DSM/DTM - related investigations of the Moorea Avatar project

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KEY WORDS: Ecosystem Modeling, Multi Sensor Data, Satellite Imagery, LiDAR, Underwater Photogrammetry

ABSTRACT: The Moorea Island Digital Ecosystem Avatar (IDEA) project has been initiated in 2013 by a group of international researchers to build a virtual representation of Moorea Island, which can serve as model for data acquisition, data processing and simulations for tropical islands in general. The aim of the project is to model an entire ecosystem, observe the changes through time and be able to predict future changes reliably. The Moorea IDEA project incorporates observations, experiments, existing data and theory across a coupled 3D marine-terrestrial landscape, where physical, chemical, biological, and social processes interact to shape the island's phenotype.

In order to generate the 3D physical model of the Island, multi-sensor data with varying accuracies, timestamps and spatial resolutions need to be processed and fused. High resolution optical satellite images (Pleiàdes), LIDAR data over land and water, existing DTMs, aerial film photography extracted and scanned from archives, underwater sonar measurements for modelling the bathymetry, underwater photogrammetry for monitoring the coral growth, UAV images for habitat mapping in the lagoon, accurate building reconstruction and recording of archaeological sites are among the data being processed in the project.

This paper describes some of the aspects of the project, as they relate to the generation of surface models, in detail and addresses the processing methods and the problems encountered during the processing of multi-sensor and multi-resolution data. High resolution DSMs and orthoimages have been generated by image matching using Pleiàdes images with 70 cm pan resolution acquired over Moorea and the nearby island Tetiaroa in summer 2014. Large height errors caused by false matches have been corrected manually. A DTM of Moorea with 5 m grid spacing has been generated by manual measurements. Tetiaroa has been scanned by a green laser. This allows us to compare the different techniques with each other. High resolution bathymetry data from green LiDAR flights of both Moorea and Tetiaroa is available and will also be integrated into the generated DSM. We also measured in Moorea the footprints of houses and a single height and the roads in 3D from the Pleiades images.

In addition we measure at regular intervals the coral growth in several test areas on the fore-reef and fringing reef by underwater photogrammetry. The final physical 3D model, amended by landuse data and other semantic information will provide a presentation and a geospatial analysis platform to the project participants from many other disciplines. Building on the Moorea Island Digital Ecosystem Avatar (IDEA) platform (http://mooreaidea.ethz.ch), our overall goal is to develop data-driven models of the spatio-temporal dynamics of all processes of relevance on land and in the sea. Advanced computational simulations will be developed.

1. INTRODUCTION

The Moorea Island Digital Ecosystem Avatar (IDEA) project has been initiated by several universities and research institutes (UC Berkeley, CNRS-EPHE, ETH Zürich, Oxford University, UC Santa Barbara and MCR LTER) in 2013. It is an extensive long-term project funded by diverse organizations. The Moorea IDEA Consortium currently involves more than 20 research groups with approximately 80 participants. The Moorea Island is part of French Polynesia and located in the Pacific Ocean in the southern hemisphere near Tahiti Island. It is one of the most researched islands in the world (Cressey, 2015; Davies et al., 2016). One of the main goals of the project is to transform the data into a virtual lab and test different scenarios to analyze the changes and the effect of human activities to our ecosystem. The island avatar shall include all sorts of data related to land, the marine environment and air, including climate, vegetation, geological and biological data, etc.

Such studies have long been a topic for ecological experts, but they usually focus only on one part of it (e.g. cities, land use, climate, etc.). The Moorea IDEA project also aims at integrating the different studies on one platform and observe interaction through it. A similar study has been initiated in Crete (Crete IDEA, 2015), which shows the growing interest in the field.

The 2030 Goals Agenda of United Nations (2016) also emphasizes the importance of strong collaboration among scientists, governments and the societies. The Moorea IDEA project aims at offering an approach which can serve for the achievement of many of these goals, especially the ones related to sustainable management of the water and energy resources, taking action for climate change and its impacts, conservation and sustainably use of the marine resources, protecting and restoring the terrestrial ecosystems, managing forests, and promoting peaceful and inclusive societies for sustainable development.

The main motivations for choosing the Moorea Island for this study are its location far from the continents, with not too many external effects, relatively small size with 13 km x 15 km, with a small number of inhabitants (ca. 17 000), and a large amount of data which has been collected since 1970 within several research projects. Besides the underwater, coral reefs and underwater species, the Moorea Biocode project codes all species larger than one millimeter living on the island (Moorea Biocode, 2017). When the project is completed, it will bring important novelties in ecosystem modelling (Cressey, 2015). The working groups formed under the project are:

- Data science
- Mapping and visualization
- Physical modelling
- Biological modelling
- Social modelling
- Integration

The main aim of this paper is to describe briefly the project and some of the DSM/DTM related results.

