Documentation for the innovative use of terrestrial laser scanning technology in a paleoseismic investigation

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Introduction

This report presents field and laboratory procedures and results from our summer 2009 terrestrial laser scanning (TLS) efforts for a number of San Andreas Fault (SAF) paleoseismic trenches on the Bidart fan site in the Carrizo Plain, California.

A total of eight trenches were excavated in the study area, of which five were scanned over the span of three days in early July, 2009, using the Zoller+Fröhlich (Z+F) Imager 5006i terrestrial laser scanner (Figs. 1 and 2). The objectives of these efforts were to:

1. Test the effectiveness of TLS in capturing trench wall details such as fault zone structure, paleochannel geometry, individual gravel clasts, and individual sedimentary packages to compare with base photomaps used in conventional trench logging techniques.
2. Test the effectiveness of TLS in capturing subtle morphologic details of surface manifestations of SAF-related deformation that are otherwise poorly imaged in the B4 dataset (the 5-m suspect offset channel in particular).
3. Evaluate scanner and target setup protocol for this innovative use of TLS technology, and use it as a guide for future TLS efforts in paleoseismic investigations.

Post processing of the raw data was conducted using the Z+F LaserControl software that was provided with the scanner. This will be described in detail in the Data Processing and Analysis section of the report.

Figure 1. The Z+F Imager 5006i terrestrial laser scanner in action.

Figure 2. The Z+F storage configuration. Left case contains an extra scanner battery pack, battery charger, and tribrach. Central small case contains laptop and laptop accessories (charger, mouse, etc.). Right large case contains the Z+F Imager 5006i scanner. The compact nature of the Z+F setup makes it ideal for easy storage and transporting (via commercial airlines or commercial carrier shipping) to and from remote regions.

General Comments for Field Setup

The following section describes factors that need to be considered during the field protocol for scanning paleoseismic trenches using a terrestrial laser scanner, followed by specific field setups for the SAF trenches on the Bidart fan site.

Factors affecting scanner setup

The high portability and scan speed of the Z+F Imager 5006i scanner makes it an ideal terrestrial laser scanner for close-range (<80 m) and remote scan setups. Several important factors need to be considered when choosing scanner positions prior to departing the office/base camp.

Camera lighting conditions

There are no lighting restrictions when operating the Z+F Imager 5006i scanner solely to acquire point clouds of trench walls. However, important considerations must be taken when using the scanner's mounted digital camera to color point clouds and produce orthophotos of scans. Large differences in shading of the morning and afternoon trench walls have the potential to render the scanner's photographs useless for point cloud coloring and orthophoto generation due to the large differences in photograph contrast. Therefore, it is imperative that the scanner and trench walls be evenly shaded for scans performed in daylight hours. For deep trenches (>10 ft depth) the most effective shading items are broad plywood sheets placed across trench walls. For shallower trenches (< 1 m) a surveyor's tent may be placed over the scanner and a large tent placed over the trench to provide the most even lighting conditions. If scanning at night, a copious number of construction lights may be used to illuminate trench walls evenly.

Scanner temperature

The manufacturer-recommended operating temperature range for the Z+F Imager 5006i scanner is 32-104 °F (0-40 °C). Average ambient air temperatures in and around the Bidart fan trenches during our TLS efforts were between 100-117°F (38-47 °C). This resulted in several interrupted scans because the Z+F Imager 5006i scanner is designed to power down if its internal temperature exceeds the recommended operating temperature in order to protect critical instrument components. Therefore, when scanning in high ambient temperatures, it is recommended to keep the scanner cool by using ice packs, water bladders (e.g., Camelbak) filled with ice, etc., for uninterrupted scans.

Factors affecting target setup

The Z+F LaserControl software uses predefined targets for its semi-automated point cloud registration process. Each target consists of a uniquely numbered square that is divided into four triangles, two black and two white, and are printed on non-glossy 8.5" x 11" paper (Fig. 3). Careful considerations should be taken during target set up, which include:

1. Carefully securing a copious number of targets to stable, flat surfaces (such as a clip board or trench shores) to minimize target distortion and movement.
2. Placing targets on surfaces that are readily accessible by a survey reflector (if a total station setup is desirable).
3. Minimizing the obliquity of each target relative to the scanner to ensure success of the semi-automated registration process in Z+F LaserControl. Depending on the feature of interest, high-obliquity target-scanner angles may be inevitable. Thus, the success of the scan registration process will highly depend on the total number of targets and their spatial distribution in the study area. Additionally, the bottom edge of each target should be as level with the ground as possible to ensure a diagonal cross mark (X) is formed by each target, versus a vertical cross mark (+), in order to minimize edge effects within the scans.
4. Ensuring an even spatial distribution of targets throughout the landscape and along trench floors and ceilings to make sure each scan has enough well-orientated targets for registration.
5. Making sure target identification numbers are not obscured by objects (e.g., shores, spoil piles) in the scan images.
6. Creating a sketch map of the target and scanner locations. This is critical in areas where target obstruction is unavoidable (e.g., in densely shored trenches where visualizing the entire target is not possible).
7. Target distance. The Z+F Imager 5006i scanner is a close- to medium-range scanner (between 0.3 m and 79 m), and works very well in trenches that are no less than 1 m wide. However, it is advisable that targets be set no farther than ~25 m from the scanner to guarantee target identification and scan registration in Z+F LaserControl.

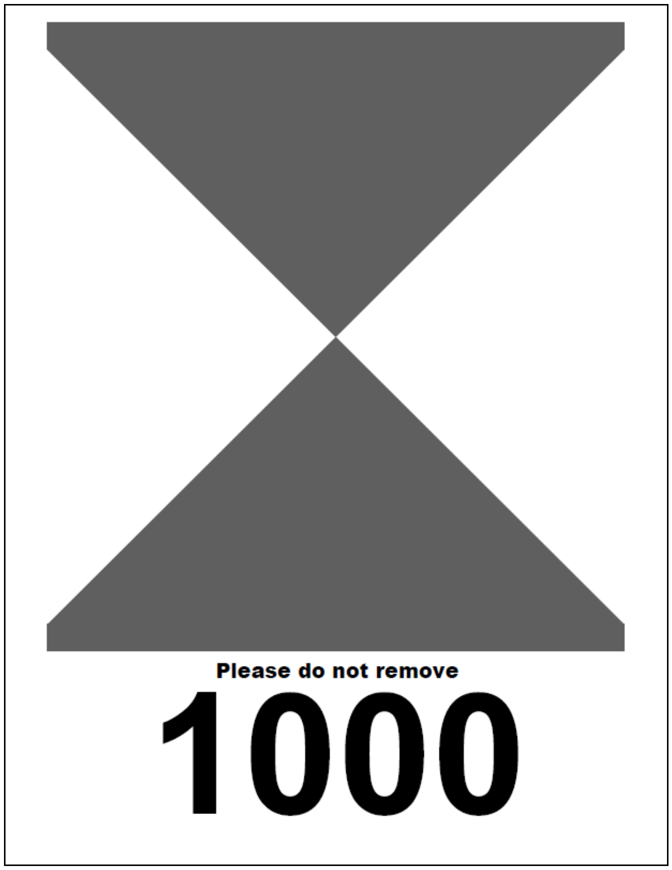


Figure 3. Example of a target for the Z+F Imager 5006i scanner. Each target is uniquely numbered, printed on an 8.5" x 11" sheet, and secured to flat surfaces.

Bidart Fan TLS Setup

T18 target and scanner setup

A total of twelve targets were strategically placed in T18 (Fig. 4). Two targets were taped to flat aluminum sheets and placed on the trench floor, and two other targets were taped to the undersides of broad plywood sheets that were placed across the trench walls to provide even lighting conditions. Eight targets were attached to two 1.5" x 8" x 8' planks that were secured vertically to the trench shores (Fig. 4). Our feature of interest was the fault wall of T18 that contained cut-and-fill deposits of the fault-upstream offset channel. This section of the wall was divided into two panels between three shores.

T18 was scanned from twelve scan positions at three depths. Four scans were performed at the bottom of the trench, where the scanner was placed on a clipboard directly on the trench floor. Four other scans were conducted in mid-depth where the scanner was placed on a 1.5" x 8" x 8' plank resting on the lower shore pistons. The same setup was used for the upper four scans using the upper shore pistons for support during the shallower scans.

Figure 4. Target locations in T18 with the first scan position on the trench floor.

T19c target and scanner setup

Twelve scan positions and thirteen targets were used in the scan setup of T19c (Fig. 5). The first set of scans was conducted from the trench floor. For the second set of scans, the scanner was placed on a stable base to acquire elevated scans of the trench walls.

Figure 5. Target and scanner setups for T19c.

T19 surface target and scanner setup

A total of ten scan positions were used to scan the suspect 5-m offset channel of T19. The Z+F Imager 5006i scanner and tribrach were mounted on a standard surveying tripod for each scan position (Fig. 6). Fourteen targets were attached to cars, plywood sheets, and water jugs that were strategically placed around T19.

