to the shore with a steeply sloping reef plate of around 8-10 degrees at the drop off followed by a gentle slope of 1-2 degrees then descending to 40m. A comparison with the bathymetric chart 1494 shows good agreement with no significant shoal features uncharted. Complete data coverage has been achieved to the project specification, with consistent depths of 40m (CD) achieved. Topographic data coverage of the coastline has been achieved to 200m inland providing an overlap with data collected by AAM.

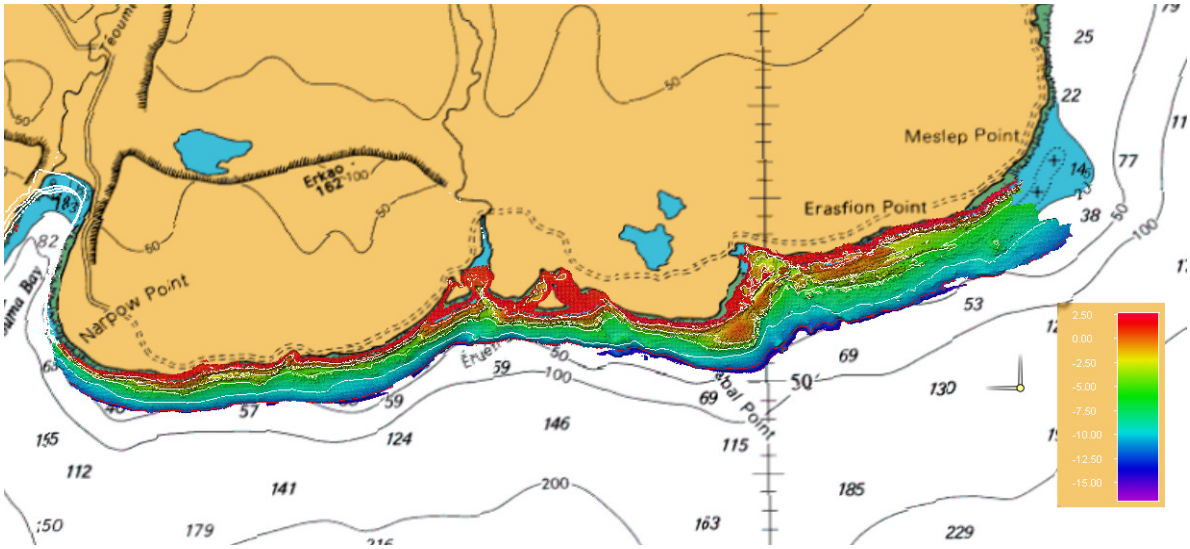


Figure 40: Area H gridded at 5m

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

Latitude	Longitude	Least Depth (CD Port	Remarks
17°	168° 26.4550'E	13.95m	Wreck – H Note 001

Table 14 Position of Wreck (H Note 001)

Area I

Area I is a small river entering the sea near Eruti Lep. Depths range from drying 2.6 to 16m in the bay where the river enters the sea. Area I is characterised by a shallow convoluted waterway , which is overhung by trees and vegetation. The turbidity in the river was average at the time of survey and sufficient coverage has been achieved to determine the river profile. Bathymetric and Topographic data coverage of the coastline and river area has been achieved in the area surveyed.

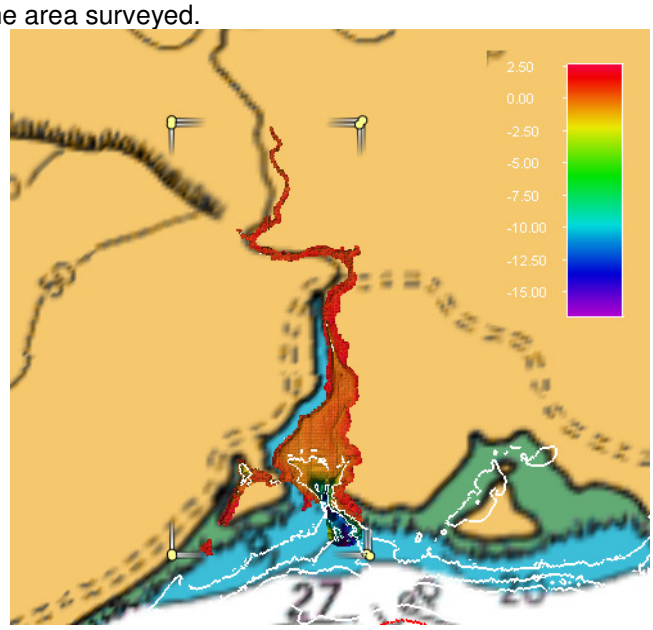


Figure 41: Area I gridded at 5m

Area J

Area A covers the area between Narpow Point the Ekusavat Lagoon heading west around Pango Point to Worowloa Point. Area J is predominately characterised by a highly indented coastline with numerous small bays, islets and lagoons between Narpow and Pango Point. Depths ranged from drying heights to 46m at Chart Datum. The shallow reef plate areas are more extensive in the south. Heading west the coastline becomes steeper with a narrower reef plate as the area becomes more open to the prevailing sea conditions. Examination of the contours from chart 1494 show some significant differences with contours lying closer inshore than currently charted as the reefs drop steeply from the shoreline. Complete data coverage has been achieved to the project specification, with consistent depths of 40m (CD) achieved. Topographic data coverage of the coastline has been achieved providing an overlap with the data collected by AAM.

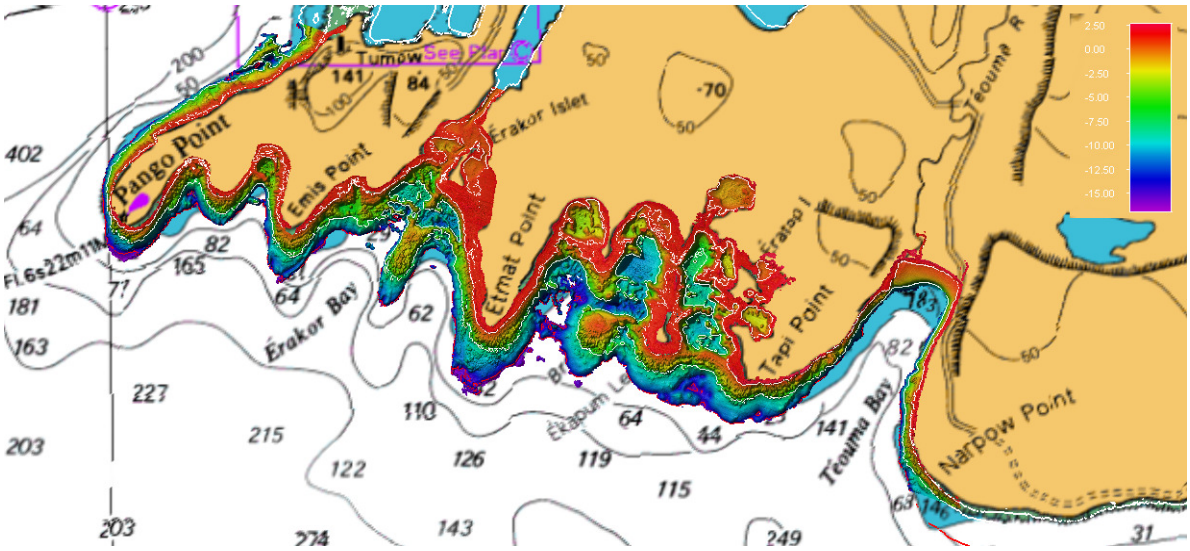


Figure 42: Area J gridded at 5m

One Hydrographic Note has been submitted with this report relating to a charted rock where no depths were available in the following position

Latitude	Longitude	Least Depth (CD Port	Remarks
17°	168° 19.7756" E	2.03m	Shoal – H Note 002

Table 15 Position of Charted Rock with Updated Depth (H Note 002)

Area K

Area K covers Ekusavat Lagoon and the Areas from Worowloa Point to Hideaway Island and the Port Vila Bay Area. Depth across the area varied between drying heights and 44m. Ekusavat Lagoon consists of two lagoons connected to the sea via a narrow channel. Maximum water depths seen varied between 5 and 12m. Port Vila Bay is made up of a number of smaller bays bisected by a shallow reef plate and Reriki Island. Examination of the contours in the bay area show a steep sided topography which was also seen in the gathered bathymetry with depths descending to in excess of 40m rapidly in all areas of the bay except the entrance which had a minimum depth of 12.94m along the recommended track:

