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U.S. DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
National Marine Fisheries Service
Pacific Islands Fisheries Science Center

NOAA Technical Memorandum NMFS-PIFSC-93
https://doi.org/10.25923/h2q8-jv47

December 2019

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Rhonda Suka[1,2], Mollie Asbury[1,2], Courtney Couch[1,2], Andrew Gray[1,2], Morgan Winston[1,2], and Thomas Oliver[2]

[1] Joint Institute for Marine and Atmospheric Research
University of Hawaii
1000 Pope Road
Honolulu, Hawaii 96822

[2] Pacific Islands Fisheries Science Center
National Marine Fisheries Service
1845 Wasp Boulevard
Honolulu, HI 96818

NOAA Technical Memorandum NMFS-PIFSC-93

December 2019

U.S. Department of Commerce
Wilbur L. Ross, Jr., Secretary

National Oceanic and Atmospheric Administration
Neil A. Jacobs, Ph.D., Acting NOAA Administrator

National Marine Fisheries Service
Chris Oliver, Assistant Administrator for Fisheries

Recommended citation

Suka R, Asbury M, Couch C, Gray A, Winston M, Oliver T. 2019. Processing Photomosaic Imagery of Coral Reefs Using Structure-from-Motion Standard Operating Procedures. U.S. Dept. of Commerce, NOAA Technical Memorandum NOAA-TM-NMFS-PIFSC-93, 54 p. doi:10.25923/h2q8-jv47

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Science Operations Division
Pacific Islands Fisheries Science Center
National Marine Fisheries Service
National Oceanic and Atmospheric Administration
1845 Wasp Boulevard, Building #176
Honolulu, Hawaii 96818

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Corresponding authors

Courtney Couch (courtney.s.couch@noaa.gov)
Rhonda Suka (rhonda.suka@noaa.gov)

Cover image: Courtney Couch, NOAA Fisheries.

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Abstract

This document provides detailed procedures for collecting and processing imagery using Structure-from-Motion techniques developed by Ecosystem Sciences Division (ESD) in collaboration with Scripps Institution of Oceanography and the University of Hawaii at Hilo. These procedures are designed to efficiently generate coral demographic and benthic community metrics across the broad spatial scale of the Pacific Rapid Assessment and Monitoring Program. This pipeline consists of four key steps: (1) Image collection by SCUBA divers, (2) Data management, post-processing, and QC, (3) Generating 3-D models and 2-D orthophotos in Agisoft Metashape, and (4) Extracting demographic data in ArcMap. This SOP is the result of comprehensive testing of different camera systems, collection techniques, and software. While the following procedures are designed to meet ESD needs, we primarily use commercially available cameras and software, making these methods adaptable based on programmatic capacity and needs.

1. Introduction

Despite covering less than 0.1% of Earth's surface, coral reefs are among the most biologically diverse ecosystems on the planet. They provide hundreds of billions of dollars in ecosystem services through fisheries, coastal protection, building materials, new biochemical compounds, and tourism. Rising sea surface temperature from global climate change has resulted in more frequent and severe coral bleaching events, which have caused extensive mortality and are projected to become more severe in the future. In addition to global threats, coral reefs are also facing a myriad of local threats, such as overfishing, land-based pollution, crown of thorns outbreaks, and overuse from tourism.

In the face of accelerating changes to coral reef ecosystems, 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 Reef Assessment and Monitoring Program. 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 has used in situ visual assessments of coral communities and benthic photoquadrat imagery to generate coral demographic metrics (colony density, size structure, partial mortality and prevalence of disease and compromised health states), and percent cover of benthic taxa. ESD employs a habitat/depth-stratified random sampling design to spatially characterize reefs, which typically results in hundreds of sites surveyed each year from NOAA research vessels.

In situ 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, and increases the geographic scope. While ESD's coral reef team has collected small area photoquadrats (i.e., 0.8 m^2) of the benthos since 2002, the small size of the area imaged limits the applications of this imagery. As a novel alternative, our program has partnered with Dr. Stuart Sandin (Scripps Institution of Oceanography) and Dr. John Burns (University of Hawaii at Hilo) to extract benthic metrics from large-area mosaics (60–120 m^2) using structure-from-motion (SfM). SfM is a form of photogrammetry that generates 3-D models and 2-D mosaics of a given area by aligning 100s to 1,000s of still images from DSLR or point and shoot cameras. This technique is more cost effective and easier to conduct than alternative 3-D technologies such as LIDAR. Consequently, it has been widely applied across a variety of fields and more recently has gained utility in coral reef assessment. The 3-D and 2-D products generated through this technique provide powerful means of characterizing coral demography, benthic community structure, and habitat structure. It also allows us to freeze the reef in time and compare it against future change.

In this standard operating procedures document, we outline a novel SfM pipeline that leverages tested field collection techniques and commercial software. This pipeline consists of four key steps: (1) Image Collection, (2) Data Management and QC, (3) Generating 3-D models and 2-D orthophotos in Agisoft Metashape, and (4) Extracting demographic data in ArcMap.

This SOP is the result of comprehensive testing of different camera systems, collection techniques, and software. While there are a variety of approaches that are currently being used by field practitioners, the following techniques allow us to efficiently collect and process imagery at the scale of our monitoring program. It is our hope that the pipeline 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 3-D model generation and extraction of benthic data from imagery.

To use this SOP, you will need the following software:

- Adobe Lightroom (depending on the camera used)
- Agisoft Metashape (formerly Photoscan)
- ArcMap (version 10.6.1 or higher)

2. Methods

2.1 Data Collection

To collect SfM imagery that aligns properly to generate a 3-D model, a series of overlapping images with 60% of side overlap + 80% of forward overlap is required. Maintaining appropriate overlap will greatly increase the quality and density of the model and reduce the amount of distortion and warping in the resulting orthophoto. Imaging a coral reef to later extract coral demographic and benthic percent cover data requires including large coral colonies, as well as small recruiting colonies. Consideration also 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 surveys of different sizes. Through this exercise, we determined that the optimal survey shape is a rectangle of 20 m × 3 m. This survey 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 selection also allows us to replicate the same area that has been visually surveyed historically by ESD.

The camera distance from the substrate plays an important role in image quality and taxonomic identification. Images taken closer to the substrate are sharper, but have a smaller footprint and thus require slower swim speeds and more images to achieve necessary overlap. Conversely, images taken farther from the substrate have a larger footprint allowing faster swim speeds, but lower definition in each image. A number of trials were conducted to evaluate the optimal focal distance needed to achieve sharp, detailed imagery without overly affecting the time required for image collection. Maintaining a 1-m distance from the substrate with an 18-mm camera lens captures a footprint of the substrate of 1.03 m × 0.69 m and provides highly detailed images.

Required Training

If you are conducting these surveys, it is assumed that you have received the in-classroom and in-water training.

Equipment Needed

- Canon SL2 with housing
- Dive slate
- SfM datasheet
- Grey card
- Markers (4)

A. Canon SL2 Setup and Use

Although SfM techniques can be conducted using almost any camera, collecting imagery underwater requires special equipment. The cost and available technical support for a camera system are important considerations. ESD tested a number of underwater camera systems (Cannon G9x, GoPro5, Nikon D90, Sony A6300, and the Canon SL2). The combination of high image quality, superior white-balancing, small housing size, ease of underwater use, continuous shooting, and affordability made the Canon SL2 our camera of choice.[1] Through a series of underwater tests, we determined the camera settings that would produce the highest quality images over a broad range of operating conditions (e.g., overcast vs. bright sun, clear shallow water vs. deeper murky water, etc.). This allows the photographer to focus on swimming the plot instead of adjusting camera settings, makes image quality more consistent, and saves time underwater. These settings are displayed on the camera screen (Figure 1) to ensure accuracy before getting in the water. A copy of the settings display information is attached to the gray card for a quick and easy check while on the boat.

Figure 1. Canon SL2 LCD monitor displaying correct settings for SfM image collection.

Camera Settings Used for SfM Surveys

Image quality = L (not RAW)
Drive mode = Continuous
Image Auto Rotate = Off
Date and Time = UTC
White Balance = Custom
Autofocus = AI Servo
Live View = Off
Shutter Speed = 1/320
Aperture = F8
Shooting mode = Manual (M)
Exposure Compensation = -1/3
ISO = Auto (max 3200)
File numbering = Auto reset

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. This is ample memory to collect imagery from 4 sites (~1,400–2,000 per site). The number of images collected per site varies depending on swim speed, habitat complexity, and presence of very large colonies that require extra imaging. We have found that shooting in continuous mode all day long appears

[1] The Canon SL2 user’s manual is available at http://gdlp01.c-wss.com/gds/5/0300027455/01/eos-rebelsl2-200d-im-en.pdf.

to tax the Canon SL2. During extended field operations, we experienced error codes when white balancing in situ, which was alleviated by formatting the SD card each morning. We have also experienced a lag in the auto ISO adjustment that creates a series of dark images as the camera adjusts the ISO speed. To alleviate this problem, we stop the continuous shutter by lifting the trigger finger for a moment every 10 to 15 clicks. Higher end cameras may not have these issues.

Camera Set-up Steps

To locate the Cam, Settings, and Display menus, press the MENU button on the camera (Figure 2).

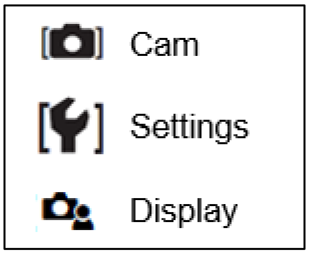


Figure 2. Canon SL2 menus.

1. If working with a new camera, ensure that the focal length has been set to 18 mm and secured with tape.
2. Turn the mode dial on the top of the camera to select the manual (M) shooting mode (Figure 3).
3. Reset camera settings: Settings [4] → 'Clear settings' = 'Clear all…'
4. Configure display:
   Display → 'Shooting screen' & 'Menu Display' = Standard; Display → 'Mode guide' & 'Feature guide' = Disable
5. Format card (**DELETES ALL DATA!**): Settings [1] → Format Card = OK
6. Select image quality: Cam [1] → Image quality = (highest, no RAW)
7. Select drive mode: Cam [1] → Drive mode = 'Continuous shooting'
8. Configure image numbering: Settings [1] → 'File numbering' = Continuous
9. Stop image auto rotate: Settings [1] → 'Auto rotate' = Off
10. Set date & time: Settings [2] → 'Date/Time' = Set UTC time, mm/dd/yy format (daylight savings off)
11. Set custom white balance: Cam [3] → 'White balance' = Custom
12. Set autofocus: Cam [1] → 'AF Operation' = AI SERVO
13. Hit Live View Shooting/Movie Shooting Switch (button next to viewfinder) to toggle 'live view' shooting OFF.
14. Use the Quick Control button () and surrounding directional buttons to set:
    Shutter speed: 1/320 (decrease to 1/250 if it's too dark out)
    Aperture: F8 (increase to F10 if it's plenty bright out)
    Exposure Value: -1/3

15. Check the LCD monitor to ensure all of the settings have been correctly set (Figure 1). *Note: check this screen before every SfM dive!*

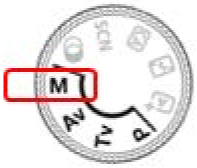


Figure 3. Canon SL2 mode dial (red box showing manual [M] shooting mode).

How to White Balance

The importance of accurate color in images cannot be understated. To identify coral and other benthic organisms accurately by humans, or especially through computer-automated systems, color is a critical component. To achieve the best color correction, we tested several in situ and post-processing methods. We discovered that color correction at depth provides superior color correction and is more time efficient than post processing imagery in software such as Adobe Lightroom. Furthermore, using an 18% gray card at depth allows the camera to set the color temperature to the existing conditions and provides better results than white balancing with a white slate. White balancing is performed before image collection on every dive.

