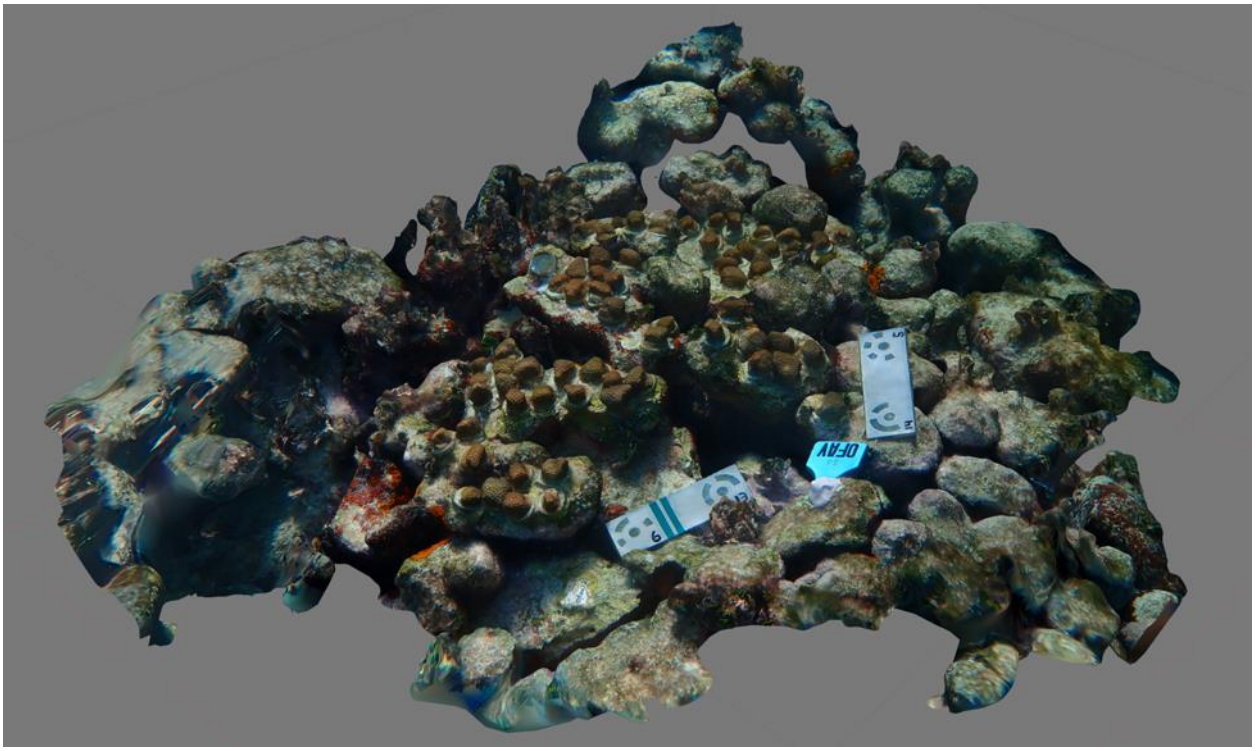
White Paper

October 9, 2023

Coral Restoration Foundation™ 3-Dimensional Monitoring Manual

First Edition - October 2023



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CORAL RESTORATION FOUNDATION™

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Introduction

As coral restoration projects around the world continue to grow, in the number of colonies returned to reefs and the diversity of species utilized in intervention efforts, practitioners and scientists have turned to novel methods in order to monitor progress, assess efficacy, and model coral growth. Photogrammetry[1] techniques that generate 2-dimensional (2-D), orthorectified[2] mosaic images (aka "orthomosaics" or, more simply, "photomosaics") are emerging as important assessment methods. Orthomosaics can facilitate population-level analyses to better assess the impact of restoration efforts over large spatial scales; this is particularly useful when fast-growing, branching species of coral (e.g., *Acropora spp.*) are used, which regularly fragment then reattach across to create thickets beyond the initial outplant "footprint." By digitally measuring corals and other benthic organisms, countless hours of field time can be saved, and standardized measurements (of individuals or groups) can be obtained (for a summary of such a methodology specific to large-scale, coral restoration monitoring see *Neufeld and Fundakowski, 2023*, available at www.coralrestoration.org/white-papers).

While photomosaic techniques are available for branching corals, analogous methodologies for other species are lagging. For example, slow-growing, massive coral species are often outplanted at small sizes, which 2-D methods cannot accurately depict or quantify. Additionally, analyses that rely on the standard estimations of ellipsoid volume, buoyancy, or total linear extension may be able to determine an individual's growth but are limited in their ability to assess population or community-level changes.

Fortunately, photogrammetry and the process of aligning imagery used to create 2-D orthomosaics can be modified to calculate *3-dimensional* (3-D) growth metrics. The methodology outlined herein, while smaller in physical scale and perhaps more niche in application, provides a sophisticated method for accurately calculating the surface area of live tissue and volume for captive, outplanted, or wild coral colonies that vary in size, shape, and growth form.

Goals

Given the limitations of 2-D orthomosaics to sufficiently address important analytical needs of the expanding and diversifying coral restoration field, this document provides a strategy for digitally obtaining total live surface area and volumetric measurements of coral colonies in three dimensions. The technique is demonstrated using multiple software solutions. The process outlined herein involves (a) photographing the coral(s) of interest from 360°; (b) creating a small, high-resolution 3-dimensional model from the photographs using either commercially available or open-source (free) modeling software; and (c) measuring the coral(s) of interest in three dimensions within the modeling software.

This guide will use Coral Restoration Foundation's (CRF™) approach to restoring colonies of *Orbicella spp.* as an example. But the methodology we describe can be readily adapted to other species and in different contexts, such as measuring corals in the wild (e.g., as a substitute for TLE in assessing growth rates of branching colonies). Therefore, this document will be useful to coral reef restoration scientists, practitioners, or resource managers evaluating the growth of outplanted or wild coral colonies at small

[1] Process of analyzing and extracting data on real-world objects from sets of overlapping photographs
[2] Standardized "flattening" of 3-dimensional photogrammetric models into 2-dimensional imagery that corrects for inherent optical distortions related to the apparent sizes and locations of objects in the imagery

spatial scales (<~5m^2 reef area) by calculating 3-D metrics to determine live tissue surface area and/or colony volume.

Part I – In-Water Image Acquisition

In-Water Image Acquisition

To generate an intact 3-dimensional (3-D) model, between 30 and 100 images (depending on the size of the area) must be taken from various points around the area. A small, point-and-shoot camera with good resolution, like the Olympus TG-Tough series, is ideal. Regardless of the camera used, all aspects of the area (i.e., the tops and sides of the colony/outplants and any relevant surroundings) must appear in at least some of the photographs to generate a complete model.

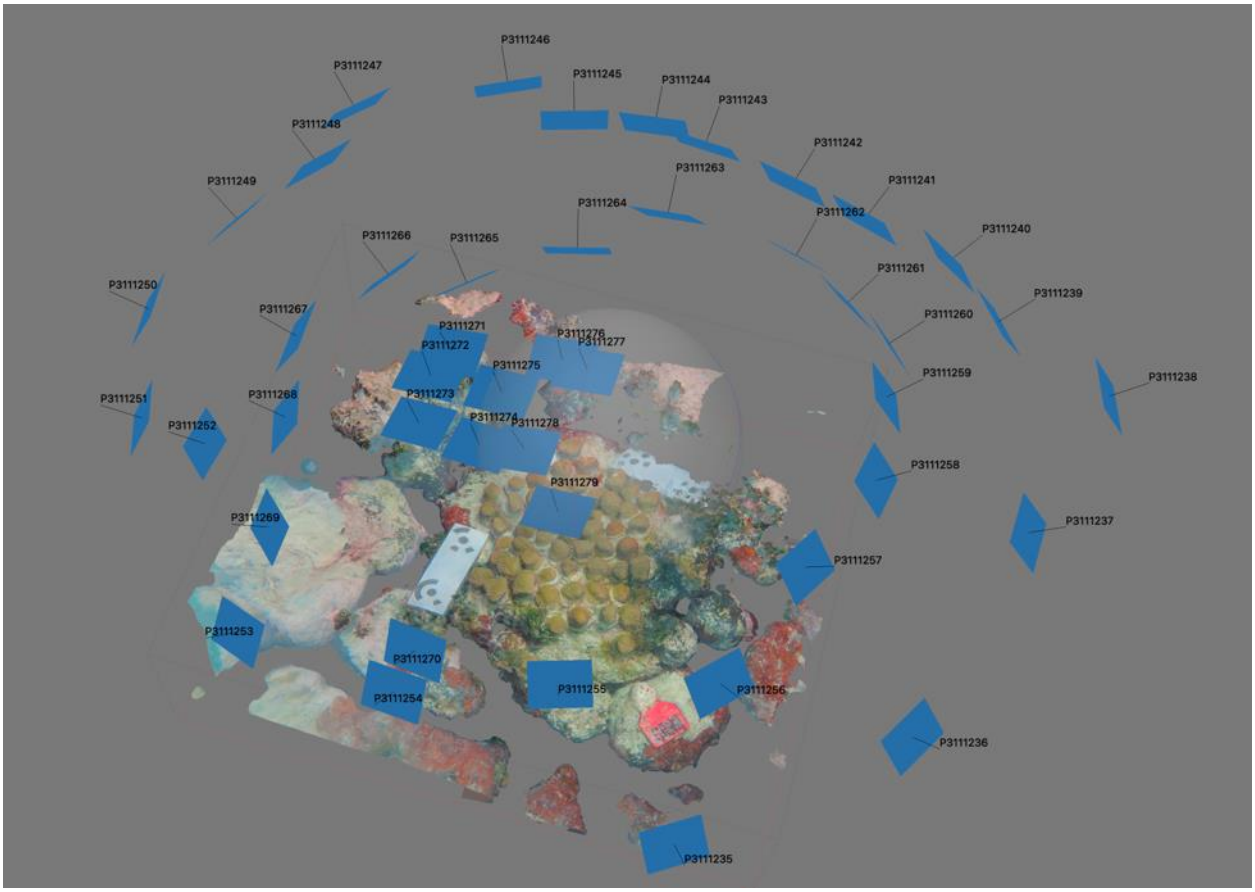
Begin the image acquisition process by placing 2-3 small-scale bars or targets throughout the area to be photographed. Because of the relatively small size of these model areas, small-scale bars in the form of flattened circular disks or rectangular bars are recommended (10-20cm total diameter). For the most accurate scaling measurements, several of these smaller markers should be placed in the area to be photographed. For more information on the coded scale bars that CRF™ uses, see *Neufeld and Fundakowski (2023)* at www.coralrestoration.org/white-papers.

Note: If the user intends to place the resulting 3-D model into Arc-GIS, Viscore, or some other georectification-based application, or if they wish to properly orient the model and produce an orthorectified projection, depth measurements and/or GPS coordinates of the scale bars or some other marker will need to be taken in the field. However, to simply measure aspects of the modeled area in three dimensions according to this document's workflow, these data and rectifications of the model are not necessary; an accurate scaling is sufficient.

CRF™ recommends taking 20-60 images from vantage points surrounding and slightly above the area of interest and then taking 15-30 images from directly above the model area (in the same way the lawnmower pattern captures the top-down imagery for the other photomosaic techniques). The most time-efficient method to acquire images is to swim in a circle around the area to be photographed at approximately 1m from the subject and slightly above the subject so that your camera creates a 45-degree angle to the subject. As you swim the 360-degree circle, take a photograph every 15-20 degrees. Repeat this process a second time, but swim so that you are within 30cm of the subject. The images

taken in this second circular pass do not need to capture the full subject area but rather are used to generate finer detail in the final 3-D model. For large colonies (>1m diameter), it may be necessary to complete two of these closer circular passes- one for the upper 50% of the colony and one for the lower 50% of the colony.

Note: In order for the stitching software to accurately generate a 3-D model, the circular side-view images should minimize the amount of water shown in the background, hence the 45-degree downward angle suggested above.



Completed 3-D model showing the locations of the photographs used. Note the two circular sets of images and the series of top-down photographs near the center.

Part II – 3-D Analysis of Bouldering Corals via Agisoft Metashape

Order of Operations – Model Creation and Analysis

CRF™ utilizes Agisoft Metashape for its 3-D model generation and measurement. This software is commercially available at www.agisoft.com. Open-source software for 3-D model creation and measurement is widely available but may come with a steeper learning curve or other bugs (see "Part II - 3-D Analysis of Bouldering Corals via Free Software" below).

The standard order of operations for creating and analyzing 3-D models of bouldering corals in Agisoft Metashape is as follows:

Model Creation:

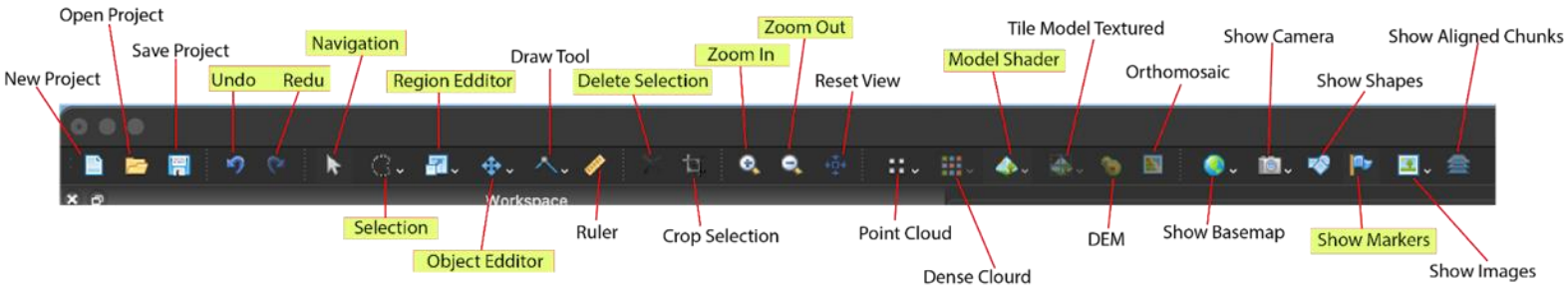
1. Import the photos of the area into Metashape
2. Align the imported photos
3. Build the model's mesh
4. Build the mesh's texture

Assign Scale:

5. Set control points
6. Set a scale for the model

Analyze Coral Surface Area and Volume:

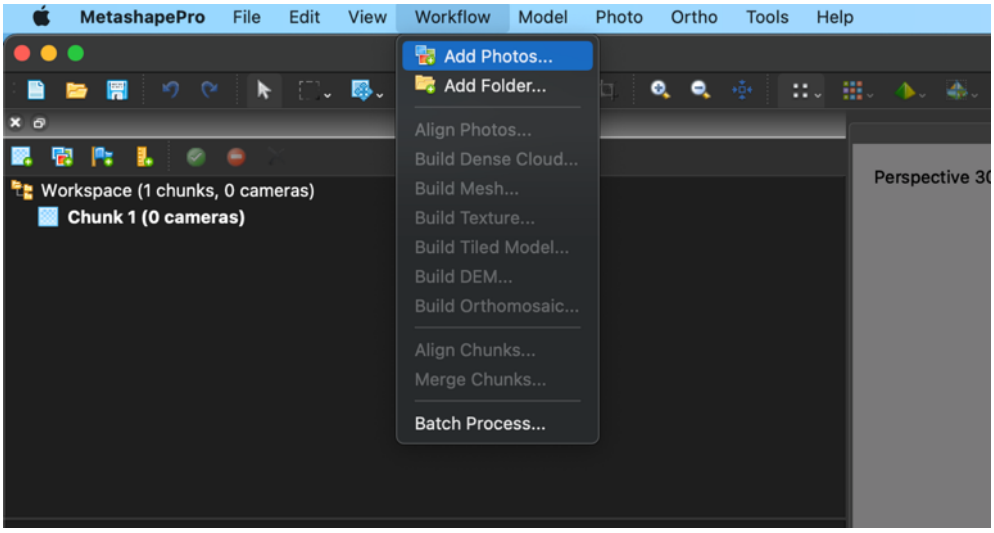
7. Select all live coral tissue
8. Invert the selection
9. Delete selected portion
10. Measure remaining surface area
11. Fill holes in the model
12. Measure the volume of the remaining model



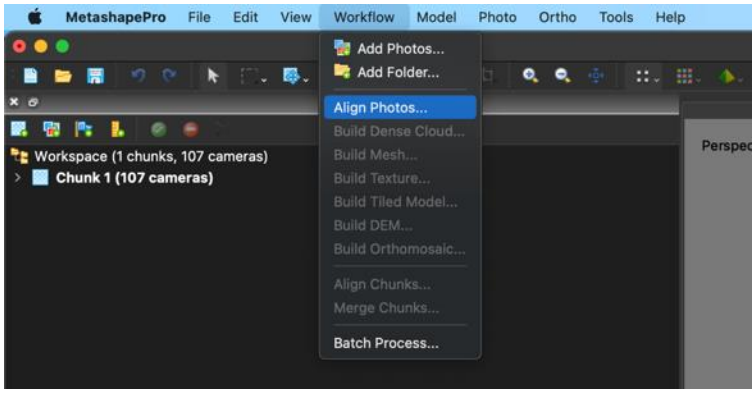
Name and location of Agisoft Metashape toolbar options; highlighted tools are ones used for this method.

