

Airborne Bathymetric Lidar and Coastal Zone Management in French Polynesia

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Key words: hydrography, ALB, LADS, SW Pacific, French Polynesia, coastal management

SUMMARY

Airborne LiDAR Bathymetry (ALB) systems are an efficient and cost effective tool to survey shallow water including rivers, lakes, estuaries and the coastal zone. The technology has been used around the world and in particular across the South Pacific region by Australian, New Zealand and French authorities since the early 1990s. ALB projects have covered numerous applications including for coastal zone management, climate change and nautical charting.

Rapid advances in technology have enabled the depth performance, data density and accuracy of ALB systems to be increased, thereby improving the speed and cost effectiveness of ALB surveys. In particular, the increased data density has expanded the utility of ALB surveys, thereby increasing the number and scope of ALB projects. Multiple ALB sensors are now frequently combined and in May - June 2015 Fugro operated a high density Riegl VQ-820-G sensor concurrently with a deep water LADS Mk 3 sensor in French Polynesia. A continuous digital elevation model was captured over the land-sea interface of the coastal fringe to satisfy three separate projects.

This paper will review the challenges of optimising ALB operations in a remote location in the SW Pacific and collecting and processing data and products. With much of the world's oceans still unsurveyed to modern standards, and the increased risks in coastal areas due to impacts of climate change and population distribution, ALB will become an increasingly important tool to support governments, organisations and citizens to make more informed and up to date decisions in these vulnerable areas.

Airborne Bathymetric LiDAR and Coastal Zone Management in French Polynesia (8170)
Yves Pastol (France), Luke Chamberlain and Mark Sinclair (Australia)

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Christchurch, New Zealand, May 2–6, 2016

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1. STAKEHOLDERS AND SURVEY REQUIREMENT

During a 5-week period in May and June 2015, Fugro conducted an ALB survey for the French Polynesian Government department, Service de l'Urbanisme (SAU), and the Moorea Coral Reef Long Term Ecological Research (MCR-LTER) program. The project was to create a seamless, precise topographic and bathymetric model of survey areas at Bora Bora, Tahiti and Moorea. Data was required in order to assess the vulnerability of land to climate change at a local level. An important outcome was to better understand risks from cyclonic swells in order to develop better risk management plans. Other planned uses for the data include for hazard and risk assessment including tsunamis, floods, landslides and earthquakes and additional uses may include water resource monitoring and management, supporting tourism initiatives (i.e. better nautical charting for the cruise ship industry and diving industry), agriculture improvements, infrastructure upgrades, port development and fisheries management.

The project was conducted under the technical supervision of the Service hydrographique et océanographique de la marine (SHOM). Expertise has been developed in this area as a result of the Litto3D® program, which has been created to provide a continuous reference digital elevation model of the coastline in metropolitan France and overseas territories for a wide number of applications.

The survey requirement in Polynesia was to collect topographic and bathymetric LiDAR survey data to map the coastal zone, including coastal lagoons and ocean areas to at least the 40 metre isobath and heights to the 10 metre topographic contour. The SAU survey areas included Moorea, part of Tahiti and Bora-Bora (Figures 1 – 4).

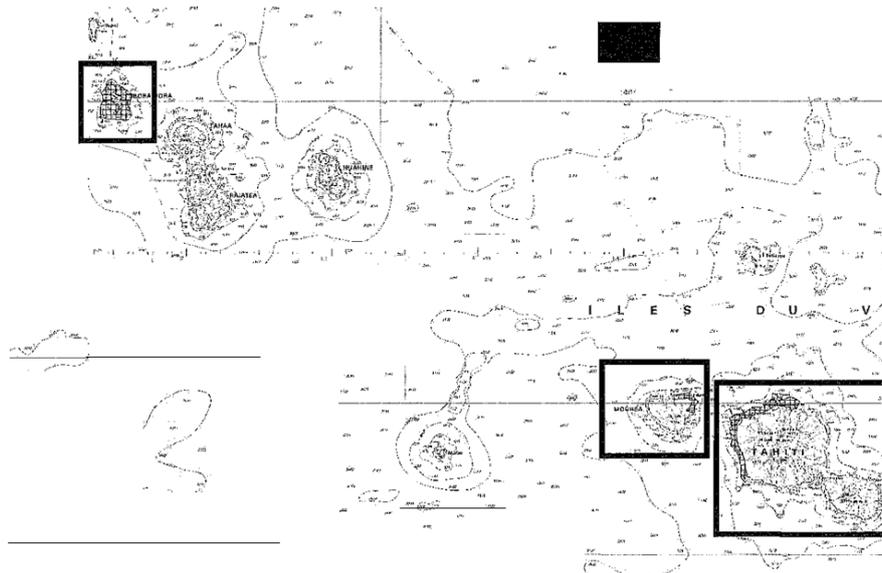


Figure 1 – Location of French Polynesia Project Areas – Tahiti, Moorea & Bora-Bora

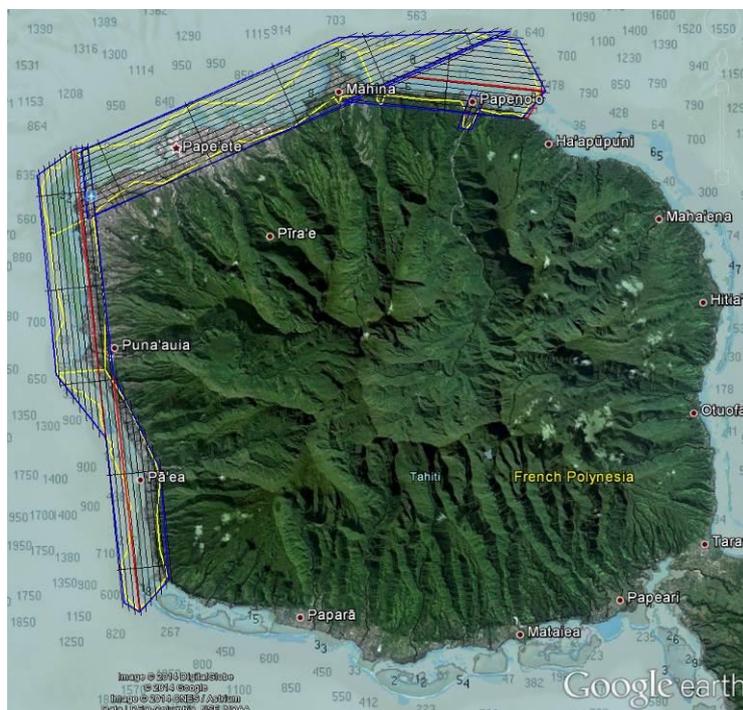


Figure 2 – SAU line plan – Tahiti

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 Yves Pastol (France), Luke Chamberlain and Mark Sinclair (Australia)

FIG Working Week 2016
 Recovery from Disaster
 Christchurch, New Zealand, May 2–6, 2016

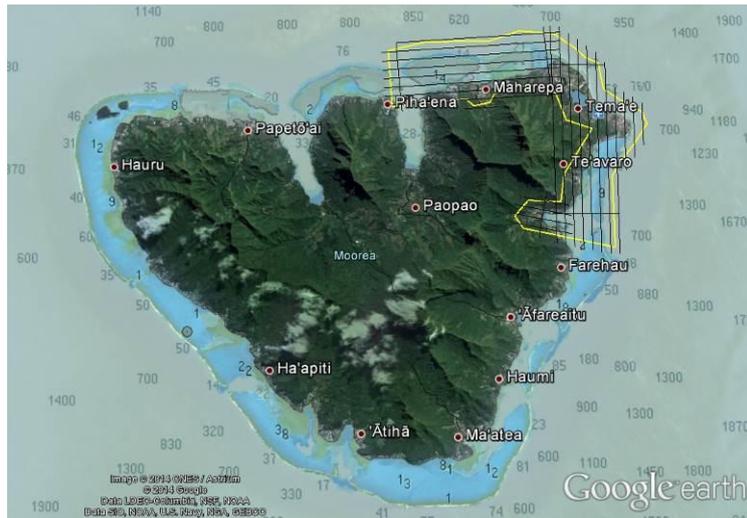


Figure 3 – SAU line plan – Moorea

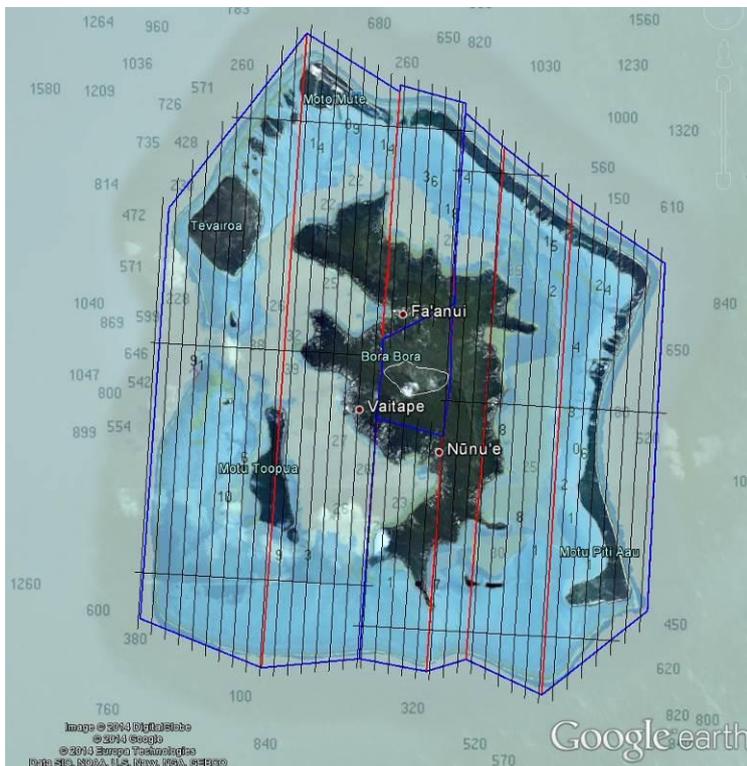


Figure 4 – SAU line plan – Bora-Bora

When the SAU survey became more widely known two additional organisations also developed projects which were subsequently awarded and conducted concurrently. An additional area was

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Yves Pastol (France), Luke Chamberlain and Mark Sinclair (Australia)

FIG Working Week 2016
Recovery from Disaster
Christchurch, New Zealand, May 2–6, 2016

added on the south side of Tahiti for the local government department Direction de l'Équipement (DEQ).