1. Take a photograph of the gray card at depth ensuring that the card fills the entire view, that it is held perpendicular to the substrate, and that the card is not in shadow. Note that the camera will not focus on the card, which is not an issue (Figure 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 the beginning of every SfM dive.

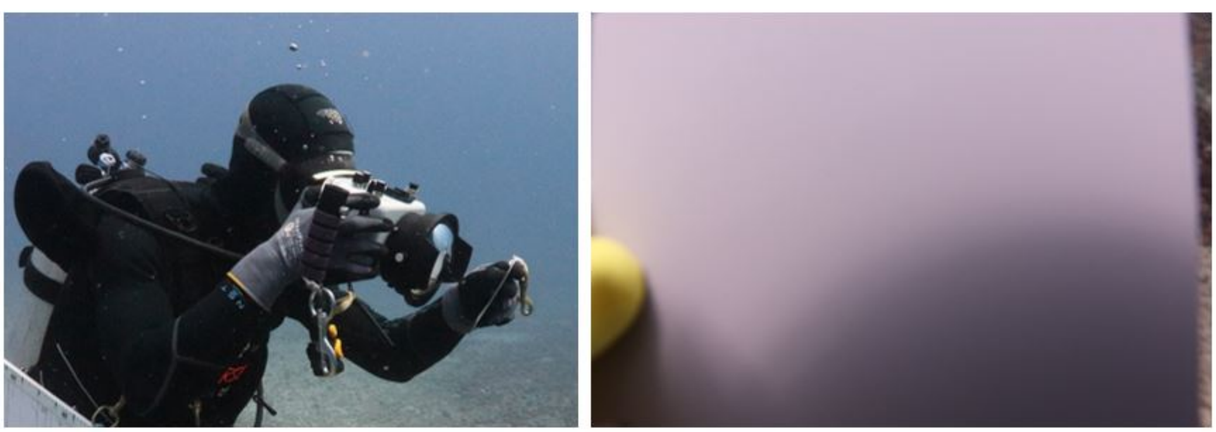


Figure 4. Example of a diver correctly color balancing with an 18% gray card. Left: A diver photographing a gray card at depth, ensuring that the card fills the entire view, that it is held perpendicular to the substrate and that the card is not in shadow. Right: Acceptable gray card photograph; note that camera is not focused on the card, which is not an issue.

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 dome port) and install a vacuum seal port.
1. Ensure a charged battery and a blank SD card have been inserted.
2. Format the SD card: Settings[1] → Format Card = OK
3. 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.
4. Use the vacuum seal to depressurize the housing (between 5 and 10 in Hg).
5. Check for changes in pressure over time (can leave overnight). A decrease in pressure may indicate a leak.
6. Insert the plug into the vacuum port to seal before diving.
7. Check camera settings.
8. 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).
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 Kimwipes 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.

B. Ground Control Point (GCP) markers

The Airsoft Metashape software provides a set of software-identifiable patterns or markers that can be used as GCPs. These markers allow the 3-D models to be accurately scaled. In a dynamic coral reef environment, it is important that the markers stay in place during the survey and are also small and light enough for divers to manage safely. Our original markers were constructed from lightweight PVC, easily disturbed when deployed in surge or current. To resolve this issue, we built stainless steel bars with markers attached that measure 25 cm × 5 cm, and weigh about 1 kg each (Figure 5). These GCP markers stay in place, are easy for divers to carry and deploy and scale models as well as our historical 0.5-m-long GCP markers.

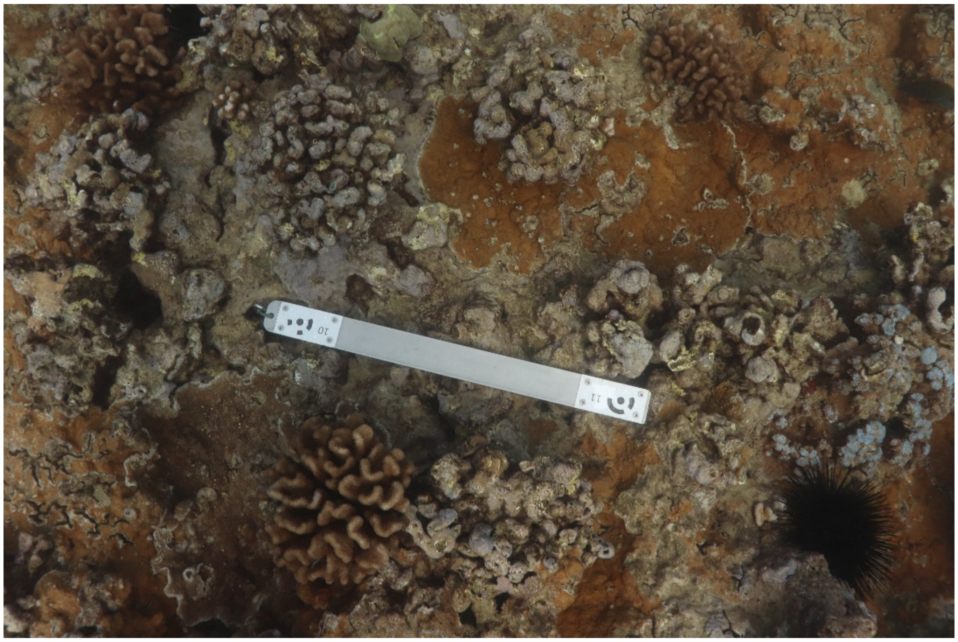


Figure 5. GCP marker with Agisoft patterns at the ends used to identify the GCPs and scale the models.

C. Survey Method

At each benthic survey site, a SfM survey is conducted along one 18-m transect line. This line contains four 2.5-m × 1-m segments beginning at each of the 0, 5, 10, and 15 meter marks. At each site 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 distance from the transect line should increase by ~0.5 m with each consecutive pass, with the first pass running directly alongside the line.

General Diving Evolution

> *Note: One person is responsible for collecting SfM images each day, and one person is in charge of preparing the camera for the next day.*

Equipment per diver
Diver 1: Transect reel, 2 Ground Control Point markers (hereafter: GCP markers)
Diver 2: Camera, 1 surface marker float, 2 GCP markers and a slate

Setting up the site (GCP markers are placed at 0, 5, 10, and 15 m)
Diver 1: Deploy transect line and place 2 GCP markers.
Diver 2: Secure surface marker float, place 2 GCP markers.

Survey process
Diver 1: Records SfM metadata
Diver 2: Takes SfM photos

Finishing up
Diver 1: Rolls up transect line and collects 2 GCP markers
Diver 2: Retrieves surface marker float and collects 2 GCP markers

Survey Plot Setup

Place GCP markers about half a meter away from transect line at the beginning of each survey segment (Figure 6). Make sure the GCP markers are facing up and are stable. Record the depth at the center of bar and record all numbers in the appropriate boxes on the SfM data sheet (Figure 7). Write any notes that would be helpful later (deviations in GCP placement, GCP moved during survey, etc.). At the end of the day, record the latitude and longitude of the site on the SfM data sheet, which can be obtained from the dive navigation data sheet.

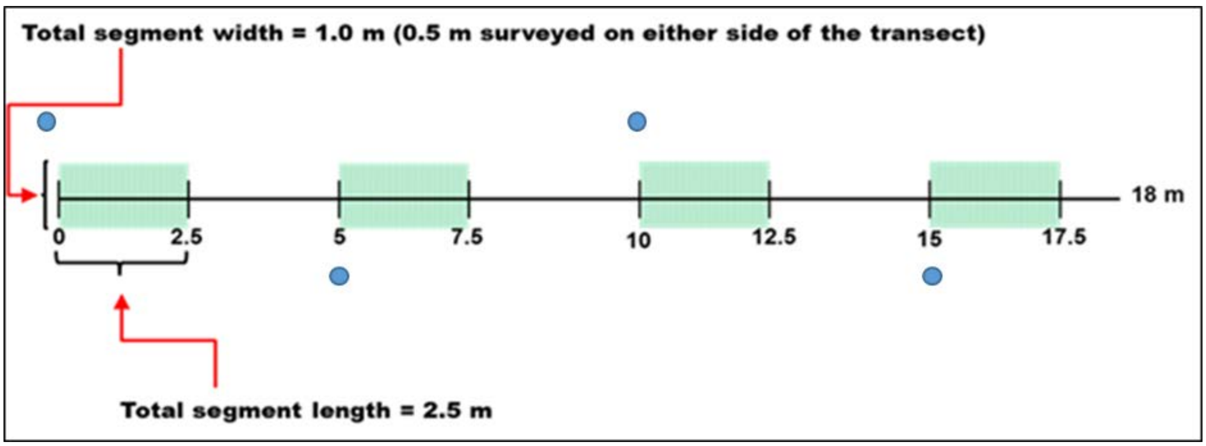


Figure 6. Benthic survey transect line with visual survey segment areas highlighted in green; blue dots show where GCP markers are placed for SfM image collection.

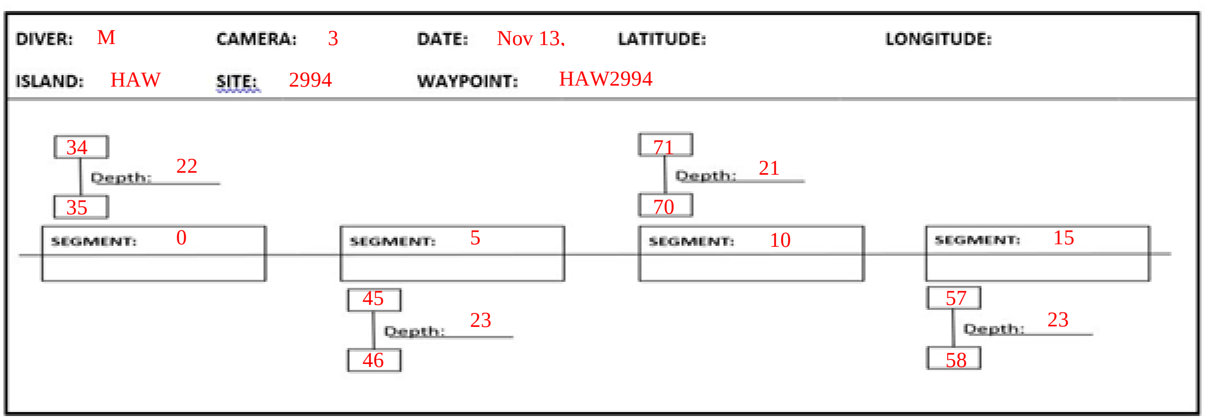


Figure 7. Completed SfM datasheet. GCP marker numbers are recorded in the small boxes; depth is recorded in feet, and date is recorded as the local date (not UTC).

Image Collection

A 3 m × 20 m belt transect should take about 10 minutes to swim. To properly collect quality images, adhere to the following pointers:

- Swim at a sustainable speed (each pass should take around 1.5 minutes; 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.
- Lift off the shutter button every 10 images (clicks) to allow camera to reset (not doing this will produce a string of very dark images).
- If Live View is turned off, you will not see an image appear in the viewfinder when you take a picture, but you will hear and feel the shutter firing. If you notice the shutter firing slowly, curb your swim speed to ensure appropriate overlap.
- Look through the viewfinder to make sure that the transect line is near the 1/3 mark in your viewfinder on the first pass, and each pass after that should be about half a meter further from the transect (Figure 8). It may help to look down the transect line and find a feature to swim towards if the transect line is moving at all.
- Keep shooting while turning to start the next pass.
- Adjust the camera angle for vertical surfaces without getting blue water in image. If you are working on a slope, make sure that you are taking photos perpendicular to the reef to avoid blue water in the image.
- 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.
- If you lose your place, go back to the last area that you can remember. The SfM survey should take 10 minutes.

Note: the software can stitch images together much faster if they are continuous and have good overlap. The goal is to have each seafloor feature appear in three consecutive images to ensure adequate coverage. It is very important to make sure that each feature is captured in multiple images so that the model can be scaled accurately.