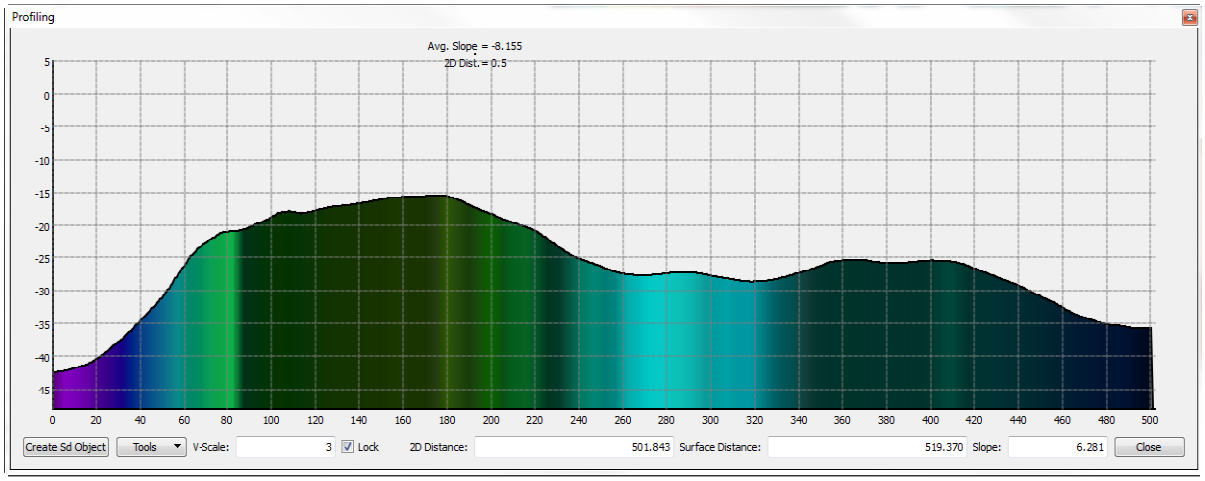


Figure 43: Port Vila Bay Recommended Track Depth Profile

Full coverage was not achieved throughout the bay due to the water clarity and nature of the seabed. Significant shallow water areas were found between Ifira and the mainland and also to the North of Port Vila Bay. The coastline running along the eastern side of Mele Bay makes up the remainder of the area surveyed; assessment of the contours and depths shows broad agreement with those charted. Complete data coverage has been achieved to the project specification, with consistent depths of 40m (CD) achieved throughout the area surveyed.

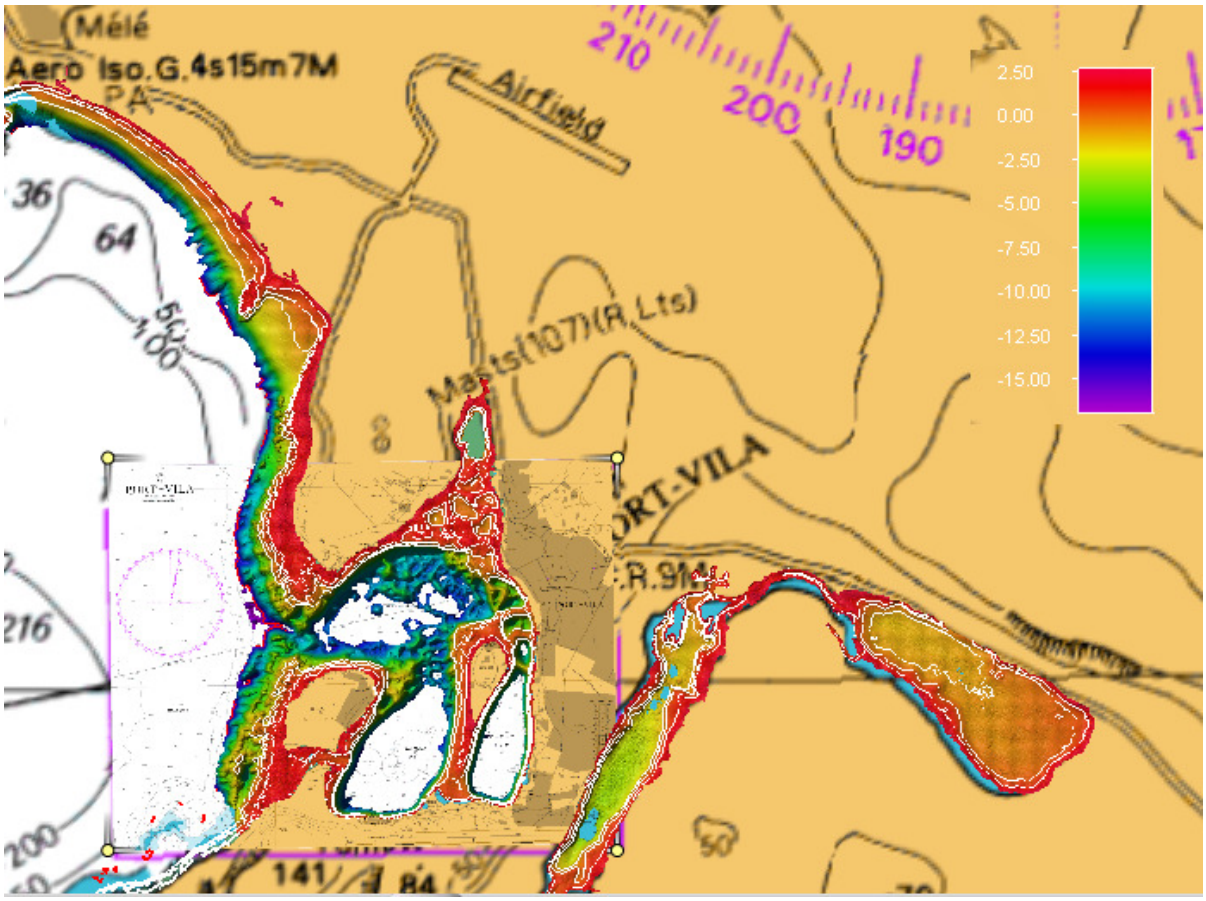


Figure 44: Area K gridded at 5m

Area L

Area L extends from Hideaway Island to Mateo Tiupeniu Point covering the Northern and Western sides of Mele Bay. Area L is characterised by a small fringing reef plate extending along the coast with a number of off lying pinnacles and larger reef structures. Comparison with the existing chart shows that the contours on the western side of the bay are much closer to shore than currently charted. A number of small pinnacles were discovered

around Hideaway Island which have been raised as a Hydrographic Note. 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.

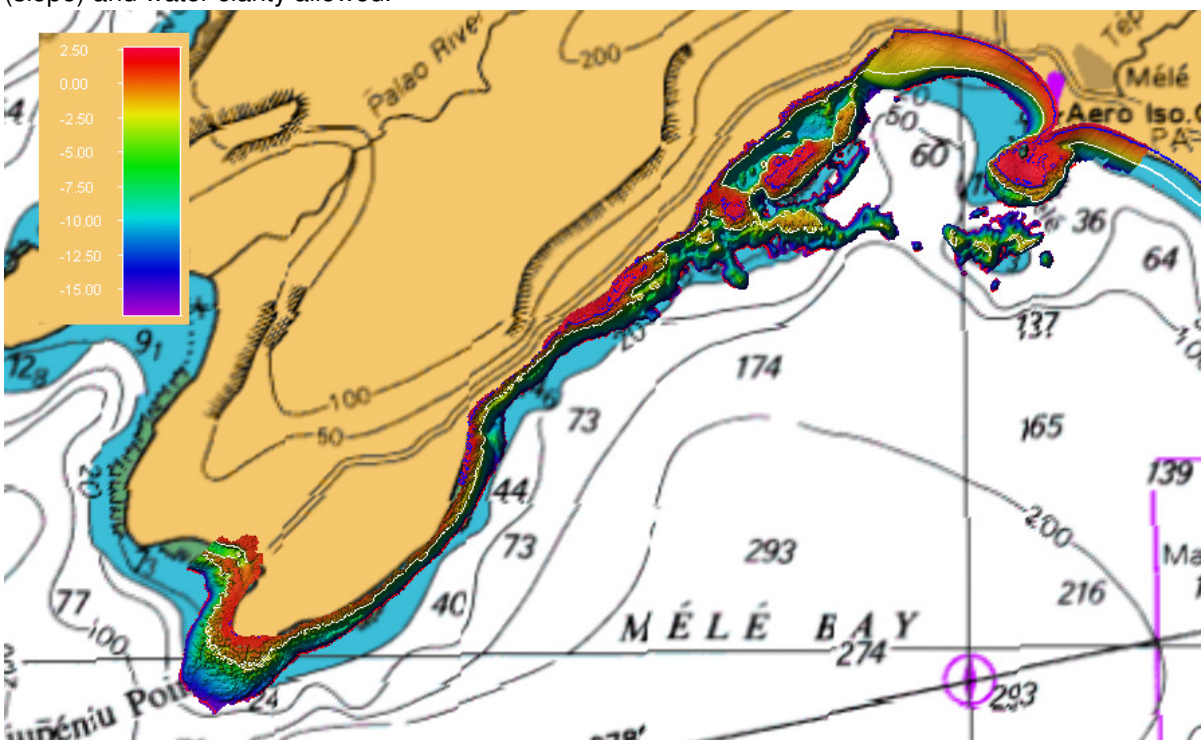


Figure 45: Area L gridded at 5m

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

Latitude	Longitude	Least Depth (CD Port	Remarks
17°	168° 15.1344" E	31.52m	Uncharted Shoal– H Note

Table 16 Position of Uncharted Pinnacle(H Note 003)

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.

7.6 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).
- Tables showing comparison of adjusted bathymetric and topographic data are shown below. Both show good correlation to the land surveyed TIP points.

	TIP1_MSL_121122	**TIP2_MSL_121122**	**TIP3_MSL_121122**	**TIP4_MSL_121122**
Average dz	-0.023	-0.093	-0.067	-0.101
Minimum dz	-0.278	-0.293	-0.132	-0.182
Maximum dz	0.113	0.15	-0.005	-0.033
Average magnitude	0.067	0.099	0.067	0.101
Root mean square	0.086	0.12	0.081	0.107
Std deviation	0.083	0.075	0.049	0.035

Table 1: Bathymetric Data Comparison with Test Points (after shift)

	Site			
	TIP1_MSL_121116	TIP2_MSL_121116	TIP3_MSL_121116	TIP4_MSL_121116
Average dz	-0.041	-0.114	-0.044	0.031
Minimum dz	-0.258	-0.169	-0.055	-0.014
Maximum dz	0.053	-0.030	-0.028	0.105
Average magnitude	0.047	0.114	0.044	0.034
Root mean square	0.063	0.116	0.045	0.045
Std deviation	0.048	0.019	0.011	0.033
Average Residual Dz	0.002			

Table 2: Topographic Data Comparison with Test Points (after shift)

- 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.

