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Australian Institute of Marine Science

3D habitat reconstructions of benthic communities

Long-term Monitoring of the Great Barrier Reef

Standard Operational Procedure Number 12

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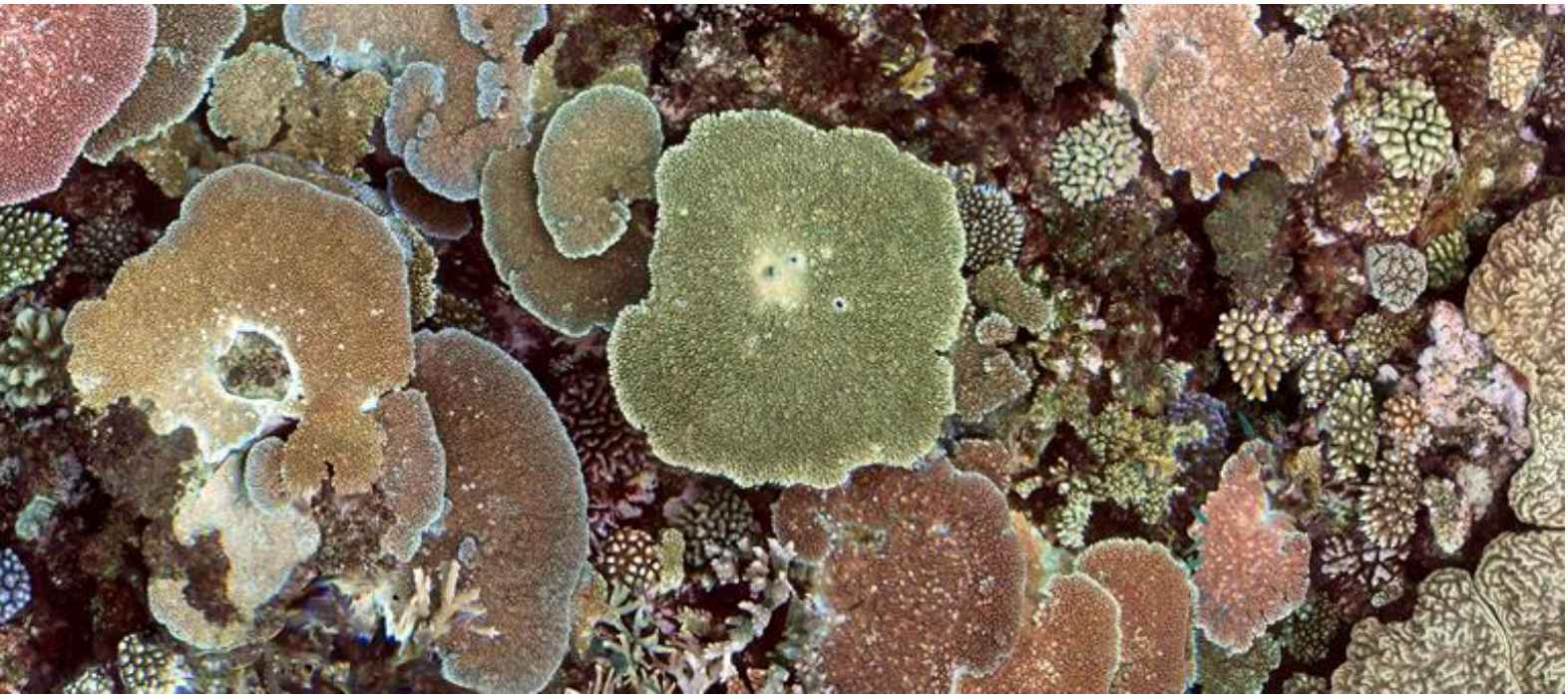

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Three-dimensional reconstruction of habitat from Rib Reef: Manuel Gonzalez Rivero

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1 SUMMARY

The Australian Institute of Marine Science's Long-term Monitoring Program (LTMP) monitors benthic and reef fish assemblages on coral reefs, as well as crown-of-thorns starfish populations and other agents of coral mortality (bleaching, coral diseases and *Drupella*), using a variety of techniques.

This document is Standard Operational Procedure Volume 12, produced by the Long-term Monitoring Program at the Australian Institute of Marine Science. It details the standard procedures for three-dimensional (3D) habitat reconstruction.

Details for other surveying methods used by the LTMP including the sampling design (SOP 13), can be found in a series of Standard Operational Procedures published online:

https://www.aims.gov.au/docs/research/monitoring/reef/sops.html

2 INTRODUCTION

Habitat structure is a key driver to resilient marine ecosystems; biodiversity, function, and the trajectory of reef communities are inextricably linked to the success of ecosystem engineers such as corals creating structure and thereby creating refuge for fish and other reef organisms (Gratwicke and Speight 2005a, Gratwicke and Speight 2005b, Harborne et al. 2012). There is increasing evidence that coral reefs' resilience to climate change is related to a reef's 3D structure (Bozec & Mumby 2015, Graham et al. 2015). For example, as coral reefs begin flattening after disturbances, fish that perform vital services to the coral reef have difficulties finding refuge and move away from the flattened sections of reef.

Our ability to predict and manage the impacts of environmental change on reefs is impeded by a lack of data on the relationship between 3D structural complexity and biotic assemblages across spatial and temporal extents (Pygas et al. 2020). Digitising reefs of the GBR across space and time will help fill these gaps and advance our fundamental understanding of how to improve climate adaptation of coral reefs and reporting to management authorities (Calders et al. 2020).

Current monitoring programs rarely measure the 3D structural complexity of coral reefs and therefore, are unlikely to improve understanding of related ecological processes. Thus, the lack of 3D data is limiting our understanding of reef status and trajectory in a warming ocean (Calders et al. 2020). To quantify the 3D structural complexity of coral reefs across spatial and temporal scales, the benthic component of the LTMP produces 3D terrain reconstructions using close-range photogrammetry in conjunction with photo transects used to quantify benthic reef communities.

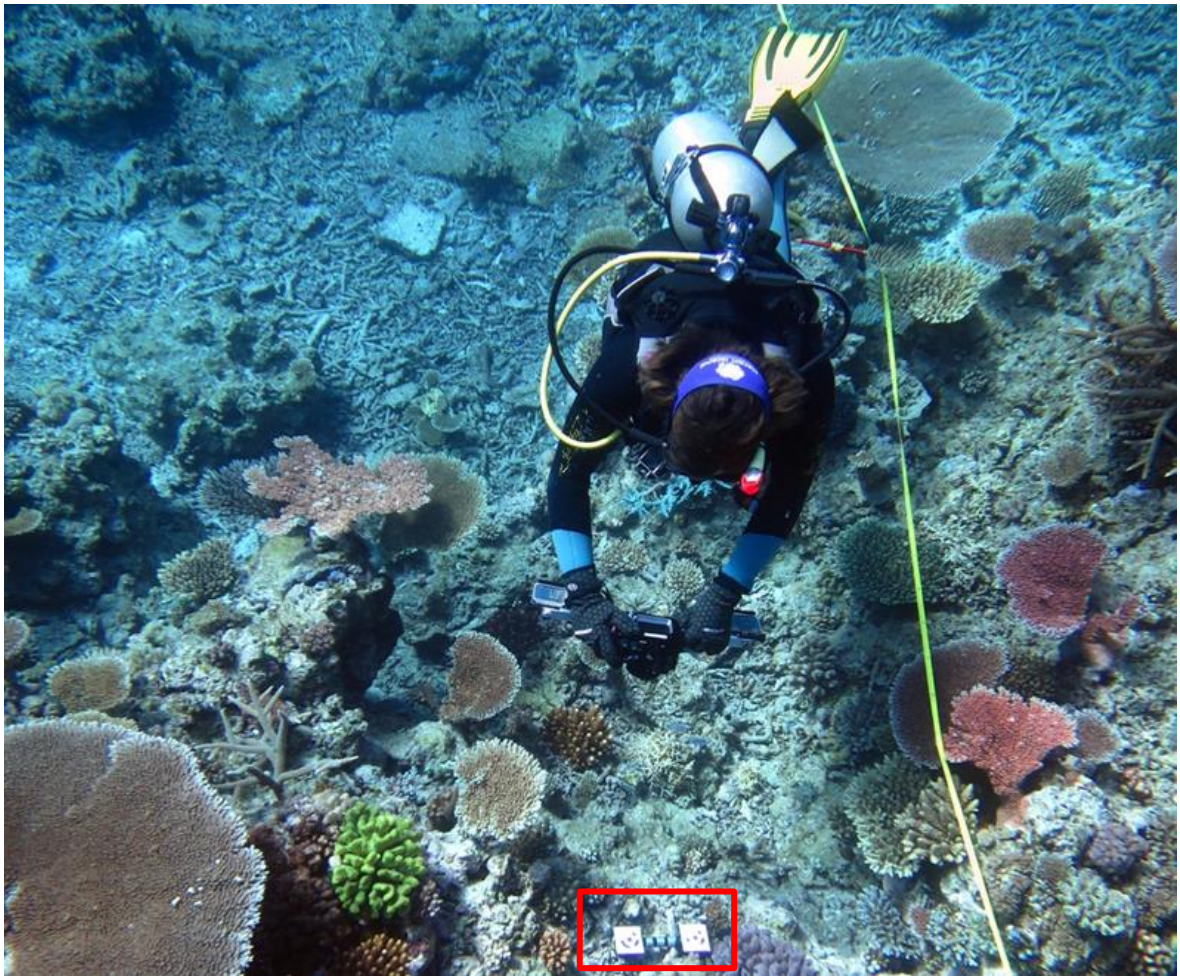


Figure 1. An AIMS diver collecting imagery along a transect for producing a 3D terrain reconstruction. This is accomplished using a paired-arrangement of Go-Pro cameras set apart by 40cm, the picture also shows the scale bar laid on the reef as a reference used to scale the 3D reconstruction (inside red rectangle).

To estimate the structural complexity from transects, sequential images are collected along the first ten metres of each transect, using a dual camera set up (Figure 1), to recreate a high-resolution 3D terrain reconstruction of the reef substrate, here after referred to as 3D models (Figure 2). These models are a representation of the reef topography and area produced from overlapping two-dimensional images using Structure from Motion (SfM) algorithms (Ferrari et al. 2016). SfM is a close-range photogrammetric technique that finds correspondence between images and tracks common features (edges, shapes, etc) from one image to the next. The feature trajectories are then used to reconstruct their location in the 3D space and create a high-resolution (millimetric scale) tridimensional representation of the reef topography (Figure 2).