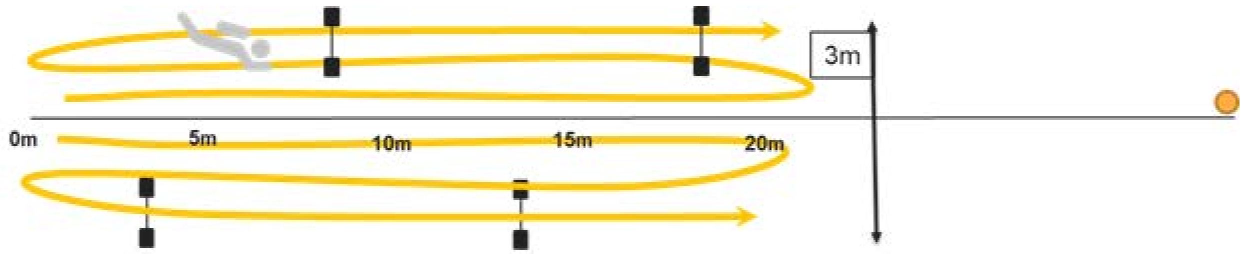


Figure 8. Swim paths of SfM diver during image collection shown by yellow arrows, with three paths 0 to 20 m on each side of the transect. GCP marker position is shown for each segment.

Shooting Large Colonies and 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 imaged area, the diver should collect additional imagery of the colony outside the belt. 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. 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.

Air or Bottom Time-limited 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 10-m mark (thereby collecting imagery for two segments, 0 and 5 m).

2.2 Data Management

Good data management is a crucial component of this pipeline. With imagery and data moved multiple times between servers and software programs, there are many opportunities for errors. The guidelines listed below were developed specifically to meet ESD needs, but the framework could be easily adapted by other organizations.

A. Camera Download

Data managers will upload all original imagery from each day to the backup drive. We suggest using a naming convention such as:
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 (Figure 9) for the sites surveyed that day. This document is a crucial part of the pipeline and allows us to track the status of the site data from image collection to model generation to demographic data extraction. Contact rhonda.suka@noaa.gov for a copy of the tracking spreadsheet. The person in charge of preparing cameras for the day should also completely fill out the date, photographer, team, region, island, camera #, site #, survey size, survey type, GCP marker #s, and depths from the field data sheets and dive navigation sheets.

B. Saving Images to Site Folders & QC

1. All SfM imagery is copied from the backup drive to whichever drive a different drive where all imagery will be sorted using a standardized naming convention and folder structure.
2. The grey card photo, photo of datasheet, and any other miscellaneous photos worth keeping are put within a folder called 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 data sheets 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 data sheets.
   - 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. Make any notes on the spreadsheet about image quality issues or notations made on the field data sheets, such as “GCP markers moved” or “only 10 m of transect surveyed.”
   - Ensure that the field data sheet is completely filled out.

C. Using Adobe Lightroom to Adjust Image Exposure

Canon SL2 cameras create low ISO series of photos intermittently during SfM surveys (Figure 9). This can be managed by releasing the shutter button during the survey for a brief moment every 10 clicks. For SfM models, this is sufficient unless many of the images are still underexposed; however, underexposed imagery is unsuitable for image annotation (manual or automated) with applications such as Coral Point Count with Excel extensions (Kohler et al. 2006) or CoralNet (Beijbom et al. 2015).

Figure 9. String of image thumbnails with an example of a series of dark underexposed images in the seventh row.

To ensure that image quality is suitable for annotation using CoralNet, we developed the following Quality Control (QC) procedure in Adobe Lightroom.

1. Open Lightroom and in the 'Library' tab click the '+' next to 'Folders' in the side bar (Figure 10).
2. Select 'Add Folder' and choose the folder you want to edit based on site number (e.g., MOL-2158). This will add all of the images within that folder to Lightroom. Make sure all images are checked and click on Import.

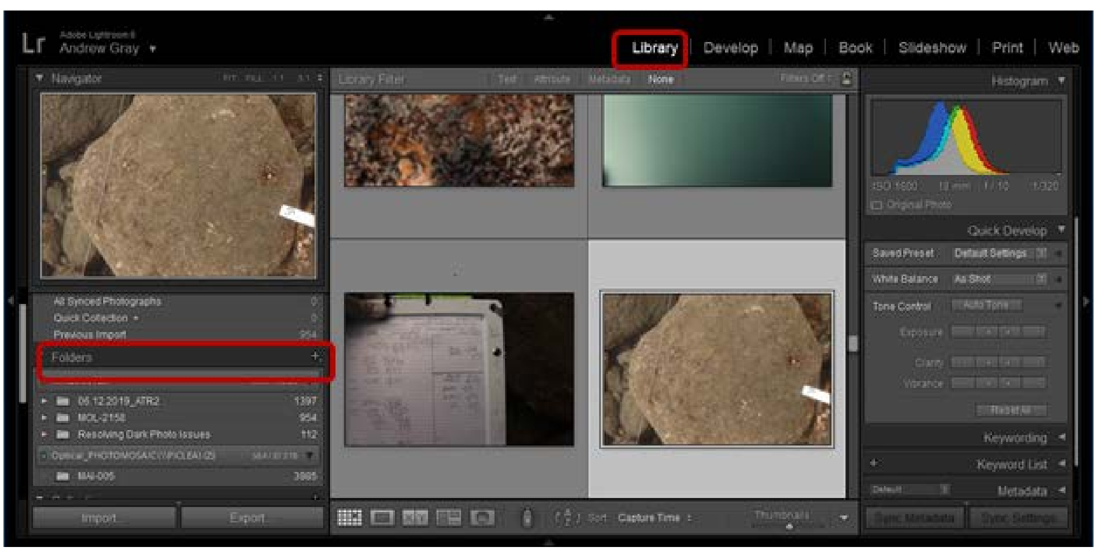


Figure 10. Lightroom interface highlighting the 'Library' tab and the 'Folders' selection in the sidebar.

Once a folder is imported into Lightroom, it will provide you with virtual copies of photos from the folder. You can make changes to these photos, but they will not change the actual file. To change the file, export the edited photos to replace the dark photos.

3. Click on the folder name in the sidebar under ‘Folders’ to view photos you just imported.
4. Sort them by ISO by clicking on the ‘Filters Off’ text at the upper right corner of the thumbnails window.Select ‘Exposure Info.’ You can now select photos by highlighting them in the ISO column (Figure 11).
5. Select all photos with low ISO. This should encompass most, if not all, of the dark photos. Also, select an ISO somewhere in the middle that appears to have some perfectly exposed photos.

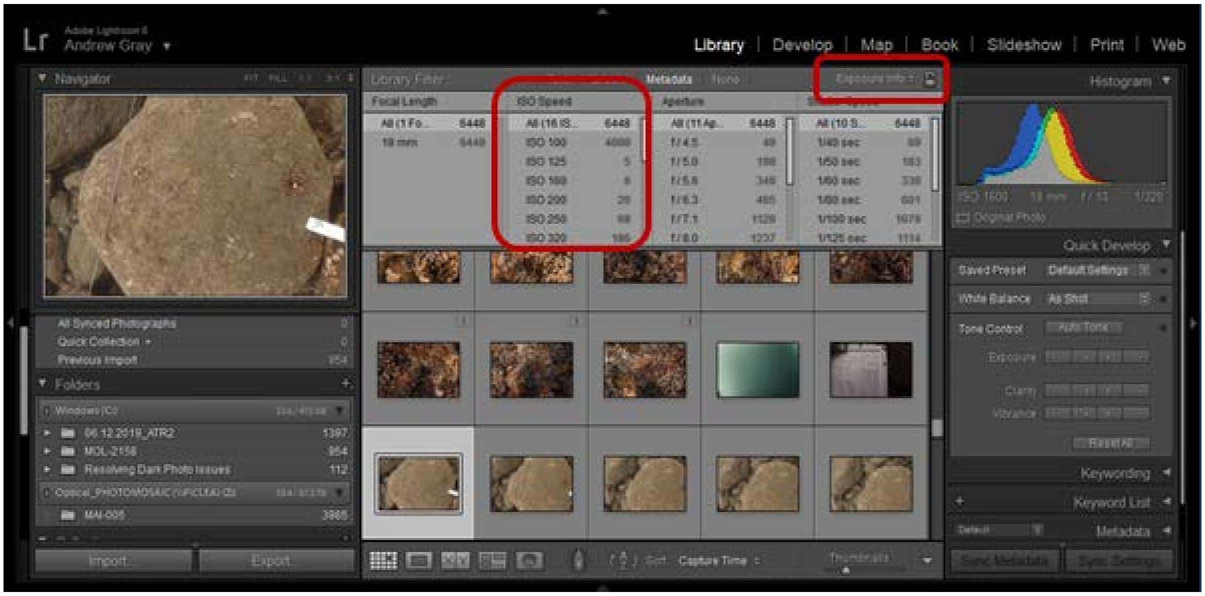


Figure 11. Lightroom interface highlighting the location of the Filter tab and the ISO selection within the ‘Camera Info’ filter.

6. Next, switch to the ‘Develop’ tab, click on the well-exposed image in scroll bar below so that it shows in viewing window, then press Ctrl+A to select all the images; make sure the Sync button is on (not Auto Sync).
7. In the ‘Settings’ tab, select Match Total Exposures. Each image will be adjusted to match the exposure of the well-exposed image (Figure 12).

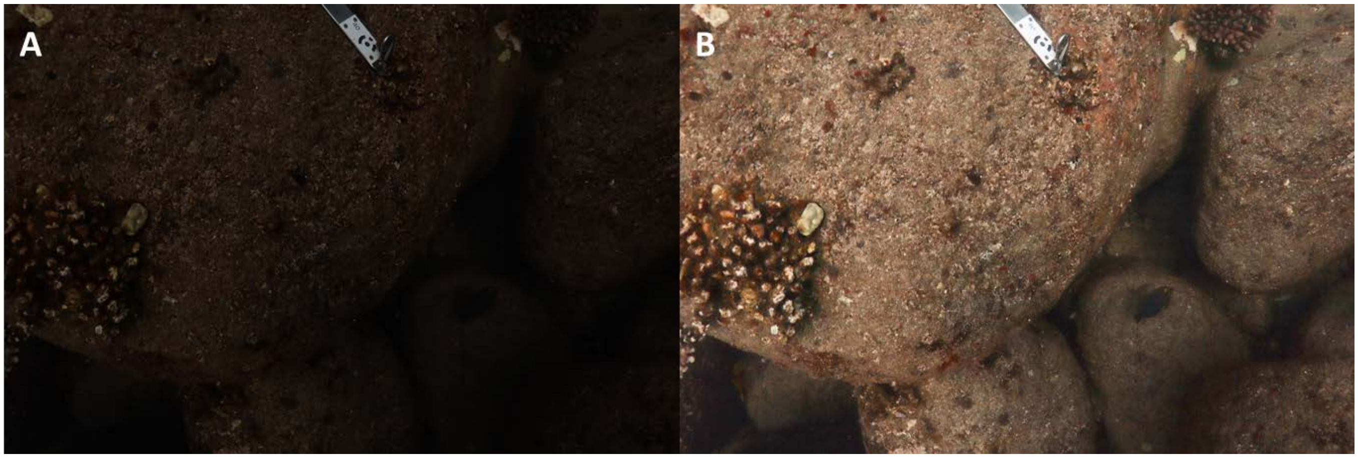


Figure 12. (A) Example of dark image created by light sensor issues with the SL2. (B) Example of the same image after the exposure correction.

Figure 13. Lightroom interface screen with thumbnails displayed at bottom of window.

