Processing Coral Reef Imagery Using Structure-from-Motion Photogrammetry: Standard Operating Procedures (2023 Update)

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Cover: Reconstructed coral reef 3D scene by Damaris Torres-Pulliza, NOAA Fisheries

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Abstract

The Pacific Islands Fisheries Science Center (PIFSC) has been testing, improving, and streamlining its Structure-from-Motion (SfM) processing pipeline to produce permanent digital records of coral reefs across the U.S. Pacific Islands and Territories. The SfM-derived imagery and 3D models allow us to effectively extract high quality coral demographic data that are comparable to the rapid ecological assessment (REA) data collected by scuba divers as part of the National Coral Reef Monitoring Program (NCRMP), including coral density, colony size, colony condition, and taxonomic identification data. The coral reefs digital models are generated from thousands of photos taken in-water along a subset of randomly selected REA sites using the belt transect survey pattern approach. Ultimately, the digital products are analyzed by expert annotators to replicate, test, or directly extract REA data from imagery, leveraging computer power and software innovations while reducing SCUBA divers time underwater. This SOP was developed in collaboration with Scripps Institution of Oceanography, the University of Hawai'i at Hilo and the Hawai'i Institute of Marine Biology to increase logistical efficiency in the field while continuing to produce streamlined coral demographic and benthic community data across the broad spatial scale of NCRMP. The SfM workflow consists of five key steps: (1) survey planning, (2) field procedures, (3) data management, (4) data processing in Agisoft Metashape, and (5) data extraction in ArcGIS Pro. This SOP is the result of comprehensive testing of different camera systems, data collection methods, and software. The objective of this SOP revision is to provide updates incorporated in 2022 to Suka et al. (2019), including: updated model building parameters in Agisoft Metashape; refined steps to reduce error in model geometry; standardized parameters to generate consistent SfM products; and updated methods to extract demographic metrics that migrate from ArcMap to ArcGIS Pro. While this work provides a foundation for the future use of SfM photogrammetry that meet the Ecosystem Sciences Division (ESD) needs, we primarily use commercially available cameras and software, making these methods adaptable based on programmatic capacity and needs. Further, while this SOP focuses on belt transects, the procedures described here apply to building SfM models from photos collected using a variety of photogrammetric survey patterns or research applications beyond REA. For example, ESD uses the same SfM pipeline to process photos collected following the spiral survey pattern over fixed sites to support monitoring impacts of coral bleaching events, extract benthic parameters to estimate reef carbonate budget, quantify reef 3D complexity, and assess temporal coral vital rates.

Introduction

In the face of accelerating changes to our climate, it is critical that we robustly document the status and trends of the world's coral reefs to best highlight resilient reefs and identify resilience-supporting management practices. NOAA's Ecosystem Sciences Division (ESD), formerly the Coral Reef Ecosystem Division, has been monitoring Pacific coral populations and benthic communities since the early 2000s as part of the Pacific National Coral Reef Monitoring Program (NCRMP). ESD is charged with monitoring the status and trends of coral reefs across 40 primary islands, atolls, and shallow banks in the Hawaiian Archipelago (including Papahānaumokuākea Marine National Monument), the Mariana Archipelago (Guam and the Commonwealth of the Northern Mariana Islands, including the Marianas Trench Marine National Monument), American Samoa (including Rose Atoll Marine National Monument), and the Pacific Remote Island Areas Marine National Monument (Wake, Johnston, Palmyra, and Kingman Atolls and Howland, Baker, and Jarvis Islands). Historically, ESD used diver-based visual Rapid Ecological Assessments (REA) to generate demographic metrics (colony density, size structure, partial mortality, and prevalence of disease and compromised health states) of coral communities. The REA surveys are conducted across 200–400 randomly selected hard bottom sites per NCRMP region each year, with four 1 × 2.5 m replicate segments along a 1 × 18 m belt transect (Winston et al., 2020).

In situ visual assessments are the foundation of most global coral reef monitoring programs; however, use of image analysis is increasing as it reduces cost and complexity of field operations, provides a permanent record of benthic conditions at the time the imagery is taken, and increases the geographic scope even in areas difficult to access. While ESD's coral reef team has collected small area photoquadrats (i.e., 1 m^2) of the benthos since 2002, the small size of the area imaged limits the applications of this imagery. Spurred on by recent advancements in the fields of photogrammetry and computer vision for mapping applications, our program has partnered with Scripps Institution of Oceanography, University of Hawai'i at Hilo, and Hawai'i Institute of Marine Biology to extract benthic metrics from large-area image mosaics (60–130 m^2) derived using Structure-from-Motion (SfM) photogrammetry. SfM is a robust, cost effective, and user-friendly approach for constructing fully rendered digital models of a given scene from photography by matching features identified across 100s to 1,000s of overlapping photos taken from offset positions. Consequently, this technology has been widely applied across a variety of terrestrial and aquatic fields and more recently has gained utility in coral reef science. The high-resolution products generated through SfM provide powerful means of characterizing coral demography, benthic community structure, and reef geometric complexity. The data products also allow us to freeze the reef in time and compare it against future changes. ESD's goal is to transition our core REA surveys from the traditional in-water visual assessments to imaging and 3D reconstructing belt transects through SfM back at the office. Ultimately, expert annotators will be able to leverage computer power and software to generate comparable coral demographic data to the existing in-situ diver surveys while reducing divers time underwater (Couch et al., 2021).

In this standard operating procedures document, we provide updates incorporated in 2022 to Suka et al. (2019). The primary updates include substantial improvements in post-processing to improve data quality and more specifically include updated SfM model building parameters in Agisoft Metashape, refinement of steps to reduce error in model geometry, steps to export consistent SfM products, and updated methods to extract demographic metrics that migrate from ArcMap to ArcGIS Pro. The outlined workflow creates high-resolution image maps and 3D models from extensive photo sets that leverage tested field collection techniques, consumer-grade digital cameras, and commercial software. This SOP is designed specifically around belt transect surveys as part of NOAA NCRMP-Pacific and, therefore, references our specific survey design, data management servers and practices, and annotation from imagery specific to ESD. The workflow here described generally consists of five key steps: (1) survey planning, (2) field surveys, (3) data management, (4) data processing, (5) data visualization and extraction. While there are a variety of approaches that are currently being used by SfM field practitioners, our techniques allow us to efficiently collect and process quality input imagery at the scale of our monitoring program. It is our hope that the workflow discussed in this SOP can be easily adapted to other coral reef and marine ecosystem monitoring programs. Beyond this SOP, ESD is also collaborating with partners to identify and test cyber infrastructure that leverages machine learning and cloud processing, leading to more efficient model rendering and data extraction from imagery.

To use this SOP, we recommend the following software:

- Adobe Lightroom (optional to improve image exposure and overall visual quality)
- Agisoft Metashape (Version 1.7.1 or higher)
- Viscore (August 2021; optional for 3D model and photos visualization)
- ArcGIS Pro (Version 2.8.0 or higher for annotations)

Section 1: Survey Planning

The basic requirement for the 3D reconstruction of a scene through SfM photogrammetry is having a complete set of high quality overlapping images taken from offset perspectives. However, to derive quantitative data with accurate scale, color, and texture, further planning considerations should include camera and lens characteristics, camera settings, watertight camera housing, varying lighting conditions, ground geospatial controls, and a survey choreography that is safe, repeatable, and efficient. This document is designed to provide a foundation for future use of SfM photogrammetry that meets ESD needs. We primarily use commercially available cameras and software, making these methods adaptable based on programmatic capacity and logistics.

1.1 Collecting Photos for Benthic SfM Photogrammetry

Imaging configuration involving overlap perspective and camera height relative to the sea floor are key to estimating camera positions and rendering correct 3D geometry. Furthermore, these considerations also play important roles in the survey ground distance coverage and image sharpness for taxonomic identification of the benthos. For example, images taken closer to the substrate are sharper but have a smaller footprint, thus requiring more survey paths and images to achieve necessary coverage. Conversely, images taken farther from the substrate have a larger footprint allowing coverage of the same survey area with fewer swim paths, resulting in lower image definition. A number of trials were conducted to evaluate the optimal focal distance needed to achieve sharp, high-quality imagery for data extraction without overly affecting the time required for underwater image collection. Maintaining a 1 m distance from the substrate with the 24MP Canon SL2/3 DSLR, 18 mm camera lens and 6” dome port captures a substrate footprint of about 1.03 m × 0.69 m per image and provides high-quality detailed results. Further, a set of images captured with 60% of side and 80% of forward offset overlap provides good model geometry while reducing the potential for data gaps during reconstruction.

Surveying a coral reef to later extract coral demographic and benthic percent cover data requires imaging colonies across a range of sizes, from a few centimeters to meters in diameter. Consideration needs to be given to the spatial heterogeneity of a site and limiting large areas of soft substrate. Given that our historical in situ benthic surveys were conducted along belt transects, we tested a number of square and rectangular shaped survey plots of different sizes. Through this exercise, we determined that the optimal survey plot shape is a rectangle of 3 m × 20 m. This sampling method allows us to remain within our operational time constraint (~10 minutes) and capture most large colonies, with the exception of very large coral thickets. This survey approach also allows us to replicate the same area that has been visually assessed historically by ESD.

1.1.1 Required training

It is assumed that NCRMP divers conducting these surveys have received in-classroom and in-water SfM training. Training materials are stored on the PIFSC network at:

\\PICBILLFISH\General\Benthic\SfM\SfM Training and Presentation.

For users outside of NOAA, please use the contact information above for inquiries about the most recent training materials.

1.1.2 Equipment used by ESD

- Canon SL2/SL3 with Ikelite housing, 6” dome port, and predefined camera settings
- Dive slate with pencil
- SfM datasheet
- 18% gray card for color balancing at depth
- 3–4 ESD customized scale bars with coded markers [Appendix A]
- 30 meters transect tape
- Surface marker buoy with reel to indicate diver’s position and attract attention of surface support

1.2 Camera System

Although SfM techniques can be conducted using almost any camera, collecting imagery underwater requires special field logistics and equipment considerations. The cost, compactness, portability, and available technical support for a camera system are important considerations. ESD tested a number of underwater camera systems (Canon G9x, GoPro5, Nikon D90, Sony A6300, and the Canon SL2). The combination of higher quality lenses, image resolution, superior white-balancing, user control of camera settings, portability, continuous shooting, and affordability made the Canon SL2[1] our camera of choice (Figure 1.1). In 2022, ESD switched to using the upgraded successor Canon SL3[2] because Canon no longer sells the SL2. Note this camera has a shutter actuation of approximately 100,000 images. SL2 and SL3 cameras are essentially the same camera with small differences in software and camera body. Through a series of underwater tests, we determined the camera settings that would produce the highest quality images for SfM processing over a broad range of operating conditions (e.g., overcast vs. bright sun, clear shallow water vs. deeper murky water, Table 1). This allows the photographer to focus on swimming the plot with control instead of adjusting camera settings underwater.

[1] Canon SL2 user manual: http://gdlp01.c-wss.com/gds/5/0300027455/01/eos-rebelsl2-200d-im-en.pdf
[2] Canon SL3 user manual: https://gdlp01.c-wss.com/gds/2/0300034502/01/eosrebelsl3-eos200d2-ug-en.pdf

Figure 1.1 Structure from Motion image acquisition equipment. The compass attached to the scale bar is optional (Appendix A)

1.3 Camera Settings

Standardized settings make image quality more consistent across reef surveys. These settings are displayed on the camera LCD screen (Figure 1.2) and can be compared against the same figure attached to the back of the white balancing gray card to ensure settings' correctness before getting in the water and at depth, before image collection.

Figure 1.2 Canon SL2/3 LCD screen displaying correct settings for SfM image collection. Check this screen before every SfM dive and survey.

Table 1.1 Overview of Camera Settings Used for ESD Surveys*

Settings	Function	Background
Focal length	Fixed at 18 mm	To obtain a wide enough field of view. Hint: use painters' tape to fix the focal length at 18 mm if using a variable zoom lens. (Figure 1.1)
Shooting mode	Manual (M)	Allows for shutter speed, aperture, and ISO controlled adjustments.
Aperture	Fixed at F10	Wide enough to have more of the image lit, sharp, and in focus.
ISO	Auto (max 3200)	Allowed to vary for a correct exposure given changing lighting conditions at depth, but keeping in mind that the higher the value, the greater the graininess.
Shutter Speed	Fixed at 1/320	Fast enough to minimize motion blur.
Image Quality	High quality (L) JPEG	RAW is a preferred SfM image format to reduce image-specific artifacts from compression and for post-processing flexibility. However, the SL2/3 camera only takes ~1 frame per second (fps) in RAW, compared to ~5 fps in JPEG. ESD uses JPEG given operational time constraints (~10 minutes per site), but will continue to test higher end systems that allow moving to RAW in a way that supports our field logistics.
Drive mode	Continuous	**To collect ~5 fps, this ensures plentiful image overlap while maintaining a sustainable swimming speed. If needed, the number of images to include in the models can be reduced at the office. **
AF operation	AI SERVO AF (Moving Scenes)	***This autofocus operation is suited for instances in which the focusing distance keeps changing whilst swimming at 1 m above complex reef substrates. Focus will adjust to the scene features passing directly under the selected camera AF point while the shutter button is pressed continuously.
Metering mode	Evaluative	To measure and compensate exposure to the lighting conditions of the whole frame with emphasis on the selected focus point.
Exposure Compensation	-1/3	To regulate the camera's tendency to overexpose at depth.
White Balance	Custom	Use 18% gray cards to balance the quality of light and color at depth.

Settings	Function	Background
Auto Lighting Optimizer	Disable	Disabled to favor exposure compensation settings.
Lens aberration correction	ON/OFF	Peripheral illumination correction: ON Chromatic aberration correction: ON Distortion correction: OFF Diffraction correction: OFF
Picture Style	Standard	Ensures accurate expression of natural colors that are consistent across the photo set while pressing the shutter button continuously.
High ISO speed NR	OFF	Noise reduction may result in loss of sharpness.
Image Auto Rotate	OFF	To process images with consistent orientation
Date and Time	UTC	For time format consistency across geographic zones
Live View	OFF	To save battery power and minimize fog from camera heat
File numbering	Auto Reset	Starting at zero—following SD card formatting—helps with daily data management

* The breadth of camera designs and settings options available requires careful considerations to understand SfM project-specific tradeoffs implied by different imaging strategies. However, even after thorough considerations, it is possible to not always see the full advantages of the settings selected. Our camera systems and settings are continuously reviewed and dynamically updated in favor of mission efficiency, quality imagery and to stay current with technology trends. Please use the contact information above for the latest updates.

** Shooting in continuous mode will provide excellent overlap and allow you to survey the area more quickly. The drawback is it requires large data storage and more frequent servicing due to expired shutters.

*** ONE SHOT is another good drive mode alternative for SfM image collection as it can lock the focus throughout the survey for a more stable SfM lens solution per photo set. However, there is a steep learning curve to master sharp focus consistently among numerous benthic divers.

To avoid opening the underwater housing in the field and to allow all day operation of the cameras, ESD selected 256 GB SD cards that can hold about 10,000 images. For ESD, this is ample memory to collect imagery from 4 belt surveys (~1,200–2,000 per belt). The number of images collected per belt plot varies depending on swim speed and reef structural complexity. Highly complex reefs typically require extra imaging to better capture their 3D intricacies. We have found that shooting in continuous drive mode all day long appears to tax the Canon SL2/3. During extended field operations with high camera use, we experienced error codes when white balancing in situ which was alleviated by formatting the SD card each morning and by rotating available cameras regularly.

1.3.1. Camera set-up steps

To locate the main menu function tabs *Cam*, *Settings*, and *Display*, press the MENU button at the back of the camera (Figure 1.3).

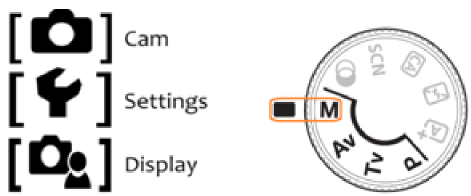


Figure 1.3 Canon SL2/SL3 main menu function symbols (left). Turn mode dial to Manual [M] (right).

1. If working with a new camera, ensure that the focal length has been fixed to 18 mm with painters' tape.
2. Turn the mode dial on the top of the camera to select the *Manual* [**M**] shooting mode.
3. Reset camera settings: [🔧4] → "Clear settings" → "Clear all…".
4. Configure display:
   [📷👤] → "Shooting screen" & "Menu Display" → Standard;
   [📷👤] → "Mode guide" & "Feature guide" → Disable.
5. Format card (DELETES ALL DATA!): [🔧1] → Format Card → OK.
6. Configure image numbering: [🔧1] → "File numbering" → Continuous.
7. Stop image auto rotate: [🔧1] → "Auto rotate" → OFF.
8. Set date & time: [🔧2] → "Date/Time" → Set UTC time, mm/dd/yy format (daylight savings off).
9. Select image quality: [📷1] → Image quality → L (highest, no RAW).
10. Select drive mode: [📷1]$_{SL2}$ or [📷2]$_{SL3}$ → Drive mode → "Continuous shooting".
11. Set autofocus: [📷1]$_{SL2}$ or [📷6]$_{SL3}$ → "AF Operation" → AI SERVO.
12. Lens aberration correction: [📷2]$_{SL2}$ or [📷1]$_{SL3}$ →
    "Peripheral illumination correction" & "Chromatic aberration correction" = ON
    "Distortion correction" & "Diffraction correction" = OFF
13. Set custom white balance: [📷3]$_{SL2}$ or [📷4]$_{SL3}$ → "White balance" → "Custom".
14. Set Picture Style: [📷4] → "Standard" S.
15. Set ISO speed: [📷2] → "Auto".
16. Set ISO Auto: [📷2] → "Max.:3200".
17. Set Metering mode: [📷3] → "Evaluative".

18. Set Auto Lighting Optimizer: [3] → “OFF” OFF.
19. Hit Live View Shooting/Movie Shooting Switch (button next to viewfinder) to toggle “live view” shooting → “OFF”.
20. Switch Image Stabilization → “OFF”.
21. Use the Quick Control Q button and surrounding directional buttons to set:
    Shutter speed → 1/320 (decrease to 1/250 if it’s too dark out)
    Aperture → F10 (increase to F11 if it’s plenty bright out)
    Exposure Value → -1/3 -3..2..1..0..1..2..+3.
22. Check the LCD monitor to ensure all of the settings have been correctly set before every SfM dive (Figure 1.2).

1.3.2. Ikelite housing setup and use

Before each day of diving

1. If working with a new housing, remove the focus ring from inside of the dome port (must first take off the dome port) and install a vacuum seal port.
2. Ensure a charged battery and a blank SD card have been inserted.
3. Format the SD card: Settings[1] → Format Card = OK
4. Check the O-ring to ensure it is free of hair and all other particulates. Examine it through the Plexiglas once the housing door has been clipped on.
5. Use the vacuum seal to depressurize the housing (between 5 and 10 Hg).
6. Check for changes in pressure over time (can leave overnight). A decrease in pressure may indicate a leak.
7. Insert the plug into the vacuum port to seal before diving.
8. Check camera settings.
9. Take a test photo in the housing to ensure that the battery and SD card are inserted, the camera is properly aligned in the housing, and the lens cap is off.

Following each day of diving

1. Soak the housing in warm fresh water for at least 10 minutes (longer is better) before removing the camera.
2. Press all buttons on the housing underwater while soaking.

After every few days of use

1. Remove O-rings (including dome port O-ring).
2. Inspect O-rings for damage or stretch and replace if needed.
3. Clean O-rings and housing grooves in which they are situated (lint-free Kim wipes may be recommended).
4. Lubricate O-rings.
5. Clean particulates out of the dome port with air, brush, or very clean lint-free cloth.

For long-term storage

1. Remove O-ring and store in a Ziploc bag.
2. Grease the O-ring before the next use.

1.3.3. How to white balance at depth

The importance of accurate color in images cannot be understated. To identify benthic organisms and their condition accurately by humans, or especially through computer-automated systems, color and good contrast are critical components. To achieve the best color correction, we tested several in situ and post-processing methods. We found that color correction at depth provides superior color grading and is more time efficient than post-processing imagery in software such as Adobe Lightroom prior to annotation. In addition, if you are using JPG imagery, your ability to make post hoc color corrections will be limited as opposed to using RAW imagery. Furthermore, using an 18% gray card as neutral color provides better results than white balancing with a white dive slate. White balancing is performed at depth to set the color temperature to the existing conditions and before image collection on every dive.

1. Take a photograph of the gray card at depth ensuring that the card fills the entire frame. Hold the card at a slightly upward angle with the sun to your back to take full advantage of the available ambient light and ensure that the card is not in shadow. Note that given the close distance and lack of contrast, the camera may not focus on the card but that is not an issue for white balancing (Figure 1.4).
2. Press the MENU button, then scroll to select the Cam menu. Select Cam [3] → 'Custom White Balance' → SET = OK.
3. Always white balance the camera at depth at the beginning of every SfM dive.

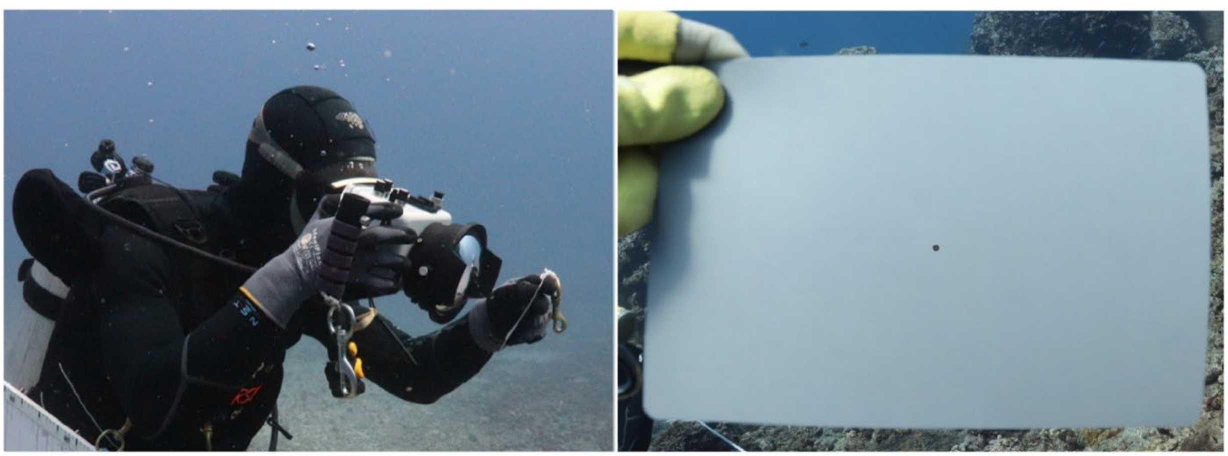


Figure 1.4 Example of a diver correctly color balancing with an 18% gray card. Left: A diver photographing a gray card at depth, ensuring that the card fills most of the frame and that it is facing the sunlight without producing shadows. Right: Good gray card photograph example. Optionally, draw a dot in the center of the gray card to provide a focus point and reduce camera delay or lag taking photos.

1.4 Coded Markers and Scaling

The Agisoft Metashape software provides a set of coded patterns (markers) that can be used to establish reference positions and scale for mapping. When placed at a known distance apart on a rigid bar, the markers are used to constrain the true size of objects for accurate measurements. In a dynamic coral reef environment, it is important that the scale bars stay in place during the survey and are also small and light enough for divers to manage safely underwater. Our original scale bars were constructed from lightweight PVC and were easily disturbed when deployed in surge or current. To resolve this issue, we built stainless steel bars printed with coded targets that measure 0.3 m × 0.0 5m, and weigh about 1 kg each (Figure 1.5, Appendix A). These scale bars are heavy enough to stay in place and are easy for divers to carry and deploy. While the current distance between scale bar markers is generally set to about 0.2500 m, we are taking extra steps to improve precision (i.e., 0.0001 m) and calibrate distance measurements regularly.