The survey was also extended to cover the entire island of Moorea for the Moorea Coral Reef LTER project. When it became known that areas around Moorea were being surveyed for SAU, a separate proposal was submitted by investigators from the Moorea Coral Reef LTER site to the U.S. National Science Foundation's Long-term Ecological Research program which funded the additional survey area and enabled ALB coverage for the entire coast of Moorea (Figure 5). This additional survey took advantage of the significant fixed costs already required to deploy equipment and personnel from the main project for SAU.

Over the past several decades Moorea has become an international centre for coral reef science and attracts researchers worldwide working at two marine field stations on Moorea (Gump and CRIOBE). Some of these researchers are organizing into a broader research consortium called MooreaIDEA (Moorea Island Digital Ecosystem Avatars) which aims to construct advanced computational models of a range of complex socio-ecological systems, particularly islands (coupled natural-human systems) and cities (built environment) using Moorea as a template. Thus the ALB data from this survey are expected to benefit a substantial international scientific user base.



Figure 5 – Moorea Coral Reef LTER additional line plan – Moorea

DEQ. This additional requirement was to collect an accurate and detailed representation of topography and bathymetry of a small region (the mouth of the Taharuu river) on the southern coastline of Tahiti in the vicinity of Papara as shown in Figure 6.

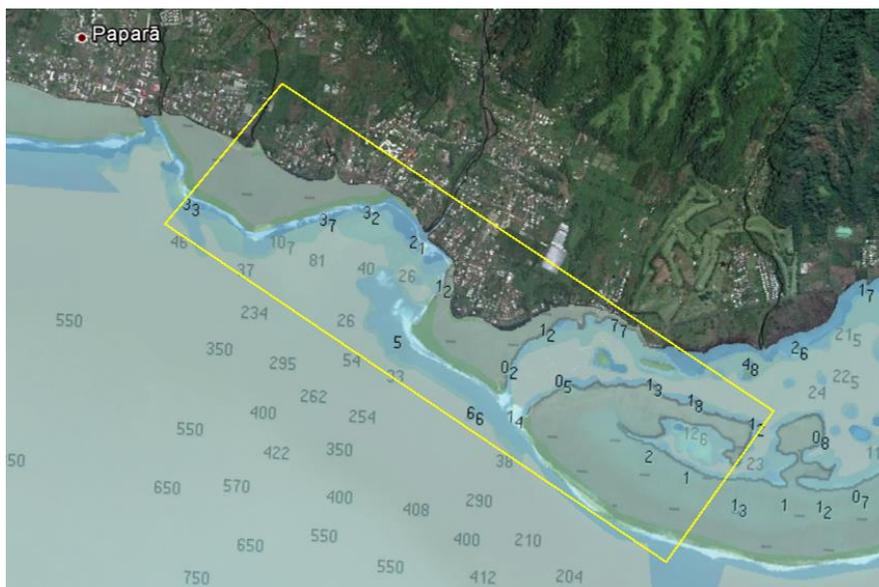


Figure 6 – French Polynesia DEQ additional Project Area – Tahiti

Fugro used the following sensors for the combined bathymetric and topographic survey:

1. **Fugro LADS Mk3 ALB sensor** (for shallow and deeper water to > 70 metres)
2. **Riegl VQ-820-G topo/bathy sensor** (for land and shallow water to depths of < 15 metres).

The sensors were installed front and rear in the survey aircraft and operated simultaneously to collect LADS Mk3, Riegl VQ-820-G and aerial imagery to measure the seafloor and adjoining coastline. This combination of the two bathymetric LiDAR sensors is ideal for this requirement as it provides high resolution data at nominally 4 pts / meter over land and shallow water (from the Riegl) and excellent depth penetration to up to 80 metres (from the LADS Mk3 sensor); the maximum depth performance of both systems is subject to water clarity. This approach provides exceptional performance in deep water, shallow water and on land and results in the capturing of a smooth land – sea continuum.

The required products from the projects include raw and processed data from both sensors relative to local and ellipsoidal datums in LAS format. The local horizontal and vertical datums were relative to the Geodesic Network of French Polynesia (RGPF) and General Levelling of French Polynesia (NGPF) datum. In addition, the following products were also required: merged LADS/Riegl data in LAS format, gridded DEM at 1 and 5 metre resolutions (for the Moorea Coral Reef LTER), georeferenced mosaic imagery in 2 km tiles in geotiff format, mosaics in ECW format, Report of Survey and ancillary data including reports of geodetic survey control, survey coverage achieved and navigation aids detected.

Specific risks to the project were identified which included the remoteness of the region, managing the timely import and export of equipment, managing the challenging survey conditions including the impact of swell, low reflectivity seabed due to black sands on certain beaches, challenging environmental conditions due to the combined impact of high mountains and low cloud bases and lack of existing survey infrastructure, including poor survey control on Bora Bora. How these risks were managed is discussed throughout subsequent sections of this paper.



Figure 7 –Mt Rotui, Baie de Opunohu (left) and Baie de Cook (right) on Moorea – illustrating challenges presented by high ground and low cloud on airborne data collection

2. SURVEY OPERATIONS

Due to the disposition of the survey areas, the French Polynesia survey campaign was divided into two main databases, one for the Tahiti / Moorea survey areas and the second for the Bora Bora area. The Fugro LADS Mk3 and RIEGL VQ-820-G ALB sensors are used simultaneously to satisfy the requirements of deep water bathymetry as well as high resolution shallow water and topographic data.

The project was managed by Fugro LADS Corporation (FLCPTY) with assistance from a local survey firm for establishment of benchmark data, survey control and ground test points. SHOM provided technical oversight, and MCR-LTER provided end user data requirements. Operations were based from Faa'a International Airport, and the survey was estimated to require 5 sorties of up to 4 hours each and a forward deployment to Bora Bora with an additional 2 sorties.

The field deployment was conducted from 27 May to 29 June 2015. There were no safety issues, lost time injuries or defects during this timeframe.

2.1 Mobilisation and Set To Work Period

Airborne Bathymetric LiDAR and Coastal Zone Management in French Polynesia (8170)
Yves Pastol (France), Luke Chamberlain and Mark Sinclair (Australia)

FIG Working Week 2016
Recovery from Disaster
Christchurch, New Zealand, May 2–6, 2016

A field survey office was established at the Sarah Nui Hotel in Papeete on 28 May 2015. The survey aircraft, a Beechcraft A90, arrived on 3 June having been delayed by adverse weather. Bringing the aircraft to Polynesia required significant logistics planning of freight and customs to facilitate the rapid mobilising of both aircraft and equipment from the USA and Australia respectively. Bladder tanks were installed in the aircraft to provide additional endurance for the long over water legs; this required the survey equipment to be removed, and also required waiting for favourable weather conditions prior to departure of the aircraft.

Set to work activities occurred between 4 June and 9 June. These included removal of the temporary bladder tanks, installation of the LADS and Riegl equipment into the aircraft, conducting layback surveys to measure offsets and conducting geodetic observations and static position checks of the installed equipment. The first flight was conducted on 10 June.



Figure 8 – Beechcraft King Air A90 on arrival in Polynesia.



Figure 9 – LADS and Riegl equipment were installed in the aircraft on arrival in Polynesia.

2.2 Weather and Environmental Conditions

Airborne Bathymetric LiDAR and Coastal Zone Management in French Polynesia (8170)
Yves Pastol (France), Luke Chamberlain and Mark Sinclair (Australia)

FIG Working Week 2016
Recovery from Disaster
Christchurch, New Zealand, May 2–6, 2016

The weather conditions were expected to be ideal for this time of the year however frequent low pressure systems passed through the area bringing periods of rain, strong winds, low cloud and swell above 2.5 metres. As a consequence, significant periods of downtime were experienced from 13 - 18 and 20 - 22 June when no survey flights were conducted. In addition, 3 sorties were aborted early due to low cloud.

Outside these periods of inclement weather, the environmental conditions were generally favourable for ALB data collection. Swell required careful management, particularly when surveying the offshore edges of reefs.

2.3 Acquisition Overview

Tahiti and Moorea consisted of 20 main sub survey areas and were flown from Faa'a International Airport. Bora Bora consisted of 2 main sub survey areas which were flown as a forward deployment over the course of three days. All areas were surveyed with LADS at 4.5 x 4.5 metre laser spot spacing. Riegl data was collected at a density of > 4 points / square metre. Refly lines were also flown where required. In excess of 95% coverage of the seabed was achieved in each survey area.

2.3.1 Geodetic Control and Position Fixing System

All ALB data during data acquisition was referenced to the International Terrestrial Reference Frame 2008 at epoch 2015.4 (ITRF08) datum, GRS80 ellipsoid, in UTM coordinates (Zone 5 south – Bora Bora, Zone 6 south – Tahiti / Moorea) and heights relative to the GRS80 ellipsoid through the application of a Kinematic Global Navigation Satellite System (KGNSS) solution. Data was then transformed to Réseau Géodésique de la Polynésie Française (RGPF) datum using the parameters shown in Table 1.