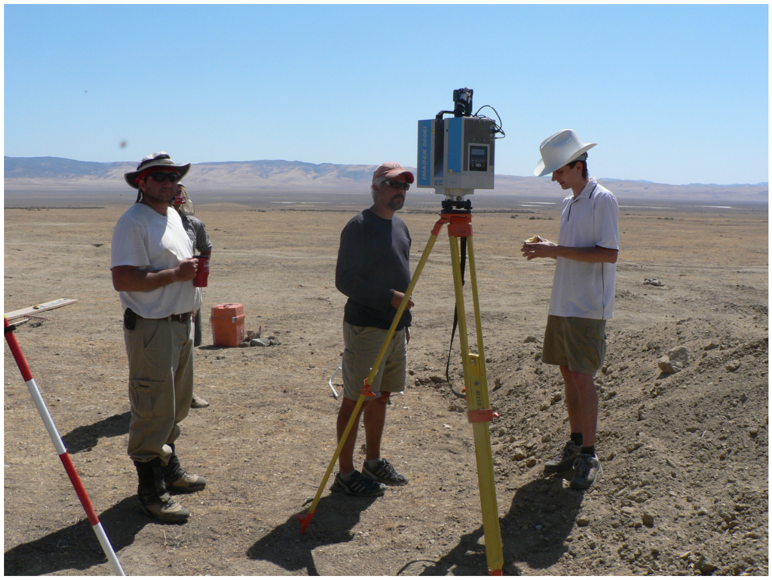


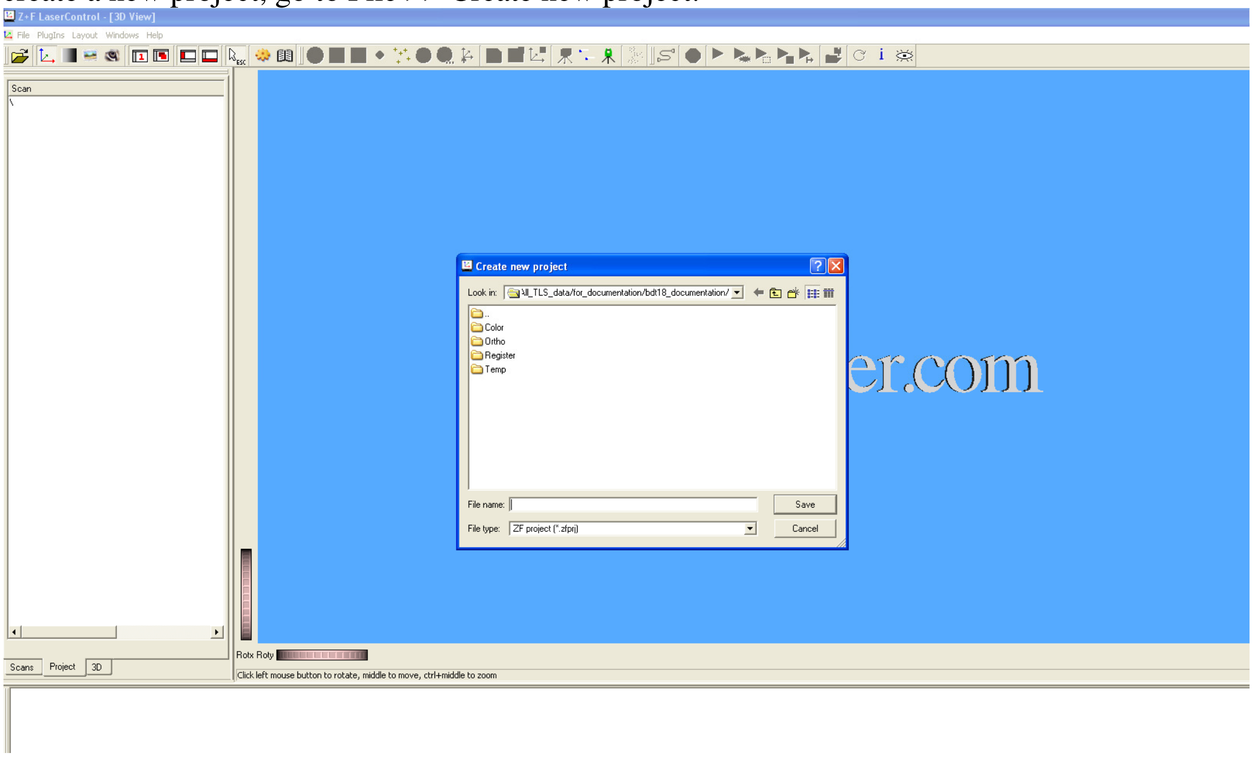
Figure 6. Target and scanner setups for the surface of T19.

Data Processing and Analysis

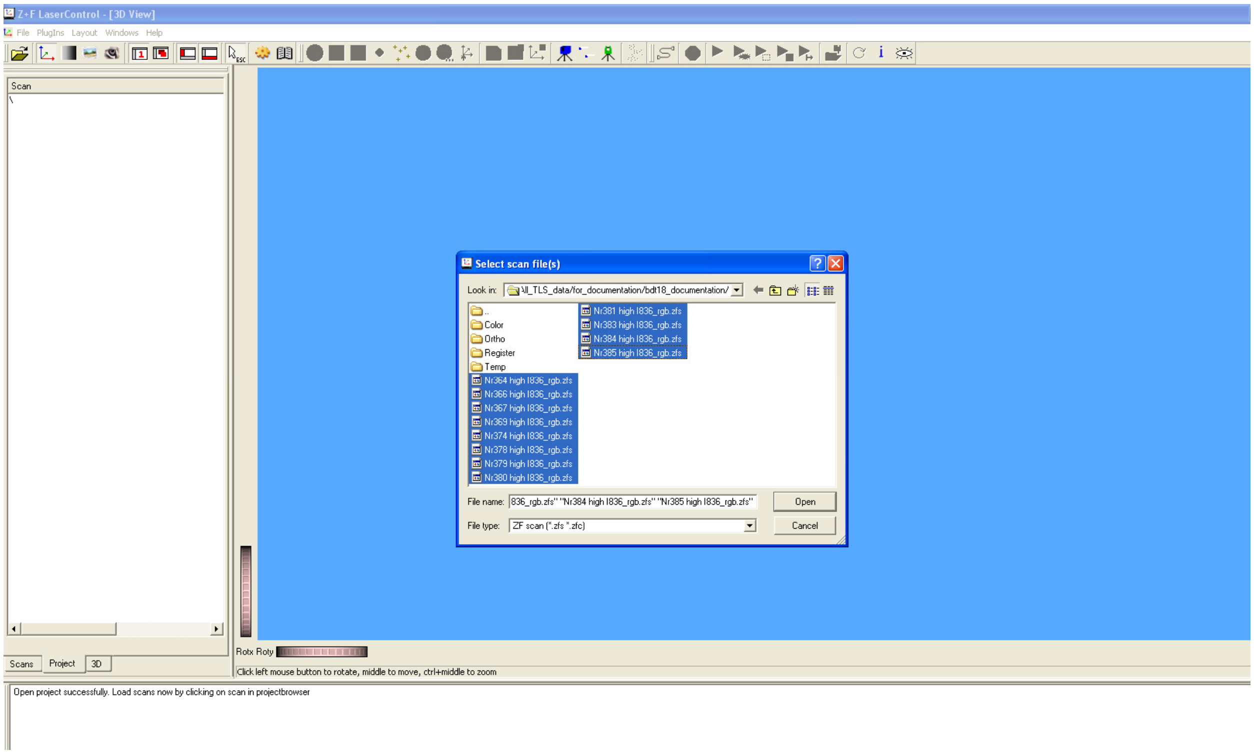
The Z+F Imager 5006i saves scans in the proprietary .zfs format. Scan files for each of the trenches were transferred from the scanner to a computer using a USB flash drive. The scans were grouped together in separate folders according to trench number. The following steps will document the processing procedures using the T18 dataset as an example.

Creating a new project and adding scans

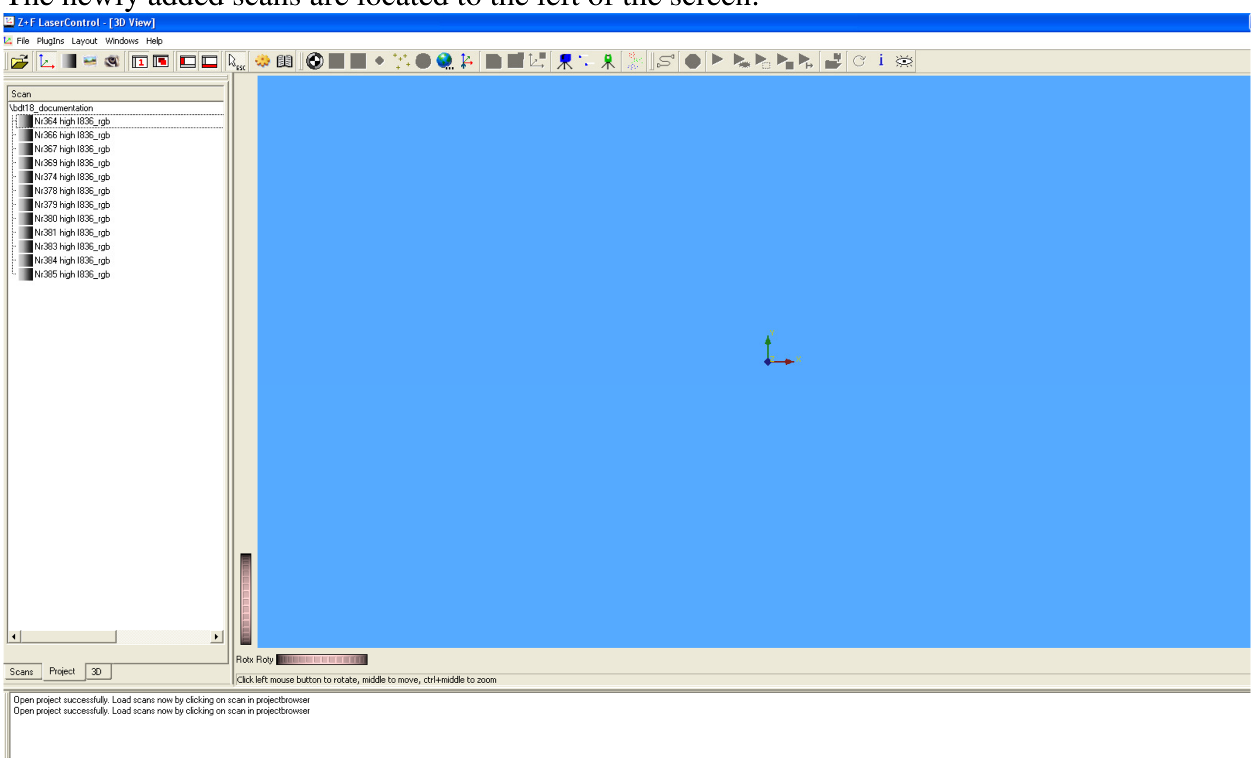
Data processing in Z+F LaserControl is facilitated using *Projects* (saved as .zfprj files). For users familiar with the ArcGIS suite, .zfprj files are analogous to .mxd for AcrMap projects. To create a new project, go to File >> Create new project:



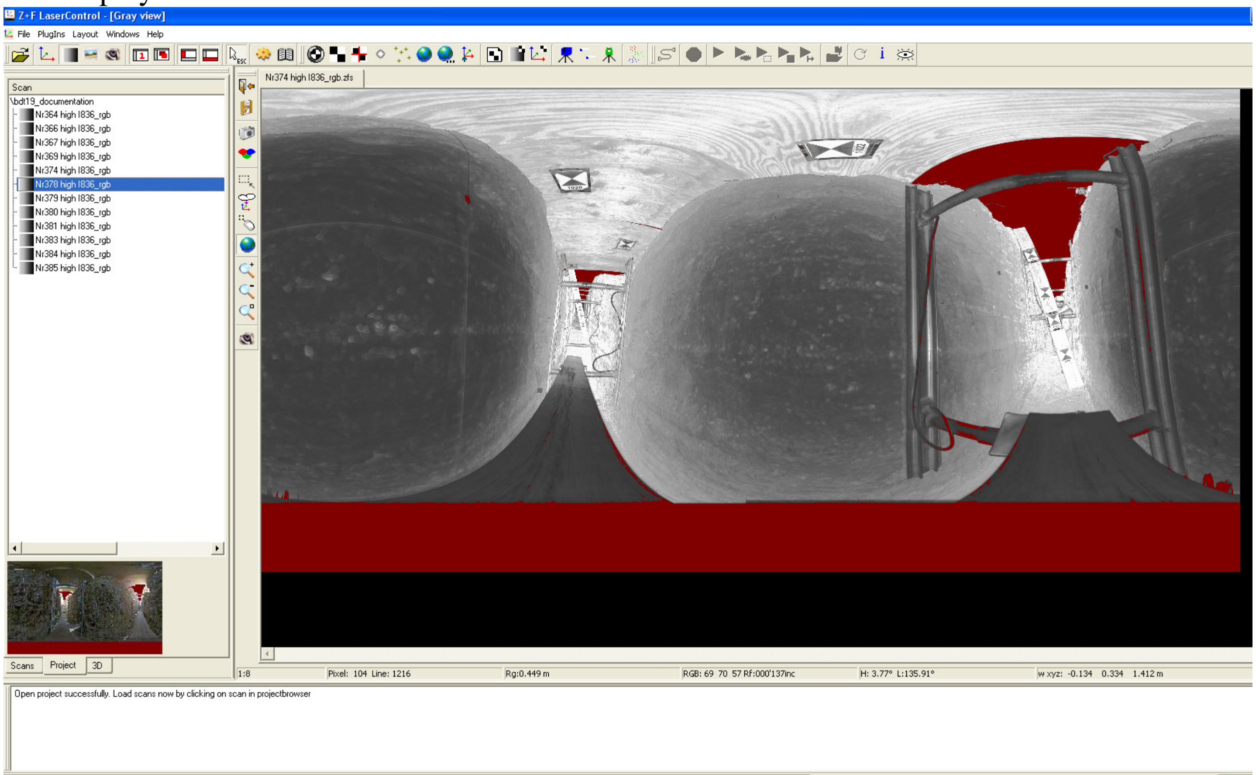
Enter a project name, and click Save, then select the scan files from the scan directory (you can add multiple scans using either the Shift or Ctrl keys on your keyboard):



The newly added scans are located to the left of the screen:

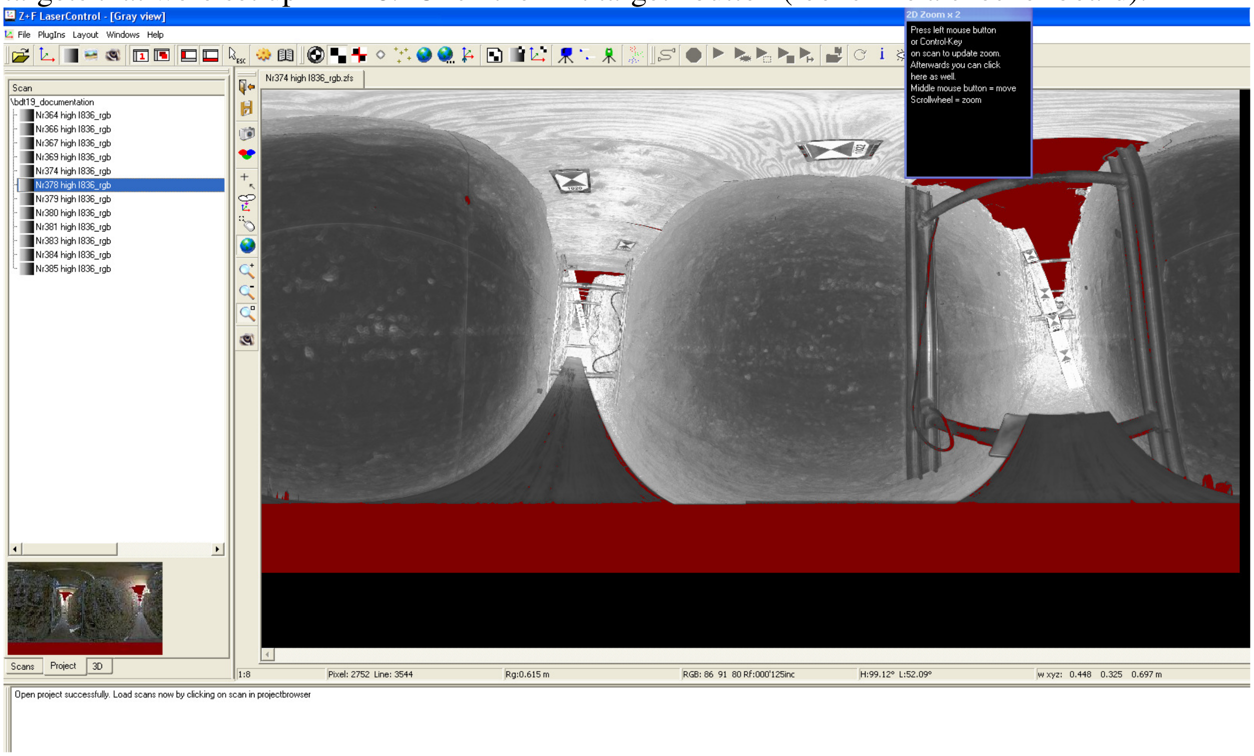


Selecting a scan will display a preview image below the list of scans. Double clicking a scan will display it in 2D:

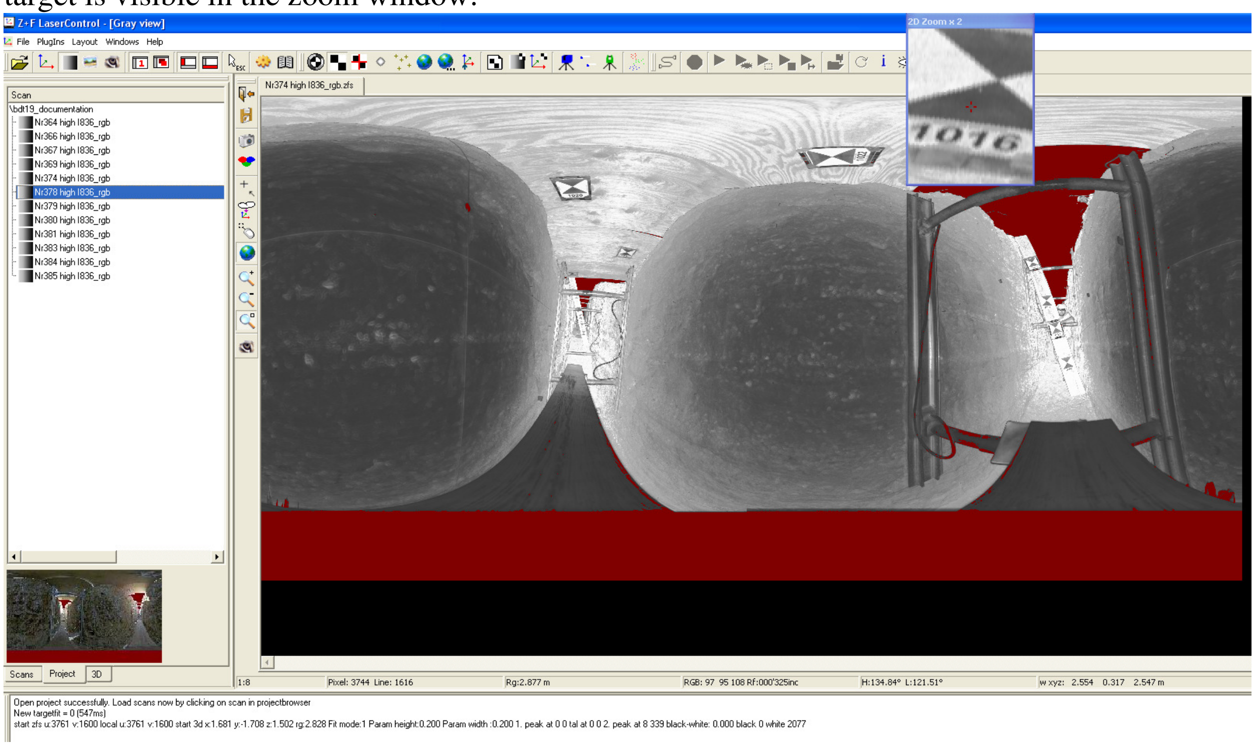


Fitting targets

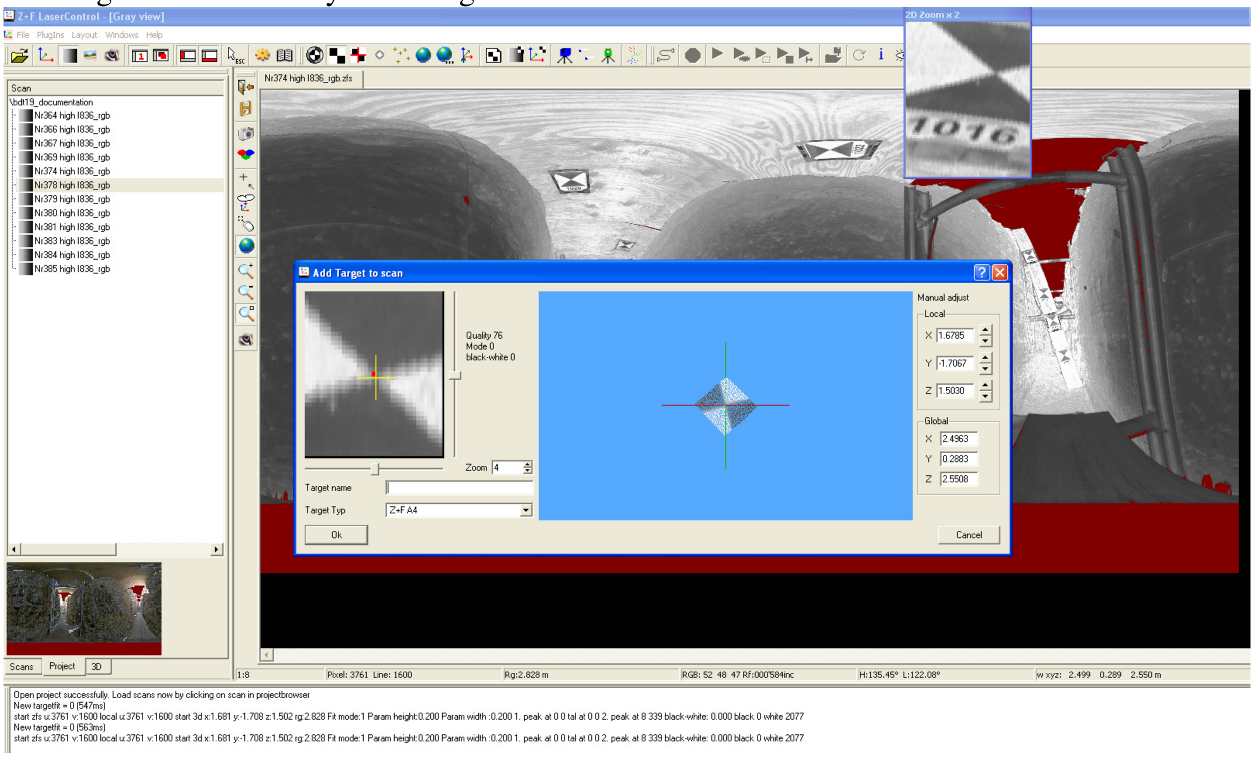
In order to produce meaningful data, all scans need to be registered (i.e. aligned) using the targets that were set up in T18. Click the "Fit target" button (looks like a checker board):



Left click and hold the mouse curser in the 2D image and drag to a target until the center of the target is visible in the zoom window:

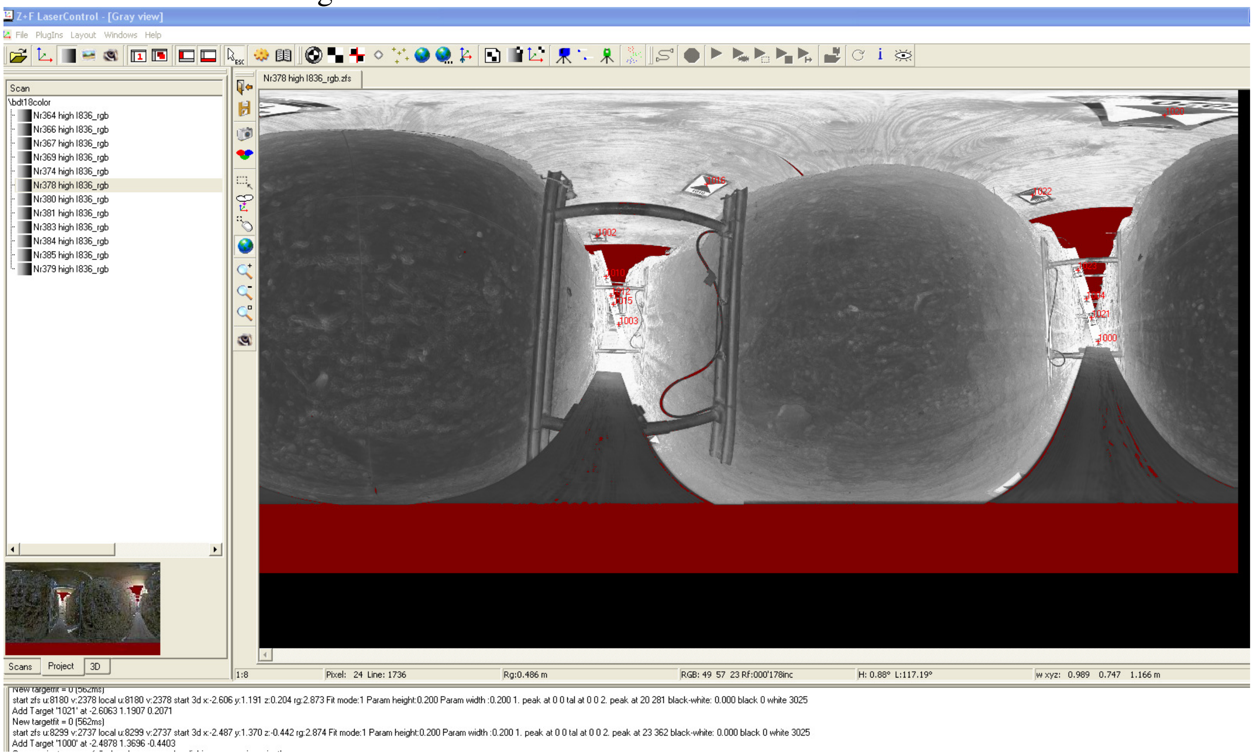


Left click once in the zoom window near the center of the target. A new window will open, showing the automatically fitted target center:



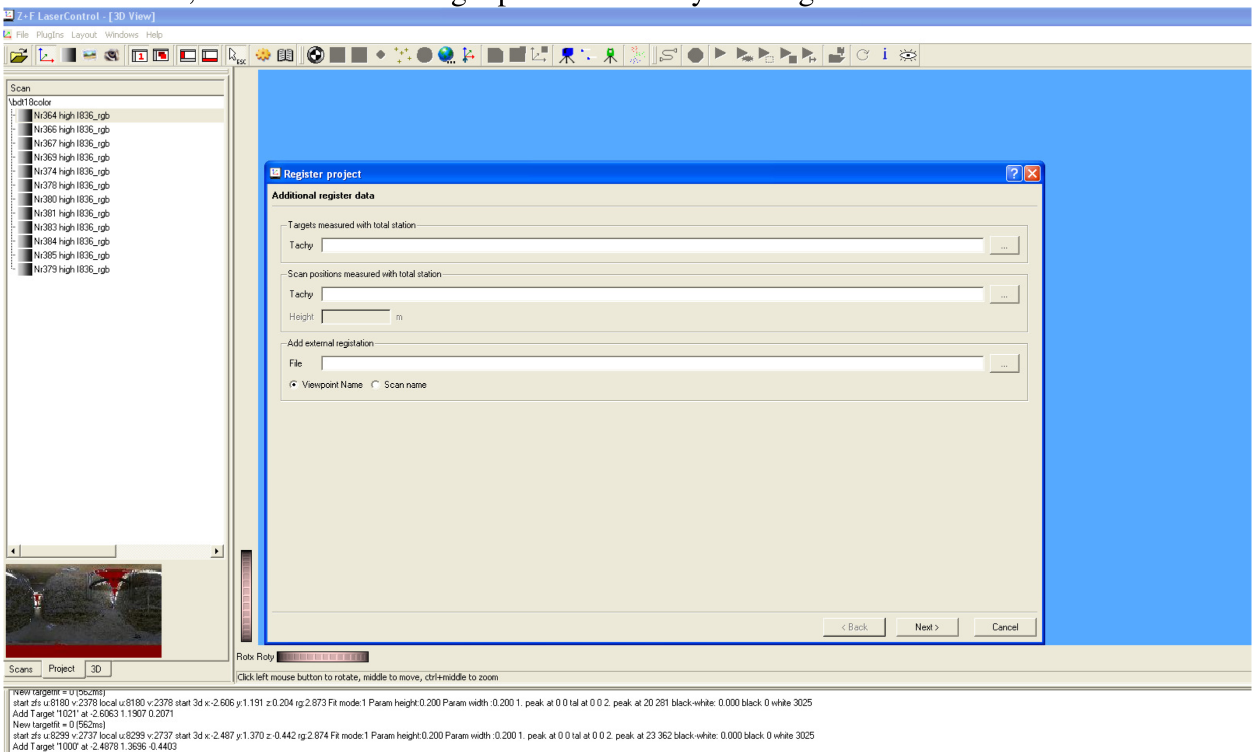
In the "Target name" field, enter a target name or number that is unique to the target you're about to fit. Hit OK when done, and pick out as many targets as possible in this scan. Once complete, close this scan's 2D view (button that looks like a door with an arrow pointing toward it), and repeat the above steps for the other scans.

