Towards multiscale data fusion of high-resolution space borne and terrestrial datasets over Tristan da Cunha

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Abstract

Ever improving low-cost, lightweight and easy to use sensing technologies are enabling the capture of rich 3D datasets to support an unprecedented range of applications in geosciences. Especially low-cost LiDAR systems as well as optical sensors, which can be deployed from terrestrial or low altitude aerial platforms, allow the collection of large datasets without detailed expert knowledge or training. Dense point clouds derived from these technologies provide an invaluable source to fill the gap between highly precise and accurate terrestrial topographic surveys and large area Digital Surface Models (DSMs) derived from airborne and space borne sensors. However, the collection of reliable 3D point clouds in remote and hazardous locations remains to be very difficult and costly. Establishing a reliable georeference, ensuring accuracy and data quality as well as merging such rich datasets with existing or space borne mapping provide additional challenges. The presented case study investigates the data quality and integration of a heterogeneous dataset collected over the remote island of Tristan da Cunha, South Atlantic Ocean. High-resolution 3D point clouds derived by terrestrial laser scanning (TLS) and drone photogrammetry are merged with space borne imagery while preserving the accurate georeference provided by ground control derived from geodetic observations.

The case study presents a cross-validation of terrestrial, low altitude airborne as well as space borne datasets in terms of coregistration, absolute georeference, scale, resolution and overall data quality. Following the evaluation a practical approach to fuse this heterogeneous dataset is applied which aims to preserve overall data quality, local high resolution and accurate georeference and to avoid edge artefacts. The conclusions drawn from our preliminary results provide some good practice advice for similar projects. The final topographic dataset enables mapping and monitoring of local geohazards as, e.g. coastal erosion and recent landslides thus also supporting the local population.

Introduction

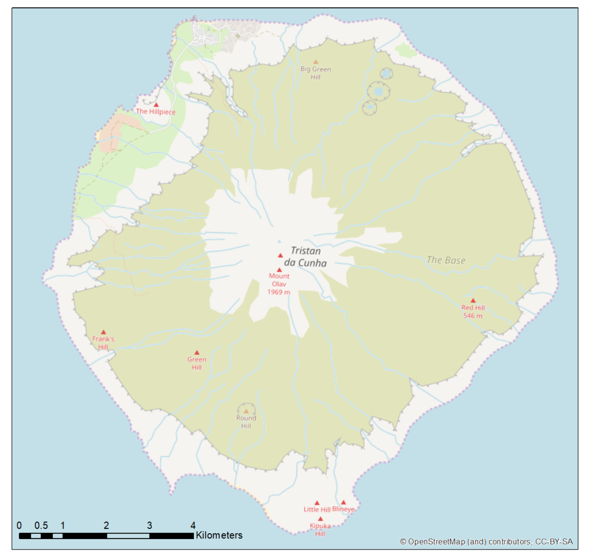

Figure 1: Topographic map of Tristan da Cunha (TdC) from Open Street Map (OSM)

The small volcanic island of Tristan da Cunha is known as one of the most remote locations on Earth. It is located at 37° 04'S and 12° 19'W in the Southern Atlantic Ocean approximately 1950km west from Cape Town, South Africa, and 2900km east of Buenos Aires, Argentina. Tristan has a circular shape with a diameter of 10-12km and coves a surface of 96km² and its highest point is Queen Mary's Peak with 2062m. The last eruption of its volcano dates back to 1961. Tristan is also the home of a small population of approximately 200 people and hosts a number of important research installations. Its remote location, rough climatic conditions and consistent cloud coverage provides exceptional challenges for terrestrial, aerial as well as space borne data acquisition for mapping and environmental monitoring. The island seem poorly mapped and only basic topographic maps provided by Open Streetmap (OSM) where publically available.

Amongst many other scientific instruments, the island also hosts a state of the art continuous Global Navigation Satellite System (GNSS) station and tide gauges operated in a cooperation between University of Luxembourg (UL) and the United Kingdom National Oceanography Centre (NOC). New tide gauges where installed alongside a new state of the art GNSS station by Professor Teferle in September 2017.