Throughout the survey, the real-time position of the systems was derived from a multi-frequency Trimble BD982 GNSS receiver (POS AV). Real-time PPP corrections from the Fugro Marinestar GNSS service were received and applied by the receiver to the raw GNSS positions.

L1/L2 carrier phase PPK GNSS positions were calculated using POSpac MMS for Tahiti and Moorea. These positions were imported into the Ground System and RiProcess and applied to all LADS and Riegl soundings respectively. The SAU permanent GNSS base station in Papeete was used. For the survey in Bora Bora no permanent GNSS base station existed and a PPP solution was used.

A three parameter horizontal transformation was defined for each survey area to transform the data from ITRF08 (Epoch 2015.4) to RGPF as follows:

- For Tahiti, 48 hours of data from the SAU GNSS base station, PPT1, was submitted to AUSPOS to calculate its ITRF08 position. The Cartesian XYZ differences between the

ITRF08 and quoted RGPF coordinates of the base station provided the parameters for the transformation.

- For Moorea, a 24 hour GNSS observation on a primary survey mark in the survey area was conducted by Fugro LADS personnel and then submitted to AUSPOS to determine its position in ITRF08, with the differences used to determine the XYZ parameters to RGPF.
- For Bora Bora, due to the unreliability of the RGPF datum on the island, two survey marks were selected and then observed by the local survey contractor for around 24 hours before submitting to AUSPOS. These were then compared with the AUSPOS processed position. An average of the XYZ parameters from the logging sessions were used as the parameters for Bora Bora.

Table 1 below is a summary of the parameters for each area.

Parameter	Tahiti	Moorea	Bora Bora
X	1.066	1.065	0.663
Y	-0.767	-0.822	-0.916
Z	-0.579	-0.541	-0.769

Table 1: Cartesian 3 parameters transformations from ITRF08 to RGPF in French Polynesia

ALB data was transformed and supplied to the Geodesic Network of French Polynesia (RGPF, based on ITRF92 epoch 1993.0) and heights relative to the General Levelling of French Polynesia (NGPF). The methodology to transform the ellipsoidal heights to orthometric heights used the following Geoid models:

- For Tahiti and Moorea, the methodology to transform the ellipsoidal heights to orthometric heights used the Tahiti Moorea Geoid Model (University of French Polynesia) located on SAU ftp site: <ftp://reseau.sau.dyndns.org/modele%20de%20geoid/>
Details of this geoid model can be found in the paper: Shih et al. (2015) High-resolution gravity and geoid models in Tahiti obtained from new airborne and land gravity observations: data fusion by spectral combination. Earth, Planets and Space (2015) 67:124 <http://www.earth-planets-space.com/content/67/1/124>
- For Bora Bora the methodology to transform the ellipsoidal heights to orthometric heights used a geoid base on information from the EGM96 (Earth Gravity Model 1996) as defined in CircePF documentation.

The correctness of these parameters was independently verified by SHOM using other GNSS data (logged by SAU and post-processed with SHOM's methods).

Geodetic control was identified as a major risk for the project that could lead to issues with acceptance of the data and the intended uses and modelling. In particular, the weakness of the geodetic network in Bora Bora required special treatment.

Following this process, checks of the data against Topographic Integration Points (TIPs) were conducted. As a result, an additional vertical correction was applied to the Tahiti and Bora Bora Riegl data which was adjusted deeper by 0.12 metres. The final TIP results are described in section 4.7.

2.4 Positioning Quality Checks

The positioning systems were subject to verification prior to and during data collection to ensure the positioning systems were operating correctly.

- **Static Position Check.** The derived coordinates of the aircraft LADS GNSS antenna were determined relative to the control on the tarmac at Faa'a International Airport. A static position check was conducted on 07 June 2015. Data were logged by the Fugro LADS Mk3 and RIEGL VQ-820-G positioning systems over a two-hour period; this enabled the positions to be verified against the known surveyed points.
 - Results of the LADS Mk3 session on 07 June 2015 were GNSS only ± 6.739 metres (95% confidence), PPK GNSS PPP ± 0.037 metres (95% confidence) and PPK GNSS base station ± 0.051 metres (95% confidence).
 - Results of the RIEGL VQ-820-G session on 07 June 2015 were GNSS only ± 8.074 metres (95% confidence), PPK GNSS PPP ± 0.077 metres (95% confidence) and PPK GNSS base station ± 0.067 metres (95% confidence).
- **Dynamic Position Check.** During each sortie, GNSS data were logged on the aircraft. The LADS Mk3 real-time GNSS PPP and the post-processed KGNSS PPP positions of the aircraft have been compared. The mean difference was 0.578 metres (95% confidence) and the maximum difference was 2.263 metres.

These results are consistent with correct system performance.

DATA PROCESSING

In the initial stages of the data processing, the datasets of the two respective LiDAR systems are kept separate and follow the general stages as per figure 10 below. During the data collection phase the focus in the field is to confirm, after each sortie had been flown, that the required coverage had been achieved and to verify the quality of both datasets.

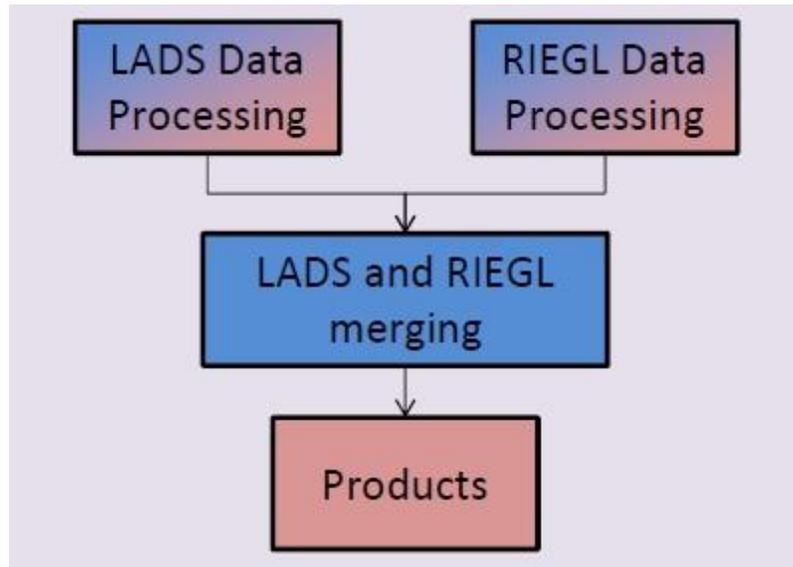


Figure 10 – Overall Data Work Flow Diagram

For LADS Mk 3 processing, on completion of each flight the post processed GNSS solution using a local permanent GNSS base station is applied to the raw data and digital images. The data are then processed on the Ground System (GS) to produce depth, position and a series of confidence parameters. Each sounding and associated confidence data are stored in the database. A line review of the data quality is conducted by the senior hydrographic surveyor and the survey party chief then decides if any part should be reflight for such things as systematic issues, areas of turbidity and poor coverage. The general flow of processing of the LADS Mk3 data is shown in Figure 11, with the focus during the field data collection stage in the field highlighted in pink.

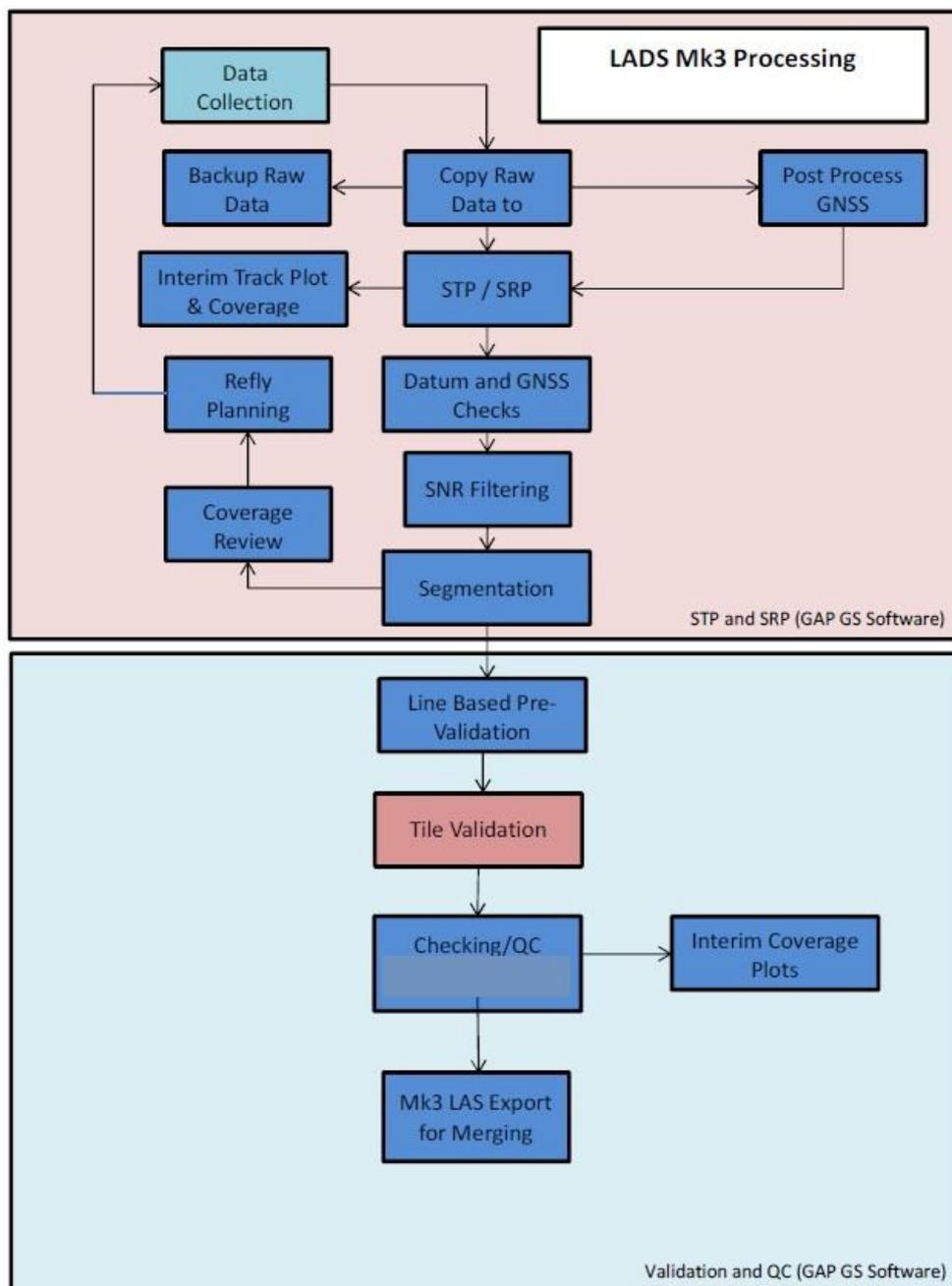


Figure 11 – LADS Mk3 Data Work Flow Diagram

In a similar process the RIEGL VQ-820-G has an initial stage conducted in the field to assess the general quality of the flight line data after each sortie and assessments made if any had to be reflown. Once the senior hydrographic surveyor is satisfied that the data is of acceptable standards it gets passed to a water surface modelling stage to enable refraction corrections to be applied.