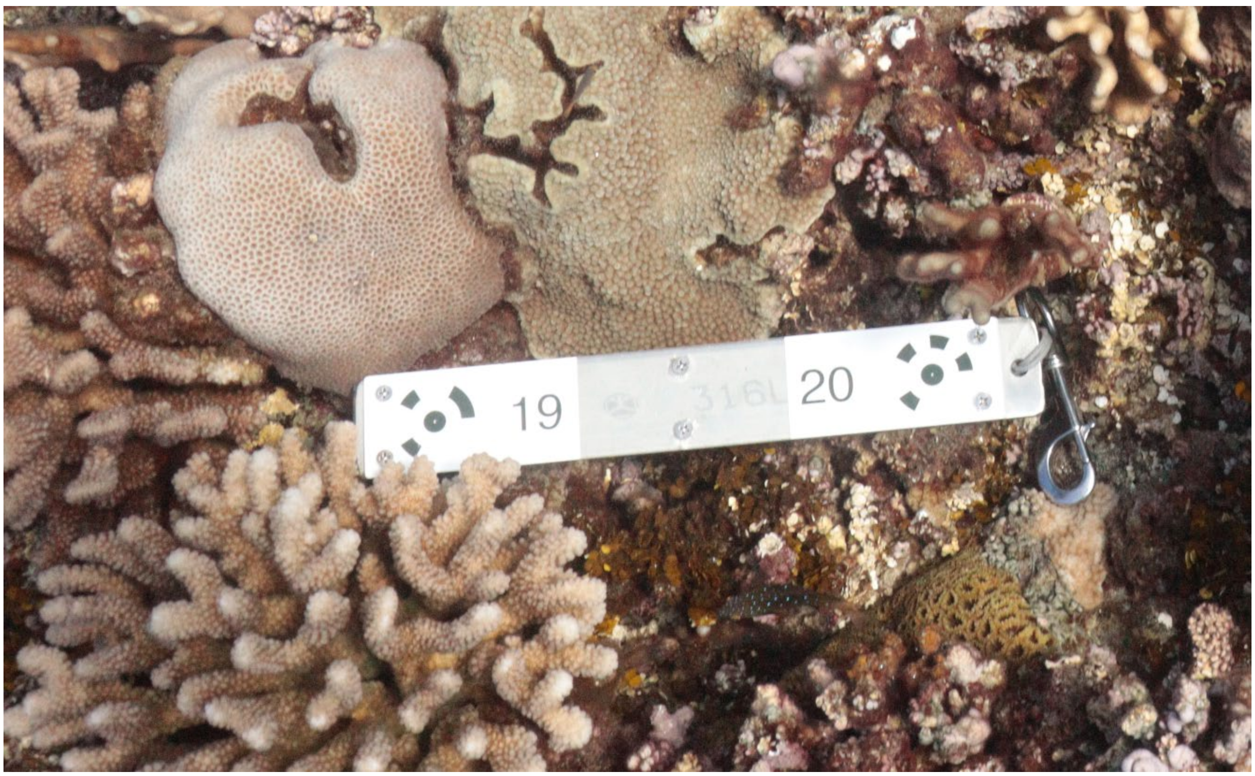


Figure 1.5 A scale bar with two coded Metashape target patterns (also known as ground control points) as end markers whose centers are about 0.25 m apart from each other. These markers can be automatically detected by the software and used as model checkpoints and horizontal geospatial scaling.

Section 2: SfM Survey Procedures

At each ESD stratified random survey site, SfM surveys are conducted along 20 m transect lines deployed along the targeted depth contour. After laying out the scale bars and white balancing the camera, a series of overlapping images are taken by swimming three paths along each side (six total passes) of the transect line, 1 m off the substrate. The horizontal distance from the transect line should increase by ~0.5 m with each consecutive pass, with the first pass running directly alongside the transect line which is used as navigation reference. See Rodriguez et al. (2021) and Pizarro et al. (2017) for details about the spiral image collection pattern technique over circular shaped survey plots.

2.1 Overview to Underwater Survey Evolution

Tasks will vary depending on the number of divers on a team, but the team will need the certain equipment and will conduct the listed tasks.

Equipment: Transect reel, 3–4 scale bars, camera and housing (+ 1 backup camera set up), gray card, surface marker float, slate with datasheet and pencil

Setting up the site (scale bars are placed at 0, 5, 10, and 15 m): Secure surface marker float, deploy transect line, place scale bars

Survey process: Record SfM metadata (see Fig. 2.2), white balance the camera and take SfM photos

Finishing up: Roll up transect line, collect scale bars, and retrieve surface marker float

2.2 Survey Plot Setup

Place scale bars about half a meter away from the transect line at 0, 5, 10 and 15 m (Figure 2.1). Make sure the scale bars are facing up, stable, and lying flat over the substrate. Take the time to carefully measure the depth at the center of the bar and record all numbers in the appropriate boxes on the SfM datasheet (Figure 2.2). To ensure proper scaling and depth orientation, it is recommended to place a minimum of 4 scale bars as this will allow the downstream software to orient the resulting model into the top-down projection plane better than using 3 scale bars, which is the minimum necessary. Write any notes that would be helpful later (deviations in scale bar placement, scale bars moved during survey, etc.). At the end of the day, record the latitude and longitude of the site on the SfM datasheet, which can be obtained from the dive navigation datasheet.

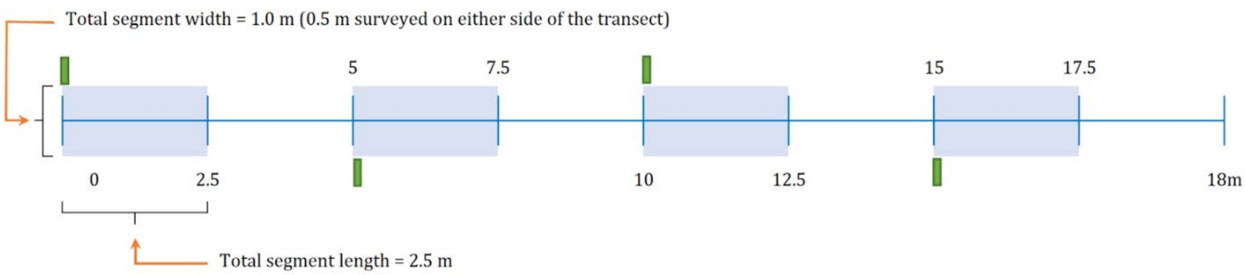


Figure 2.1 Benthic survey transect line with visual survey segment areas highlighted in blue; green bars show where scale bars are placed for SfM image collection.

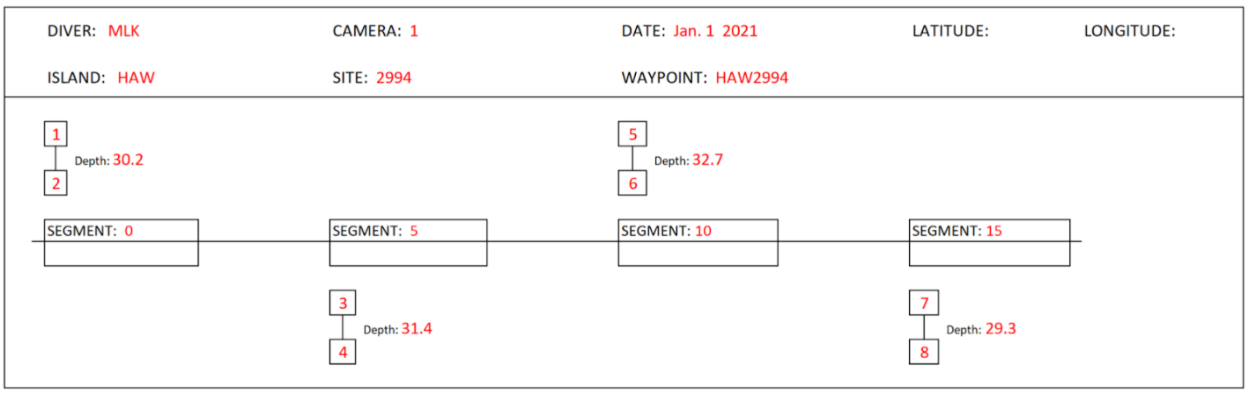


Figure 2.2 Example of completed SfM datasheet. Scale bar target numbers are recorded in the small boxes; depth is recorded in feet to the highest precision available, and date is recorded as the local date (not UTC).

2.3 Image Collection

A 20 m × 3 m belt transect shooting continuously should take about 10 minutes to swim. To properly collect quality images, adhere to the following pointers when imaging the reef using the Canon SL2/3 cameras:

- Before getting in the water, check the camera settings, the battery indicator, and the SD storage availability, notice if there is moisture in the underwater housing and test white balancing the camera. Also, conduct a white balance test to ensure buttons and menu settings are operational. If you see a problem, switch to the backup camera.
- While getting ready to shoot photos at depth, check the dome port after removing the cover to ensure there are no bubbles. If you see bubbles or debris, wave your hand near the dome port to remove them.
- White balance the camera colors at depth as detailed in Section 1.3.3.
- To start collecting images, gauge your distance from the substrate (i.e., 1 m above), and be sure to have proper buoyancy and trim position. Clip away any dangling gear from the camera field of view. Also, take the time to look forward and plan your fly path considering the topography ahead and noticing useful navigation landmarks.
- Look through the viewfinder to make sure that the transect line is near the 1/3 mark in your viewfinder on the first pass. Each pass after that should be about half a meter

further from the transect (Figure 2.3). It may help to look down the transect line and find a feature to swim towards if the transect line is moving at all.

- Shoot the site continuously and while turning to start the next pass.
- With *Live View* turned off, you will not see an image appear in the viewfinder while taking photos. However, you will hear and feel the shutter firing. If you notice it firing slowly, curb your swim speed to ensure appropriate overlap.

Note: the software can match and pair image features more precisely if they are represented in multiple continuous images. The goal is to have each seafloor element appear in at least three consecutive offset images to ensure adequate 3D reconstructions. It is very important to make sure the scale bars are also captured in multiple images so that the model can be scaled accurately.

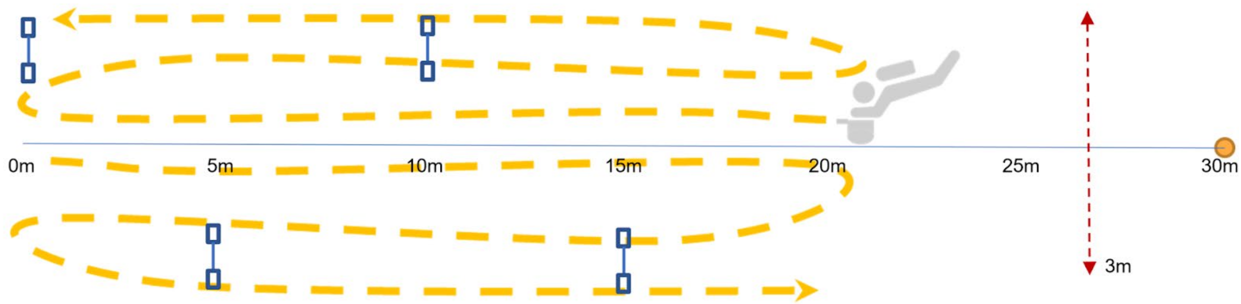


Figure 2.3 Swim paths of SfM diver during image collection shown by yellow arrows, with three paths 0 to 20 m on each side of the transect tape. Scale bar position is shown for each segment.

- Swim at a sustainable speed (each pass should take around 1.5 minutes depending on conditions; swimming too quickly will result in blurry images, while swimming too slowly will accrue too many images) at approximately 1 m off the bottom following benthic contour to 20 m mark on the transect line while holding down the shutter button.
- Reduce the effect of casting your own body shadow into the field of view. Shadows can affect image clarity and increase uncertainty during SfM reconstruction. While it is not always possible to avoid body shadows entirely, their effect can be minimized by extending the arms—and camera—forward away from your body (Figure 2.4.).

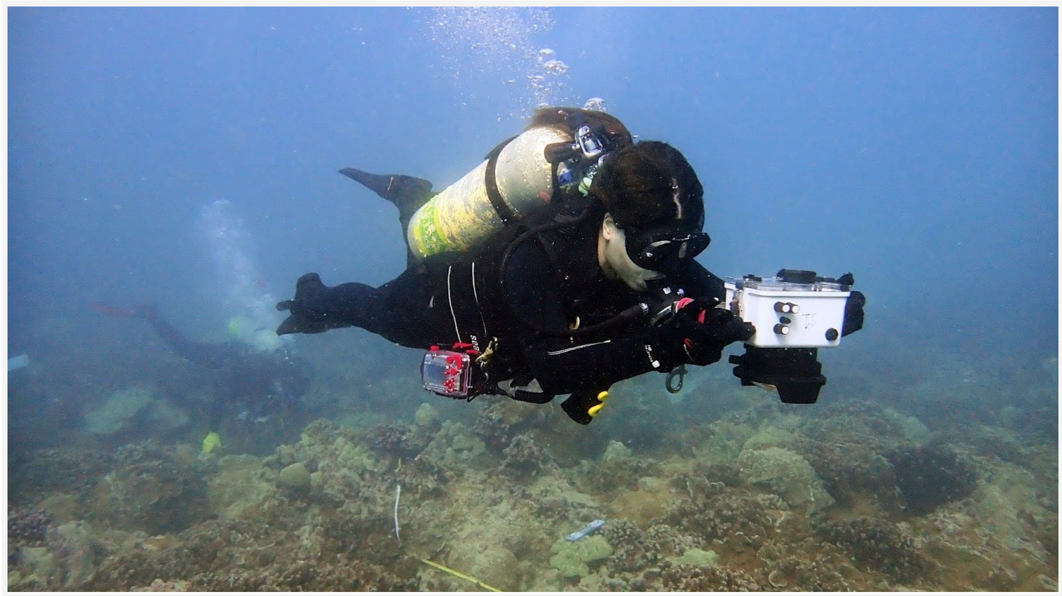


Figure 2.4 Benthic diver taking photos at 1 m height from the substrate, with camera angles mostly perpendicular to the reef. Extending the arms forward while holding the camera away from the body can help minimize casting large shadows into the camera field of view.

- Adjust the camera angle up to a maximum of +/- 35° for vertical or sloping surfaces, making sure to avoid any blue water background in images (Figure 2.5). While changing the camera angle, use flowy movements, avoiding fast camera wobble at all times.
- Angles that are mostly perpendicular to the substrate are preferable; avoid taking a large number of oblique photos relative to the substrate. Only adjust when flying over large or sloping topographic features (Figure 2.6).

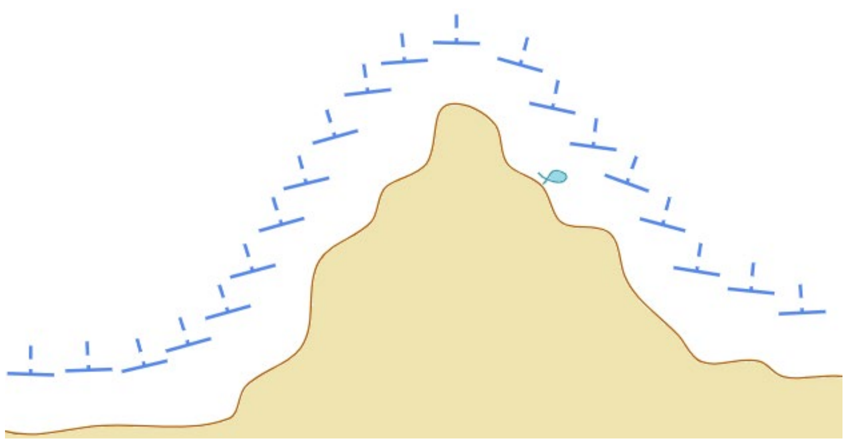


Figure 2.5 Illustration of suggested camera angles amenable to capture areas of high topographic relief. Using shallow oblique angles over vertical or sloping surfaces allow capturing the side face of structural features for a more complete 3D reconstruction of the scene.

- Avoid taking a large number of oblique photos relative to the substrate. Point the camera lens straight down, unless flying over a large topographic feature.
- If you have to stop the survey for any reason (i.e., high surge moves you off the transect), make a note of where you stopped, then start taking photos again a meter before that point to ensure you have good overlap and coverage. If you lose your place, go back to the last area that you can remember.
- Consider adding a separate pass to capture targeted imagery 0.5 m from the benthos to better capture juvenile corals, disease lesions, or other areas of interest that require high image definition. Provided you avoid blue water, these images can also be reconstructed into the larger model.

Note: The software can match and pair image features more precisely if they are represented in multiple continuous images. The goal is to have each seafloor element appear in at least three consecutive offset images to ensure adequate 3D reconstructions. It is very important to make sure the scale bars are also stable and captured in multiple images so that the model can be scaled accurately.

2.3.1 Shooting high relief areas

You will likely experience situations where very large colonies extend outside the 20 m × 3 m survey area. For large colonies whose center point falls inside the plot area but colony boundaries extend outside the imaged area, the diver should collect additional imagery of the colony outside the belt when possible. If a colony is massive, rise up into the water column and angle the camera to try and get more of the colony in each image; shoot several overlapping pictures at higher angles but avoid blue water backgrounds. Note, when working in thickets of branching corals, it may be difficult or impossible to image the entire colony/thicket. If imaging an entire colony is not possible, make a note on your datasheet of the species and approximate maximum diameter.

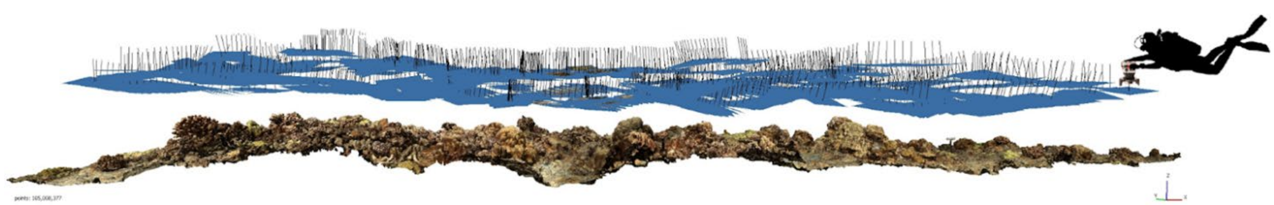


Figure 2.6 Side view of a SfM-derived model showing camera poses (blue) and orientation (black lines). The estimated camera poses recreate the diver's swim path position and height during data collection. Height variation also shows how closely the diver followed the reef's contour at 1m distance above the substrate.

2.3.2 Air or bottom time-limits scuba diving protocols

Deep dives limit time underwater; therefore, a contingency plan should be discussed before each dive to prioritize the work. For a two-person dive team, the same evolution described above should be followed, except the SfM diver would only collect images to the 13 m mark (thereby collecting imagery for only three segments, 0, 5, and 10 m). It is still recommended to place 3 scale bars.

Section 3: Data Management

Good data management and data management plans are crucial components of this pipeline and should be one of the first topics you consider when developing a new monitoring program. With imagery and data moved multiple times between servers and software programs, there are many opportunities for errors. Take some time to consciously build a data strategy that aligns to project priorities and outcomes, helps guide data collection field efforts, drives friendly data usage, and improves data storage and archiving. The guidelines listed below were developed specifically to meet ESD needs, but the framework could be easily adapted by other organizations.

3.1 Camera Download

If possible, download the imagery from the SD cards into one location before sorting them by sites. This can serve as your imagery back up. ESD data managers will upload all original imagery from each day to the backup drive: Z drive CameraDownload folder (this is an overnight process) using the following naming convention:

Z:\CameraDownload\ISLANDCODE\SFM_BENTHIC_MEMORYCARD_#\MM-DD-YEAR

Do not remove any imagery from this folder as it needs to remain intact. The photos in the CameraDownload folder are the only assurance that any reconstruction will be successful and that a backup exists in case of a problem with the imagery in the months and years after the cruise.

Two SD cards are provided for each camera. At the end of each dive day, the full SD card is given to the Data Management team (put in the “to be uploaded” container on their desk), and a new card should be loaded into the camera for use the following day. Each SD card is numbered to match the camera number. Double check to make sure your card number matches the camera you are using (i.e., camera 7 has cards 7A and 7B). The person in charge of preparing cameras for the day should do this task.

At the end of each day, update the SfM tracking spreadsheet for the sites surveyed that day. This document is a crucial part of the process and allows us to track the status of the site data from image collection to model generation to demographic data extraction. An example of the tracking sheet is provided in Appendix B. For ESD users, contact the SfM team for the location of this document. The person in charge of preparing cameras for the day should also completely fill out the field datasheets and dive navigation sheets. Double check that all entered information is correct.

3.2 Image Organization and QC

On an NCRMP cruise, one member from a team will stay back each day to organize SfM images for all teams.

1. Each day, all SfM imagery is to be copied from the CameraDownload folder to:

   M:\\PICLEA\Optical_PHOTOMOSAIC

According to cruise ID, island, and site number use the following naming convention:

M:\MISSIONID\Optical_PHOTOMOSAIC\ISLANDCODE\REA\TEAM\SITE-ID

For imagery collected in 2022 or after, please contact the NCRMP benthic lead for the latest information about data cataloging and storage.
According to survey site type, region, mission ID, island and site number use the following naming convention:

N:\Site_Type\REGION\MISSIONID\ISLAND\SITE-ID

2. The gray card, datasheet, and any other miscellaneous photos worth keeping are put within the MISC folder:

   M:\MISSIONID\Optical_PHOTOMOSAIC\ISLANDCODE\REA\TEAM\SITE-ID\MISC

   For imagery collected in 2022 or after, copy such imagery from CameraDownload folder to:

   N:\Site_Type\REGION\MISSIONID\ISLAND\SITE-ID\MISC

3. The SfM data tracking spreadsheet needs to be updated to enter the "total images shot" column (does not include images in MISC folder) and initial the "Images moved to site folder" column once transfer is complete.

4. QC of the SfM images and datasheets should be performed. This includes the following:
   - Check that the sites listed on the tracking spreadsheet match the sites listed as SfM sites on the dive navigation sheets and field datasheets. Fill in any missing information on the tracking spreadsheet.
   - Check the Site folders to ensure that all miscellaneous photos are in the MISC folder.
   - Scan through each of the site folder images for any images with fins, hands, blue water, etc. and move them to the MISC folder (Figure 3.1).
   - Make any notes on the spreadsheet about image quality issues or notations made on the field datasheets, such as "scale bars moved" or "only 10 m of transect surveyed."
   - Ensure that the field datasheet is completely filled out.
   - JPEG images that were not color corrected in the field and/or a large proportion of underexposed (dark) images can be unsuitable for image annotation and may need to be corrected in Adobe Lightroom (See Suka et al., 2019 for details on color and exposure correcting). However, it is not recommended to use corrected images in Agisoft as it can decrease the detection capability and accuracy of tie point matches. Alternatively, consider using the Tools → Set Brightness option in Metashape.

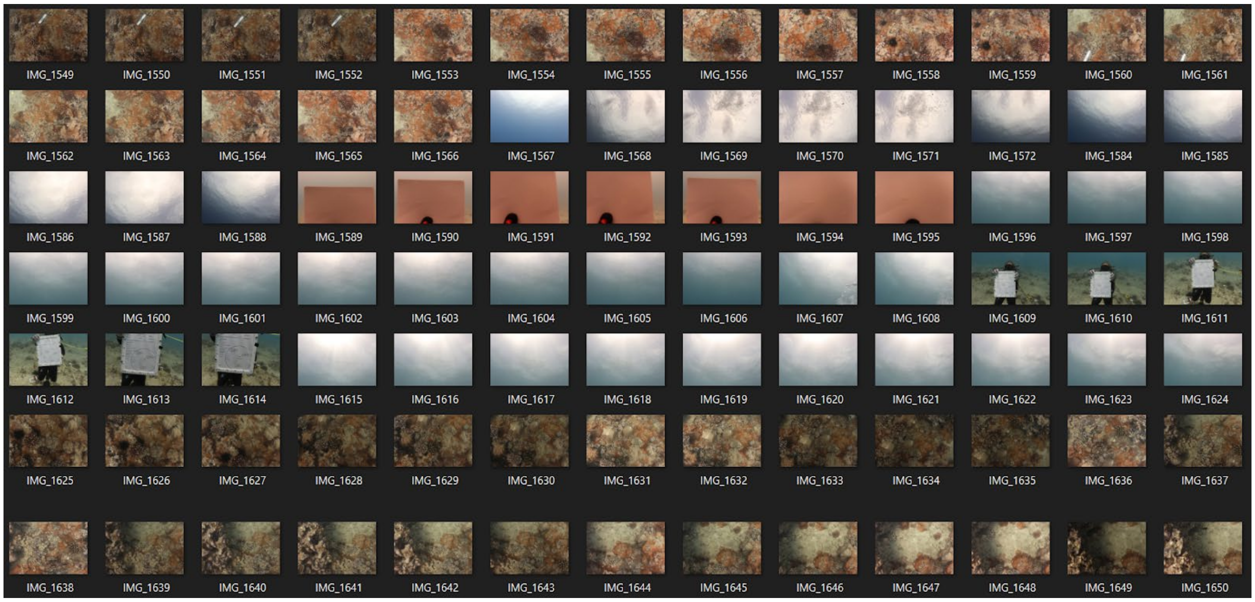


Figure 3.1 To assist with image organization, it is useful to take plenty of photos of the water column and datasheet as it helps to call attention to the beginning and end of each site survey. The distinct non-reef photo set can be easily identified while scrolling through thousands of photos, making it easier to distribute images into their corresponding site folders.

Section 4: Data Processing in Agisoft Metashape

Once the images have been collected, quality checked, and organized, they can be processed to digitally reconstruct the 3D geometry of a coral reef scene through SfM. The scaled products can then be annotated to categorize and measure benthic features. Our processing workflow utilizes three software: Agisoft Metashape, Viscore, and ArcGIS Pro. Agisoft allows processing of images into dense point cloud (DPC) through SfM photogrammetry from which to extract geometrically correct 3D meshes, orthomosaics and digital elevation models (DEMs). Viscore [Section 5] is used to visualize the DPC and easily access underlying raw imagery. As a proprietary software, you may not have access to Viscore yet; in this case, we have provided alternative methods using Metashape. ArcGIS Pro [Section 6] is the tool used to analyze and annotate coral reef benthic features over the DPC derived image maps. Additionally, please refer to Suka et al. (2019) for optional steps to color correct and white balance images using Adobe Lightroom.

This section lays out the steps to generate image-based 3D models through SfM using Agisoft Metashape Version 1.7. By first aligning the images, the software is able to reconstruct a 3D DPC of the reef from which we can derive various image map products for data visualization and measurement. Other than belt transect surveys, this workflow describes the general processing steps that are also used for all ESD SfM image collection patterns, including spirals shaped surveys at fixed sites for Vital Rates and Reef Budgets analysis (Rodriguez et al., 2021; Barkley et al., 2023).