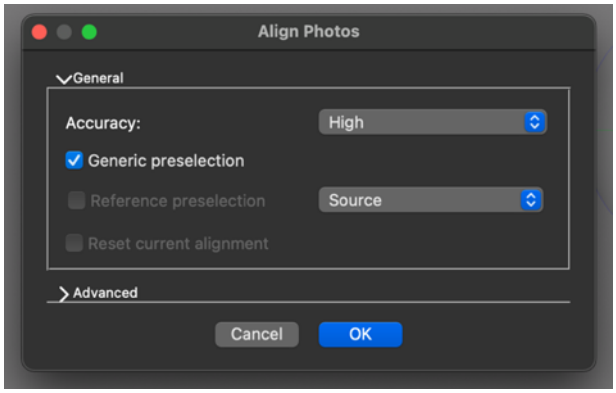
Importing and Aligning Photos, Building Meshes, and Textures

1. Open Agisoft Metashape and import the desired coral cluster photos into the workspace. This can be accomplished either by clicking the icon immediately above the "Workspace" area or by selecting the <Add Photos> option under the <Workflow> menu, as shown below.

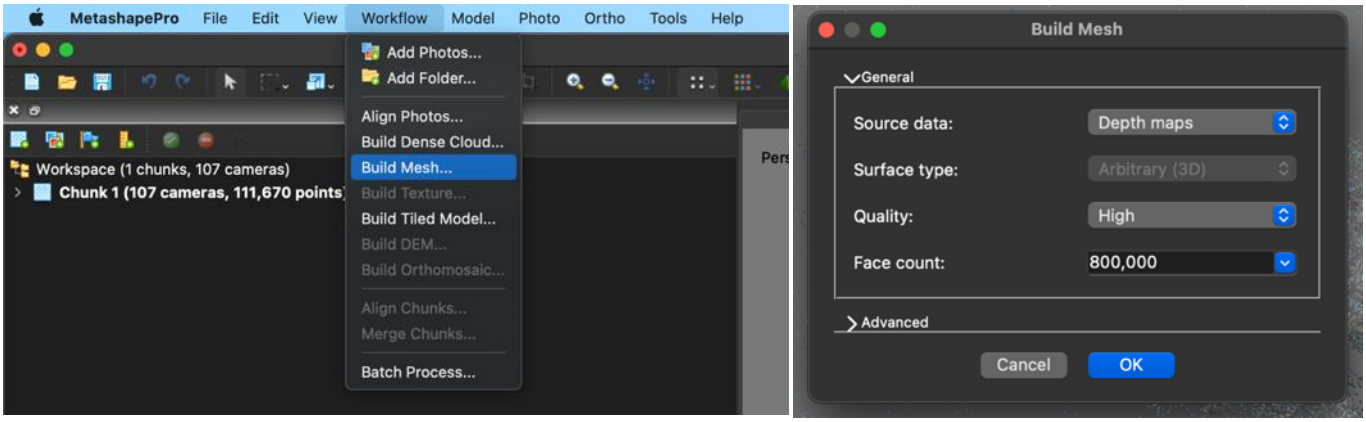


2. Once all photos have been added, the photos can be aligned. From the <Workflow> menu, select <Align Photos>. For most cases, the <High> accuracy setting is sufficient. Click <OK>.
    a. After photos have been aligned, make sure that the point cloud generated from this step resides within the "Region Box" (the thin red outlined cube). Resize it as needed with the "Move Region" tool in the upper left section of the icons.

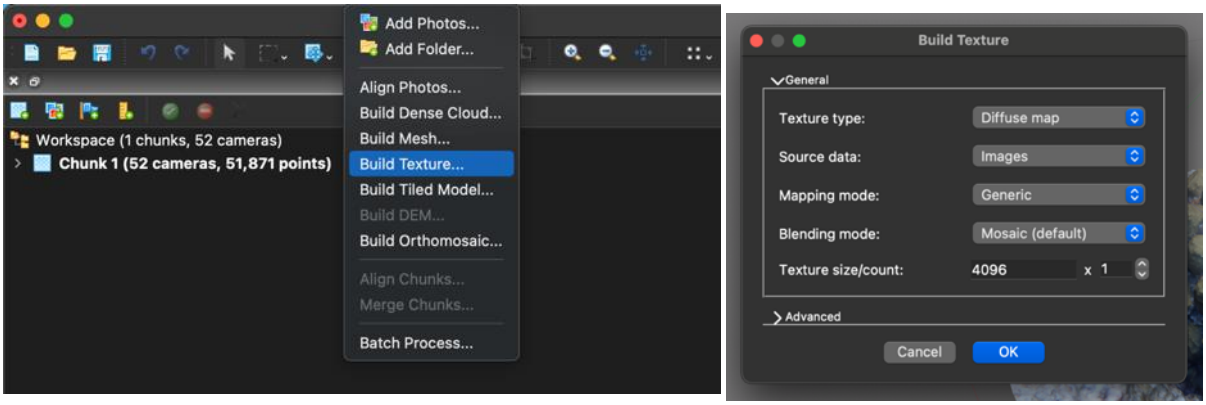




3. After the photos have been aligned, the model's mesh can be built. Under the <Workflow> menu select <Build Mesh>, and then choose <Depth Map> as the "Source data" option, <High> for the "Quality", and a "Face count" of at least <800,000>. Click <OK>.



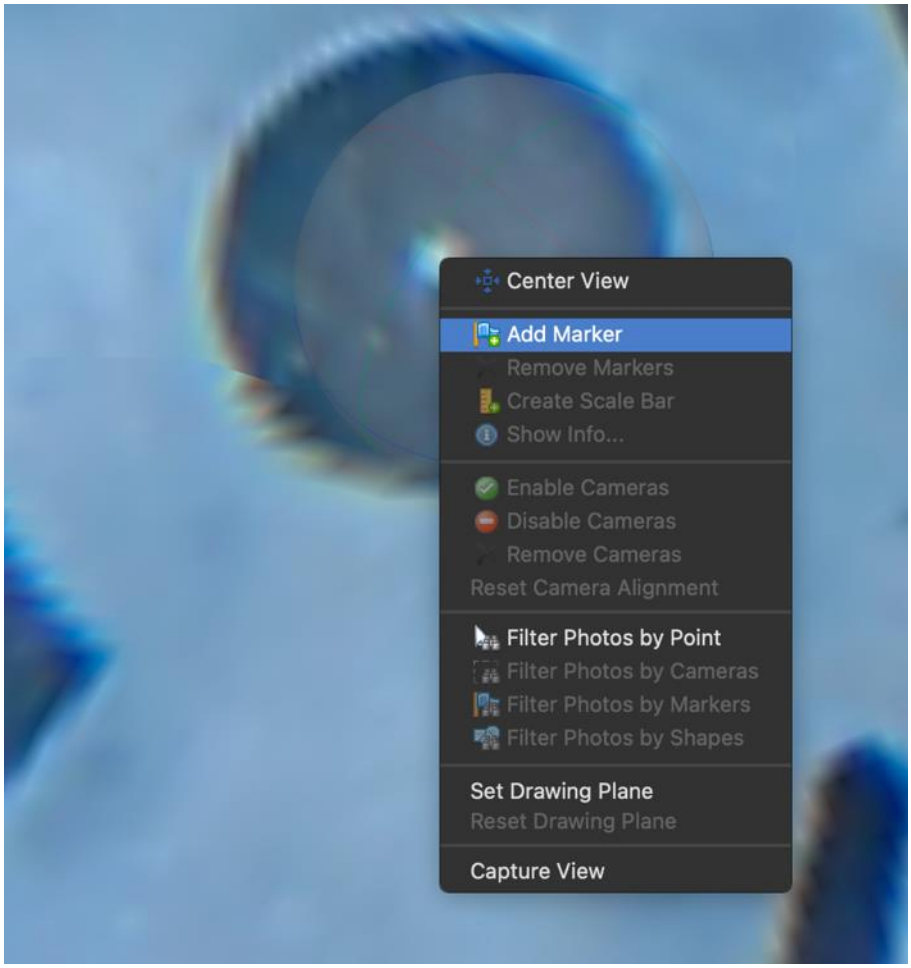
4. After the mesh is built, build the texture for the model by selecting the <Workflow> menu, then choosing <Build Texture>. Accept the default settings and click <OK>.



Assigning Scale

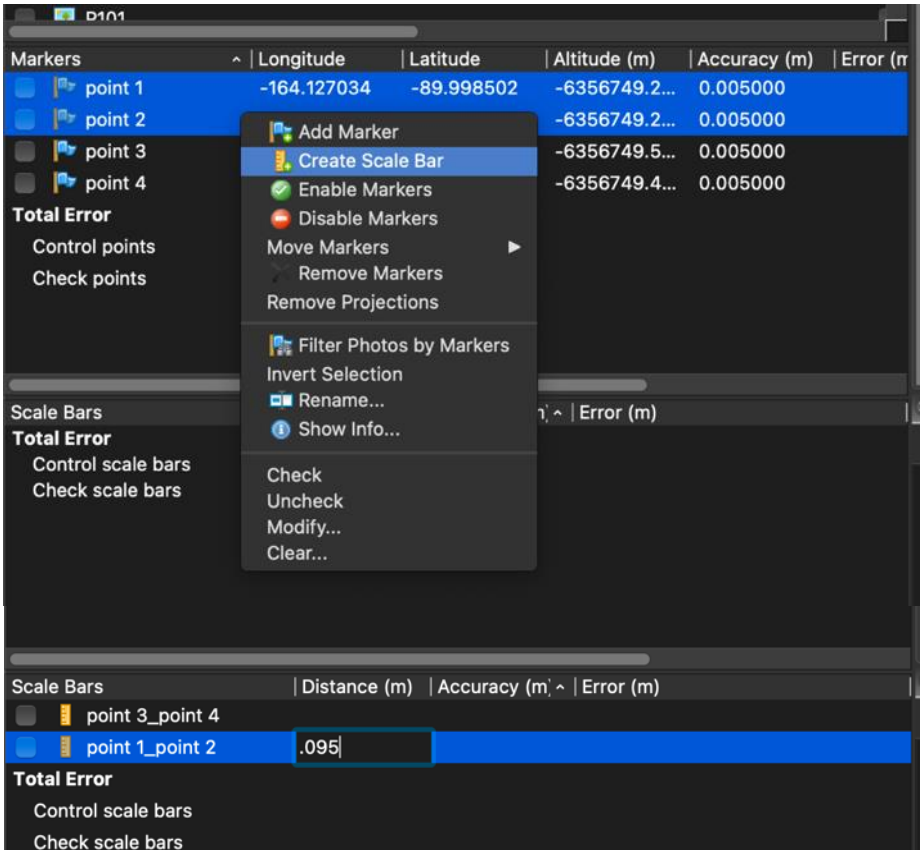
Now that the model's mesh has been created and textured, a scale must be assigned to the model so that measurements can be made within Metashape. This process starts by carefully selecting points on the mesh to set as control points. For this workflow, the points will be placed on the coded, 12-bit target scale bars that were used during the initial in-water image acquisition.

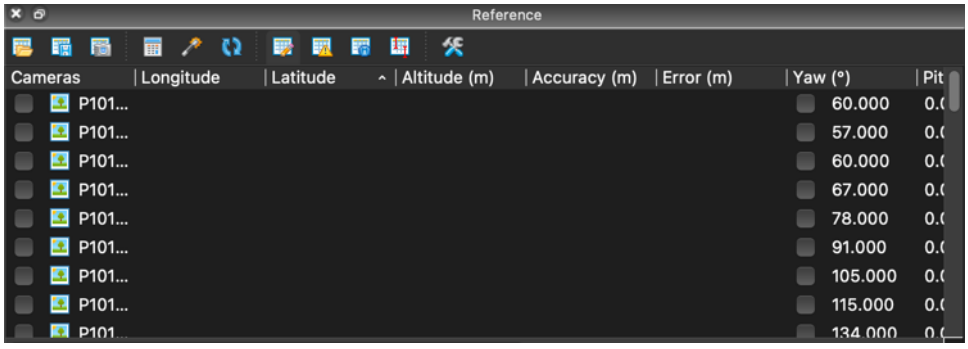
1. On the model, find a target, right-click, and select <Add Marker>. A small flag should be placed on the model in this location. If no flag appears, it is likely that the viewing option for markers is toggled off; simply turn this on by clicking the "Marker" icon (a small blue flag) in the top toolbar.



2. Repeat this step for each target present in the model.
    a. The steps of placing markers can be accomplished in two additional ways:
        i. From the <Tools> menu, select <Detect Markers>. If coded targets from Agisoft are used, this method is automatic but may be less accurate than the other methods described.
        ii. Filter the original photographs used to generate the model by right-clicking on a marker in the model, then choosing <Filter Photos by Point>. Then place your marker in the correct location on the photo (right-click, <Add Marker>). This marker will now be seen in additional photographs containing this point. To ensure accuracy, select several of these additional photographs and correct the marker's automatically determined location (if inaccurate) by clicking and dragging the flag icon on the photograph. This method is the most accurate and the most time-consuming.
3. All markers added to the mesh will be listed in the "Reference" panel (see below).
    a. In this window, highlight the two markers of a scale bar (hold the "SHIFT" key while clicking). Check that these points both reside on the same scale bar.

b. Right-click on either highlighted marker and then choose <Create Scale>, and a new line will appear in the "Scale Bars" panel below.
c. Double-click on the empty area under the "Distance" column and enter the known distance in meters. Press "ENTER" on the keyboard.
d. Repeat for all scale bars present in the model, then ensure the tick box on the left of each scale bar is selected.
e. Refresh the model in the reference window by clicking the blue circular "Refresh" button in the "Reference" panel toolbar. Above the "Reference" panel, the selected "Chunk" should show [S] at the end of the chunk name.





Use the circular arrows icon (above "Longitude") to refresh the model and apply a created scale bar.

If the model is to be placed into an Arc-GIS, Viscore, or a similarly georectified workspace, or if orthorectification is desired, enter the depths and locations for scale bars or other markers now. Additional information on including depth marker data can be found in *Neufeld and Fundakowski (2023)*, available at www.coralrestoration.org/white-papers.

Analysis – Selecting Corals for Analysis

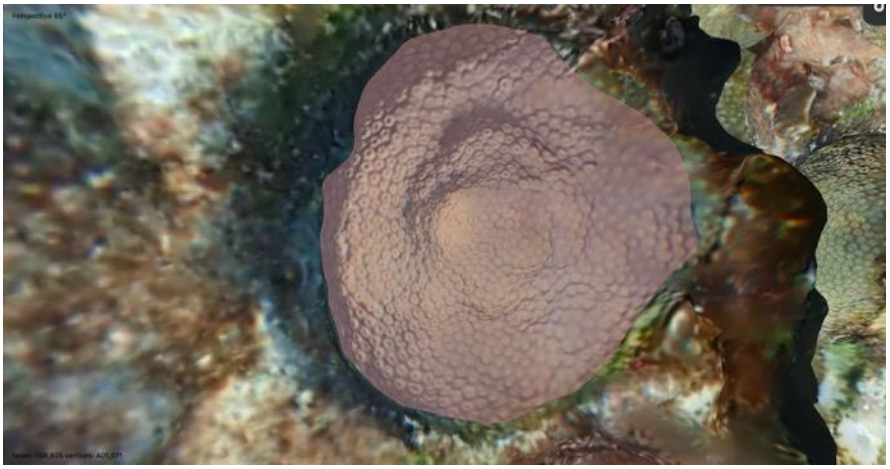
Once the model has been scaled appropriately, tracing and analysis can be conducted. Properly orienting the model before selecting any coral tissue is an important determinant for the speed and efficiency at which this process can be done.

1. Select the "Navigation" tool and double-click on the desired coral to set an anchor point; this will create a pivot point so when the model is moved with the navigation ball, this point will always be in the center.
2. Click and hold the grey navigation ball and rotate the model to obtain the appropriate viewpoint. For best results with rounded or dome-shaped corals, align the view from the underside of the model so that the viewer is looking straight down the barrel of the coral (i.e., can see all sides and the top of the coral colony).
    a. The goal is to get the entirety of the coral into view without obstruction in front of or behind it. Viewing the coral or model from the top-down will often result in such obstructions and, thus, the selection of underlying, non-coral material from elsewhere in the model.