To recreate the 3D models, the algorithm searches for common points (at pixel scale) in overlapping frames, matches them, and determines the position of the camera for each frame. The next step builds a dense point cloud based on the estimated camera positions and pictures (Ferrari et al. 2016). Points are then joined creating a 3D mesh made of triangular faces, over which the texture (colour information) of the 2D images on a pixel-by-pixel bases is overlaid to create a 3D model. Metrics are extracted either from the dense cloud or the 3D mesh, but the texture 3D model is useful for visualisation (Ferrari et al. 2016).

Figure 2. Sample 3D reconstruction from a transect section.
This reconstruction is comprised by hundreds of thousands of points in the 3D space, from which multiple metrics of structural complexity can be extracted (i.e., 3D rugosity).

Previous evaluations of the accuracy of 3D reconstructions using this methodology suggests that the technique can replicate the 3D structure of coral reefs within millimetres of error (Figueira et al. 2015). From these models, structural complexity is estimated by computing the rugosity index over the 3D meshes or point clouds, using the approach described in González-Rivero et al. (2017) and Friedman et al (2012).

The rugosity index is a measure of the deformation of a surface relative to its planar projection, and it is a common metric used to characterize the architecture of reef habitats (Graham and Nash 2013), where a value of 1 depicts a perfectly flat surface and the index increases with the complexity of surface convolutions.

While rugosity is common metric to represent structural complexity of coral reefs, additional metrics are also derived from these models to capture a more complete picture of the habitat structural complexity and its changes over time. These include curvature, range of heights, slope, among others. This Standard Operational Procedure describes the methodology for sampling and data analyses presently used by the LTMP at AIMS to recreate the 3D models of reef substrate and derive the structural complexity metrics of these systems (Figure 3).

Consequently, some aspects of the manual are specific to the equipment used in this program. This Standard Operational Procedure is also intended to act as a guide for other users who wish to use photography to map and monitor habitat structural complexity of benthic communities on coral reefs.

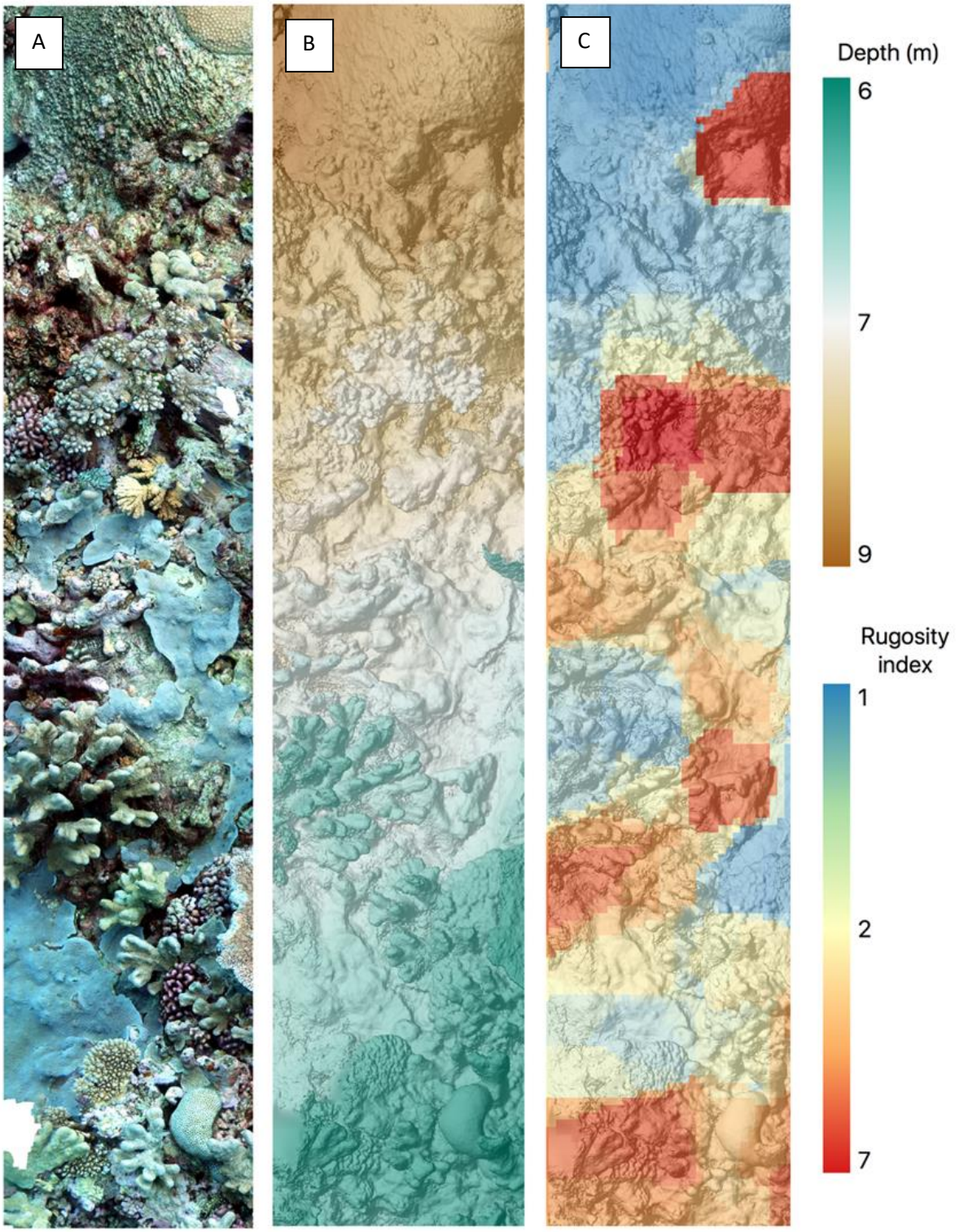


Figure 3. A visual representation of the outputs to estimate structural complexity of coral reefs using photogrammetry and 3D data analysis.

A) Top view of a 3D reconstruction from a transect; B) High-resolution bathymetry generated from the 3D reconstruction; and C) Interpolated rugosity index estimated at specific point locations across the 3D reconstruction.

3 HABITAT RECONSTRUCTION

The following standard procedures are used by LTMP for collecting images to make 3D habitat reconstructions of sessile benthic communities and quantifying structural complexity. They are specific to the objectives of the program but may be easily modified to satisfy other research objectives.

3.1 Personnel

A minimum of three people is required for the collection of 3D habitat data using this technique. One person is required to lay the tape and place scale markers evenly along the transect. The second person will follow and capture both sides of the 10m transect. The third person is required to remain in the boat as a divers' attendant and surface support.

LTMP 3D habitat surveys are conducted concurrently with surveys of reef fishes (Emslie and Cheal, 2018), juvenile corals (Jonker et al 2020), and coral disease and other agents of coral mortality along the same transects (Miller et al 2020).

3.1.1 Field Equipment

To make 3D habitat reconstructions, the following list of equipment is required in the field.

- 1 x waterproof case with:
  - 2 x GoPro Hero 6 cameras
  - 2 x 128 GB memory cards
  - Battery chargers
  - SD card reader
  - 2 x GoPro underwater housings,
  - Manuals for camera and housing
  - Set of QR code transect identifiers (Figure 4)
  - Transect markers (GCP) for habitat reconstruction (See Figure 6)
  - Red filter for each Go Pro.
- 1 x metal bar (~ 0.6 m) and butterfly screws to attach Go Pros 405mm apart.
- Laptop
  - Reefmon database data entry software (not available yet)
  - Application for sorting images (see Data Management section 4) - not necessary but will save you time.
  - Agisoft Metashape (If using a network licence, this needs to be checked out via ICT to the user for the length of the field trip)
- External hard drive to store and back up images and data (2 x 4TB for each sampling year).

Figure 4. A set of QR code transect identifiers.
These are used by the LTMP to allow automatic sorting of images on the camera's SD card from the photo transects into their respective transects.

3.2 Equipment Preparation

3.2.1 GoPro Hero Camera Settings

1) Check each camera to ensure the date and time are correct.

2) Ensure the memory cards have been downloaded and erased prior to camera set up and the batteries are fully charged.

3) Leave all settings to default except for:

   a) Auto rotation fixed to "down".

   b) Default mode to time lapse photos at 0.5s intervals (Camera with a clock symbol).

   c) Field of view set to "Linear

3.2.2 GoPro Hero 6 Housing

1) Check both sides of the housing window for the lens are clean. Use a lens cleaning tissue or the lens cleaning fluid with the soft lens cleaning cloth.

2) Wipe your finger around the silicon O-ring for the housing and visually inspect to ensure there is nothing on the O-ring. Do not use silicone grease on GoPro housings.

3) Close the housing and secure the clip.

3.3 Camera Set Up

To collect the habitat reconstruction data the GoPro cameras should be mounted 405 mm apart onto a stainless-steel bar, through predrilled holes with butterfly nuts. If benthic surveys using the photo transect method are done concurrently, the photo-transect camera (Nauticam housing) should be placed in the middle of the bar and the GoPro camera lenses should be facing the direction of the transect camera (Figure 5). When tightening the butterfly nuts, ensure that the spring washer is on the same side of the bar as the butterfly nut (i.e., opposite side to the GoPro camera).

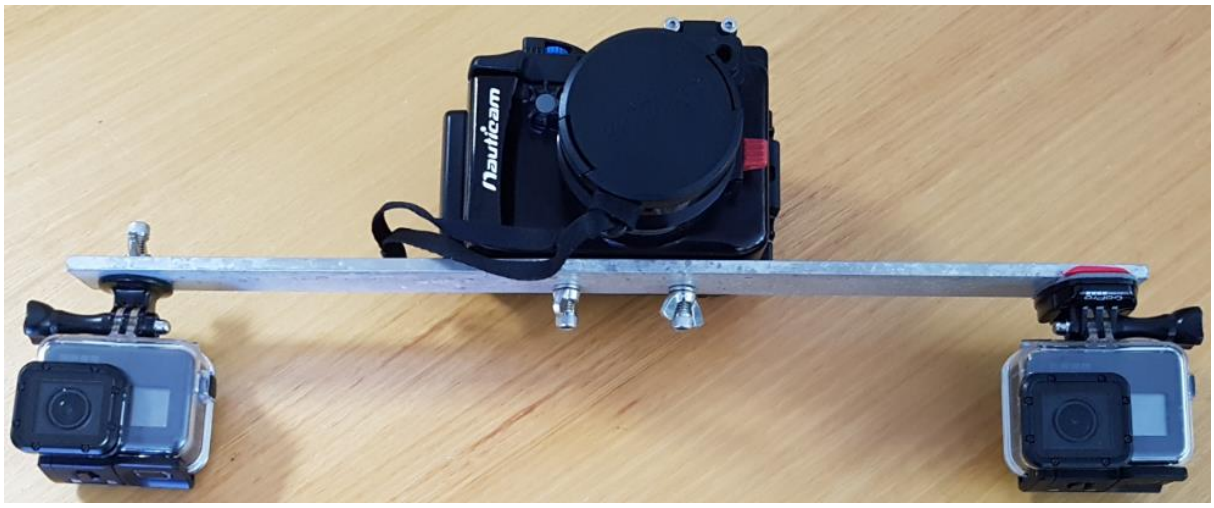


Figure 5. Overview of the camera set up where GoPro cameras are used for recreating and measuring the habitat structural complexity.
The "transect camera", in the middle is used to collect the high-definition images for estimating benthic composition and specific details can be found in SOP 10, Surveys of benthic reef communities using underwater digital photography and counts of juvenile corals.

