Acquiring 3D Samoa to Increase Climate Resilience

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Key words: climate resilience, Airborne LiDAR Bathymetry, LADS, Topographic LiDAR, Samoa, Risk Assessment, CRCSI

SUMMARY

Pacific Islands Countries have been elevated in the priority listing for natural hazard risk profiling and vulnerability assessment. Prior to 2015, when performing national risk assessments, government officials and stakeholders utilised a combination of local knowledge and low scale datasets that didn’t allow appropriate planning for hazards.

Through the use of remote sensing, Fugro helpled the Samoan Government and Ministry of Natural Resources to identify risks, understand the exposure and better manage vulnerabilities and impacts from hazards such as sea level rise, flooding, tsunamis, landslides, storm surge and cyclones. This paper will look at the international standards for capture & QA, results and operations of airborne terrestrial LiDAR, aerial imagery and airborne LiDAR bathymetry technology supplemented by satellite based RADAR and archived imagery datasets for the independent nation of Samoa.

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1. BACKGROUND TO THE SURVEY REQUIREMENT

In Samoa 70% of the population lives within 1km of the coast and most of the nation's critical infrastructure lies within this zone. This critical infrastructure includes roads, bridges, dams, hospitals, schools, port facilities, power plants, factories, airports and tourist infrastructure. Eighty percent of the Samoan coastline is sensitive or highly sensitive to erosion, flooding, landslides and weather and climate-related extreme events, such as tropical cyclones, storm surges and droughts. Rapid economic and urban growth predominates the coastal areas, increasing the exposure of people and assets to climate related hazards (MNRE 2014).

Over the past decade several disasters have struck Samoa. Severe Tropical Cyclone Evan affected Samoa between December 11 and 15 2012, causing widespread damage in Apia, complete power failure, as well as water supply system failure for the main island of Upolu. Heavy rainfall meant the Vaisigano, Tafitoala and Vaimoso Rivers broke their banks, and although the Emergency Operations Centre was activiated before the worst conditions hit, four lives were lost when water swept away village homes. The TC Evan damage amounted to US$207 million and a death toll of 14 people (DMO MNRE 2013).

On 29th September 2009 an 8.1 magnitude earthquake in the Samoan Islands region generated a tsunami which caused significant damage across Samoa, American Samoa and Tonga. The Pacific Tsunami Warning Centre recorded a 3-inch rise in sea levels near the epicentre and even though evacuations occured across the pacific region, more than 135 people were killed in Samoa. Eastern and southern areas of the Upolu coast were hit with 9m waves, and over twenty villages were destroyed. Around US$150 million in damages occured as a result of the tsunami (RELIEF WEB Oct 2009).

In 2011 a cyclone disaster simulation was performed by the Samoan Government. One of the key recommendations of this simulation was to address the lack of available and current mapping datasets. The report identified issues with "the lack of available datasets to provide immediate analysis", and "the difficulty for mapping experts to provide accurate descriptions as the base data is not current" (HEAL 2012).

To address the mapping issues the Corporate Research Centre for Spatial Information (CRCSI) worked with the Samoan government in mid-2014 to outline the requirements for developing a state-of-the-art "3D Samoa". This included advising on tender specifications to create a national elevation and bathymetry dataset. Bathymetric and topographic LiDAR was the chosen technology to accurately and comprehensively map the islands, for disaster management, hazard mapping and as a foundational dataset.

2. THE SURVEY REQUIREMENT & AREA

The bathymetry and elevation data within this project was procured under the World Bank Funded "Pilot Program for Climate Resilience (PPCR)" – Enhancing the Climate Resilience of Coastal Resources and Communities (ECR). The main client for the datasets is the Ministry of Natural Resources (MNRE) and Planning and Urban Management Agency (PUMA). The objective of the ECR project development is to support coastal communities to become more resilient to climate variability and change. ECR's aim is to reduce the vulnerability of Samoa's population and natural environment to climate risks, and enhance the capacity of natural systems and coastal communities to recover from chronic and acute impacts associated with climate change and extreme weather events.

An up-to-date, accurate and detailed elevation dataset was deemed critical for identifying and managing risks for infrastructure development, safety of communities and protection of the natural environment. The ECR includes the following key tasks:

- Protect roads and public utilities
- Protect buildings
- Protect land
- Protect coastal springs
- Conserve wetlands
- Re-vegetate degraded areas
- Control sand mining
- Manage coastal reclamation
- Regulate coastal land use

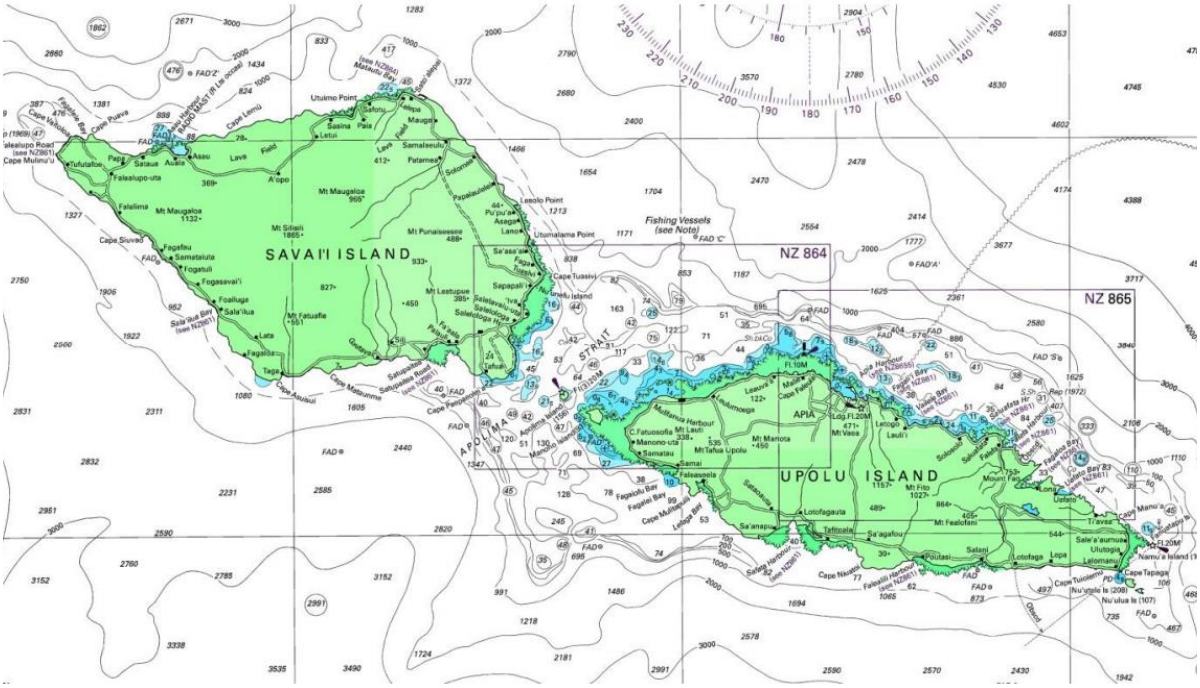

Figure 1: The islands of Upolu and Savaii of Samoa.