View of a coral colony to be selected and analyzed from the underside of the full model.

3. Once the coral is properly oriented, click the bottom right corner of the "Selection" tool on the toolbar, then choose the <Freehand> option.
4. Trace the boundaries of the coral tissue on the chosen coral. To ensure that all coral tissue has been included in the light pink selection, return periodically to the "Navigation" tool, rotate the model, and add to or subtract from selection as needed.

a. For Mac users, the "COMMAND" key must be held when adding to an existing selection. Windows users need to hold "CONTROL". Without this, the first selection will be lost (neither Agisoft's "Undo" tool nor the common "COMMAND/CONTROL-Z" keyboard shortcut will reproduce a lost selection). To remove excess selections, hold down the "SHIFT" key on the keyboard and draw around the extra selections (the "COMMAND/CONTROL" key does not need to be held down for the removal of selections).



A fully traced and selected coral colony, viewed from the underside of the model.

In cases where multiple corals are analyzed in one model, repeat this process until all the corals are selected, remembering to hold "COMMAND/CONTROL" while adding new selections.

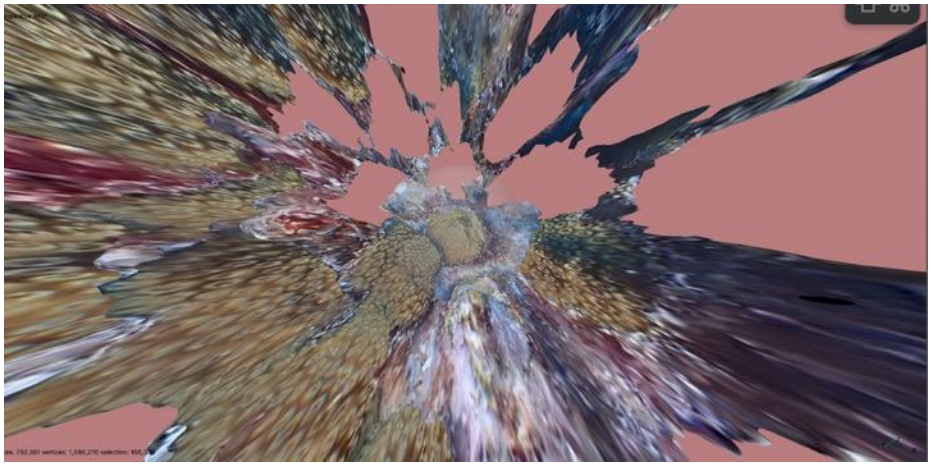
To recap the process:

1. Using the "Navigation" tool, choose a coral to measure and anchor it with by double-clicking coral in the model
2. Rotate the model to the underside view of the chosen coral
3. With the "Selection" tool, draw around the perimeter of the coral tissue
4. Double-check that all the coral has been selected and make additions or subtractions
5. Repeat for any additional corals, if desired (remember that "COMMAND/CONTROL" must be held down to make multiple selections.

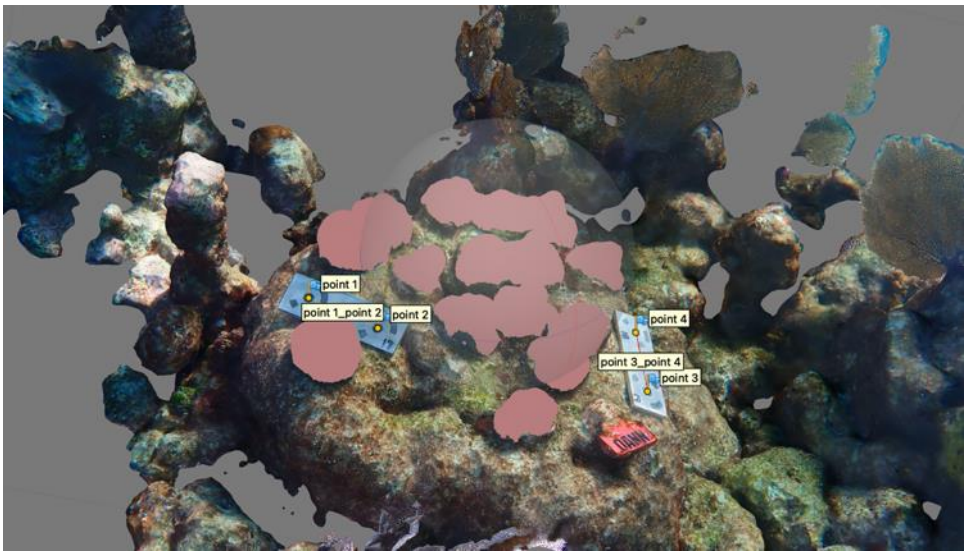
Tips and Tricks

- When making multiple selections, instead of continuously holding down the "COMMAND/CONTROL" button, go into the computer keyboard settings and enable Sticky Keys. This will effectively leave the "COMMAND/CONTROL" key in the "on" position.
- When Sticky Keys is "on" for the "COMMAND/CONTROL" key, switching between the "Selection" tool and the "Navigation" tool will have secondary actions. For example, the "Navigation" tool changes from a rotating tool to a panning tool. Zooming in and out now changes the perceived focal length of the model and can have some very disorienting views (in some instances, however, this effect can be used to help select all visible coral in a singular view).

- It is recommended that Sticky Keys be turned off when orienting the model. However, remember to turn it back on when making more selections.
    - On Mac computers, enabling Sticky Keys and then pressing "COMMAND" will only keep "COMMAND" turned "on" for one action. To keep "Command" held down indefinitely, simply press "COMMAND" twice after enabling Sticky Keys.
- In Metashape, the space bar can be used to toggle between the current tool and the previous tool. This simplifies toggling between the "Navigation" and "Selection" tools while rotating/orienting the model and tracing the model.
- Keystroke shortcut order of operations:
    - Orient the model normally with the "Navigation" tool
    - Choose the "Selection" tool
    - Enable Sticky Keys
    - Press "COMMAND" twice when ready to trace
    - Press "COMMAND" once to turn the Sticky Keys off
    - Press the "SPACE BAR" to move back to the "Navigation" tool
    - Rotate and double-check selection area
        - If adding missing coral tissue, press the "SPACE BAR" and then "COMMAND" twice before adding to the selection
        - If subtracting from the selection, press "SPACE BAR" and then press and hold "SHIFT" while encircling areas to be removed
    - Double-click on the next coral to be selected and repeat



The effect of zooming in or out on a model while the "COMMAND" key is held.

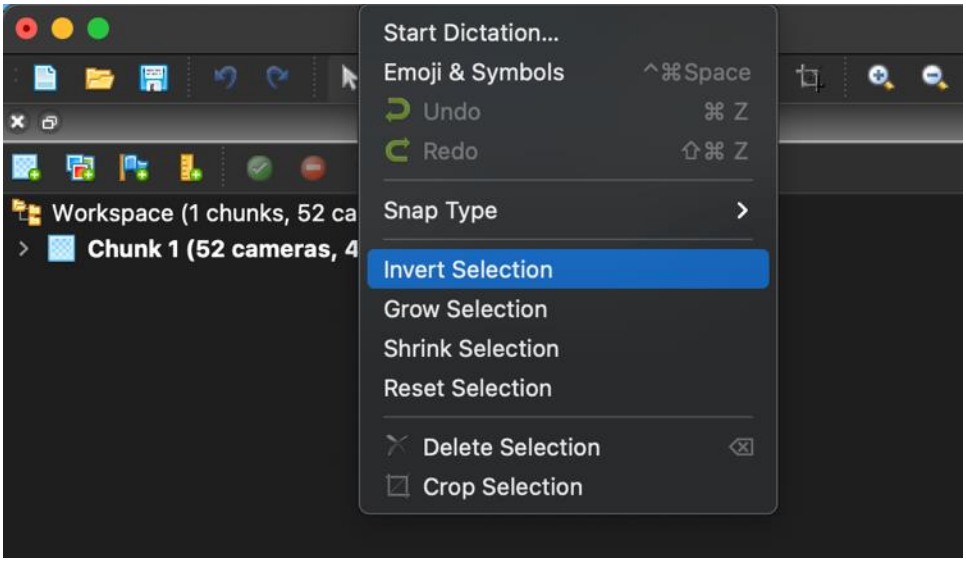


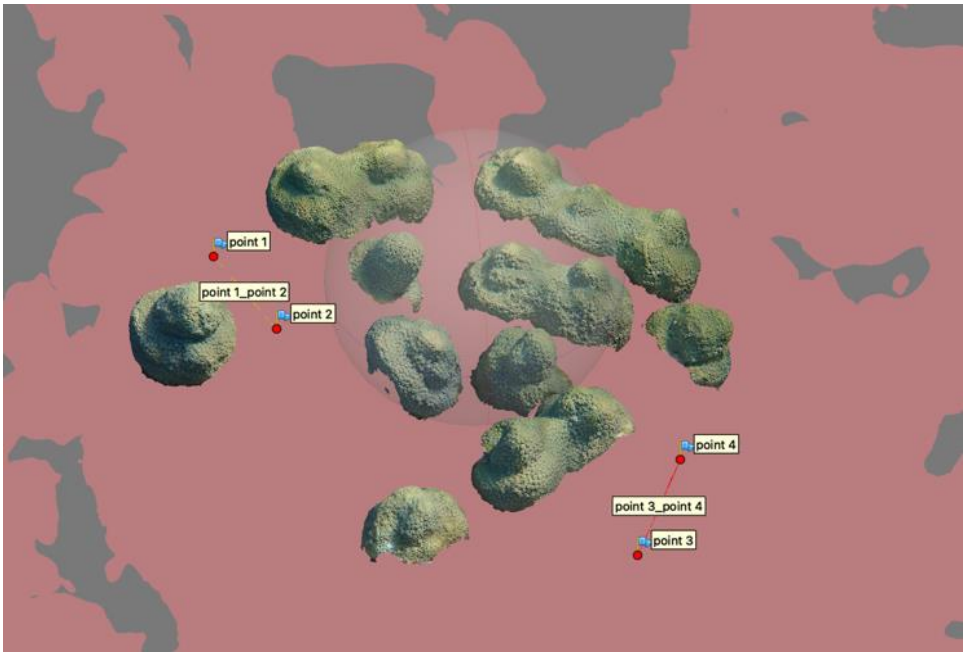
A fully selected model, where each coral to be measured has been selected.

Analysis – Measuring Surface Area and Volume of the Selection

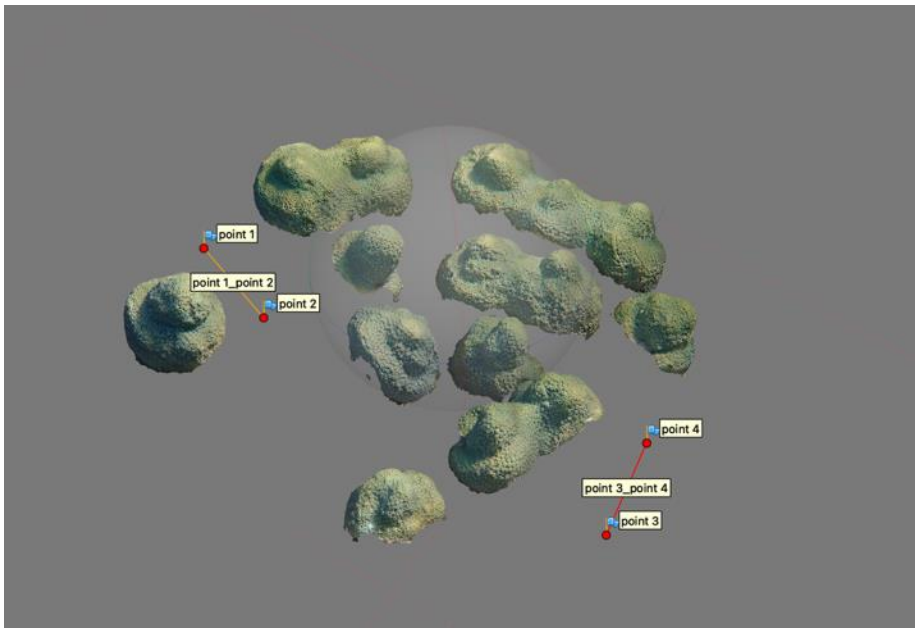
Once all the coral tissue has been selected, it is ready to be analyzed.

1. To begin this process, go to the <Edit> menu at the top left of the screen and select <Invert Selection>. Press the "DELETE" key to remove all non-coral portions of the model.





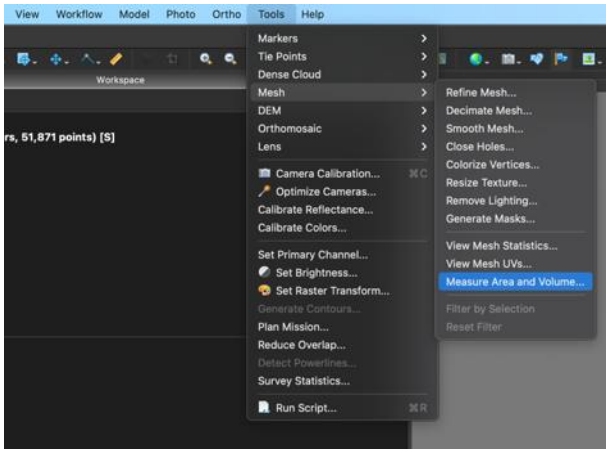
2. The model should now only include the coral tissue and the scale bar lines created in the earlier scaling step.

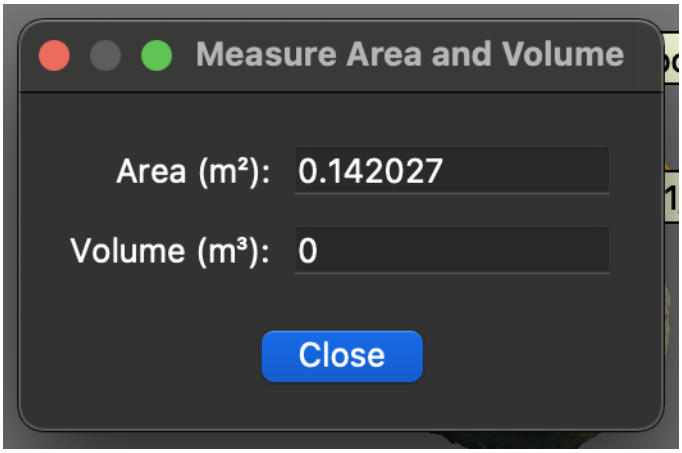


Updated model showing only corals to be measured, following the inversion of the original selection and deletion of non-coral portions of the model.

Now that there is only the coral left in the model, the surface area of the remaining selection can be measured.

1. In the <Tools> menu, choose <Mesh> and then <Measure Area and Volume>.
2. The small dialogue box will give two numbers:
    a. Surface area (m^2) of the remaining selection.
    b. Volume (m^3) (note that at this time, the volume value will be 0, as Metashape cannot complete this calculation while the model mesh has holes).





3. To calculate volume, follow the <Tools> menu again, but now select <Mesh> and then <Fill Holes>.
4. In the dialogue box, move the slider to 100% and click <OK>.
5. Pink polygons will appear under the coral tissue, filling the underside of your selection.
6. With the holes in the model filled, follow <Tools>, then <Mesh> and then <Measure Area and Volume>, as before.
    a. Again, a small box will appear with values for surface area and volume; however, note that the surface area value is now inaccurate, as the surfaces used to fill the model's holes in the previous steps are now included in that measurement.