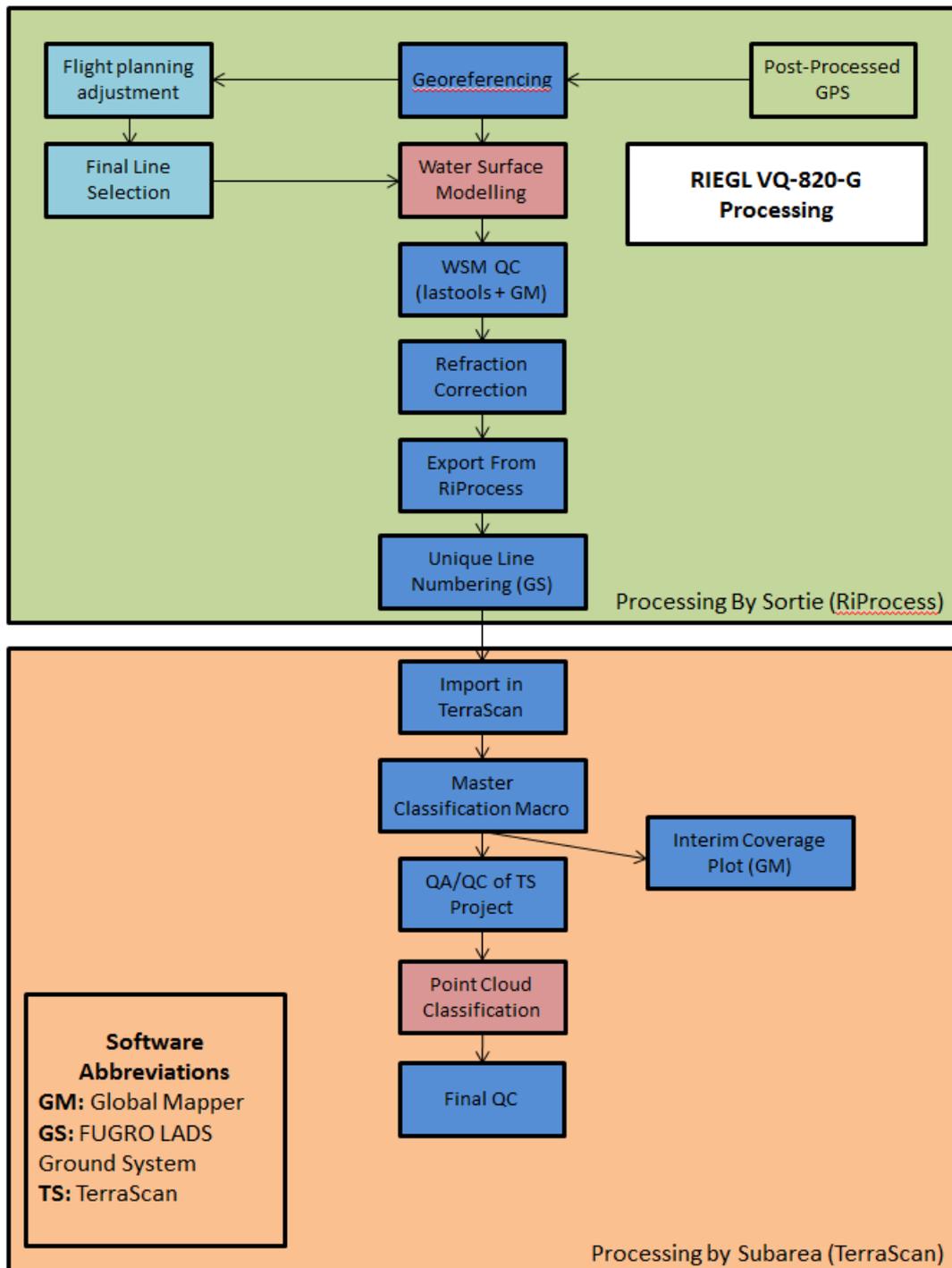


Figure 12 – RIEGL VQ-820-G Data Work Flow Diagram

Following data collection, all data are relocated to the Fugro LADS data processing office in Kidman Park, Adelaide for further refinement and product generation.

Airborne Bathymetric LiDAR and Coastal Zone Management in French Polynesia (8170)
 Yves Pastol (France), Luke Chamberlain and Mark Sinclair (Australia)

FIG Working Week 2016
 Recovery from Disaster
 Christchurch, New Zealand, May 2–6, 2016

The LADS Mk3 data undergoes a validation, quality control and export phase, conducted by hydrographic surveyors who operate the Airborne System and trained in data processing procedures, described as follows:

- Validation pass - which comprises of a line by line detailed inspection and editing of the data. All features are inspected and incorrect returns due to turbidity or noise are removed or edited. Comments are recorded for each edit made, and attributes can be assigned to the data consistent with the S-57 nautical charting format. All operator interactions during the validation phase are logged so that complete traceability, ownership and consistency are maintained. It is at this stage that the “cut-off” value is applied to the upper shallower limit of the LADS Mk3 data and assumed to be filled by the RIEGL VQ-820-G, typically 5 metres depth.
- Quality Control – an independent review of the LADS Mk3 data is conducted by area, as opposed to by line. This is the most important phase of the process. The position, depth, run and other relevant attributes are extracted from the database for use in the generation of TIN models and gridded data sets to produce contour plots, sun-illuminated colour-banded images, coverage check plots and difference plots. Anomalies found are digitally recorded and reported for remedial action.
- Final Coverage review and Export for Merging – At this stage the interim Riegl data coverage is imported and assessed in the Ground System for gaps in the shallow regions and data is recovered where necessary. Once completed all data is exported in LAS v1.2 format and ready for the merging process.

The continuation of the RIEGL VQ-820-G data processing also occurs as follows. Following on from the refraction corrections, all RIEGL flight line data are then cross referenced to the LADS Mk3 database to get assigned the corresponding line number. From this point the RIEGL VQ-820-G data undergoes a classification, quality control and coverage output phase, described as follows:

- Classification – An initial automatic macro is applied and conducts a basic level one classification in Terrascan. It then undergoes a further refinement manually to identify noise and ensure the ground and seabed classes are true. While a full classification was not required for this project any manmade features such as navigation aids and wrecks were also identified in a separate class for reporting.
- Classification Quality Control – an independent review of the RIEGL VQ-820-G data is conducted by the senior survey personnel to ensure the correct assignment of classes has been applied.
- Coverage Review – on completion of the QC, a final RIEGL VQ-820-G coverage plot is output and used in the final stage of the LADS Mk3 coverage review, by importing into the GS, as described in the preceding LADS Mk3 processing steps.

The final phase of the data processing workflow is the merging, approval and product generation of the ALB datasets, as described in figure 13 below. LAS data from both the LADS Mk3 and RIEGL VQ-820-G is fed into TerraScan. During this stage all the horizontal and vertical datum transformations were applied to take it from ITRF08 / GRS80 to the required RGPF / NGPF datum, described in Section 2.3.1. A final quality control / approval review was conducted to either accept, refer data back for rework, or in a small percentage of cases reject data not required. The following checks were conducted:

- Difference plots generated and profiles reviewed between the junction of the LADS Mk3 and Riegl VQ-820-G datasets.
- Review final coverage and any gaps within the contracted survey area.
- Check final reduced datasets against the topographic and bathymetric benchmarks to assess data has met the required accuracy for each respective LiDAR system, being;
 - LADS Mk3 – Horizontal accuracy better than 2.28m (95% confidence) and vertical better than 0.40m (95% confidence).
 - RIEGL VQ-820-G – Horizontal accuracy better than 1.00m (95% confidence) and vertical better than 0.20m (95% confidence).
- Check all cross-ties against the final reduced datasets.