3.4 Field Sampling Procedure

In suitable light conditions, typically in horizontal visibility greater than 5 m, images are taken along the first 10 m of each transect, with the cameras held approximately 1.5 – 2.0m above the reef substrate. Before commencing each transect, lay three, or more, scalebars at approximately even intervals along the transect. A scalebar is comprised of a pair of unique Ground Control Points (GCP), with a fixed, known distance between the centres of the two GCPs, (Figure 6). A GCP is a pattern recognised by Metashape and can be printed by clicking on Tools > Markers > Print Markers. It is important to ensure the markers are not scratched or damaged before use, if they are damaged, replace them.

Each individual GCP is assigned an identifying number (Figure 6), it is critical that these numbers are used only once per transect as a repeated GCP will cause an error in the reconstruction of the transect. The LTMP uses scalebars, which are created from predesignated pair of GCPs with a known, fixed distance apart (150mm), the scalebars are used by Metashape to assign scale to the 3D reconstruction and all features within it (i.e., corals). It is imperative that the camera can capture unobstructed images of both GCPs facing upwards on each scalebar and equally, it is also important that the scalebars are laid where they are unlikely to be repositioned by surge or currents, particularly if there are to be

multiple passes capturing images over the same area. If a marker moves during imaging, that transect needs to be re-imaged.

The following steps describe how to conduct the transect, while completing these steps, the diver should attempt to maintain a consistent altitude (1.5 – 2.0 m) above the substrate and swimming speed with the entire transect (first 10 m of each LTMP benthic transect) which should take approximately one minute.

1) Before commencing the transect, ensure that both GoPros are parallel to each other while the dive buddy places all three scalebars within the first 10 metres of the transect.

2) The GoPro cameras are setup to automatically turn on to the correct settings, once switched on, press the "record" button (If the mode button is pressed by accident, simply turn the GoPro off and back on).

3) Hold the QR code tag for the specific transect in front of each GoPro for 3 seconds.

4) To begin the transect, swim along the righthand side of the transect with the cameras capturing images 1.5 m above and parallel to the reef substrate keeping the transect tape just visible in the left-hand side of the view finder of the left-hand camera.

5) Once the outward leg of the transect has been completed, slowly turn around and continue photographing from the left-hand side of the transect, keeping the transect tape just visible in the left-hand side of the view finder of the left-hand camera.

6) Upon completion of the transect, stop both GoPro cameras and begin the photo-transect survey as described in SOP 10.

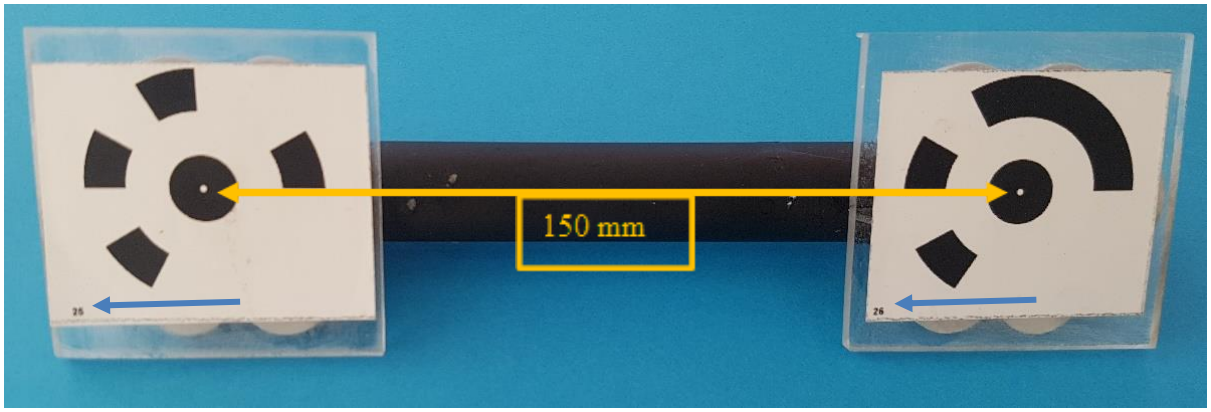


Figure 6. A scalebar with the yellow arrows denoting what Metashape considers to be the centre points of the two GCPs.
The distance between the two centre points is known and can provide scale to the 3D models and by-products, the scale bars used by LTMP are typically 150mm between these two points. The blue arrows denote the identifying numbers of each GCP, it is important that none of the GCPs used on the transect have matching identifying numbers.

4 FIELD DATA MANAGEMENT

Many of the processes in Metashape are internally scripted, so it is important the images from the camera are organised into folders using a standardised system to allow the program to function properly. For LTMP data, the images should be sorted into a folder structure identical to the photo-transects described in SOP 10 (Jonker et al. 2020), i.e., the images are sorted first by reef, then into their corresponding sites and transects (e.g., *ReefName/SiteNumber/TransectNumber*).

4.1 Download Images to Field Computer

There are 2 ***alternative*** methods to sort images (manually or semi-automatically using python code), regardless of which of the two you use, images first need to be copied into the computer following the steps and structure explained in this section. Then apply either of the 2 sorting methods explained in sections 4.2 or 4.3.

1) Create a folder labelled unsorted, this is where you will download all images from the cameras into (do not download from cameras yet).

2) Within the unsorted folder, create a folder labelled according to the reef surveyed (e.g., THETFORD REEF).

Note: Make sure the name of the reef folder corresponds to the name in the database, a list of the reef names as they appear in the database taken on each cruise.

4.2 Manually Sort Images

Typically, the LTMP uses a folder labelled “unsorted” to use as a staging point to sort the images from the photo-transects into their respective transects as described in SOP 10 (Jonker et al 2020). To remain consistent, this SOP will mirror the methods described in SOP 10 where possible.

1) Within the reef folder, create a folder called LC (left camera) and RC (right camera).

2) Copy the images from SD cards of the left-hand and right-hand cameras into the LC and RC folders.

3) While the images are copying, create a folder for each transect of each site labelled “SiteXTranX” as shown in Figure 7. Folder structure for transects of reefs with each folder name corresponding to each transect. Keeping this format is important due to the scripts in Metashape being mapped to these folder names. below.

   Tip, there is pre-named set of folders on the backup drives underneath the “folder structure” directory, this will save you from individually creating and naming each folder.

4) Open the LC folder and sort the image files by the date they were modified, from earliest to latest. This can be sorted by clicking on the “Date Modified” tab up the top of file explorer in Window and clicking it twice.

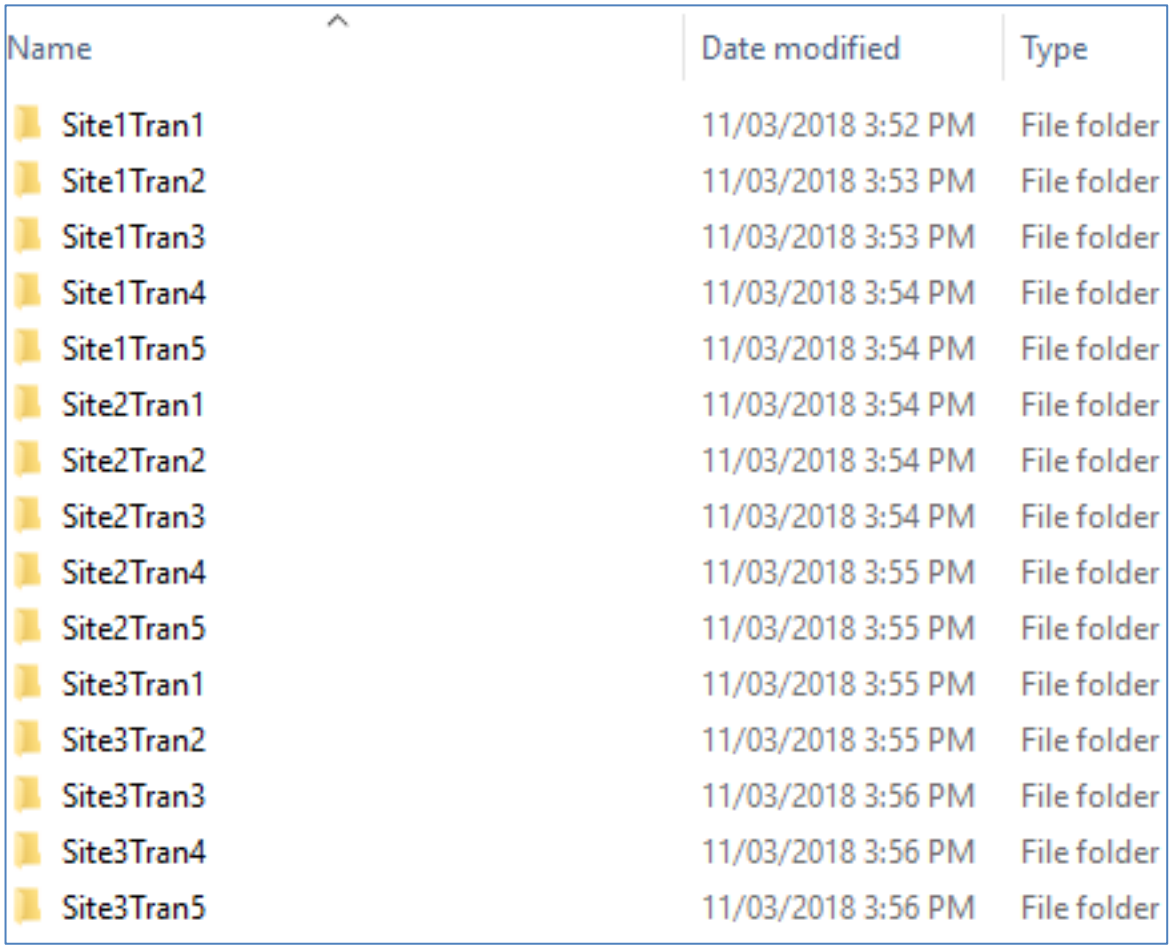
5) Because the images for the habitat reconstructions are collected at the beginning of the LTMP transects at 0.5 second intervals, there is an obvious time gap between the images from each transect. In Figure 8 it can be seen that the timestamp in the Date modified column of the last selected file is 2:38 PM, and the first of the non-selected files is 2:52 PM. These time stamps can be used to sort the images into their respective transect folders shown in Figure 7.