3. THE STRATEGY ADOPTED TO COMPLETE THE WORK

The Samoa project areas were added to a Fugro facilitated South-West Pacific campaign in mid-2015 that also included projects for coastal engineering, scientific assessments and benthic habitat mapping in French Polynesia. The Samoa acquisition covered around 4,000km^2, encompassing 1,100 km^2 of the seafloor and 2,900 km^2 over the islands.

Fugro used the following sensors for remote sensing acquisition:

1. **Fugro LADS Mk3 ALB sensor** (for shallow and deep water to 50m depth)
2. **Riegl VQ-820-G topo/bathy sensor** (for land and shallow water to 15m depth)
3. **Riegl 760 topographic sensor + Phase One Camera** sensors (for the land)

The bathymetry sensors were installed side-by-side in a survey aircraft, and operated simultaneously to collect LADS Mk3, Riegl VQ-820-G and aerial imagery to measure the seafloor and adjoining coastline. The combination of the two bathymetric LiDAR sensors is ideal for coastal requirements as it safely and comprehensively provides high resolution data, nominally 4pts per m^2 over land and shallow water (from the Riegl), and excellent depth penetration to nominally 50m pending water clarity (from the LADS Mk3 sensor). The combination of sensors offers exceptional performance in deep water, shallow water and on land for a smooth land – sea continuum.

The benefits of using Fugro's unique, current generation configuruation of high power LADS Mk3 sensor and high frequency Riegl sensor includes:

- confidence in using accurate and realistic 3D datasets of the deep reef areas, seamlessly joined to the high density shallow/topo areas;
- assurance that the most powerful laser system on the market, used by dedicated professionals with proven workflows provides comprehensive coverage in all environmental conditions;

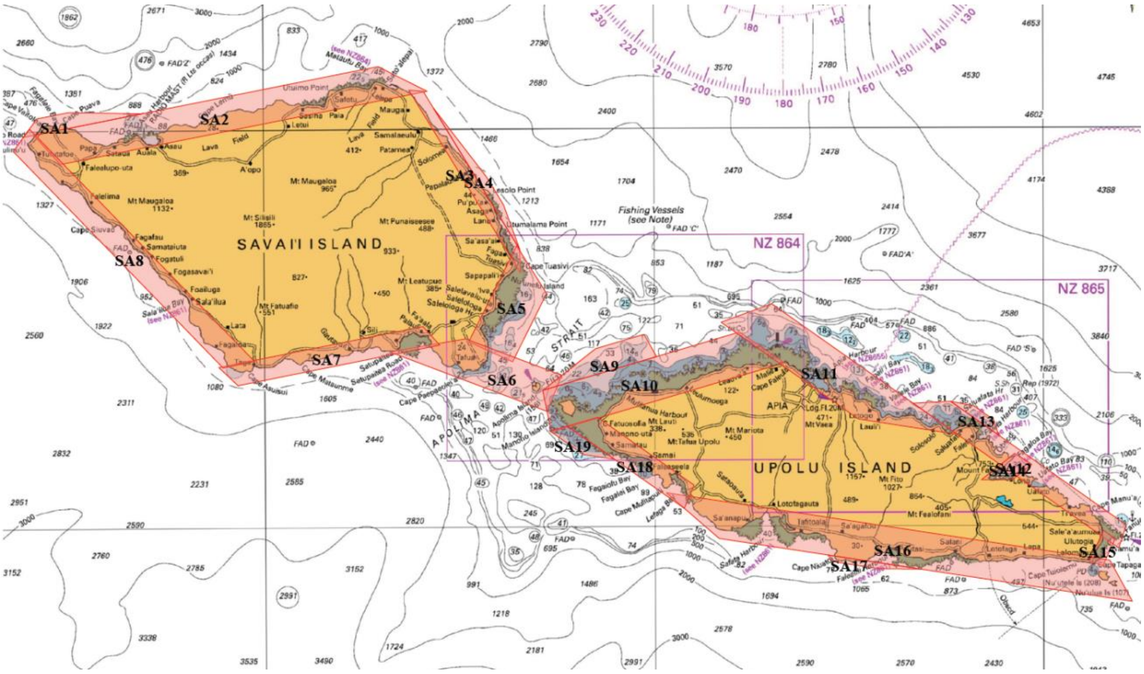

Figure 2: Airborne Bathymetric LiDAR Sub-Areas

The following products were required from the capture:

- Classified LiDAR Points in LAS format
- LiDAR Intensity Image Mosaic
- Surface Model (DSM)
- Terrain Model (DTM)
- Canopy Height Model
- Foliage Cover Model
- Contours

- Aerial Photography
- Seamless DTM Mosaic
- Seamless contour mosaic

Ancillary data including flight trajectories, tidal data, survey marks, project reports, 3D images and metadata were also provided.

The Samoa survey areas were divided into two main areas, one for Upolo Island and the second for Savaii Island. Figure 3 below shows the planned flight lines for the Riegl 780 sensor that was used for the topographic heights.