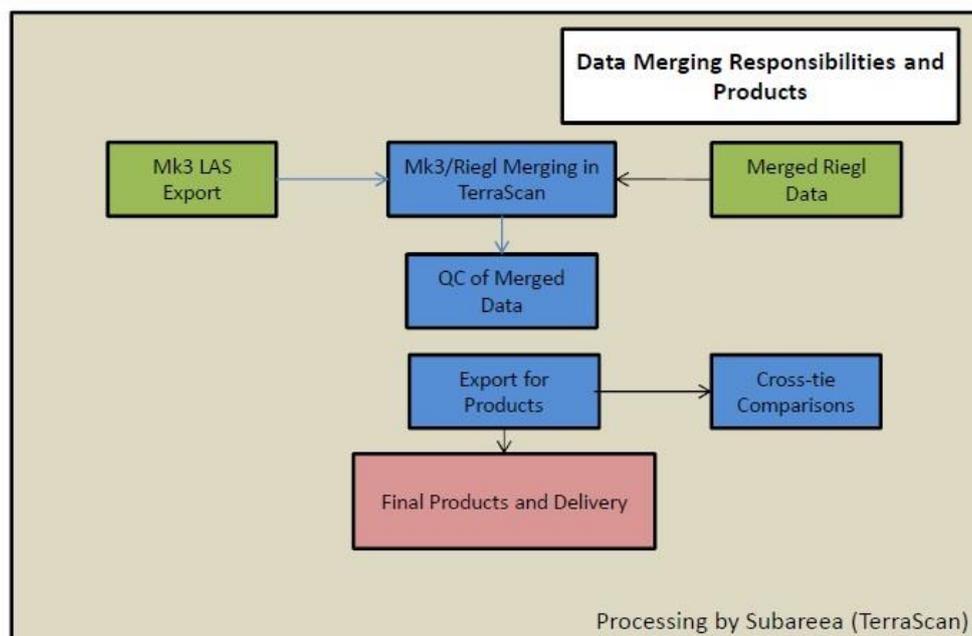


Figure 13 – Data Merging and Products Work Flow Diagram

These processes were assisted by reviewing the data against the downward looking digital camera taking two mega pixel photographs at 1 hertz. These geo-referenced images are automatically displayed in the LADS Mk3 ground system, linked to the ALB data, so that the position of soundings can be seen on the digital images. This assists the interpretation and classification of features in the data such as the coastline, islands, drying rocks, rocks awash, shallow rocks, kelp, beacons, buoys, boats, jetties, buildings and trees.

Data merging and products process includes the following steps:

- LADS Mk3 and RIEGL VQ-820-G merging in LAS 1.2 format (each sensor using dedicated point classes).
- Assess overall merged coverage and retrieve additional data from either LADS Mk3 or RIEGL VQ-820-G where required/possible to fill potential remaining gap and ultimately improve the final coverage.
- Assess overlap quality by producing overlap imagery showing the raw elevation offsets between both sensor which are 100% independent (dedicated GNSS receiver and IMU).
- Conduct line matching adjustment to produce a seamless merged LADS Mk3 and RIEGL VQ-820-G dataset (adjustment up to +/-15cm). These were primarily the result of the absolute accuracy of the calculated GPS trajectories and improved the final ALB point cloud relative accuracy.
- Produce final coverage plots and project final products (DEM, etc.).

As an additional check, preliminary 5m gridded MBES data was made available over the entire Island of Moorea and merged with a 5m grid of the combined ALB datasets. A surface comparison plot was generated between the two surfaces and the overall results of 0.4m +/- 2.66m was achieved from over 964,000 individual grid comparisons. Considering issues of slope and beam footprint from each respective system compared, these results are very pleasing.

On satisfaction that all survey areas met the required expectations, products were generated and supplied to SAU/SHOM for final QC. All data were accepted following detailed review by SHOM.

3. RESULTS

The following products were required on UTM zone 5 (Bora-Bora) & UTM zone 6 (Tahiti and Moorea) south grid, relative to RGPF and NGPF datums:

- All raw LADS Mk3 LiDAR data
- All raw RIEGL VQ-820-G LIDAR data
- All raw survey control data
- Processed ellipsoidal data in LAS format, reduced to GRS80 spheroid
- Processed orthometric data in LAS format, reduced to the RGPF / NGPF datum
- Final Coverage in ESRI shp format (polygon)
- Navigation aids in ESRI shp format (point)
- Processed aerial imagery, 1km x 1km tiles geotiff format
- Processed aerial imagery mosaic in ECW format

Airborne Bathymetric LiDAR and Coastal Zone Management in French Polynesia (8170)
Yves Pastol (France), Luke Chamberlain and Mark Sinclair (Australia)

- Field and Survey Reports in PDF format

For metrics and analysis, the French Polynesia survey was broken up into the three survey areas. The areas were surveyed when the effects of swell were at a minimum by maximising opportunities when conditions were calmest over the outer reef edges.

3.1 Timings

The survey activities for the SAU project areas were completed in 22 data collection hours that included 1.5 hours of time lost due to aborted flights due to low cloud and other instrument issues. This was within the timings expected during the planning stages of the project.

3.2 Coverage

For all survey areas in Tahiti, Moorea and Bora Bora the required minimum 95% coverage to the 40 metre isobath were achieved. The final coverage areas and percentages are as follows:

Area	Required SqKm (+10m drying to 40m depth)	Achieved SqKm (+10m drying to 40m depth)	Area percentage covered
Tahiti	86.52	85.21	98.5%
Moorea	84.51	82.59	97.7%
Bora Bora	99.60	95.15	95.0%

Table 2: SAU coverage areas and % complete

In general, excellent coverage was obtained throughout all three areas to the required depth, with few gaps in the data. There were isolated areas of turbidity which predominantly affected the coverage in the deeper areas of:

- north coast of Tahiti: Papeete Harbour and Vaiare Baie.
- Baie de Cook and Baie de Opunohu on the Island of Moorea.
- Baie Faanui in Bora Bora.

Some particularly turbid areas were experienced along the northern survey areas of Tahiti including Papeete Harbour (Figure 14).

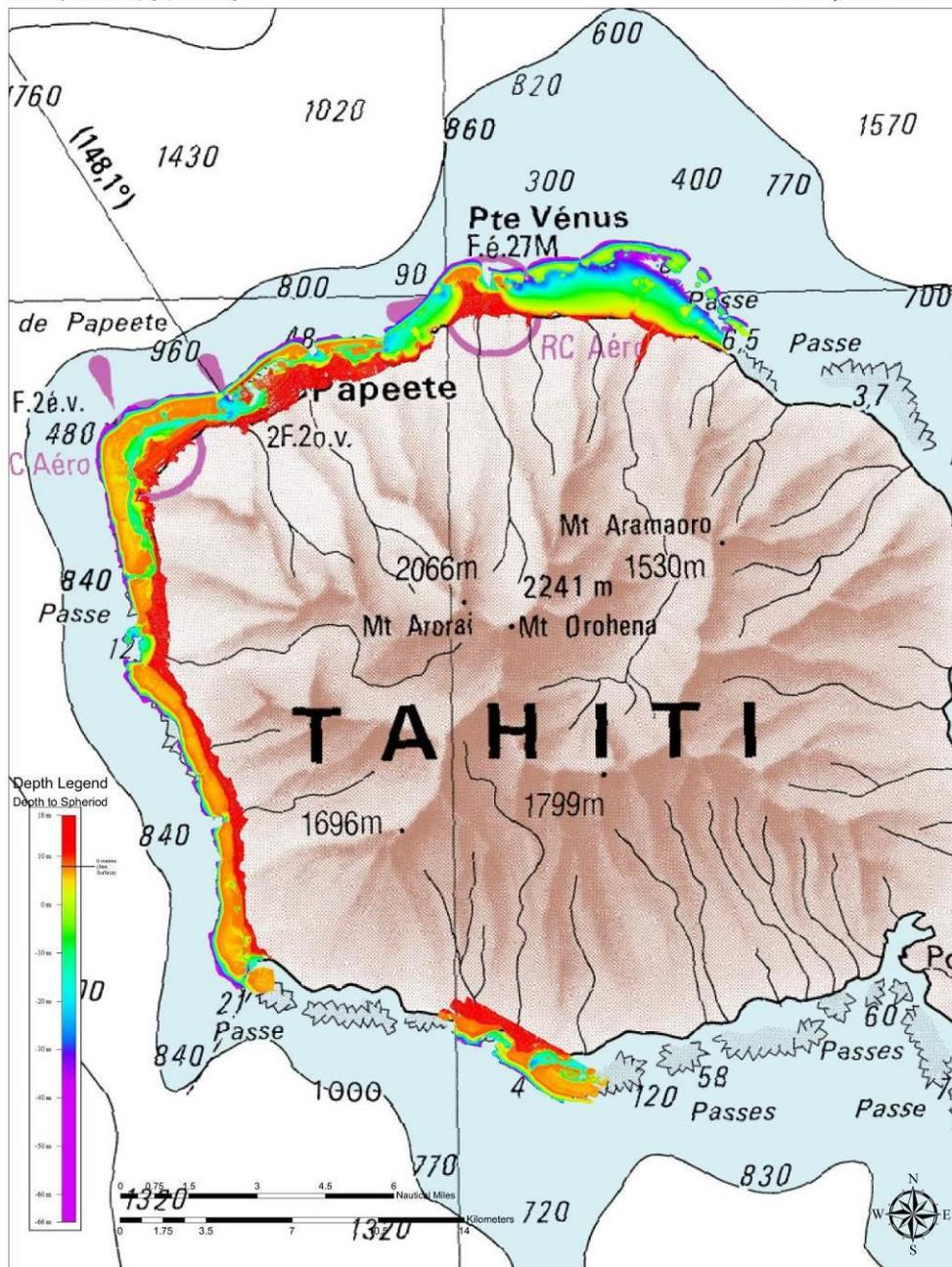


Figure 14 – Tahiti LiDAR survey coverage

Some gaps in the coverage also occurred due to higher levels of turbidity in the deeper areas within deep bays and inner reefs of Moorea (Figure 15).