1.0 Observed Flight Runs

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

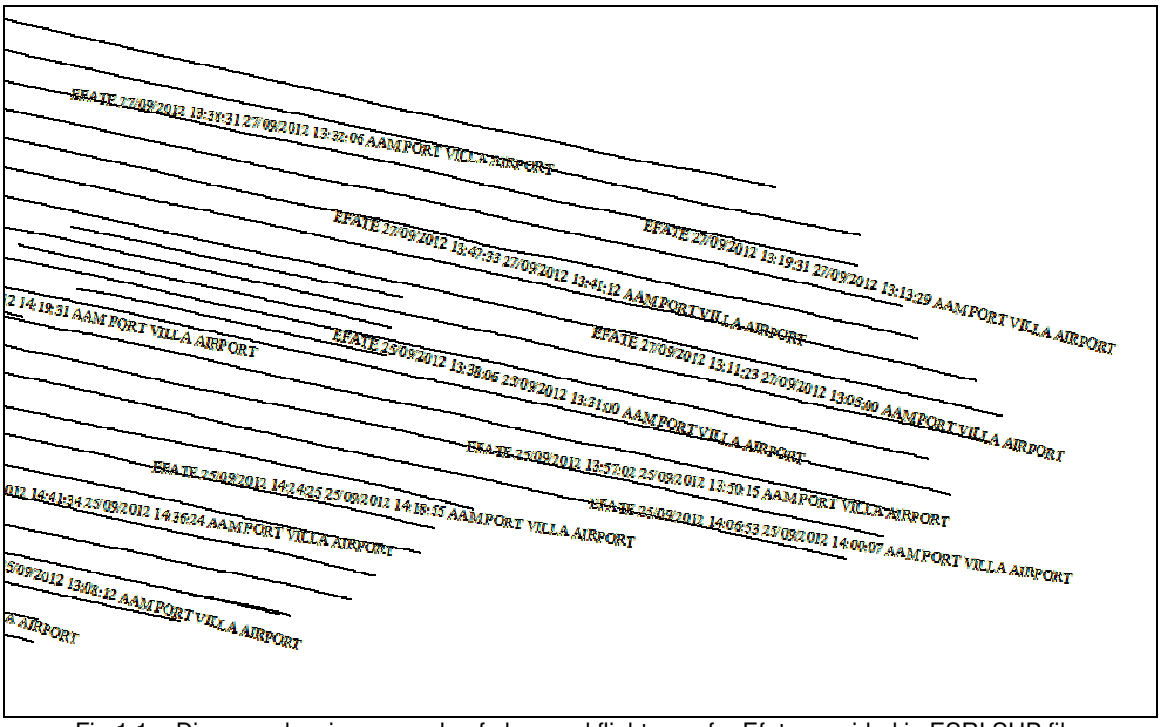


Fig 1.1 – Diagram showing example of observed flight runs for Efate provided in ESRI SHP file.

2.0 Survey Control Check Points

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

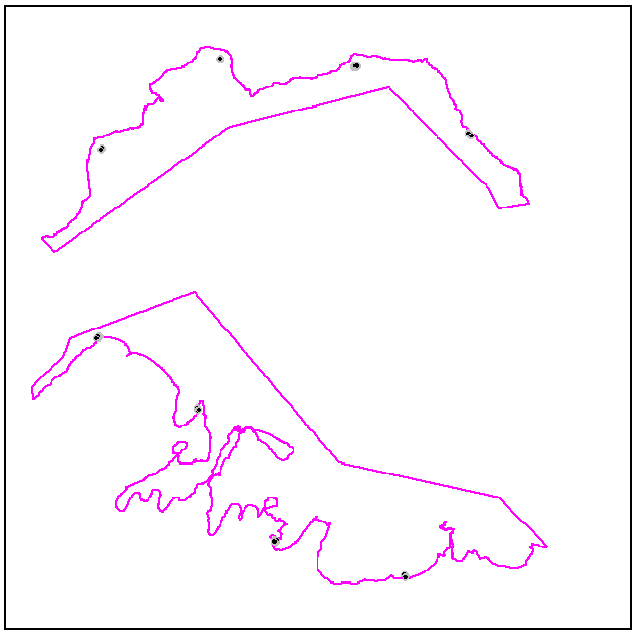


Fig 2.1 – Test Point Locations on Efate

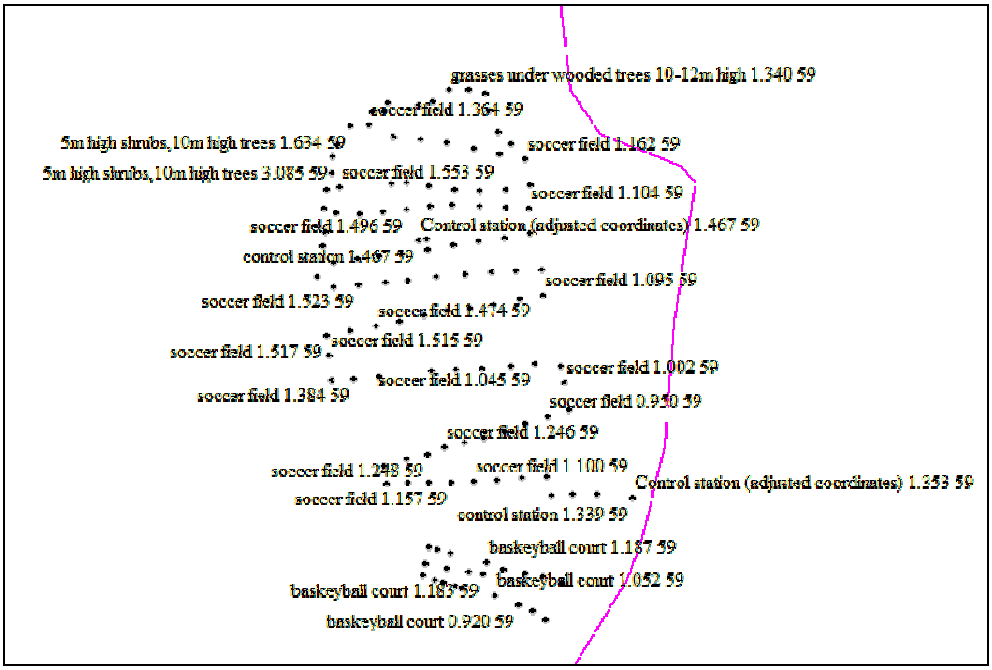


Fig 2.2 – Example of Test Point Locations for one area on Efate.

3.0 Results of Horizontal & Vertical Calibration Checks

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

3.1 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 to 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.

3.2 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
Efate	e233n8051	6.358
	e227n8058	5.709
	e222n8058	5.973
	e216n8058	5.441
	e212n8056	5.662
	e209n8053	6.522
	e205n8048	6.299
	e205n8040	5.844
	e212n8043	6.117
	e214n8040	6.024
	e218n8037	6.606
	e217n8032	6.378
	e225n8032	6.065
	e224n8029	6.038
	e230n8031	6.008
	Average Point Density	**6.070**
Malekula	e749n8233	5.986
	e750n8230	7.025
	e754n8228	5.941
	e753n8225	6.665
	e756n8220	5.817
	e762n8215	6.147
	e764n8212	6.115
	e771n8206	6.985
	e778n8200	6.126
	e786n8196	5.203
	e789n8191	6.299
	e796n8186	6.292
	e800n8179	6.789
	e796n8175	6.025
	e800n8173	6.475
	Average Point Density	**6.259**

3.3 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 both of the Islands. The data was then adjusted and re-examined against the validation plots. Below are the tabulated results for each island showing the shifts applied and the comparison after the shifts.