2. DATA

The models used within the Moorea IDEA Project can be categorized as:

- Weather and climate
- Physical oceanography
- Hydrological
- Land- and Seascape
- Ecological
- Social-ecological
- Pre-contact social

Extensive description of the models and the research groups working on them can be found in the project website (mooreaidea.org). The existing data can be categorized as:

- Biocode data: Collected within the Moorea Biocode Project (www.mooreabiocode.org).
- CRIOBE data: Physical and biological data collected by the CRIOBE research station (CRIOBE, 2017).
- MCR ILTER data: Data of the coral reefs and the lagoon system (Moorea Coral Reef LTER, 2017).
- MIRADA: Microbic biodiversity data (MIRADA, 2017)
- Landscape model: The data used here is explained in detail in the following section.
- Bathymetry: Obtained from satellite images, laser scans and sonar measurements at different times and for different depths (Moorea Coral Reef LTER, 2017).
- 3D coral data: Obtained by underwater photogrammetry with different type of cameras.
- Habitat mapping: Image data from UAV flights over parts of the lagoon.
- Social data: Obtained by the French Institute for Statistics and by the INTHENSE project (INTHENSE, 2017).
- Archaeological data (Kahn et al., 2015), also image data from UAV flights.

3. PHYSICAL MODELLING ACTIVITIES

As an initial task, the generation of a comprehensive and accurate 3D physical model of the Island is crucial, due to two reasons. First, such a model can serve as a data integration platform for the scientists and engineers, such as biologists, climatologists, etc. Secondly, the changes in the ecosystem can be best tracked using accurate spatiotemporal information. In order to generate an accurate 3D physical model, multi-sensor data with varying accuracies, timestamps and spatial resolutions need to be fused. So far, high resolution optical satellite images (Pleiàdes, Worldview-2, Quickbird), LIDAR data over land and water, existing DTMs, aerial film photography extracted and scanned from archives, underwater sonar measurements for modelling the bathymetry, underwater photogrammetry for monitoring the coral growth, UAV flights for habitat mapping in the lagoon and accurate building reconstruction and recording of archaeological sites are among the data being processed in the project. The data processing and integration methods employed for the existing data vary largely and several problems have been encountered during the integration of multi-sensor and multi-resolution data. The physical modelling activities performed so far can be listed as following:

- Processing and analysis of Pleiades image triplets for Moorea and Tetiaroa, generation and editing of Digital Surface Models (DSM)
- Manual measurements for digital terrain model (DTM) generation from Pleiades images
- Preliminary integration of the DSM and the bathymetry data
- Processing and analysis of the LiDAR data acquired on the shores
- UAV data acquisition over a small part of the land and the lagoon (for habitat mapping)
- Underwater photogrammetric activities for modelling the coral reefs (Guo, et al., 2016)

Part of these data and processes are explained in more detail in the following sections.

3.1 Satellite Image Processing

Pleiades image triplets have been ordered for tasking and acquired on June 23rd, 2014 for Moorea and Tetiaroa. Each image set of the triplets contains 4 multispectral (RGB and NIR) and one Panchromatic (PAN) channel images. Overviews of both islands are given in Figure 1. The main characteristics of the Pleiades sensor are given in Table 1.

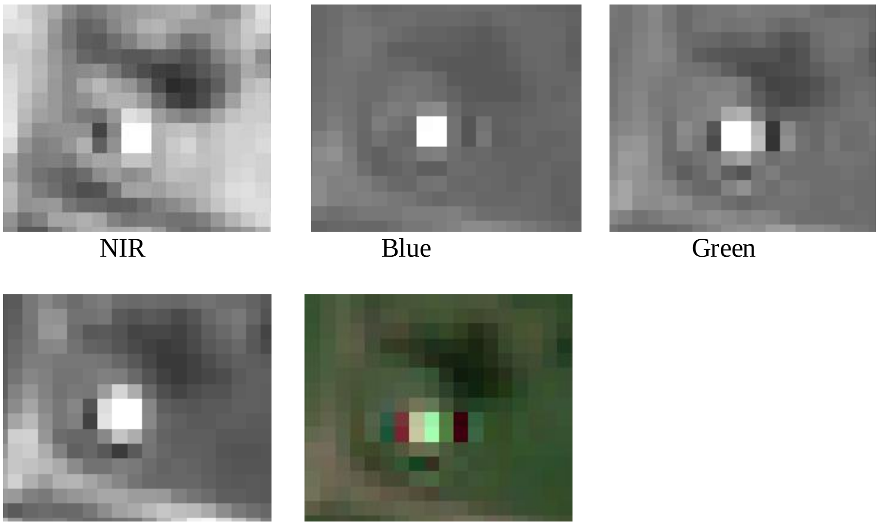
Table 1. Pleiades Sensor Characteristics (Airbus Defence and Space, 2016).