Airborne Bathymetric LiDAR and Coastal Zone Management in French Polynesia (8170)

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FIG Working Week 2016

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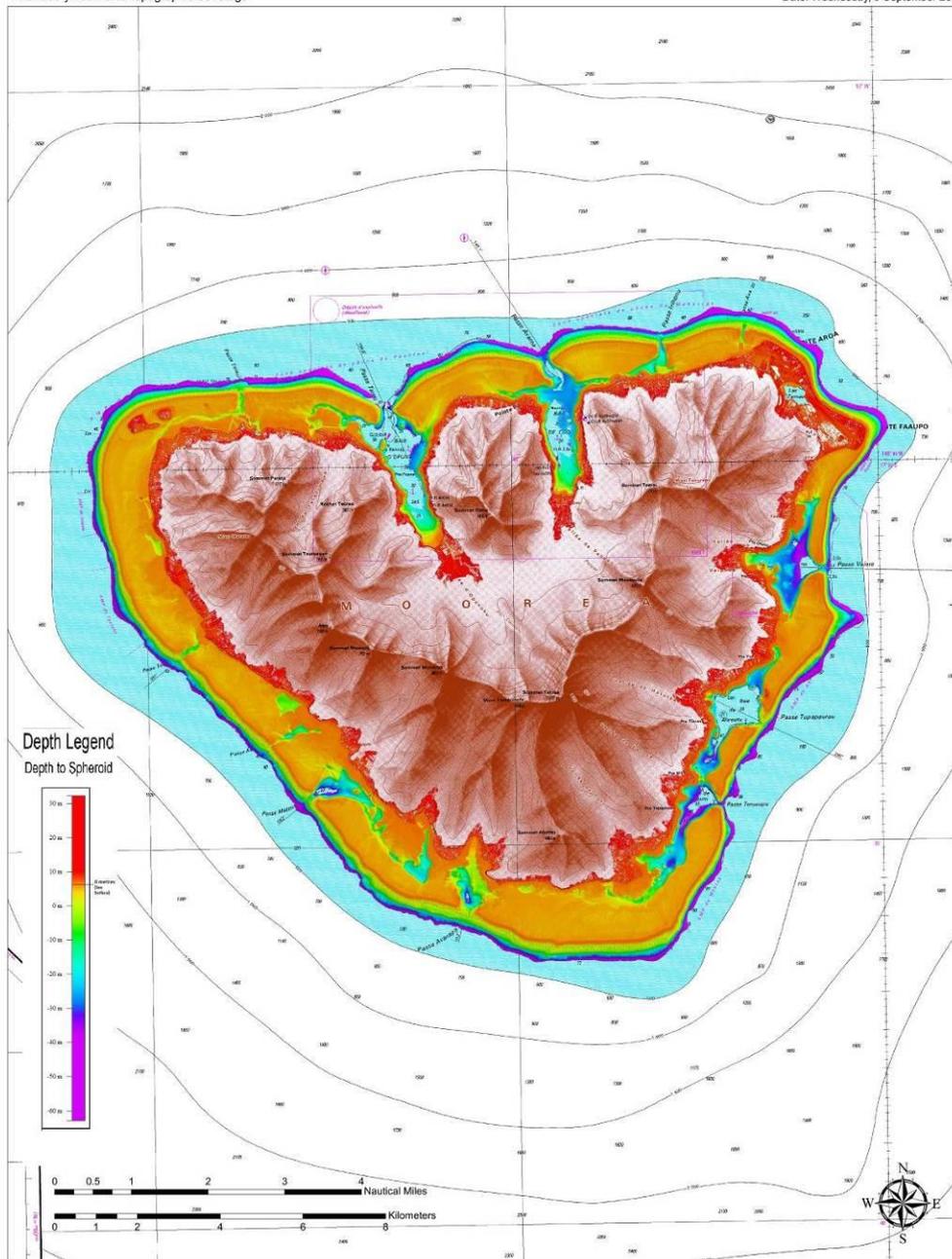


Figure 15 – Moorea LiDAR survey coverage

In Moorea, MBES coverage from a 2014 survey using a [RESON 8101-ER](#) multi-beam echosounder and [Applanix POS/MV](#) position and orientation system was made available by the MCR-LTER project, which was merged and filled in the gaps in the deeper water, more turbid bays and along the outer reef edge (Figure 16).

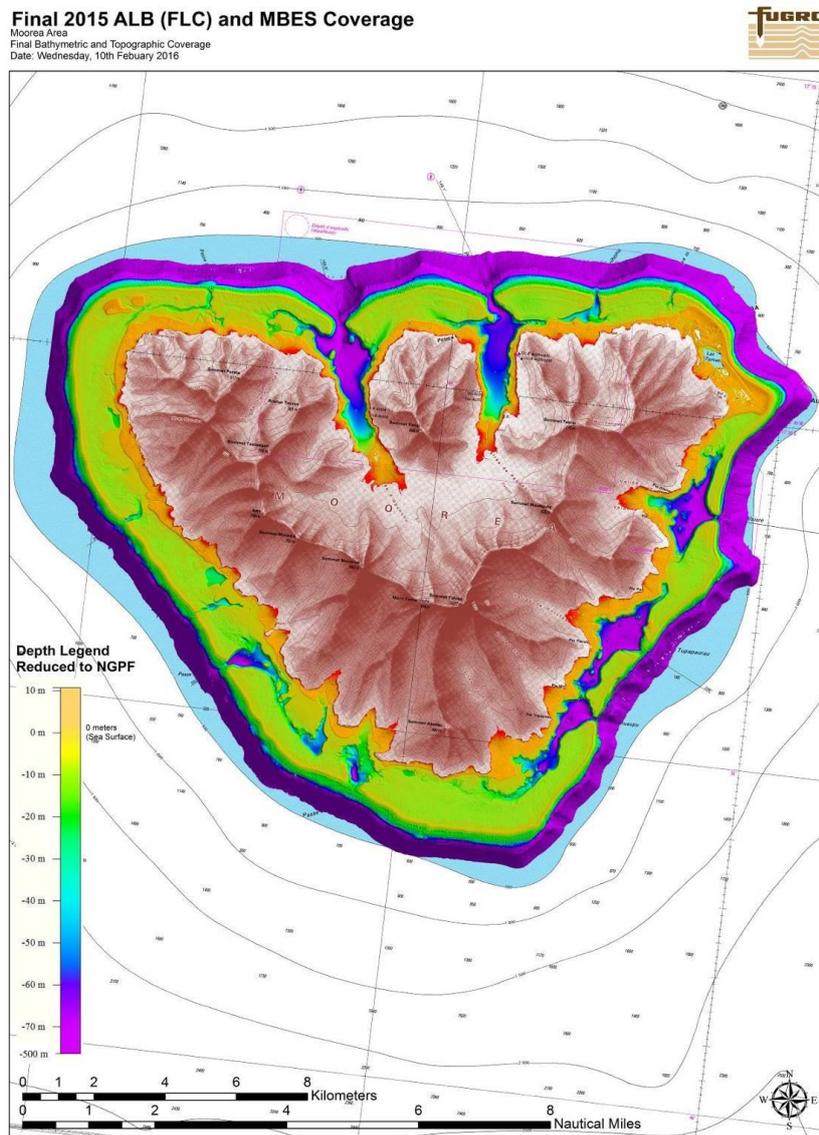


Figure 16 – Moorea LiDAR and MBES merged survey coverage

Some gaps in the coverage also occurred due to higher levels of turbidity in the deeper areas within the inner reefs of Bora Bora.

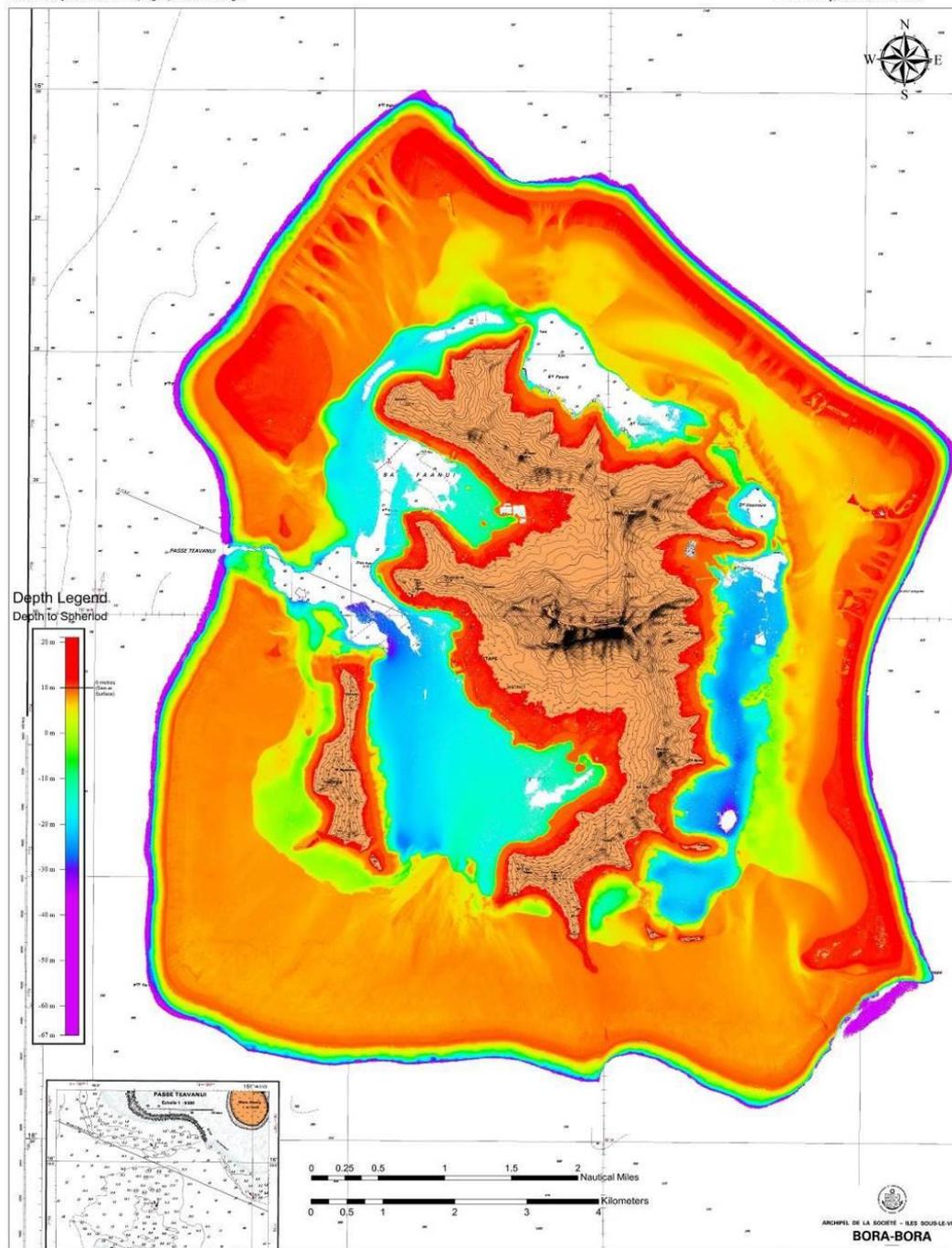


Figure 17 – Bora Bora LiDAR Survey Coverage

Airborne Bathymetric LiDAR and Coastal Zone Management in French Polynesia (8170)
Yves Pastol (France), Luke Chamberlain and Mark Sinclair (Australia)