6) Repeat steps 4 and 5 for the RC folder.

7) Upon completion, look in each of the transect folders, locate an image showing the QR code and ensure that the site and transect number on the QR tag correspond with the folder the images are located in.

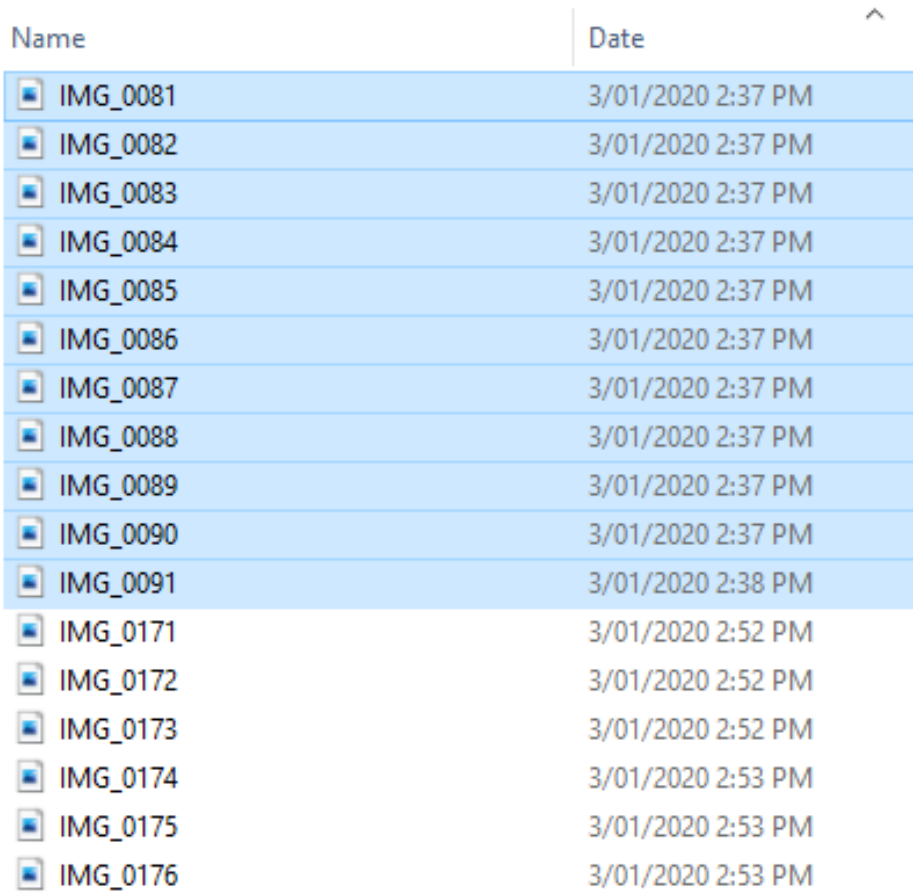
8) Delete the empty folders for any transects that were not completed (images not captured) and make a note in the field log metadata about any incomplete data.

9) When the images have been filed into their corresponding transect folders and checked, the final step is to back them up onto both the external benthic backup hard drives (creating 2 identical copies). All images from the trip, including benthic photo-transect, images for media use, and images for habitat reconstructions are backed up on the external hard drives within the relevant subfolder under the [CRUISE_CODE] folder. For habitat reconstructions, the folder "3D Transects" is where the backed-up images for the habitat reconstructions are located.



Name	Date modified	Type
Site1Tran1	11/03/2018 3:52 PM	File folder
Site1Tran2	11/03/2018 3:53 PM	File folder
Site1Tran3	11/03/2018 3:53 PM	File folder
Site1Tran4	11/03/2018 3:54 PM	File folder
Site1Tran5	11/03/2018 3:54 PM	File folder
Site2Tran1	11/03/2018 3:54 PM	File folder
Site2Tran2	11/03/2018 3:54 PM	File folder
Site2Tran3	11/03/2018 3:54 PM	File folder
Site2Tran4	11/03/2018 3:55 PM	File folder
Site2Tran5	11/03/2018 3:55 PM	File folder
Site3Tran1	11/03/2018 3:55 PM	File folder
Site3Tran2	11/03/2018 3:55 PM	File folder
Site3Tran3	11/03/2018 3:56 PM	File folder
Site3Tran4	11/03/2018 3:56 PM	File folder
Site3Tran5	11/03/2018 3:56 PM	File folder

Figure 7. Folder structure for transects of reefs with each folder name corresponding to each transect. Keeping this format is important due to the scripts in Metashape being mapped to use these folder names.



Name	Date
IMG_0081	3/01/2020 2:37 PM
IMG_0082	3/01/2020 2:37 PM
IMG_0083	3/01/2020 2:37 PM
IMG_0084	3/01/2020 2:37 PM
IMG_0085	3/01/2020 2:37 PM
IMG_0086	3/01/2020 2:37 PM
IMG_0087	3/01/2020 2:37 PM
IMG_0088	3/01/2020 2:37 PM
IMG_0089	3/01/2020 2:37 PM
IMG_0090	3/01/2020 2:37 PM
IMG_0091	3/01/2020 2:38 PM
IMG_0171	3/01/2020 2:52 PM
IMG_0172	3/01/2020 2:52 PM
IMG_0173	3/01/2020 2:52 PM
IMG_0174	3/01/2020 2:53 PM
IMG_0175	3/01/2020 2:53 PM
IMG_0176	3/01/2020 2:53 PM

Figure 8. Image files showing a noticeable time difference between the selected files and the non-selected files.
In this case there are fourteen minutes between the selected (2:38 PM) and non-selected files (2:52 PM) indicating the end of one transect and the beginning of the next. Such time stamps can be used to sort the images into their respective transect folders shown previously in Figure 7.

4.3 Use Python App to Sort Images from Command Prompt

Follow these steps to organise GoPro time-lapse images for 3D reconstruction into *SiteNumberTransectNumber* folders (details of each step below under 4.2.1):

- **Setup the application (First Time Use Only).**
- **Sort images:** This step organises all the images from the Left (LC) and Right (RC) cameras, in each Reef folder, into subfolders using a time gap to distinguish transects and sites. Then, it automatically recognises the QR codes in the images and renames transect subfolders for each camera folder.
- **Review and manually rename folders if needed**: Manually review subfolder names and allocate names to those where QR was not recognised.
- **Merge renamed transect folders from each camera**: Automatically merge subfolders from Left and Right Camera.

4.3.1 Set Up Application (First Time Use Only)

This step will only need to be completed once per computer to set up the python application required to sort the images (step 2 and 4). Please follow these steps:

1) Make sure you got a Git client installed. Otherwise check here for details.

2) Clone the following GitHub repository to your local hard drive: https://github.com/AIMS/reef3D.git Check this webpage for details if you need more information about cloning repos in GitHub Desktop.

3) Install python if not available in your computer and restart your computer. Check more info here.

4) Open the Command prompt (Windows) or terminal (MacOS). In Windows, go to the start menu and type: **cmd**

5) Follow the next steps from the cmd:

   a. Change directory to where you cloned the GitHub repository by typing in the cmd (step1)

   ```
   cd  C:\folder\where\you\have\installed
   Example: "cd C:\Users\xxx\Documents\gits\reef3D\"
   ```

   b. Change directory to image_sorter by typing:

   ```
   cd PyToolbox\image_sorter
   ```

   ```
   pip install -r requirements.txt
   ```

   c. Install python dependencies by typing:

***Trouble-shooting tip**: to check if you need to "Add Python to the PATH Environmental Variable", go to command prompt and type "python" - if you get an error saying "'python' is not recognized as an internal or external command, operable program or batch file" then you need to add Python to the PATH Environmental Variable, see instructions here. If you need to add it, you may need to contact AIMS helphub to get permission to access the Advanced System Settings. Before contacting them, you can try connecting via VPN and using Elevate in your computer.

Alternatively, you can also add python to the Path Env variable through command prompt by typing:

setx PATH "%PATH%";C:\Python38\Scripts

4.3.2 Sorting Images

This step will run a custom-made Python function to group images from left (LC) and right (RC) cameras into transects. This script uses a time gap of three minutes between images to identify a new transect and will sort them into sequentially numbered folders (i.e., 1,2,3...). It will then attempt to recognise the QR code from the first 20 images in each transect and label the folders accordingly.

1) Copy the images from SD cards of the left-hand and right-hand cameras into the corresponding Reef folder (all images into a single folder). Repeat this for each reef of the day.

2) To begin sorting the images, open the command prompt / terminal and change directory to the folder where you cloned the reef3D GitHub repository:

```
cd  C:\folder\where\you\have\installed  (e.g., cd
C:\Users\xxx\Documents\gits\reef3D\)
```

3) Change directory to image_sorter:

```
cd PyToolbox\image_sorter
```

4) Now, select the Reef folder you want to organise and identify the prefix you want to assign to these images. The Reef folder contains all the left and right camera images from transects in each Reef and cruise code. If you are sorting images after they have been copied from the field computer to the 3D-LTMP shared folder in the AIMS server (you are not in the field but in the lab), the folder will be located in the 3D-LTMP shared folder in:

```
\\tsv-isilon1\3D-LTMP\data\LTMP\[PROJECT]\[SURVEY YEAR]\[CRUISE CODE]\.
Example: \\tsv-isilon1\3D-LTMP\data\LTMP\RAP\201920\QA\AGINCOURT REEF (NO 1).
```

Note: Make sure the name of the reef folder corresponds to the name in the database, a list of the reef names as they appear in the database taken on each cruise (a list of reef names as they appear in the database is taken on each cruise).