8. Click on any of the thumbnails at the bottom of the screen to evaluate corrections (Figure 13).
9. If all corrections look better, ensure all images are highlighted (Ctrl+A), right click on one of the images from the scroll bar below, and select Export → Export → Select 'Export To: Same folder as original photo.'
10. Check the 'Put in Subfolder' box and label it 'corrected' (Figure 14). Leave all other selections as default. This will create a corrected version of the image and put it in a folder named 'corrected' within the site folder. The original dark images will remain in the site folder. You can monitor the export progress in the upper left hand corner.

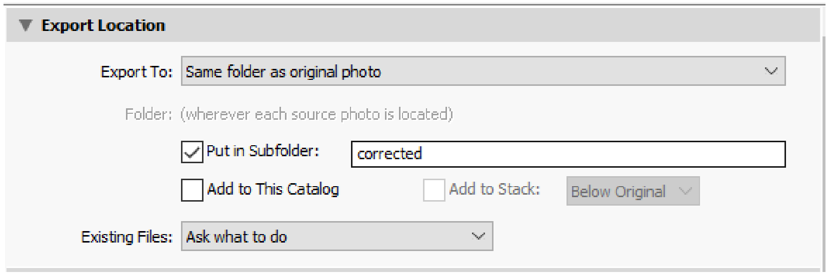


Figure 14. Export location will be a folder labeled ‘corrected’ within the site folder.

11. Finally, to have all properly exposed photos in one place, copy the rest of the photos to the ‘corrected’ folder. In Windows Explorer, navigate to the site folder and then select, cut, and copy all photos to the ‘corrected’ folder. Windows will ask if you want to skip moving photos with identical image names—skip them. The ‘corrected’ folder will have all photos from the mosaic properly exposed, and original dark photos remain in the site folder.

3. Data Processing

Once the images have been collected, quality checked, and organized, they can be processed to create 3-D point clouds and 2-D mosaic images, which can then be annotated to classify benthic features. Our processing workflow utilizes three software: Agisoft Metashape, Viscore, and ArcMap. Agisoft is used to align the imagery and create the DPC and a scaled orthophoto. Viscore is a proprietary software used to generate an accurate orthoprojection, and is not available for public use at this time; in this case, you may use the methods described in the ArcMap section using the orthophoto produced in Agisoft. ArcMap is used to visualize the orthoprojection and classify benthic features.

3.1 Generating 3-D Point clouds and 2-D Orthophotos in Agisoft

This section provides instructions on creating 3-D sparse and dense point cloud (DPC) models using Agisoft Metashape Version 1.4 from JPEG imagery obtained at the site. By first aligning the images, the analyst is able to build a DPC of the reef, which is then exported, along with the camera locations and path information. Once exported, scale bars are identified to scale the model, automatically deleting the DPC and compressing the sparse alignment points. Lastly, the mesh, texture, and orthophoto are built, and the orthophoto is exported for visual identification help in ArcMap. Note that Agisoft Photoscan is now called Agisoft Metashape.

A. System Requirements and Preliminary Steps

Memory consumption during photo alignment depends mainly on the number of photos being aligned and does not depend on the resolution of individual photos. Memory consumption during photo alignment is typically lower, but can be comparable or even exceed the amount of memory required for model building in Point Cloud mode, or in Low quality.

The building geometry (Dense cloud and Mesh generation) step usually has the largest memory footprint, especially if the model is constructed in Medium or High quality, and should be carefully taken into account. Memory consumption in Arbitrary mode depends on the number of photos, their resolution and overlap, selected quality level, and on the shape of the object. Please note that memory consumption depends significantly on the kind of object being processed. Dependency on the photo resolution is approximately linear.

CPU — Complex geometry reconstruction algorithms need a lot of 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.

Prior to opening Agisoft, take the following steps:

1. Ensure that all images/image folders are in one folder (site#).
2. Any photos containing blue water, fins, hands, or blurriness should be removed before model reconstruction and placed in a miscellaneous folder (this is usually done during the QC process described in section 2.2 B above).
3. Copy the folder containing all the images onto your personal desktop. Make sure to maintain the folder structure.
4. Create a folder in the site# folder that is titled Products.
   Save all products from Agisoft in this folder.
5. Be aware that any spaces OR periods in file names will cause issues. Name files accordingly.
6. 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 → 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 monitoring the committed memory usage under the Performance tab in Task Manager.

B. Upload and Filter Photographs

1. Open Agisoft.
2. In the '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.
3. Save the project titled site# in your Products folder.
4. Click Workflow in the upper left hand corner, choose Add Photos from the drop down menu, and click OK.
   - If there are two folders of images, repeat this process to add both sets of photos

5. In the photo pane (bottom of the screen), change view to details.
6. Right click and choose Estimate Image Quality (Figure 15).
    - Apply to all cameras

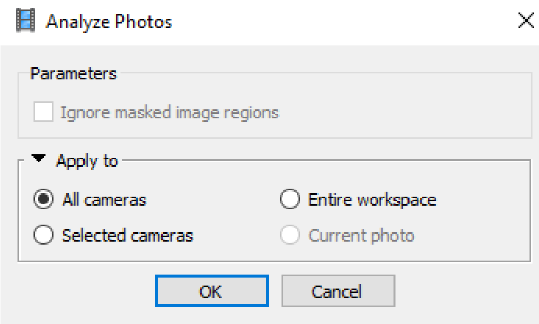


Figure 15. Example of Estimate Image Quality window with desired settings.

7. Click Quality to sort from least to greatest.
8. Disable or remove (Figure 16) 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).
    - 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 which photos to enable and try alignment again.
    - Minimum quality depends on majority. If a substantial number of photos have quality under 0.5, make the minimum higher (e.g., <0.45). If you have more than two low quality photos in a row, include at least one to minimize gaps.
    - Keep in mind that this step is a double-edged sword and 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 16. 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.

C. Generate the 3-D model

Generating the 3-D model produces a sparse cloud from matching points throughout the imagery and can take anywhere from one to five hours. The process consists of three initial steps: detecting points, matching points, and estimating camera locations. Following these steps, the DPC is built, which is the most time consuming part of the process and takes between 4 and 24 hours depending on rugosity. This is one of the most important outputs from Agisoft and will be used to create a geometrically accurate 2-D image of the reef. 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.

1. Click Workflow → Align Photos (Figure 17)
   - Accuracy: High
   - Generic preselection: No
   - Reference preselection: No
   - Key point limit: 4000
   - Tie point limit: 0
   - Constrain Features by Mask: No
   - Adaptive camera fitting: Yes

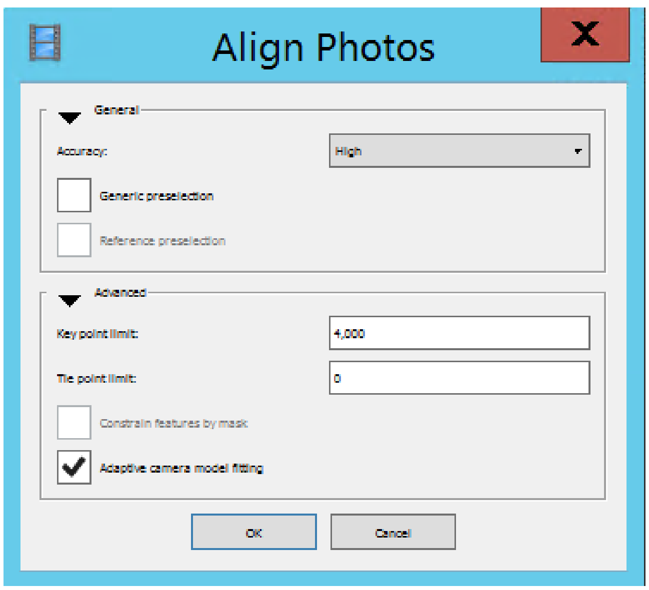


Figure 17. 'Align Photos' window in Agisoft Metashape displaying settings for initially aligning imagery.

2. Once completed (~15 min to 2 h), drop down the menu for Chunk 1 in the Workspace to ensure that all photos aligned. If more than 15 are not aligned, try again or reevaluate photos.

   Keep in mind that the total # of photos includes those that were disabled. A script can be used to determine the number of photos that were enabled. This script is called count_enabled.

   Python script for this is as follows:

   import PhotoScan

   doc = PhotoScan.app.document

```
chunk = doc.chunk
X = 0

for camera in chunk.cameras:
    if      camera.enabled:
            x = x + 1
            camera.selected = True
    else:
            camera.selected = False

print (‘Enabled images: %d ‘ % x)
```

- To determine how many photos were enabled, click on the ‘Console’ tab below the Photos Pane (View, Panes, Console) to show the Console pane. In the top banner, hover over the ‘Tools’ tab, select ‘Run Script’. In the pop up window, navigate to the count_enabled.py script. Leave the Arguments field blank, press ok. The Console pane should now show the number of enabled images. Compare this figure to the number of aligned images.

3. Save project.
4. Click Workflow → Build Dense Cloud (Figure 18)
   - Quality: Medium
   - Depth filtering: Mild
   - Do not check Reuse depth maps

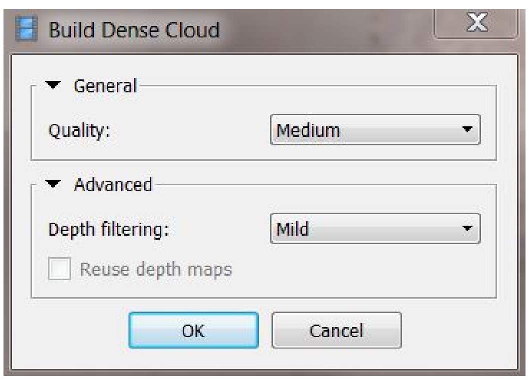


Figure 18. 'Build Dense Cloud' menu in Agisoft Metashape displaying settings for building the medium dense point cloud.

5. Save.
6. 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 19). Note that you must be viewing either the sparse point cloud (tie points) or the DPC.

Figure 19. Standard toolbar in Agisoft Metashape used to edit and clean up the dense point cloud, with A denoting the Rectangle Selection tool and B denoting the Delete Selection tool.

7. Orient your model to match the data sheet (0 m should be on the left side).

D. Export Report

The following export procedures are important for correctly archiving the project files 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. A report is exported to provide useful information regarding processing time, image overlap, and image alignment.

1. Generate Report:
   - File – Generate Report
   - Title: site#
   - Description: Processing Report
   - Projection: Top XY
   - Within Products folder, save as: site#_report.pdf
2. At this point, save the Agisoft document and close. Copy and paste the current products into the original location (e.g., from your desktop to the archive/master file) to ensure that the original DPC is saved. Considering the DPC is the most time consuming step, it is important to save this version of Agisoft. Once all documents are copied over, reopen the Agisoft document on the desktop.

E. Generate and Export Scaled Orthophoto

Agisoft is also used to create a 2-D reconstruction of the reef by stitching the JPEG imagery together, otherwise known as an orthophoto or orthomosaic. The orthophoto can contain significant artifacting and ghosting, and therefore colony size and shape may not be accurate. Artifacting can be minimized by ensuring excellent image overlap during image collection.

Add GCP markers and scale DPC

The following steps are to be done after the high DPC has been exported. Although the DPC is not scaled yet, if something goes wrong during scaling you will not need to re-run the DPC, which is the most time consuming step. Once scale bars are added and the model is optimized, any existing DPC will be deleted from the project.

1. If Agisoft GCP markers were used, click on Tools → Markers → Detect Markers:
   - Marker Type: circular 12 bit
   - Tolerance: 50
   - Uncheck Inverted (white on black)
   - Uncheck Disable parity – OK

Agisoft will automatically detect GCP markers in each image.
If Agisoft GCP markers were not used OR Agisoft did not detect them, select a photo from the photo pane with an object that can be used to scale images (or the GCP markers themselves) and add a GCP according to the following steps:

a. To place a GCP in a photo, right click and choose Add Marker.
- Avoid GCPs that are touching the edge, at a steep angle, or blurry.
- A blue flag in the corner of the photo means a GCP was detected in the image.
- A 'grey flame' in the corner of the photo means a GCP was detected but not enabled. Click and drag the GCP on the image to enable it or ignore if unwanted.
- A red dashed line may appear on the first few photos after adding a GCP, right click to Place Marker and red line will disappear.

b. Rename the GCP markers in the Reference window by double clicking on the GCP name (e.g., Target ###).
- Once you add the same GCP in 2 images, Agisoft will find those objects in the rest of the images.

c. Repeat this process for each object you want to use as a GCP.