FIG Working Week 2016
Recovery from Disaster
Christchurch, New Zealand, May 2–6, 2016

In addition, ALB seabed reflectivity was also calculated from the energy in the returned laser waveform. This can be used to deduce seabed type and is useful for habitat management. An example of the shallow water Riegl coverage from Bora Bora is shown below.

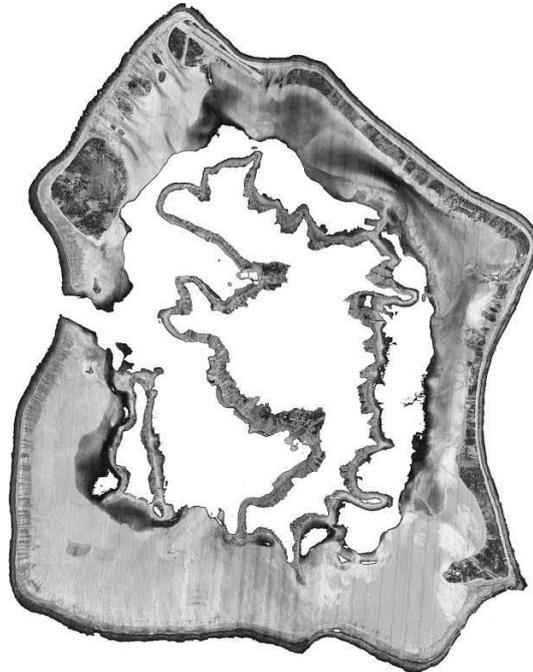


Figure 18 – RIEGL VQ-820-G Reflectance data of the Bora Bora survey area.

A significant project risk was considered to be achieving adequate coverage over areas of black sand including areas in Tahiti, which were thought to be very challenging due to low reflectivity. However, the first flights over the ground truth close west of Pointe de Vénus was over totally black sand and excellent coverage was achieved by Riegl to a depth of 13 metres, with LADS coverage extending beyond that. As a result, this risk did not eventuate.



Figure 19 – Black sand on Tahiti south coast – this was considered to be a project risk due to low reflectivity however was not an issue.

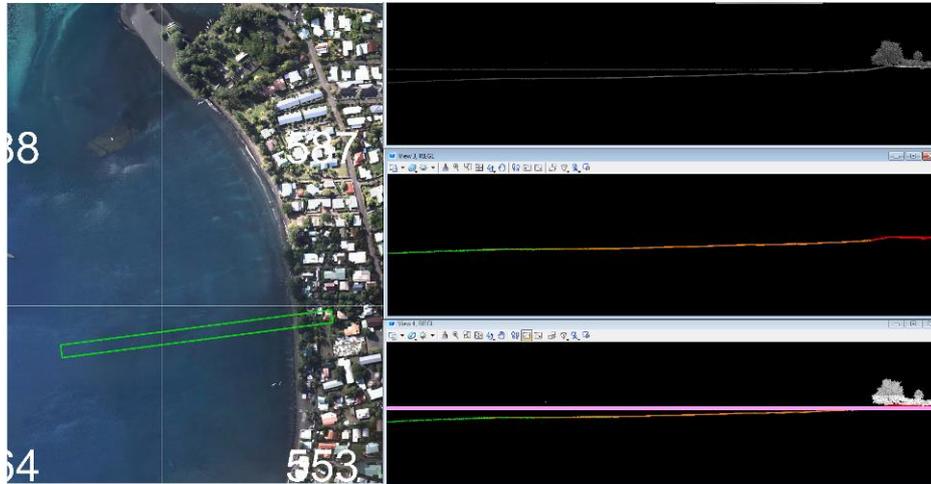


Figure 20 – Excellent LADS and Riegl coverage was achieved over these areas of black sand in Tahiti.

3.3 Depth Performance

Another important performance metric is the functioning of the laser system, which provides confidence to the dataset overall. The coverage images show that 50m water depths were regularly exceeded. The laser waveform screenshot below, in a deep reef area off Moorea, shows the Fugro LADS sensor measured a depth of 76.1 meters. This is the maximum depth ever recorded by the ALB system.

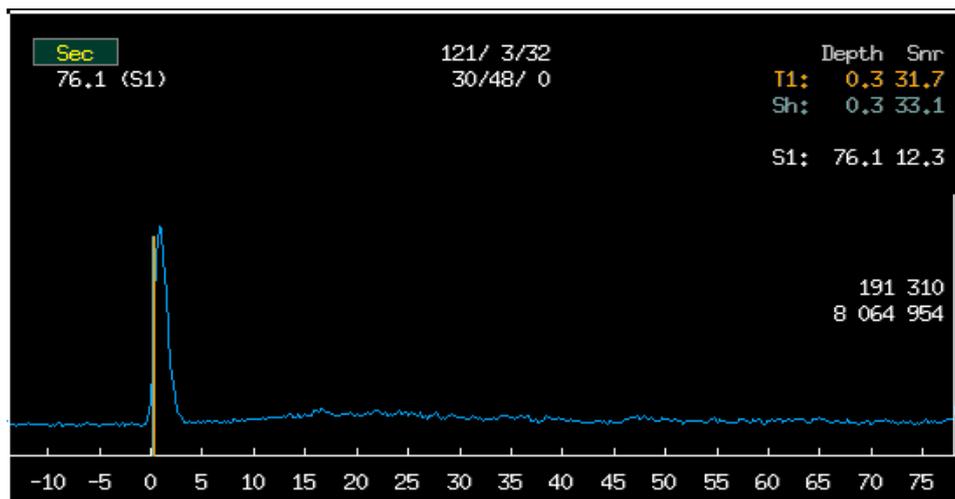


Figure 21 – Laser Waveform of 76.1m water depth return

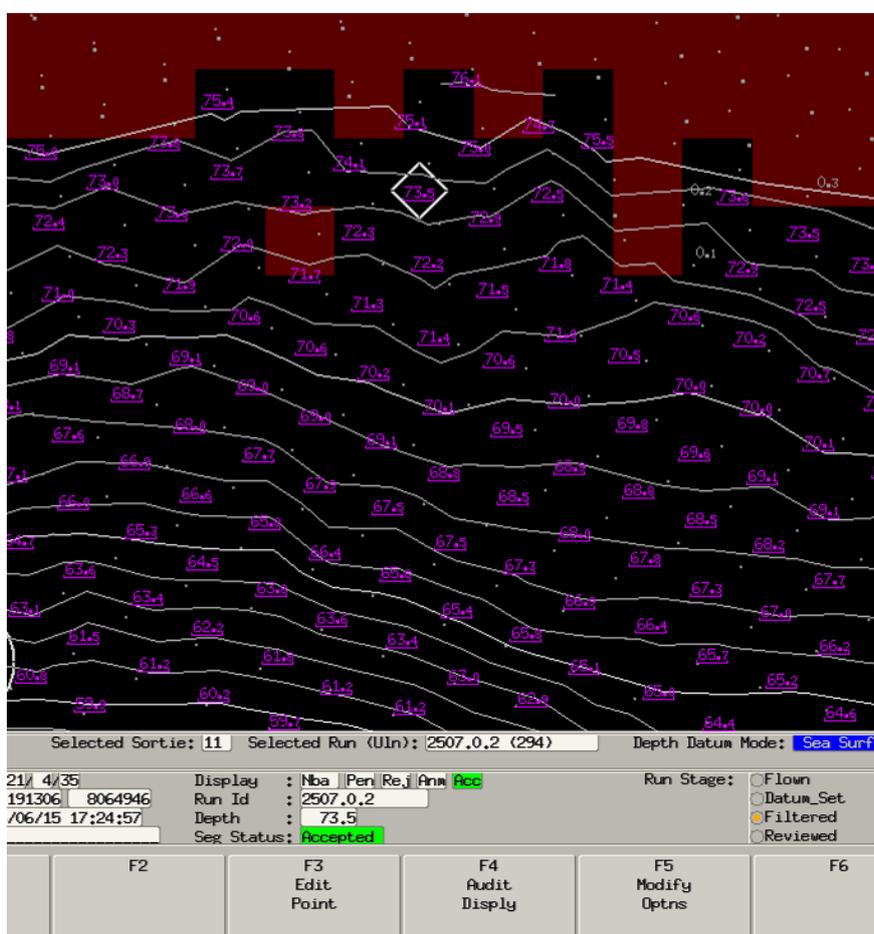


Figure 22 – Continuous ALB data covering depths to 76.1 metres.