3.3.1 Efate Topographic Analysis

Before Adjustment								
	Site							
	TIP1_MSL_121116	TIP2_MSL_121116	TIP3_MSL_121116	TIP4_MSL_121116	TIP5_MSL_121116	TIP6_MSL_121116	TIP7_MSL_121116	TIP8_MSL_121116
Average dz	0.583	0.504	0.576	0.651	0.639	0.724	0.678	0.616
Minimum dz	0.508	0.451	0.565	0.606	0.573	0.705	0.632	0.531
Maximum dz	0.673	0.558	0.592	0.725	0.670	0.767	0.862	0.787
Average magnitude	0.583	0.504	0.576	0.651	0.639	0.724	0.678	0.616
Root mean square	0.584	0.504	0.576	0.652	0.639	0.725	0.681	0.618
Std deviation	0.040	0.016	0.011	0.033	0.021	0.014	0.062	0.055
Average Dz Applied	-0.621							

After Adjustment								
	Site							
	TIP1_MSL_121116	TIP2_MSL_121116	TIP3_MSL_121116	TIP4_MSL_121116	TIP5_MSL_121116	TIP6_MSL_121116	TIP7_MSL_121116	TIP8_MSL_121116
Average dz	-0.041	-0.114	-0.044	0.031	0.019	0.104	0.058	-0.001
Minimum dz	-0.258	-0.169	-0.055	-0.014	-0.047	0.085	0.012	-0.089
Maximum dz	0.053	-0.030	-0.028	0.105	0.050	0.147	0.242	0.224
Average magnitude	0.047	0.114	0.044	0.034	0.025	0.104	0.058	0.047
Root mean square	0.063	0.116	0.045	0.045	0.028	0.105	0.083	0.061
Std deviation	0.048	0.019	0.011	0.033	0.021	0.014	0.062	0.061
Average Residual Dz	0.002							

3.3.2 Malekula Topographic Analysis

Before Adjustment				
	Site			
	TIP09_MSL_031212	TIP10_MSL_031212	TIP11_MSL_031212	TIP12_MSL_031212
Average dz	0.701	0.792	0.825	0.730
Minimum dz	0.632	0.720	0.717	0.681
Maximum dz	0.762	0.875	0.883	0.792
Average magnitude	0.701	0.792	0.825	0.730
Root mean square	0.702	0.793	0.826	0.730
Std deviation	0.030	0.040	0.036	0.024
Average Dz Applied	0.762			

After Adjustment				
	Site			
	TIP09_MSL_031212	TIP10_MSL_031212	TIP11_MSL_031212	TIP12_MSL_031212
Average dz	-0.066	0.032	0.068	-0.030
Minimum dz	-0.299	-0.040	-0.004	-0.079
Maximum dz	0.002	0.115	0.123	0.032
Average magnitude	0.066	0.040	0.068	0.033
Root mean square	0.082	0.050	0.075	0.039
Std deviation	0.050	0.040	0.032	0.024
Average Dz Applied	0.001			

3.3.3 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 Efate. The achieved accuracy of the soundings is within 0.55 meters (95% confidence) to depths of 30m.

Lidar Error Budget	A priori		Depth Range (m)				
	X/Y	Z	5	10	20	30	40
Tidal Measurements	0.05	0.05					
Co-Tidal model	0.00	0.00					
Base Station Position	0.05	0.05					
Navigation Solution GNSS + AV410	0.05	0.05					
HEII Internal Offsets and Latency	0.002	0.002					
HEII Lever Arms	0.005	0.005					
Scanner Position	0.001	0.001					

Sea Control Area	0.5	0.10					
Calibration Values	0.300	0.15					
Laser Discrimination	0	0.11					
Footprint Uncertainty x/y	2.200		2.256	2.417	2.973	3.720	4.565
Surface Angle of Incidence x/y	0		0234	0.469	0.938	1.407	1.876
Surface Angle of Incidence z		0	0.063	0.125	0.251	0.376	0.501
Totals	**2.278**	**0.244**					
A postiori x/y			**2.344**	**2.531**	**3.173**	**4.021**	**4.971**
A postiori z			**0.255**	**0.285**	**0.381**	**0.502**	**0.634**
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

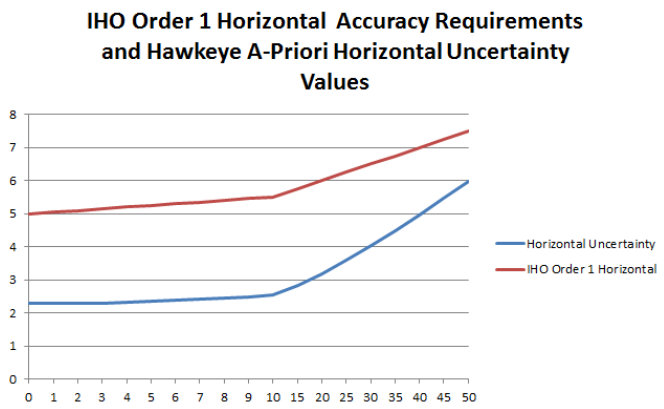
[1] Specification required by Pelydryn. May be better than this

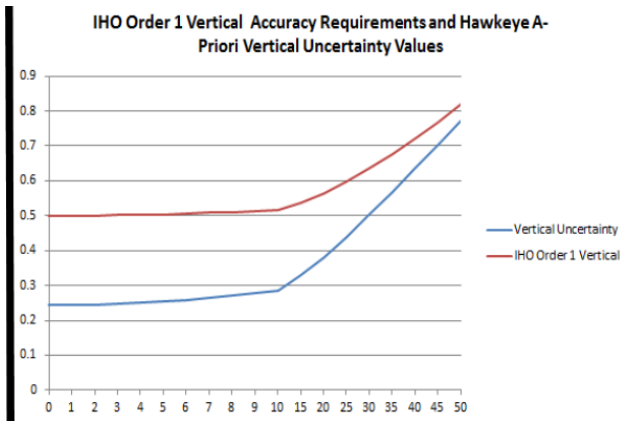
[1] Discrepency between the Control Area and the LiDAR data. This correction may already include errors from the Sea Control Area

[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'.





4.0 Establishment of MSL from Tide Gauge Observations

4.1 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.

4.2 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. Despite there being little or no tidal information available for Malekula, it was assessed that the regime would be broadly similar across the areas to be surveyed.

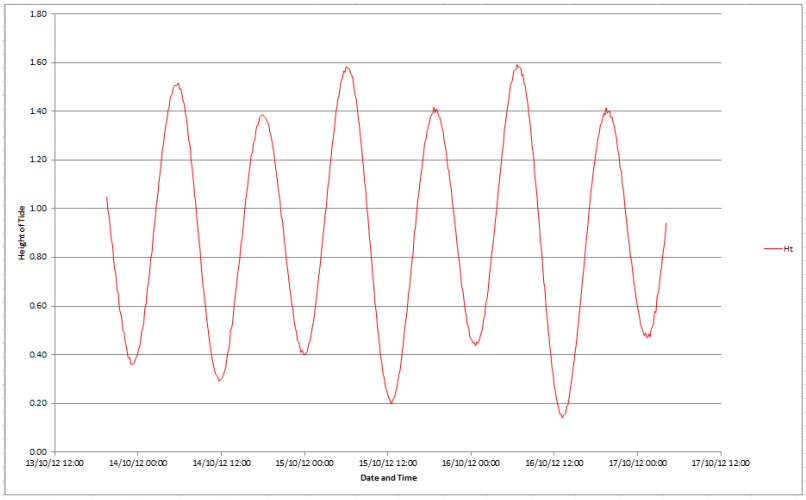


Figure 4.46 - Sample Tidal Curve Showing Tidal Regime

4.3 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.

4.3.1 Main Wharf – Port Vila

An existing gauge has been sited at this location (17° 45.409'S 168° 18.024E) since 1993 and is part of the South Pacific Sea Level and Climate Monitoring Project. In this instance the decision was made to recover the existing SEAFRAME gauge as it would provide a larger period of observations for checking MSL. A GPS Benchmark was established close to the existing SEAFRAME gauge and levelled to the Sensor mark (Van 16) and the reference mark (Van 14). These levelling runs were repeated and the results averaged to give an indication of the heights of all marks.

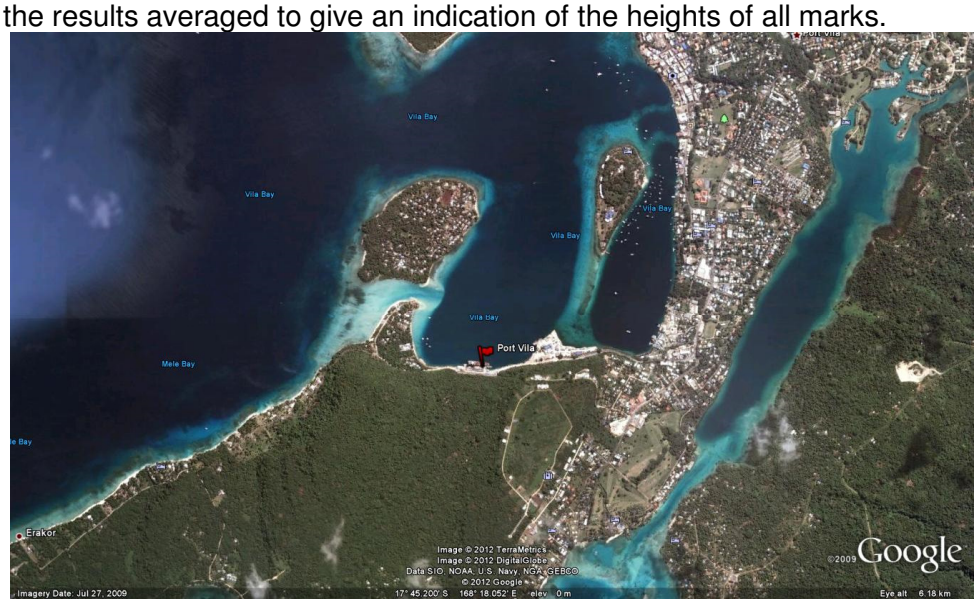


Figure 4.47 Location of Port Vila Tide Station

The tidepole installed at the station was damaged and was not usable. Due to the lack of a suitable location to insert a tidegauge in close proximity, a local mark was made levelled to the framework connecting the sensors to the jetty. Tidal observations were undertaken by measuring from this mark down to the water's surface. As the connection to Tide Gauge Zero was known it was possible to correct this reading to show the corrected Height of Tide. The observation was undertaken twice, first on 12 Oct 2012 and the second time on the 29th October 2012. This was due to an apparent lag in the time causing an offset on the data. Only the second observation was used to calculate the tide gauge zero and any corrections required.