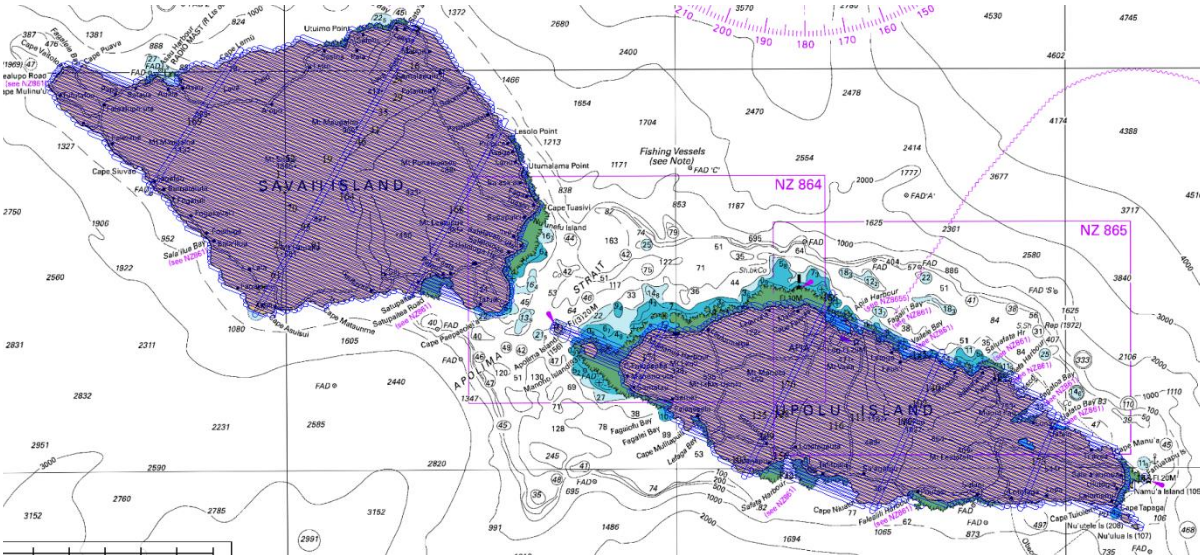

Figure 3: Airborne Topographic LiDAR Flight Lines

The survey was managed by Fugro LADS Corporation (FLCPTY) with assistance from local surveyors within the Ministry of Natural Resources & Environment (MNRE) for the establishment of survey control and ground test points. The CRCSI and Fugro helped in advising MNRE on the survey requirements during the survey.

4. SURVEY OPERATIONS

The field deployment commenced on 6 July 2015, with the last flight taking place on 9 August and the deployment was completed with staff departing the country on 10 August 2015.

4.1 Weather and Environmental Conditions

The weather conditions were generally good for the ALB survey flights, apart from low cloud which impacted the eastern end of Upolu Island. The large sub area on the south east side of Upolu was flown at a lower altitude (1400ft) to mitigate the low cloud base, resulting in a slightly higher density for the Fugro LADS Mk3 data.

Water conditions were very favourable in the majority of areas with good penetration down to 60m depth in most places. The area around Safata Bay, SW of Upolu, was very turbid as a result of discharge from the local river. This impacted the coverage in the area with no real improvement throughout the survey period. In all, no ALB sorties were aborted due to bad weather although the total time lost due to low cloud was 02:49 hours.

Weather conditions for ALT survey flights were continually impacted by low cloud, especially around the high ground on both islands. Survey lines had to be flown in multiple sections to try and achieve the required coverage. Around 80% of the survey areas were successfully flown with cloud preventing the completion of the remaining areas.

Due to the repeated cloud in high areas and impending wet season, Fugro and MNRE agreed to infill the gaps over the tops of the mountains with satellite based RADAR and archived imagery datasets. The last step in the data acquisition was to confirm the areas and arrange the best possible data to ensure fit for purpose modelling.

4.2 Acquisition Overview

The LADS Mk 3 main lines of sounding were conducted using a 5m laser spot spacing with a swath width of 352 metres, at an aircraft ground speed of 160 knots. Main lines of sounding were flown at 330 metre spacing which provided a planned 100% coverage of the seabed and ensured a 5 metre spot spacing as required by the contract.

The RIEGL VQ-820-G system was flown at the maximum high rate of 284 kHz for the duration of the survey. The swath width was 530m with a sounding density of 4 points per square metre.

The RIEGL LMS-Q780 system was flown at the maximum high rate of 350 kHz for the duration of the survey. The nominal swath width was >720m with a pulse density of nominally > 4 pulses per square metre.

4.3 Depth Benchmarks

The relative vertical accuracy of the ALB data was verified by comparing ellipsoid depth data against three benchmarks established on the same line. The benchmarks were in depths ranging from approximately 7 to 37 metres.

Twelve benchmark comparisons were conducted using 31595 individual soundings. The average mean depth difference from all benchmark comparisons was 0.01m +/-0.06 with an average standard deviation of ± 0.25m +/-0.01 (1σ). These results are comparable with previous results obtained with the LADS Mk 3 system and show it operated correctly.

The nominated relative benchmark line was flown four times during the survey period.

4.4 Topographic Integration Points (TIPs)

TIP comparisons were conducted to verify the accuracy and precision of the LADS Mk 3, RIEGL VQ-820-G and RIEGL LMS-Q780 systems in the topographic environment. All TIPs consisted of relatively flat areas of open ground (in general a large field or wide road). One TIP was surveyed by Fugro and MNRE surveyors whilst the other four TIPs were independently surveyed by AAM in 2012. Each TIP was flown at least once throughout the duration of the survey.

The Fugro/MNRE TIP comparison results yielded excellent agreement between the LiDAR data and surveyed data with an average Mean Depth Difference of **0.11m ±0.03** and an average Standard Deviation of **0.04m ±0.00**.

The AAM TIP comparison results yielded good agreement between the LiDAR data and the surveyed data with an average Mean Depth Difference of **0.06m ±0.06** and an average Standard Deviation of **0.06m ±0.04**.

5. DATA PROCESSING

In the initial stages of the data processing, the datasets of the three respective LiDAR systems are kept separate and follow the general stages of Validation, Classification, Accuracy Assessments, Quality Control, Output, Merging, Quality Control, Output and then Reporting. 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 the datasets.

The data processing continued in the Fugro offices on completion of data collection. Once all three LiDAR datasets had been fully processed they were compared to the local survey control, established for the project on both Upolu and Savaii Islands. Adjustments were applied to effectively produce a seamless topographic and bathymetric dataset on both Islands and subsequent products.

6. RESULTS

For metrics and analysis, the Samoa survey was broken up into two survey areas: the topographic and the bathymetric areas.

All bathymetric survey areas were flown with excellent results, particularly in the shallow regions less than 20 metres and clear deep reef regions, where maximum depths consistently over 60m were achieved. There was only one isolated area of river discharge and turbidity which affected bathymetry returns at Safata Bay, Upolo Island.