2. When finished detecting/adding GCP markers, use the 'magic wand' in the Reference toolbar to Optimize (REMEMBER: the dense point cloud will be deleted—make sure you have exported the DPC and cameras beforehand!).
   a. Click ALL the boxes EXCEPT 'Fit rolling shutter'.
      This will calculate the error associated with each GCP marker.
   b. Look at the Error (pix) column in the Markers pane on the far right. Each GCP marker error should be below 0.4 (Figure 20).
   c. If a GCP marker error is above 0.4, 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 in the model workspace. Close the Info window and remove the selected GCP marker on the image by right clicking. Hit 'Optimize Cameras' (magic wand) again and observe the Error for that marker. Usually removing the top one or two highest error markers from images will suffice. Continue with this process on each marker with high error until all are at or below 0.4.

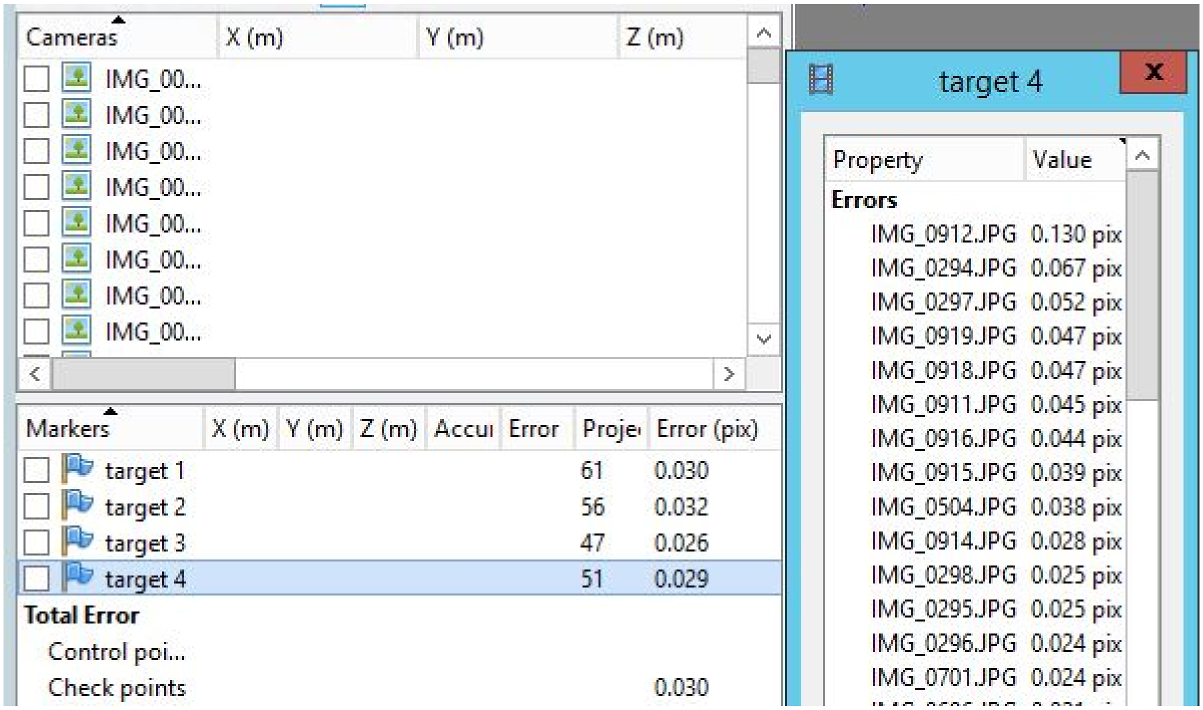


Figure 20. Agisoft Metashape screenshot highlighting low error of targets marked.

3. Under the Markers tab, choose matching marker numbers that make up a scale bar (according to the data sheet).
    a. Select both marker numbers by shift and click, then right click and choose ‘Create Scale Bar’.
    b. In ‘Scale Bar’ pane, double click under ‘Distance’ to manually add the distance between the two marker numbers in meters.
4. Use the ‘magic wand’ at the top of the Reference window to Optimize. Click ALL the boxes EXCEPT ‘Fit rolling shutter’.
5. Check the error given in the ‘Scale Bar’ tab—error in ‘Scale Bar tab should be ≤ 0.002. If error is too high, reevaluate GCP markers to lower their individual error, then optimize again.
6. Save.

The model is now scaled and only a sparse point cloud (tie points) will be present.

Generate and Export Orthophoto

1. Workflow → Build Mesh

    General
    Surface type: Arbitrary
    Source data: Sparse cloud
    Face count: 1,000,000 (custom)
    Advanced
    Interpolation: Enabled (default)

Point Classes: All
Check Calculate vertex colors

2. Workflow → Build Texture
Note: GCP markers must be identified for Texture to build
General
Mapping mode: Generic
Blending mode: Mosaic (default)
Texture size/count: 4069 × 1
Advanced
Select 'Enable hole filling'
Deselect 'Enable ghosting filter'
3. Save.
Alternatively, the above steps can be run together in a two-step process to reduce user interaction:
Workflow → Batch Process → Add →Build Mesh and Add →Build Texture (same parameters as stated above) Click on 'Save after each step' box
4. Reposition the model to match the field orientation using the field notes/data sheet; properly orient the axes using the GCP marker positions. For belt transects, 0 m (or the start of the belt) should be on the left side of the screen, while end of transect should be on the right. If the plot is a circle or a box shape, orient GCP markers according to the way they were recorded on the datasheet. This step is to avoid the model inverting itself.
5. Workflow → Build Orthophoto
Type: Planar
Projection plane: Markers (If you added markers in the previous step)
Name appropriate GCP markers for horizontal/vertical axes (see Figure 21).

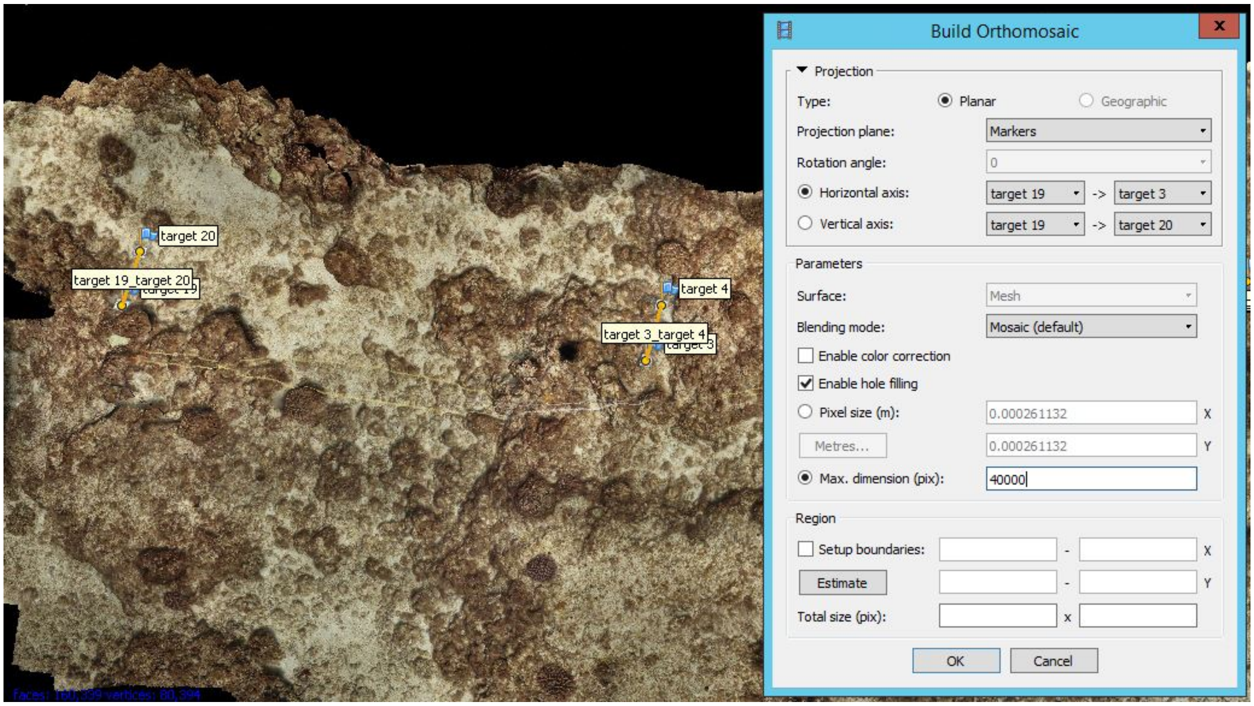


Figure 21. Screenshot of Agisoft Metashape window, showing 'Build Orthomosaic' window with GCP markers selected.

If no GCP markers: Select Top XY (assuming model was oriented according to datasheet)

Rotation angle: 0
Surface: Mesh
Blending mode: Mosaic (default)
Uncheck Enable color correction
Check Enable hole filling
Uncheck Pixel size (m) and check Max dimension (pix)
Max. Dimension (pix): 40,000 (make this smaller for smaller models)
Uncheck Setup boundaries
Leave Total size (pix) blank

6. Examine the resulting orthophoto in Agisoft to ensure orientation is correct and check to make sure the resolution is < 1.0 mm/pix. If it is higher than 1.0 mm /pix, rebuild the orthophoto using a higher Max. Dimension (pix) number.
7. File → Export Orthophoto → Export JPG/TIFF/PNG...

Coordinate System: Local Coordinates (m)
Raster
Check Pixel size (m): Auto-generated, no need to change
Do not check Max. Dimension (pix)
Uncheck Split in blocks (pix)
Raster transformation: None

Background color: White
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: JPG
JPEG quality: 99
Uncheck Write BigTIFF file
Check Write alpha channel
Export
Save as site#_orthophoto.tif

8. In the Products folder, create a folder titled ARC, and cut and paste the site#_orthophoto.tif into it. Additionally, copy this folder into its original location.

File Summary

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

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

3.2 ArcMap Demographic Annotation

In this section, ArcMap 10.6.1 is used to record features within the orthophoto, and add data that are associated with each feature, such as species ID, condition, morphology, etc. This tutorial assumes a basic understanding of ArcGIS.

Note: ESD uses Viscore, a custom software from the Sandin Lab at Scripps Institution of Oceanography, which allows us to visualize and analyze 3-D point clouds. It is used to scale and orient the DPC, which is then tiled (a.k.a. screenshot) so that a geometrically accurate, top/down image of the model is obtained. Viscore is an essential tool to properly identify corals by using its functions to look at underlying imagery in specific places throughout the model. If Viscore is not accessible to you, use this ArcMap Demographic Annotation methods section and use the Agisoft generated orthophoto for annotation. Keep in mind that substantial artifacting, ghosting, and geometric inaccuracies will be present; therefore, the demographic data may not be reliable.

Increasing the number of images and overlap of images during collection will reduce these issues.

Survey transects and segments are drawn onto the orthophoto to delineate 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.

The comprehensive SOP for data collection of rapid ecological assessment benthic surveys can be found at https://doi.org/10.25923/39jh-8993.