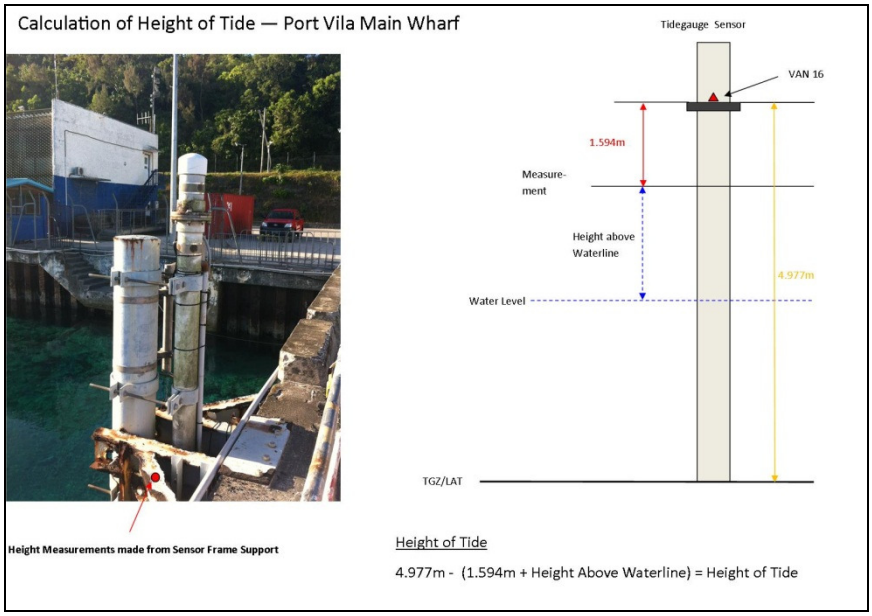


Figure 4.48 Port Vila Tide Station and Calculation of Height of Tide from Jetty

Following processing of the GPS and levelling observations the following connections were established:

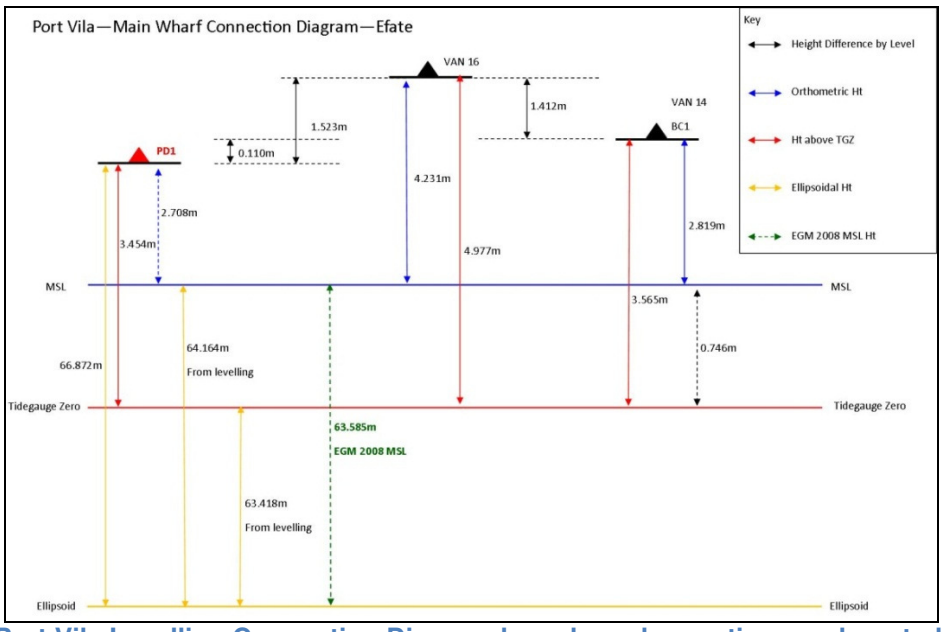


Figure 4.49 Port Vila Levelling Connection Diagram based on observations and quoted MSL values

Examination of the ellipsoid to geoid (MSL) values from levelling indicates a difference of 0.579m between EGM 2008 and the observed values. In order to validate this against the tidal record and the value of the Mean Sea Level that can be extracted the tidal data was analysed to confirm the tide gauge zero and derive MSL values. No harmonic analysis of the tidal data was undertaken. Following

a 13 hour comparison the observed tidal readings were compared against the tidegauge using data downloaded from the NTF website to confirm the zero of the gauge with the following results:

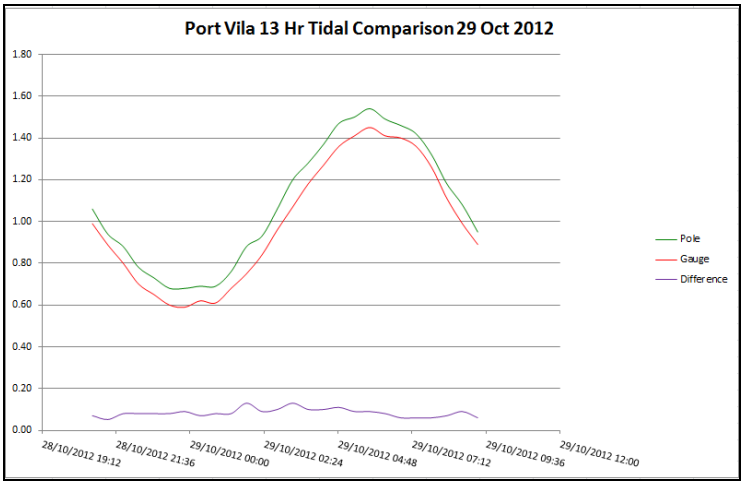


Figure 4.50 Graph showing difference between Tide Gauge and Observed Tidal Heights

From analysis of these readings it was inferred that 0.08m should be added to all gauge readings.

Having established the Tide Gauge Zero correction a series of Short Period Mean Sea Level Observations were undertaken using 39 hours of observations. The results from several observations (11, 21 and 28 Oct along with 15 Nov) were averaged (mean) and compared against the mean value of the 6 minute samples covering the period 02 Oct – 27 November 2012. From direct observation it was calculated that Mean Sea Level was 0.904m above the tidegauge zero.

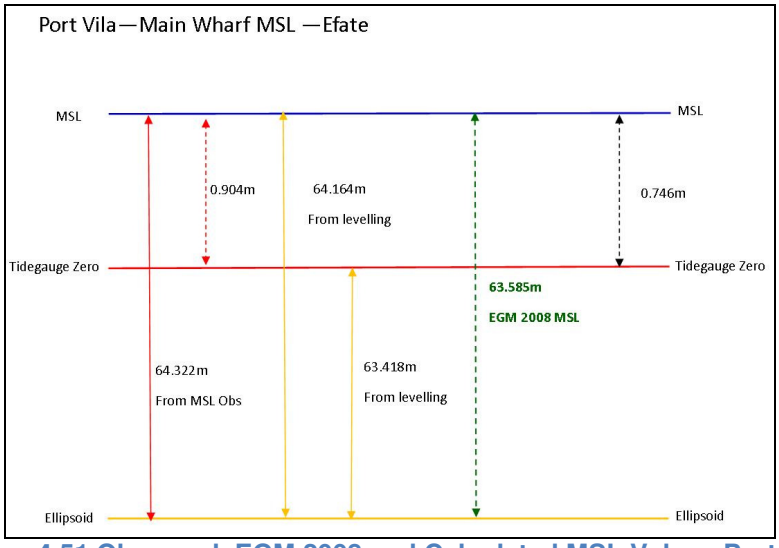


Figure 4.51 Observed, EGM 2008 and Calculated MSL Values Port Vila

Indications from the South Pacific Sea Level and Climate and Monitoring Project suggest that sea level in Vanuatu is rising at a rate of 5mm per year. Lowest Astronomical Tide was defined in 1973 at 0.746m. The observed MSL value 0f 0.904m is 0.158m different. This difference equates to the expected change in MSL since 1973 of 0.15m. This direct comparison gave confidence in the readings and the observed Mean Sea Level was accepted.

4.3.2 Emua Jetty - Efate

Following topographic surveying on the Northern side of Efate it was necessary to confirm the value of MSL in this locale. No tide station existed, however a substantial concrete jetty was situated in an ideal location and permission was granted by the local chieftain and lease holder to establish a temporary

tide station consisting of a 2m tidepole and Valeport 740 automatic tidegauge at Emua Jetty (17° 32.190' S 168° 23.167' E).

The Valeport Model 740 tide gauge has been designed to provide an accurate, easily deployed tide gauge for use in short or long term hydrographic survey operations. Low power consumption and user selectable sampling regime allow up to 2 years' autonomous operation. The transducer is vented to atmosphere and is IP 67 rated (0.5m for 30 seconds)

Figure 4.52 Location of Emua Tide Station

The jetty had a number of wooden rubbing strakes and the decision was made to fix the temporary tidal station to this with the recording unit chained to a bollard in a waterproof box. The pole and gauge were set at a level below Lowest Astronomical Tide using predicted tides to set the depth of immersion at installation. Following installation of the gauge a GPS Benchmark was established at the root of the

jetty with observations taking place for 6 hours. The top of the tidepole was levelled to the new benchmark and this was used as the basis of deriving a Mean Sea Level.

The zero of the tidepole and the tidegauge sensor were fixed in an identical position on a board fastened to the rubbing strake. A 13 hour comparison was conducted between the gauge and pole and it was found that the zero of the gauge was coincident with tidepole zero.