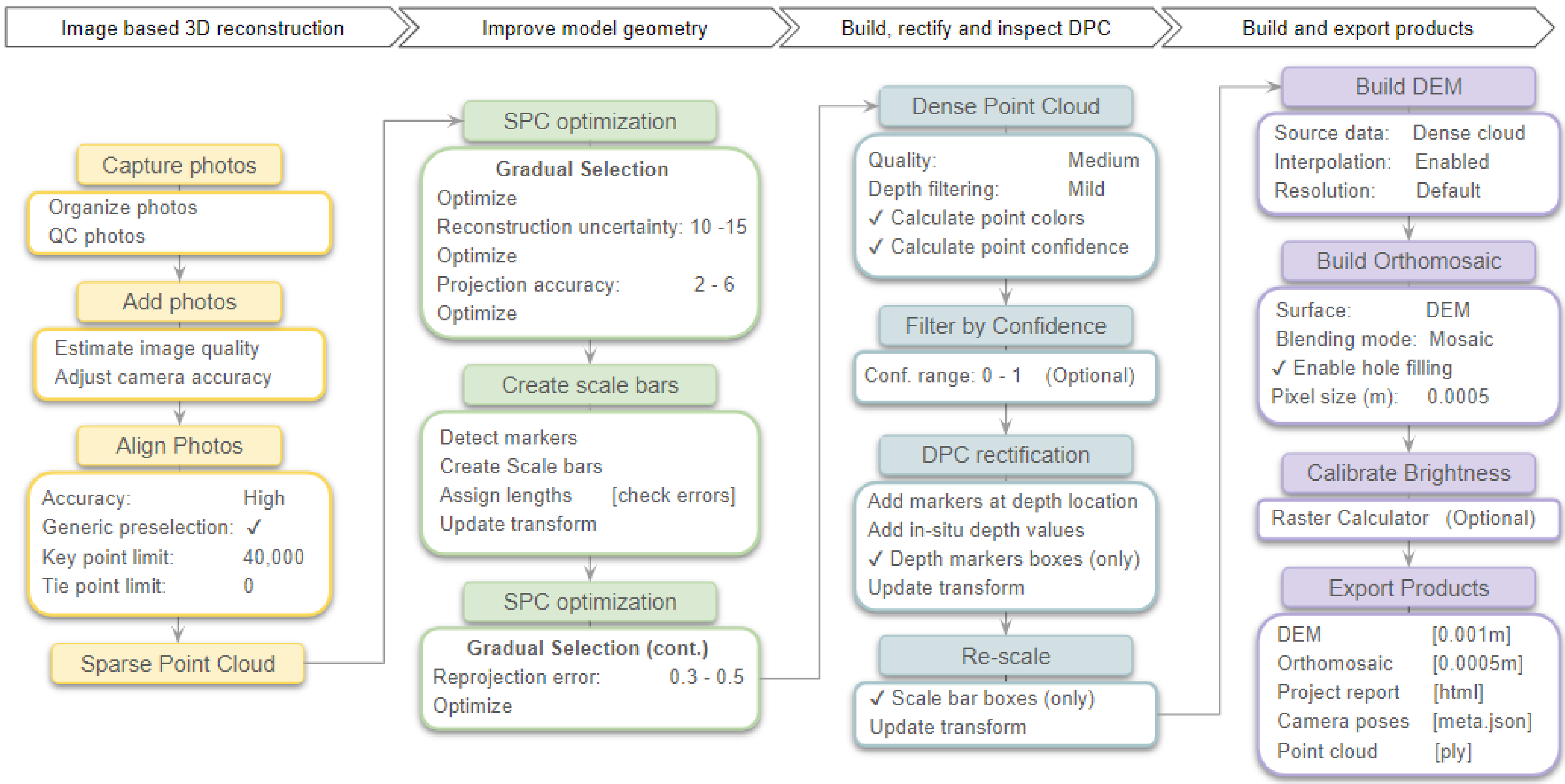


Figure 4.1 A schematic workflow of the image based 3D reconstruction and product generation of coral reef scenes through SfM photogrammetry in Agisoft Metashape.

4.1 System Requirements and Settings Preference

Memory consumption building geometry during photo alignment (SPC) does not necessarily depend on the resolution of individual photos, but on the number of photos being aligned and amount of photo overlap. Dense point cloud (DPC) building usually has the largest memory footprint, especially if a model with a large number of photos is constructed in medium or high quality. Therefore, DPC quality level should be carefully considered for large area model reconstructions.

CPU—Complex geometry reconstruction algorithms need many computational resources for processing. A high-speed multi core CPU (3GHz+) is recommended: Octa-core or hexa-core Intel Core i7 CPU, Socket LGA 2011-v3 or 2011 (Broadwell-E, Haswell-E, Ivy Bridge-E, or Sandy Bridge-E).

Motherboard—Any LGA 2011-v3 or 2011 model with 8 DDR4 or DDR3 slots and at least 1 PCI Express x16 slot is sufficient.

RAM—In most cases, the maximum project size that can be processed is limited by the amount of RAM available. Therefore, it is important to select the platform allowing installation of the required amount of RAM. Sixty−four GB RAM or more is recommended for models with more than 1,000 images: DDR4-2133 or DDR3-1600, 8 × 4 GB (32 GB total) or 8 × 8 GB (64 GB total).

GPU—Agisoft Metashape supports GPU acceleration for image matching and dense cloud generation steps (but not all steps), so a high-end OpenCL or CUDA-compatible graphics card can speed up the processing: Nvidia GeForce GTX 980 Ti, GeForce GTX 1080, or GeForce TITAN X (See Agisoft Metashape User Manual for more GPU recommendations).

Hint: *If you have Windows 10, it may be useful to update to 1709 build to monitor GPU usage. Additionally, in Windows 10, you may need to increase the Windows 10 Page File Size (i.e., Virtual Memory). This setting can be accessed through:*

Control Panel → System and Security → System → Advanced System Settings (left hand side) → Performance (Settings) → Advanced tab (Figure 4.2) → Virtual Memory Change → Uncheck 'Automatically manage paging file size for all drives' and set a custom size. Set the maximum size to be the same size or 1.5× the size as your installed RAM (for example, 1024 × (amount of RAMs in gigs) × 1.5 = page file). You can play around with the settings based on how much free HDD space you have and by monitoring the committed memory usage under the Performance tab in Task Manager.

In the Agisoft 'Tools' tab, select Preferences, select GPU tab, and check the box for any GPUs listed. This will now be the automatic setting each time you open Agisoft. (Figure 4.3).

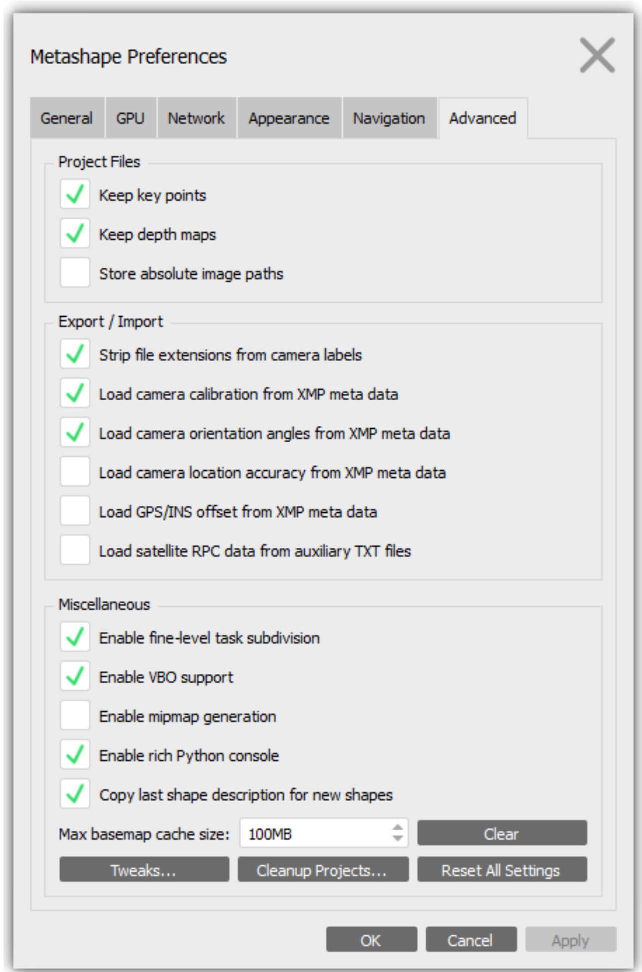


Figure 4.2 Example of the Advanced Preferences options tap.

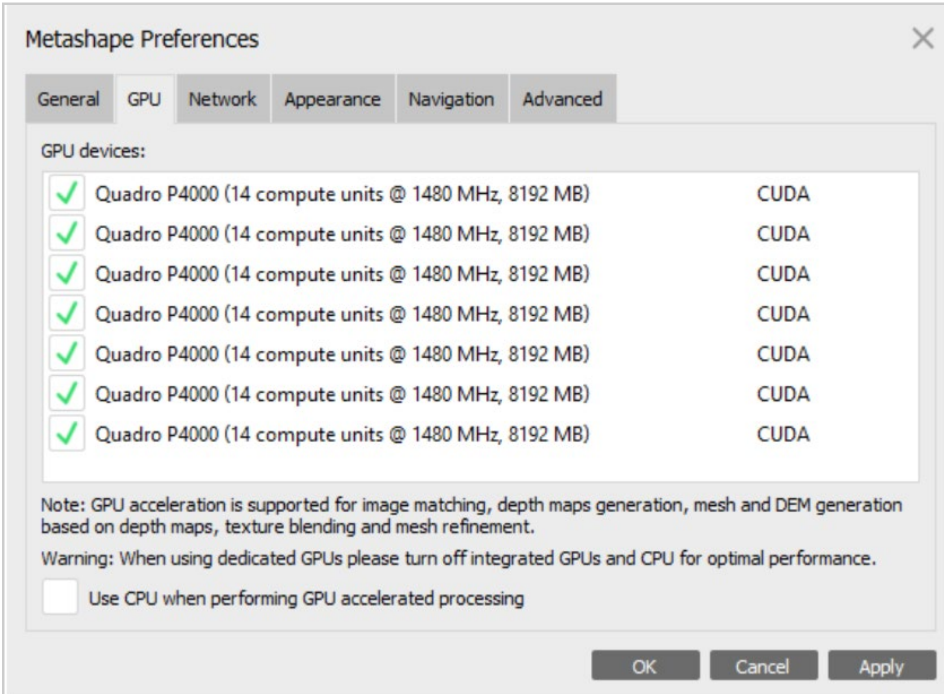


Figure 4.3 Example of preferences window with all GPUs enabled.

4.2 Organize, Add, Filter Photographs, and set Reference Settings

Prior to opening Agisoft, take the following steps:

1. Write the project log to a file as *.txt to document the process: Preferences → General Tab.
2. Ensure that all images are in one folder (*site#; e.g. OAH_0001*).
3. Any photos containing blue water, fins, hands, or blurriness should be removed before model reconstruction and placed in the MISC folder (this is usually done during the QC process described in section 3.2 above).
4. Create a folder in the *site# folder* that is titled Products.
   - Save all products from Agisoft and Viscore in this folder.
5. Be aware that any spaces OR periods in file names will cause issues. Name files accordingly.
6. Open Agisoft Metashape.
7. Save the project titled *site#* in your Products folder.
8. Click Workflow in the upper left hand corner, choose ‘Add Photos’ from the dropdown menu.
   - Select all the images you want to use and click ‘Open’
   - If there are multiple folders of images, repeat this process to add each set of photos
   - In the photo pane (bottom of the screen), change view to details.
9. Right click and choose ‘Estimate Image Quality’ (Figure 4.3).
   - Apply to ‘All cameras.’ Click on the Quality column to sort indexes from least to greatest.

- Disable or remove ([Figure 4.5]) any photos (referred to as Cameras in Agisoft) that have a quality of less than 0.5 (This is not a unit, scale is 0 to 1.0, where 0 is bad and 1.0 is good based on the sharpness the source photos).
- If a noticeable number of photos did not align, sort according to alignment, highlight all images that did not align by shift click, and right click to choose photos to enable and try alignment again.
- Minimum quality depends on the majority. If a substantial number of photos have quality under 0.5, raise the minimum (e.g., < 0.45).
- If you have more than two low quality photos in a row, include at least one to minimize gaps.
- Remember that this step is dependent on each individual photoset. If you do not remove poor photos, you risk incorrect alignment; if you remove too many, you risk incomplete alignment.

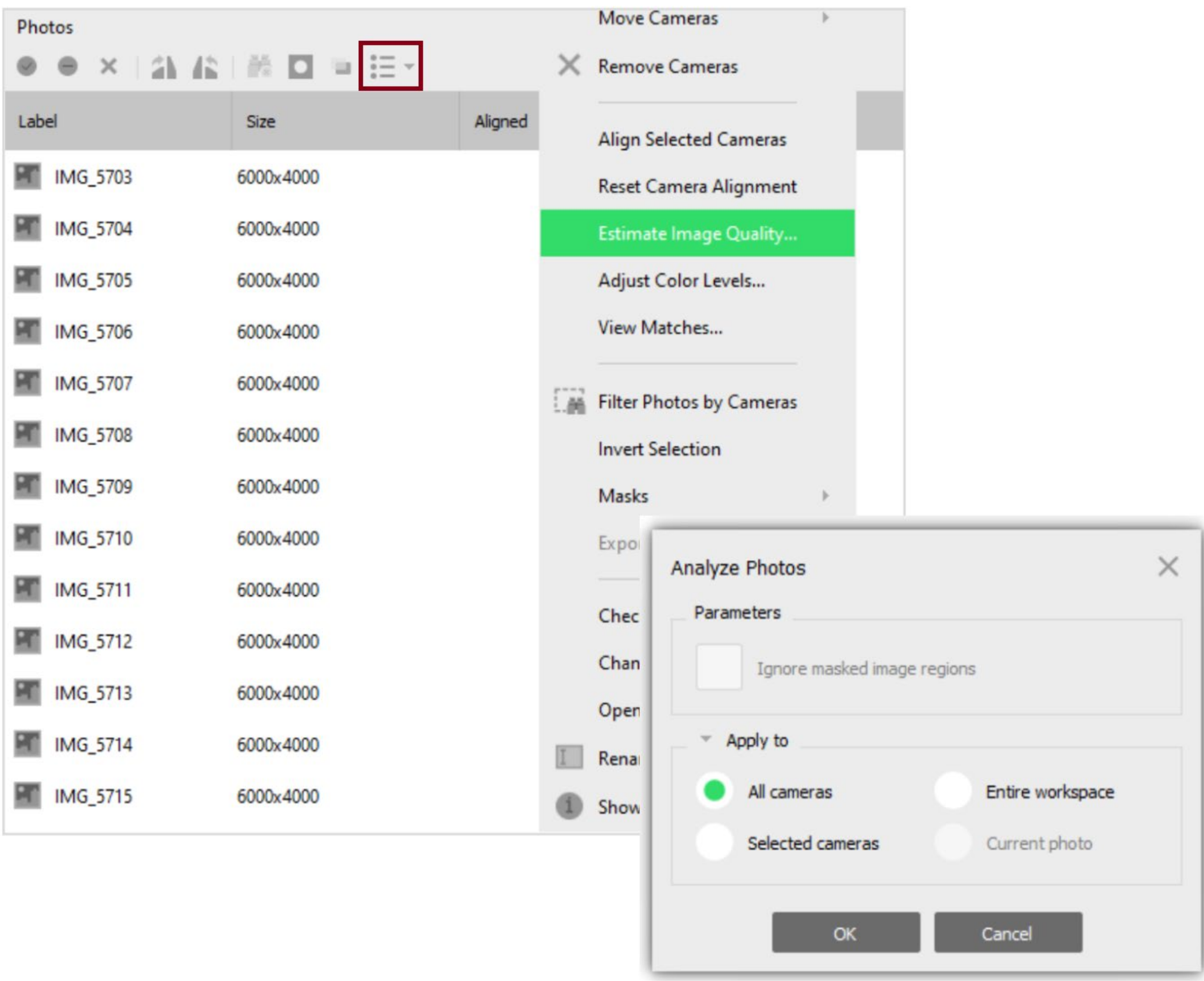


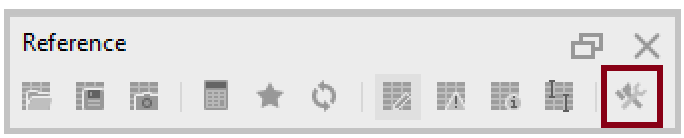
Figure 4.4 Example of 'Estimate Image Quality' window with desired settings.

Figure 4.5 Photos menu in Agisoft Metashape, with the following options: (A) Enable Camera; (B) Disable Camera; (C) Remove Camera; (D) Rotate Camera; (E) Show Masks; (F) Show Depth Maps; (G) Change View.

4.3 Photos-to-Model Processing

Once all images are loaded and quality checked, the software aligns them by identifying and matching corresponding points between images. At this stage, only a small number of high quality matches, or tie points, are retained, producing a sparse point cloud (SPC). Photo alignment can take anywhere from one to five hours depending on the number and quality of images. The process consists of three initial steps: detecting points, matching points, and estimating camera location and orientation.

1. Click the Reference settings tool on the Reference pane toolbar and adjust default setting values as in Figure 4.6.



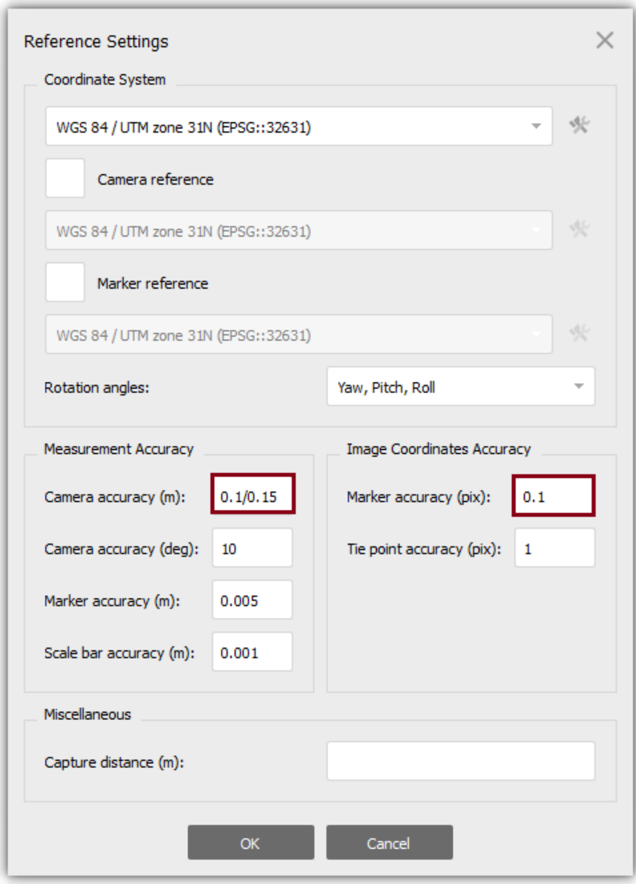


Figure 4.6 Metashape Reference Settings

Hint: 'Camera accuracy (m)' values refers to horizontal / vertical uncertainty. Also, the 'Coordinate System' is temporarily assigned to WGS84/UTM zone 31N, which denotes a UTM zone at roughly '0,0'. The correct coordinate system and projection is assigned to the models at a later stage if such data becomes available.

2. Click Workflow → Align Photos (Figure 4.7)
   - Accuracy: High
   - Generic preselection: Yes (Uncheck if there is poor image alignment and rerun. If not checked, this can cause image processing to significantly slow down).
   - Reference preselection: Unchecked
   - Key point limit: 40,000
   - Tie point limit: 0
   - Exclude stationary tie points: Unchecked
   - Guided image matching: Unchecked
   - Adaptive camera fitting: Unchecked

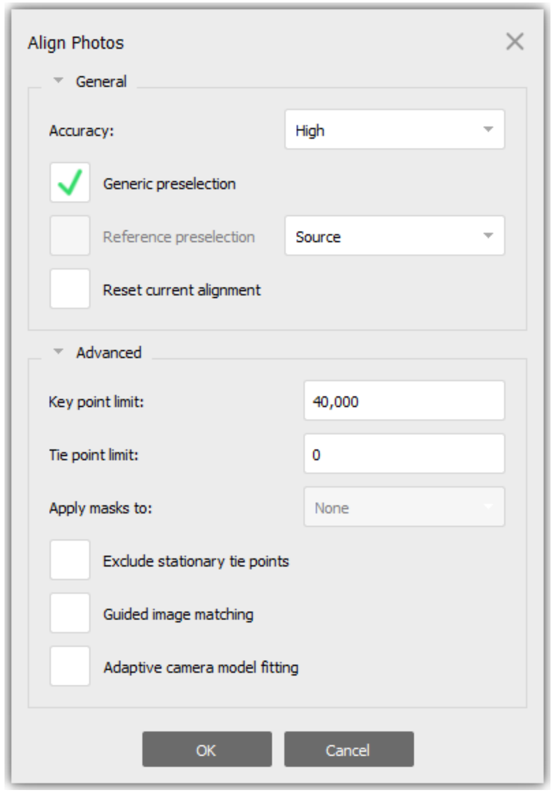


Figure 4.7 Screenshot of Align Photos dialog.

3. Once completed (~15 min to 2 h), dropdown the menu for Chunk 1 in the Workspace to ensure that all photos are aligned. If more than 15 are not aligned, try again or reevaluate the quality of corresponding photos.
4. Save project
5. Click File → Save As
    - Save an original copy of the SPC in case you need to undo any post-processing. Name the new project file as year_site#_bkup.psx and leave untouched.
    - Close the _bkup file and navigate back to the active model on which you are working.

4.3.1 Error reduction and scaling

The sparse point cloud largely defines the geometric accuracy of the 3D model. As such, it is recommended to optimize the camera internal and external orientation parameters to improve the quality of models before generating the dense point cloud. We have adapted the model optimization recommendations presented in Over et al. (2021) which aim to optimize the camera poses and orientation by interactively removing low quality geometric relations between cameras. The error reduction and re-optimization steps here set up all model products for high geometric accuracy which is vitally important for extracting quality data from these models.

1. Click on the star [ ] in the toolbar of the Reference pane to Optimize the alignment (Figure 4.8).

- Check: f, cx, cy, k1, k2, k3, p1, p2.
- Under Advanced: check ‘Estimate covariance’.
- Uncheck ‘Adaptive camera model fitting’ and ‘Fit addition corrections’.

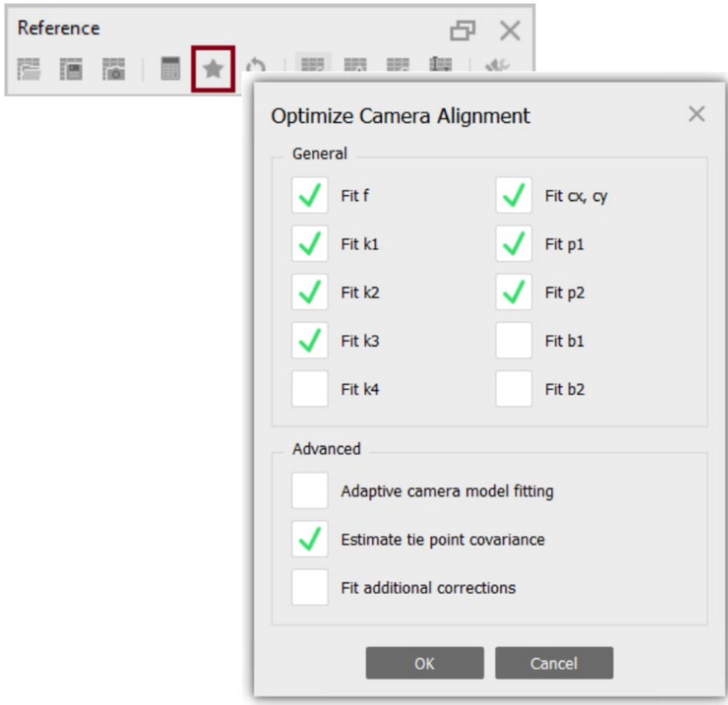


Figure 4.8 Screenshot of ‘Optimize Camera Alignment’ dialog

2. Click Model → Gradual Selection to remove low quality points and improve the model geometry in the following order (Figure 4.9):

   - *Reconstruction Uncertainty* (Figure 4.10): Find a “Level” value between 10 and 15 that selects no more than 50% of the tie points. Increase the upper value if more than 50% of points are selected.
   - Hit the ‘Delete’ key [ ] to remove the selected lower quality points and then the star [ ] in the toolbar of the Reference pane to Optimize using the same parameters as in step 1.
   - *Projection Accuracy* (Figure 4.9B): Find a “Level” value between 2 and 6 that selects no more than 50% of the remaining tie points. Increase if more than 50% of points are selected.
   - Hit the ‘Delete’ key [ ] to remove the selected lower quality points and then the star [ ] in the toolbar of the Reference pane to Optimize using the same parameters as in step 1.