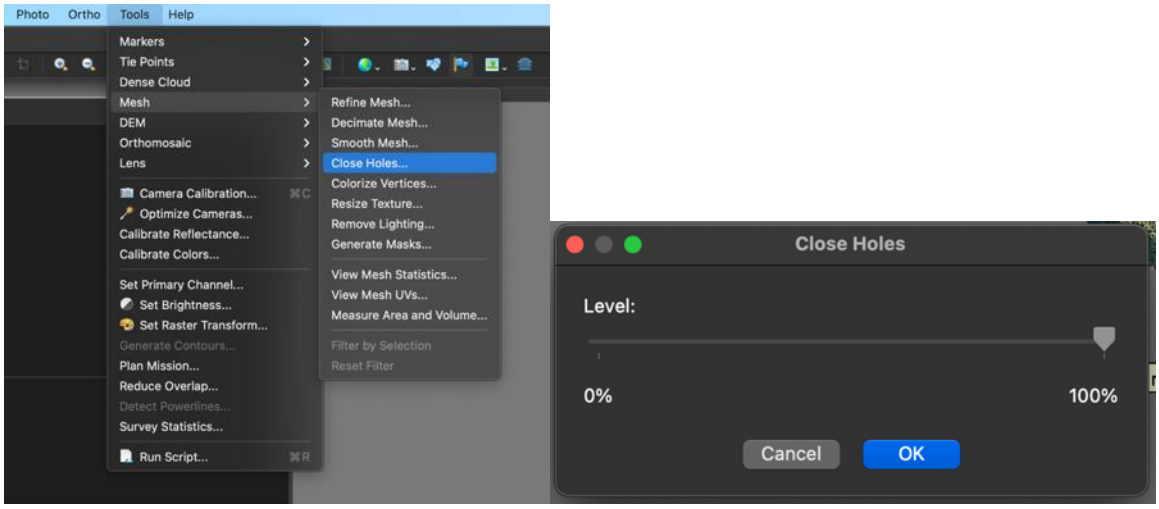


Photo
Ortho
Tools
Help
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Tie Points
Dense Cloud
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Orthomosaic
Lens
Camera Calibration...
Optimize Cameras...
Calibrate Reflectance...
Calibrate Colors...
Set Primary Channel...
Set Brightness...
Set Raster Transform...
Generate Contours...
Plan Mission...
Reduce Overlap...
Detect Powerlines...
Survey Statistics...
Run Script...
Refine Mesh...
Decimate Mesh...
Smooth Mesh...
Close Holes...
Colorize Vertices...
Resize Texture...
Remove Lighting...
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View Mesh UVs...
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Close Holes
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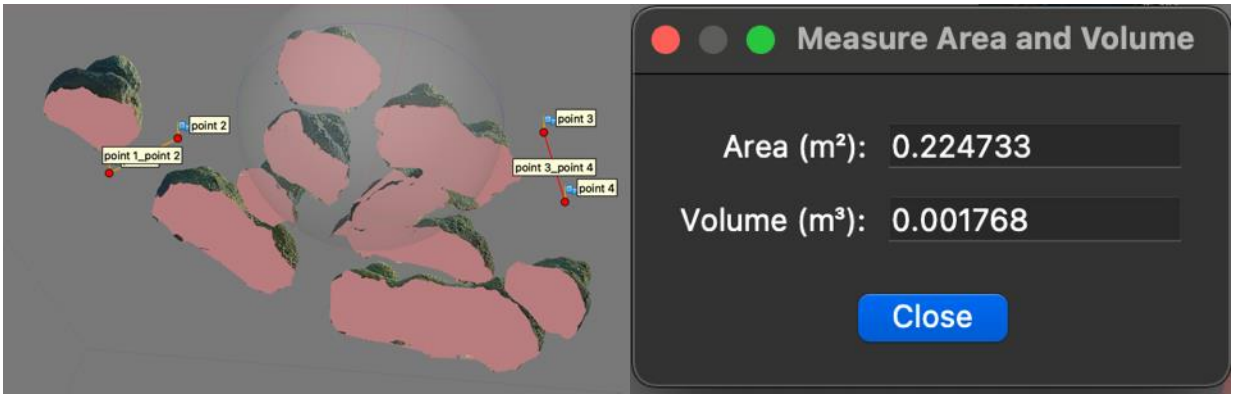
0%
100%
Cancel
OK


point 2
point 1_point 2
point 3
point 3_point 4
point 4
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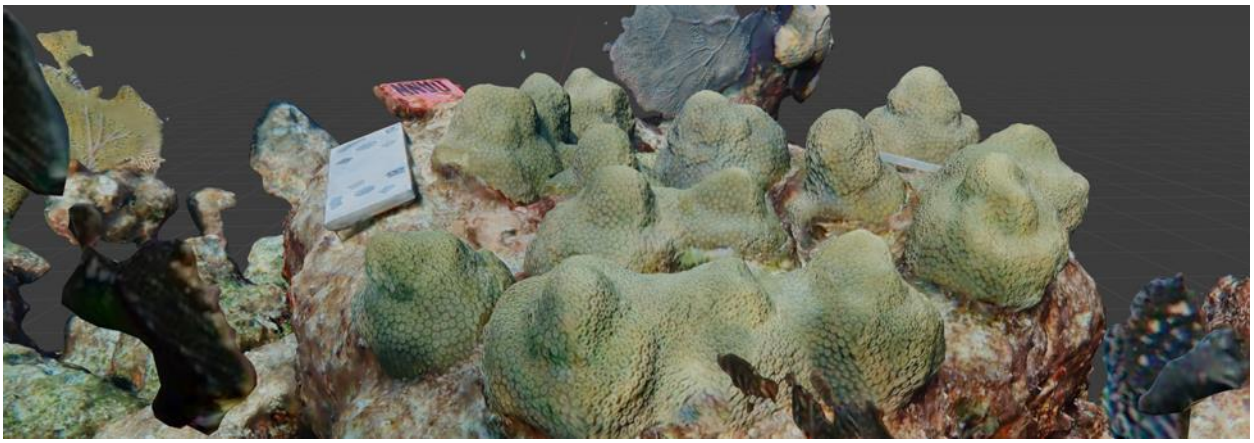
Volume (m³): 0.001768
Close

Part III – 3-D Modeling & Analysis of Bouldering Corals via Free Software



Regard3D and Blender

This section of the paper aims to offer a second, less costly method to generate similar results to the above Metashape-based method of measuring corals in three dimensions. Regard3D is a free, open-source software (www.regard3d.org) that can build three-dimensional models from photographs, but its user interface, efficiency, and usability are not on par with Metashape. After models have been generated with Regard3D, Blender (a free and open-source 3D modeling software, www.blender.org) is used to select and measure corals within the constructed model. Both programs are free to download and use, and with them, CRF generated results comparable to the Metashape method during initial testing. However, this Regard3D/Blender method is less intuitive, and while most settings are left on default, there are a few crucial options that must be changed to acquire a "clean" model and accurate measurements. The example data/screenshots in this section use the same photo set as the above Metashape analysis.

Order of Operations

The standard order of operations for the alternative free method (using Regard3D and Blender) is as follows:

Creating the three-dimensional model in Regard3D:

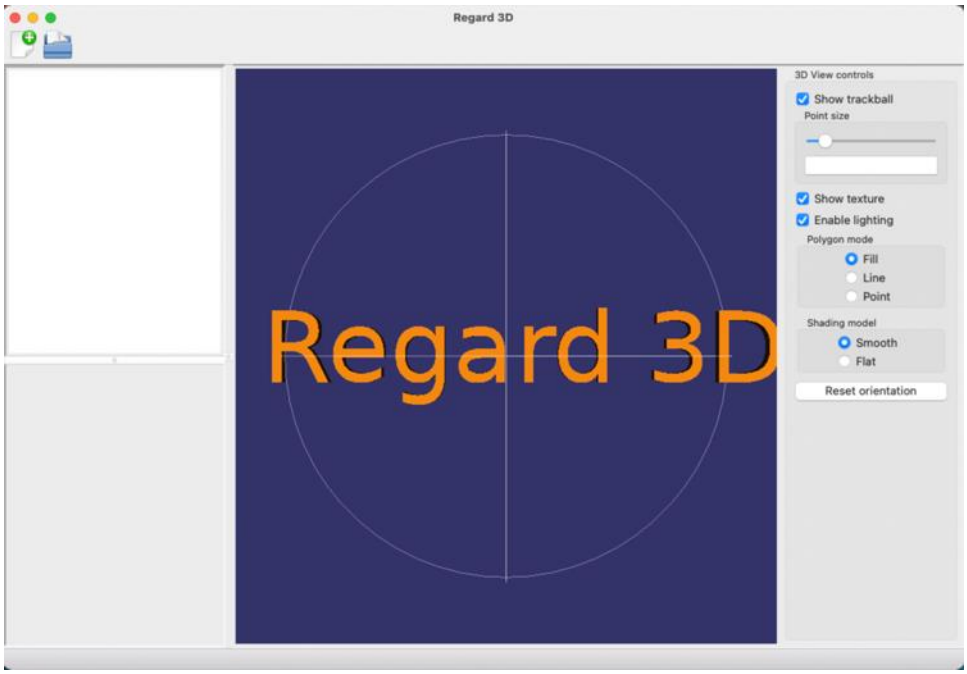
1. Add a new project
2. Add a picture set
3. Compute matches within the photos
4. Triangulation
5. Create a dense point cloud
6. Create a surface

Analysis of the model in Blender:

7. Import the model generated in Regard3D
8. Add 3D print plug-in to Blender
9. Scale the model
10. Select all the coral tissue
11. Invert the selection and remove non-corals
12. Align all remaining corals on the same plane
13. Measure surface area and volume

Note: While the in-water image acquisition process for Regard3D and Blender is identical to that of Agisoft Metashape, be aware that the process for acquiring photos for these free software solutions must be very efficient. Photo sets larger than 30-40 images per model can take a very long time to complete and may cause the programs to crash, even on a powerful computer.

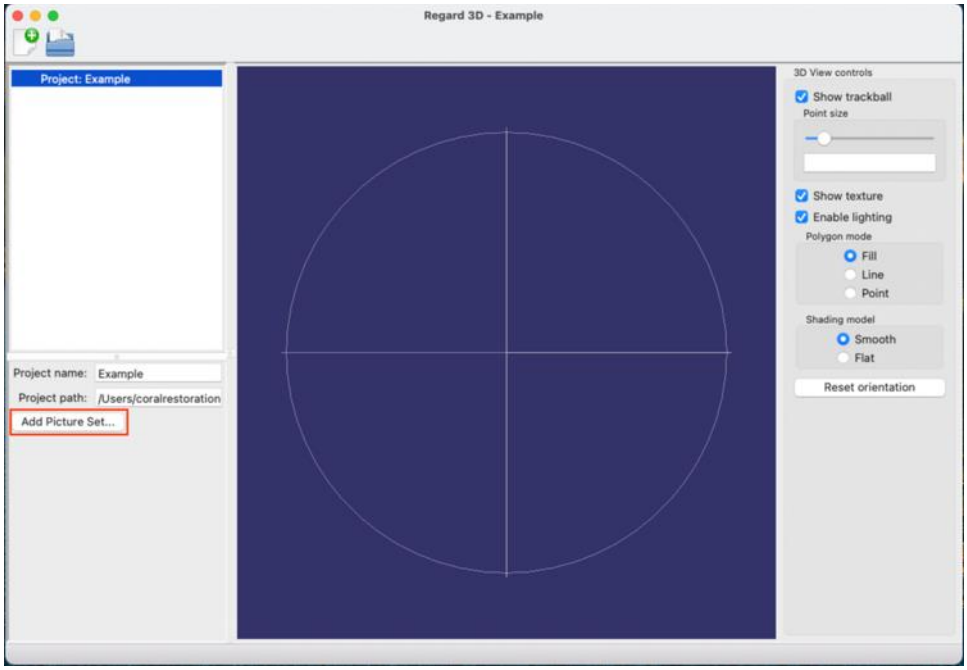
Model Creation Using Regard3D

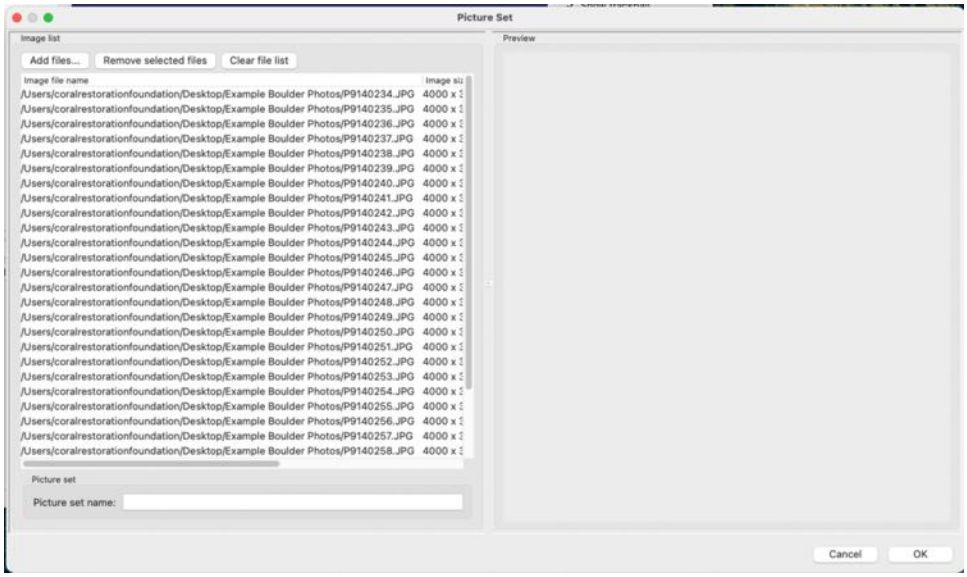


After opening Regard3D, create a new project using the "Paper+" icon at the top left of the window. Choose a save location and name for the project file.

After this, a new option will appear in the lower-left quadrant.

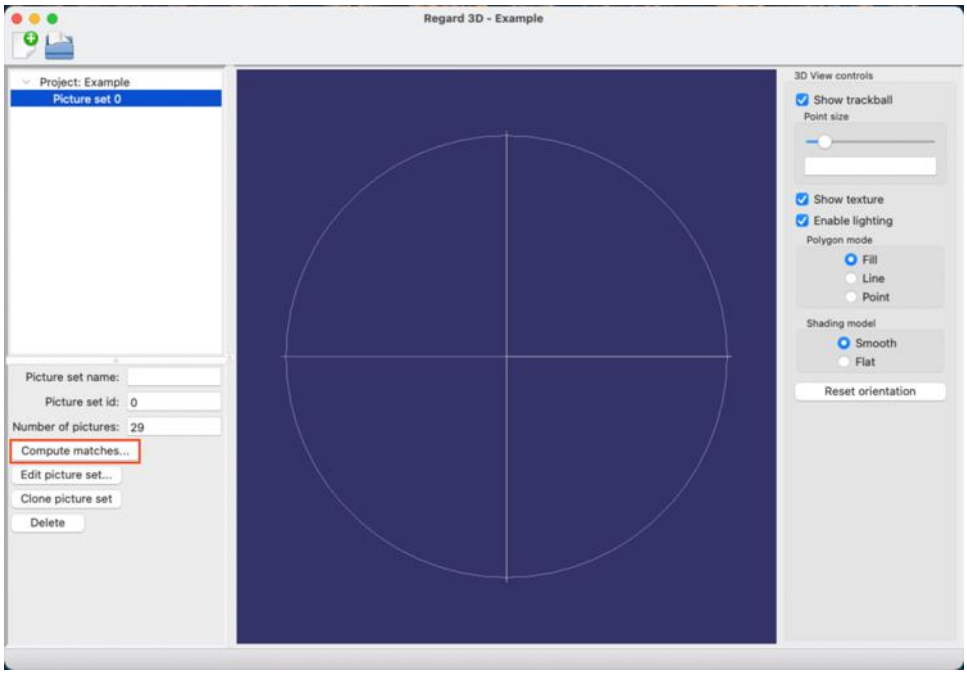
1. Select <Add Picture Set…> and add the image files that will be used to create the model.
    a. The window will fill with the image names and their metadata. At times, the metadata fields will be incomplete. To solve this, right-click in the area that says "N/A" and fill in the missing information. Filling in one cell will automatically fill in the rest. Select <OK> when everything is complete. If an error message appears, the picture set must be deleted and re-added, as the rest of the steps will not calculate properly if the error is ignored.