Spatial resolution	50-cm panchromatic 2-meter multispectral
Spectral Bands	Pan: 480-830 nm Blue: 430-550 nm Green: 490-610 nm Red: 600-720 nm Near Infrared: 750-950 nm
Image Location Accuracy	With ground control points: 1m Without ground control points: 3m (CE90)
Swath width	20 km
Revisit rate	Daily

Figure 1. Overview of the Pleiades multispectral imagery acquired over Moorea (left) and Tetiaroa (right) Islands in June 2014.

Image artefacts have been observed especially in the MS images (Figure 2). A potential reason is that the artifacts are coming from an aliasing effect due to the fact that the MTF is too high for the resampling frequency (ref.: personal communications with Astrium specialists on 23.01.2015).

Since the Pleiades images were delivered separately for each chip, the PAN images over Moorea were merged before further processing. In order to increase the matching success for the DSM generation, the PAN images were preprocessed using Wallis filtering. The method has been described in Wallis (1976). LPS tool (recently renamed as Imagine Photogrammetry) under Erdas Imagine (Hexagon Geospatial, 2017) was used for georeferencing and DSM generation.



NIR Blue Green

Red RGB

Figure 2. One example of the Pleiades image artifacts observed and shown in different channels of Moorea Pleiades images acquired on June 23rd, 2014.

For the georeferencing, Rational Polynomial Coefficients (RPCs) provided by the satellite operator have been used and their accuracy has been improved using ground control points. 16 GCPs have been measured on PAN and MS images of Moorea and 5 GCPs were measured in the Tetiaroa images. Some of the points shown in the files could either not be measured or were removed as they have been detected as outliers in the triangulation. Additional tie points generated automatically under LPS were used for the triangulation. A RPC refinement with affine parameters is performed in bundle adjustment (triangulation) of LPS. 5 points were used as control points and the remaining 11 points were used as check points in Moorea. The RMSE values obtained from check points were 1 pixel in each X,Y,Z. The sigma0 was around 0.2 pixels. Similar values have been obtained for Tetiaroa, but a smaller number of GCPs could be identified and measured.

DSMs of both islands have been generated using eATE under LPS and edited manually using "interactive terrain editing" tool under LPS. The patch size used for matching was 7x7 pixels. The editing has been done in stereo. With Terrain Prep Tool under LPS, a grid DSM was generated with 60 cm (later also 70 cm) spacing.

Pansharpening was performed for the nadir image using PCI Geomatics (pansharp2 function) and an ortho image was generated in LPS Ortho rectification. The DSM and the orthoimage are used together for visualization (ArcGlobe, PCI, ERDAS, etc.). Bathymetry data of Moorea was merged with the grid DSM produced in LPS for visualization purposes. The coastal line of Moorea was measured in stereo and used in the merging process. A screenshot of the produced model is given in Figure 3.

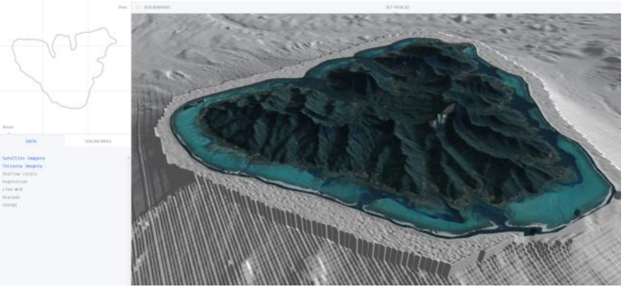


Figure 3. Screenshot of the 3D model of Moorea, produced from the Pleiades images, including bathymetric data (mooreaidea.org).

3.2 Airborne LiDAR Data

3.2.1 Data Description

Airborne LiDAR data were used for comparison with the 5 m grid DTM generated via manual stereo measurements from the Pleiades images. The LiDAR dataset was acquired as part of the airborne LiDAR bathymetric survey of French Polynesia for Moorea Coral Reef Long Term Ecological Research Program funded by U.S. National Science

Foundation. Data collection was carried out from June 10 to 26, 2015 with a RIEGL VQ-820-G topo-hydrographic airborne laser scanner system by Fugro LADS Corporation (Collin et. al., 2017). Figure 4 provides a visualization of the entire bathymetric and topographic point dataset as generated by green LiDAR.