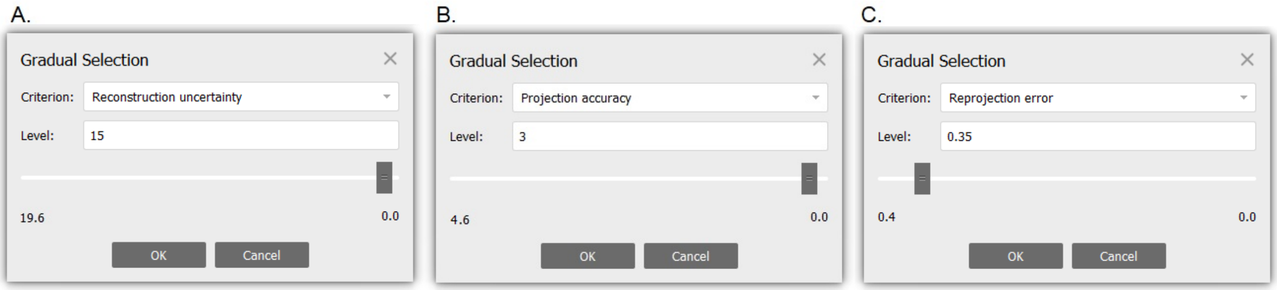


Figure 4.9 ‘Gradual Selection’ dialogs in Agisoft Metashape displaying settings for filtering the sparse point cloud. “Level” values in each panel are target values for error reduction steps: (A) Reconstruction uncertainty, (B) Projection accuracy, and (C) Reprojection error. However, threshold values may need to be adjusted if the suggested level selects too many tie points (A, B > 50%; C > 10%).

3. Save Project

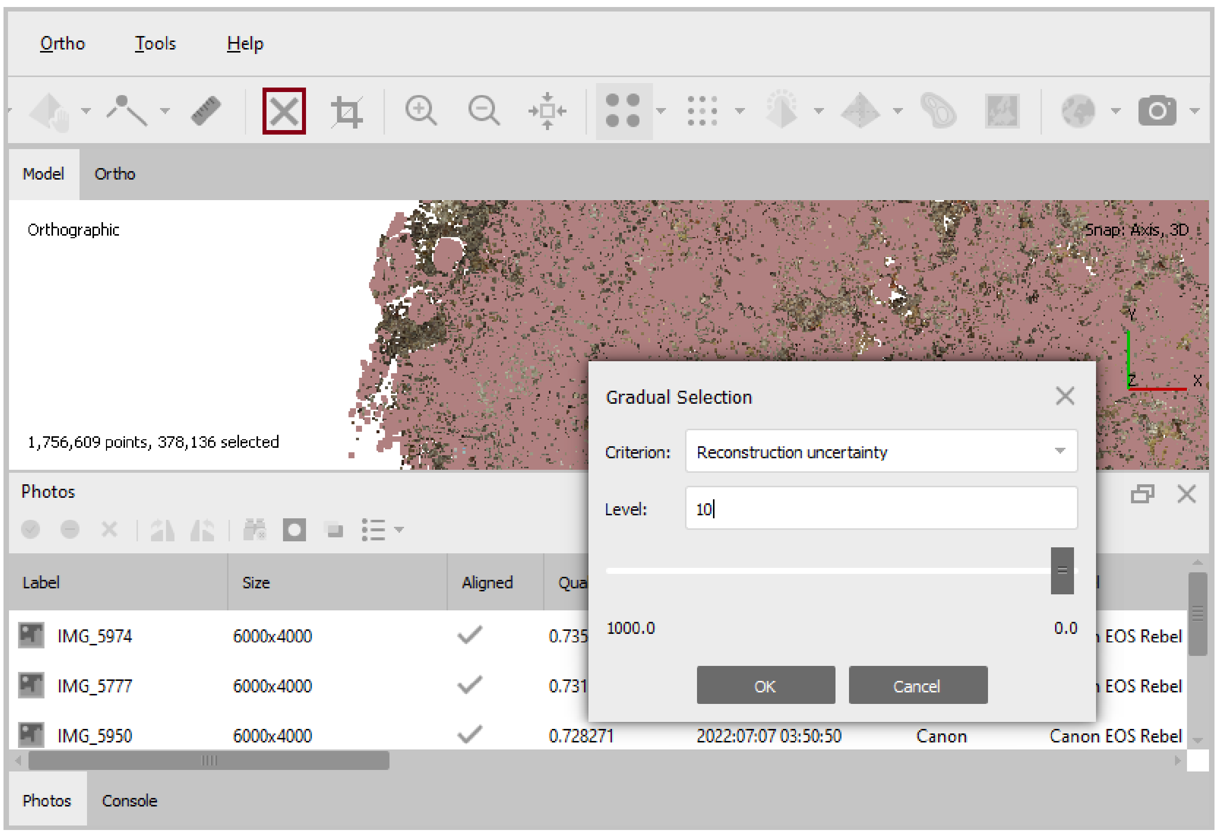


Figure 4.10 Example of Gradual Selection tie point filtering.

Hint: The number of selected points will appear on the bottom left side of the model pane, next to the total amount of available tie points.

4.3.2 Detect coded markers

1. If Metashape target patterns were used, click on Tools → Markers → Detect Markers (Figure 4.11):
   - Marker Type: circular 12 bit
   - Tolerance: 50
   - Uncheck Inverted (white on black)
   - Uncheck 'Disable parity' – OK
   - Metashape will automatically detect targets in each image.

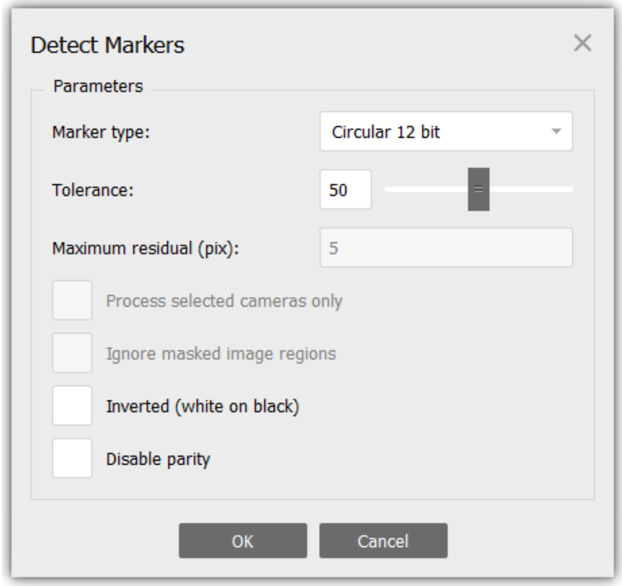


Figure 4.11 Screenshot of 'Detect Markers' dialog.

Hint: If using an older version of printed Agisoft circular targets, you must check the 'Disable parity' box in order for Metashape to decode the used target version correctly.

2. If Metashape coded targets were not used OR the software did not detect them, select a photo from the photo pane with an object that can be used to scale images (or the markers themselves) and add a marker according to the following steps (Figure 4.12):
   - To place a marker in a photo, right click over the selected feature and choose Add Marker.
   - Avoid markers that are touching the edge, at a steep angle, or blurry.
   - A blue flag on an adjacent photo showing the same feature means that the marker was successfully detected.
   - On the other hand, a white flag means a marker was detected but not enabled. Click and drag the marker on the image to improve its placement and enable it or ignore if unwanted.
   - A red dashed line may appear on the first few photos after adding a marker, right click to Place Marker and the red line will disappear.
   - Rename the markers in the Reference window by double clicking on the marker name (e.g., Target 57).

- Once you add the same marker in 2 images, Agisoft will detect those objects in the rest of the images.

3. Look at the Error (pix) column in the Markers pane on the far right. Each marker error should be under or close to 0.5 pix, keeping 5 or more projections per marker (Figure 4.13).
   - If a marker error is above 0.8, right click on the highest error marker and choose 'Show Info' to show the error associated with each individual photo.
   - Sort in descending order by clicking on the Value header. Double click the image with the highest error and the photo will pop up as an image tab.
   - Close the Info window and remove the selected marker on the image by right clicking on the marker and selecting 'Remove Marker.'
   - Continue this process on each marker with high error until all markers and total Checkpoint Error (pix) are below 0.8. Note that higher marker errors are usually observed for markers laying close to the image edges where greater image distortions are expected.

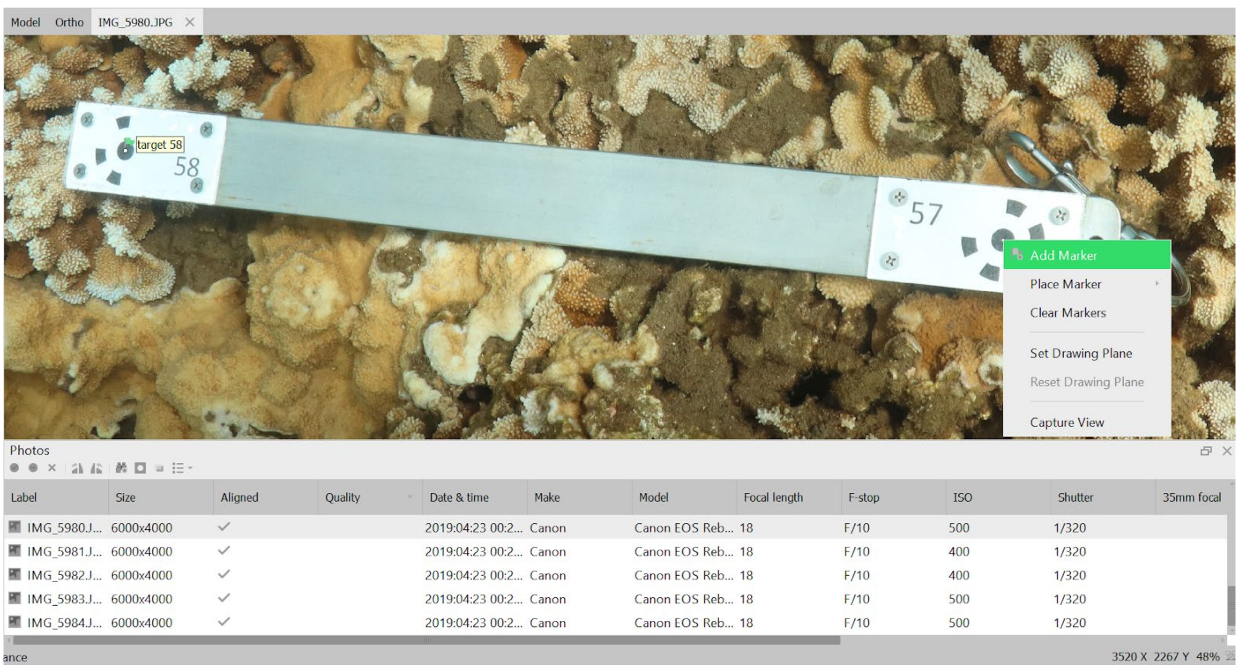


Figure 4.12 Add markers illustration.

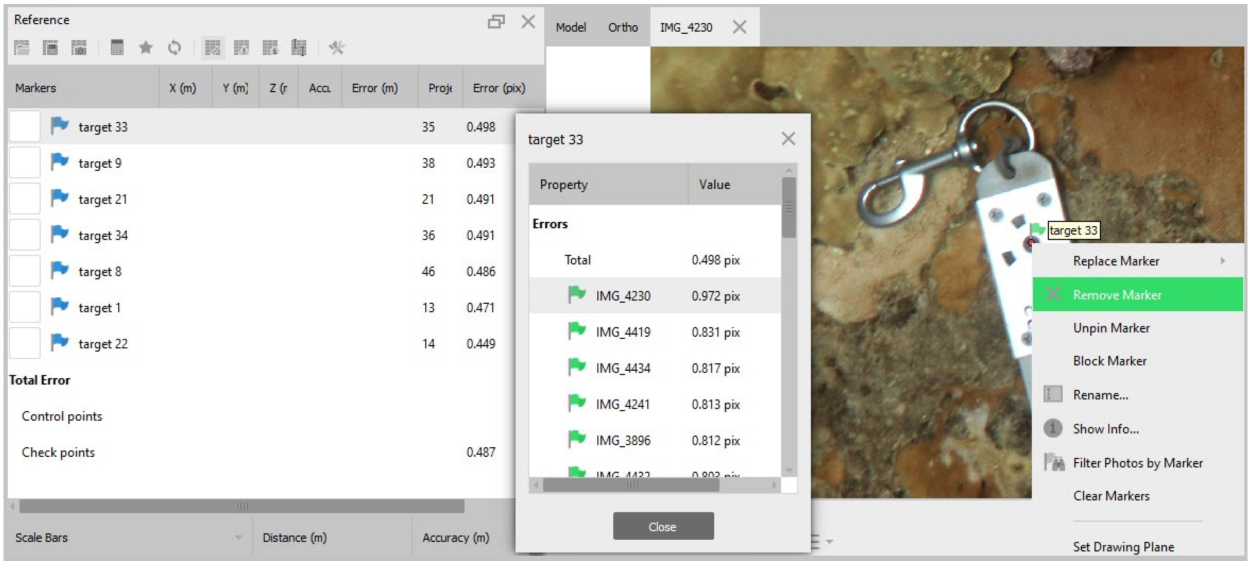


Figure 4.13 Agisoft Metashape screenshot highlighting target error dialog.

4.3.3 Create scale bar and assign measured distance

1. Under the Markers tab, choose matching markers that make up a scale bar according to the datasheet (Figure 4.14).
   - Select both markers with ctrl + click, then right click and choose ‘Create Scale Bar.
   - In the ‘Scale Bar’ pane, double click under ‘Distance’ to manually add the measured distance between the two markers in meters. For calibrated scale bars, make sure to include all the known digits of the length value.

2. Once all the scale bars with distance are added, use the ‘Update Transform’ tool [] (next to the optimize button) to scale the model based on known ground control distances.
3. Check the error given in the ‘Scale Bar’ tab—‘Check scale bars’ error should be less than or equal to 0.001 m. If error is too high, reevaluate all the tie points related to the markers to lower their individual error, then ‘update transform’ again.
4. Uncheck the box for each scale bar.
5. Save.

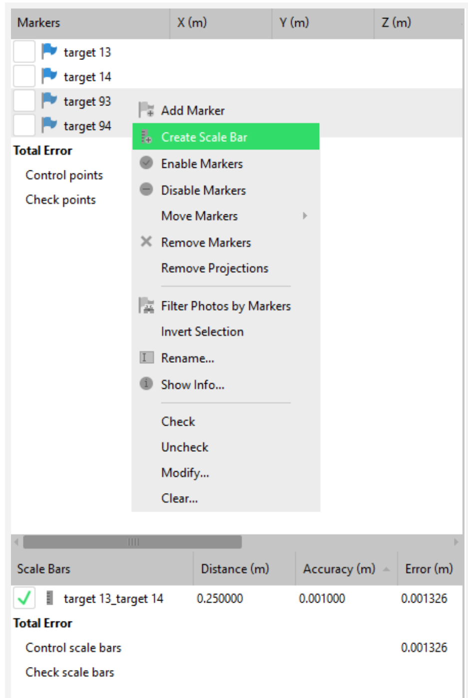


Figure 4.14 Agisoft Metashape screenshot highlighting scale bar creation.

BACK TO ERROR REDUCTION

1. Click Model → Gradual Selection (Figure 4.9C) to remove low quality points based on:
   - *Reprojection error*: Level between 0.3–0.5 (Increase number if more than 10% of the total original points are selected)
2. Hit the 'Delete' key [✕] to remove the selected low quality points and then the star [★] in the toolbar of the Reference pane to Optimize using the same parameters as in step 1.
3. Save Project.

4.3.4 Build dense point cloud

The DPC is built out of the SPC by densifying the number of matching points between source images (Figure 4.15). This is the most time consuming part of the process and takes between 4 and 24 hours depending on the structural and optical characteristics of surface features. A DPC is the main output from Agisoft and the basis from which to derive geometrically accurate reef models for measurement. Due to our field procedures and oversampling techniques, we create a medium DPC to drastically decrease processing time. In cases where a medium DPC is not sufficient, a high DPC is created, which more than doubles the processing time.

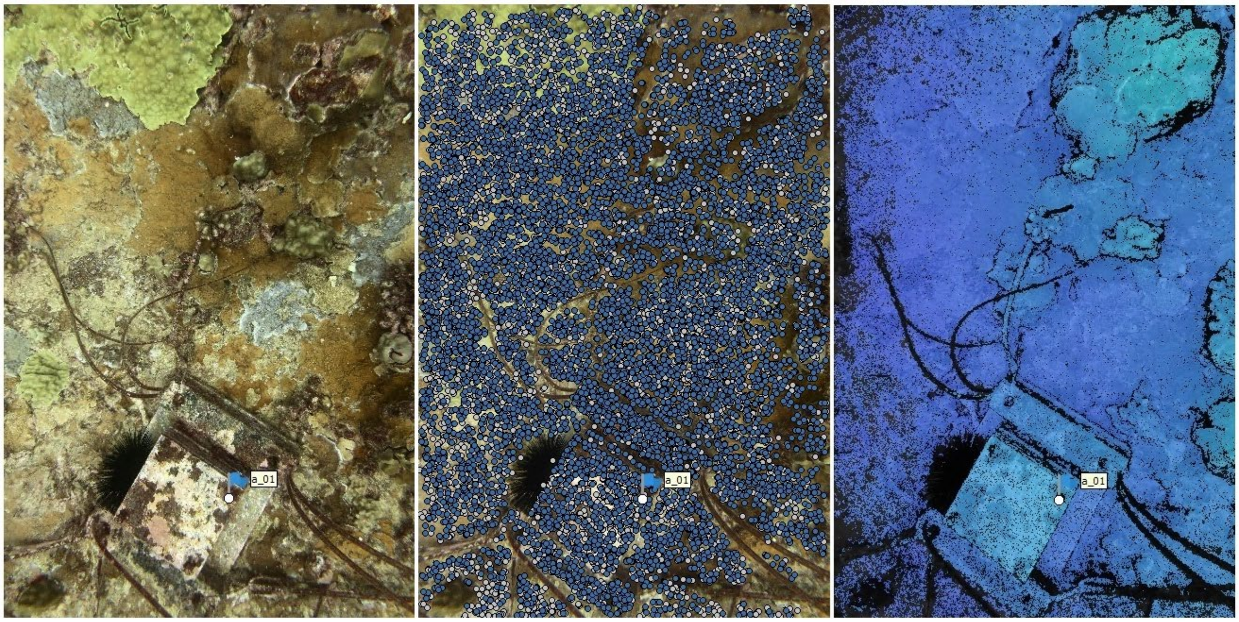


Figure 4.15 Illustration of point densification. Low contrast (i.e., black sea-urchin and shadows) or moving objects (i.e., macro algae and zip ties) tend to make low quality tie points and may result in localized point cloud data gap.

1. Ensure that the entire SPC is contained within the model region (the DPC will only be constructed from points within the region box)

2. Click on ‘Move Region’ (Figure 4.16B)

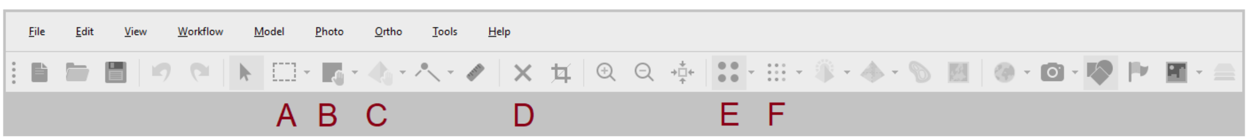


Figure 4.16 Standard toolbar in Agisoft Metashape used to edit and clean up the point cloud. (A) Rectangle Selection, (B) Move Region, (C) Move Object, (D) Delete Selection tool, (E) Show SPC, and (F) Show DPC.

3. If part of the SPC is outside of the region, click on ‘Resize Region’ and resize to capture the entire SPC. This step is optional since the software calculates bounding box dimension and orientation automatically. But it is recommended to check in case adjustments are needed.

4. Click Workflow → Build Dense Cloud (Figure 4.17)
   - Quality: Medium (high DPCs take six times longer to run)
   - Depth filtering: Mild
   - Unchecked ‘Reuse depth maps’.
   - Check ‘Calculate point confidence’.
   - Check ‘Calculate point colors’.

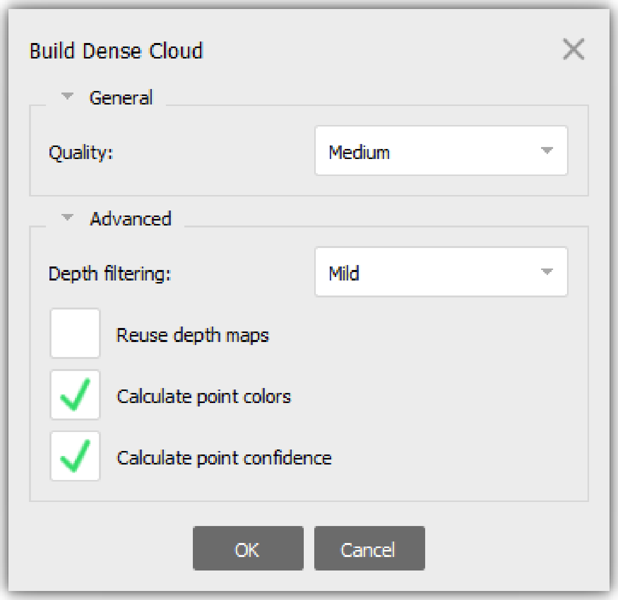


Figure 4.17 Screenshot of 'Build Dense Cloud' dialog displaying selected settings.

5. Once completed, Save the project

Filter by confidence [Optional]

Confidence values, calculated for every point on the DPC, can be used to perform additional filtering of low confidence points using the Filter by Confidence tool.

1. Click on ‘Dense Cloud’ to view DPC (Figure 4.16F). Optionally, use the cursor and rotate the 3D object to inspect the results. It is possible that you will notice some point outliers floating in z space that obviously do not belong on the reconstructed surface; these are considered noise. Manually delete these points or use if not too many. Alternatively, use the *Filter by confidence* tool over noisy DPC.

2. Click Tools → Dense Cloud → *Filter by Confidence*
    - Min: 0
    - Max: 1

   This will select all “low confidence” DPC points based on the count of overlapping image pairs used to generate a point. The higher the count, the higher the confidence. Select a range with 0 and 1 limits (Figure 4.18).

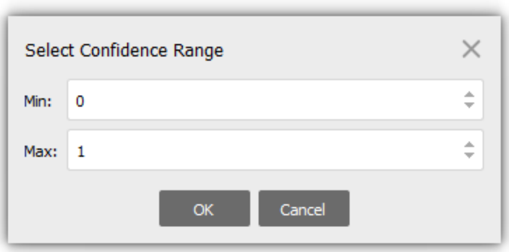


Figure 4.18 Screenshot of 'Select Confidence Range' dialog displaying used parameters.

- To visualize this process, one can optionally click the dropdown arrow of the "Dense Cloud" view option tool and select "Dense Cloud Confidence." Low confidence points will appear in warm colors and high confidence points will show in cool color gradients with values between 1 (lowest) and 255 (highest confidence).

3. Use the 'Rectangle Selection' tool to select all points and hit the 'Delete' key to filter out selected points.

4. Click Tools → Dense Cloud → Reset filter. You are now left with a filtered DPC (Figure 4.19). It is recommended to inspect the model in 3D space to look for remaining outlier points.

5. If there are noticeable points above or below the model that are not aligned or out of place, use the 'Rectangle Selection' tool and 'Delete Selection' to crop them out (Figure 4.16A). Note that you must be viewing the DPC.

6. Save Project

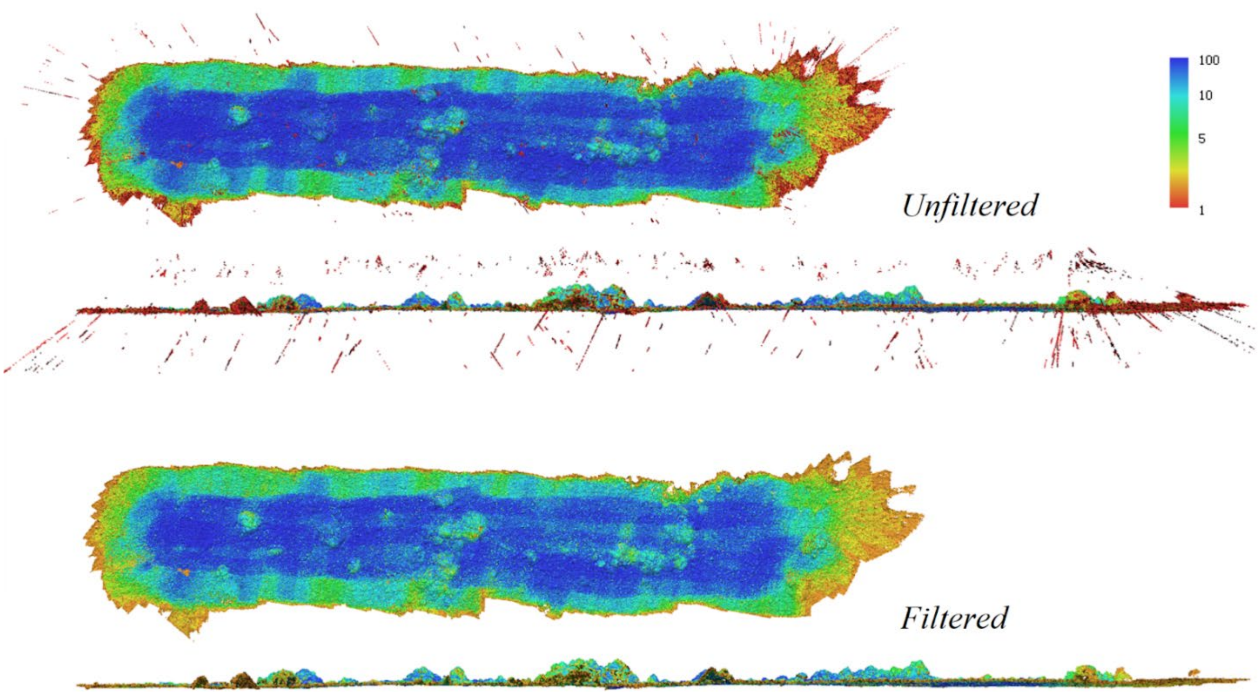


Figure 4.19 Visual comparison between unfiltered (top) and filtered by confidence (bottom) models. Note that most low confidence red points concentrated around edges of the model, reflecting expected lower overlapping image pairs and confidence at the edges. If error reduction steps are followed as above, the resulting unfiltered model will not be as noisy, showing only a few, if any, low confidence red points and the Filter by Confidence step may not be necessary.