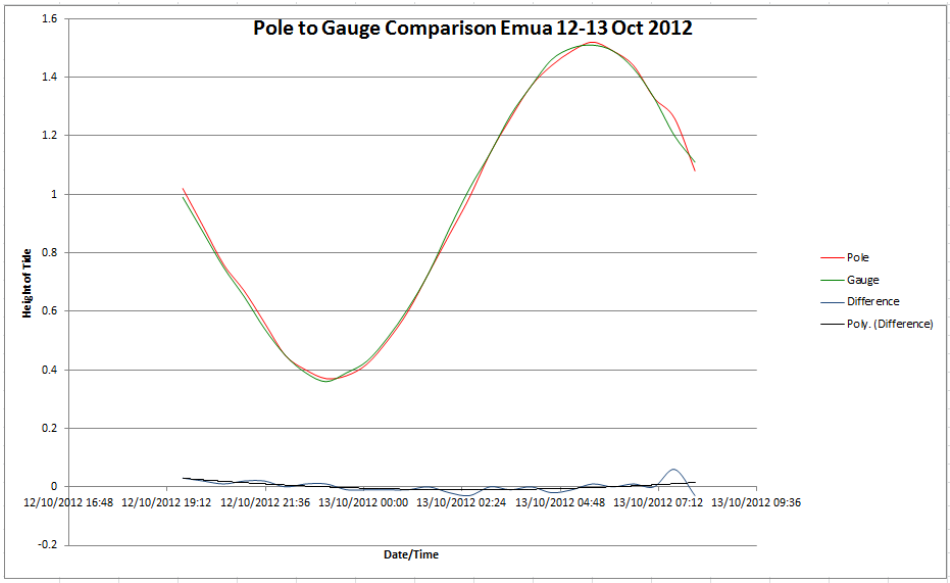


Figure 4.53 Graph showing difference between Tide Gauge and Observed Tidal Heights

Following processing of the GPS Benchmark the following connections and heights were established:

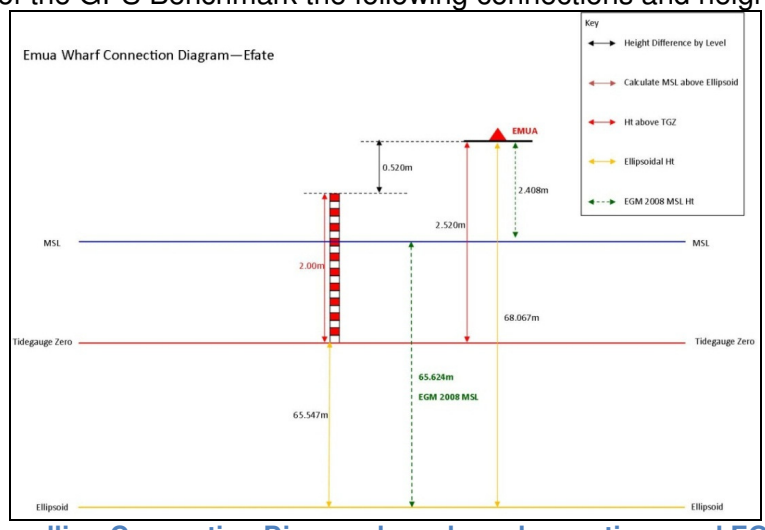


Figure 4.54 Emua Levelling Connection Diagram based on observations and EGM 2008 MSL values

The gauge was left in-situ for several days and then downloaded to allow Mean Sea Level calculations to be conducted. Several observations were made directly by reducing the tidal readings to the ellipsoid as the height of gauge zero was known (65.547m).

Having averaged the values of the MSL checks the ellipsoid-geoid separation value was calculated as 66.425m. Mean Sea Level was found to be 0.880m above the zero of the pole. This value was 0.801m higher than the EGM 2008 model, but shows broad agreement with the station at Port Vila (0.90m) and was accepted.

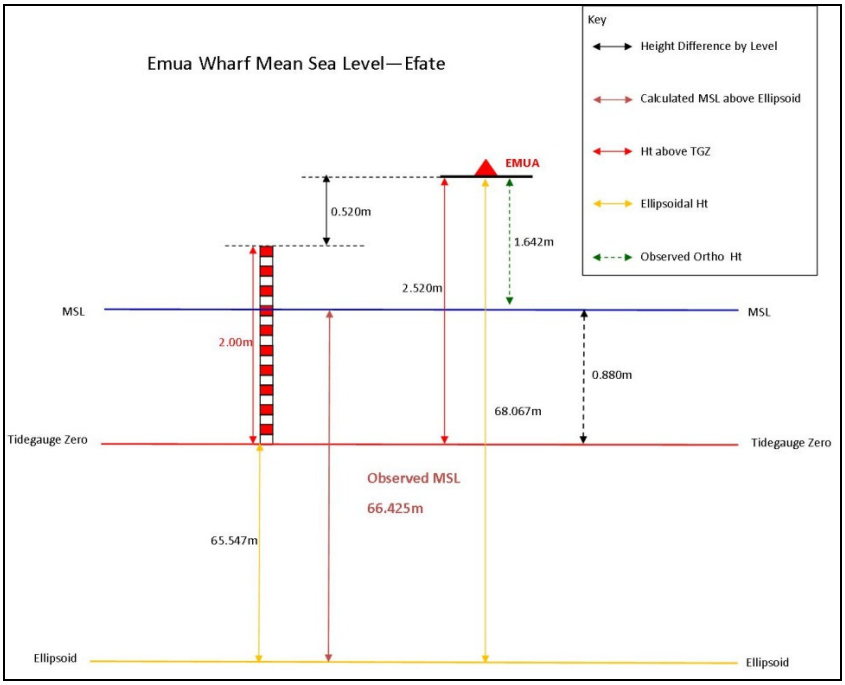


Figure 4.55 Observed, MSL Values Emua

The decision was made to leave the station in-situ as the programme had slipped due to aircraft availability and as a result it may have been possible to collect a full 28 days of observations. However on visiting the site on 20 October 2012, it was found that the station had been vandalised and the station damaged beyond repair. The loss of this and any additional data was reported separately. It is considered the values obtained give a good indication of the Mean Sea Level on this side of the island.

4.3.3 Lits Lits Jetty - Malekula

Part of the overall contract involved topographic LiDAR surveys along parts of the island of Malekula, which lay to the North of Efate. In order to reduce heights to Mean Sea Level it was therefore necessary to confirm the value of Mean Sea Level at some point on the island of Malekula. No tide stations existed on the island, however a substantial concrete jetty was situated in an ideal location midway along the east side of the island at Lits Lits Jetty (16° 06.750' S 167° 26.622' E)

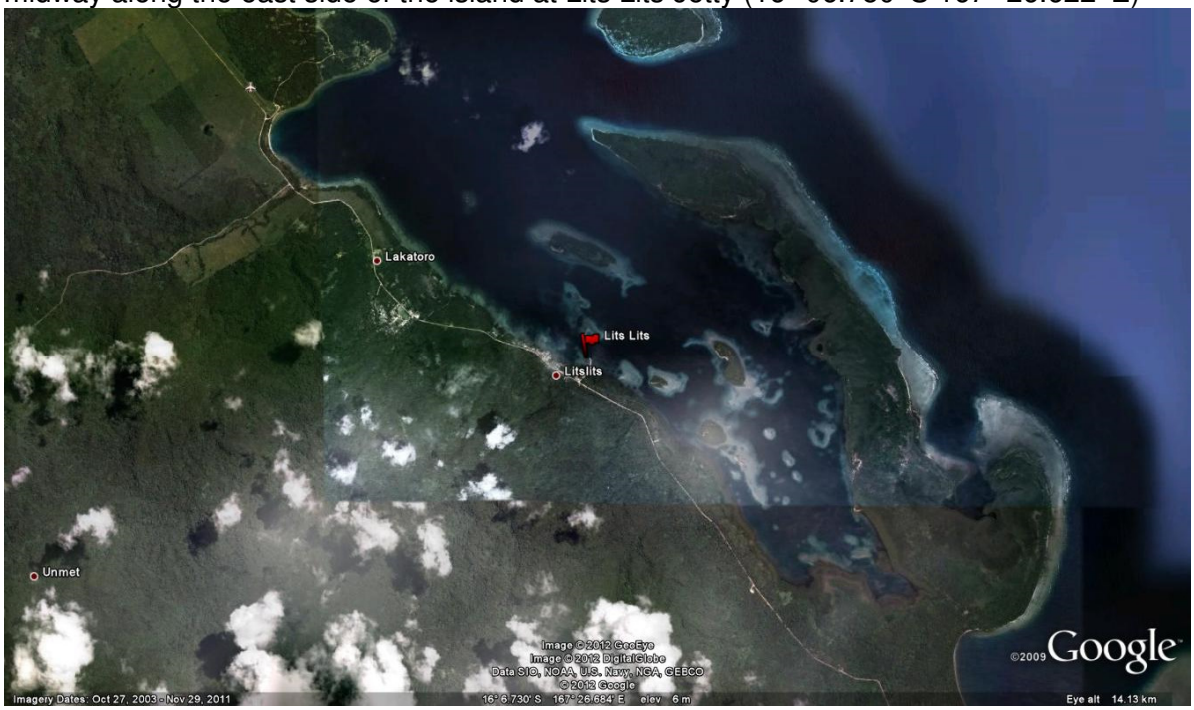


Figure 4.56 Location of Lits Lits Tide Station

Permission was granted by the local chieftain and lease holder to establish a temporary tide station consisting of a 2m tidepole and Valeport 740 automatic tidegauge.