A. Add Data

1. Use the 'Connect to a Folder' tool to add the folder that the orthophoto is in,
   - Upload the orthophoto 'Unknown Spatial Reference' will pop up → OK
     Under 'View,' click on 'Data Frame Properties'
   - Under 'General,' change 'Map' and 'Display' to meters → Apply
   - Under 'Coordinate System,' set to 'WGS 1984 UTM Zone 4N' → OK
   - If not previously done, navigate to 'Projected Coordinate System' → UTM → WGS 1984 → Northern Hemisphere → WGS 1984 UTM Zone 4N. Right click to 'Add to Favorites'.

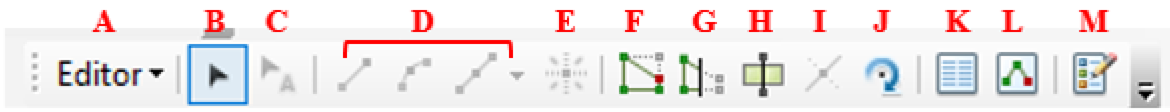
Most likely, the model colors will be incorrect. Double click the model, go to 'Symbology,' uncheck 'Apply Gamma Stretch' and change 'Stretch Type' to None.

B. Orient and Check Scale on Orthophoto

1. Under 'Geoprocessing', click on 'Results' to view the current session. This will allow you to see when Arc is working.
2. Using 'Search' (if not already there, also under 'Geoprocessing'), use 'Define Projection' (Data Management) to assign the coordinate system to all models.
   - Input Dataset or Feature Class = site#_orthophoto.tif
   - Coordinate System = WGS 1984 UTM Zone 4N.

   To see if a coordinate system was already assigned, it can be found in 'Layer Properties' under 'Source' (Spatial Reference- XY Coordinate System).
3. To check the scale, use the measuring tool to measure one of the GCPs. The measurement may not be exactly the length of the GCP if it is at an angle, but it should never measure larger than the actual length.
4. Save project as original site name. Pay close attention to where the saved file is located. It will automatically default to ArcMap default Geo Database. Save the project to the ARC folder for the site.

C. Create Transect and Segments



- A. Drop down menu
- B. Edit Tool
- C. Edit Annotation Tool
- D. Segment drawing tools
- E. Point
- F. Edit Vertices
- G. Reshape Features Tool
- H. Cut Polygons
- I. Split Tool
- J. Rotate Tool
- K. Attributes
- L. Sketch Properties
- M. Create Features

Figure 22. Editor toolbar.

1. Under Windows 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. In the Catalog, use the Connect to Folder tool to add the site folder.
3. To create the transect:
    a. Right click on the site ARC folder in the Catalog and select New– Shapefile.
        Name: site#_transect
        Feature Type: Polyline
        Spatial Reference, Description: WGS 1984 UTM Zone 4N (change this by clicking Edit…)
        Leave everything unchecked—OK
    b. Under Customize, open the Editor Toolbar (found under Toolbars).
        Drag to the main toolbar (this will only need to be done the first time).
    c. Drop down Editor and Start Editing (Figure 22).
    d. Open Create Features (Figure 22) and drag to the right side of your window to pin it there (again only needs to be done the first time opening Arc).
    e. In the Create Features window, click on site#_transect and make sure the construction tool is line (bottom right of screen).
    f. Zoom to the site#orthophoto 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 23).
    g. Use placement of GCP markers, original imagery, and field datasheet to help determine starting point of segments.
    h. Additionally, while you draw the line, the bottom left corner will approximate how long it is, although 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).

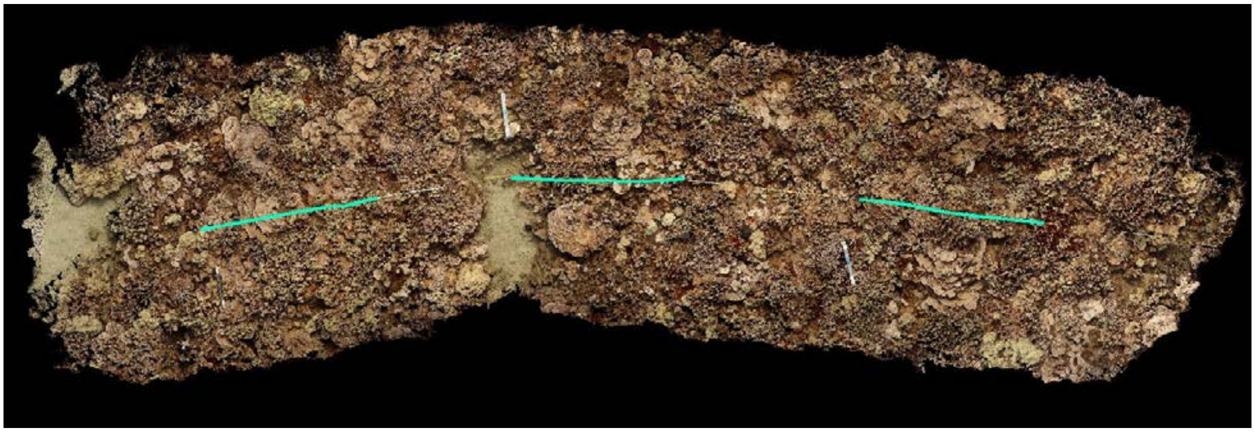


Figure 23. Screenshot in ArcMap of desired 2.5 m transect lines.

i. Once all ~2.5-m transect lines are drawn, drop down Editor (Figure 22), and Stop Editing (Save Edits).

4. To create segments:

   Under 'Geoprocessing,' click 'Buffer' (Figure 24).

   Input features: site#_transect
   Output Feature Class: site#_segments
   Linear Unit: 0.5 Meters
   Side Type: FULL
   End Type: FLAT
   Method: PLANAR
   Dissolve Type: NONE

   Once completed, segments will be drawn around your transect lines with exactly 1-m width (Figure 25).

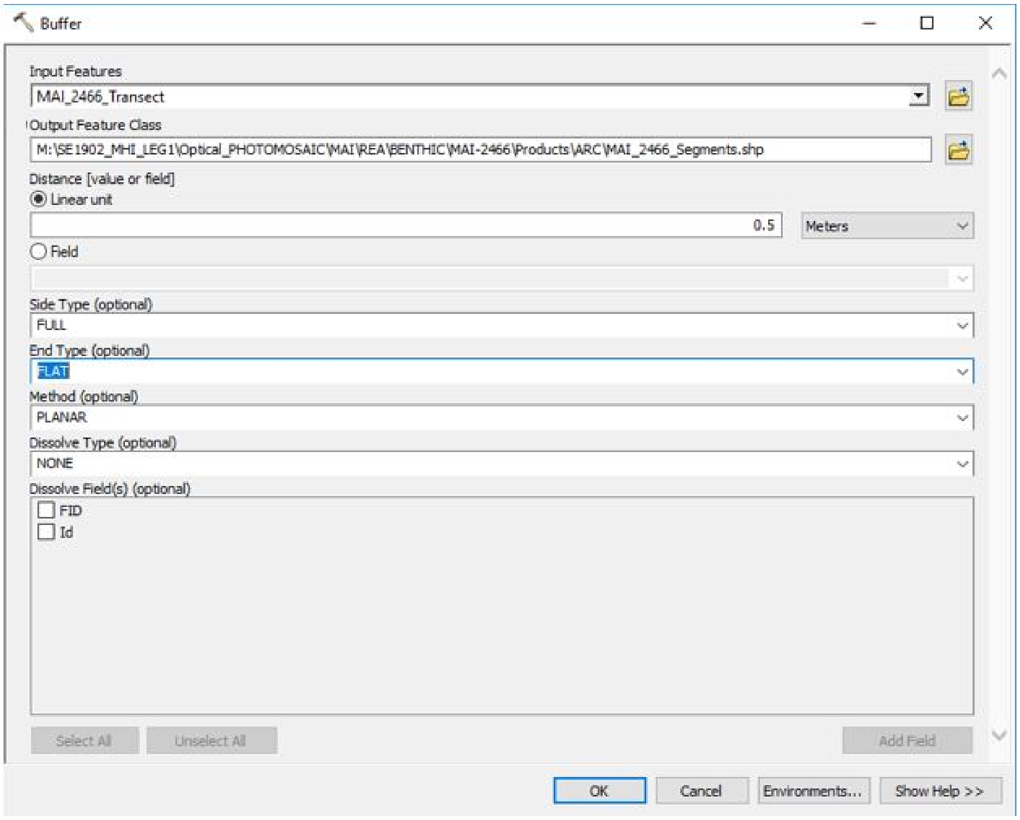


Figure 24. Screenshot in ArcMap of the buffer tool with desired settings.

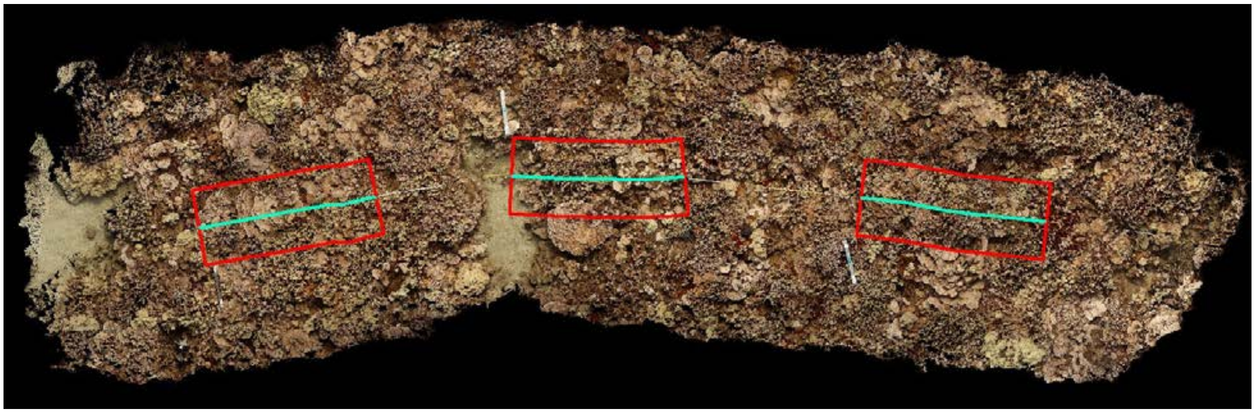


Figure 25. Screenshot in ArcMap of the segments once buffer is complete.

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 Symbol Selector where the Fill Color, Outline Width, and Outline Color can be edited (this applies for all shapefile/feature classes).

5. Save your project.

D. Set up the Geodatabase

In order to replicate the traditional standardized data collection method, a geodatabase will be set up before hand for easier annotation. The analyzer will need to input this GDB into Arc, and drop down menus will be available for all applicable columns (species, morphology, etc.). Instructions for creating a new GDB can be found in the appendix.

1. In the Catalog, navigate to the region and year you are analyzing (i.e., ASRAMP 2018). There should be a previously created Geodatabase (in this example, ASRAMP2018.gdb).
2. Click the plus sign to drop down the Geodatabase, right click on the 'template' feature class, and select Copy (Figure 26).

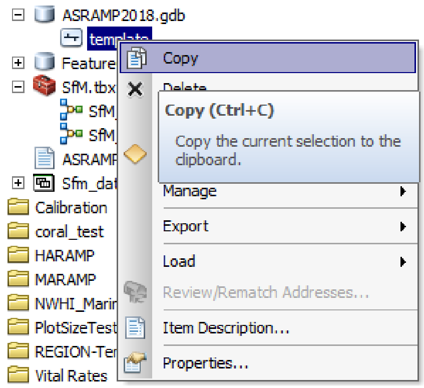


Figure 26. Screenshot in ArcMap of how to copy the template.

3. Right click on the Geodatabase (in this case ASRAMP2018.gdb), and click paste.
4. A screen titled 'Data Transfer' will pop up. The only box that is necessary to edit is in the first row in red under Target Name (highlighted in Figure 27)—change this to the project site name (i.e. site#) → OK.
6. Drag and drop this feature class into your Table of Contents.