Set Brightness [Optional]

If the DPC model comes out dark because of dark source images, use the 'Set Brightness' tool to adjust its brightness and contrast (Figure 4.20). This will help visualize and identify relevant ground features with ease. However, keep in mind that the Set Brightness adjustments only serve display purposes in Model view. To commit the adjustments to apply to the orthomosaic during export, follow the steps listed in Section 4.4.3.

- Tools → Set Brightness
- Click Estimate → Apply the suggested values or modify these as more appropriate.

Figure 4.20 Before and after view of brightness and contrast display adjustment. Notice that the software suggested much brighter estimates than optimal (500: above). Adjust the values as appropriate to account for the lighting conditions and characteristics of the scene, avoiding oversaturation (300: below).

4.3.5 Add depth and rectify model

These next steps add depth measurements to rectify the model to their top-up. The rectification process uses depth measures collected in situ with dive computers at the center of scale bars.

1. It is helpful to rotate the DPC to match the same orientation in which the field data were collected for ease of image interpretation and annotation. In the main menu, click Model → Transform Object → Rotate Object (Figure 4.16C)

- Use the mouse to rotate the model to match the scale bar positions as these appear on the datasheet. For belt surveys, the 0 m scale bar (or the start of the transect tape) should be on the left side of the screen while the 15 m scale bar (or end of the transect tape) should be on the right. If the surveyed plot is a circle or a box shape, rotate the model to match the scale bar positions as these appear on the datasheet.
- It is important to rotate the model before manually adding in markers for vertical (Z) rectification in order to obtain updated X, Y values.

Note: *If geographic coordinates are available, these can be used to orient models to their geographic north. In the Reference pane, substitute the 'Markers' X, Y to their correct Longitude and Latitude values and 'Reset View'. It is important to also define the corresponding 'Coordinate System' on the 'Reference Settings' window to display the correct projection and location.*

2. Manually add markers by zooming into the DPC over the area where the depth measurements were recorded in the field (e.g., center of scale bars)
   - Important to zoom in as close as possible to place the marker on the scale bar (Figure 4.21).
   - Right click on location where you want to add depth information and hit 'add marker.'
   - Double click over the added marker in the reference pane and rename to distinguish from previously detected markers (e.g., depth ##).

3. Add in depth values under the correspondent Z column according to the datasheet. Ensure that values in feet are converted to meters and are input as negative values (or else the model will be oriented upside down).

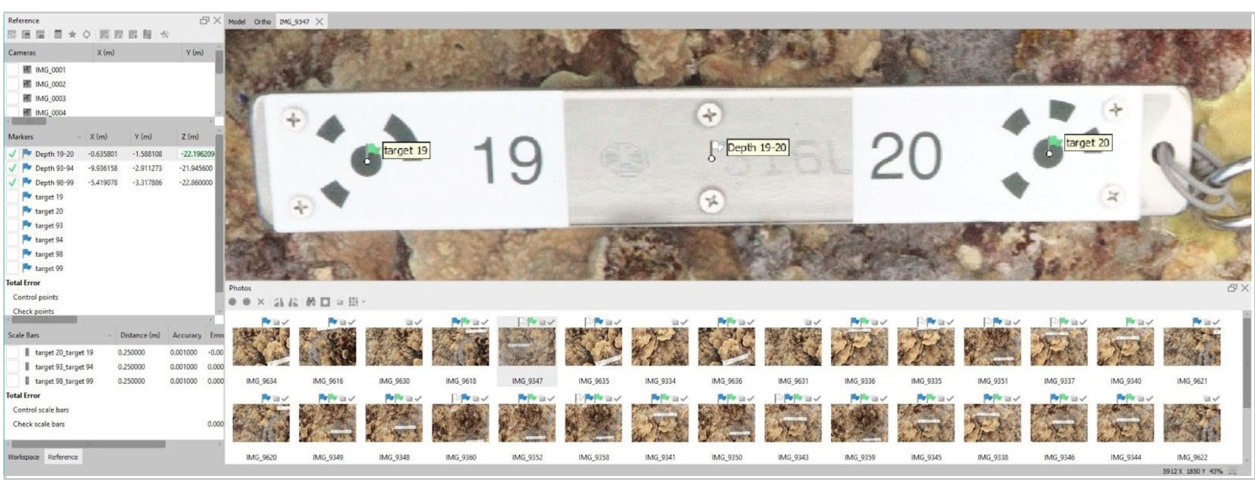


Figure 4.21 Illustration of marker placement and depth value editing in Metashape for rectification.

4. Once all depth values are entered, check the box for each added depth marker and click 'the 'update transform' tool [ ] to update their x, y, *z* position.

5. Lastly, but importantly, uncheck ALL the marker boxes and re-check the scale bar boxes. Click ‘update transform’ tool to recover the reference ground distance. Ultimately, the “Check scale bars” should have total error values < 0.001 m (Figure 4.22).

Scale Bars	Distance (m)	Accuracy (m)	Error (m)
target 98_target 99	0.250000	0.001000	0.000198
target 96_target 97	0.250000	0.001000	0.000566
target 23_target 24	0.250000	0.001000	-0.000767
Total Error			
Control scale bars			
Check scale bars			0.000562

Figure 4.22 Screenshot showing ‘Scale Bars’ pane with 'Check scale bars' error.

Hint: A goal for model re-scaling is to regain the higher distance accuracy of the scale bars, which is better than the depth accuracy attained from measuring depth with dive computers.

6. Save Project

The model is now rectified vertically and horizontally scaled and can be used to derive orthorectified imagery for annotation and measurement.

Note: With the inclusion of calibrated scale bars to the SfM program that have greater precision distance measurements (i.e., 0.0001m), we will use one or two calibrated scale bars as checkpoints to better determine and report model accuracy based on ‘Check scale bars’ error additional to the reprojection errors currently reported. The number of calibrated scale bars used as checkpoints in model accuracy reporting will depend on the number of scale bars visible in the model. For example, if a model has four scale bars, two will be used for scaling and two as checkpoint. The checkpoints errors are to be documented in the SfM spreadsheet under ‘checkpoint_error.’ Once the error is documented, check all available scale bars and repeat ‘update transform’ [ ] to take advantage of all available scale bars in minimizing any localized model distortion. Save the project.

4.4 Model-to-Map Products

Once the DPC is generated, it provides the foundational geometry to calculate 2.5D Digital Elevation Model (DEM) and 2D orthomosaics, both of which are planimetric projections of the coral reef surface as seen from a top view. While pixels in orthomosaics capture the visual properties of reef elements as described by the photos (i.e., red, green, blue), DEM pixel values estimate variation in depth at location. DEMs can be used to analyze structural complexity, also known as rugosity from colony- to reef-scale level. Orthomosaics, on the other hand, can be used to visually characterize the identity and condition of benthic components at the time the photographs were taken. Agisoft uses

2.5D gridded DEMs or polygonal 3D meshes to project the DPC's x, y, z geometry into a coordinate system. Hence, one of these two products needs to be defined prior to building an orthomosaic. We use DEMs rather than 3D meshes as the orthoprojection source to build orthomosaics because our survey design mostly captures photos from top down view in order to efficiently cover large areas of reef.

4.4.1 Build DEM

A Digital Elevation Model (DEM) is a rectified 2.5D projection of the scaled DPC with each pixel value representing depth.

Hint: The model must be scaled and rectified prior to calculating a DEM.

1. Workflow → Build DEM (Figure 4.23)

    Projection
    - Type: Geographic
    - Local Coordinates (m)

Hint: If the model is georeferenced, choose the appropriate coordinate system and projection from the dropdown options.

    Parameters
    - Source data: Dense cloud
    - Quality: (default)
    - Interpolation: Enabled (default)
    - Point classes: All (default)

Hint: Interpolation: 'Enabled' provides a hole-free continuous surface to derive more spatially continuous orthomosaics. However, some project applications may require image maps that retain the integrity of the data without the smoothing effect that comes with interpolation. In such cases, use Interpolation: 'Disabled'. Please refer to the Metashape manual for additional details.

    Region
    - Setup boundaries: unchecked
    - Resolution (m): default
    - Total size (pix): default
    - Check Write World file

Hint: The default DEM resolution responds to the density of the DPC and describes the finest resolution attainable from it.

2. Click Ok.
3. Examine the resulting DEM in Metashape to ensure orientation and overall quality meet the expectations.
4. Save Project.

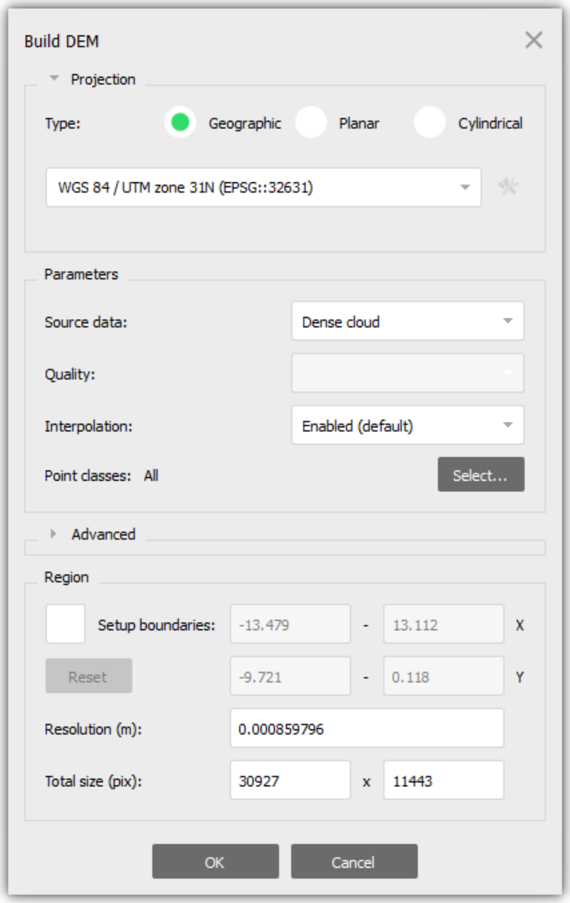


Figure 4.23 Screenshot of 'Build DEM' dialog with selected parameters.

4.4.2 Build orthomosaic

An orthomosaic is a composite image formed by smoothly blending the original photos which are then projected onto the surface of an object and transformed to a chosen projection. In this case, the DEM serves as the selected surface onto which the images are projected to derive orthomosaics.

Hint: Image orthorectification requires an existing scaled and rectified topographic surface from which to build the orthographic projection or orthomosaic.

1. Workflow → Build Orthomosaic (Figure 4.24)

Projection

- Type: Geographic
- Local Coordinates (m)

Note: If the DEM is georeferenced, the same projection information will be provided for orthomosaic build by default.

Parameters

- Surface: DEM
- Blending mode: Mosaic (default)
- Deselect ‘Refine seamlines’
- Select ‘Enable hole filling’
- Deselect ‘Enable ghosting filter’
- Pixel size (m): 0.0005

Note: *As with the DEM, the software will default to the finest resolution possible to build the orthomosaic based on the resolution of the underlying imagery. Given the specs of our cameras, pixel size tends to be around 0.0002 m (Figure 4.24, left). At that resolution, it may take hours to build the mosaic. For time and storage efficiency, we build the orthomosaics with a pixel size of 0.0005 m (Figure 4.24, right), a resolution amenable for most of our data applications.*

Note: If using projected coordinates, the ‘Pixel size’ value may display in angle units. For simplicity, click the ‘Meters’ button under pixel size and enter a value in meters in the pop-up window.

Region

- Setup boundaries: unchecked

2. Click Ok
3. Examine the resulting orthomosaic in Metashape to ensure overall quality is correct.
4. Save Project

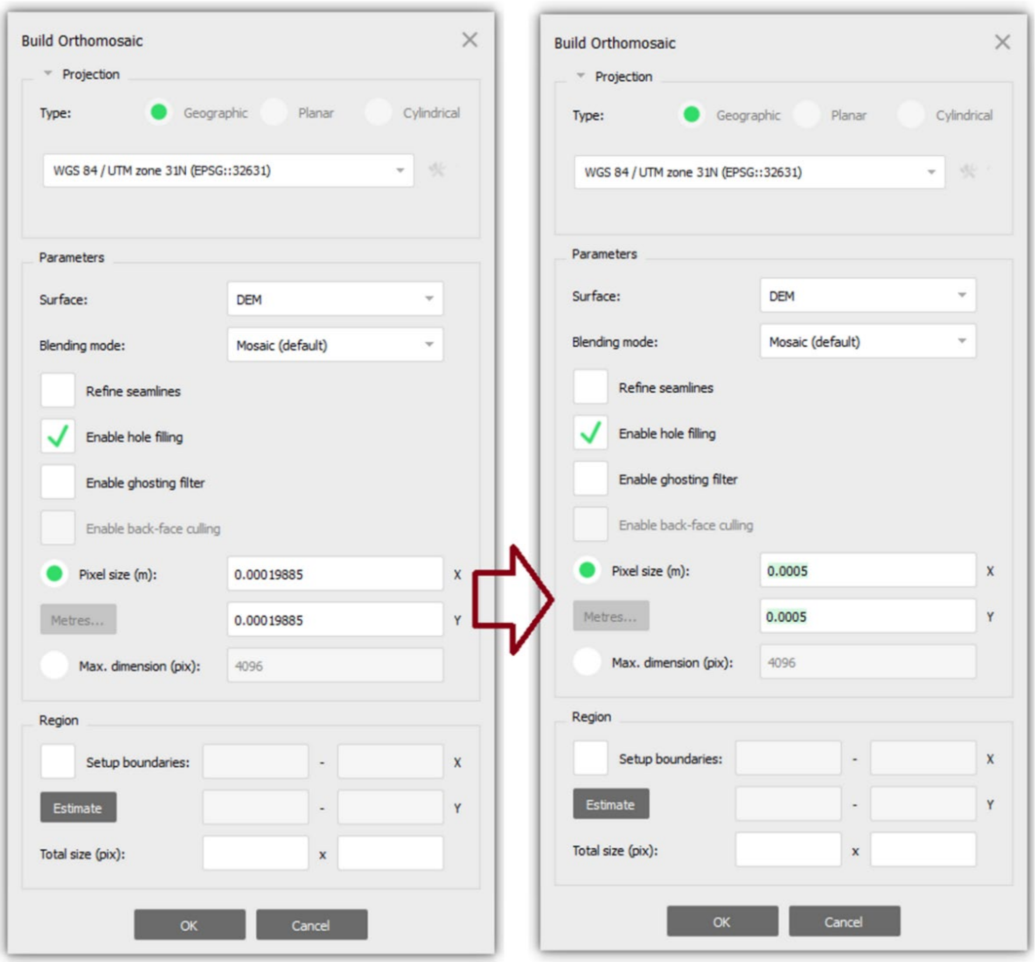


Figure 4.24 Agisoft Metashape screenshots showing 'Build Orthomosaic' settings with 'Pixel size' values updated.

4.4.3 Export image map products

Export DEM

1. File→ Export DEM → Export TIFF/BIL/XYZ... (Figure 4.25)
   - Adjust pixel size to 0.001 m
   - Leave other parameters as Default
2. Click Export
3. Save as: \StRS_Sites\Year\MissionID_Region\ISLAND\SITE\Products\ARC\ year_site#_dem.tif

Hint: *Pixel size should always be equal to or greater than the resolution the software suggests as this is the finest pixel size to which the data can be resolved without creating a false impression of increased details where there is none.*

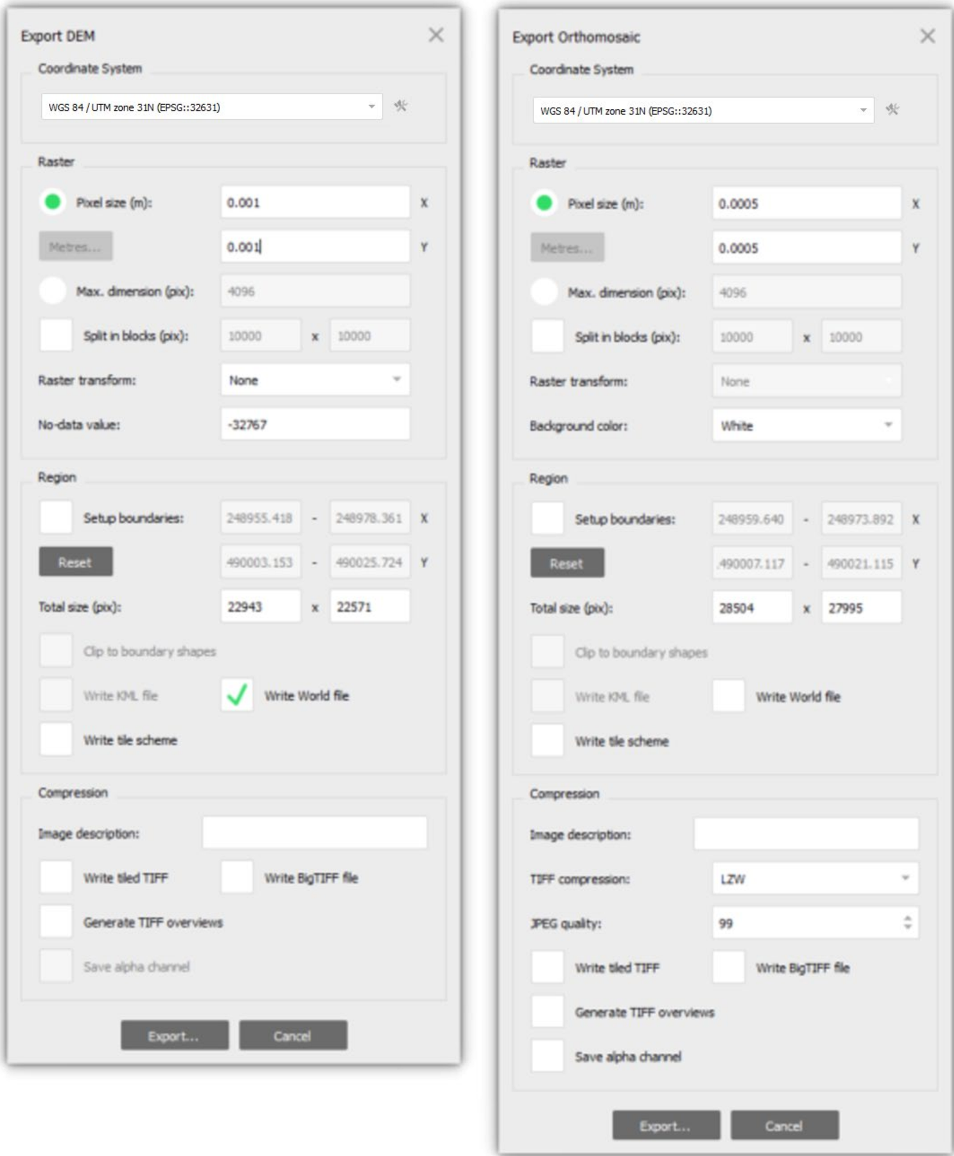


Figure 4.25 Export DEM and orthomosaic parameters.

Brightness adjustments prior orthomosaic export [Optional]

If the orthomosaic looks dark and requires brightness adjustments, use the Raster Calculator tool to commit set brightness to the imagery when exporting. This way, the orthomosaic will be more effective for visual benthic annotations or automated image segmentation. However, if the brightness is appropriate, omit this step.

- Tools → Set Raster Transform
- Select the CIR Calibration tab on the Raster Calculator dialog and update the diagonal values in the color matrix with an appropriate brightness factor. Enter the brightness factor as percentage (i.e., for 250 brightness enter 2.5).
- Click OK to commit the adjustments (Figure 4.26)

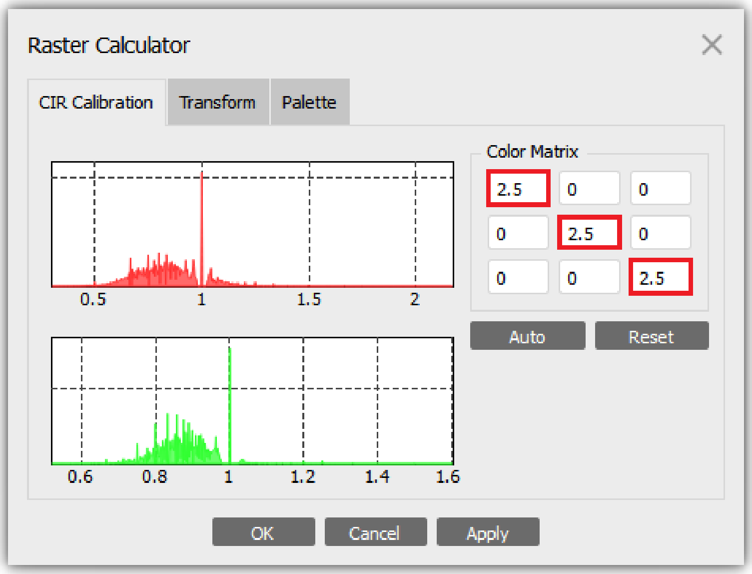


Figure 4.26 Raster Calculator dialog showing brightness calibration example.

Export Orthomosaic

1. File → Export Orthomosaic → Export TIFF/BIL/XYZ... (Figure 4.25)
   - Coordinate System: Local Coordinates (m)

   Raster
   - Change Pixel size (m): enter 0.0005 for both x and y
   - Do not check Max. Dimension (pix)
   - Uncheck Split in blocks (pix)
   - Raster transformation: None
   - Background color: White

Hint: *Depending on the application, reduce the pixel size to 0.0002 m for finer image detail, but consider the impacts on storage capacity.*

   Region
   - Do not check Setup boundaries
   - Total size (pix): Auto generated, no need to change
   - Check Write World file
   - Uncheck Write tile scheme

   Compression
   - Image description: Leave blank
   - TIFF compression: LSW
   - JPEG quality: 99
   - Uncheck Write BigTIFF file
   - Uncheck Write alpha channel

Export

- Save as year_site#_mos.tif

2. In the Products folder, create a folder titled ARC, and export the year_site#_mos.tif into it (Figure 4.27).

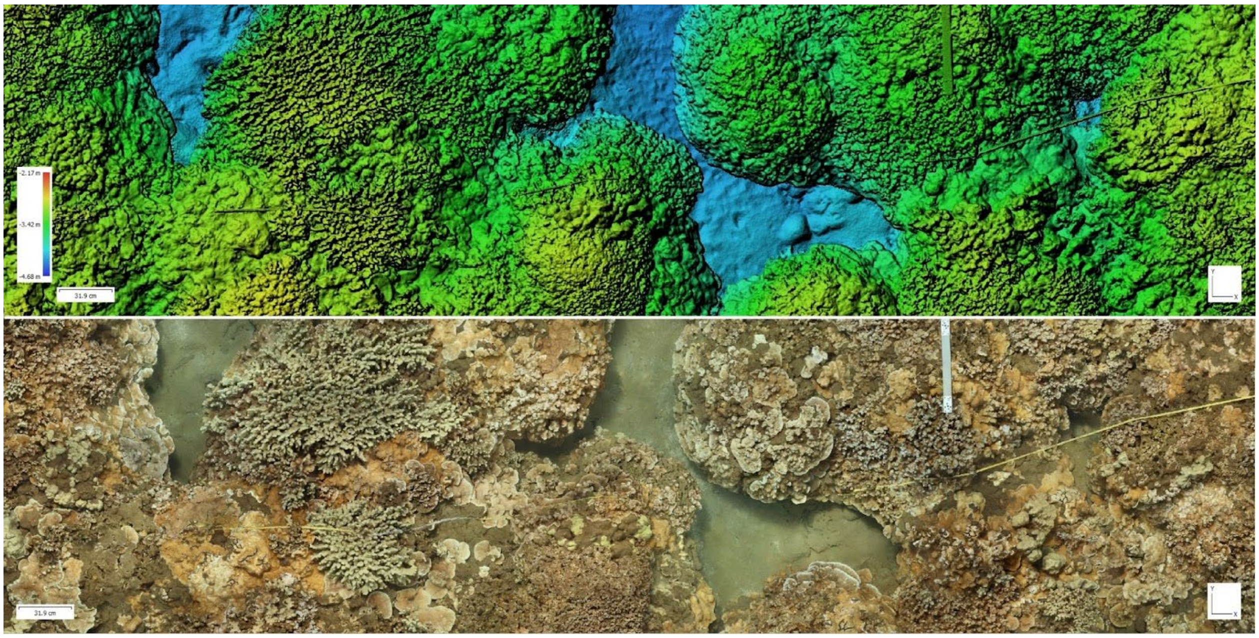


Figure 4.27 Agisoft Metashape illustration of DEM and orthomosaic image products.

Generate and Save Report

The SfM processing reports generated from Agisoft Metashape provide information on model building parameters and metrics (e.g., processing times for each step). This report is important for improving confidence in SfM techniques as well as providing important metrics for the reproducibility of each survey and model generation (Figure 4.28).