Figure 2: continous Global Navigation Satellite System (GNSS) station (right) and tide gauges (right) in the harbour area of Edinburgh of the Seven Seas

This provided a rare opportunity to conduct a limited local terrestrial and aerial data acquisition campaign with the aim to map the local area around the harbour while the work was completed. A highly accurate Ground Control network required for the installations of the stations could also be used to provide superior Ground Control for an aerial image acquisition using a low-cost consumer grade D-rone (small unmanned aerial system - UAS). Pointclouds were acquired around the area of the research installations and harbour using terrestrial laserscannering (TLS) as well as SFM-MVS based on the drone images.

To produce base mapping data of the complete island Very High Resolution (VHR) optical space borne imagery from Digital Globe WorldView constellation was acquired. Thanks to the generous support by the Digital Globe Foundation a comprehensive dataset of 32 multitemporal image scenes was received. This dataset will give us the opportunity to extract a Digital Surface Model (DSM) of the island, thus enable a number of Geoscience application. Unfortunately, the space borne dataset arrived too late ahead of this conference to be fully exploited in our case study.

Acknowledgements

The installations and survey work was funded through projects at the University of Luxembourg (in particular SGSL) and the National Oceanography Centre. We acknowledge the help and support from the community, various contract workers and local administration of Tristan da Cunha, the contributions from the IGN, France, with respect to the DORIS station and the IGS for their satellite and data products.

Satellite image(s) courtesy of the DigitalGlobe Foundation

The Data Set

Data Source	Platform	Sensor		Product	Scale (approx.)	Precision	Resolution	Accuracy Specifications
Geodetic GNSS Observations		Geodetic-Grade GNSS	various Leica		N/a	1mm		sub centimetre accuracy
Tachymetry	Terrestrial	Total Station (TS)	Leica TS30		1/10	1mm		sub centimetre accuracy
Terrestrial Laserscanning (TLS)		TLS	Leica P20		1/10		1.6@100m	
Drone Photogrammetry	Low Altitude Airborne	Small UAS	DJI Phantom 3 Pro		1/50		1.5cm GSD	
Aerial Photogrammetry and Mapping	Airborne	manned aircraft	Not available					
Very High Resolution (VHR) Satellite Imagery	Space borne	Satellite	WorldView 3 (WV3)	Standard 2A	1/1000		0.31cm GSD (Pan Nadir)	5m CE; 2.3RMSE *
			WorldView 2 (WV2)	Standard 2A	1/1500		0.46cm GSD (Pan Nadir)	5m CE; 2.3RMSE *
			QuickBird (QB2)	Standard 2A	1/2000		0.61cm GSD (Pan Nadir)	5m CE; 2.3RMSE *
Topographic Base Mapping			Open Street Map		1/10000	N/a	N/a	

* Technical Reference Digital Globe, 2016

Table 1: Overview of the datasets acquired for this study

Highly precise geodetic observations provide superior ground control for TLS and drone photogrammetry covering the area of interest near the harbour. The space borne VHR satellite imagery provides full coverage of the island in approx. 0.5m resolution.

Geodetic Observations and Control Network

GNSS Station

The continuous GNSS station TCTA (1035) and point 1003 were observed continuously for 3 days. The coordinates were derived from the daily observation files using PPP and employing the Bernese GNSS Software V5.2. The coordinates were then averaged over the 3 days. Stations 1002, 1003, 1006 and 1005 were occupied for 2 hours each and their coordinates were obtained from static processing using Leica GeoOffice 8.0 in which the coordinates of TCTA were fixed to the values obtained from PPP. In all processing precise IGS satellite orbit and clock products were used as well as individual GNSS antenna calibrations.