Caution was used to survey regions when the effects of swell were at a minimum and to maximise opportunities when conditions were calmest over the outer reef edges in all areas. Most survey areas on the outer extremities have a very steep seabed, and as they were surveyed in relatively calm conditions the extinction depth of the Lads Mk3 System was routinely over 60m, an excellent result.

6.1 Timings

The survey activities for the Samoa project areas were completed over a 39 day window that included 20 sorties where time was lost due to aborted flights due to low cloud and rain. This was outside the timings expected during the planning stages of the project. MNRE and Fugro agreed to extend the contract to allow for the purchase and delivery of satellite datasets to fill in gaps over the permanently cloud-covered mountain tops, as well as the complexities of merging four different terrain datasets and three imagery datasets.

6.2 Coverage

For the bathymetry, in all survey areas in Samoa the required minimum 95% coverage was achieved. The final coverage areas and percentages are as follows:

Area	Number of 50x50m Grids (+5m drying to 30m depth)	Number of 50x50m Grids >50 soundings	Area % covered
Upolu	54030	53432	**98.89%**
Savaii	127952	123520	**96.54%**

Table 1: Samoa ALB coverage areas and % complete

For the topography, overall, it is considered that the required coverage of 95% has been achieved in the Upolu and Savaii survey areas when combining the ALT and Satellite derived coverage. At the completion of data processing the coverage areas and percentages, including the Satellite coverage shown in Figures 4 and 5, were calculated and provided in Table 2, as follows:

Area	Required SqKm	Achieved SqKm	Area percentage covered
Upolu – Total	1140	1310	115%

(Riegl LMS 780)		1135	85%
(NextMap 10 Satellite)		175	15%
Savaii – Total	1713	1806	105%
(Riegl LMS 780)		1578	87%
Satellite RADAR		228	13%