The success of the automated target recognition process depends significantly on how well the targets are imaged by the scanner. See *Factors affecting target setup* (page 3) for more on this. Here are all the fitted targets for the above scan:

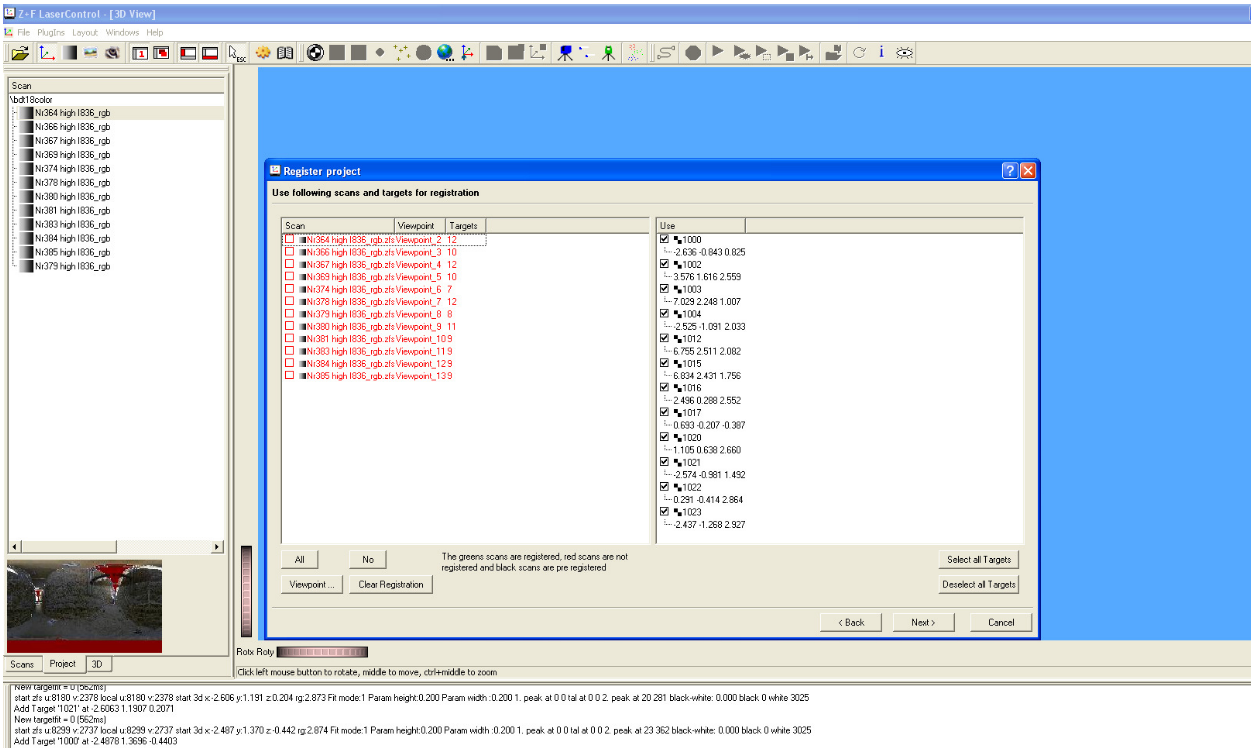


Registering multiple scans

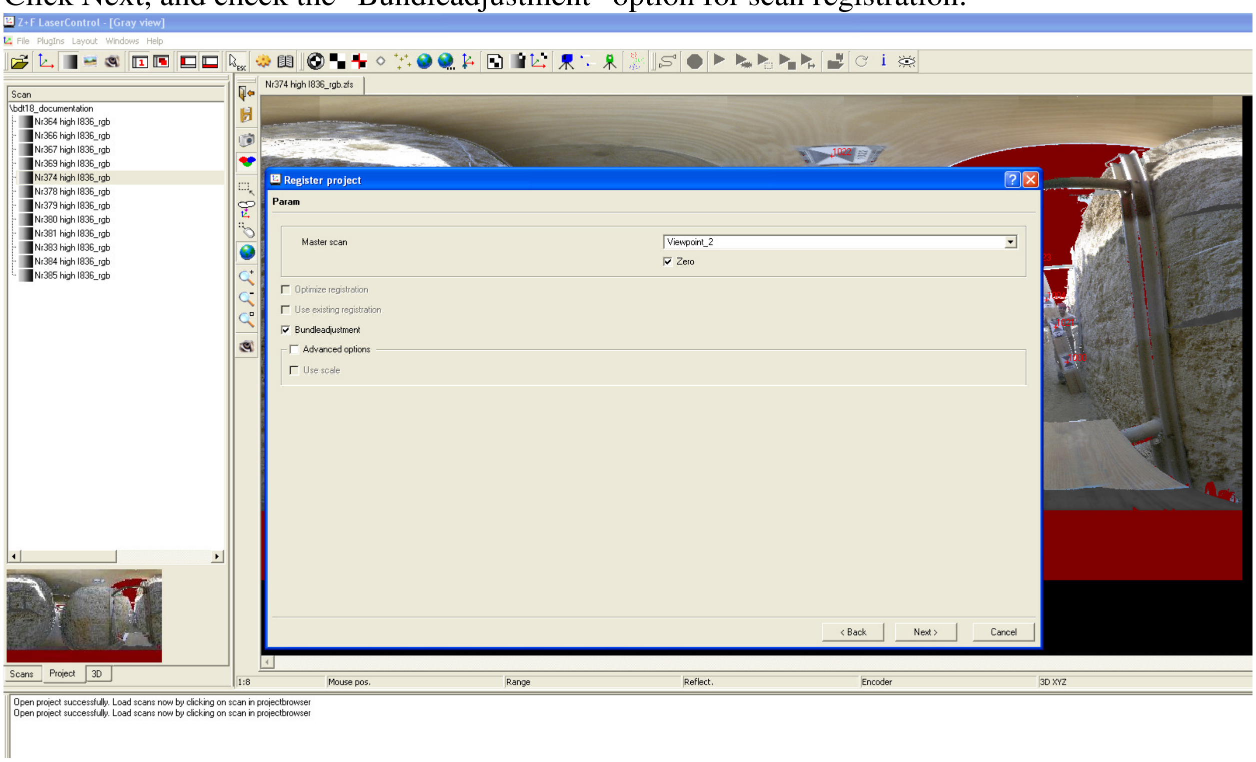
Once all targets have been fitted for each individual scan, click the “Register all scans…” button (looks like a blue sphere with three dots) to register all scans that are in the current project using the fitted targets. The first dialogue box will ask for additional registration data that you may have available, such the scan or target positions surveyed using a total station:



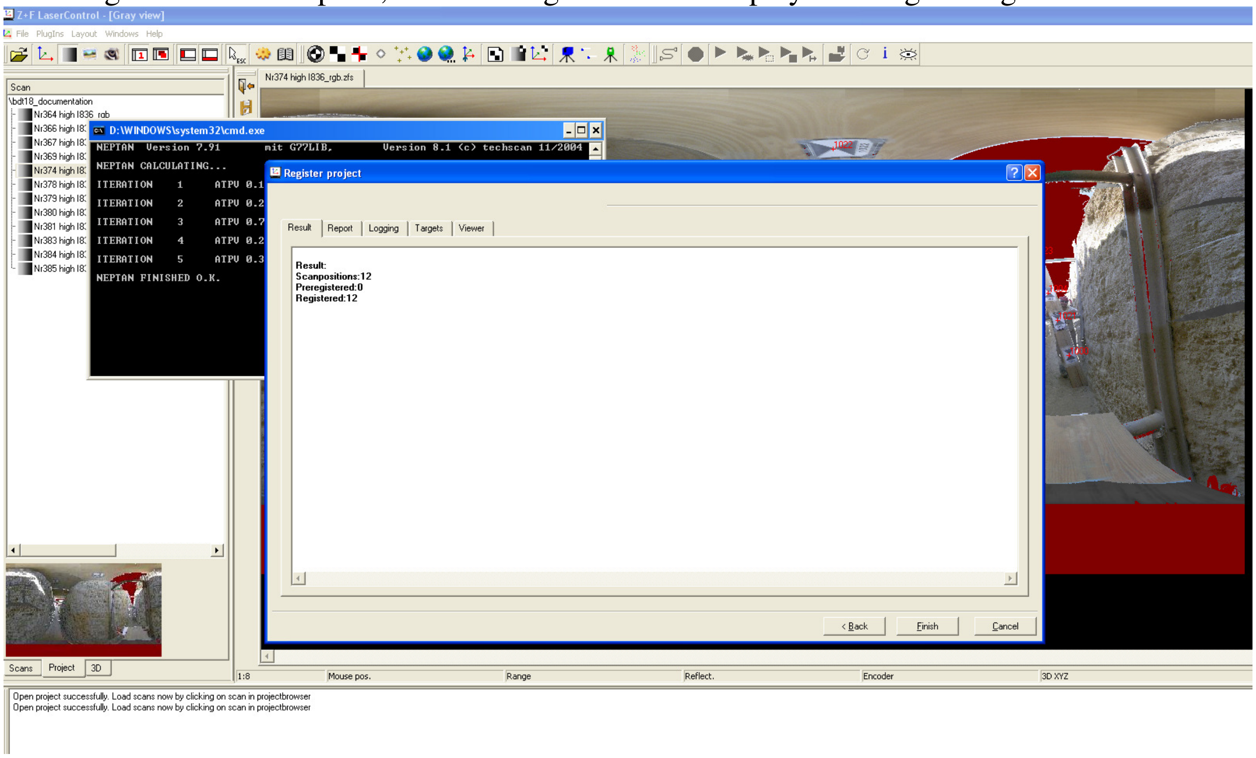
Since neither the targets nor scan positions for T18 were surveyed, I clicked the next button. In the following dialogue box, select the scans you want to register. Green scans are registered, whereas red ones still need to be registered:



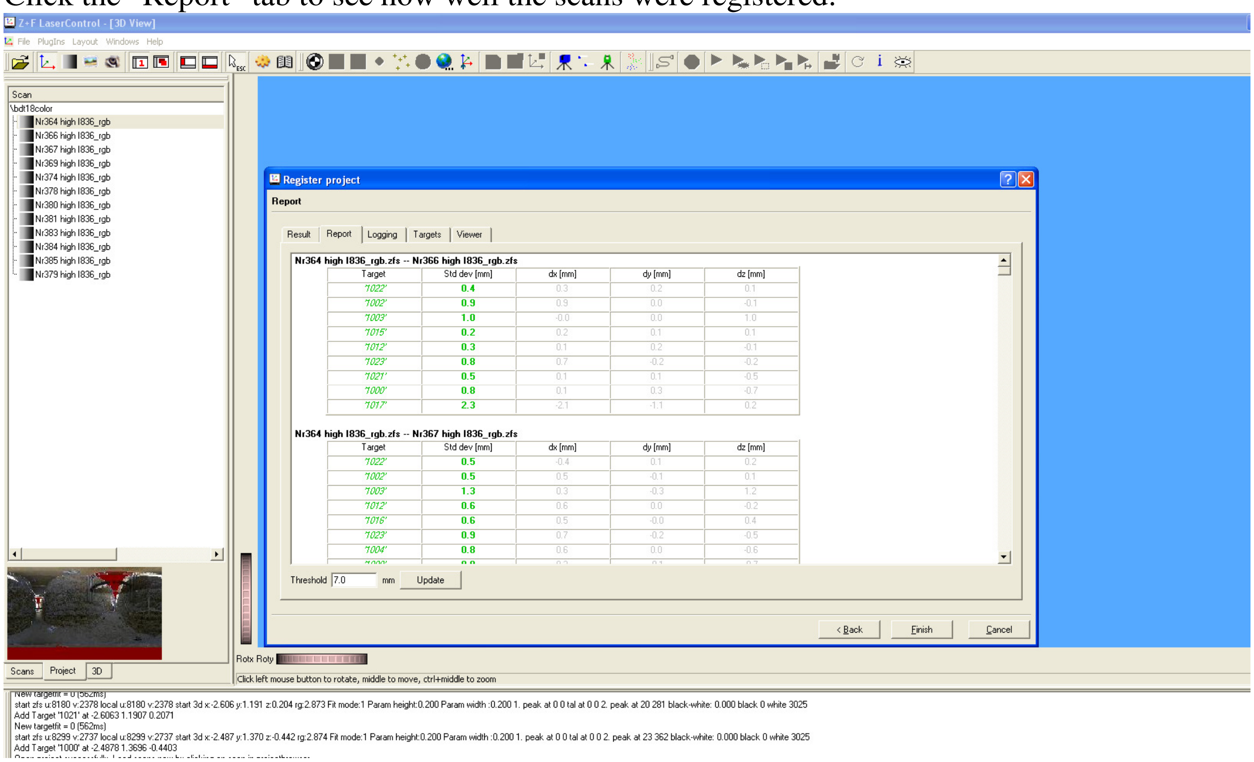
Click Next, and check the "Bundleadjustment" option for scan registration:



Once registration is complete, a new dialogue box will display showing the registration results:



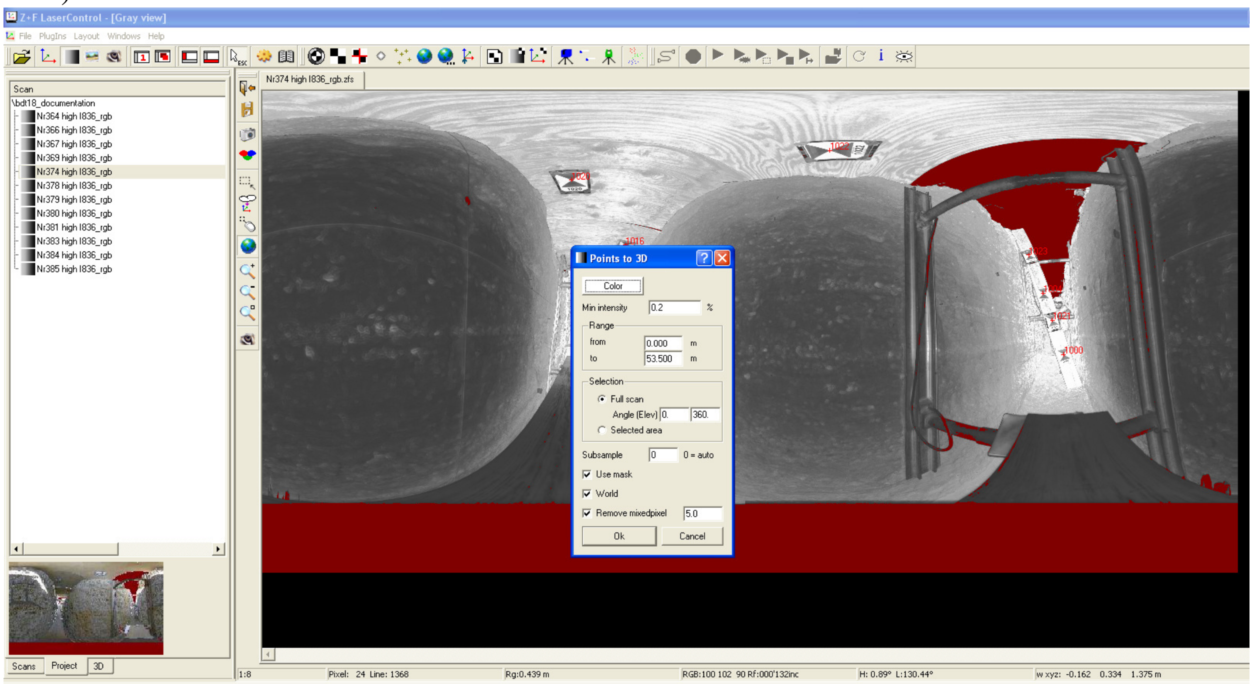
Click the "Report" tab to see how well the scans were registered:



Green targets represent a good fit between scans, whereas red targets represent large misfits. Depending on the tolerance of your study to errors, a few red targets may not affect the registration by much (they didn't for T18's case). However, if the standard deviation for a target is anomalously large, one (or more) of the targets was likely not fitted correctly (or not named correctly) in one (or more) of the scans. If this happens, go back and make sure all targets were named correctly (this is where a sketch map of the target position will be your savior!).

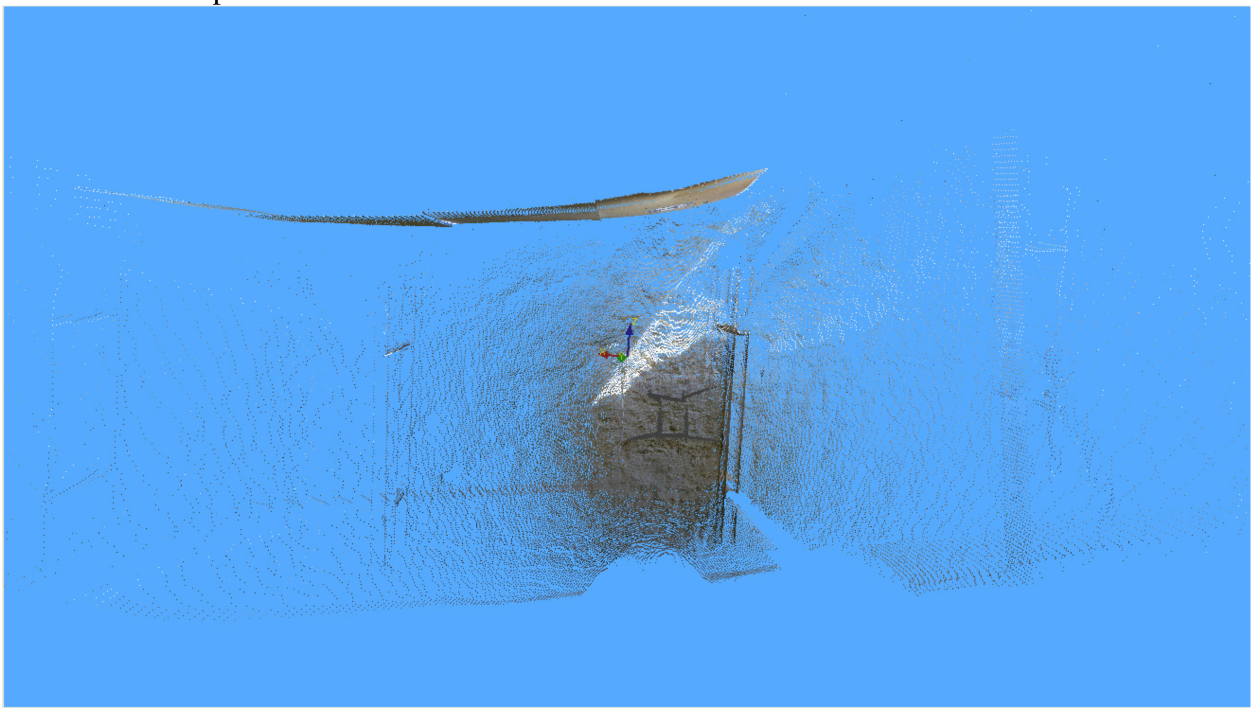
Displaying a scan as a 3D point cloud

Scans can be displayed as 3D point clouds in Z+F LaserControl. The success of this feature will depend on your computer's processing power and graphics card. Double click a scan in 2D view. Click the "Points to 3D" button (looks like a white blob with an arrow pointing to xyz axes):