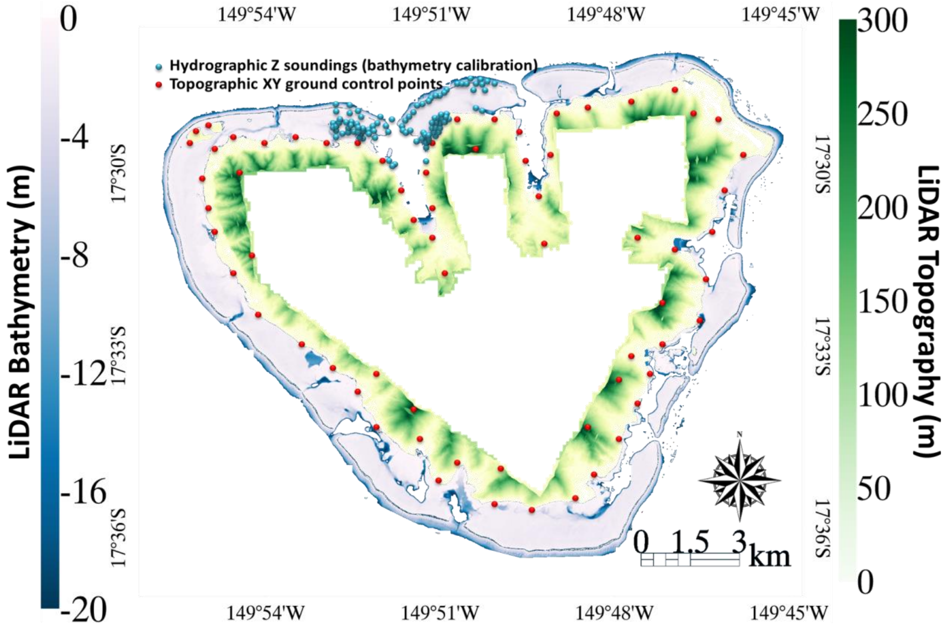


Figure 4. Topobathymetry Digital Surface Model of Moorea coastal fringe derived from a green LiDAR mission. Red points represent locations of the topographic ground control points, while blue points represent locations of the hydrographic soundings derived from SHOM navigational chart (courtesy Antoine Collin and Jim Hench)

3.2.2. Preprocessing

We have checked the completeness of the LiDAR data first by counting the number of strips falling into each 2 m x 2 m grid cell using LASTools software. We counted points from up to 8 strips in a grid cell. Figure 5a illustrates the point density color coded with a blue-red scale with red representing 30 or more pts/m^2. Figure 5b shows the area used for further processing and analysis.

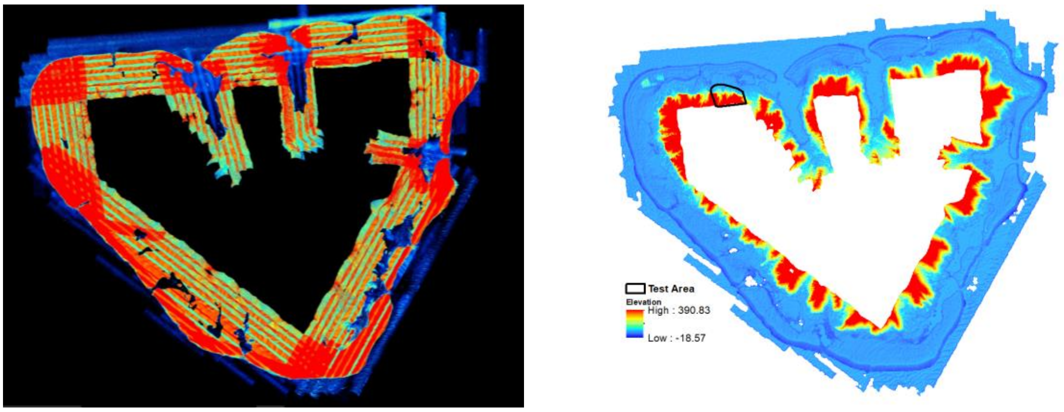


Figure 5. a) Point density map of the LiDAR dataset, b) Test area used for further processing and analysis.

The LiDAR point cloud datasets were provided in LAS v1.2 format with each point coded with one of 10 different classification codes, namely, classes 1, 2, 3, 7, 8, 9, 10, 14, 17, and 18. Some of these classes correspond to standard LAS format specifications. Several classes were assigned and defined by the data provider while some were not clearly specified. We have retained classes 1, 2, 17, and 18 for analysis. Class 1 consists of unclassified points both on land and over water. Class 2 includes ground points as per LAS specifications. Classes 17 and 18 are observed to include unrefined off-ground and ground classes in higher terrain with noise. Figure 6 shows selected classifications in part of the dataset. The term “noise” is often used in this connection, where large numbers of points do not correspond with an expected height location. In terms of Least Squares estimation these observations should better be called “blunders” or “gross errors”. They are spurious observations, whose origin is not always very clear. If now comparisons with other datasets are performed with the goal of determining the accuracy of a particular measurement method (be it by LiDAR or by image matching), those points should be eliminated prior to comparison, because they usually do not reflect measurement errors but errors in object definition.