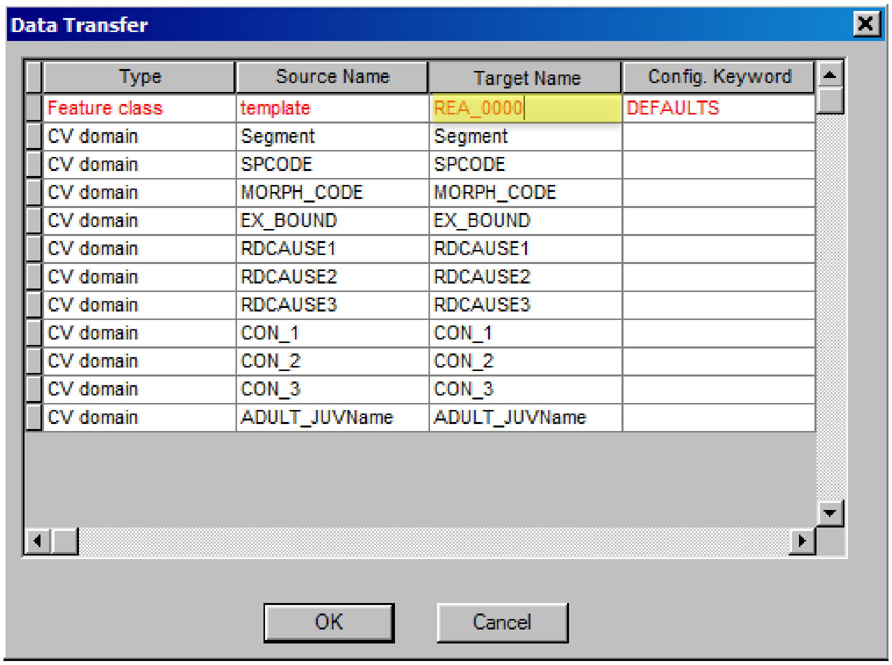


Figure 27. Screenshot of Data Transfer window in ArcMap.

E. 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 partners 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. 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 (Swanson et al. 2018).

1. Drop down Editor and Start Editing the site# layer (the GDB file you just dropped into your table of contents).
2. In the table of contents, right click on the orthophoto, site#orthophoto, and select Zoom to Layer.
3. In 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 28).
   - Ensure that all lines are drawn on the orthophoto.
   - 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 it will show an x at the center; if the middle is not inside, delete your line.

- 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.

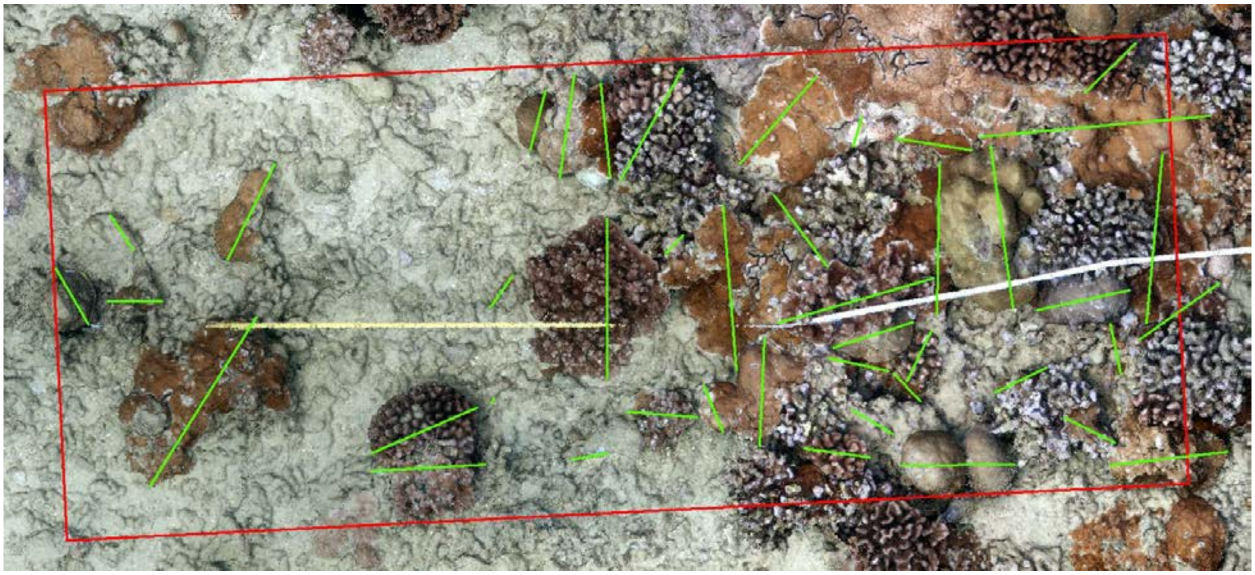


Figure 28. Screenshot in ArcMap of maximum diameter lines drawn on all the colonies in the segment.

- Make it a habit to save your edits often (drop down in editor toolbar) so that no work is lost.

6. Once all colonies are identified throughout the desired segment, turn editor off and save your edits.
7. Right click on your site# layer and Open Attribute Table.
8. For ANALYST, OBS_YEAR, MISSION_ID, SITE, SEGLENGTH, and SEGWIDTH use the following steps to easily complete the columns:
   a. Make sure that editor is off.
   b. Right click the column name in the attribute table.
   c. Select ‘Field Calculator…’
   d. Enter the value you would like repeated throughout the column (if text use quotations) – OK (Figure 29).

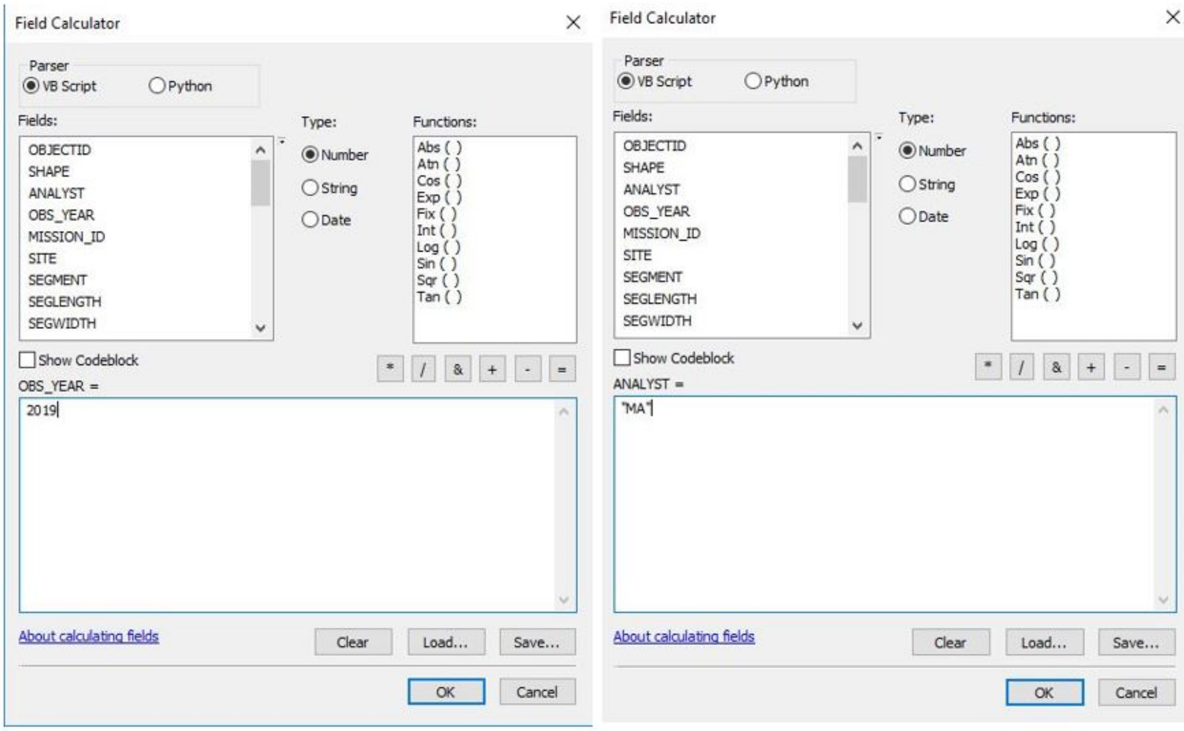


Figure 29. Screenshots in ArcMap of how to properly use the Field Calculator function. To the left shows the proper settings for a numerical field, the right shows the proper settings for a text field.

9. Once the above columns are filled, resume editing.
10. Following the guide and definitions below (Table 1), fill out the attribute table. Double click the grey square in front of OBJECTID to highlight the specific colony you are analyzing.
11. Continue going down the attribute table while relying on the underlying imagery to identify mortality and condition.
12. Once all colonies are identified and analyzed (Figure 30), end the editing session and save your edits.

Table 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)
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)
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_ OBSERVED	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)
FRAGMENT_YN	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 = drop down 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)
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

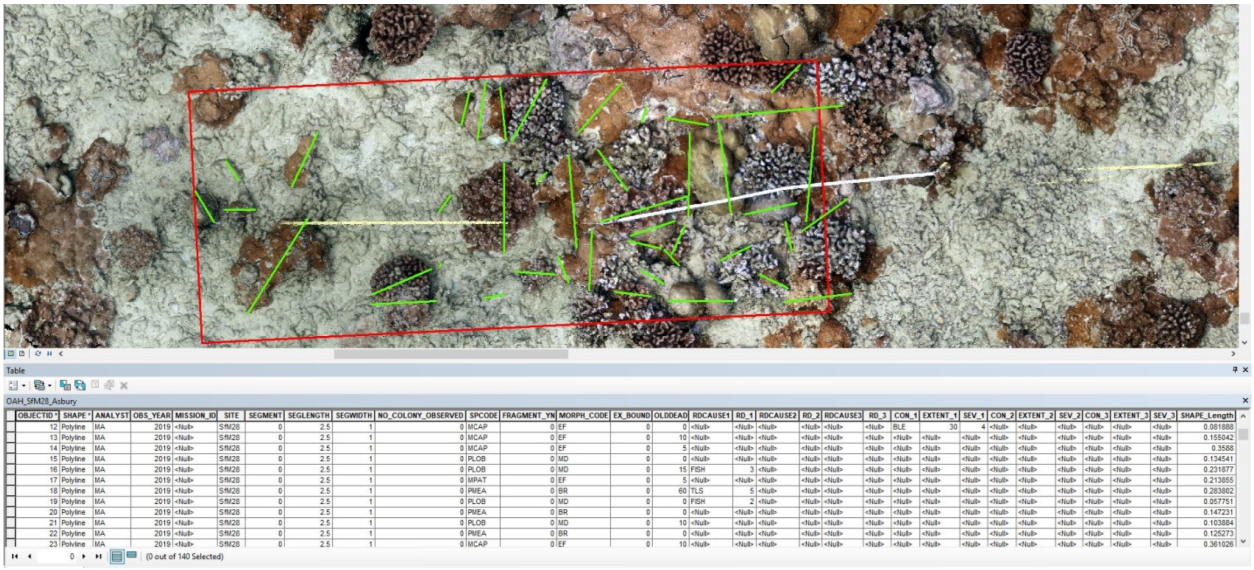


Figure 30. Screenshot in ArcMap once all colonies in the segment are analyzed.

F. 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 is in the geodatabase.

1. Open a blank ArcMap document and open the Catalog.
2. Navigate to your geodatabase, and use the Toggle Contents Panel button to change the view (Figure 31).