Airborne Bathymetric LiDAR and Coastal Zone Management in French Polynesia (8170)
 Yves Pastol (France), Luke Chamberlain and Mark Sinclair (Australia)

FIG Working Week 2016
 Recovery from Disaster
 Christchurch, New Zealand, May 2–6, 2016

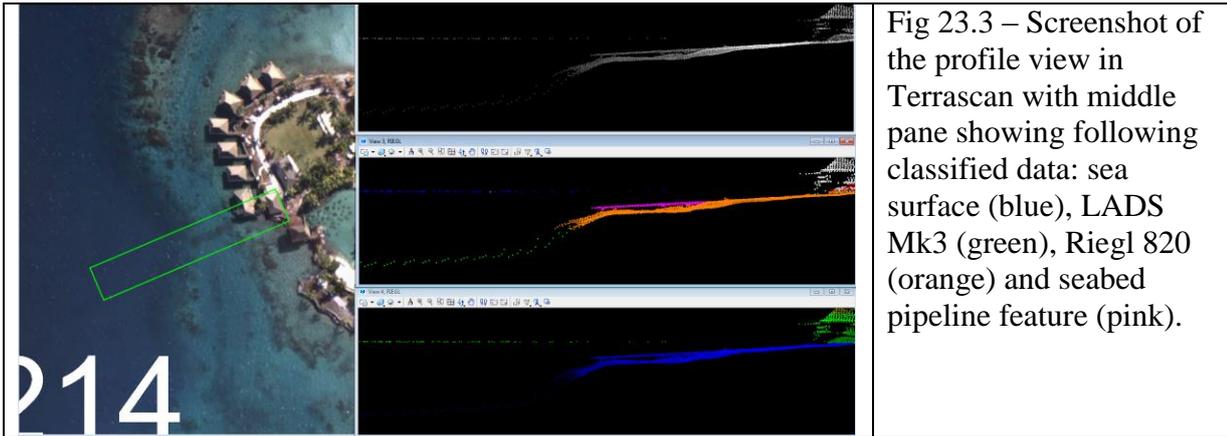


Fig 23.3 – Screenshot of the profile view in Terrascan with middle pane showing following classified data: sea surface (blue), LADS Mk3 (green), Riegl 820 (orange) and seabed pipeline feature (pink).

A 1-metre target was laid in a depth of 14 metres in the survey area by SHOM in early June and was detected by the LADS system (Figure 24) due to the very clear conditions. This was at the limit of detection on the raw laser waveform; normally the minimum practical object detection size by ALB is 2 metres (IHO order 1a) which still requires clear conditions for a high seabed and target waveform signal to noise ratio to be measured.



Figure 24 – detection of 1 metre target in Polynesia.

3.5 Positioning Accuracies

Airborne Bathymetric LiDAR and Coastal Zone Management in French Polynesia (8170)
 Yves Pastol (France), Luke Chamberlain and Mark Sinclair (Australia)

FIG Working Week 2016
 Recovery from Disaster
 Christchurch, New Zealand, May 2–6, 2016

The positioning accuracies from the SAU survey are shown in the table below. No gross errors were detected and better results were obtained using the KGNSS PPP position.

Positioning System	Baseline Distance (km)	Theoretical GNSS Accuracy x,y (m) (95% confidence)	Theoretical GNSS Accuracy height (m) (95% confidence)	Absolute GNSS Accuracy x,y (m) / LADS / Riegl (95% confidence)	Absolute GNSS Accuracy height (m) LADS / Riegl (95% confidence)
RT GNSS	N/A	5.0-10.0	10.0-15.0	6.739 / 8.074	5.484 / 5.968
KGNSS PPP	N/A	0.150	0.200	0.037 / 0.077	0.010 / 0.029
KGNSS BS	4.55	0.100	0.150	0.051 / 0.067	0.088 / 0.094

Table 3: Positioning Systems Theoretical Vs Actual

3.6 Benchmark Accuracies

The final LADS data were compared against the gridded benchmark surface which were independently measured by acoustic methods and statistics were generated which include the number of points compared, the mean depth difference (MDD) and the standard deviation (SD) between the data sets.

The total number of benchmarks compared during the survey was 14. All comparisons were made to the final reduced NGPF datum. The table below shows these results.

BM ID	Nominal Depth	Number of Comparisons	Average MDD	Average SD (1σ)
1	5.8m	13218	-0.03	0.17
2	15.4m	12682	-0.01	0.17
3	18.2m	5518	0.06	0.33
4	14.2m	12380	0.02	0.11
	Total	43798	0.01	0.15

Table 4: Vertical accuracies of water benchmark areas

In summary, fourteen benchmark comparisons were conducted using **43,798** individual soundings. The average mean depth difference from all benchmark comparisons was **0.01m +/-0.04** with an average standard deviation of \pm **0.15m +/-0.15 (1sigma)**. These results are comparable with previous results obtained with the LADS Mk3 and RIEGL VQ-820-G systems and show they operated correctly.

3.7 Topographic Accuracies

TIP comparisons were conducted to verify the accuracy and precision of the LADS Mk3 and RIEGL VQ-820-G systems in the topographic environment. The TIP's consisted of an athletics field in Papeete and the airport tarmac area on Moorea and Bora Bora. They were surveyed by the local survey contractor with the reference data supplied relative to the RGPF/NGPF and flown during the survey operations. The LiDAR data was then processed and validated prior to comparisons being conducted. These are the results:

TIP ID	Average Height	Number of Comparisons	Average MDD	Average SD (1σ)
7	10.8m	2455	-0.01	0.03
12	1.3m	1182	-0.09	0.06
6	3.7m	1022	-0.15	0.03
	Total	4659	-0.08	0.04

Table 5: Vertical accuracies of TIP areas

Note the Mean Depth Difference of the three lines over TIP 6 varied between -0.13 and -0.22 (mean -0.15); although the standard deviation between each individual line and the TIP was low (i.e. 3 cm), the range in the Mean Depth Differences of 12 cm is mainly due to the accuracy of each individual GPS trajectory and within the expected absolute accuracy of the data

A total of number of **4,659** individual soundings were calculated with the average mean depth difference from all TIP comparisons was **-0.08 +/- 0.07 metres** with an average standard deviation of **0.04 ± 0.02 metres (1σ)**. These results are comparable with previous results obtained with the LADS and RIEGL systems and show they operated correctly.

4. CONCLUSION

In May – June 2015 ALB data was collected by Fugro for SAU, Moorea Coral Reef LTER and DEQ over the coastline in Moorea, Bora Bora and parts of Tahiti. The LADS and Riegl systems were operated concurrently to provide data that seamlessly connects land and sea; high density coverage was achieved of coastal infrastructure, the beach and in shallow water and data extended offshore to depths of 50 metres off Moorea and Tahiti and 60 metres off Bora Bora, with a record maximum ALB depth which exceeded 75 metres. There are some gaps in some deeper and more turbid areas; in Moorea these were covered by a previous MBES survey; the merged data sets provide complete coverage of the coastal zone.

The remote survey area, steep topography and challenging environmental conditions provided a number of project risks which were effectively identified and managed.

The resulting data set is suitable for many applications including: managing the risks from climate change including severe weather events of storms and floods, impacts of earthquakes including landslides and tsunamis, input to circulation and wave models, and for understanding ecological processes on shallow coral reef substrates.

With large populations and infrastructure concentrated along the increasingly vulnerable coastal zone, ALB technology can provide data suitable for assessing risks and mitigating adverse impacts of natural disasters. The technology is particularly effective in the Pacific due to its operational versatility and cost effectiveness, despite the remoteness and hazardous nature of these areas.

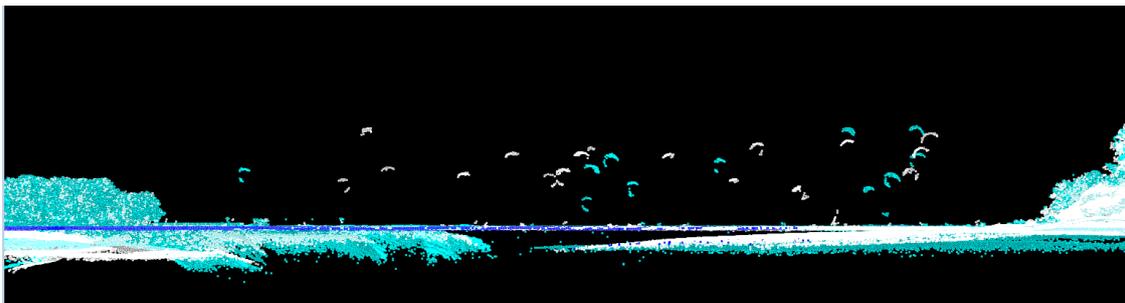


Figure 25 – Raw Riegl data detecting kite surfers off Pointe de Vénus, near where Captain Cook observed the transit of Venus in June 1769.

BIOGRAPHICAL NOTES

Mark Sinclair is Managing Director of Fugro LADS Corporation (Adelaide, South Australia). He has a wide marine background and is certified as a level 1 professional hydrographic surveyor through the AHSCP. Prior to joining LADS he served as a Commander in the Royal Australian Navy Hydrographic Service.

Luke Chamberlain is the Data Processing Manager of Fugro LADS Corporation (Adelaide, South Australia). He was the Project Manager for the ALB surveys in French Polynesia and Samoa in 2015 and has completed an International Hydrographic Organisation Category A training course.

Yves Pastol is the SHOM senior hydrographic surveyor for the Litto3D project. He has provided technical oversight of numerous ALB survey projects in mainland France and overseas territories.

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FIG Working Week 2016
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FIG Working Week 2016
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Christchurch, New Zealand, May 2–6, 2016