Figure 3: Leica TS30 total sation in-front of the DORIS station

Terrestrial Survey

A terrestrial survey was conducted using a high precision total station (Leica TS30) and a high-precision digital level (Leica DNA03) on October 7-8 and 13, 2017. The primary aim of this survey was to establish a local ground control network which will enable the monitoring of the newly established continuous GNSS station (TCTA), the monitoring of the vector between the GNSS station and IGN Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS) station, and the monitoring of the tide gauge benchmark network, which dates back to the 1960s. This highly precise GCN provided an ideal basis to establish the Ground Control used for the aerial survey, which took place on October 8 and 13, 2017. 9 Photogrammetric targets where established as Ground Control Points (GCPs) for the Using the Leica TS30 total station the coordinates of the GCPs have been determined to an absolute accuracy of better than 1 cm in XYZ.

Figure 4: Overview of the Geodetic Ground Control Network with Photogrammetric GCPs

Projection and Datum

Throughout this study all dataset were projected into UTM Zone 28H (South) coordinates based on the WGS84 Datum. The vertical datum was defined as WGS84 Ellipsoidal heights.

Base Mapping

Based on its remote location and small population the island seems poorly mapped. Opens Street Map (OSM) as shown in Figure 1 seems to be the only digital topographic mapping dataset freely available. Meta information about the data quality was not available.

We compared the Geolocation of the much-generalised OSM dataset with the geodetic GCN. Due to its limited extend the CGN only provides a single point of reference, which was sufficient to estimate the translations in Easting and Northing. The OSM map is displaced by approximately 37m in Easting and 69m in Northing (Figure 5).

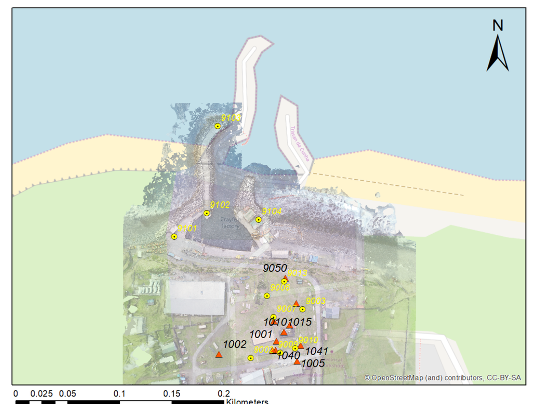

Figure 5: Displacement of OSM compared to the geodetic GCN

Terrestrial Laser Scanning (TLS)

We deployed a Leica P20 laser scanner to acquire a dense point cloud around the observatory and the harbour area. On October 6 and 13, 2017, the weather conditions seemed good enough to attempt TLS observations. However, many problems prevented the systematic collection of the 3D point clouds over the whole area of interest. It is assumed that the persistent wind, although relatively low for the island, caused some of the issues. After the return of the instrument to the University, several other issues were discovered that required the laser scanner to be sent to service. It is not clear yet, if the problems on the island can be associated to these issues.

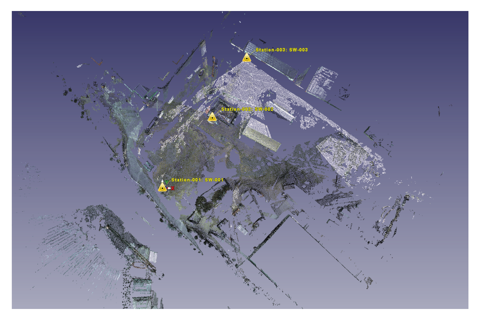

Figure 6: Overview TLS stations

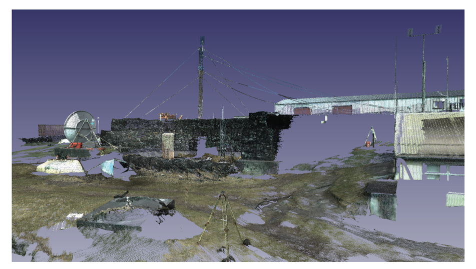

Figure 7: Scan collected over

TLS Registration

Nevertheless, 3 Scans where collected which are providing a good coverage around the areas the research installations (Figure5). Due to the difficulties on-site, the Scan shows a high noise level (Figure 6) and do not include sufficient control targets. This made it difficult to register and georeferenced the pointclouds. Using Leica Cyclone (V9.1.4) Iterative Closest Point (ICP) algorithm, we achieved an alignment error of 19mm between Scan 1 and 2 and 25mm between Scan 2 and 3.