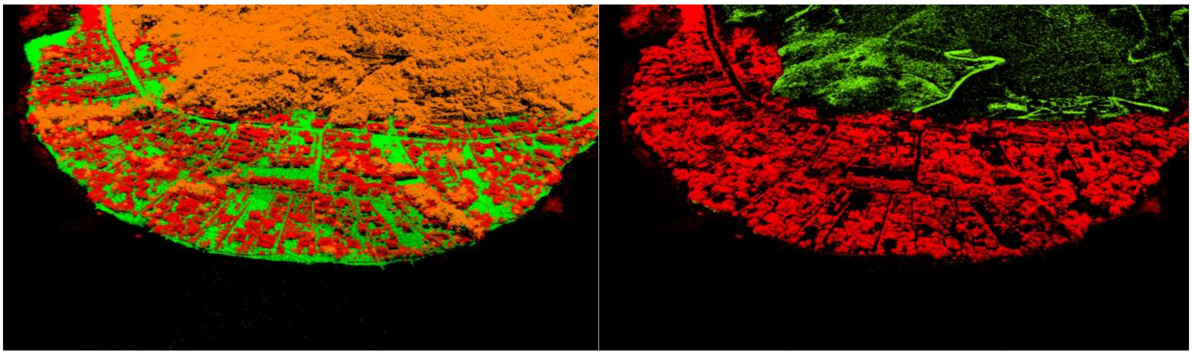


Figure 6. Point classes in part of the LiDAR dataset. Left: Classes 1 (red), 2 (green), and 17 (orange). Right: Classes 1 (red) and 18 (light green).

We have selected a small part of the dataset covering approximately 0.9 km x 1.3 km area for further analysis by removing the points that are not on land, using a manually generated coastline mask. Next, we have removed the "noise" points by applying a point count threshold within 4 m x 4 m x 1 m voxels. We have removed all points within a voxel, if the point count within the voxel was less than 5.

The LiDAR flight did not cover higher terrain past a narrow coastal strip. As mentioned previously, we had observed that points classified as Class 18 included mainly the ground points with "noise" at higher terrain with the potential to be reclassified as ground after "noise" removal. Once inspected in detail, we have found parts of the terrain to be missing in this classification making it unreliable for further analysis. Therefore we have extracted ground points for the study area using LASTools software with a step size of 5 m considering only the last returns. This ground filtering completed the mentioned missing parts but overly smoothed especially one of the ridges. We proceeded with the latter ground filtering result since it provided a more complete ground point cloud. Figure 7 shows side by side the ground points as a combination of classes 2 and 18 by the data provider vs. our ground filtering.

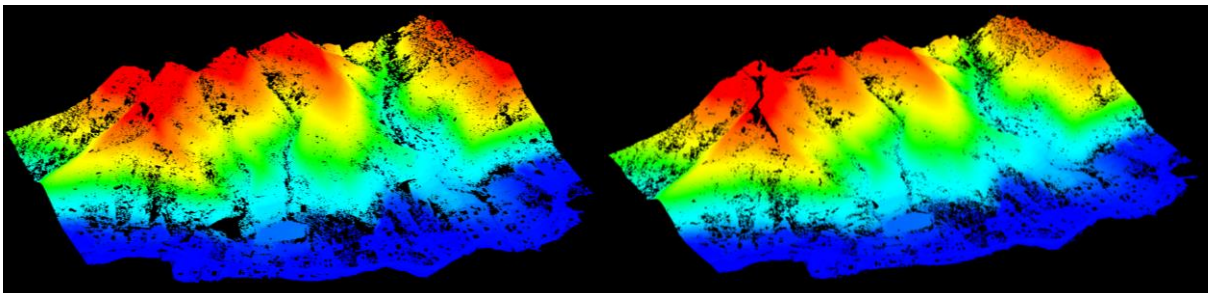


Figure 7. Ground points. Left: Classes 2 & 18 by data provider. Right: Ground filtering with 5 m step size.