Table 2: ALT and Satellite percentage of survey areas covered

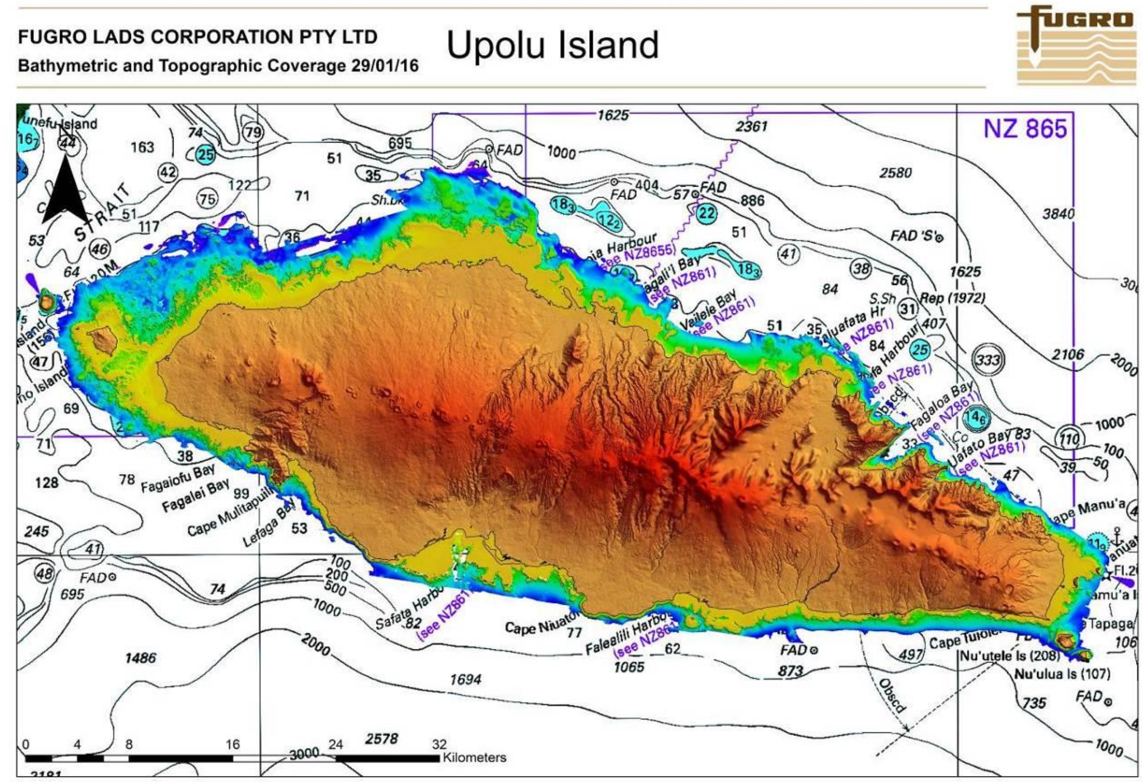

Figure 4 – Final Merged Survey Coverage – Upolu Island

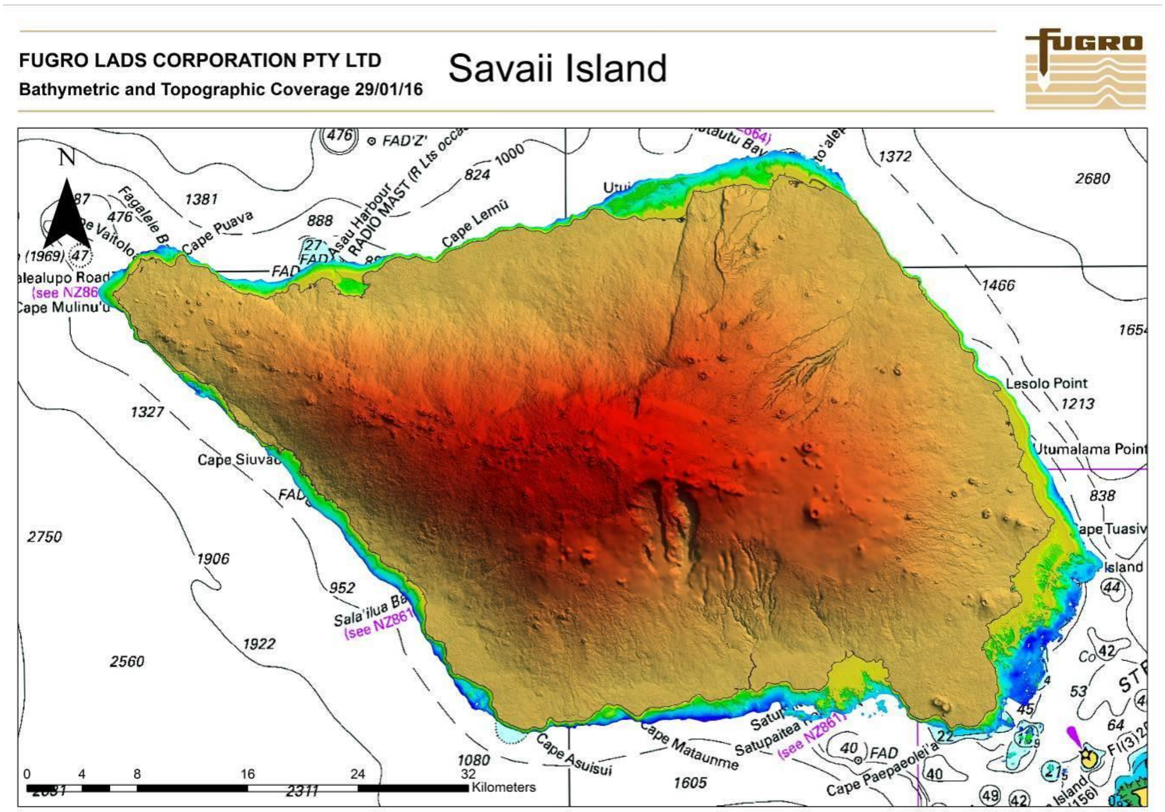

Figure 5 – Final Merged Survey Coverage – Savaii Island

The imagery sources were merged to produce a seamless 3 band 8 bit RGB orthophoto. The 3 datasets were initially pre-processed separately and georeferenced. The Pleiades imagery required to fill in the high altitude, low cloud areas was georeferenced using the rational polynomial coefficient model.