1. File → Export → Generate Report

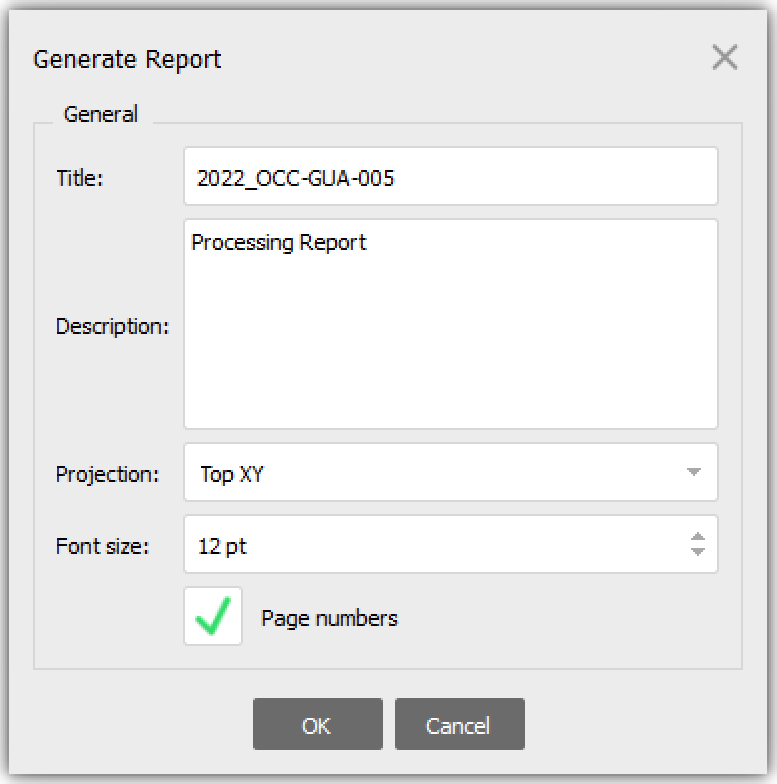


Figure 4.28 Generate report parameters.

Export

- Save as year_site#_rpt.html

Hint: *Other than being user friendly, the machine-readable format logical structure of HTML files allows for automated data extraction that can feed metadata information to facilitate data archiving and sharing.*

4.5 SfM Workflow Automation

ESD has been testing, enhancing, and streamlining its SfM image processing pipeline in recent years to produce coral reef photos and 3D models from which to extract high-quality measure data. While the present pipeline achieves most goals, it still necessitates a significant amount of essential human interaction. ESD recently automated the majority of the procedures in the SfM data processing operations listed above in order to function more efficiently and effectively. The automated pipeline of Agisoft Metashape is composed of three primary tiers and is scripted in Python: (1) Automated photos-to-3D model photogrammetric processing including the improved error reduction steps, (2) a human-in-the-loop checkpoint for model rectification and overall quality control, and (3) automated products generation and export that are consistent and ready for data extraction and analysis.

This automated approach offers many benefits, especially by drastically reducing human intervention and allowing consistent model parameterization. Further, model-specific log files keep track of the process for prompt troubleshooting and are used to inform high-quality metadata for data reporting, archiving, and sharing. A downside to this approach is that error reduction (by removing poor-quality tie points) and optimization are not performed on a case-by-case basis. To operationalize the process over hundreds of models, thresholds are set during *Gradual Selection* to automatically retain more than 50% or 10% of the tie points, respectively, and the camera model is optimized after each of the error reduction steps [Section 4.3, Figure 4.9]. Although uncommon, any model-specific issues can be detected and addressed during the human checkpoint. ESD will continue to explore data collection and processing methods that improve efficiency, quality, and productivity as part of NCRMP, including AI techniques and cloud computing. The source code repository for automation is available at GitHub [link].

4.5.1 Tier 1: Photos-to-DPC [Automated]

Once the SfM photography from the field is quality evaluated and sorted, the model build processing is divided into three main tiers. Tiers one and three are fully automated, and the Python script closely follows the operating procedures steps described above (Figure 4.1).

4.5.2 Tier 2: Human-in-the-loop checkpoint

After the dense point cloud models have been automatically generated, filtered, and scaled, a human checkpoint is performed. This includes checking for all the steps listed below and in that order:

Table 4.1 DPC quality control steps within automation data processing

Activity	Brief Description
DPC QC	Model QC takes place over the DPC. Double click on the DPC to display it in the viewer.
Change view	With the Model viewer selected, hit the number 5 key to toggle from Perspective to Orthographic view.
Rotate Model (belts)	*Model → Transform Object → Rotate Object.* For belt surveys, the 0 m scale bar (or the start of the transect tape) should be on the left side of the screen, while the 15 m scale bar (or the end of the transect tape) should be on the right.
Markers errors	Notice any large errors. Adjust marker locations over photos if necessary. It is not ideal to spend time on this, but it is worth checking.
Scale bars	Check if the scale bars were correctly set during automation and that the errors are low.

Activity	Brief Description
DPC QC	Model QC takes place over the DPC. Double click on the DPC to display it in the viewer.
Change view	With the Model viewer selected, hit the number 5 key to toggle from Perspective to Orthographic view.
Rotate Model (belts)	*Model → Transform Object → Rotate Object.* For belt surveys, the 0 m scale bar (or the start of the transect tape) should be on the left side of the screen, while the 15 m scale bar (or the end of the transect tape) should be on the right.
Rectify 3D model by adding measured depth	Manually add a marker at the center of each scale bar. Edit the depth values for the corresponding marker as per the process tracking spreadsheet. Check the boxes of the newly added markers and hit the 'update transform' tool [ ] to commit the depth values and rectify the model. If less than three markers are selected, the transformation will not update (Section 4.3.5). *Note*: Some models will only have two scale bars. Look for a 'dog tag' around the 0 m mark and add the corresponding marker and depth measure to it.
Re-commit scaling	The model scaling may shift after rectification. Use the 'update transform' tool [ ] again, but with each of the scale bar boxes checked to ensure that the correct ground scaling is maintained.
Clean manageable DPC noise	Turn the model to the side [Hit 1 key] and manually rotate around to inspect the model in 3D space. Identify and remove obvious outliers if any, but be mindful not to remove actual data points.
Filter by Confidence (optional)	If the model is considered to be too noisy, proceed with the Filter by Confidence steps to further remove low confidence points (Section 4.3.4).
Calibrate Brightness (optional)	If the DPC looks dark because of dark source photos, use the Raster Calculator tool to calibrate and apply brightness corrections to the orthomosaic during export. *Tools → Set Raster Transform*. Under the CIR calibration tab, fill the diagonal matrix with the desired brightness factor and apply (i.e., for 250 brightness correction use 2.5). (Section 4.4.3).
Save Project	-

4.5.3 Tier 3: DPC to data products [Automated]

Following the quality control steps, products can be generated automatically and exported to their respective directory folders.

Table 4.2 List of products derived from DPC for analysis

Export Naming Conversion	N:\StRS_Sites\2023\RA2301_AS-PRIA\ROS\ROS-5222\Products\ARC ▪ 2023_ROS-5222_dem.tif [0.001m resolution DEM] ▪ 2023_ROS-5222_mos.tif [0.0005m resolution orthomosaic] ▪ 2023_ROS-5222_rpt.html [Metashape report] ▪ 2023_ROS-5222.cams.xml / .meta.json [camera poses] ▪ 2023_ROS-5222.ply [point cloud]
Save Project	

Section 5: Data Visualization

5.1 Visualizing 3D Point Clouds and Underlying Imagery

This section describes options to visualize the raw SfM imagery in Viscore. Accessing the raw imagery used for model building is essential for accurately recording coral colony demographics as derived products as the orthomosaic may not provide the necessary resolution for proper annotation. Accessing the raw imagery can be done using Viscore, or Agisoft Metashape if Viscore is not available to you. Also, consider exporting the orthomosaic at its native photographic resolution [0.0002 m rather than 0.0005 m suggested here] if CPU, time, and storage are not limiting factors.

5.1.1 Export DPC and cams

The following export procedures are important for correctly archiving the project files to ensure proper conversion to Viscore and overall organization. Follow the naming conventions listed below exactly as they are written, as any difference in file names can result in broken links and unsuccessful conversions in later sections. It is also crucial that the cams are properly exported at this step; if they are not, the functions of Viscore necessary for annotation will be unusable. In the last step, a report is exported to provide useful information regarding processing time, image alignment, and model construction error metrics.

1. Export the DPC:
    - File – Export Points…
    - Within Products folder, save as: year_site#.ply
    - Coordinate System: Local Coordinates (m)
    - Shift: X: 0; Y: 0; Z: 0
    - Source data: Dense cloud
    - Point classes: All
    - Select Point colors
    - Select Point normals
    - Select Point confidence
    - Select Binary encoding – OK
    - If these settings are not available, ensure that you saved the file as a standard PLY

2. Export Cameras: *(Note: If you do not have Viscore installed on your computer, you will need to locate the script titled ‘extract_meta’ in V:\\PICQUEENFISH\Optical\PHOTOMOSAIC (1))*
    - Tools – Run Script...
    - Script: C:/vid/setup/extract_meta.ply
    - Arguments: Leave blank

This step automatically creates a .cams file and a .meta file within the Products folder named according to the naming convention of the Agisoft document. (e.g., year_site#_cams.xml and year_site#.meta.json).

File Summary

The following files/folders should now be associated with each model and should be in the Products folder for the site:

- Year_site#.psx: Agisoft project file that opens model project
- Year_site#.files: Agisoft project file folders containing all the data for the model
- Year_site#.ply: Dense point cloud
- Year_site#_cams.xml: Locations and orientations
- Year_site#.meta.json: Camera locations and orientations
- Year_site#_report.pdf: Processing report
- Year_site#_dem.tif (located in ARC folder within Products): Exported DEM
- Year_site#_orthomosaic.tif (located in ARC folder within Products): Exported orthomosaic

5.2 Using Viscore for Image View

Viscore is a custom software from the Sandin Lab at Scripps Institution of Oceanography, which allows us to visualize and analyze 3D point clouds (Petrovic et al., 2014). Additionally, Viscore can be an essential tool to properly identify corals by using its functions to look at underlying imagery in specific locations throughout the model. If Viscore is not accessible to you, continue to the following sections titled Using Agisoft for point cloud visualization and image view.

This section is an abbreviated version of the Sandin Lab's Guide to Viscore 07/26/21 (Petrovic et al., 2014). Using this SOP, you will be able to directly link the 3D DPC created by Agisoft with the underlying imagery to help identify coral and other colony-level features. You will also be able to create an orthoprojection that is a geometrically accurate and take a screenshot the model (Suka et al., 2019).

Controls: (make sure you have a mouse with a middle scroll ball)

- Left click: rotate and move model
- Double click: set an anchor point (all rotating movement will be anchored around this point)
- Right click + drag mouse towards/away: zoom in and out
- Right click + left click: pan around model
- Control + scroll: increase/decrease point size
- F5: refresh
- F11: enter or exit full screen
- M: move controls and menus, scroll to increase/decrease size
- Alt + middle click: add markers
- Esc: Quit

5.2.1 File conversion

Viscore uses custom file formats to convert the standard 3D files (in this case .ply) to a format the software can understand. Therefore, it is necessary to convert the .ply file to a .vml file. Once converted, you will be left with a .vml and a project folder containing all of the point data.

1. Open the Project folder that contains the DPC (.ply) and cameras (cams.xml and meta.json) files.
2. Open C:\ drive and open the folder 'vid.'
3. Drag and drop the point cloud (.ply) into 'vc5prep-goldi-slowply.'
   - This may take a few minutes. Command is finished once 'Press any key to continue' appears.
   - This will convert .ply into .vml.

5.2.2 Link imagery

Modifying the .vml allows Viscore to access all underlying imagery, which can be used for VCP and image overlaying features. This step is crucial so that the model and underlying imagery can be easily accessed when annotating.

1. Open the .vml file in Notepad (Figure 5.1).
2. In the text, after dd and within the quotation, add set[agicams/s1][imagepath/]
   - Make sure that all slashes are the same forward slash orientation.
   - If multiple sets of images were used to build the DPC in Agisoft, add another set [agicams/s2][imagepath/] after a space following the first.
   - Additionally, open the meta.json file in Notepad to ensure that the correct link to the imagery is there. If the Agisoft products were created on another computer, this may need to be corrected. If the camera paths in the meta.json file do not match the image file paths:
   - In the text, after dd and within the quotation, add:
     set[agicams/replace1/from][imagepath_in_meta.json/]
     set[agicams/replace1/to][imagerypath/] for just the parts of the image path that don't match (likely the first few folders)
   - If multiple sets of images were used to build DPC in Agisoft, add another set
     set[agicams/replace2/from][imagepath_in_meta.json/]
     set[agicams/replace2/to][imagerypath/]

```
<PtVisTest type="V4fC4b">
 <SpriteSetup cfg="newiota" load="budget[20][20] addlocal[index-D2xyJO.xml]
[OAH-MMM2/]" type="V4fC4bT4bN4bA4b" vis="size[0.0075] nearfar[1][200] focal_length[18] mcap[1.][0.8][0.0][1.][cfn] dd

set[agicams/s1][M:/MHI_2021_SFM/StrRand_Sites/OAH/OAH-MMM2/]

" vsync="-1"/>
</PtVisTest>
```

Figure 5.1 Screenshot of .vml file in Notepad after correct modification.

3. Save .vml file.
   - If the meta.json file includes the Products folder in the file path, this means that the images were not relinked in Agisoft. In this case, you will need to open Agisoft, relink the images (right-click on any image, Change Path, apply to all), and re-export the point cloud and camera script. This step will only work if the orthomosaic has not been created yet; only the alignment (sparse point cloud) and DPC should be in the workspace.

Note: If Viscore files are moved to other computers/drives and these files are not kept within the drive, this image path will need to be changed according to the new drive! If this happens, repeat above steps and everything should adjust accordingly.

5.2.3 Viscore menus

Vis-opt

Use this to change visual options when viewing the 3D model (Figure 5.2).

Figure 5.2 Screenshot of vis-opt menu in Viscore: (1) closest distance (closer points will not be shown, scroll to decrease); (2) farthest distance (if model is partially in view, scroll to increase); (3) focal length of virtual camera; (4) background options; (5) render mode (keep on splat); (6) number of points in current view; (7)point size (ctrl+scroll changes this value); (8) N/A; (9) N/A.

Cams

Turn on to view camera paths or use image-overlaying features such as drape (Figure 5.3).

Figure 5.3 Screenshot of cams menu in Viscore: (1) current camera set, click to scroll through options (will initially start as none); (2) turn on to enable image overlay feature. If file path is incorrect, it will read as (images missing), drag drop image file to update image paths; (3) turn on to view camera positions as dots; (4) turn on the view swim path.

Drape

This feature allows sections of the model to be viewed with an image draping over the selected area. The clear picture of the area subsequently created is extremely useful when delineating and identifying colonies.

1. Turn cams on.
2. Turn drape on (the model should flash once).

3. Turn colors on, scroll red to ~1.0 so that the model is <u>not</u> true to color. This step is optional for easier identification of an image's location.
4. Maneuver to the specific area you want to view, and click the tilde (~ key) in the upper left of your keyboard. An image should drape over the nearest area.
5. Press Ctrl+up/down arrow key to move up or down the model, which will move according to the camera path.
6. To move to a different area, maneuver the model and press the ~ again, repeat as needed.
7. A point can also be placed, and drape will show images containing that exact point (same controls: ~ and ctrl + up/down)
   - Once a point is dropped, click ~ (the point will not be on the desired location).
   - Then click ctrl + up/down and the point should jump to the desired location.
8. When finished using drape, restore the colors to their original numbers (all should be one as long as the images were white-balanced underwater), turn drape off, and turn cams off.

5.2.4 Model setup

When first opened in Viscore, the model will be disoriented, and the points will be large. The following steps are necessary to ensure the model will be correctly displayed when accessing Viscore in the future. Additionally, once the model is first opened, multiple files will automatically be created. Therefore, it is also important to test the image links in this step.

1. Open .vml file with vc5. If you do not have the vc5 logo (gold star) icon as an option, right click to Open with → Choose default program → Browse... locate in C:\vid\vcgo.
   - When first opened, you should see your mosaic with a star background. If you cannot see your mosaic, scroll and/or rotate until it becomes visible.
   - The orientation of the model and the point size will be incorrect.
2. Turn on vis-opt, and change ‘near’ to 0.005, to be able to zoom in on the model much more closely
3. Turn Ortho on, zoom in, and change the point size by Ctrl + scroll.
   - If large portions of the model are missing once ortho is on or the model is not showing, increase the width of the slice by scrolling over it (last number on the top row).
   - Decrease point size until the image starts shimmering, then slowly increase size until the shimmer goes away.
4. Turn Ortho off and zoom out so that the whole model is visible.
5. If the Heads Up Display (HUD, a.k.a. menu) is very small or in a difficult place, hover your mouse over it (or where you think it is) and press M on your keyboard. Zoom using the middle scroll to increase the HUD size and move the mouse to where you want it to go. Press M to drop it.
6. Next to *(default)*, click ‘edit’ on, save, and ‘overwrite?’
   - This will set your default view; click revert to redisplay this view.
   - You will know this is complete when it no longer displays ‘edit off’ and ‘new’.
   - If the model is too close to the screen or you are having difficulties, refer to the Vis Opt menu below to change the viewing screen of the 3D model.
7. Turn ‘cams’ on. Click ‘none’ to turn on the camera paths for the model

- Alt + middle click to place a marker (Figure 31).
- Markers can be moved by pressing the middle click and dragging.

8. Markers can be deleted by highlighting the marker (marker will be in a pink circle) and clicking delete in the HUD.
9. Markers will arbitrarily be named alphabetically in the order in which they are dropped. Open Google Chrome.
10. Open localhost:9090/jsd/pq.xhtml and images containing that point should appear.
    - Scroll + middle click to scroll through photos and scroll to zoom in or out.
11. If images are not being displayed or they are wrong, take the following steps:
    - Check the file path for typos and make sure cams.xml, .meta.json, and the .vml file are in the same folder.
    - Ensure there are NO periods, spaces, or dashes are in any of the file path… if there are, replace all with underscores, reconvert .ply to .vml, and start over.
    - Check meta.json file for typos.
12. If these steps do not work, try to re-export the products from Agisoft (DPC and cams) or ask for help.

If using orthomosaics from Agisoft Metashape for data extraction, then scaling, orienting, and exporting an orthoprojection in Viscore is not necessary and can be used for easily accessing underlying raw imagery only.

5.3. Using Agisoft for Image View

If Viscore is not accessible to you, Agisoft can be used to visualize the 3D point clouds and the underlying images necessary for demographic annotation.

1. Open Agisoft project and click on the DPC to view the detailed point cloud.
2. Zoom in to desired location on the DPC (e.g., coral colony or transect tape).
3. Right click on the DPC and click ‘Add Marker.’ This will create a new marker on the DPC (Point #).
4. Navigate to the ‘Reference’ tab, right click on the new marker, and select ‘Filter Photos by Marker.’ Only the photos containing the new marker will remain in the ‘Photos’ tab.
5. Double click on a thumbnail in the ‘Photos’ tab to open an image. It is generally good practice to open multiple images of the same point to ensure you see different angles of the desired location.
6. After you are done viewing a part of the DPC, right click on the marker in the ‘Reference’ tab, select ‘Remove Markers,’ and hit OK to avoid placing too many new markers on the DPC.
7. Repeat from step 3 to view different objects in the DPC.

Note: You can also right click a point on the DPC and select ‘Filter Photos by Point’ to avoid adding new markers; however, we have found that adding markers enhances ease of tracking locations within raw imagery.

Section 6: Data Extraction

6.1 Demographic Annotations in ArcGIS Pro

In this section, ArcGIS Pro 2.8.0 or later is used to record features within the orthomosaic, calculate size, and add data that are associated with each feature, such as species ID, condition, or morphology. This tutorial assumes a basic understanding of ArcGIS. Transects and segments are then drawn onto the orthomosaic to highlight the specific survey areas. The analyst then begins annotation using a previously created Geodatabase while following traditional benthic survey protocols to properly identify colony boundaries, mortality, and conditions. Ensure that you have an ArcGIS Pro for Advanced license to be able to use all necessary functions for annotation.

Refer to Winston et al. (2020) for the latest Data Collection of Rapid Ecological Assessment Benthic Surveys Standard Operating Procedures.

6.1.1 Add data

1. Use the 'Add Folder' tool under the 'Insert' tab to add the folder that the orthomosaic is in (e.g. M:\SE1902_MHI_LEG1\Optical_PHOTOMOSAIC\MAI\REA\BENTHIC\MAI-2532\Products\ARC)
2. Upload the orthomosaic using the 'Add Data' tool under the 'Map' tab
   - 'Unknown Spatial Reference' will pop up in the upper right corner
3. Under 'Analysis,' click on 'Tools' and search for 'Define Projection'
   - Input Data set or Feature Class = year_site#_mos.tif
   - Under 'Coordinate Systems,' set 'Current XY' to 'WGS 1984 UTM Zone 4N' ('Projected Coordinate System' → UTM → WGS → Northern Hemisphere)
   - If not previously done, right click to 'Add to Favorites.'
4. Most likely, the model colors will be incorrect. Click the model layer, go to the 'Appearance' tab at the top, click on the dropdown menu under 'Stretch Type' and change to None.
5. The orthomosaic should already by properly scaled if it was scaled and oriented in Agisoft; however, confirm it is correctly scaled by using the Measure tool under the 'Map' tab and measuring an object of known distance (e.g., a scale bar).

6.1.2 Create transect and segments

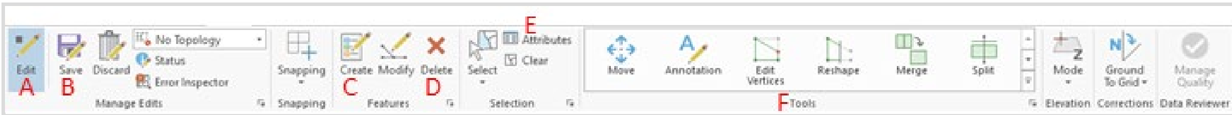


Figure 6.1 Editor Toolbar. (A) Turn editor on/off; (B) Save edits; (C) Create features; (D) delete selected annotation; (E) open attribute table; (F) annotation tools

To create the transect:

1. Under the View tab on the top of the screen, click Catalog, drag, and drop to the right side of the window to pin it there (this only needs to be opened the first time using Arc).
2. Right click on the site ARC folder in the Catalog and select New–Shapefile.
    - Feature Class Name: year_site#_transect
    - Geometry Type: Polyline
    - Coordinate system: WGS 1984 UTM Zone 4N (change this by clicking the globe icon)
    - Leave everything unchecked — Hit Run
3. Open Create Features (Figure 6.1) and drag to the right side of your window to pin it there (again only needs to be done the first time opening Arc).

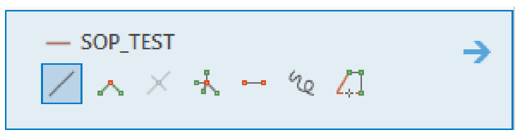


Figure 6.2 Create Features segment construction toolbar. Line tool is selected.

4. In the Create Features window, click on year_site#_transect and make sure the construction tool is line (Figure 6.2).
5. Zoom to the year_site#_mos.tif and click once at the beginning of the transect (0 m) to begin drawing a line along the tape. Continue dropping points while following the transect and double click to end once you get to the 2.5 m mark. Begin another line by clicking once at the 5 m mark and end at the 7.5 m mark. Repeat this for the segments 10–12.5 m and 15–17.5 m if necessary (Figure 6.3).
6. Use placement of scale bars and field datasheet to help determine starting point of segments; you may also open the orthophoto to get a better visual of where the transect line lies and use features as landmarks to help you place the line on the orthomosaic.
7. Additionally, while you draw the line, turn on dynamic constraints in the bottom left corner to approximate length.
    - If the distance shown is in feet, click the down arrow in the bottom middle of the screen, click ‘Format Location units,’ and set ‘Distance Units’ to meters. This will show the distance between each click when drawing the segment.
    - Keep in mind that the line will most likely not be exactly 2.5 m due to the curvature of the tape. Follow standard benthic protocol when determining

where the segments end (i.e., if 0.2 m of the tape is wrapped around a colony, make sure to add 0.2 m to the end of your line).

8. Once all ~2.5 m transect lines are drawn, go to the Edit tab and hit 'Save.' Go to the Map tab and click 'Explore' to stop editing.

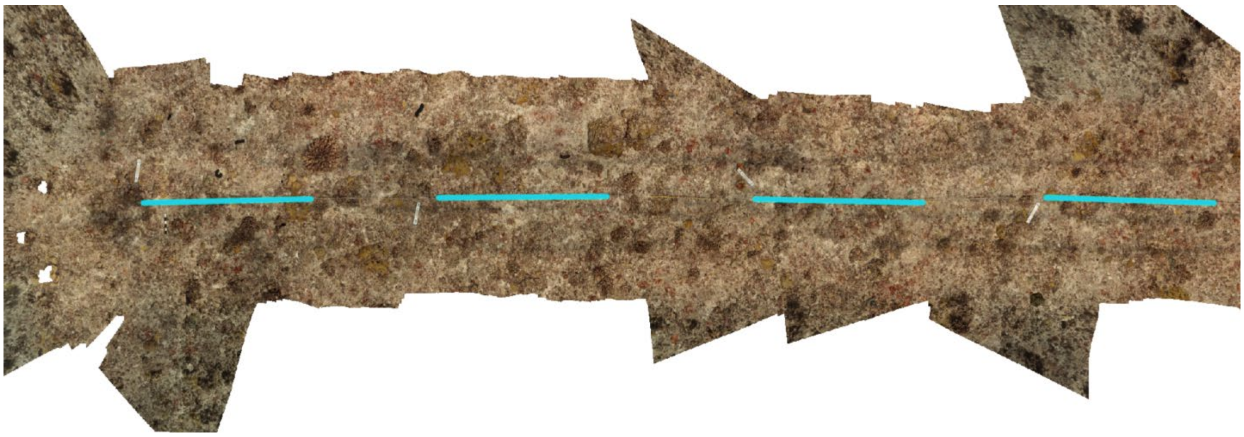


Figure 6.3 Screenshot in ArcGIS Pro of desired 2.5 m transect lines.