Low Altitude Aerial Survey

As it would be extremely difficult and costly to capture aerial mapping data using photogrammetric grade or LiDAR sensors over such remote locations, low-cost drones seem to be the ideal tool to provide aerial images over a limited area of interest. An off-the-shelf DJI Phantom 3 Professional drone was used to acquire aerial photography around the harbour area. For this, a flight application was made to the Administrator of Tristan da Cunha. The mission aimed to collect high-resolution imagery suitable to create detailed maps of the area of interest but also to collect panoramic photographs of the surrounding areas for documentation purposes.

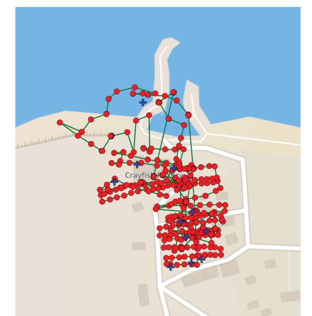

Figure 8: Overview of flight trajectories over OSM

Flight Missions

Weather conditions permitted 2 flight missions which were conducted during October 8 and 18, 2017. Due to the harsh conditions with high wind speeds both missions where executed as free flights missions in manual mode. As there is little to no internet connectivity on the island the usual flight planning apps were unusable.

Overall, 373 useable images where acquired which provide good overlapping coverage of the areas around the harbour and the research installations, as well as a number of perspective and panoramic imagers in a range of altitudes. Figure 9 gives an overview of the acquired block of images. 11 photogrammetric targets around the confined area of interest provided highly accurate ground control.

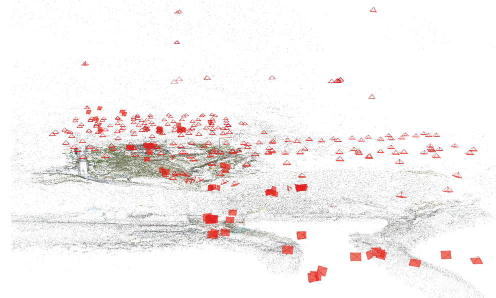

Figure 9: 3D view showing camera positions and attitude over a sparse point cloud after SFM by ColMap

Data Analysis

The oftware packages deployed included the open source package ColMap (Schönberger and Frahm, 2016) and the commercially available AgiSoft PhotoScan (V1.3.5), Bentley Context Capture(V5) and Pix4D Mapper (4.2.25). Processing image blocks using these highly integrated software tools is a largely automatic process with few options for user inputs and control. Pix4D and Bentley Context Capture provide data quality reports, which contain crucial information about the success of the photogrammetric process. The following section will present results based on Context Capture and Pix4D.

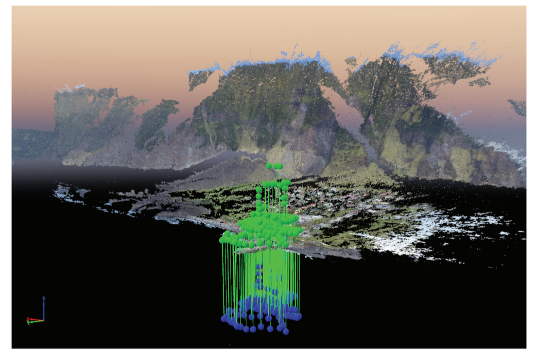

Figure 10: Overview results of bundle block adjustment PiX4D using all images incl. panorama photographs

Aerial Triangulation

The presented results of the areal triangulation are based on Pix4D bundle block adjustment. All usable images were included in the image orientation process including all panoramic images as they might provide additional information. Figure 10 shows the results of the final Bundle block adjustment and dense image matching. It is interesting to note that many feature points were picked up in the surrounding slopes far from the area of interest. As the visualisation of the complete point cloud shows an impressive scenery, it must be noted that features out of the area of interest include large extrapolation features and may not be suited for any demanding applications.