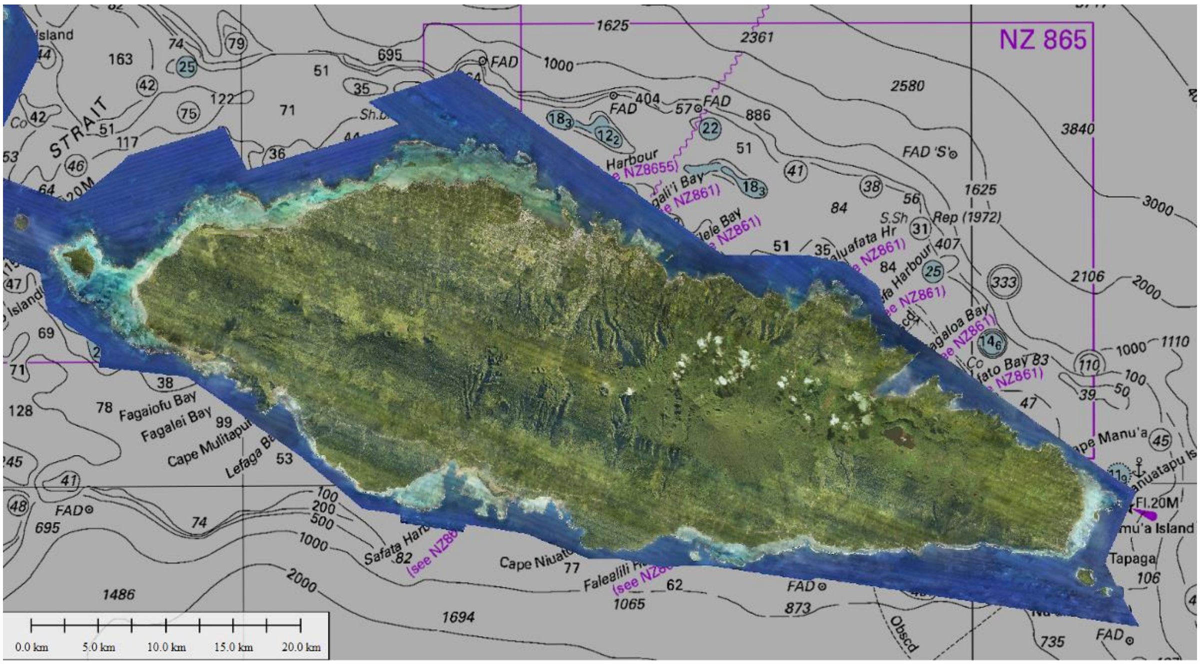

Figure 6 – Final Merged Orthometric Imagery – Upolu Island

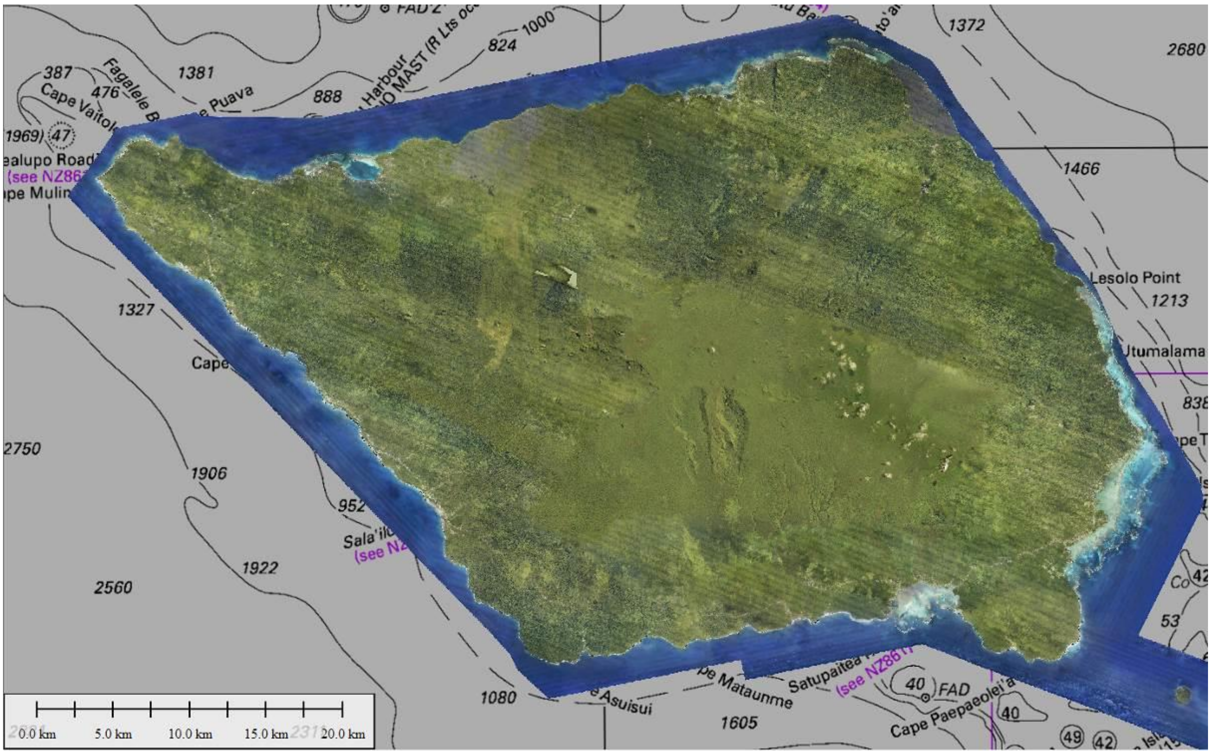

Figure 7 – Final Merged Orthometric Imagery – Savaii Island

6.3 Seabed Features

Whilst not the primary task of the project, our processing team of hydrographic surveyors also regard updating nautical charts as an important output of the project. This occurs by analysing the soundings and their raw laser waveforms and theaerial imagery in shallow water. An example of a seabed feature within Apia Harbour is the wreck in the table below:

Point	Surveyed Latitude	Surveyed Longitude	Easting	Northing	Run Number	Comments
1	13°49'42.5" S	171°49'08.6" W	416886	8471110	20022	Wreck

The accuracy, density and coverage of the ALB data exceeds historical hydrographic data and is most suitable for updating the nautical charts of Samoa.

6.4 Quality Assurance

The Cooperative Research Centre for Spatial Information (CRCSI) has developed the QA4LiDAR data standard for Australia, NZ and the Pacific over the last three years. Developed in collaboration with Australian State and Commonwealth Government departments this software automates the checking of:

- Delivery Completeness & Spatial File Corruption
- File Naming, Shapefile Attributes & Horizontal Coordinate System
- Classification Statistics
- Accuracy of Survey Control
- Point Density & DEM Resolution
- Flight Line Coverage
- Absolute & Relative Vertical Accuracy
- Visual Checks

With a significant investment in the LiDAR capture, MNRE required Fugro to deliver the data to the QA4LiDAR standard. The CRCSI performed the quality assurance on the data before delivery to the Samoan Government. As assessed by the CRCSI, the LiDAR data delivered to Samoa meets, and in parts exceeds, the QA4LiDAR standard.

Several notable features of the data recognised during the quality assurance process include:

- 46.5 billion points were captured (37.1 billion topographic and 9.4 billion bathymetric)
- 70% of topographic LiDAR points captured were in high vegetation (trees >10m)
- 7% of the topographic LiDAR points were classified as ground (ground point density of 0.77 points per m^2)

- 20% of bathymetric LiDAR points were classified as seabed
- The highest ground point in Samoa is 1858m above MSL, and the deepest bathymetric measurement was 75.2m below MSL.
- The project achieved a pulse density of 4.73 points per m^2 surpassing the requirement of 4 points per m^2.
- The absolute vertical accuracy of the survey was 22cm at 95% confidence meeting the 30cm requirement.

7. SAMOA'S USE OF THE DATASETS

During training sessions held in Apia in February-March 2016, numerous stakeholders from across the Samoan Government showed great interest and enthusiasm in accessing and utilising the datasets. These included participants from the Water Resource Division, Disaster Management Office, Planning and Urban Management Authority, Land Transport Authority, Mapping Unit, Meteorology Division and Road Safety Office, within the Ministry of Environment and Natural Resources, Ministry of Works, Transport and Infrastructure, and the Ministry of Finance. Immediate uses of the datasets are underway with taking the data and analysis to community consultations in early March 2016. Examples of the uses include:

- Landslide mapping to guide building, road access and planning decisions at Mt Veae
- Coastal Erosion mapping
- 2050 1m Sea Level Rise mapping
- Modelling the Cyclone Ofa (Max Storm Surge Event)
- Modelling Tsunami Impacted Areas from 2009
- Identifying and mapping Samoan reefs
- Updating the mapped road network, and computing cut and fill volumes for new road developments
- Updating water catchment areas and monitoring river changes
- Updating flood maps (replicating previous events)

Samoa have recognised a number of activities which need to be undertaken to build the capacity within country to use the elevation data for many applications, including those listed above. As such they are framing activities around the following seven strategic pillars to fulfill the identified outcomes (some of the key activities are identified below):