The prefix for the image is the string used to rename all the images to follow this naming convention:

[REEF NAME]_[VISIT NO]_[IMAGENUMBER].JPG

[IMAGE NUMBER] is automatically generated, so the prefix entered in the function below should be: [REEF NAME]_[VISIT NO]. For example: AGINCOURT REEF (NO 1)

5) Run the file sorter from the windows terminal:

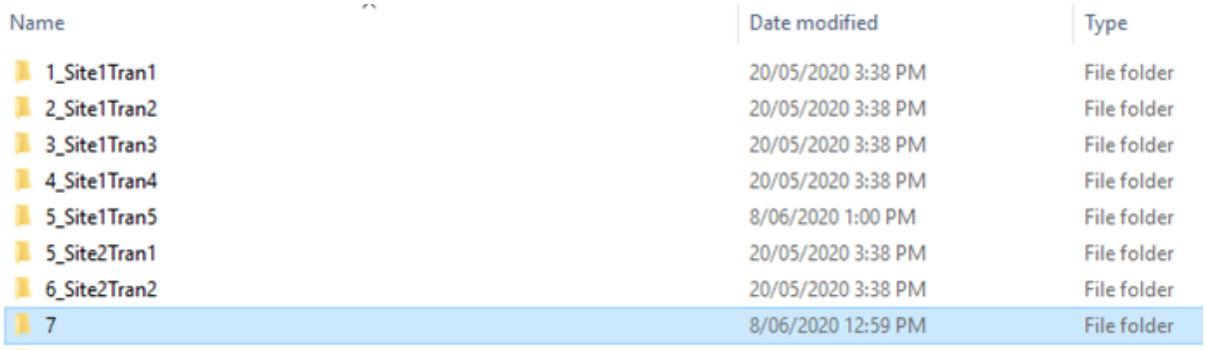
```
python3  step1_sortRename.py "[REEF FOLDER]" "[PREFIX]"

Example:

python3 step1_sortRename.py
"/media/pearl/3d_ltmp/data/LTMP/RAP/201920/QA/agincourt reef (no 1)/"
"AGINCOURT REEF (NO 1)"
```

***Tip: Please note that arguments (reef folder and prefix) are quoted (" "). Otherwise, the function will not recognise names with blank spaces.**

4.3.3 Review and Manually Rename Folders:

Once the software has finished, review the images contained in these folders to ensure the sorting process was successfully completed without errors.

Occasionally, not all the QR codes are identified by the scanning software, where this is the case, the script will have kept the sequential numbering of the transect without inserting the proceeding Site#Tran# label shown in Figure 9. Where this is the case, open the folder and find an image capturing a QR tag and manually rename the folder to correspond with the transect listed on the QR tag.



Name	Date modified	Type
1_Site1Tran1	20/05/2020 3:38 PM	File folder
2_Site1Tran2	20/05/2020 3:38 PM	File folder
3_Site1Tran3	20/05/2020 3:38 PM	File folder
4_Site1Tran4	20/05/2020 3:38 PM	File folder
5_Site1Tran5	8/06/2020 1:00 PM	File folder
5_Site2Tran1	20/05/2020 3:38 PM	File folder
6_Site2Tran2	20/05/2020 3:38 PM	File folder
7	8/06/2020 12:59 PM	File folder

Figure 9. Showing folders containing images labelled by the software.
These are labelled by their sequence number followed by the site and transect numbers where it has successfully read the QR tag for the corresponding transect, where it is unable to read the QR tag it will only label the folder as the sequence number in this this figure by the folder "7" seen in the highlighted folder on the bottom.

Upon reviewing and renaming the transect folders, remove the numbers preceding the Site#Tran# to be consistent with the folders shown in Figure 7. Folder structure for transects of reefs with each folder name corresponding to each transect. Keeping this format is important due to the scripts in Metashape being mapped to these folder names.

4.3.4 Merge the Renamed Transect Folders from each Camera.

This script will match folders from the Left and Right Cameras (LC and RC folders) making them suitable to process in Metashape. Upon confirming that all images have been correctly sorted into their respective transects, delete the LC and RC folders if they have been created.

To merge folders run this script from the same terminal window as above:

```
python3 step2_mergeCameras.py
Example: "/media/pearl/3d_ltmp/data/LTMP/RAP/201920/QA/agincourt reefs (no 1)/"
```

****IMPORTANT NOTE****: Deleting the RC and LC folders is irreversible! Ensure the sorting and renaming is correct before deleting these folders (as per step 4.3.3).

4.3.5 Troubleshooting

Consider the following tips when working from the HPC:

3d_ltmp is mounted in:

```
/mnt/isilon
```

You need to load the python3 module. For this go to terminal and type:

If you get the following error: “Import Error: Unable to find zbar shared library”. Do this:

```
module load python/3.5.1
sudo apt-get install libzbar-dev libzbar0
```

4.3.6 Using Image Sorter on the HPC

Login into the HPC interactive and Launch a XTERM session:

https://hpc-interactive.aims.gov.au:3443/

Pull git repository to your home directory. From terminal, change directory to where you want to install this repository **[FIRST TIME ONLY]**

```
cd ~/Documents
mkdir gits
git clone https://github.com/AIMS/reef3D.git
```

NOTE: it will ask you for your username and password for GitHub

Load the python module

```
module load python/3.5.1
```

Change directory to the image sorter folder where you install the GitHub repository:

```
cd ~/Documents/gits/reef3D/PyToolbox/image_sorter
```

Install dependencies (libraries required)

```
pip install -r requirements.txt
```

Isilon is mounted in the following directory. Use this directory to locate the folder you want to sort:

```
/mnt/isilon
Example: /mnt/isilon/data/LTMP/RAP/201920/QA/
```

***Tip**: You must have an AIMS git hub account to do this (Access the AIMS/reef3D repository), if you don’t have one please contact Murray Logan at m.logan@aims.gov.au

5 PROCESSING DATA (3D MODELLING)

Images are processed into 3D reconstructions and 2D orthomosaics using Agisoft Metashape Professional (Autodesk, Inc. Version 1.5.2, note this is not the latest version – do not update the version if prompted). The following steps describe the process to generate the 3D models of the reef substrate to estimate the metrics of structural complexity (e.g., rugosity). The steps below are divided into three workflows:

- Pre-processing software licensing and connectivity set-up
- Processing data – from images to 3D models and 2D orthomosaics
- Metric extraction

****NOTE ON PROCESSING****: We have scripted most of the settings for image processing to ensure consistency and automatic image processing which allows for efficient batch processing, for instance, you can line up 15 chunks and leave them processing overnight. We have compiled the 12 scripts for processing in one file called "*LTMP_process_batch.xml*". We will refer to this file as "the batch file" several times throughout these instructions, the 12 processing steps will be run in groups, rather than all together, to implement a few manual quality checks (Figure 14). **The instructions below assume you are connected to the VPN and internet if you are planning to process while in the field you should save the batch file (*LTMP_process_batch.xml*) and associated script files locally before you go to the field.**

5.1 Pre-processing Data Set Up

There are three ways to process the data with the most suitable being dependent upon the speed of your internet connection. While Network processing is preferred, it will not always be possible, hence we have included instructions for all the options. These three processing alternatives are defined by if data is processed remotely (using AIMS processing network – preferred option) or locally (on your own computer), and if locally determine if you will have internet and VPN connectivity (Figure 10).

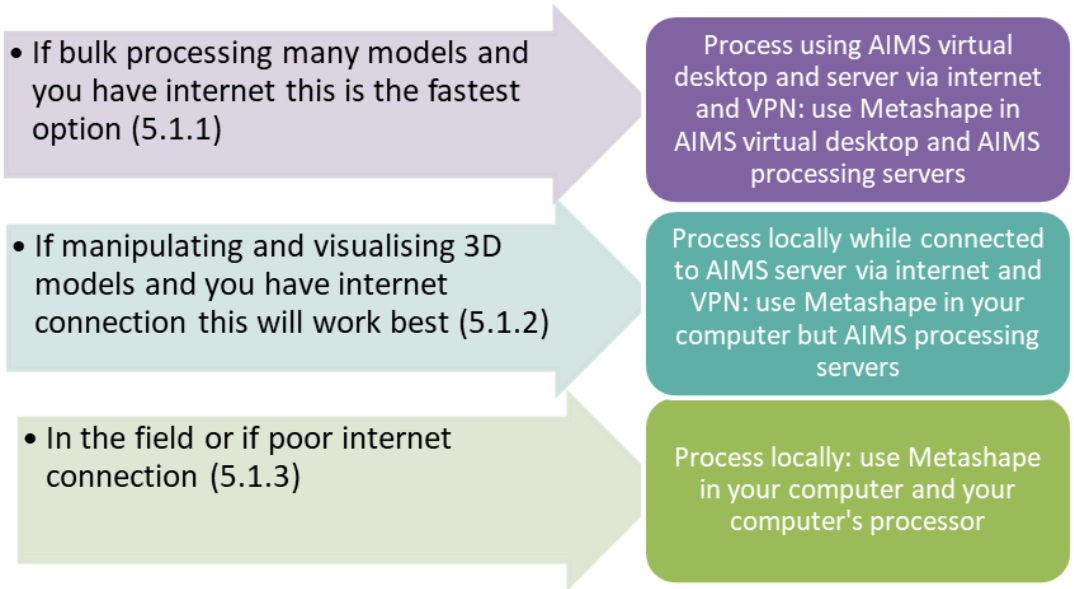


Figure 10. A flowchart showing the three alternative options for processing data from images to 3D models and 2D orthomosaics.
Which way you choose will depend on the task at hand and internet connectivity. Each option requires slightly different pre-processing set up.

1) Process data using AIMS virtual desktop and network of processing servers (preferred option as it is a lot faster and more efficient):

   a. Connect to the internet and the AIMS network using Cisco AnyConnect mobility services App (VPN) and your credentials.

a) Launch the "Remote Desktop Connection App" from Windows and Input the terminal address in the "Computer" field (tsv-termsrv01.aims.gov.au). Add your AIMS username by clicking "Show Options" and connect.

b) From within the virtual desktop, add a network drive to map the data repository in this computer. For this use the following address (here are instructions on how to map a network drive in Windows 10): \\tsv-isilon1\3D-LTMP

c) Open Metashape Pro and check that for the computer you are using, Metashape has Network Processing enabled (that it is connected to the server) by hovering mouse over symbol on the bottom right corner of the Metashape window. If it is not connected to server go to Tools>Metashape Preferences, a window will pop-up, select the 3rd tab on the top menu "Network" and ensure the settings look like shown in Figure 11. You should check that: (1) the "Enable network processing" box is selected, (2) the "Host name" and "Port number" are correct (host name = metashape-qmgr.aims.gov.au, port number = 5840), and (3) the root is set to the letter where you mounted Isilon onto your drive (normally "Z").