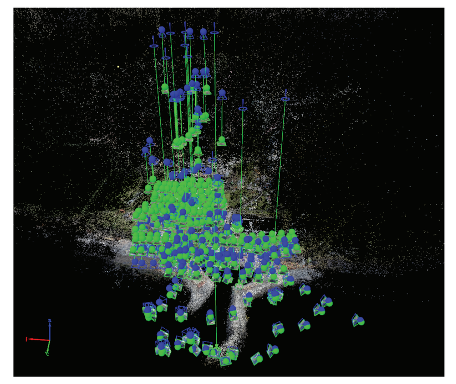

Figure 11: bundle block adjustment Pix4D, large height offset between drone positions and GCPs

To investigate the accuracy of the geopositioning using only the onboard GPS of the drone the aerial triangulation was performed in various steps: a) without any GCPs, b) with 5 GCPs c) with 10 GCPs. As shown in Figure 11 and Table 2 the estimated geolocation accuracy of the photogrammetric blocks are within a few meters in Northing and Easting but off by around 190m in height. Height offsets seem to be a common issue when using low-cost drones. Misinterpretation errors of height/altitude information from EXIF headers have been reported many times in popular media and internet discussion forums. By deploying GCPs, the absolute positional accuracy was estimated in the range of few cms.

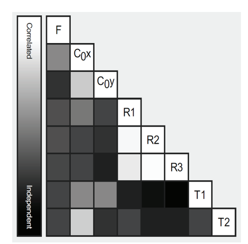

Figure 12: Correlation Matrix of Camera calibration parameters (Pix4D)

Bundle Block adjustment		Images		Cam Calibration			RMSE					
	GCPs	Gelocated	in Calibration	Focal length	Principal Point		Ground Control Points			Check Points		
				f [pixel]	cx [pixel]	cy [pixel]	X	Y	Z	X	Y	Z
1	0 GCP 11 Check points	373	363	2344.570	2000.511	1492.125				1.093	1.121	191.39
2	5 GCP 6 Check points	373	363	2344.784	2000.359	1492.292	0.011	0.014	0.016	0.013	0.018	0.066
3	10 GCP 0 Check points	373	363	2344.402	2000.224	1492.185	0.011	0.015	0.0193			

Table 2: results of bundle block adjustments

Investigations on the stability of camera systems deployed from small UAS by Cramer et al. (2017) and Gerke and Przybilla (2016) found that such cameras are often geometrically unstable and require frequent re-calibration. All adjustments performed also included the self-calibration of camera parameters. The correlation matrix in Figure 12 confirms a strong block geometry and a reliable calibration.

To verify the results of the bundle block adjustment an Orthophoto generated by Bentley Context Capture without ground control was compared to the photogrammetric GCPs (Figure 13). This comparison showed a translation in Northing of 2.20m and in Easting of 0.11m.

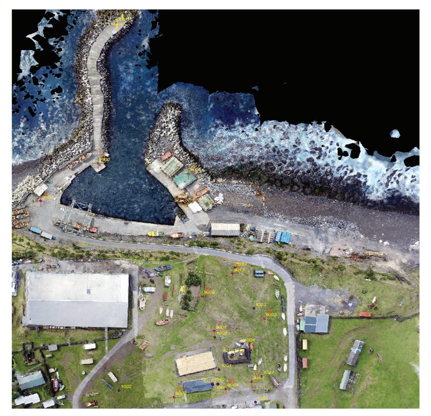

Figure 13: cross-validation of Orthophoto to processed without GCPs vs with GCPs

Completeness and Visual Point Cloud Quality

The quality of the point cloud generation depends heavily on the image quality and the bundle block adjustment. While all tools performed well; Figure 14 shows visualisation of a dense point cloud. The point cloud shows great detail and a low noise level.

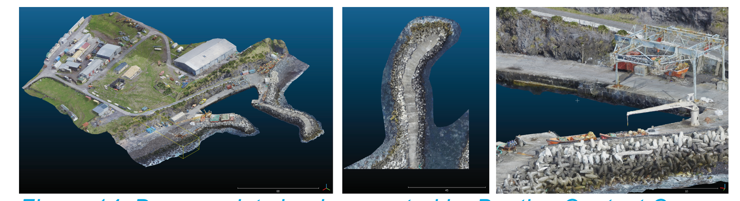

Figure 14: Dense point cloud generated by Bentley Context Capture

Space borne High Resolution imagery

An image Grant award by the Digital Globe Foundation (DGF) provided access to Digital Globe archive data from its fleet of VHR optical Earth Observation Satellites including Quick Bird (QB2), WorldView 2 (WV2) and WorldView 3 (WV3). Overall 32 satellite scenes where provided which have been collected over a period of almost 10 years (Table 3).