Figure 4.57 Malekula Jetty and Tide Station

The jetty had a number of large rubber rubbing strakes and the decision was made to fix the tidal station to this with the recording unit chained to a bollard in a waterproof box. The pole and gauge were set at a level below the expected LAT using predicted tides. Following installation of the gauge a GPS Benchmark was established at the opposite side of the jetty with observations taking place for 6 hours. The top of the tidepole was levelled to the new benchmark and this was used as the basis of deriving a Mean Sea Level.

A 13 hour comparison was conducted between the gauge and pole and it was found that the zero of the gauge was 0.02m shoaler than Tide Pole Zero and 0.02m should be added to gauge all readings.

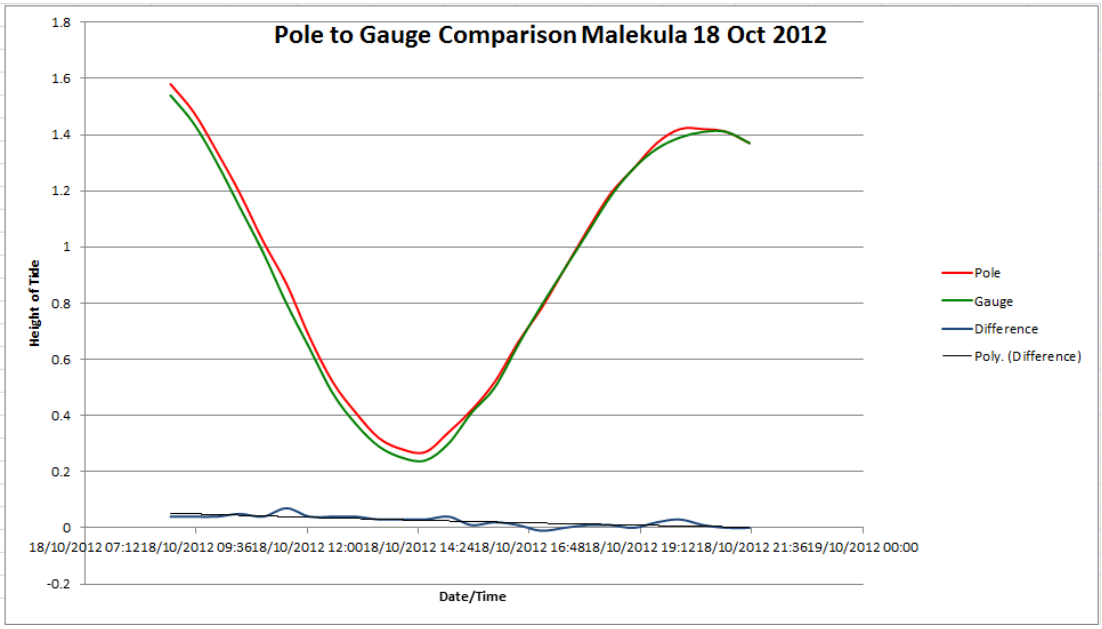


Figure 4.58 Graph showing difference between Tide Gauge and Observed Tidal Heights

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

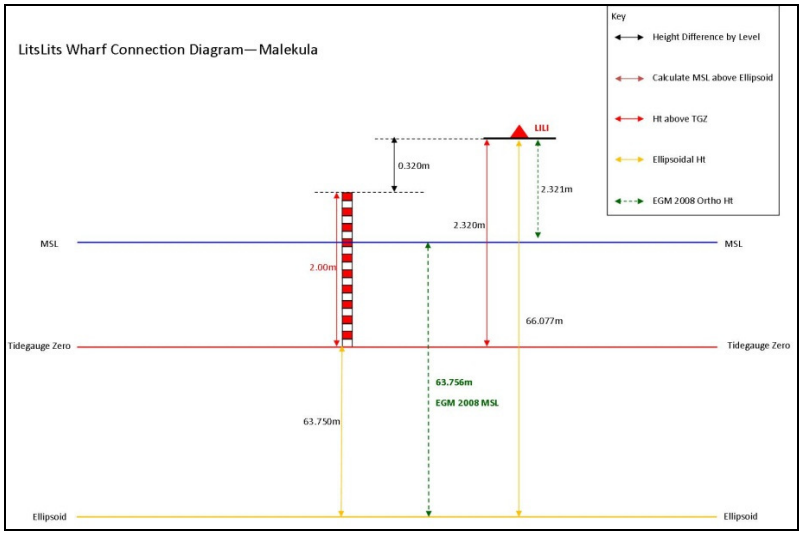


Figure 4.59 Malekula Levelling Connection Diagram based on observations and EGM 2008 MSL values

The gauge was left in-situ between 18th October and 25th October 2012 and then the gauge was recovered and downloaded to allow Mean Sea Level calculations to be conducted. Several observations were made directly reducing the tidal readings to the ellipsoid.

Having averaged the values of the MSL checks the ellipsoid-geoid separation value was calculated as 64.783m. Mean Sea Level was 1.033m above the zero of the pole.

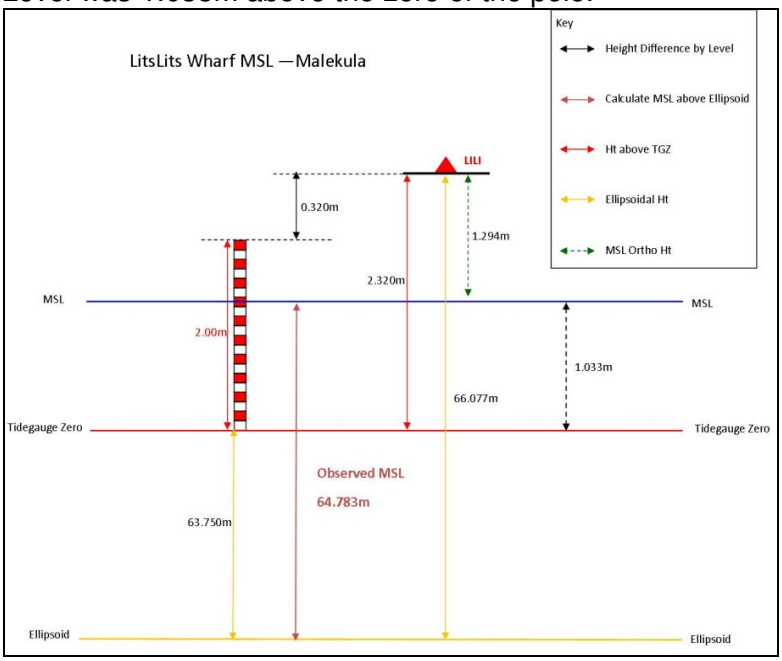


Figure 4.60 Observed, MSL Values Malekula

The derived Mean Sea Level appears to be consistent when compared to the values obtained in Efate and were accepted. The change in MSL is inferred to be a result of a change in the tidal regime and also possibly some impounding effects as the jetty was located in a lagoon area.

4.4 Mean Sea Level Comparisons

4.4.1 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
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**

4.4.1 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.

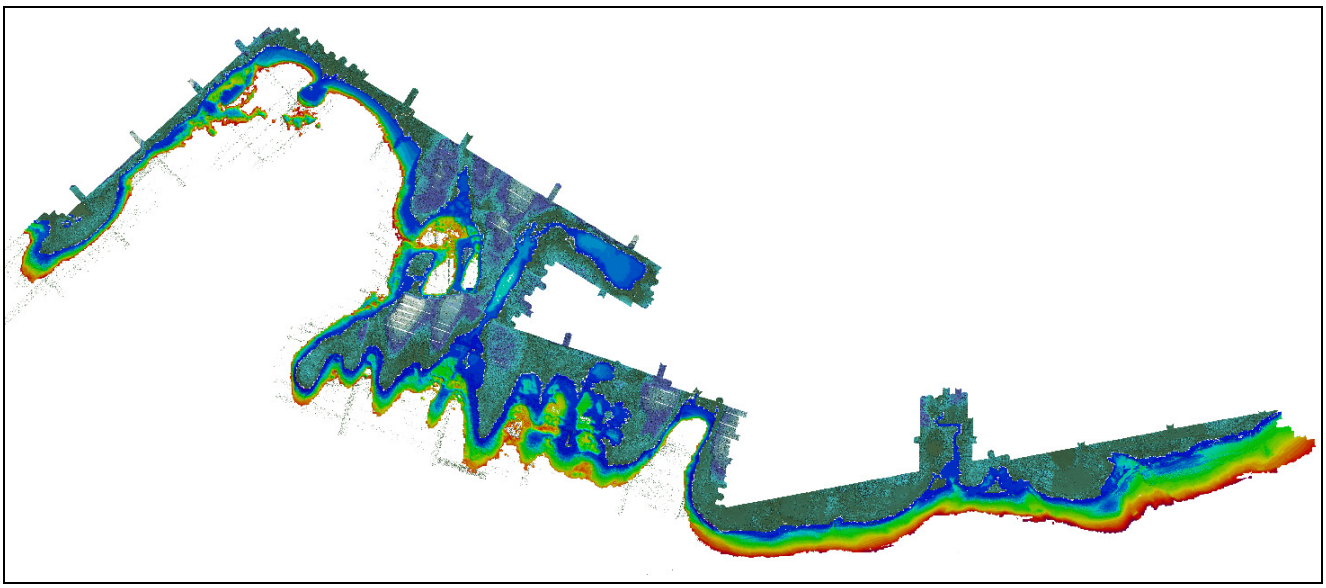
It is assessed that following analysis of the data that the Mean Sea Level Values obtained are accurate to 0.004m when compared to the last 3 years of tidal records at Port Vila. These differences seen are within the likely range of accuracies as stated in The International Oceanographic Commissions 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