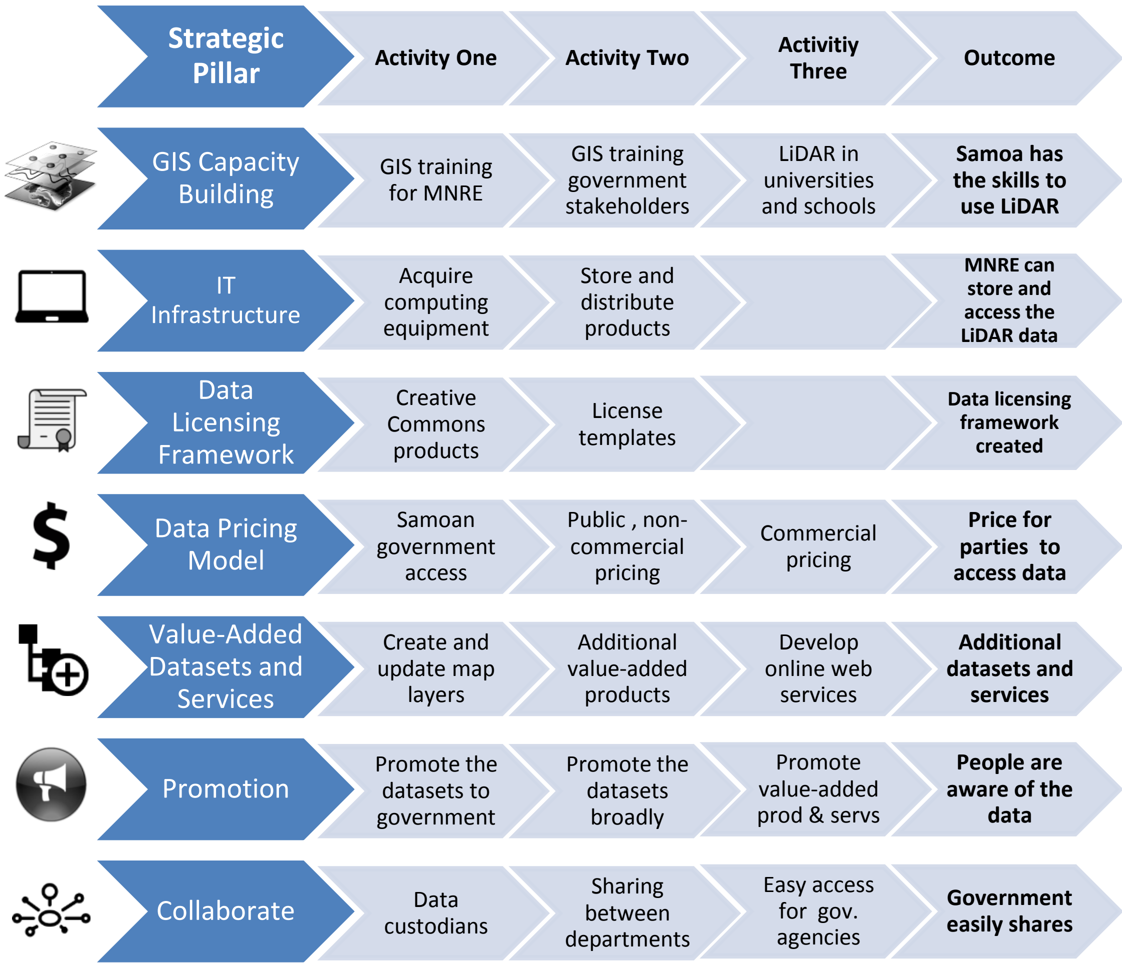

Figure 8 – Strategic pillar to build GIS capabilities within Samoan Government

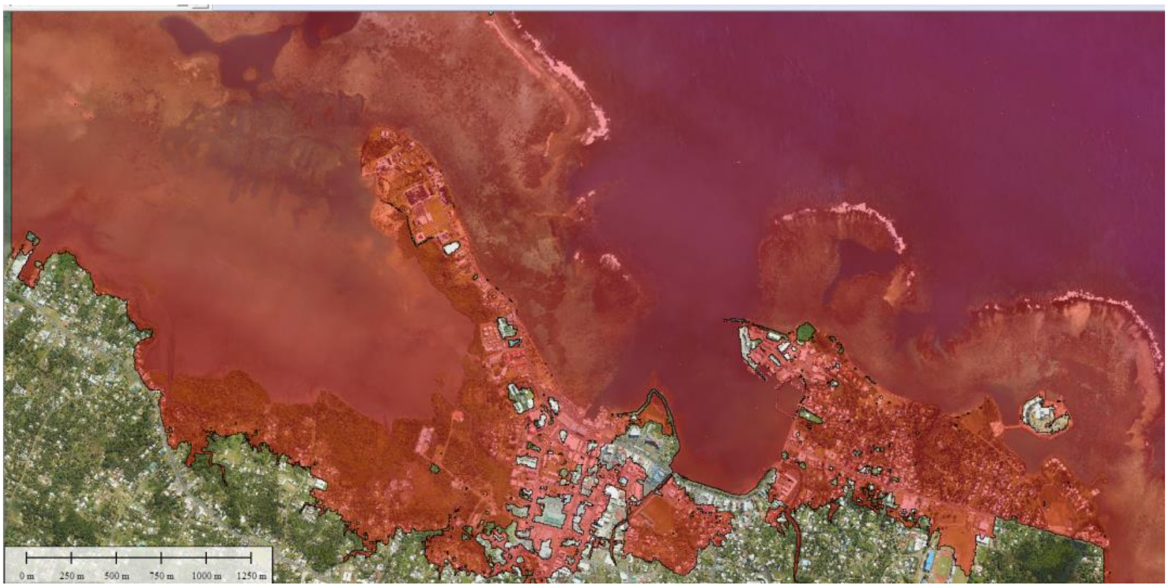

Figure 9 – example of 100 year max event at Apia, rise of 2.17m

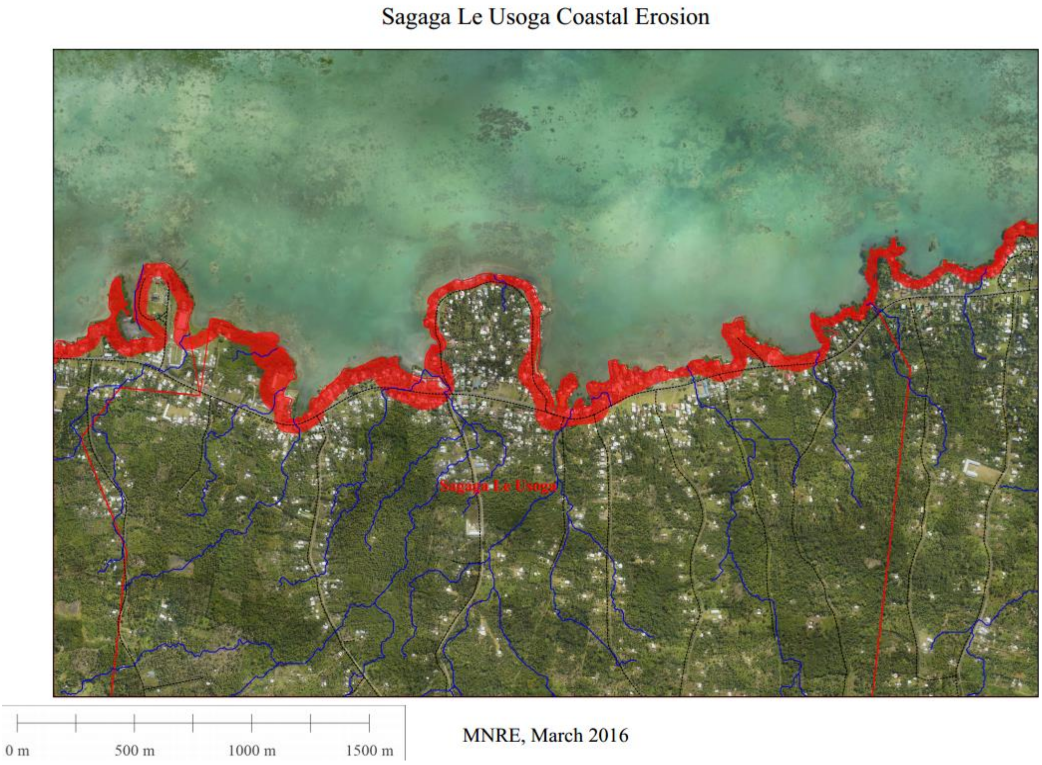

Figure 10 – example of community consultation map showing the high erosion zone

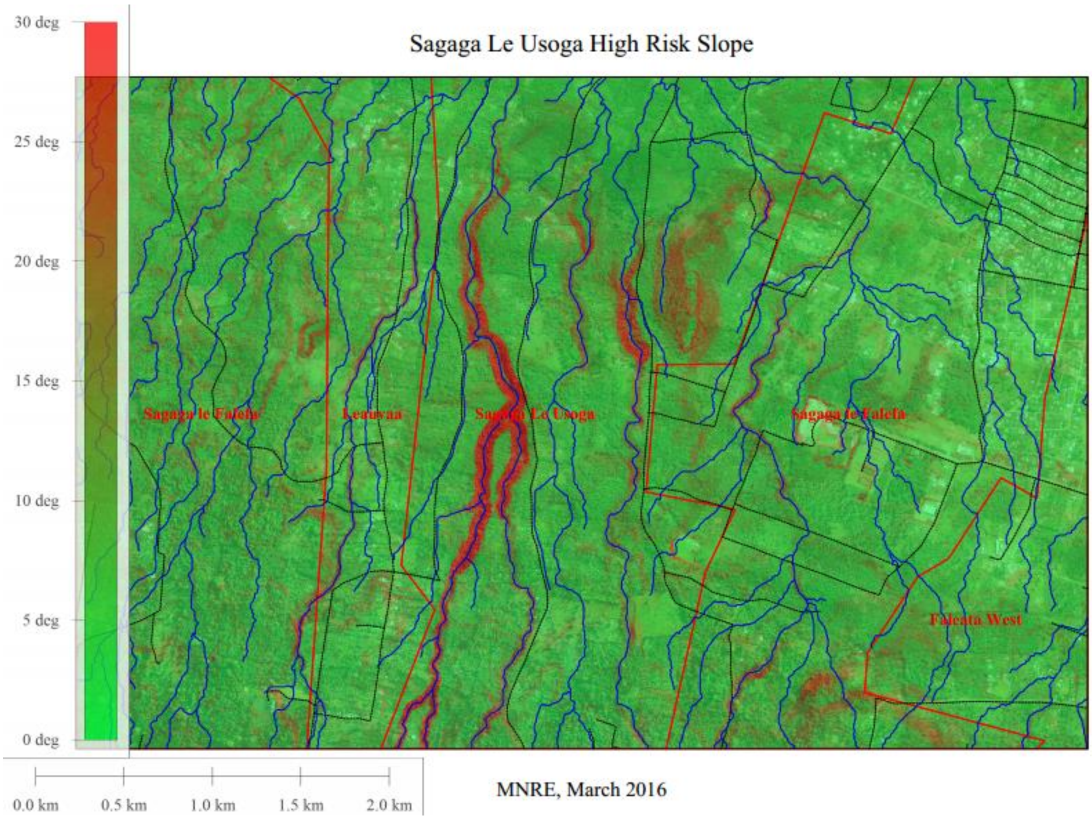

Figure 11 – example of community consultation map showing the high risk slope area, near roads and buildings

It is also recommended this data be made available to LINZ to enable the nautical charts of Samoa to be updated to improve safety of navigation.

8. CONCLUSION

The current generation of Airborne LiDAR bathymetry sensors provide coverage of topography and bathymetry from combined overlapping sorties. This helps to reduce costs for multiple deployments of systems and allows more expensive vessel based work to be better utilized. Combining the bathymetry with LiDAR topography datasets, provides a cost effective solution to accurately cover large areas. Resulting in a seamless deep reef to mountain peak LiDAR-based 3D model.

As a result of the 2015 LiDAR project commissioned by Planning and Urban Management Agency (PUMA), Samoa is now the most comprehensively mapped country in the World. It is the first country to have completely mapped in precise and accurate detail its elevation from "ridge to reef". Countries like the USA, Australia and France are actively pursuing more accurate elevation datasets, however their size means it will not be completed to the level that Samoa has achieved for some years, if at all. Samoa are in a fortunate position that they now have an exceptional asset in "3D Samoa".

Samoa is now developing the capacity in country to make full use of the dataset to gain maximum benefit from this acquisition to use the LiDAR dataset, and its derived products and services.