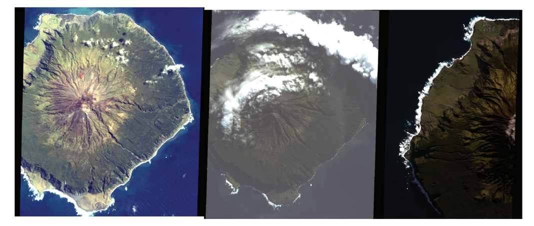

Figure 15: VHR Satellite Imagery, QB2 2010 (left), WV2 2011(centre), WV3 2015(right)

Figure 15 shows a good example of a QuickBird2, a WorldView2 image with substantial cloud coverage and a very clear WorldView3 image. Cloud coverage, atmospheric effects and local artefacts caused by overexposure are common problems of VHR space borne satellite images. Table 3 highlights the scenes used in this study in green. For this study, the satellite data could only be used for 2D mapping.

The received satellite images were expected to be georeferenced but not orthorectified, thus suitable for DEM extraction. The extraction of high-resolution DEMs from VHR satellite images has been demonstrated and assessed many times (Angiuli and Remondino, 2010; Hu et al., 2016; Poli and Toutin, 2010).

First investigations have revealed the received scenes where delivered as WorldView 'View-Ready, Standard 2A' products which have high geolocation accuracy of 5m CE90 or 2.3m RMSE. To achieve this, a georectification has been applied which makes it impossible to extract a high-quality elevation data. With the kind support of DGF, suitable satellite images are expected to become available which will enable this work.

While detailed investigations are ongoing, first validations have shown the good coregistration between VHR satellite images and the orthophoto generated from the drone imagery which is within the specifications of Digital Globe (Figure 16).