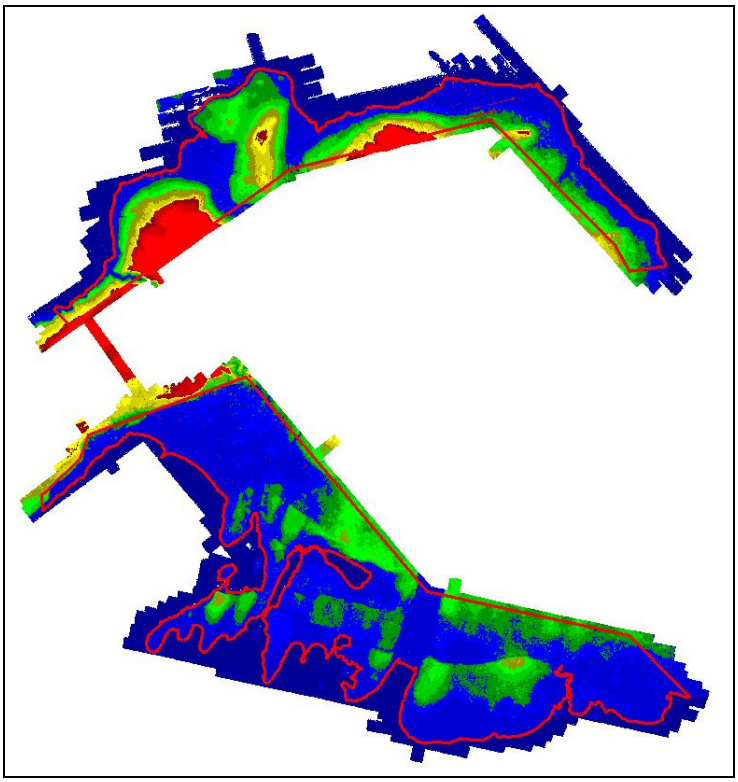
observations and analysis. The insertion of temporary GPS benchmarks at Luganville will allow a local connection to be derived and allow the data from the gauge to be more fully analysed.

5.0 Validation Plots for LiDAR and Imagery

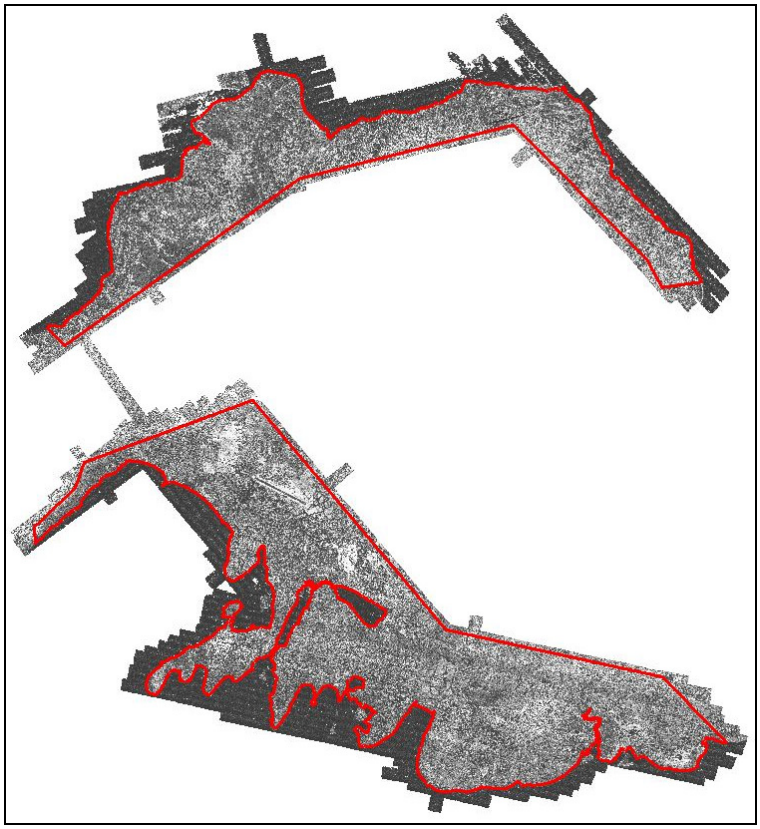
5.1 Efate Bathymetric LiDAR Capture



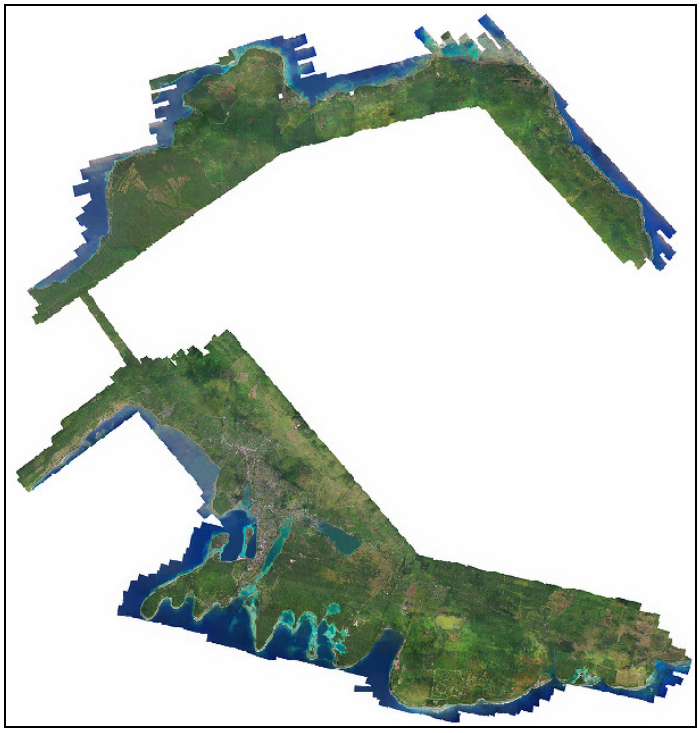
5.2 Efate Topographic Elevation



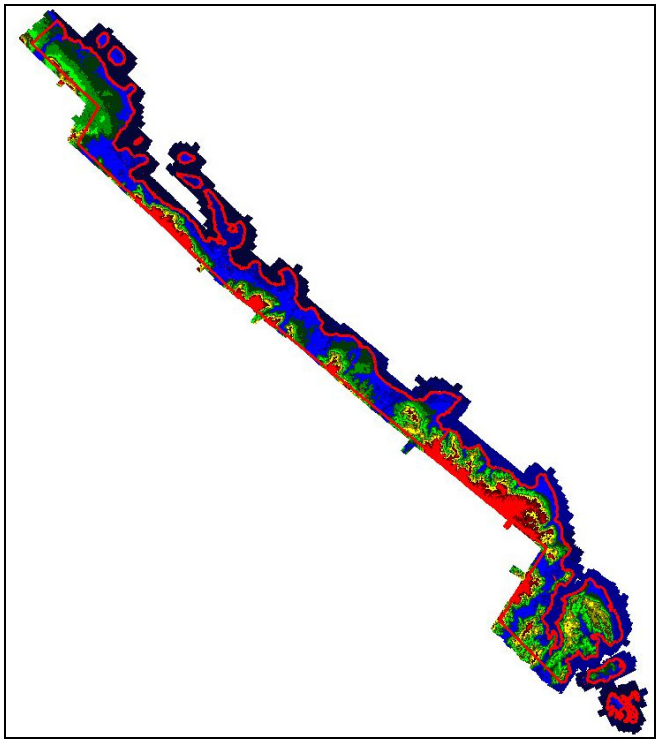
5.3 Efate Topographic Intensity



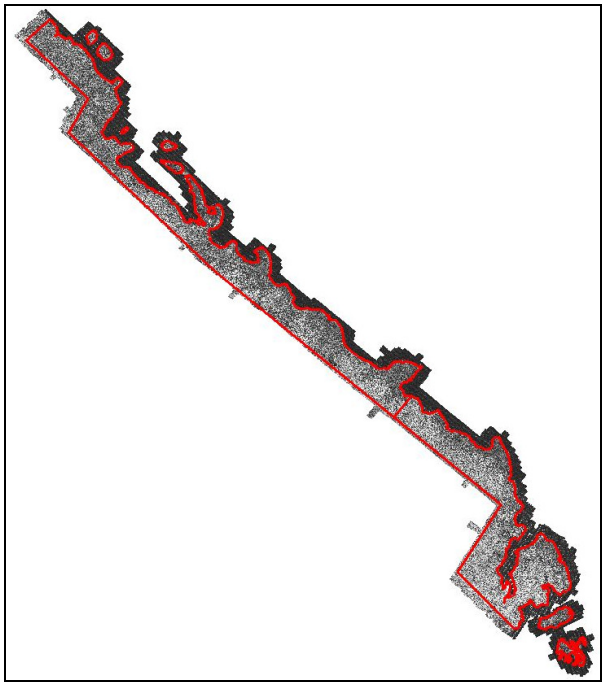
5.4 Efate Topographic Imagery



5.5 Malekula Topographic Elevation



5.6 Malekula Topographic Intensity



5.7 Malekula Topographic Imagery