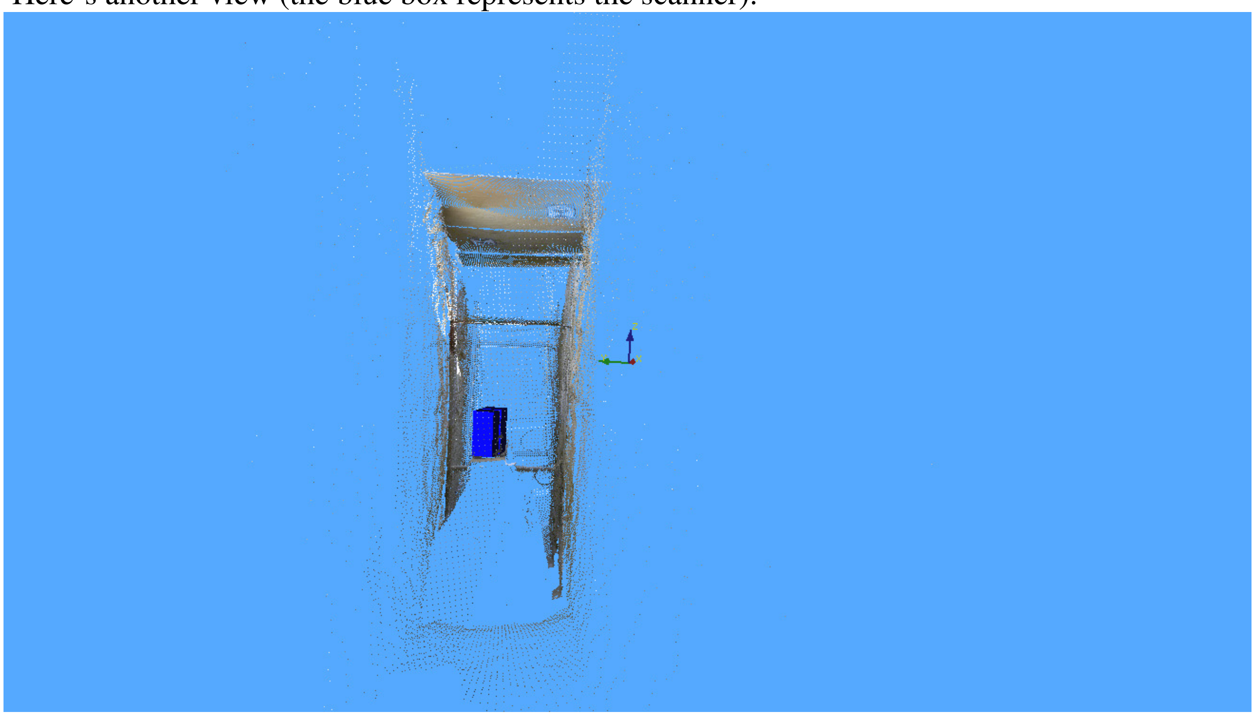


This dialogue box allows the user to set the minimum intensity to use when displaying the point cloud, the range (distance of points from scanner), the full scan or a selected area within the scan, the "Subsample", and any masks used in the pre-processing of the data. The "Subsample" field allows the user to define the density of the resulting point cloud. The smaller the subsample value, the higher the point cloud density. The lower the subsample value, the more processor demanding and longer this process takes. Click OK, and switch to the 3D view (button located in the top-left hand corner of the menu, looks like xyz axes).

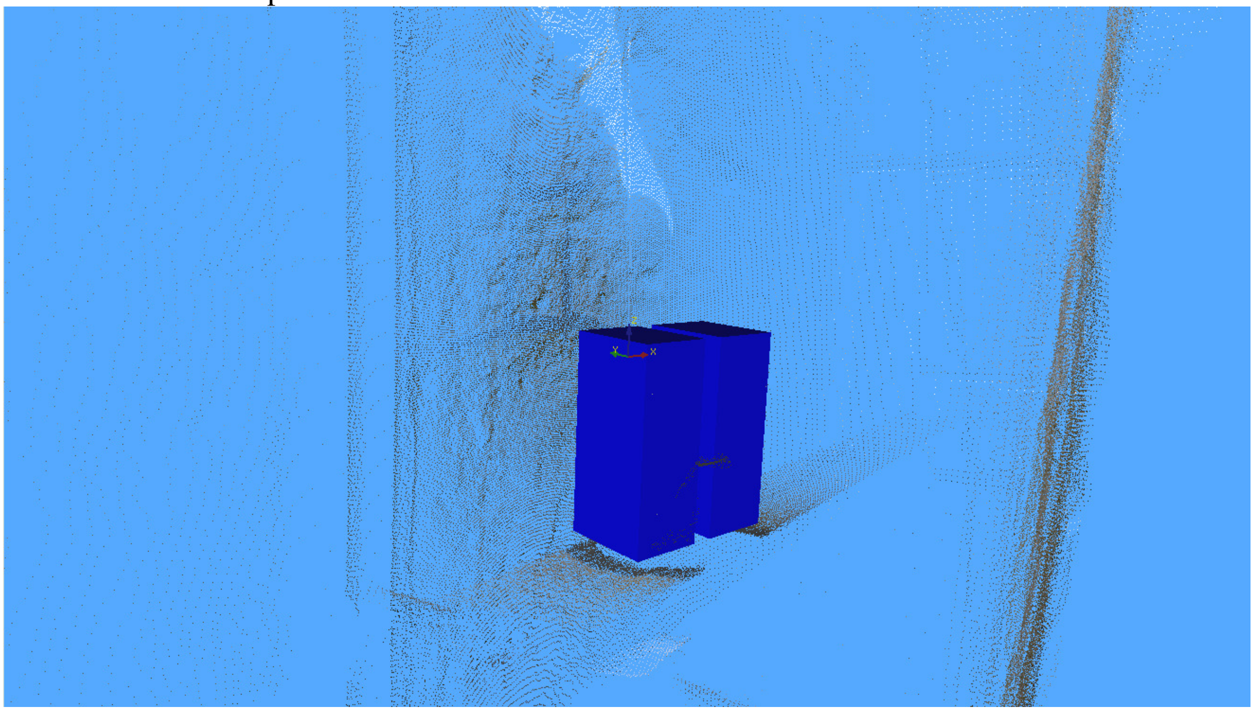
Here's what the point cloud for the above scan looks like:



Here's another view (the blue box represents the scanner):



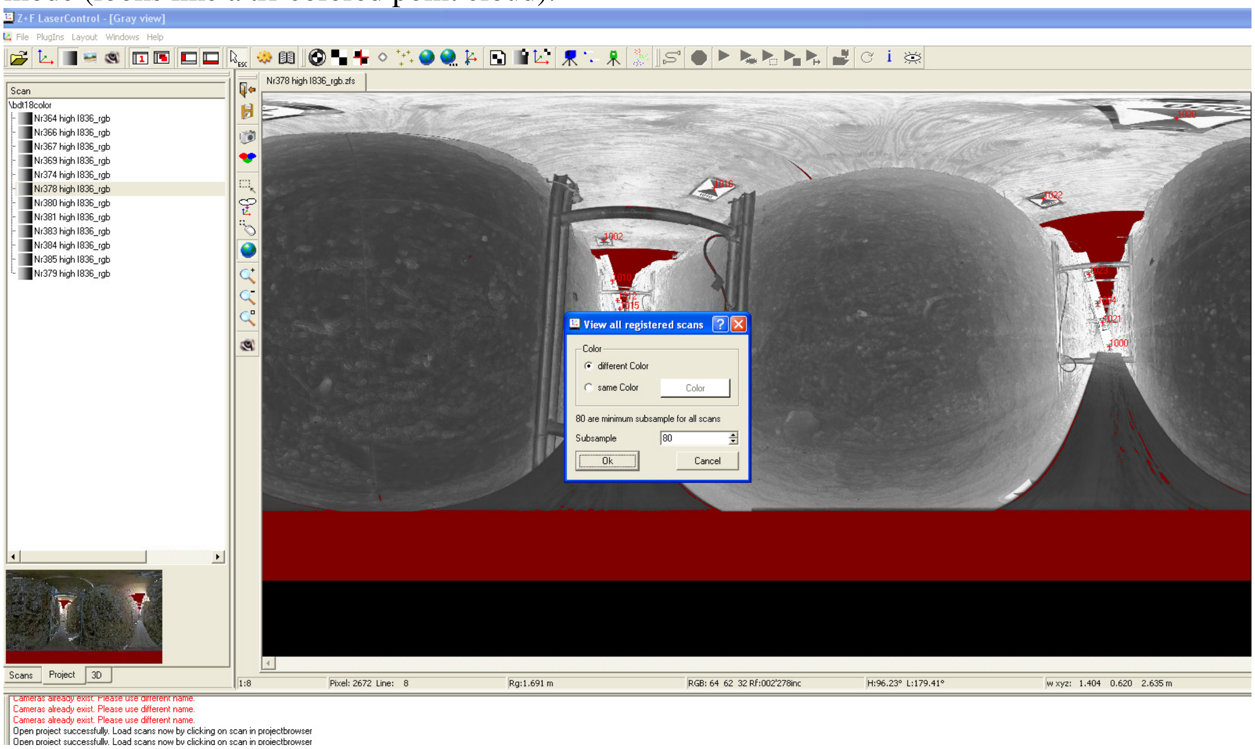
And here's a close-up view from inside the trench:



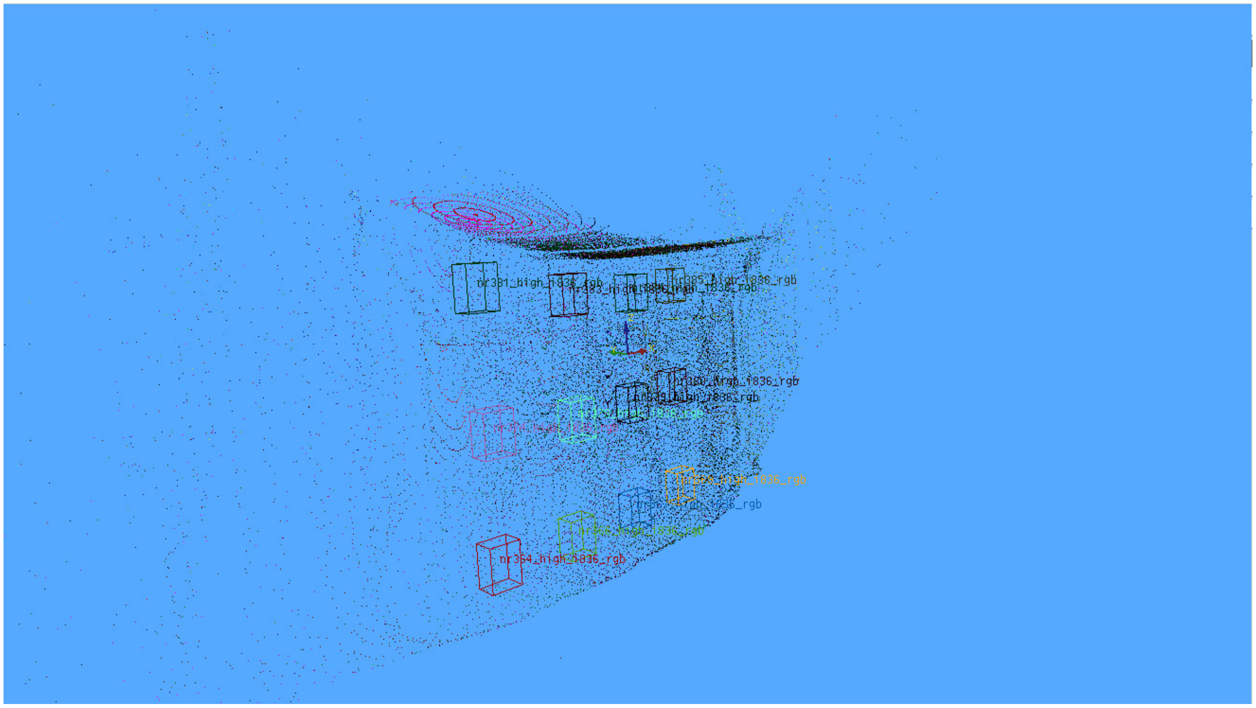
You can repeat the above steps to add as many scans as you want to the 3D point cloud view.