4) Process data using your computer and the AIMS network of processing servers (this is the best option if you want to maximise processing speed but also want to visualise models – as the remote desktop connection to the server can have slow rendering speeds, so a local computer will perform better for model visualisation and manipulation) – the first 2 steps (install software and license) are a onetime only step, so after doing them for a given computer you can skip to step 5.2:

   a) Install Agisoft Metashape Pro in your computer from this link.

   b) The first time you use a given computer you will need to add the server license file to the folder where Metashape has been installed. Click here Server License to download and save the Metashape license file, move the file to the folder in the computer where Metashape has been saved (normally in C:\Program Files\Agisoft\Metashape Pro). Skip this step in the future.

   c) Connect to the internet and AIMS VPN before opening Metashape for the license to work, if you are not connected to the VPN Metashape will open but it will prompt you to activate the license.

   d) Add a network drive to map the data repository in this computer. For this use the following address (here are instructions on how to map/mount a network drive in Windows 10 (https://www.dummies.com/computers/pcs/mapping-a-network-drive-on-your-windows-10-pc/)): \\tsv-isilon1\3D-LTMP

   e) Open Metashape Pro and check that for the computer that you are using Metashape has *Network Processing* enabled (that it is connected to the server) by hovering mouse over symbol on the bottom right corner of the Metashape window.

If it is not connected to server go to *Tools>Metashape Preferences*, a window will pop-up, select the 3rd tab on the top menu "*Network*" and ensure the settings look like shown in Figure 11. You should check that: (1) the "Enable network processing" box is selected, (2) the "Host name" and "Port number" are correct as in Figure 11 (host name = metashape-qmgr.aims.gov.au, port number = 5840), and (3) the root is set to the letter where you mounted Isilon (normally "Z").

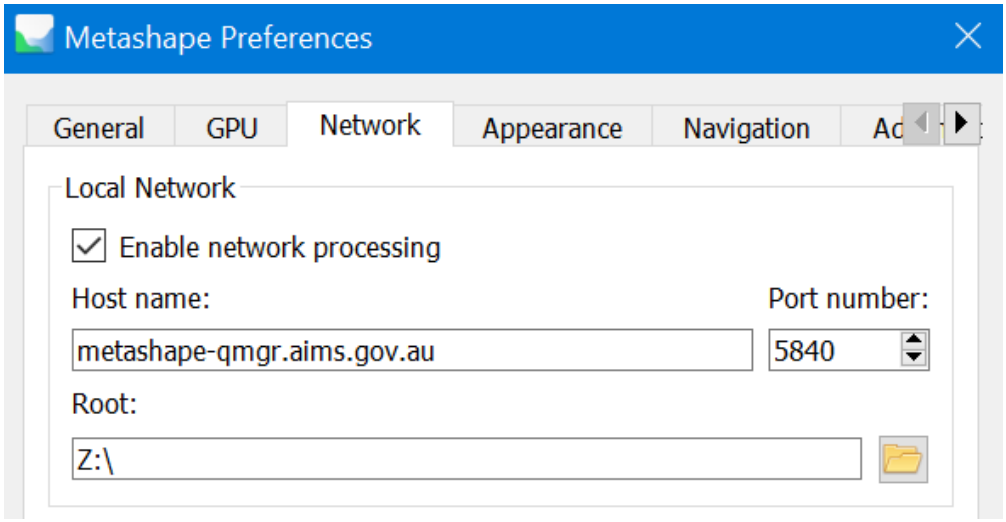


Figure 11. An example of correct settings to enable network processing for image processing in Agisoft Metashape.

5) Process data locally without internet access. You need to do 4 things while online to enable off-line processing:

   a) Install Metashape Pro in the field computer: follow step 2) a. above.

   b) Copy the server license to the field computer: follow step 2) b. above.

   c) 5.1.3.3. Check out a license (from within Metashape) while connected to the internet and VPN borrow a license by Opening Metashape and going to Help > Activate Product and clicking on "Borrow License" in the pop-up window, then enter the number of days you will be offline and request the license.

   d) Copy the folder [\\isilon\3d_ltmp\scripts] to the root of C:\

   e) To store the images, create the folder structure C:\data\LTMP*PROGRAM CODE**YEAR CODE**CRUISE CODE**REEF NAME* e.g. C:\data\LTMP\RM\202021\QE and store the images sorted into transect folders there.

   f) Use the processing batch file LTMP_process_batch_LOCAL, this can be found in: [C:\scripts\batch_jobs\LTMP_process_batch_LOCAL].

   g) The Processing Status Spreadsheet can be downloaded from here.

5.2 Processing Data

1) Open the Processing Status Spreadsheet in teams if you are connected to the internet, or from your computer if you are in the field.

2) To start processing images, open Metashape Pro and Go to *Workflow > Add Folder*, then navigate to and select the folder corresponding to the reef you want to process (e.g. Chinaman). This will import all images from each transect into a separate "Chunk" or folder within Metashape.

3) Rename each Chunk as per Reefmon reef name in front of the site and transect numbers (i.e. "CHINAMAN_Site1Tran1"), do this for each of the 15 chunks. Check there are 15 chunks (Site 1-3, Transects 1-5) imported, otherwise note it in the Notes on your processing status spreadsheet.

4) Save the project in the following folder (if connected to the VPN): [\\isilon\3d_ltmp\projects\[PROGRAM]\[YEAR]\[REEFNAME]. If not connected to the VPN save the project within the corresponding reef folder as per LTMP naming and folder structure, explained in section 4 (Field data management).

5) Click on *Workflow> Batch Process* and load the following batch script [\\isilon\3d_ltmp\scripts\batch_jobs\LTMP_process_batch]. In the pop-up window shown in Figure 12 there are 13 steps, select steps 1-6 by ticking the boxes on the left of each of step and click "OK". If *Network Processing* is enabled a pop-up window will ask if you want to process it over the network, click yes unless you have no internet or VPN connection. Below is a brief description of each process number:

   a) Process #1: Run script: Load calibration parameters for camera lens used for the survey: Choose the following calibration file: "isilon\calibration\calibration.xml"
   b) Process #2: Run script: Remove images with quality below the 0.5 threshold
   c) Process #3: Detect markers: automatically identify the markers (GCPs)
   d) Process #4: Run Script: Set distance between the markers. (Run script)
   e) Process #5: Aligns Photos: Detects matching features between images before aligning them relative to each other.
   f) Process #6: Run script: Align images that didn't align in the first pass. (Run script)

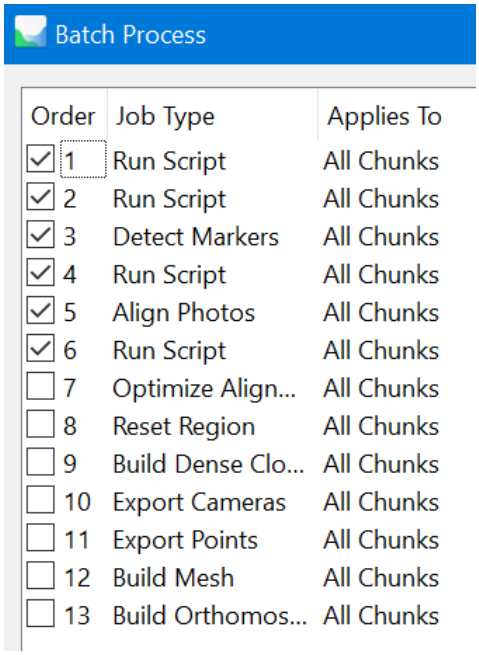


Figure 12. The list of processes to create 3D reconstructions and ortho-mosaics from 2D images. These steps are sequential but are ran in groups to ensure the quality of the product. Processes 1-6 are initially executed in the processing batch file, upon completing quality checks described later in the document, processes 7-9 are then executed.

6) Once processes 1-6 have completed (Figure 12), and the images have been aligned, ensure that on each transect, at least six GCP markers (3 scalebars) were detected and each marker has ten or more verified projections. The number of markers can be checked by expanding the Markers folder and the number of projections of projections for each marker can be checked by clicking on its corresponding target number shown in Figure 13 below.

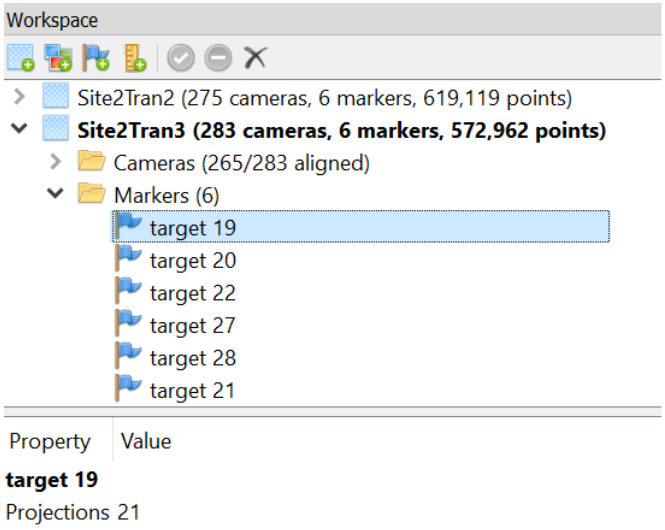


Figure 13. Showing the six markers and the number of projections for the selected marker underneath.

7) If less than 6 markers were detected by the script in step 5c), you will need to manually add the undetected GCPs and verify their placement on the images for at least 10 images by:

a) Go to *View>Photos* this will show you a window with all photo thumbnails, on the top menu of the Photos window use the Change view>Large button to make thumbnails large and quickly find images with the undetected marker, double click on one image with the undetected marker (Figure 14). An alternative method is that if Metashape has detected the missing markers paired marker on the scalebar, simply right click on the paired marker and select *Filter Photos by Marker*.

b) Position your mouse on the centre point of the marker, right click your mouse and select *Add Marker* (Figure 14), once you click on *Add Marker* the menu will disappear and you will see a little flag with a label saying "point#" (the number will automatically increment to avoid duplicate naming). A flag will also appear next to the thumbnail of the photo where you added the marker (Figure 15).

c) Repeat steps 7a) and 7b) until there is at least 10 images with the same marker, this will increase the accuracy of a marker's location in the 3D model point cloud), you can count the number of thumbnails with green flags if in doubt (Figure 15).

d) Rename each marker (i.e., "point#") with the corresponding GCP number "target xx" (Figure 6).

e) Verify you have added and renamed missing markers in at least 10 images per marker for each of the 15 transects (Figure 15).

Figure 14. Example of how to add marker manually in Metashape (Step 7b).