3.2.3 Comparison of the DTMs

We compared the ground point cloud of the LiDAR mission with the DTM that was manually generated on a 5 m x 5 m grid from the Pleiades stereo pair (forward and backward images). A total of 14076741 LiDAR points exist in the area. 2233874 points out of those have been classified as ground and compared with 39984 DTM points from the manual measurements. We have calculated the Euclidean distance of each point in the Pleiades DTM to the local triangulation of their eight nearest neighbors in the LiDAR dataset using the open source CloudCompare software (CloudCompare, 2017). First the two datasets were co-registered with the Iterative Closest Point (ICP) method of Besl and McKay (1992) as implemented in CloudCompare. This resulted in the following translational values: dX = -0.407 m, dY = -0.327 m, and dZ = -0.078 m. Because these values were in the subpixel domain we did not transform the datasets before error analysis. The RMSE values resulted in RMSE(X) = 1.35 m, RMSE(Y) = 1.26 m, RMSE(Z) = 1.82 m. Figure 8 presents the absolute Euclidean distances in color coded form.

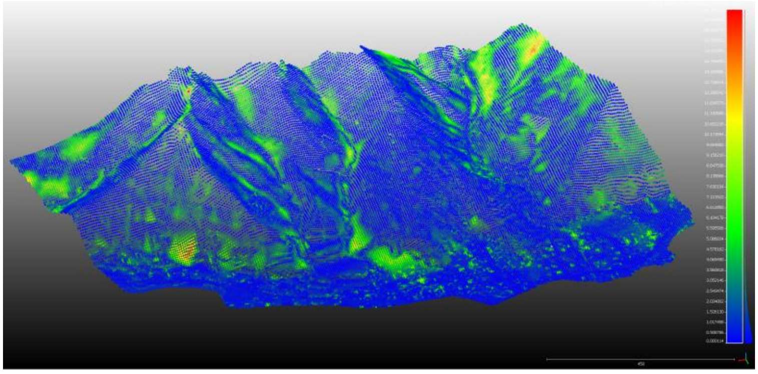


Figure 8. Euclidean distances between the Pleiades manually measured DTM and the LiDAR data.

In a similar study Collin et al., 2017 compare the LiDAR data with DSM data produced by ENVI software from Pleiades stereo and triplet models for the whole island of Moorea. They achieve values of around RMSE(Z) = 8 m. This value is below expectations. It may be caused by the facts that (a) they do not use GCPs for improvement of the RPCs georeferencing, and (b) because they compare the image-derived DSM with a LiDAR point cloud that still may include spurious observations (non-DSM points).

3.3 Underwater Photogrammetric Activities

Our objective of underwater photogrammetric works is to obtain accurate 3D models of corals and further to extract its changes in 3D over time in order to monitor and quantify the growth status of coral reefs in detail, which will then be correlated with the ecological models to discover changes and trends in the evolution of the island environment. Because the average annual growth rate of coral in Moorea is estimated at about 30-50 mm, this requires the accuracy of obtained 3D models to be on mm level.

Accuracy is a very important but challenging issue for underwater photogrammetric modeling and obviously little addressed so far in the literature. There are several factors. First, the underwater camera model is much more complicated than its counterpart in air, since the light must travel through the water body, the waterproof housing, and the air before the lens. This multi-media case causes serious refraction problems. Secondly, the properties of the water body (ambient light, temperature, pressure, turbidity, salinity, etc.) have a great influence both on the geometric and the radiometric models of the imaging process. These parameters are highly correlated with the water refractive index, which shows a strong variability over time and space for seawater in particular. Thirdly, illumination conditions of underwater are also highly complicated. A great amount of the sunlight radiation is reflected on the surface and absorbed, and the different components of light in different wavelengths are absorbed differently so that it makes the underwater environment look bluish and greenish. Surface waves cause very disturbing glints moving around in an extremely complex pattern. Moreover, floating surface material, turbidity, scattering, and backscattering of the external light sources all cause problematic factors to lead to poor illumination conditions underwater. This may lead to unsharp images and could considerably affect image quality. Lastly, underwater is mostly a tough working environment for image acquisition and for control targets setting and it becomes quite laborious in order to acquire satisfying image quality, good coverage and overlap, and accurate and well distributed control points.

The goal of our underwater photogrammetric work consists of two system approaches:

(a) To explore the accuracy limit that can be achieved with the photogrammetric methodology, considering high quality hardware and software components and an advanced methodology
(b) To generate a pipeline for data acquisition and processing that can be handled by non-experts in the field of photogrammetry, which may compromise somehow on the side of accuracy and costs.

To achieve these goals we apply the following working steps:

- **Accuracy assessment**. In order to explore the possible accuracy level an accuracy assessment was firstly conducted (Guo et al., 2016). We compared the accuracies of 3D point clouds generated by using images acquired from a system camera mounted in an underwater housing and the popular GoPro cameras respectively. A precisely measured calibration frame was placed in the target scene in order to provide accurate control information and also quantify the errors of the measurement procedure. In addition, several objects with various shapes were arranged in the air and underwater and 3D point clouds were generated by automated image matching. These were further used to examine the relative accuracy of the point cloud generation by comparing the point clouds of the individual objects with the objects measured by the system camera in air (the best possible values). Given a working distance of about 1.5 m, the GoPro camera did achieve an accuracy of 1.3 mm in air and 2.0 mm in water. The system camera achieved an accuracy of 1.8 mm in water, which meets our requirements for coral measurement in this system.