High Resolution Satellite Imagery - Digital Globe Constellation							
	Date of Acquisition	Satellite	GSD (Pan-Mean)	Channels	Scene	Coverage	Cloud Cover
1	27/07/2017	WV3	0.43	Pan + Mul(8)	057747693030_01_P008	West 70%	snow and clouds 40%
2	19/04/2017	WV2	0.60	Pan + Mul(8)	057747693020_01_P012	East 50%	4%
3	19/04/2017	WV2	0.47	Pan + Mul(8)	057747693020_01_P013	East 40%	2%
4	03/04/2017	WV2	0.51	Pan + Mul(8)	057747693020_01_P007	East 40%	South
5	03/04/2017	WV2	0.57	Pan + Mul(8)	057747693020_01_P008	East 40%	South
6	01/06/2016	WV3	0.38	Pan + Mul(8)	057747693030_01_P009	90%	snow and clouds 60%
7	01/06/2016	WV3	0.32	Pan + Mul(8)	057747693030_01_P005	East 60%	snow and clouds 30%
8	01/06/2016	WV3	0.35	Pan + Mul(8)	057747693030_01_P006	95%	snow and clouds 50%
9	01/06/2016	WV3	0.42	Pan + Mul(8)	057747693030_01_P002	East 80%	snow and clouds 30%
10	27/12/2015	WV2	0.56	Pan + Mul(8)	057747693020_01_P003	West 30%	low (North)
11	27/12/2015	WV2	0.61	Pan + Mul(8)	057747693020_01_P006	West 40%	low (North)
12	16/12/2015	WV2	0.52	Pan + Mul(8)	057747693020_01_P011	100%	North West
13	16/12/2015	WV2	0.58	Pan + Mul(8)	057747693020_01_P010	100%	North West
14	21/11/2015	WV2	0.53	Pan + Mul(8)	057747693020_01_P005	100%	0%
15	21/11/2015	WV2	0.58	Pan + Mul(8)	057747693020_01_P004	100%	0%
16	06/09/2015	WV2	0.53	Pan + Mul(8)	057747693020_01_P009	West 10%	low
17	01/08/2015	WV3	0.41	Pan + Mul(8)	057747693030_01_P011	West 50%	none
18	10/03/2015	WV3	0.39	Pan + Mul(8)	057747693030_01_P010	Full	North 30%
19	03/03/2015	WV3	0.39	Pan + Mul(8)	057747693030_01_P007	Full	South East 50%
20	22/10/2014	WV3	0.39	Pan + Mul(8)	057747693030_01_P004	Full	North 30%
21	22/10/2014	WV3	0.43	Pan + Mul(8)	057747693030_01_P003	Full	North 40%
22	10/12/2014	WV3	0.40	Pan + Mul(8)	057747693030_01_P001	Full	South East 50%
23	12/10/2013	WV2	0.60	Pan + Mul(8)	057747693020_01_P001	West 40%	North 20%
24	02/05/2011	WV2	0.51	Pan + Mul(8)	057747693020_01_P002	80%	North 50%
25	13/03/2012	WV2	0.53	Pan + Mul(8)	057747693020_01_P014	99%	0%
26	13/03/2012	WV2	0.57	Pan + Mul(8)	057747693020_01_P017	East 40%	0%
27	05/02/2012	QB2	0.65	Pan + Mul(4)	057747693010_01_P002	80%	South
28	10/12/2010	WV2	0.52	Pan + Mul(8)	057747693020_01_P016	South East 25%	low
29	18/04/2010	WV2	0.52	Pan + Mul(8)	057747693020_01_P015	West 40%	low
30	15/02/2010	QB2	0.64	Pan + Mul(4)	057747693010_01_P001	90%	very low
31	07/02/2009	QB2	0.66	Pan + Mul(4)	057747693010_01_P004	West 50%	South
32	20/01/2009	QB2	0.67	Pan + Mul(4)	057747693010_01_P003	West 50%	very low

Table 3: Summary of VHR satellite imagery provided by the Digital Globe Foundation. Scenes used for this study are marked in green

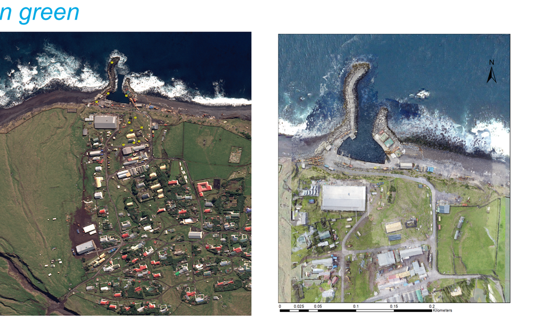

Figure 16: left site WorldView3 scene with overlayed GCPs; right site Orthophoto merged with Quickbird2 images

Conclusions and Future Work

During the October 2017 the University of Luxembourg in collaboration with the National Oceanography Centre (NOC, Liverpool) installed a state-of-the-art GNSS station and two new tide gauges on Tristan da Cunha. This required a high-precision survey of the existing benchmarks as well as the establishment of a new ground control network, allowing the monitoring of all benchmarks and of the vector between the GNSS antenna and DORIS antenna.

This mission also provided the opportunity to collect 3D mapping data using a terrestrial laser scanner and a small UAS around the local area of harbour and research installations. The high-precision survey network provided highly accurate ground control to georeference this dataset. With the award of an image grant by the Digital Globe Foundation, a rich dataset of high-resolution satellite data is available to generate new 3D mapping data and enable a range of geoscience applications.

We assembled a comprehensive, high-quality dataset on a remote location which provided an excellent opportunity to investigate the data quality and data integration issues. The heterogeneous data set includes highly accurate geodetic data, very rich high-resolution 3D data as well as large-scale VHR satellite imagery.

The future work will include the creation of a high resolution island DSM, thorough cross-examination in order to merge into a consistent dataset which provides reliable coregistration and accurate Geolocation.

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