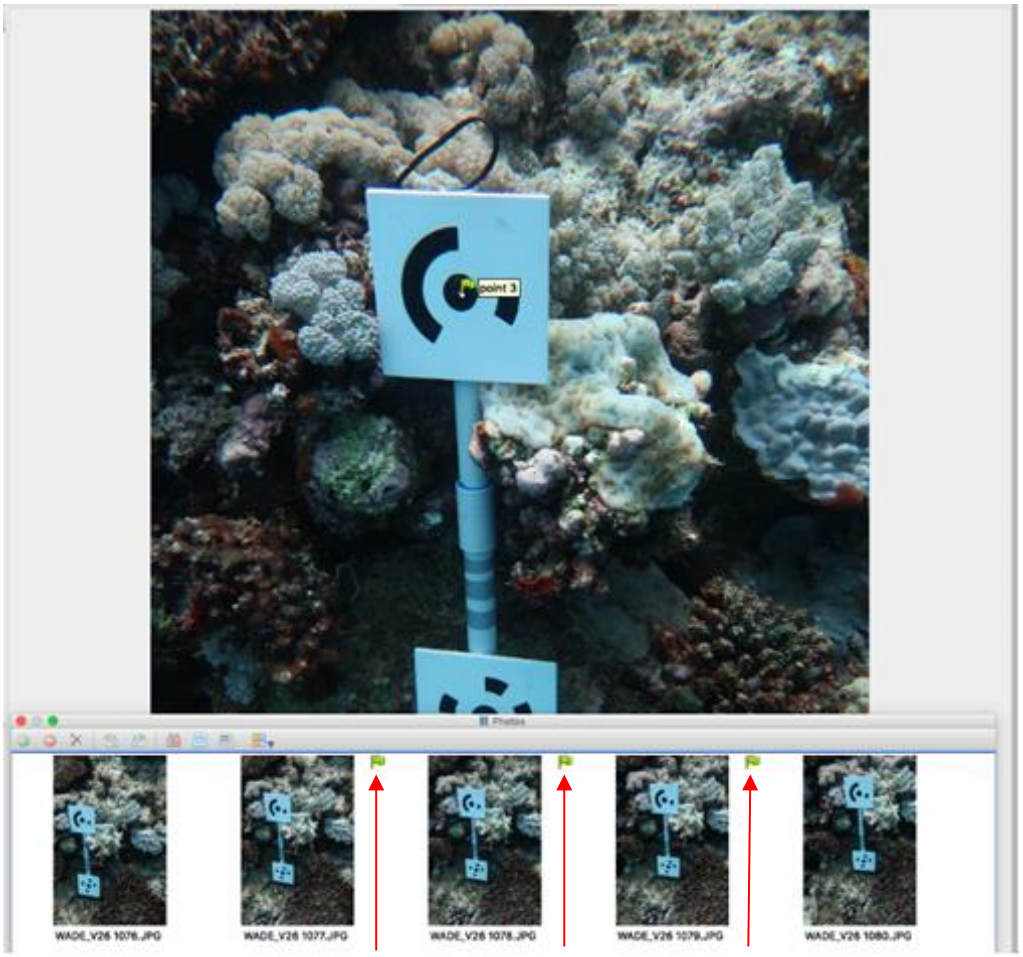


Figure 15. The red arrows showing the flags next to the images that Metashape detected GCP markers in.
After adding a marker, you will see a flag on the image and next to the corresponding thumbnail in the Photos windowpane (red arrows – in this example the target has only 3 projections).

8) To automatically set the distance between targets and create scalebars, re-run step 5d above (load batch script, only ticking process #4 and click the run button).

9) Align images and optimise alignment by re-loading the batch file from step 5 and run processes # 5 and #7.

10) Reset model region manually by going to *Workflow>Model>Transform Region> Reset Region*. This can be done through the script local on the local machine although it is a good opportunity to ensure all images fall within the region by doing it manually.

11) Check the quality by looking at the number of images aligned and enter the number of images and number of images aligned in the Processing Status Spreadsheet (here). The spreadsheet will automatically calculate the percent of images aligned. If at least 80% of the images have aligned, then continue with the next step. Otherwise stop and make a comment in the comment column of the processing status sheet stating: “stopped processing due to low quality in alignment, less than 80%”.

12) Assuming alignment was 80% or higher, reload the LTMP process batch script from Step 5 and tick the boxes for process #9 “Build Dense Cloud”. You will not need to select process #8 “Reset region” as this has already been completed manually.

13) Visually inspect the quality of the Dense Cloud once processing is completed. A good dense cloud should resemble Figure 16Figure 17B. Common problems are large holes in the point cloud (Figure 16A) and bad alignment of images leading to many scattered points (highlighted by the blue rectangle in Figure 17A) outside of the bounding box (highlighted by the blue arrow).

    a) Large holes in the Point Cloud are usually due to lack of data acquisition in those areas, hence the only way to fix it is to take more images (make a note in the Processing Status Spreadsheet and don’t continue processing).

    b) Bad alignment can be addressed by clicking on the *Camera Icon*  denoted by the red arrow in Figure 17B. If it shows cameras outside of the bounding box (denoted by the white arrow). Click the *Free Form Selection tool*  shown in Figure 17C and select the cameras that are outside of the bounding box. Right-click on the cameras and select “Disable Cameras” shown in Figure 17D and re-build the Dense Cloud (Step 12). Re-inspect the Dense Cloud.

14) If the model is good quality, orientate the view so that it is looking directly down upon the reconstruction, see Figure 18, using the *Rotate Object* tool  (this can also be found in *Model> Transform Object > Rotate Object)*. Once completed, reload the batch script described in Step 5 and run processes #10 “Export Cameras” and #11 “Export Points”.

15) Once the model has been correctly orientated reload the batch script from Step 5 and select processes #10 “Export Cameras” and #11 “Export Points”. Before running processes #10 and #11, two folders need to be created for Metashape to export the points in to. These two folders are:

\\isilon\3d_lmtp\exports\cameras\[PROGRAM]\[YEAR]\[CRUISE CODE].

\\isilon\3d_lmtp\exports\pointsXYZ\[PROGRAM]\[YEAR]\[CRUISE CODE].

16) The path to export the points and the cameras to need to be edited. To do this, click the *Edit* button in the batch script window and changing the path by double clicking the path box in the *Edit Job* window.

17) In the *Edit Job* window, double click the path box, in there the program code, the year code and the cruise code need to be entered to reflect the cruise that is being processed.

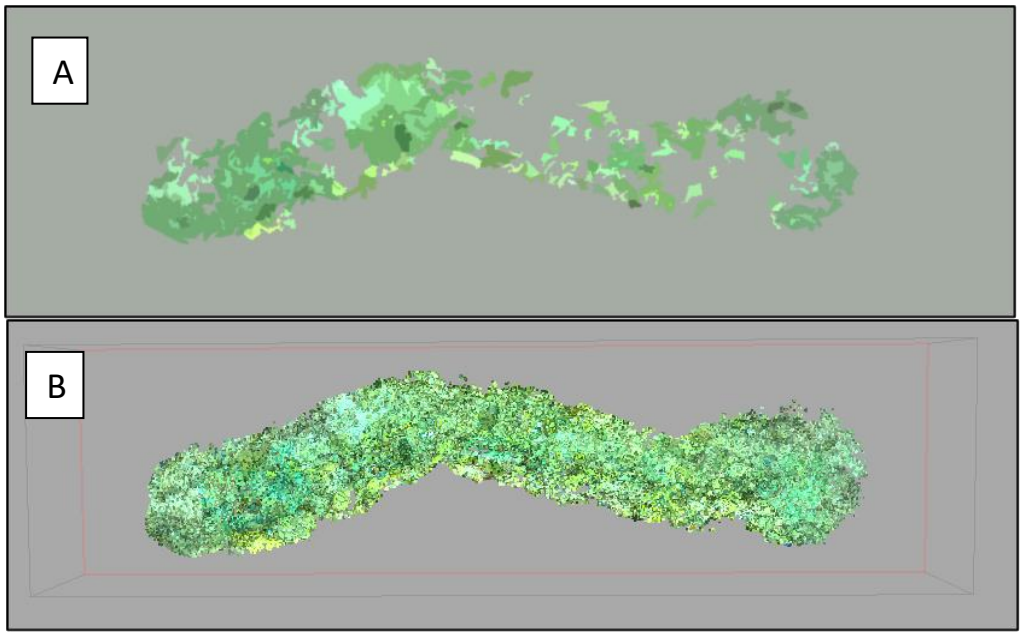


Figure 16. Showing the difference between a poor alignment and a quality alignment. Panel "A" shows a point cloud with many holes due to lack of data or bad data acquisition and Panel “B” displaying a completed model showing defined edges with very few scattered points outside of the bounding box, which is the lines surrounding the reconstruction.

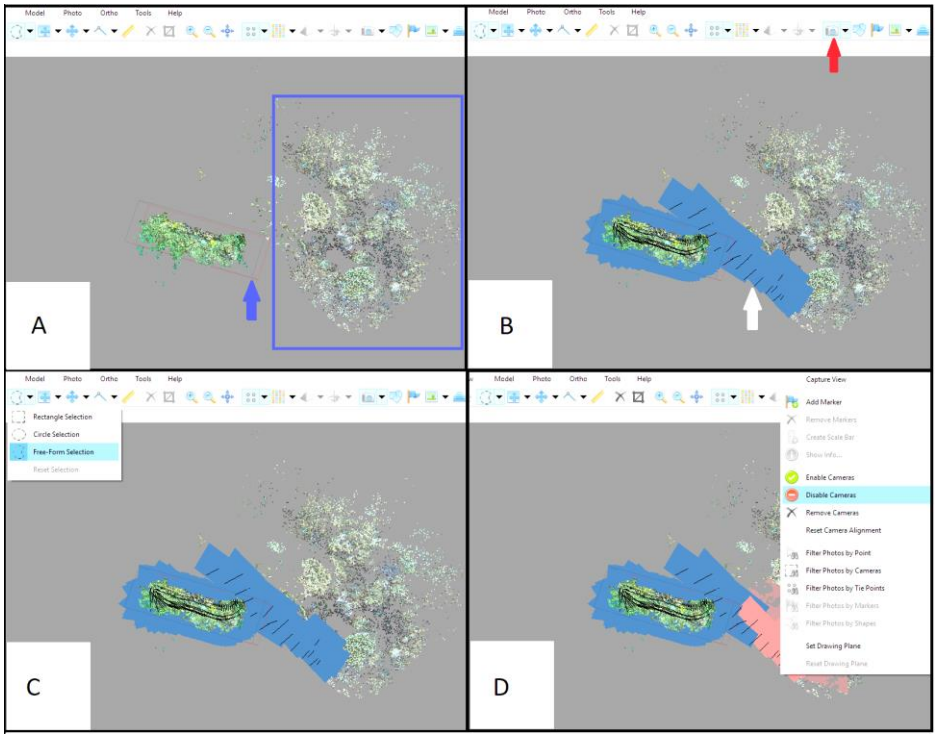


Figure 17. An example of an alignment problem in Panel "A" and how to rectify it in the proceeding panels.