- **Image pre-processing**. Underwater image acquisition is quite laborious, in particular if sites have to be revisited because images are missing. Therefore we follow the concept of bulk image acquisition, that is, we produce more images than usually required by either video sequences or time-laps imaging. Thus it becomes a heavy task to screen the raw image data. We developed a software to automatically select images according to their sharpness and overlapping rate. We also noted that certain diving housings, especially those flat diving boxes cause different refraction shifts in different wavelengths. This Chromatic Aberration (CA) is increasing non-linearly towards the image borders. It causes image blur and would significantly affect the quality of 3D point clouds. Therefore we carried out CA correction with our software to enhance image quality as well.

- **Ground control targets setting and measurement**. It is very difficult to locate well defined natural objects as ground control targets in the dynamic underwater environment. Everything is changing there over time. When dealing with deformation measurements, a geodetic network is essential to realize a stable and unambiguous reference frame through the accurate and permanent installation of Ground Control Points (GCPs). Such a network must permit a robust reference frame for the geo-referencing of images blocks in the different time periods of data acquisition. Therefore, the comparison among subsequent photogrammetric models must be based on an accurate, stable reference system of control points. Thus we designed a set of instruments and methodologies to set well defined ground control targets and precisely measure the ground control information in planimetry and height (Capra et al., 2017). We considered 3 methods for accurate measurements of the control heights, which are of particular importance: (a) A panoramic photogrammetric technique, (b) hydrostatic leveling, and (c) laser pointer-based leveling. In practice we only implemented method (c). The planimetry was measured with tapes and a particularly designed measuring rod. Our current results achieved in the geodetic network adjustment of a large test site of 5m x10m, show an average accuracy of 2 cm (horizontal) and 0.5 cm (vertical) for the adjusted coordinates on the basis of redundant distance and elevation difference observations, which basically meet the requirements.

We are using 4 different camera configurations: Single GoPro, 2 GoPros on a fixed stereo basis, 5-camera head of GoPros, and a Lumix DMC-GH4 camera in a dome-shaped housing. Figure 9 shows equipment for control point marking and measurement and for image acquisition. Figure 10 shows our green laser pointer on a tripod and its underwater use for leveling.

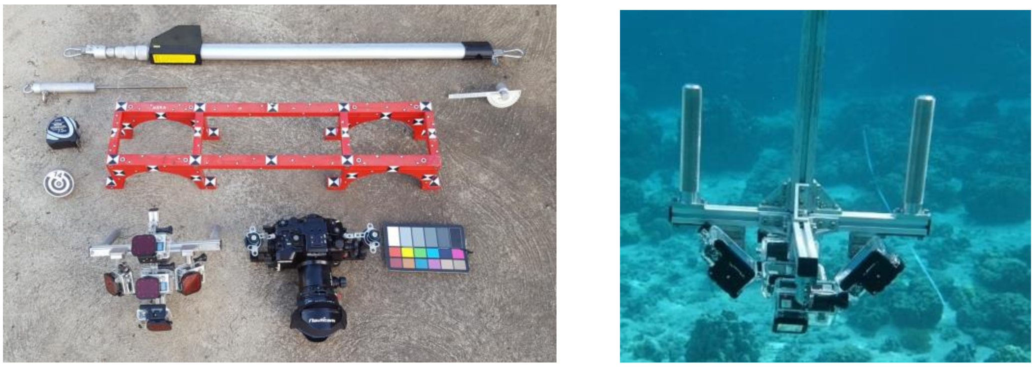


Figure 9: Left: Equipment used for image acquisition and control point measurement. Right: 5-head GoPro cameras.

There are a number of coral areas of sizes 5mx5m, 5mx10m, 10mx10m, and 5mx50m transects, which serve as test areas for coral investigations. We put in control points and surveyed all of them and we produced various image blocks. For each imaging “flight” we do an a priori system calibration using our 3D test frame for geometry and a colour chart for colour adjustment (Figure 9).

Figure 10. Leveling with green laser pointer for accurate height difference determination in control points.

Here is not the place to report about these activities in detail. Figure 11 left shows a typical underwater image with a control point in the center, and the control point distribution for a 5mx10m area. Figure 12 left shows the image configuration for a 10mx10m area and right provides a view onto the computed 3D coral model.