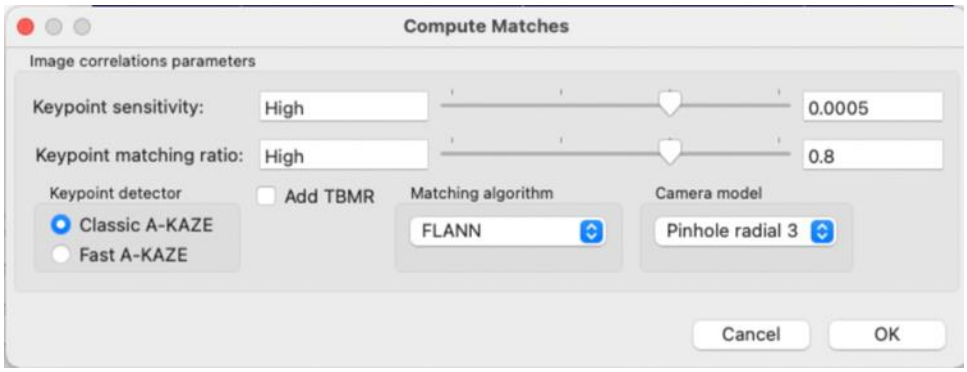




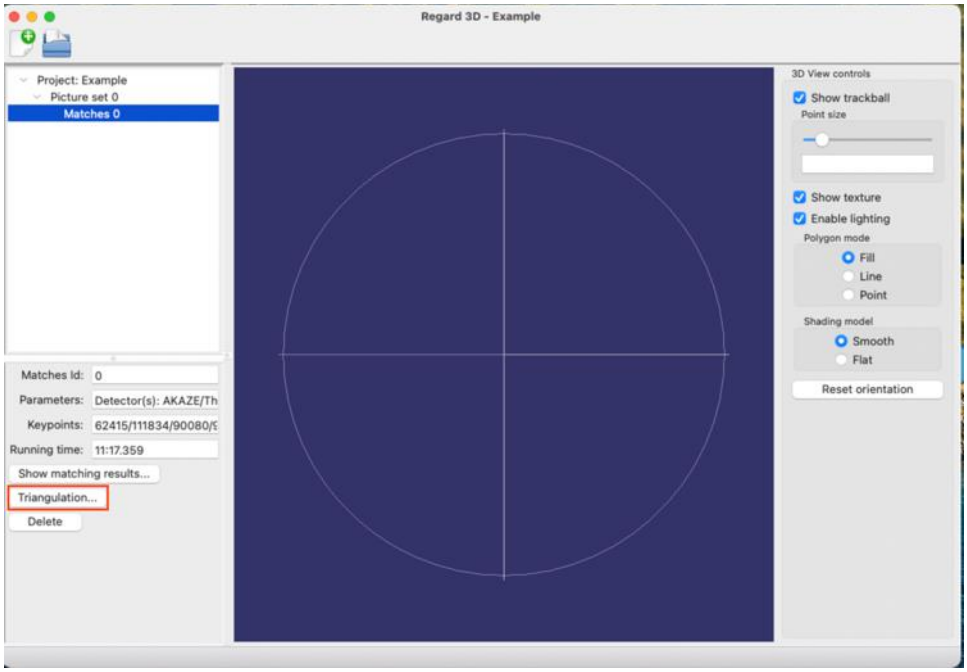
2. Select <Compute matches…> and a window will appear with various options.
    a. For “Keypoint sensitivity”, move the slider to <0.0005>.
    b. For the “Keypoint matching ratio”, move the slider to <0.8>.
    c. The remaining options should be set as follows:
        i. “Keypoint detector” to <Classic-A-KAZE>
        ii. “Add TBMR” should be left unchecked
        iii. “Matching algorithm” set to <FLANN>
        iv. “Camera model” set to <Pinhole radial 3>

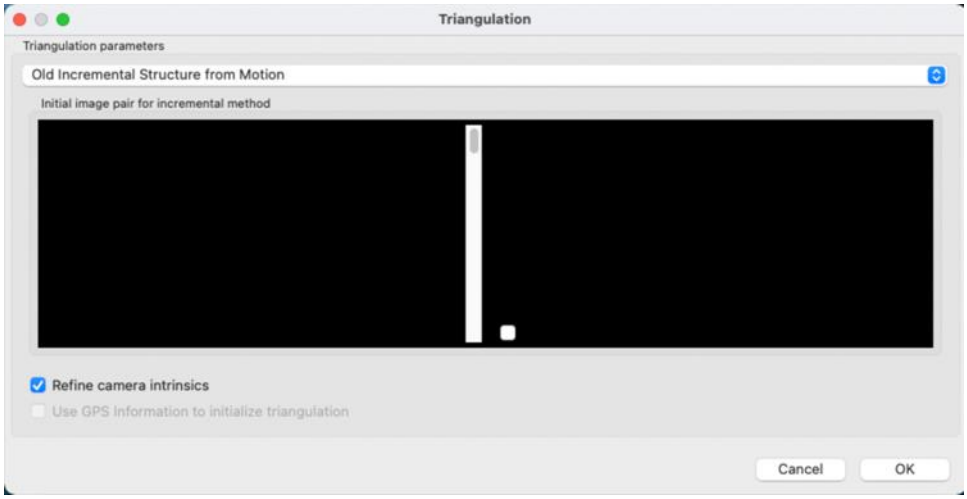
d. Altering these and other options will add significant calculation time with little increase in result quality.
e. Select <OK>.



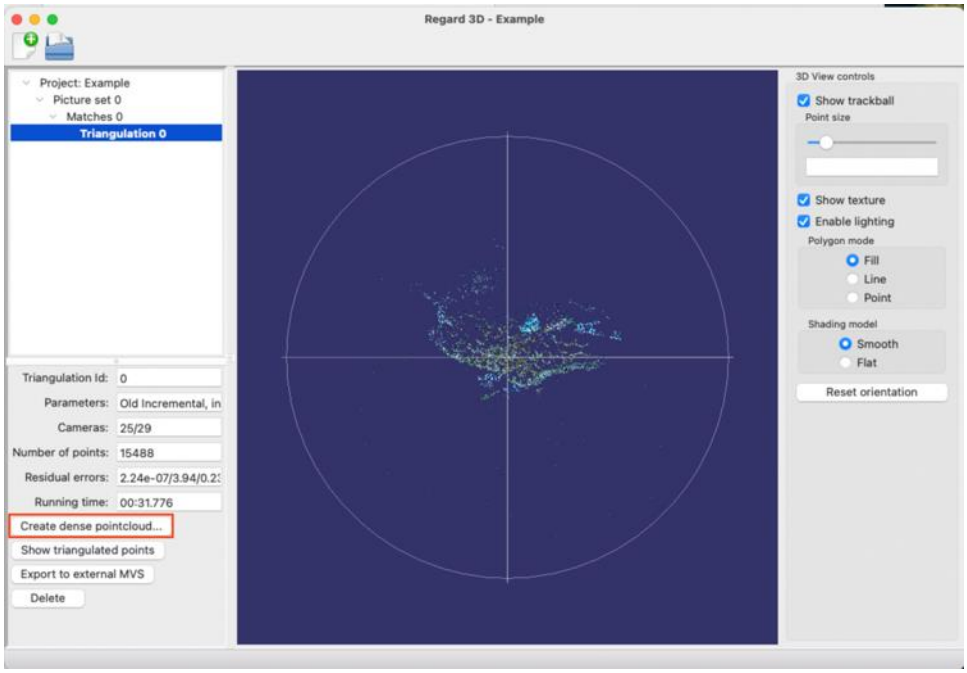


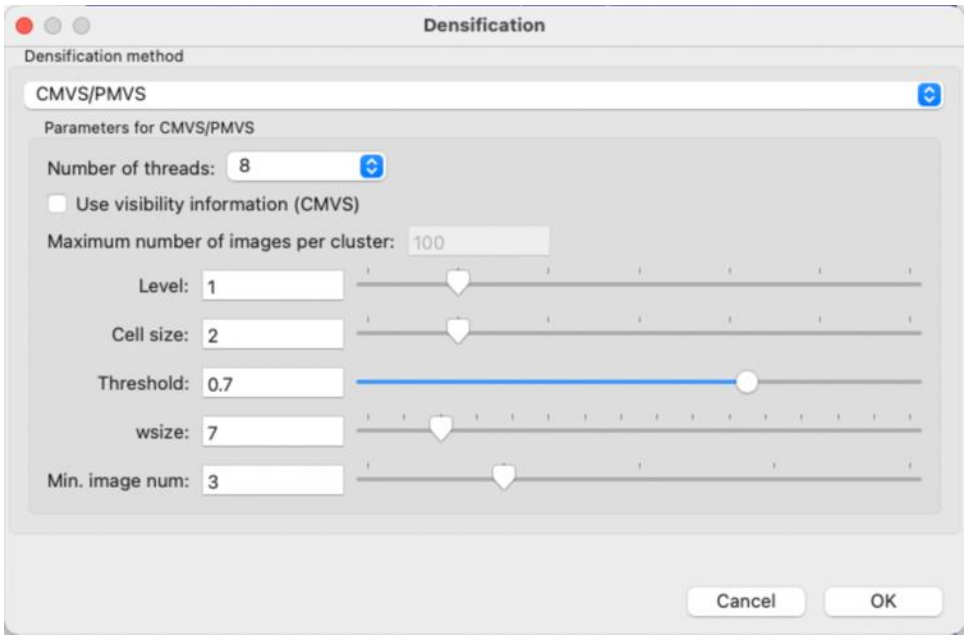
3. Once the photos have been checked for similarities, select the <Triangulation…> option.
   a. At the time of this manual's creation, the <New Incremental Triangulation> does not work and will give an error message if it is used. Instead, select the option <Old Incremental Triangulation> and make sure that "Refine camera intrinsics" is selected/checked. Select <OK>. This will create the initial point cloud.





4. Select <Create dense pointcloud…>.
    a. Select <CMVS/PMVS> as the "Densification method".
    b. Deselect "Use visibility information (CMVS)".
    c. The remaining options should be left at their default selection:
        i. Level set to "1"
        ii. Cell size set to "2"
        iii. Threshold set to "0.7"
        iv. W size set to "7"
        v. Min image number set to "3"
    d. Select <OK> to create the dense point cloud



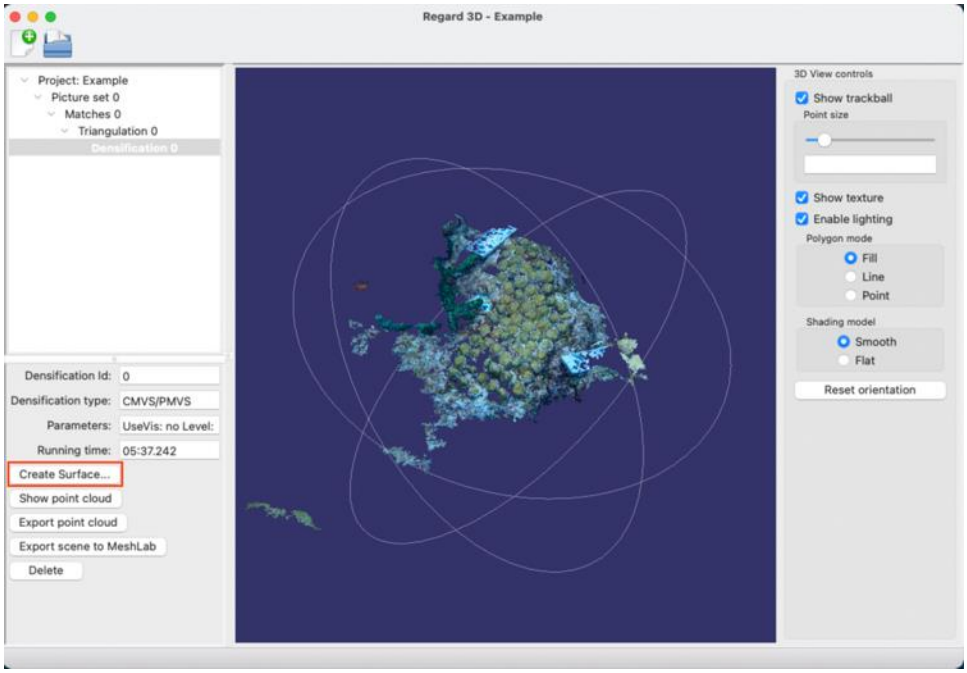


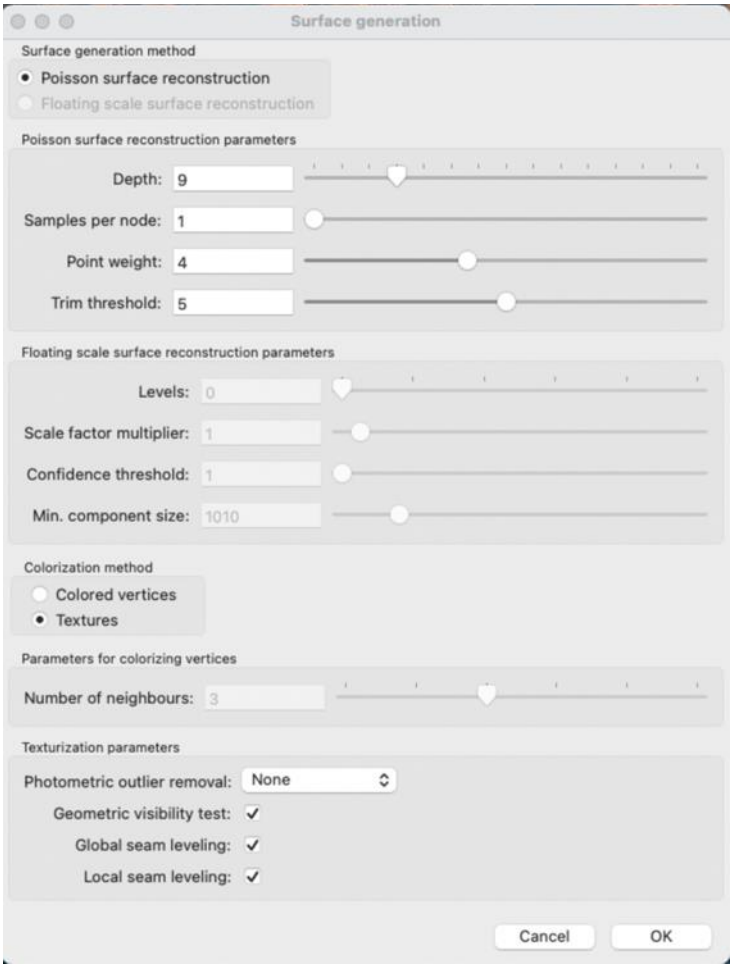
5. Select <Create Surface…>
    a. Choose “Poisson surface reconstruction”.
    b. Set the sliders to the following levels:
        i. “Depth” set to “9”
        ii. “Samples per Node” set to “1”
        iii. “Point Weight” set to “4”

iv. "Trim Threshold" set to "5"

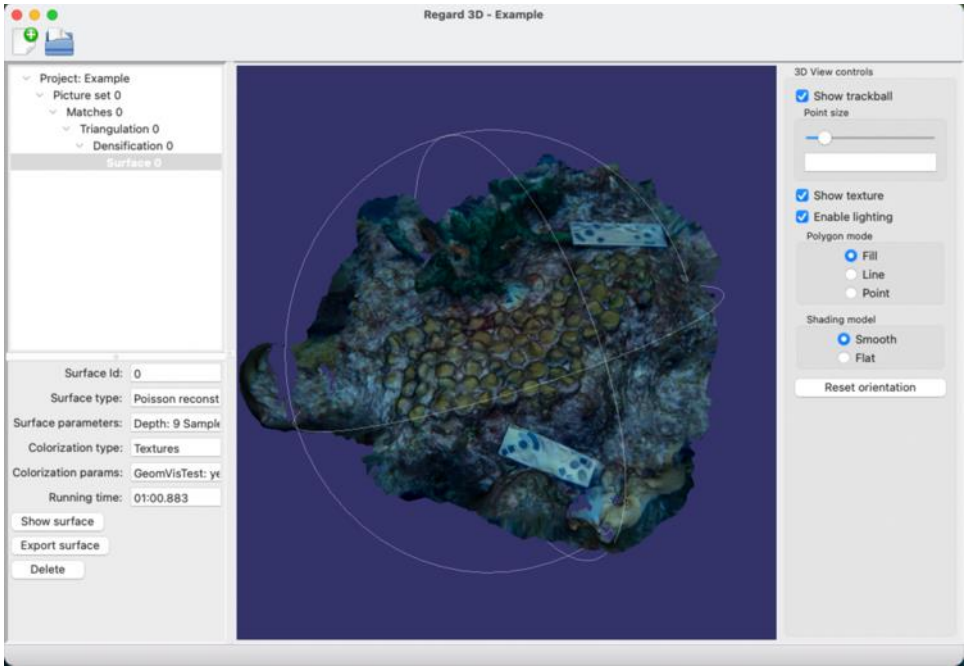
c. At the bottom of the window, there are texture options for the surface; make sure "Geometric Visibility Test", "Global Seam Leveling", and "Local Seam Leveling" are selected/checked. Keep "Photometric outlier removal" set to "None."