To create segments:

1. Right click on the transect layer, click on selection, then click on select all.
2. Under 'Analysis,' click 'Buffer' (Figure 6.4).
    a. Input features: year_site#_transect
    b. Output Feature Class: year_site#_segments
    c. Linear Unit: 0.5 Meters
    d. Side Type: FULL
    e. End Type: FLAT
    f. Method: PLANAR
    g. Dissolve Type: NO DISSOLVE

3. Save your project.

Once completed, segments will be drawn around your transect lines with exactly 1 m width (Figure 6.5).

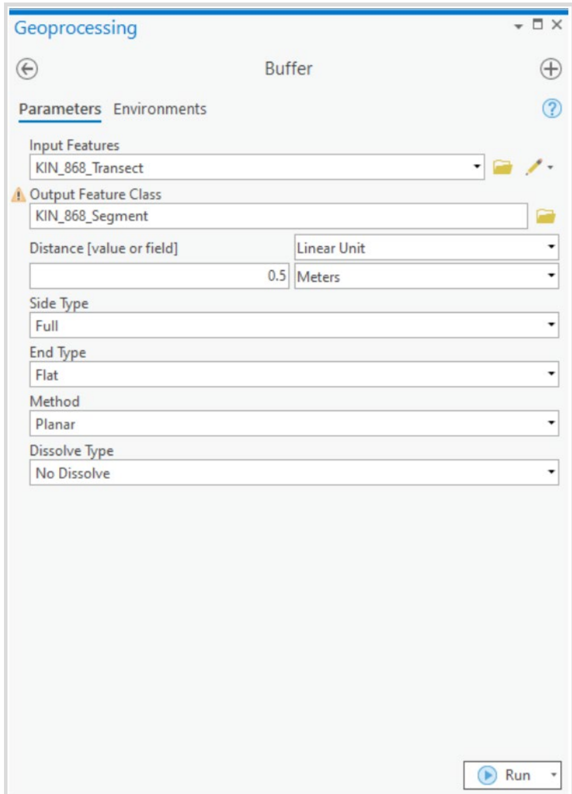


Figure 6.4 Screenshot in ArcGIS Pro of the buffer tool with desired settings.

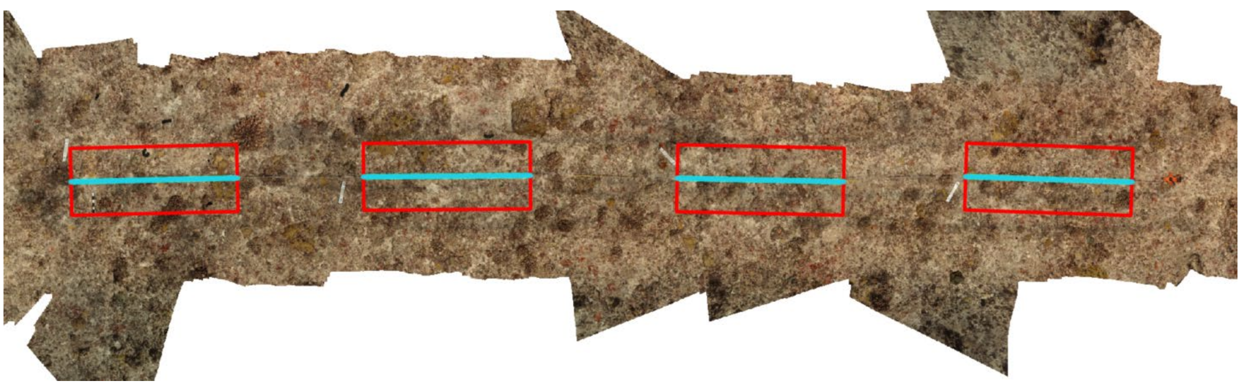


Figure 6.5 Screenshot in ArcGIS Pro of the segments once buffers are created.

Hint: To make the segments a different color or thicker line, click on the colored box under the layer name. This will open up another window titled Symbology where the Fill Color, Outline Width, and Outline Color can be edited (this applies for all shapefile/feature classes).

6.1.3 Set up the geodatabase

In order to replicate the traditional standardized data collection method, a geodatabase will be set up beforehand for easier annotation. The analyzer will need to input this GDB into Arc and dropdown menus will be available for all applicable columns (species, morphology, etc.). See Appendix C for instructions on creating a new GDB.

1. In the Catalog, navigate to the region and year you are analyzing (e.g., NCRMP, 2022). There should be a previously created Geodatabase (in this example, HARAMP2019.gdb).
2. Click the plus sign to drop down the Geodatabase, right click on the 'template' feature class, and select Copy.

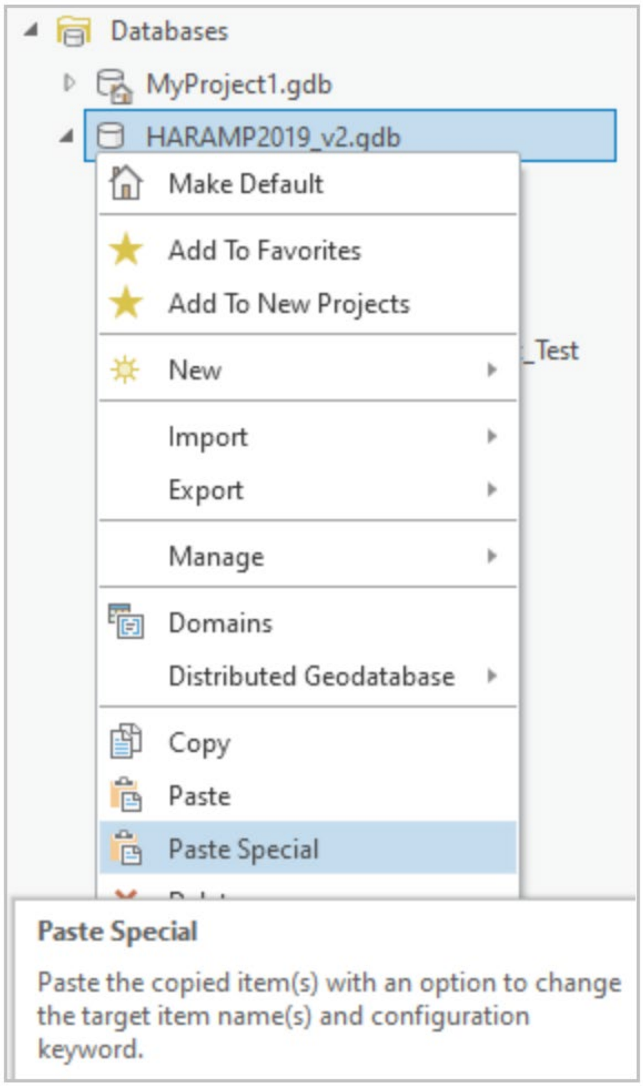


Figure 6.6 Screenshot in ArcGIS Pro of how to copy and paste the template.

3. Right click on the Geodatabase (in this case HARAMP2019.gdb) and click paste special (Figure 6.6).
4. A screen titled 'Paste Special' will pop up. The only box that is necessary to edit is in the first cell in red under Target Name—change this to the project site name (e.g. year_site#_lastname) → OK (Figure 6.7).

- Ensure that all dashes in the site name are converted to underscores or the ‘Paste Special’ function will not run.

5. Drag and drop this feature class into your contents panel.

Drag and drop this feature class into your Contents panel

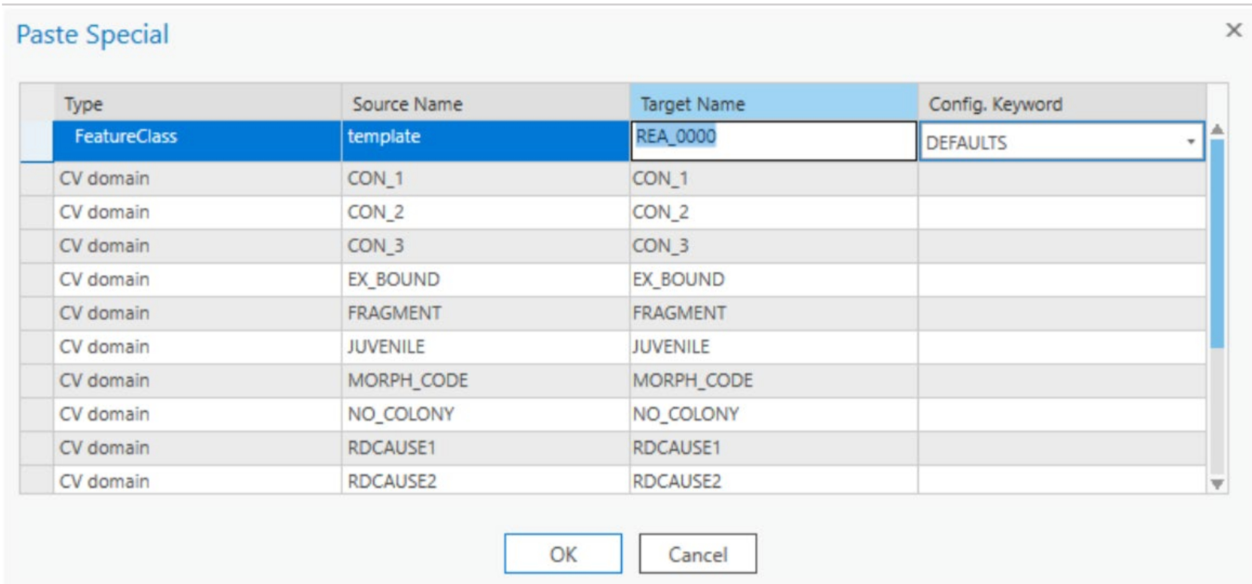


Figure 6.7 Screenshot of Paste Special window in ArcGIS Pro when creating a new GDB from a template.

6.1.4 Coral colony annotation

Eventually we will be extracting colony-level data using full segmentation and classification. Given how time consuming our current by-hand delineation methods are, we are collaborating with several computer scientists to expedite this process. In the meantime, in order to extract colony-level data that are comparable to our historical methods, we will assess colonies and record data similar to the benthic REA methods (Winston et al., 2020). This is done by drawing a line over the maximum diameter of a colony and recording demographic data by hand. These demographics include identifying taxa code, determining old and recent dead, reasons for recent dead, and conditions following standard benthic survey protocol (Winston et al., 2020).

1. Drop down Edit and click Create Features to start editing the year_site# layer (the GDB file you just dropped into your table of contents).
2. In the table of contents, right click on the scaled orthomosaic, year_site#_mos.tif, and select Zoom to Layer.
3. In the Create Features pane, click on your site template and make sure the construction tool at the bottom of the pane is Line.
4. Making your best approximation of the maximum diameter, click on one edge of a colony and double click on the other edge to add a colony to the attribute table.

5. Continue this until all colonies within the desired segments are identified (Figure 6.8).
    - Ensure that all lines are drawn on the scaled orthomosaic.
    - Remember the 50% rule: Only colonies with 50% or more area inside the plot should be counted. If you are unsure, draw the line and click the 'Move' tool under the 'Edit' tab (Figure 6.1). Click on the annotation to see if the center point of the annotation is within the plot.
    - Start several meters above the substrate before zooming into an area of interest to ensure that you are correctly assessing boundaries of large colonies. See the benthic SOP for more details.
    - Use image view or the draping features in Viscore or Agisoft to ensure you are not missing fragmented or light colored colonies.
    - Make it a habit to save your edits often (save button in the edit tab) so that no work is lost.

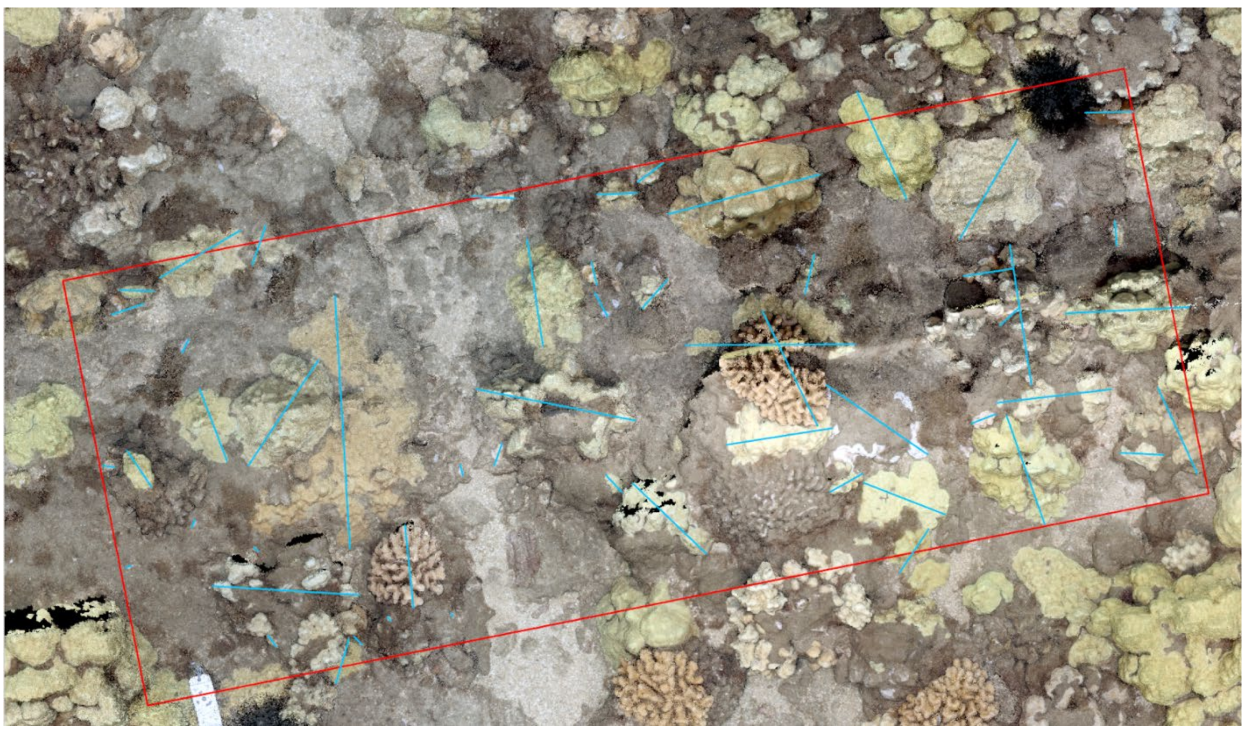


Figure 6.8 Screenshot in ArcGIS Pro of maximum diameter lines drawn on all the colonies in the segment.

6. Once all colonies are identified throughout the desired segment, save your edits and 'Explore' in the Map tab.
7. Right click on your year_site# layer and click Attribute Table.
    - For ANALYST, OBS_YEAR, MISSION_ID, SITE, SEGLENGTH, and SEGWIDTH use the following steps to easily complete the columns:
    - Right click the column name in the attribute table.
    - Select 'Field Calculator…'
    - Enter the value you would like repeated throughout the column (if text, use quotations) – OK (Figure 6.9).

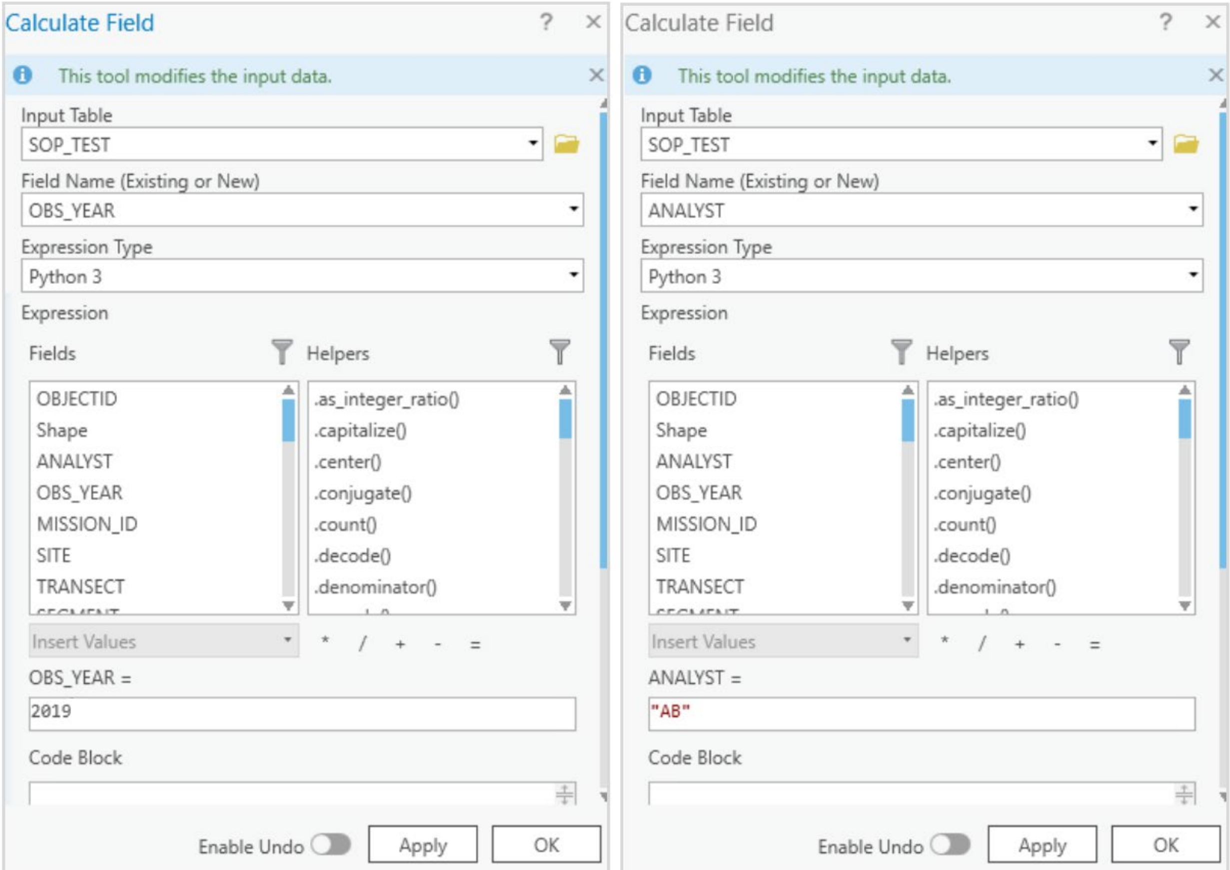


Figure 6.9 Screenshots in ArcGIS Pro of how to properly use the Calculate Field function. To the left shows the proper settings for a numerical field, the right shows the proper settings for a text field.

8. Once the above columns are filled, resume editing.
9. Following the guide and definitions below (Table 6.1), fill out the attribute table. Double click the gray square in front of OBJECTID to highlight the specific colony you are analyzing.
10. Continue completing the attribute table while relying on the underlying imagery to identify mortality and condition.
11. Once all colonies are identified and analyzed (Figure 6.10), end the editing session and save your edits.

Table 6.1 Definitions for each annotation column in Arc attribute table.

Name	Definition
OBJECTID	Arc will automatically assign this number
SHAPE	Arc will automatically fill
ANALYST	Type: Text = your initials (e.g., MA)

Name	Definition
OBS_YEAR	Type: Short Integer = the year (e.g., 2019)
MISSION_ID	Type: Text = the mission name (e.g., SE1902)
SITE	the site name (e.g. KAH-608)
TRANSECT	Type: Text = drop down of A or B (A meaning First, B meaning Repeat)
SEGMENT	Type: Short Integer = drop down menu of 0, 5, 10, 15
SEGLENGTH	Type: Short Integer = length of segment in meters (e.g., 2.5)
SEGWIDTH	Type: Short Integer = width of segment in meters (e.g., 1)
NO_COLONY	Type: Short Integer = drop down of 0 or -1 (-1 meaning yes, 0 meaning no)
SPCODE	Type: Text = drop down of taxon code based on taxon list (e.g., PLOB)
JUVENILE	Type: Short Integer = drop down of 0 or -1 (-1 meaning yes, 0 meaning no)
REMNANT	Type: Short Integer = drop down of 0 or -1 (-1 meaning yes, 0 meaning no)
FRAGMENT	Type: Short Integer = drop down of 0 or -1 (-1 meaning yes, 0 meaning no)
MORPH_CODE	Type: Text = drop down of colony morphology code (e.g., MD)
EX_BOUND	Type: Short Integer = drop down of 0 or -1 (-1 meaning yes, 0 meaning no)
OLDDEAD	Type: Short Integer = percent of old dead (e.g., 15) If no old dead, leave blank
RDCAUSE1	Type: Text = drop down of specific recent dead cause code (e.g., TLS)
RD_1	Type: Short Integer = percent of RDCAUSE1 dead (e.g., 2) If no recent dead, leave blank
RDCAUSE2	Type: Text = dropdown of specific recent dead cause code
RD_2	Short Integer = percent of RDCAUSE2 dead
RDCAUSE3	Type: Text = drop down of specific recent dead cause code
RD_3	Type: Short Integer = percent of RDCAUSE3 dead
CON_1	Type: Text = drop down of specific coral health condition code (e.g., BLE) If no condition, leave blank
EXTENT_1	Type: Short Integer = percent of colony affected by CON_1 (e.g., 90)
SEV_1	Type: Short Integer = severity ranking for CON_1 if BLE (e.g., 5)

Name	Definition
CON_2	Type: Short Integer = severity ranking for CON_2 if BLE
EXTENT_2	Type: Short Integer = percent of colony affected by CON_2
SEV_2	Type: Short Integer = severity ranking for CON_2 if BLE
CON_3	Type: Text = drop down of specific coral health condition code
EXTENT_3	Type: Short Integer = percent of colony affected by CON_3
SEV_3	Type: Short Integer = severity ranking for CON_3 if BLE
SHAPE_Length	Type: Double Integer = length of max. Diameter

	OBJECTID *	Shape *	ANALYST	OBS_YEAR	MISSION_ID	SITE	TRANSECT	SEGMENT	SEGLENGTH	SEGWIDTH	NO_COLONY	SPCODE	EX_BOUND	JUVENILE	FRAGMENT	REMNANT	OLDDEAD	MORPH_CODE
1	1	Polyline	CA	2019	SE1902	MAI-2502	A	0	2.5	1	<Null>	PLOB	<Null>	<Null>	<Null>	<Null>	10	MD
2	2	Polyline	CA	2019	SE1902	MAI-2502	A	0	2.5	1	<Null>	PLOB	<Null>	<Null>	<Null>	<Null>	3	EM
3	3	Polyline	CA	2019	SE1902	MAI-2502	A	0	1	1	<Null>	MOSP	<Null>	-1	<Null>	<Null>	<Null>	EM
4	4	Polyline	CA	2019	SE1902	MAI-2502	A	0	2.5	1	<Null>	PLOB	<Null>	<Null>	<Null>	<Null>	10	MD
5	5	Polyline	CA	2019	SE1902	MAI-2502	A	0	2.5	1	<Null>	PMEA	<Null>	<Null>	<Null>	<Null>	0	BR
6	6	Polyline	CA	2019	SE1902	MAI-2502	A	0	1	1	<Null>	MPAT	<Null>	-1	<Null>	<Null>	<Null>	EM
7	7	Polyline	CA	2019	SE1902	MAI-2502	A	0	2.5	1	<Null>	MPAT	<Null>	<Null>	<Null>	<Null>	25	EM
8	8	Polyline	CA	2019	SE1902	MAI-2502	A	0	2.5	1	<Null>	PCOM	<Null>	<Null>	<Null>	<Null>	75	KN
9	9	Polyline	CA	2019	SE1902	MAI-2502	A	0	2.5	1	<Null>	PLOB	<Null>	<Null>	<Null>	<Null>	80	MD
10	10	Polyline	CA	2019	SE1902	MAI-2502	A	0	1	1	<Null>	MCAP	<Null>	-1	<Null>	<Null>	<Null>	EM
11	11	Polyline	CA	2019	SE1902	MAI-2502	A	0	1	1	<Null>	MPAT	<Null>	-1	<Null>	<Null>	0	EM
12	12	Polyline	CA	2019	SE1902	MAI-2502	A	0	1	1	<Null>	PLOB	<Null>	-1	<Null>	<Null>	<Null>	EM

Figure 6.10 Screenshot in ArcGIS Pro once all colonies in the segment are analyzed.

6.1.5 Extracting data

By using a geodatabase, we are able to export the whole database once all sites in a given location are annotated. This mirrors our current method, which organizes benthic demographic data by region. Each site's attribute table can be exported individually, although the following method assumes all sites within a region are annotated and all corresponding demographic data are in the geodatabase.

1. Open a blank ArcGIS Pro project and open a new basemap.
2. Navigate to your geodatabase in the Catalog tab on the right side and click the drop down to see all files in the geodatabase (Figure 6.11).