Panel "A" showing scattered points within the blue box outside of the bounding box can be an indication of an alignment problem as seen in Panel "B" where the Cameras are outside of the bounding box. To fix this click on the selecting tool shown in Panel "C", select the Cameras outside of the bounding box, right click and select "Disable Cameras" from the menu shown in panel "D".

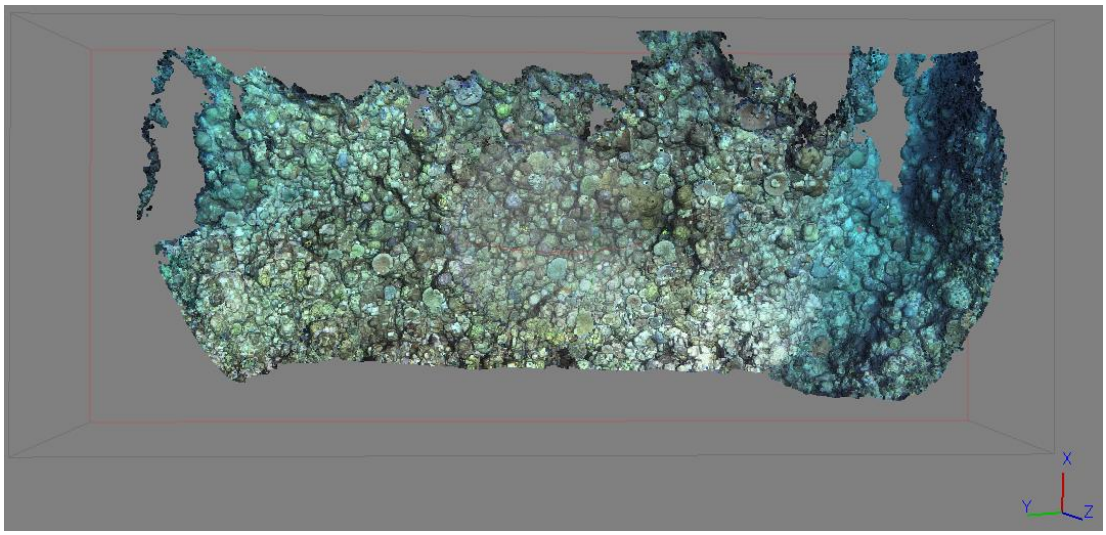


Figure 18. An example of a correctly orientated model.

Before exporting the cameras and points, it is important to ensure the model is orientated so that the observer is looking directly down upon the model. This is to ensure that when the metrics are extracted, they are consistent across all models.

Important notes and tips:

- *For each step that has "run script" or starts with "export" change the mapped network drive letter to the same as your computer if the network drive isilon\3d_ltmp doesn't map to Z.*
- *If images are imported into the project in the field the path to the data will need to be changed once back in AIMS so it maps to Isilon. To do this: Right click on an image from a chunk. Then select "Change path". Relocate photos in the Isilon path and click apply to "Entire workspace". Then navigate to where the images are stored (in isilon). Make sure "all file formats" are selected and then click on the same image that was originally selected. And choose ok.*
- *To rotate the model, Model> Transform Object> Rotate Object. This changes the large orb to a smaller orb.*
- *To re-center the view (if you "lose" the model) right click in the Model window and select "Center view.*
- *If you are on the AIMS network or VPN, you can monitor the progress of the job by using Agisoft's Network Monitor Tool, simply enter metashape-qmgr.aims.gov.au into the host name and use 5840 as the Port (18).*

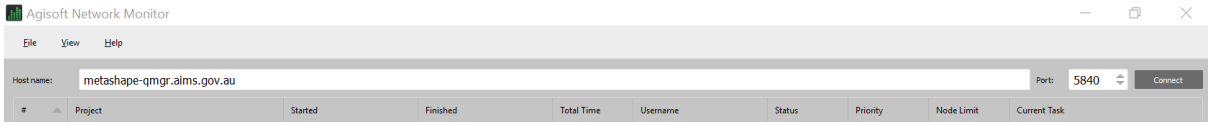


Figure 19. The required network settings to view the progress of jobs on the HPC using the Agisoft Network Monitor software

5.3 Metric Extraction

Important for the interpretation of the AIMS LTMP 3D metrics is the spatial extent at which they are captured. This method uses virtual quadrats placed on hundreds of locations in the model to estimate the metrics described in the table below. To account for spatial extent, three quadrat sizes are often used in the scripts to generate 3D metrics which is captured in the variable called **qsize**: 0.1m, 0.2m and 0.5m. Spatial resolution is kept constant across quadrat sizes (spatial extents).

Table 1. Summary of metrics extracted from The Dense Point Clouds produced by LTMP.
More details from this method can be found in Friedman A, Pizarro O, Williams SB, Johnson-Roberson M (2012) Multi-Scale Measures of Rugosity, Slope and Aspect from Benthic Stereo Image Reconstructions. PLoS ONE 7(12): e50440. https://doi.org/10.1371/journal.pone.0050440.

Variable Name (code)	Description	Ecological interpretation
Rugosity (rgsty)	Defines how convoluted the reef substrate is, where values equal 1, this metric describes a flat terrain and the larger the value the more complex or convoluted is the substrate.	The higher substrate rugosity is, the more surface there is for benthic biota to occupy, this has been related to greater food availability, greater diversity and greater niche availability for both sessile and mobile fauna.
Terrain Slope (slope)	Angle, in degrees, of the overall slope of the reef within the quadrat.	Fitness metrics, such as growth, of benthic organisms (i.e. coral recruits) have been related to slope incline. For instance, coral recruits are found in higher abundance on vertical surfaces compared to horizontal ones.
Terrain Aspect (aspect)	Compass direction that a slope faces, and it is measured in radians. This is circular metric, so sin and cos functions should use to separate eastern from northern components.	Aspect is related to the exposure of a reef area to important environmental drivers such as water flow and light, which have been linked to coral reef community structure and function.
Concavity (concavity)	Defines the shape of the slope of the reef substrate within a quadrat. It is calculated by the second order differential of the terrain heights (Laplacian operator). Convex is positive and concave is negative.	This exploratory metric might influence the amount of activity (i.e. bite rates) a reef area might be subject to. It might also be related to other important ecological processes, such refugia from large predators.
Deviance of elevation or height (meandevz)	Measures the variance of heights within a quadrat. Measures how much the heights in a quadrat vary from the mean or the "peakiness" of the substrate in a quadrat, the greater the variance the "peakier" the reef. It does not account for direction.	The “peakiness” of the substrate has been related to the diffused boundary layer, which can influence the acidity of the water a benthic organism experiences as well as nutrient cycling and productivity of the system.
Coefficient of variance range of elevations or heights (rangezCV)	This is range between the lowest and highest elevation of the reef substrate within a quadrat. It is presented as the coefficient of variance across the transect. It measures how much the heights in a quadrat vary from the mean. It does account for direction so a positive and a negative value don't cancel each other out.	Like the meandevz, the rangedevz also represents the “peakiness” of the substrate, but across the transect rather than across the quadrat. At this spatial extent, peakiness of the reef could be related to several important ecosystem state metrics, such as diversity, coral cover and bleaching susceptibility.
Median of range of elevations or heights (rangez median)	The range of heights between the lowest and highest elevation of the substrate within a quadrat. It is presented as the median of these range values across a transect. Measures the height at which 50% of the observations are lower and 50% are higher - it is a measure of central tendency. The higher this value is, the higher the number of individual tall structures in a transect.	The number of tall structures in a reef influence the detectability of predators as well as the potential escape routes a prey might access. Hence, this metric might influence mobile organism behaviour, amongst other important ecological processes.

1) Calculate structural complexity metrics described above from Dense Point Clouds

a) Launch HPC interactive. Make sure you are connected to the VPN (if working remotely). Launch an internet browser and type the following address: https://hpc-interactive.aims.gov.au:3443/

b) ***Launch a GNOME session***

c) ***From the Terminal***:

i) Pull the git repository to a folder called "gits" in your desktop by typing "cd /export/home/l-p/[YOUR USERNAME]/Desktop/gits/gits pull https://github.com/AIMS/reef3D.git "

ii) Load the Matlab module by typing "module load MATLAB/R2018a"

iii) Change directory to script folder by typing "cd /export/home/l-p/[YOUR USERNAME]/Desktop/gits/reef3D/data_analyses"

iv) Run function to calculate structural complexity metrics by typing "matlab -nodisplay -nodesktop -nosplash -r "summary_transect [PATH_TO_POINTS] [PATH_TO_CAMERAS] [PATH_TO_SCRIPTS] [PATH_TO_EXPORT_FOLDER]"

WHERE:

[PATH_TO_POINTS] is the directory path to the point clouds folder for the specific cruise code

(e.g., '/mnt/isilon/3d_ltmp/exports/pointsXYZ/RM/201819/OR/')

[PATH_TO_CAMERAS] is the directory path containing the camera pose for the specific cruise code

(e.g., '/mnt/isilon/3d_ltmp/exports/cameras/RM/201819/OR/')

[PATH_TO_SCRIPTS] is the directory path where the scripts are contained

(e.g., '/export/home/l-p/mgonzale/Desktop/gits/reef3D/')

[PATH_TO_EXPORT_FOLDER] is the folder where to export the results.

(e.g., '/mnt/isilon/3d_ltmp/exports')

Example code for step 1)c)iv):

```
matlab -nodisplay -nodesktop -nosplash -r "summary_transect
'/mnt/isilon/3d_ltmp/exports/pointsXYZ/RM/201819/OR/'
'/mnt/isilon/3d_ltmp/exports/cameras/RM/201819/OR/' '/export/home/l-
p/mgonzale/Desktop/gits/reef3D/'  '/mnt/isilon/3d_ltmp/exports'"
```

6 REFERENCES

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Calders K, Phinn S, Ferrari R, Leon J, Armston J, Asner GP, Disney M (2020) 3D imaging Insights into Forests and Coral Reefs. Trends in ecology & evolution 35: 6-9

Ferrari R, McKinnon D, He H, Smith RN, Corke P, González-Rivero, M, Mumby PJ, Upcroft B (2016) Quantifying multiscale habitat structural complexity: a cost-effective framework for underwater 3D modelling. Remote Sensing 8:113

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