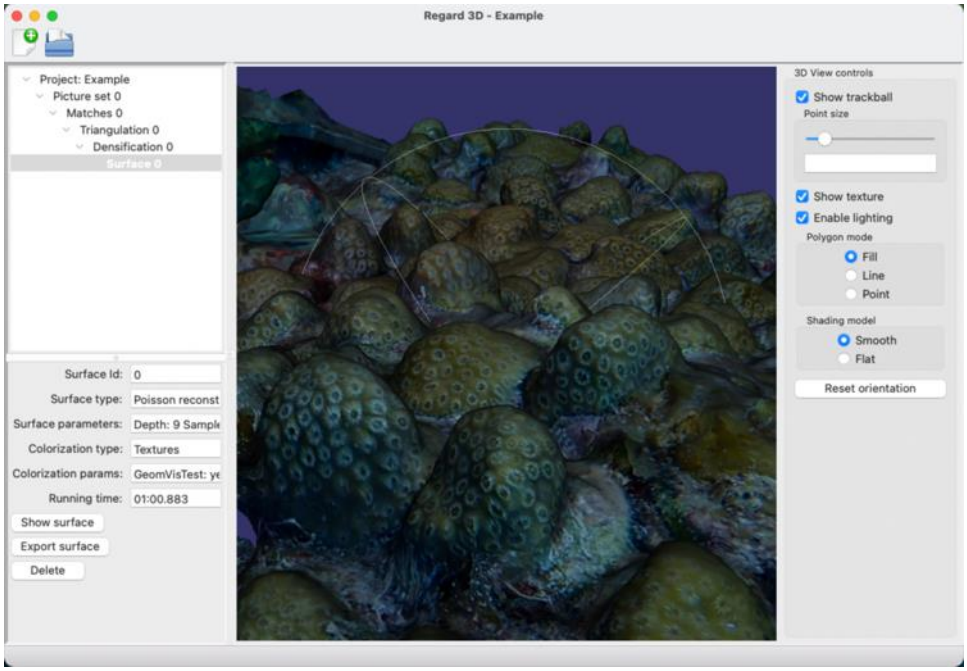
d. Select <OK> to generate the mesh/texture.





Once all these steps have been completed successfully, the surface and texture should be built and ready for export. Select <Export Surface> and save the file as an .obj file to a known location.


Regard 3D - Example
Project: Example
Picture set 0
Matches 0
Triangulation 0
Densification 0
Surface 0
Surface Id: 0
Surface type: Poisson reconst
Surface parameters: Depth: 9 Sample
Colorization type: Textures
Colorization params: GeomVisTest: ye
Running time: 01:00.883
Show surface
Export surface
Delete
3D View controls
Show trackball
Point size
Show texture
Enable lighting
Polygon mode
Fill
Line
Point
Shading model
Smooth
Flat
Reset orientation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Shading model
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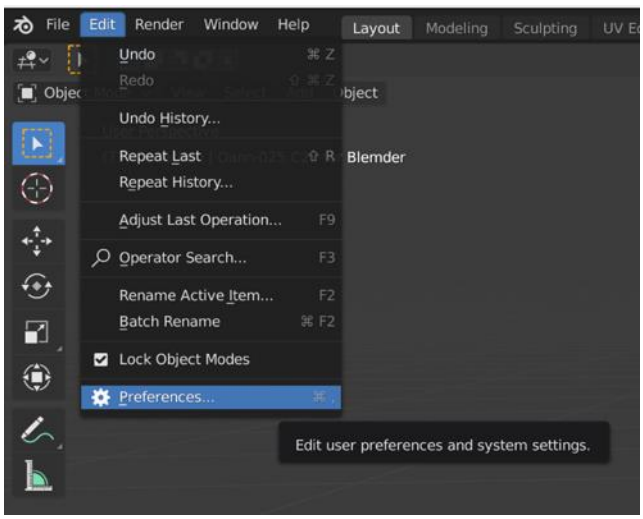
Flat
Reset orientation

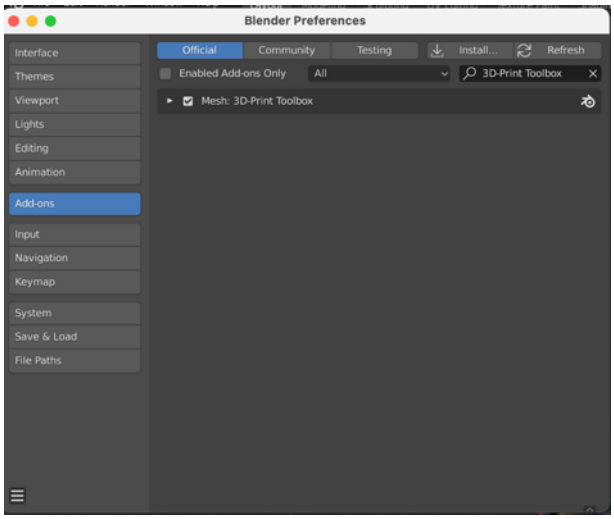
Analyzing the Model in Blender

When the Blender software opens, there are four main parts of the window. The largest and most obvious one is the "3D Viewport", where all models and manipulation will be done. The top right side of the window displays information about how objects in the scene are organized and named. Below the viewport is the "Timeline", and to the lower right side are "Model Properties" options. These last two sections are not used in this methodology.

The first thing to do after opening Blender is to delete the default cube, which is the grey 2m x 2m x 2m cube always at the center of the "3D Viewport" at the start of a new project. Simply right-click on it and delete it, or select the cube to highlight it, press "X" on the keyboard, and select the delete button.

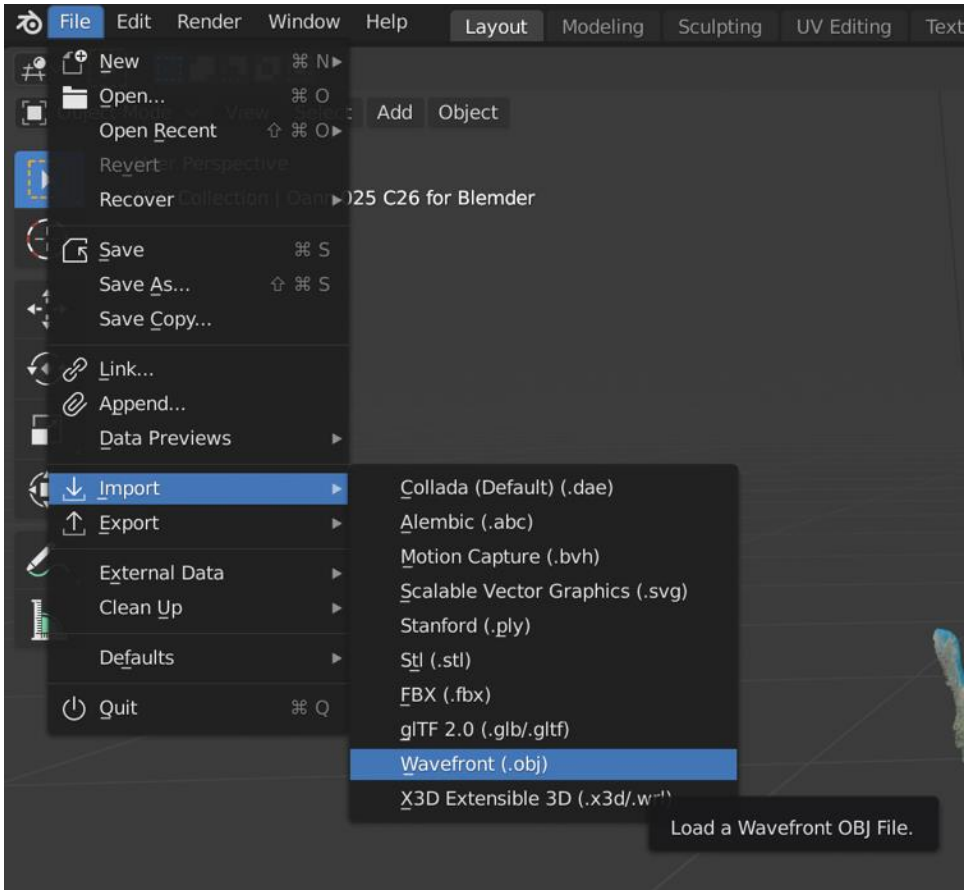
The final step before a model is imported is to add a plug-in for the program. At the top of the window, select the <Edit> menu and then choose <Properties>. A window of settings will appear. Go to <Add-ons>, search "3D-Print Toolbox", and make sure there is a checkmark next to it. This add-on includes the ability to measure surface area and volume for a mesh; the rest of the add-on features are not needed. (This step will only have to be done once; after it has been selected, it will remain in the program until it is deselected.)





Blender is now ready for the model analysis process.

1. Under the <File> menu, choose <Import>, and select the "Wavefront (.obj)" option.



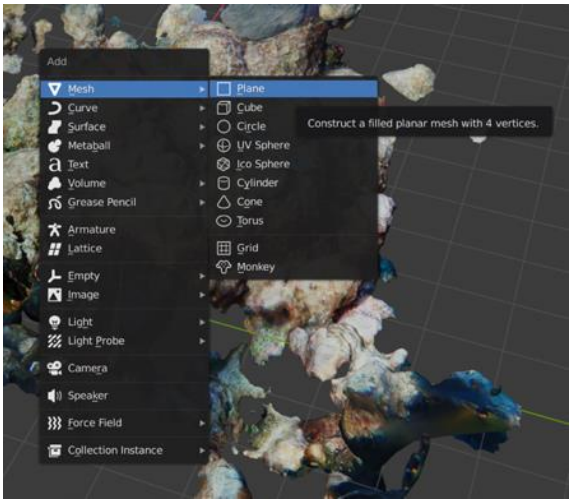
2. Find and select the .obj file previously made in Regard3D, then click the blue <Import OBJ> button in the bottom right. A grey-shaded model will appear.
    a. To add the model's color and texture, locate the four circles at the top right of the "3D Viewport" window. These are the mesh viewing options; select the third one (it looks like a circle with a quarter of it in grey and the opposite quarter with grey lines) or the "Material Preview".

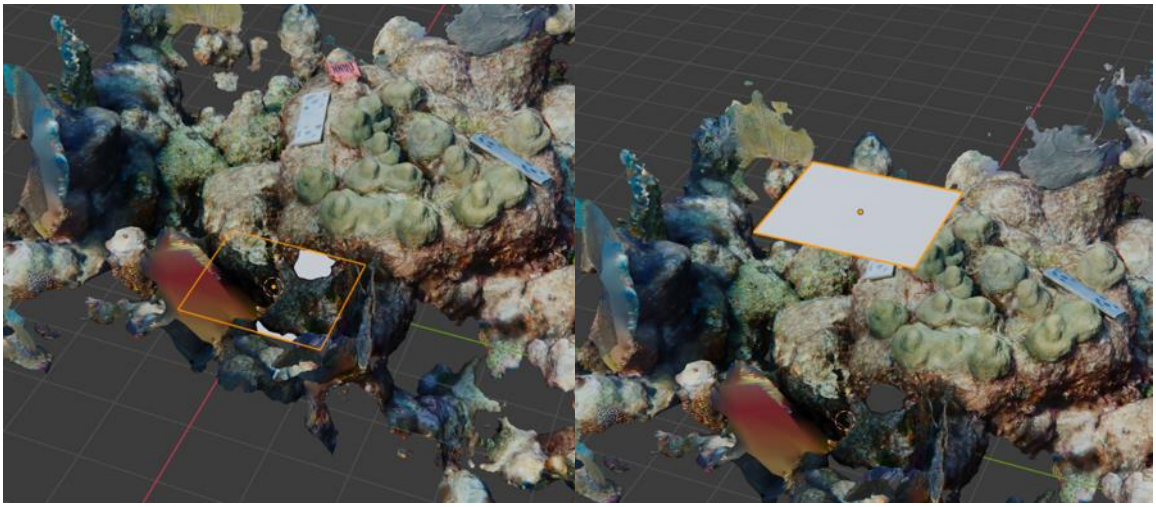
3. When models are imported into Blender, they are often rotated to an abstract orientation. To fix this, first select one of the ends of the 3D coordinate directions at the top right corner of the window (the X-Y-Z in Red, Blue, and Green). Selecting one of these circles will snap the model into that direct orientation. Once that is done, press the "R" key on the keyboard to rotate the model. "R" is the rotating key; the model will rotate wherever the mouse is dragged and will stop once a left-click is made.
    a. Once one of the X-, Y-, or Z-coordinates has been selected, the model will only rotate along that plane.

Scaling the Mesh Using Blender

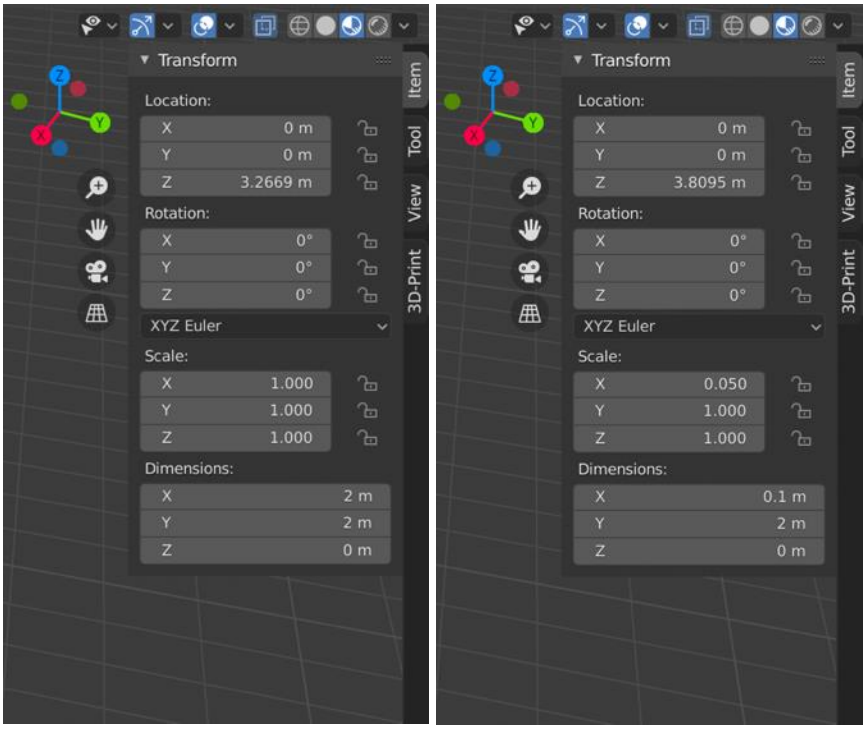
Once the model is in a desired orientation, it can be scaled. In CRF's testing, this process was slightly less accurate than Metashape but still within acceptable limits. Unfortunately, Blender does not have any automatic scaling tool like Metashape, where points on the model can be assigned a distance that is then applied to the full model. Rather, an "artificial scale bar" must be created, the known size must be applied to it, and then the model must be manually resized until the scale bar in the model matches perfectly with the artificial scale bar of known size that has just been created.

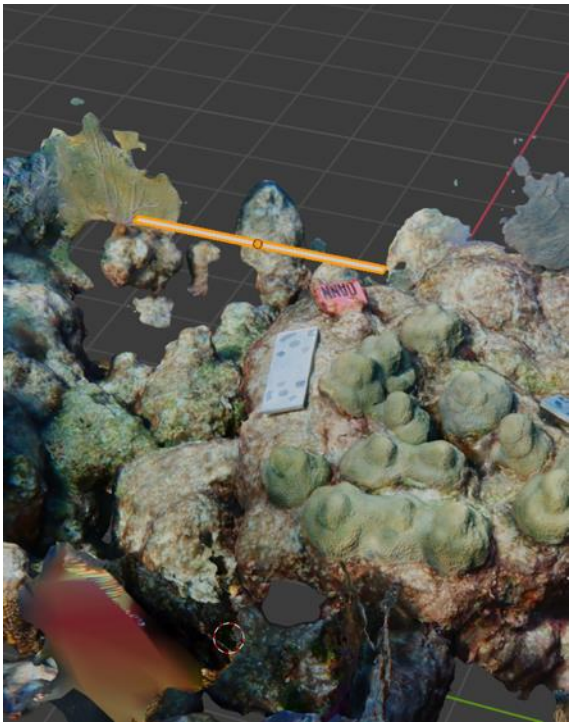
1. First, press "SHIFT-A" on the keyboard to bring up the "Add" window. A box will appear where your mouse is with many different objects and categories to add to the 3D viewport. Hover your mouse over the top <Mesh> option and select <Plane>. A 2m-by-2m grey rectangle will appear in the center and will become the artificial scale the coral model will be compared to. Once the plane has been loaded in, it may be under the mesh of the coral; simply click on the square and press "G" on the keyboard (move key) and then "Z". This will only move the object in the Z plane. Using the mouse, now drag up and make a left mouse click to place the object where you want it.