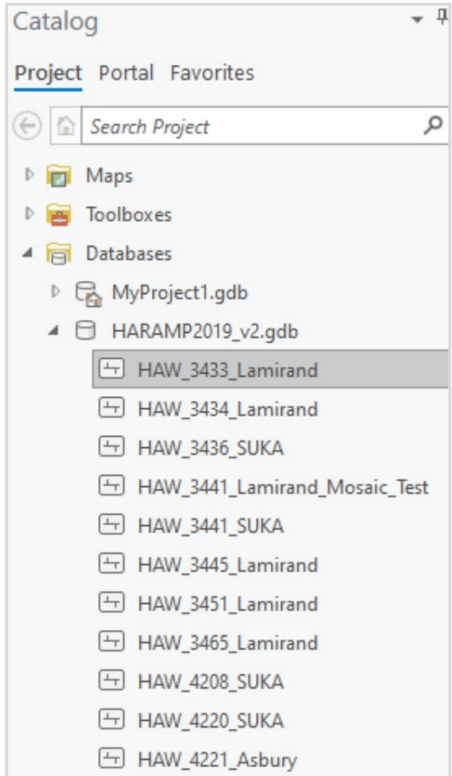


Figure 6.11 Screenshot of the Catalog window in ArcGIS Pro, showing a geodatabase with the different site annotations shown as shapefiles.

3. Under the 'Analysis' tab, click on 'Tools' and search for the 'Merge' (Data Management) Tool.
    - Input Datasets: Click on 'Browse…' and use Shift + click to highlight all of your site files in the geodatabase and click add files
    - Output Dataset: navigate to desired saving location.
        - Name: missionID_demographics
        - Save as type: Feature classes
4. Leave everything as shown in 'Field Map' (optional).
5. Once complete, a new shapefile with all the data will be in your Table of Contents.
6. Right click on missionID_demographics in the Table of Contents and click Data -- Export Table.
7. A window named 'Export Table' will pop up
    - Input Rows: missionID_demographics
    - Output location: navigate to desired saving location
    - Output Name: missionID_demographics.txt **(make sure to type out .txt)**
8. Navigate to where you saved your export and make sure it is there.
9. Once finished, close ArcGIS Pro (there is no need to save your document).

Glossary

ArcGIS: Software used to scale the orthomosaic, draw segment boundaries, and extract coral reef demographic data.

Attribute Table: A tabular file containing information about a set of geographic features, usually arranged so that each row represents a feature and each column represents one feature attribute.

Classification: Determining and assigning the lowest taxonomic level, either species or genus, to a segment.

Dense Point Cloud (DPC): Detailed 3D set of overlapping data points arranged in space according to position and orientation of each image.

Digital Elevation Model (DEM): A 2.5D orthographic projection of the scaled DPC with each pixel representing depth (i.e., height of reef surface structures from top-view). Used as the base projection for creating a geometrically accurate orthomosaic.

Geodatabase: A database used primarily to store, query, and manipulate spatial data. Geodatabases store geometry, a spatial reference system, attributes, and behavioral rules for data. A geodatabase allows multiple users to input spatial data into a single database to allow for easier data collation.

Grid: A grid template exported from Viscore that provides an accurate scale reference for each individual orthoprojection. This grid is used to scale the orthoprojection in ArcGIS Pro.

Model: Within the context of this document, the word "model" is used to indicate the products resulting from processing individual photos into 3D points or a 2D mosaic image.

Orthomosaic: A scaled 2D projection of an image mosaic with ground coordinates determined by an orthorectified DEM. Used for analysis and data extraction.

Orthoprojection: An internal use of the word referring to 2D screenshot of dense point cloud that was scaled and oriented using Viscore (see Suka et al., 2019). Used for data visualization.

Orthorectify: Displays a spatially accurate map representation of the substrate by creating a planimetric image at every location with consistent scale across all parts of the model.

Photogrammetry: A form of technology that allows users to extract 3D information from 2D images taken from stereo or single cameras.

Raster: A matrix of cells (pixels) arranged in rows and columns. In ArcGIS, rasters can be images (.jpg or .tiff) or outputs from models (grid files). Each cell contains information such as RGB color.

Rectification: The process of defining a plane to match that of a top-view map using in-situ collected depth measures over markers captured in the imagery.

Rugosity: The surface roughness (complexity) or variance in height of seafloor.

Scaling: Process that corrects measurement and size of model.

Segmentation: Defining and drawing an outline (polygon) around a colony; also referred to as delineation.

Shapefile: A line, point, or polygon feature. Each feature contains information (the attribute table) that can be edited and populated, such as max diameter, species code, and percent old dead.

Sparse Point Cloud: 3D set of overlapping data points aligned by feature matching and the position and orientation of each image.

Targets: Reference patterns placed on a scale bar with a known distance between target center points. In the field, the markers and scale bars provide a calibrated indication of distance for metric data extraction.

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Appendix A. How to Build SfM Scale Bars

ESD has tried several versions of scale bars and found the model listed below (Figure A 1) to be the most practical for the higher energy wave environments that we often survey.

Figure A 1. Example of a scale bar used by ESD.

Materials (amount for one marker; Figure A 2)

1. (35 cm) 316 stainless steel bar 3/16" thick, 2" wide.
2. (1) 2" × 12.5" × 1/8" thick polycarbonate, reverse-printed with targets 0.25m apart. Polycarbonate is preferable over acrylic Plexiglas because it doesn't chip or crack as easily.
3. (1) 10-24NC tap and handle (handle not pictured, have backup taps)
4. (4) 11/16" drill bit, rated to cut steel (4 in case they dull or break)
5. (8) 10-24 × 3/8" stainless steel machine screws, flat Phillips head.
6. (1) Jig: Starboard plastic sheet or similar, cut to 12.5", holes drilled 1cm from corners and center (no photo)
7. (1) Extra-large sliding bolt snap.

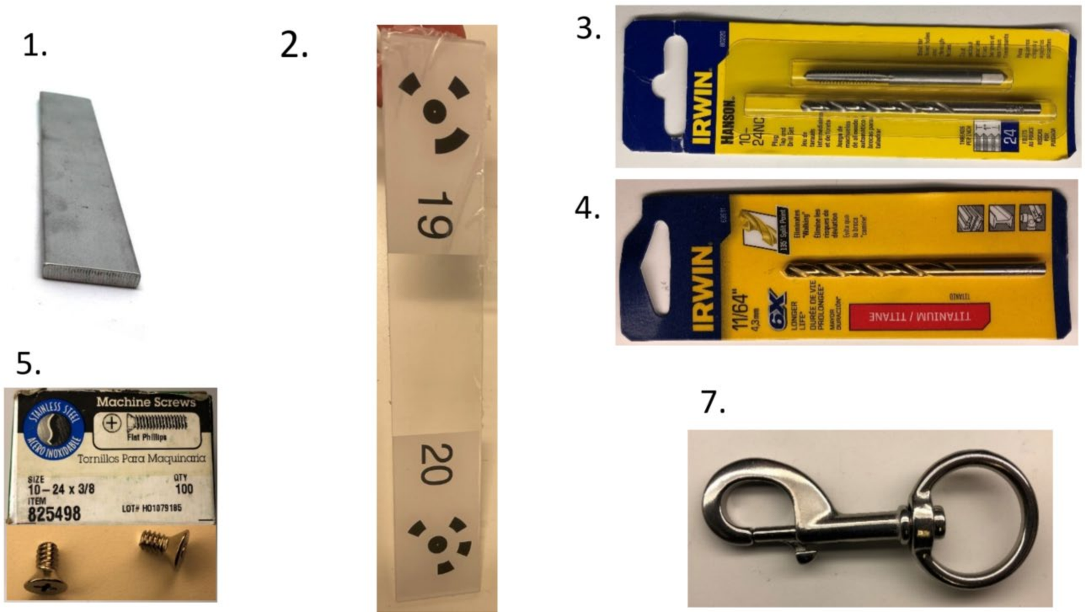
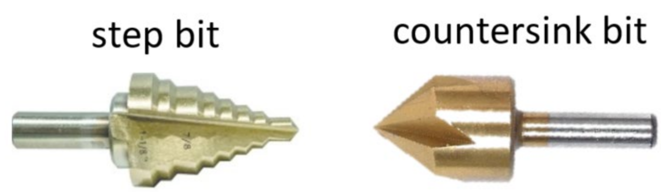


Figure A 2 Tools and materials used for building scale bars.

Tools

- Band saw (for cutting steel bar)
- Grinder and wire wheel
- Drill press
- Drill bit 3/8” or similar
- Countersink bit
- Cutting oil
- Hand drill with step bit
- Phillips head screwdriver
- Blue tape
- Clamps
- Ruler (cm)



<u>Process</u>

Prepare the steel bar

1. Cut the stainless steel bar to 35 cm lengths using the band saw. Light pressure and cutting oil are optional. Cut corners of bar off at one end if you like (use your discretion to create a rounded edge).
2. Use the grinder then the wire wheel to smooth all edges.
3. With the drill press and cutting oil, drill a 3/8” (or similar) hole centered 1 cm from the rounded edge of the steel bar. Then use the step bit in the hand drill to bevel the edges of the hole (slow speed, no oil).

Drill polycarbonate

4. Using the jig, drill six holes in each polycarbonate tile. Holes should be 1 cm from the corners and 1 cm from the edge in the middle of the tile for a total of 6 holes.

5. Tape each tile to a steel bar in the desired location. Use enough blue tape to secure the tile.

Drill steel

6. Place a polycarbonate tile on top of a bar and clamp in place. You will be lining up the 11/64” drill bit with the existing holes in the polycarbonate. Drill. Use cutting oil and slow speed. If the bit makes a lot of noise, it is dull and needs to be replaced.
7. Line everything up again and drill the next hole. Placing an unused 11/16” bit in the hole you just drilled helps maintain the alignment. Repeat for all six holes.
8. With the countersink bit, drill holes in the polycarbonate for screw heads so they can fit flush. It is worth practicing on a scrap of Plexiglas until you get the hang of it.
9. Use the tap to tap threads into the steel bar. You are using a larger drill bit than the taps because stainless is tough to work with and it will be very difficult to tap holes created with the “correct” size bit.
10. Wash the oil off of everything, remove the blue tape, and screw the Plexiglas to the bar with the targets still attached.
11. Attach the bolt snap to the bar with the line. Burn ends of line to keep them from fraying.

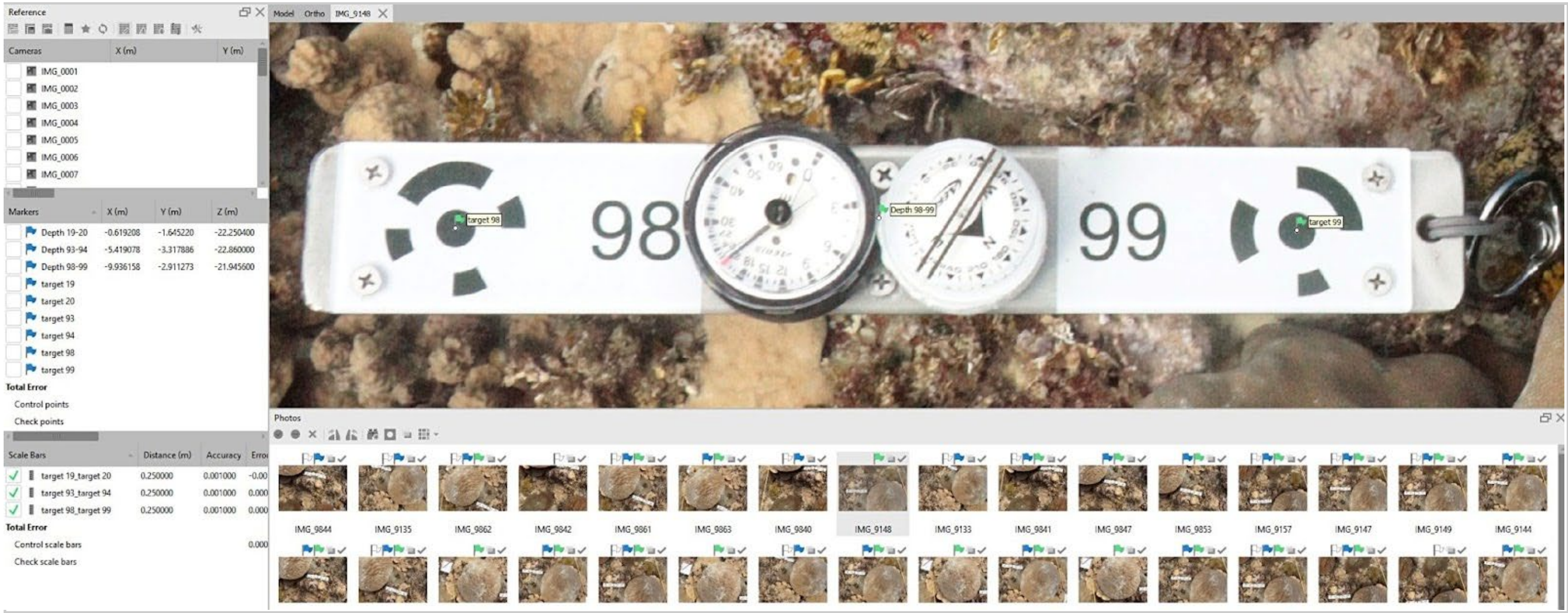


Figure A 3 Example of a scale bar with a compass and depth gauge in an image in Agisoft Metashape.

Note: For added ground reference metadata, ESD optionally adds simple and lightweight compass and depth gauge instruments to the scale bars. The compass is mounted over an inch thick plastic to minimize magnetic interference from the stainless steel bar and both instruments are attached to the scale bar with a piece of Velcro and a cable tie to keep them in place ([Figure 1.1](#)). The depth gauge can assist with data entry errors or fill data gaps for SfM model rectification. In combination with the site's GPS point collected above water, the compass angle. and the distance between markers—extracted from the scaled DPC—provide insights for approximating the geographic coordinates and true north orientation of SfM models through triangulation. While not currently implemented as part of our program, efforts are in place to document the ground truth geographic location of SfM-derived image maps.

Appendix B. SfM Imagery and Process Tracking

Good data management is a crucial component of this pipeline. With imagery and data transferred multiple times between servers and software programs, there are many opportunities for errors. A tracking spreadsheet or database is a crucial part of the workflow and allows us to track the status of the site data from image collection to model generation to demographic data extraction. Below is an example of how ESD tracks SfM processing. More columns can be added based on processing and data extraction needs. Contact a corresponding author for a more recent copy of ESD's tracking database.

A.

												Markers Metadata																	
Survey Date	Cruise Leg	Diver	Team	Region	Island	Cam #	Site	Survey Size	Lat (N)	Long (E)	Survey Type	0m Marker	0m Depth (ft)	5m Marker	5m Depth (ft)	10m Marker	10m Depth (ft)	15m Marker	15m Depth (ft)	File Path	Images Sorted	Total images shot	Total images size (GB)	QC images & field data	Notes	Exposure Correct	Mosaic Rugosity Level
3/30/2023	3	MSL	Benthic	AS	SWA	14	SWA-983	3x20m	-11.05968	-171.0906	belt	13,14	40	19,20	41	40,41	34	89,90	38	N:\StRS_S	MSL	1681	18.4	MSL		—	low
3/30/2023	3	NBO	Benthic	AS	SWA	14	SWA-961	3x20m	-11.05094	-171.0917	belt	19,20	17	89,90	18	13,14	19	40,41	18	N:\StRS_S	MSL	2077	22	MSL		—	high
3/30/2023	3	DTP	Benthic	AS	SWA	11	SWA-986	3x20m	-11.06827	-171.0787	belt	44,45	53	83,84	50	23,24	55	29,30	51	N:\StRS_S	MSL	2338	27.6	MSL	Swim path	—	high
3/30/2023	3	CA	Benthic	AS	SWA	11	SWA-975	3x20m	-11.06195	-171.0677	belt	23,24	28	44,45	30	29,30	30	83,84	30	N:\StRS_S	MSL	1571	19.1	MSL	Extra photc	—	med
3/30/2023	3	IGB	Benthic	AS	SWA	11	SWA-949	3x20m	-11.06732	-171.0766	belt	29,30	18	84,85	18	23,24	16	83,84	16	N:\StRS_S	MSL	560	6.89	MSL		—	low
3/31/2023	3	JC	Benthic	AS	SWA	13	SWA-978	3x15m	-11.06314	-171.0704	belt	40,41	59	19,20	60	13,14	65			N:\StRS_S	MSL	1808	22.2	MSL		—	low
3/31/2023	3	MA	Benthic	AS	SWA	13	SWA-982	3x20m	-11.05496	-171.0637	belt	19,20	41	89,90	40	13,14	44	40,41	41	N:\StRS_S	MSL	1715	18.1	MSL		—	med
3/31/2023	3	CSC	Benthic	AS	SWA	13	SWA-952	3x20m	-11.04924	-171.0672	belt	89,90	21	19,20	16	13,14	17	40,41	17	N:\StRS_S	MSL	1801	21.5	MSL		—	med
3/31/2023	3	JDG	Benthic	AS	SWA	11	SWA-995	3x15m	-11.05769	-171.0914	belt	23,24	58	29,30	61	44,45	59			N:\StRS_S	MSL	3473	40.5	MSL		—	high
3/31/2023	3	BH	Benthic	AS	SWA	11	SWA-968	3x20m	-11.06247	-171.088	belt	44,45	33	83,84	36	29,30	34	23,24	36	N:\StRS_S	MSL	3103	34.6	MSL		—	high

B.

Agisoft														Viscore						ArcGIS								
Processing Priority	# of photos	Computer used	# models running	Proc. Notes	Align Photos	DPC (med)	Export DPC & Cams	DPC QC	DEM	Ortho-mosaic	Export orthos	Total data size Agisoft (GB)	Model Notes	Convert to vml	Link Images	Scale	Rectify	Add to Viscore lite	Notes	Assigned to:	What to Annotate	Rescale & Draw segments	Size Colonies	ID & % Mortality	Recent Dead & Condition	Juveniles	Total ArcGIS Time	Notes
1	1675	Bluefin	4	complete	4:57	6:12	JC	IB	FL	FL	FL	16.9		CA	CA	CA	CA											

Figure B 1 Example of the centralized metadata file that is populated immediately after data collection to keep track of the imagery (A), and that is updated with every data product creation steps from SfM model build in Agisoft Metashape to coral demographic image annotations in ArcGIS Pro (B).

Appendix C. Creating a Geodatabase

All processes were applied in ESRI's ArcGIS Pro 2.8.0 or later. The described processes can be standardized by creating a customized ArcGIS toolbox using Model Builder.

1. Create File Geodatabase using Create File GDB (Data Management) tool.
   - File GDB Location: path to a folder where the geodatabase is stored.
   - File GDB Name: name of geodatabase.
   - File GDB Version: CURRENT.

2. Create a table in Excel that will be converted to your domains in the GDB. This step will create the attribute domains you will have in the geodatabase. Attribute domains are rules in a geodatabase used to constrain the values allowed in any particular attribute for a table or feature class within, which will let the analyst utilize a standard dropdown menu. We use short codes that make conversion into our data cloud easier, although these can be full names according to what you are surveying (Figure C 1). Name this table according to the geodatabase you are creating (we name according to location and year for better organization e.g., HARAMP2019_codes; Figure C 2).

SEGMENT	SEG_CODE	TRANSECT	TRANS_CO	SPCODE_N	SPCODE	MORPH	MORPH_C	JUVENILE	JUV_CODE
0	0	First	A	Unknown	UNKN	Encrusting	EF	Yes	-1
5	5	Repeat	B	Acropora c	ACYT	Encrusting	EM	No	0
10	10			Acropora p	APAN	Encrusting	EC		
15	15			Acropora g	AGEM	Mounding	MD		
				Acropora l	AHUM	Plating	PL		
				Acropora s	ACSP	Bifacial Pl	BP		
				Coscinarae	CWEL	Foliose	FO		
				Cyphastre	CYSP	Laminar	LM		
				Cyphastre	CAGA	Laminar-c	LC		
				Cyphastre	COCE	Branching	BR		
				Cycloseris	CVAU	Knobby	KN		
				Diaseris sp	DIAS	Columnar	CO		
				Fungia scu	FSCU	Table	TB		
				Fungia sp	FUSP	Mounding	ML		
				Gardinero	GPLA	Disc (free	FR		
				Leptastrea	LBEW				
				Leptastrea	LPRU				
				Leptastrea	LPUR				
				Leptastrea	LTRA				
				Leptoseris	LINC				
				Leptoseris	LESP				
				Montipora	MCAP				
				Montipora	MFLA				

Figure C 1 Screenshot of the attribute domains table for the Hawaiian Archipelago. Note: only a subset of the codes are shown here.

1. Convert your Excel document to a CSV file
2. Create attribute domains in the geodatabase using the Table to Domain (Data Management) tool
3. Input Table: table containing coded field values and description field values
    - Code Field: field in the input table containing coded values (e.g., SPCODE)
    - Description Field: same field as above (SPCODE)
        - Can add a column that contains the description for the individual codes, although we do not use this (Figure C 1)
    - Input Workspace: the path to geodatabase created in step 1.
    - Domain Name: name of domain
4. Repeat the Table to Domain tool for all attribute domains you want in your column.
5. The following list domains are what we add to our geodatabase (definitions for each found previously in Table 6.1): condition (CON),

exceeds boundary (EX_BOUND), fragments (FRAGMENT), morphology (MORPH_CODE), no colony observed (NO_COLONY_OBSERVED), recent dead cause (RDCAUSE), segment (SEGMENT), species (SPCODE), juvenile (JUVENILE), remnant (REMNANT), transect (TRANSECT)

6. Once all list domains are added, create a template polyline feature class in geodatabase using the 'Create Feature Class' (Data Management) tool.
   - Feature Class Location: path to geodatabase created in step 1.
   - Feature Class Name: template
   - Geometry type: Polyline
   - Template Feature Class (optional): Leave blank
   - Has M (optional): DISABLED
   - Has Z (optional): DISABLED
   - Coordinate System (optional): WGS1984 UTM Zone 4N
7. Your template feature class will automatically be dropped into your Table of Contents.
8. Add appropriate fields to the template polyline feature class and apply domain if applicable (these will be your drop down menus) using 'Add Field' (Data Management) tool (Figure C 2).
   - Input Table: template
   - Field Name/Field Type/Domain: see Table C1
   - In this tool, when wanting to create your fields with the drop down menus (the attribute domains you developed earlier using excel), type the exact name of your 'Code Field' in the domain box.

Table C 1. Example of Field and Domain set up for attribute table with drop down menus.

Field Name	Field Type	Length	Domain
ANALYST	TEXT	50	
OBS_YEAR	SHORT		
MISSION_ID	TEXT	255	
SITE	TEXT	50	
TRANSECT	TEXT	50	TRANS_CODE
SEGMENT	SHORT		SEGMENT
SEGLENGTH	FLOAT		

Field Name	Field Type	Length	Domain
SEGWIDTH	FLOAT		
NO_COLONY	SHORT		NO_COLONY_ OBSERVED
SPCODE	TEXT	50	SPCODE
EX_BOUND	SHORT		EX_BOUND_CODE
FRAGMENT	SHORT		FRAGMENT
JUVENILE	SHORT		JUV_CODE
REMNANT	SHORT		REMN_CODE
OLD DEAD	SHORT		
MORPH_CODE	TEXT	50	MORPH_CODE
RDCAUSE1	TEXT	50	RDCAUSE
RD_1	SHORT		
RDCAUSE2	TEXT	50	RDCAUSE
RD_2	SHORT		
RDCAUSE3	TEXT	50	RDCAUSE
RD_3	SHORT		
CON_1	TEXT	50	CON
EXTENT_1	SHORT		
SEV_1	SHORT		
CON_2	TEXT	50	CON
EXTENT_2	SHORT		
SEV_1	SHORT		
CON_3	TEXT	50	CON
EXTENT_3	SHORT		
SEV_3	SHORT		

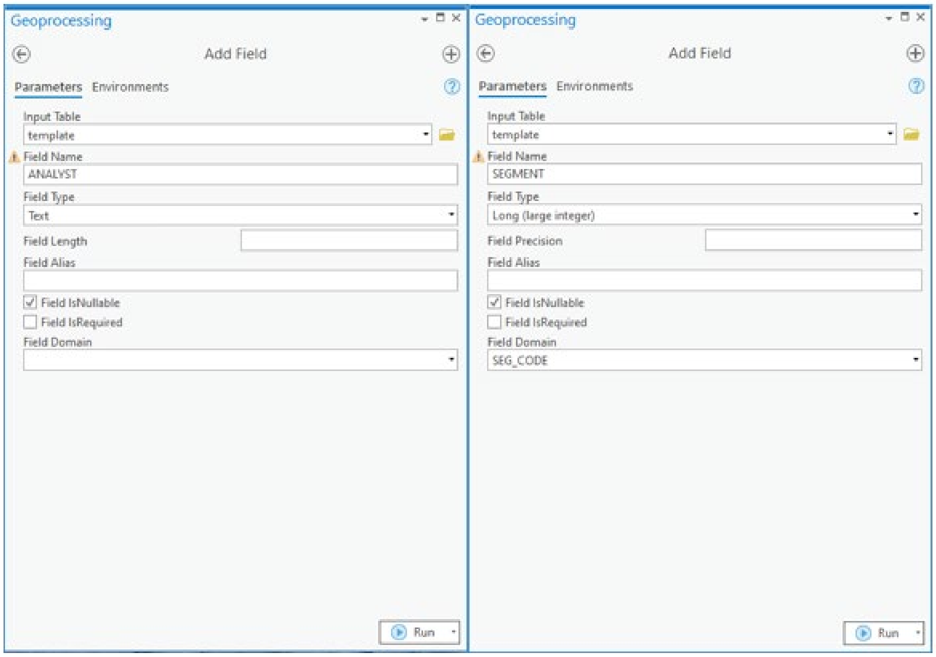


Figure C 2 Screenshots of the Add Field tool in ArcGIS Pro.