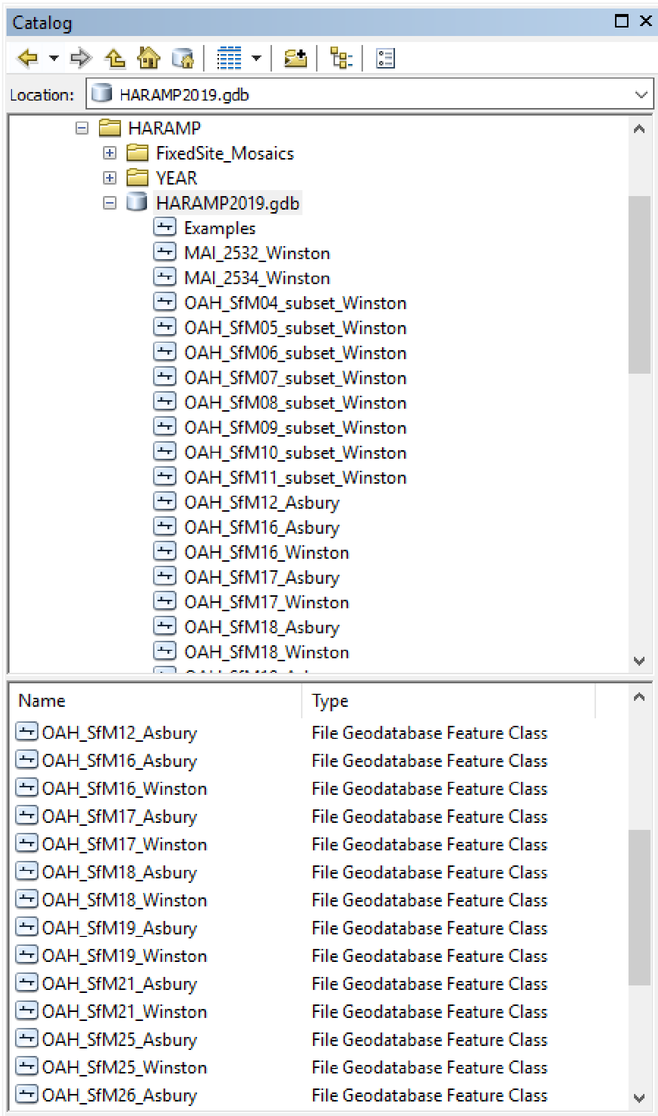


Figure 31. Screenshot of the Catalog window in ArcMap, showing a geodatabase with the different site annotations shown as shapefiles.

3. Using the search toolbar, open the ‘Merge’ (Data Management) Tool.
   Input Datasets: Use Shift + click to highlight all of your site files in the geodatabase shown in the bottom pane of the catalog, and drag and drop
   Output Dataset: navigate to desired saving location.
      Name: missionID_demographics
      Save as type: Feature classes
   Leave everything as shown in ‘Field Map’ (optional).
4. Once complete, a new shapefile with all the data will be in your Table of Contents.
5. Right click to open the Attribute Table.

6. Under ‘Table Options’ choose ‘Export.’

    Export: All records

    Output table: navigate to desired saving location

    Name: missionID_demographics.txt (make sure to type out .txt)

    Save as type: Text file
7. ArcMap will ask “do you want to add the new table to the current map?” = No.
8. Navigate to where you saved your export and make sure it is there.
9. Once finished, close ArcMap (there is no need to save your document).

4. Glossary

ArcGIS: Software used to scale the orthoprojection, 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 3-D set of overlapping data points arranged in space according to position and orientation of each image.

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 ArcMap.

Ground Control Points (GCP): Reference markers placed on the benthos during the survey. Includes scale bar patterns with a known distance between center points.

Mesh: A polygonal model based on the point cloud.

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

Orthophoto (also referred to as orthomosaic): 2-D image of model created by stitching photos together and laying them across a polygonal mesh. Not geometrically accurate and often contains severe artifacting and ghosting.

Orthoprojection: 2-D screenshot of geometrically accurate and oriented dense point cloud. This is created in Viscore and used for analysis and data extraction by ESD.

Orthorectify: Displays a spatially accurate representation of the model.

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.

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

Photogrammetry: A form of technology that allows users to extract three-dimensional information from two-dimensional images taken from stereo or single cameras.

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: 3-D set of overlapping data points aligned by feature matching and the position and orientation of each image

Texture: A texture is created and draped over the mesh, based on the original image quality and texture atlas size (a texture atlas is a large image that has a collection of sub images; each image is a texture map for a part of the whole image which is used to assign texture to that part of the image).

5. References

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Appendix

Creating a Geodatabase

All processes were applied in Esri's ArcGIS Desktop 10.6.1. 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.
    a. File GDB Location: path to a folder where geodatabase is stored.
    b. File GDB Name: name of geodatabase.
    c. 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 drop down 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 32). Name this table according to the geodatabase you are creating (we name according to location and year for better organization; Figure 31).

SEGMENT	SPCODE	MORPH_CODE	EX_BOUND_NAME	RDCAUSE1	CON_1
0	UNKN	EF	-1	DZGN	ALG
5	ACYT	EM	0	WSY	FUG
10	APAN	EC		TLS	SGA
15	AGEM	MD		PUS	PTR
	AHUM	PL		BFI	BIN
	ACSP	BP		BRD	TIN
	CWEL	FO		BBD	PRS
	CYSP	LM		CIL	DIS
	CAGA	LC		PRED	BLE
	COCE	BR		COTS	BLP
	CVAU	KN		FISH	DAMG
	DIAS	CO		GAST	
	FSCU	TB		OVRG	
	FUSP	ML		MACA	
	GPLA	FR		OCTO	
	LBEW			ZOAN	
	LPRU			TUNI	
	LPUR			CORM	
	LTRA			SEDI	
	LINC			DAMG	
	LESP			UNKN	
	MCAP				
	MFLA				

Figure 32. 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
    i. Code Field: field in the input table containing coded values (e.g., SPCODE)
    ii. Description Field: same field as above (SPCODE)
        1. In this field, you could add a column that contains the description for the individual codes, although we do not use this (Figure 33)
        2. Input Workspace: the path to geodatabase created in step 1.
        3. 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 1): condition (CON), exceeds boundary

(EX_BOUND), fragments (FRAGMENT), morphology (MORPH_CODE), no colony observed (NO_COLONY_OBSERVED), recent disease cause (RDCAUSE), segment (SEGMENT), species (SPCODE)

6. Once all list domains are added, create a template polyline feature class in geodatabase using ‘Create Feature Class’ (Data Management) tool.
    a. Feature Class Location: path to geodatabase created in step 1.
    b. Feature Class Name: template
    c. Geometry type: Polyline
    d. Template Feature Class (optional): Leave blank
    e. Has M (optional): DISABLED
    f. Has Z (optional): DISABLED
    g. 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 34).
    a. Input Table: template
    b. Field Name/Field Type/Domain: see Table 2
    c. In this tool, when wanting to create your fields with the drop down menus (the attribute domains you developed earlier using excel), you type the exact name of your ‘Code Field’ in the domain box.

SPCODE_NAME	SPCODE
Unknown Scleractinian	UNKN
Acropora cytherea	ACYT
Acropora paniculata	APAN
Acropora gemmifera	AGEM
Acropora humilis	AHUM
Acropora sp	ACSP
Coscinaraea wellsi	CWEL
Cyphastrea sp	CYSP
Cyphastrea agassizi	CAGA
Cyphastrea ocellina	COCE
Cycloseris vaughani	CVAU
Diaseris sp	DIAS
Fungia scutaria	FSCU
Fungia sp	FUSP
Gardineroseris planulata	GPLA
Leptastrea bewickensis	LBEW
Leptastrea pruinosa	LPRU

Figure 33. Example of descriptive field column for code field.

Table 2. 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		
MISSIONS_ID	TEXT	255	
SITE	TEXT	50	
SEGMENT	SHORT		SEGMENT
SEGLENGTH	FLOAT		
SEGWIDTH	FLOAT		
NO_COLONY_OBSERVED	SHORT		NO_COLONY_ OBSERVED
SPCODE	TEXT	50	SPCODE
FRAGMENT	SHORT		FRAGMENT
MORPH_CODE	TEXT	50	MORPH_CODE
OLD DEAD	SHORT		

Field Name	Field Type	Length	Domain
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		

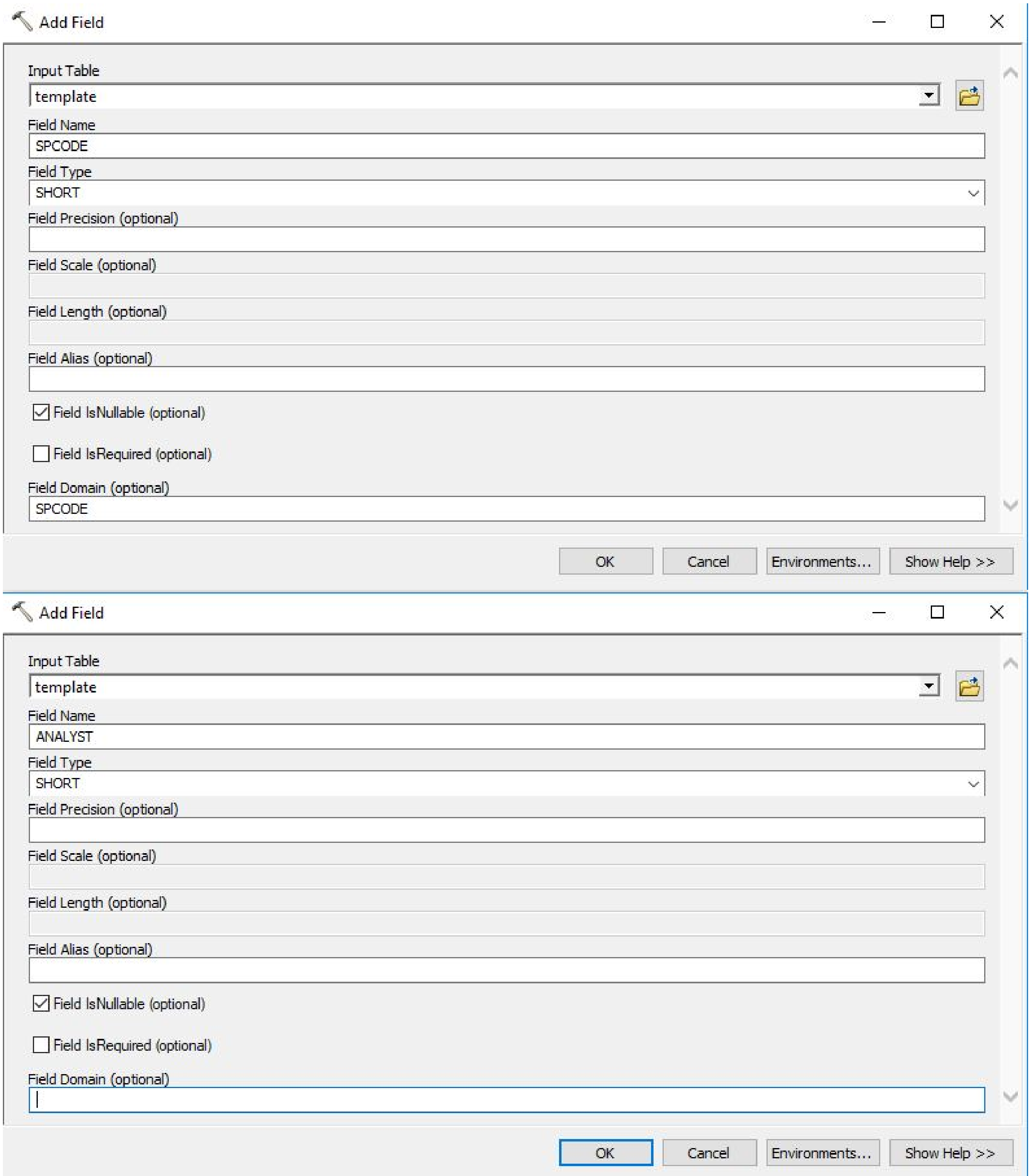

Figure 34. Screenshots of the Add Field tool in ArcMap.