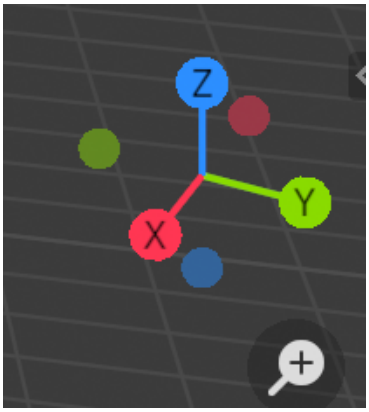


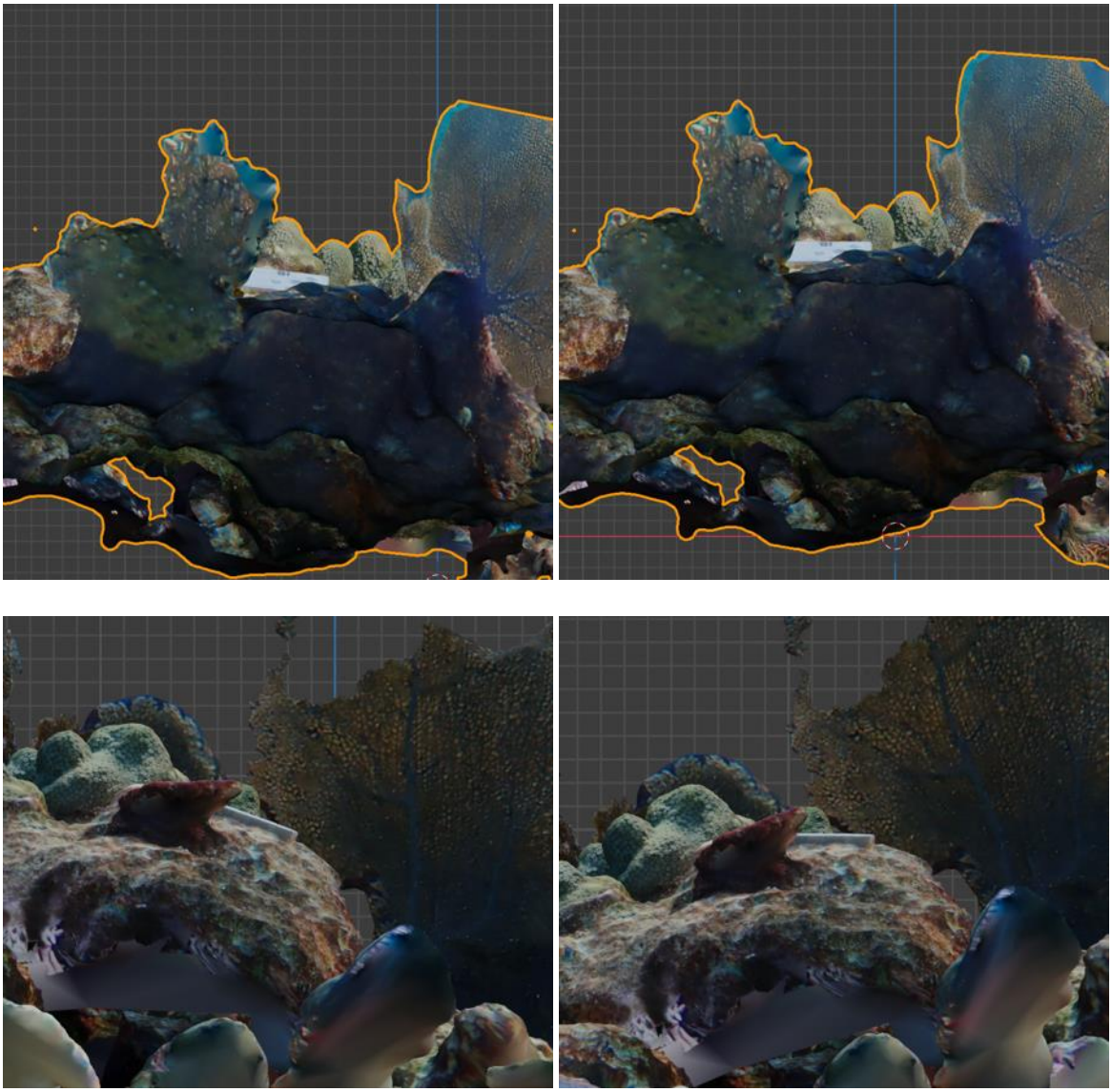
2. To get one side of the rectangle to be the desired size, press "N" on the keyboard, which will bring up sliders for multiple options. Select the <Item> tab at the top, where there are options for location in 3-dimensional location, rotation, scale, and dimensions. In the dimensions, there should be a "2m" in the X and Y. In one of the "2m" entries, input the known distance between the two target centers (i.e., the actual length of the scale bar in the model). For this example, the width of the artificial scale bar is set to 0.1m, the distance between the targets on our real-world scale bar.



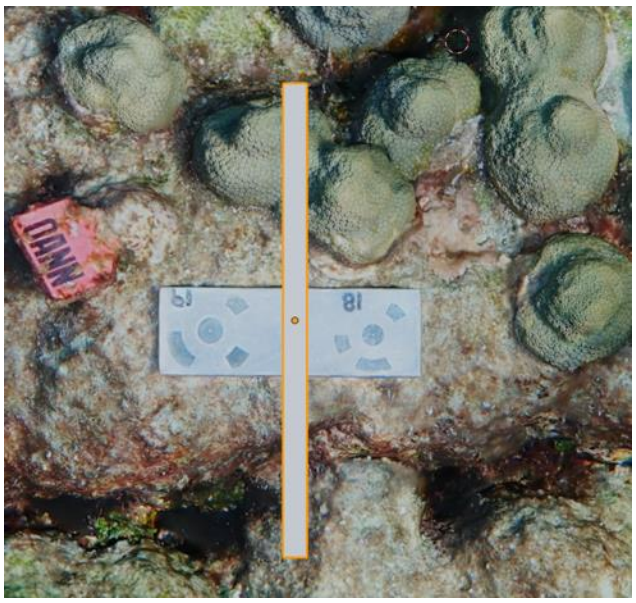


3. Next, before the model is ready to be resized, it may need to be reoriented so the scale bar in the model faces directly up. With the coordinate axis at the top right, the red, green, and blue circles can be selected to rotate the view to that true side. This is useful since rotating the model without a "locked" axis will move the model in three dimensions at once. As before, during the model import steps, select one of the coordinate circles, press "R" on the keyboard to rotate, and use the mouse to move the object. Left-click once the model is in the correct position. Repeat these steps for each of the X, Y, and Z orientation circles separately until the model aligns with the artificial scale bar.





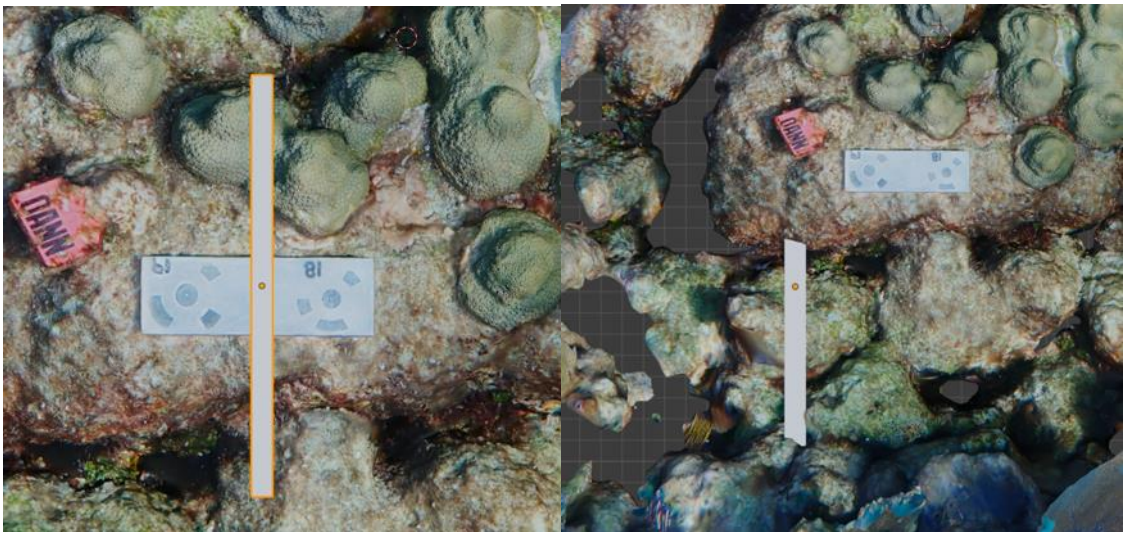
4. Press the "Z" orientation on the axis to get the top-down perspective and move the artificial scale bar directly over the scale bar in the coral mesh. Moving the scaled plane is accomplished by pressing "G" on the keyboard and using the mouse to move the object. Left-click for it to be anchored in place.

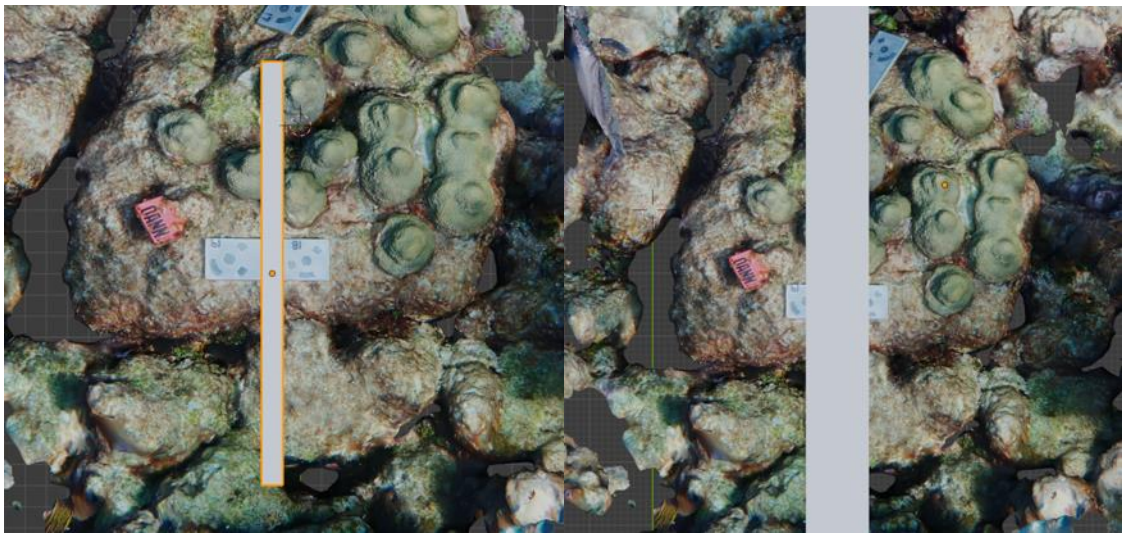


5. At this point, the model will probably be much bigger than the gray artificial scale bar, so press "S" on the keyboard and drag the mouse in and out to manipulate the model's size, then left-click to stop the resizing. Due to how Blender determines where the center of the mesh is, resizing the coral model may move it away from the scaled plane or render the artificial scale bar inside the model, as seen below. To get around this, periodically move the coral model back

so the scale bar is under the plane. This may take a few times to finally get the model to the correct size.

a. This step takes a lot of movement keys, but as a reminder:
    i. "S" to resize
    ii. "G" to move the object
    iii. "G" then "Z" to move an object back under or below the model
b. The end goal for this step is to get the known, inputted dimension of artificial scale bar (here, the width) to match the know distance of the real scale bar (here, the distance between the 12-bit target centers) as closely as possible.





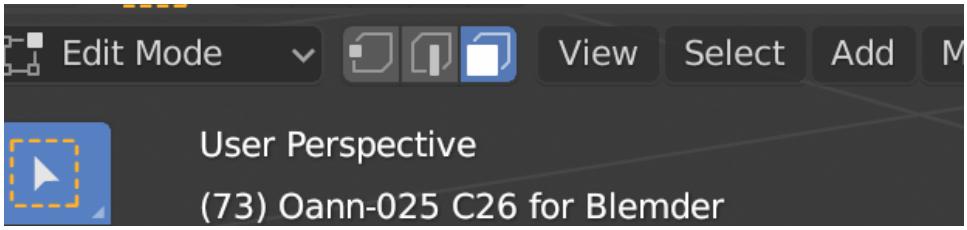
The width of the gray, artificial scale bar was set to 0.1m and now aligns with the known distance of 0.1m between the centers of the coded targets in the model's actual scale bar.

6. Once the model is scaled to perfectly match the size of the artificial scale bar, you may delete the artificial scale bar or hide it by pressing the "eye" icon next to its name on the "Object List" in the upper right portion of the screen.
    a. If the model has been scaled to a very small size, it can be hard to zoom in and control. To fix this, use the "N" menu from Step 2 above, select the <View> tab, and select the eyedropper tool in "Lock to Object". Either select the model in the viewport or the name of the object in the top right object listing and drop the "Clip Start" from "0.1m" to a value closer to "0.0001m".

Analyzing the Mesh in Blender

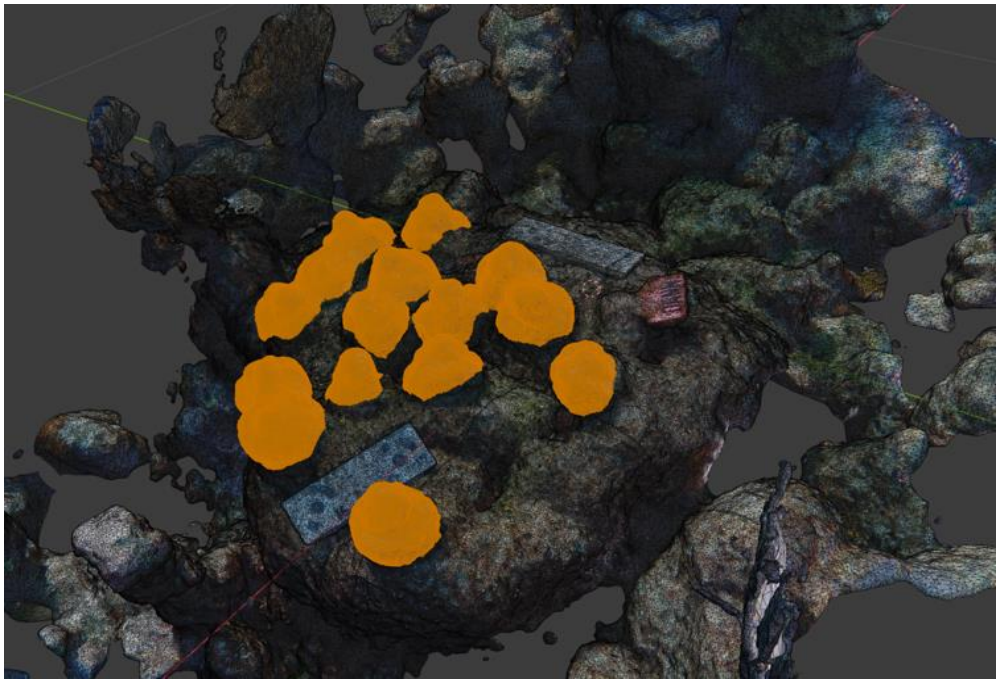
After scaling, the model is ready to be analyzed. To select the coral tissue for analysis:

1. Select the model and press "TAB" on the keyboard. This will bring up the "Edit" view and allow for individual sections of polygons on the mesh.
2. There are three different selection options in Blender: vertices, edge, and face. Make sure the <Face> selection is chosen.
    a. "Face" selection is the third option in the upper left (a large solid grey square in front of an outlined grey square).