Planning of operations in the SW Pacific have their issues, and these were observed with multiple no-flights or averted flights due to low cloud over planned survey areas. Nonetheless, due to the diligence of the survey teams, pragmatism of the Samoan Government, the sensors used and workflows followed, the data captured, processed and provided aligns to the goal to improve the planning and management of coastal areas, reduce disaster risk and improve foundation datasets.

BIOGRAPHICAL NOTES

Alex Cowdery is a Business Consultant of Fugro LADS Corporation (Adelaide, South Australia). His background is in marine science, remote sensing and hydrographic surveying. Prior to LADS he worked with Department of Defence and Royal Australian Navy performing hydrographic surveys across Australia as well as other remote sensing consultancies across Australia.

Dr Nathan Quadros is the Rapid Spatial Analytics Research Program and Business Development Manager at the CRC for Spatial Information. He completed his PhD in 2008 investigating issues with airborne LiDAR in the coastal zone. In 2011 Nathan joined the CRCSI, managing and advising on numerous LiDAR projects around Australia and the Pacific. In particular, he coordinated the delivery of bathymetric and topographic LiDAR to Tonga, PNG, Vanuatu and Samoa, along with the training and capacity building for these countries to use the data. Nathan has spent significant time investigating bathymetric LiDAR issues. His recent reports have covered topics such as bathymetry user needs and challenges, and bathymetric acquisition technologies and strategies. His current focus has been more generally on airborne LiDAR acquisition and data quality standards.

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