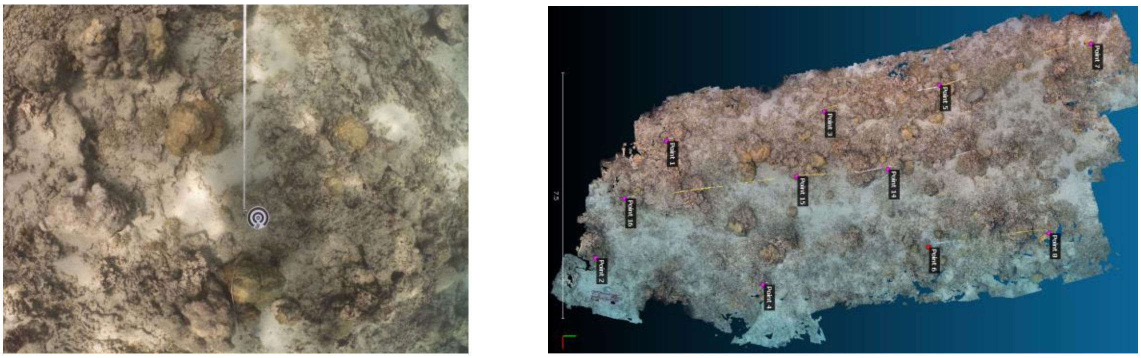


Figure 11. Left: Typical underwater image with control point in the center. Right: Typical control point distribution for a 5mx10m area on the fringing reef

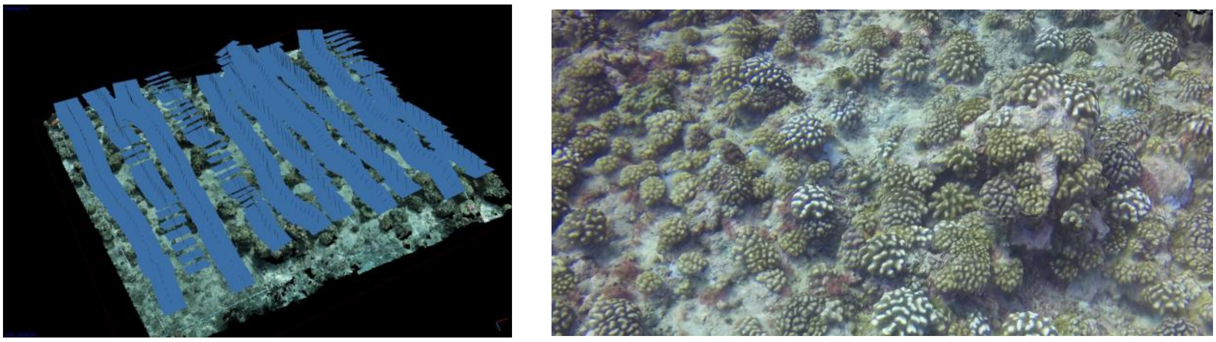


Figure 12: Left: Image configuration for the coverage of a 10mx10m area on the backreef. Right: View onto the 3D coral model

4. CONCLUSIONS

This paper describes the objectives of the Moorea Island Digital Ecosystem Avatar (IDEA) project and addresses some of the challenges encountered during the physical modelling activities. Here we focus on the analysis of the Moorea land model. We compared the manually measured DTM from a Pleiades stereo model with a point cloud from a green LiDAR mission. Although the LiDAR point cloud has been pre-processed and classified by the data provider there were still plenty of spurious observations. This needed additional manual editing, which takes a long time. Therefore we reduced our test to a relatively small area of 0.9 km x 1.3 km. Comparing both data sets we received an RMSE (Z) of 1.82 m. This does not necessarily reflect the pure measurement accuracy, because LiDAR is potentially much more accurate and also manual stereo measurements will lead to better results. The problem is that the surface is not a closed, smooth, firm material surface, but we have here vegetation of varying height and composition, many hard edges from man-made objects, etc. A measurement grid of 5mx5m will not catch many important edges and the laser will produce spurious observation in multi-layered objects like vegetation. So the problem is not so much that of measurement accuracy but of modeling fidelity.

An even more interesting investigation will be the comparison of diverse bathymetric techniques as sonar, green laser and photogrammetry, which have been used on the Moorea and also on the Tetiaroa reefs.

We also measured 3D surfaces of coral patches for coral growth investigations with underwater photogrammetry. Here we are working at another resolution level with image footprints around 1mm and also accuracy requirements in the mm - domain. We describe the principles of our approaches. Detailed reports will be published elsewhere.

ACKNOWLEDGEMENTS

This study is being supported by the members of Moorea IDEA Consortium (mooreaidea.org). We are specifically grateful to Prof. A. Capra, University of Modena for his help with the measurement of the underwater control points and the acquisition of the underwater images.

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