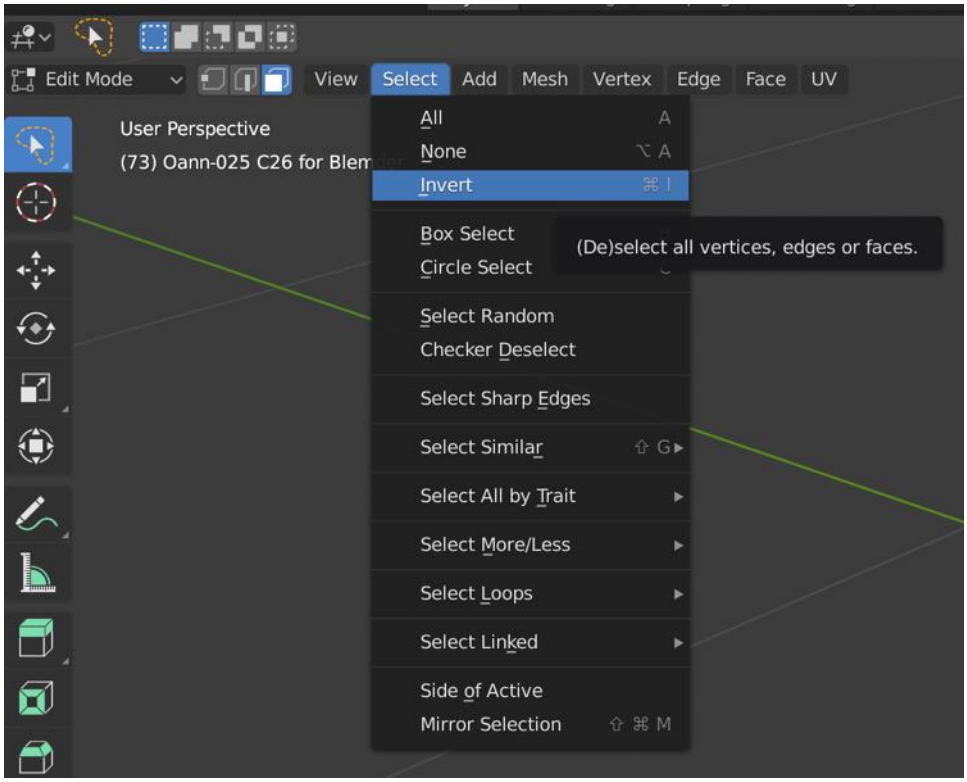


3. Make sure the cursor button is selected at the top of the options menu on the left side, and press "W" on the keyboard until a squiggly circle appears on the menu's cursor icon.
4. At the top right of the window, press the <Toggle X-Ray> button.
    a. The Toggle X-Ray button looks like two squares, one slightly in front of the other. This allows for the selection of all the polygons that may be behind others in the model.

5. Rotate the model upside-down and use the cursor to individually select each coral from the underside of the model.
    a. Using the freehand selection tool, outline each coral. In Blender, it is harder to deselect than it is to add to an existing selection, so it's good practice to trace bit by bit and add more if needed.
    b. Hold "SHIFT" for making multiple selections.
    c. In Blender, "COMMAND-Z" on Mac and "CONTROL-Z" on PC (Edit -> Undo) will bring back lost selections if accidental deselection occurs. There appears to be a limit on the amount of "undoing" that can be done, but this feature is useful if the SHIFT key is forgotten for one click.
    d. Also note that Blender does not have the same double-click option as in Metashape to lock in a focal point, so efficient maneuvering of the model may take time to learn in Blender.
        i. There are two modes of movement in Blender, both utilizing the click wheel on the mouse.
            1. The first mode is rotation, which is accomplished by clicking on the scroll wheel on a mouse and dragging the model around. On a laptop, this movement is accomplished by moving around the trackpad with two fingers.
            2. The second mode of movement is panning, which rewuires holding the "SHIFT" key while using the click wheel on the mouse. Once either the SHIFT key or the click wheel is released, the model will stop. On a laptop, hold "SHIFT" while moving around the trackpad with two fingers.



6. Invert the selection by using the <Select> tab just to the right of the "Face Selection" option and choose <Invert>. Then, delete the inverted selection by either right-clicking and choosing <Delete Faces> or by pressing "X" on the keyboard and selecting <Delete Faces>.


Edit Mode
View
Select
Add
Mesh
Vertex
Edge
Face
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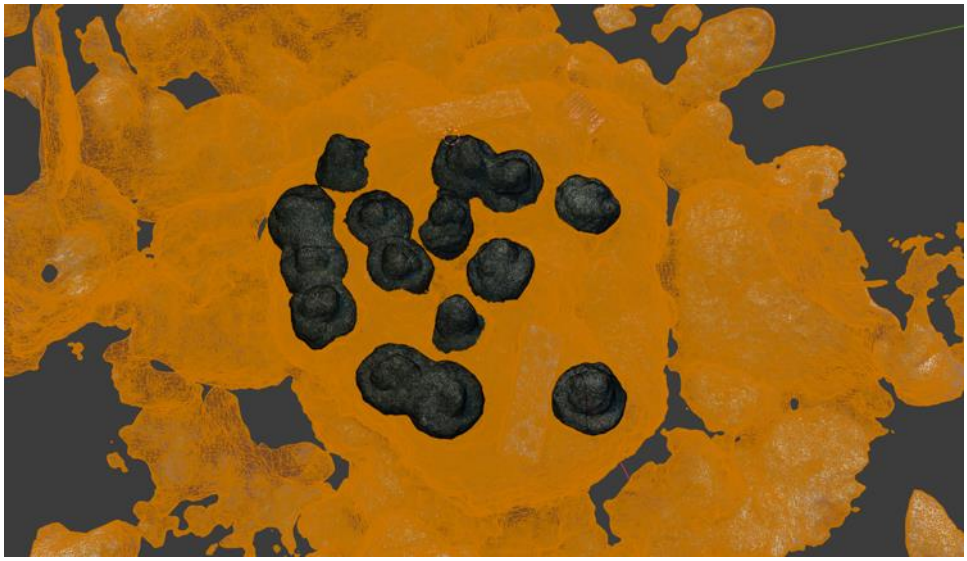
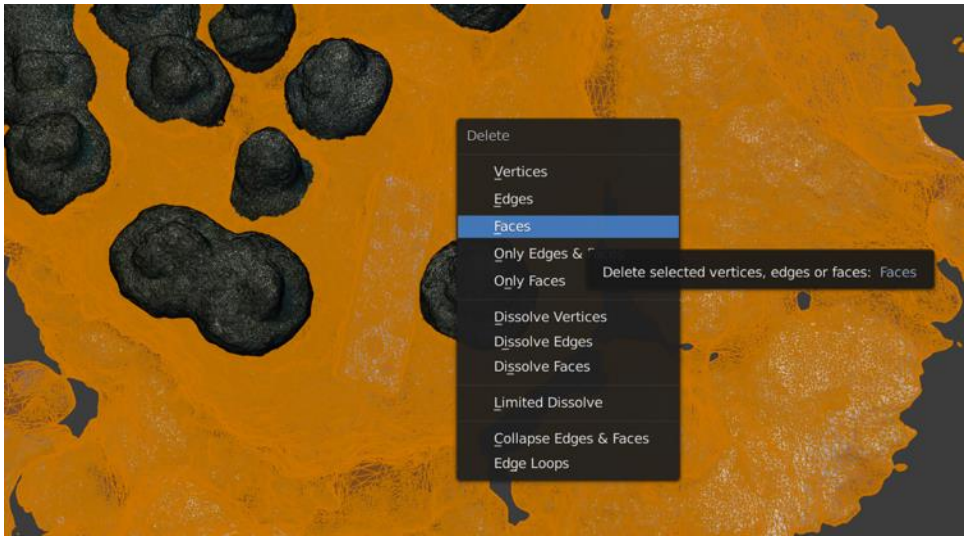
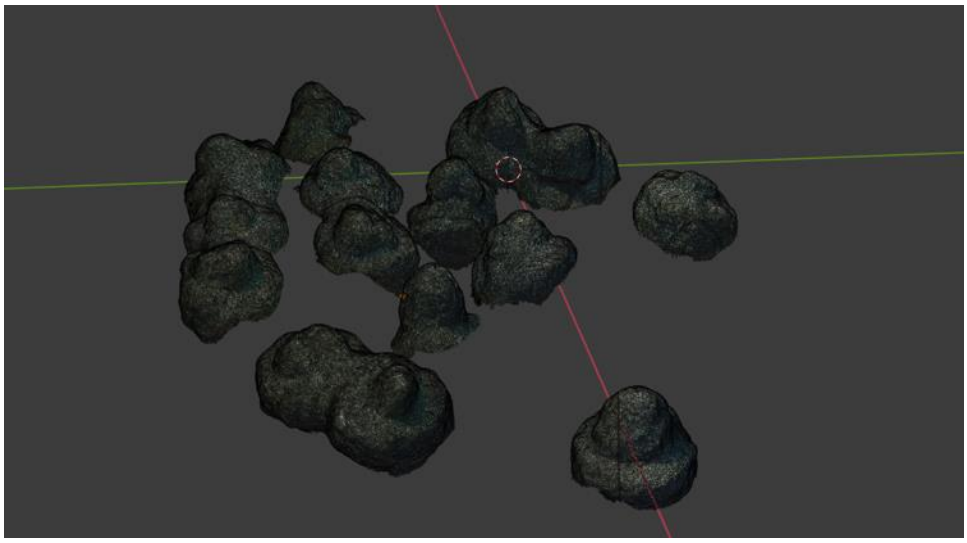
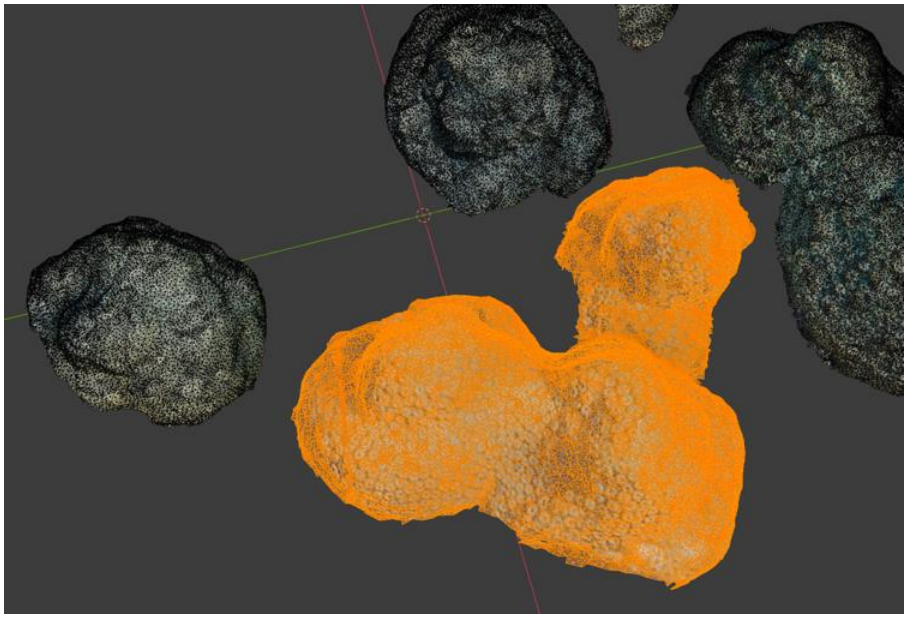
User Perspective
(73) Oann-025 C26 for Blen
All A
None ⌥ A
Invert ⌘ I
Box Select
Circle Select
(De)select all vertices, edges or faces.
Select Random
Checker Deselect
Select Sharp Edges
Select Similar ⇧ G
Select All by Trait
Select More/Less
Select Loops
Select Linked
Side of Active
Mirror Selection ⇧ ⌘ M

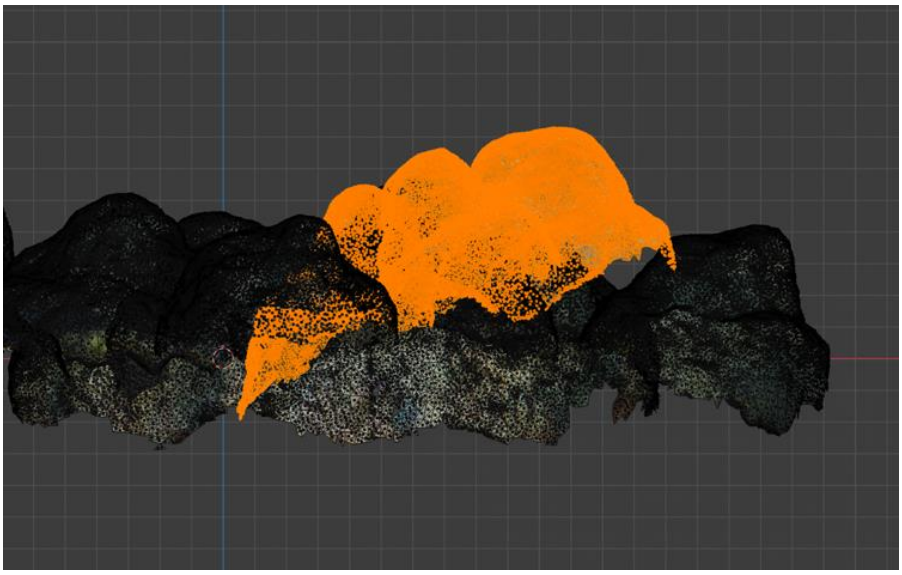


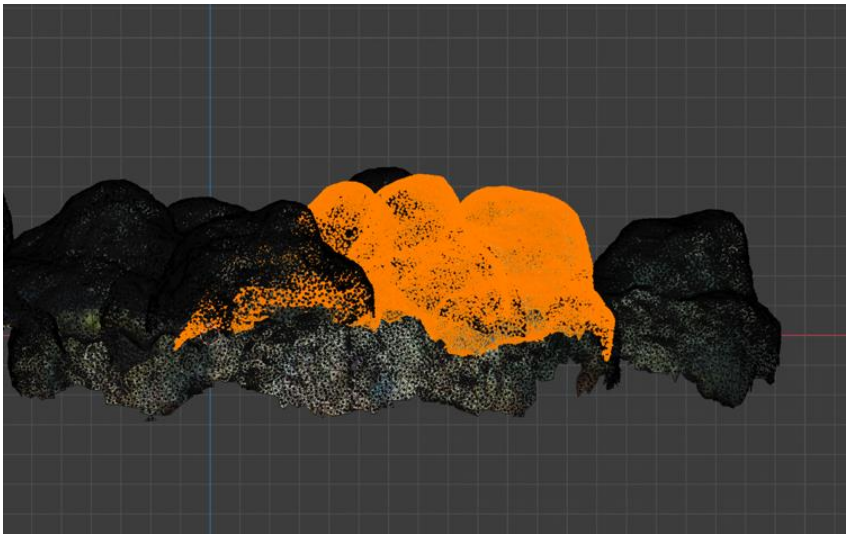




7. Each portion of the remaining model must now be aligned to the same plane for accurate analysis. One at a time, select each coral colony and rotate or move it as necessary until all colonies are in the same plane. To move a selected coral, press “G” on the keyboard.
    a. Remember that selecting “X”, “Y”, or “Z” on the axis icon will lock the model in that direction for much more accurate rotational movement in a single plane/dimension.

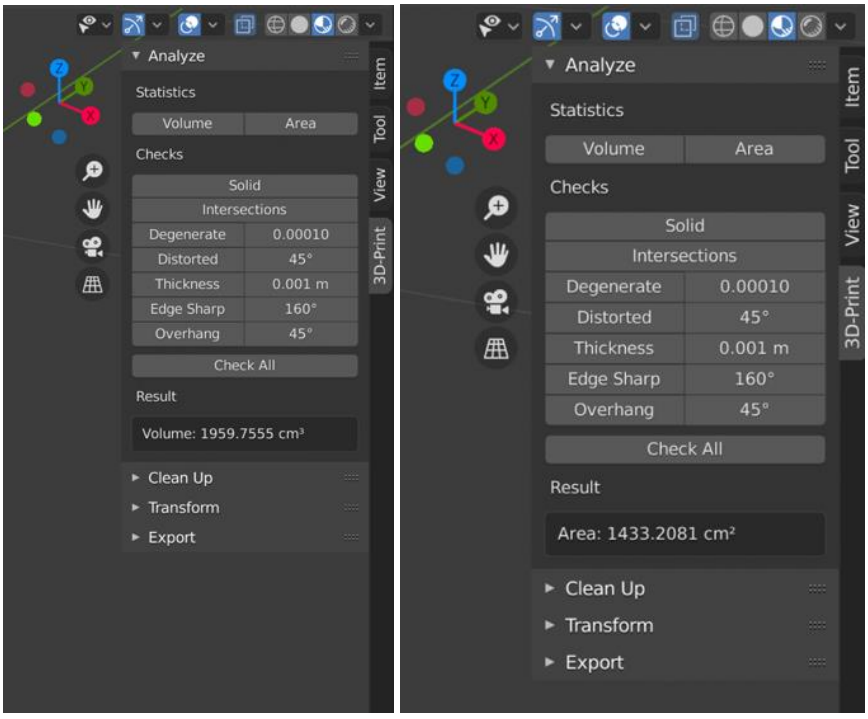






8. Once corals have been aligned, press “TAB” on the keyboard to return to “Object Mode”. Select all parts of the model and press “N” on the keyboard to bring up the object menu.

9. Select the last menu tab that says <3D-Print> and find surface area and volume under the “Statistics” section. Click on the desired metric to display its statistics under the “Results” section.



Additional resources can be found on the Coral Restoration Foundation™ website:
www.coralrestoration.org