Displaying the registered scans as 3D point clouds

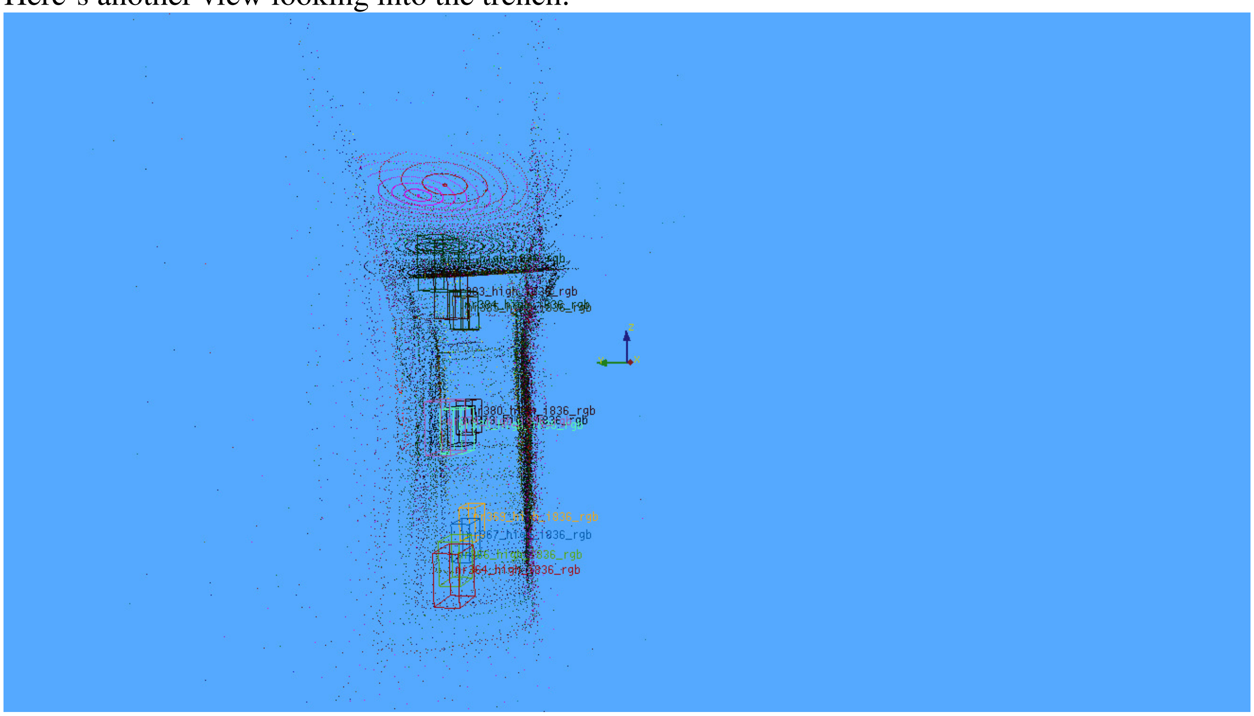
We can also display the entire dataset as a combined 3D point cloud (provided the scans have been registered). Click the "View all registered scans as 3D overview" button in the 2D grey mode (looks like a tri-colored point cloud):



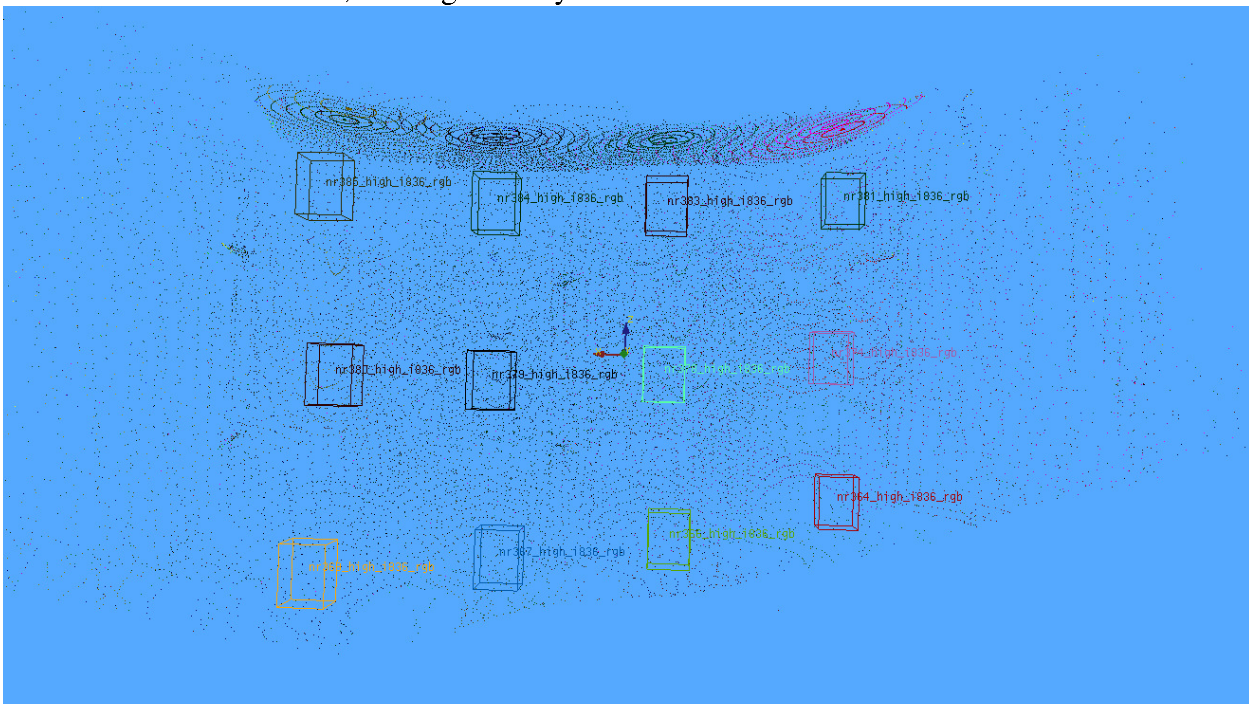
The dialogue box allows the option to display each scan's point cloud using different colors or the same color. When displaying the point clouds of all scans (as I'm about to do now), Z+F sets a minimum subsample value of 80 (so that the computer doesn't crash). This process may take some time depending on how many scans you have in the project and the subsample value you entered. Use the "Fly" tool (looks like a white-gloved hand) to rotate the point cloud. Here's one view of what the combined 3D point clouds for T18 look like:



Here’s another view looking into the trench:



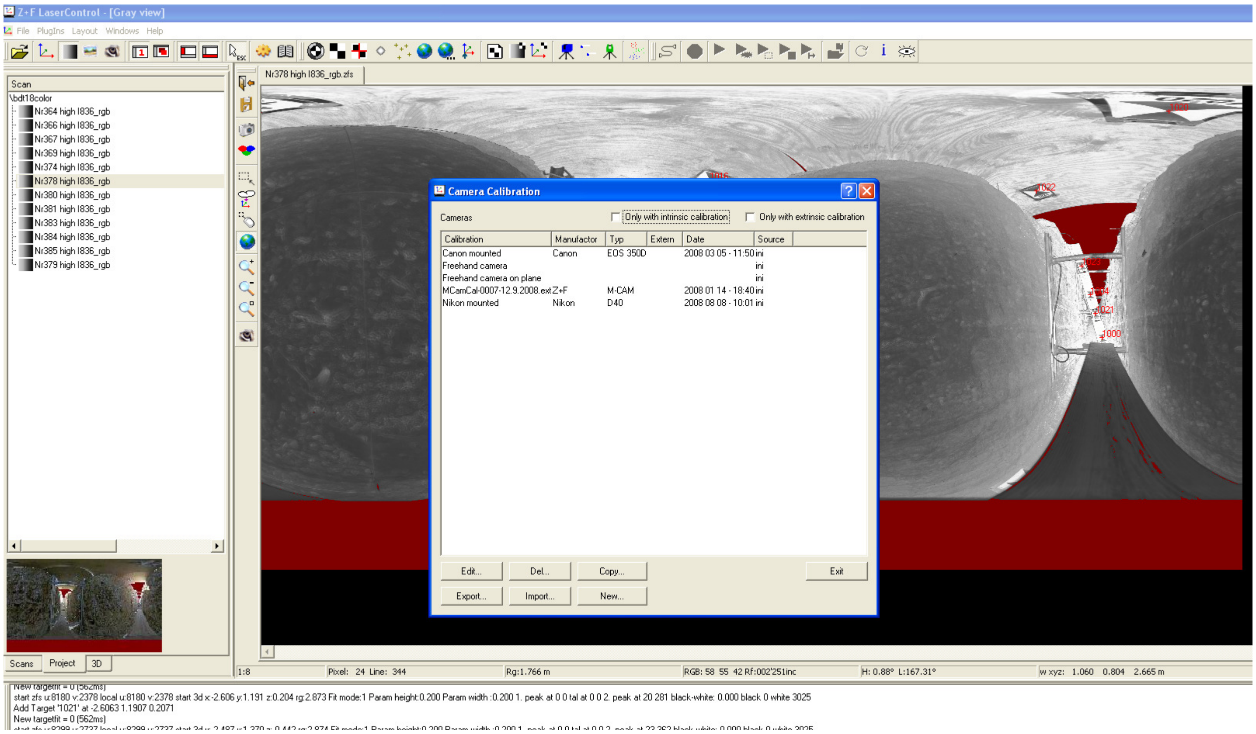
And here’s one more view, looking sideways this time:



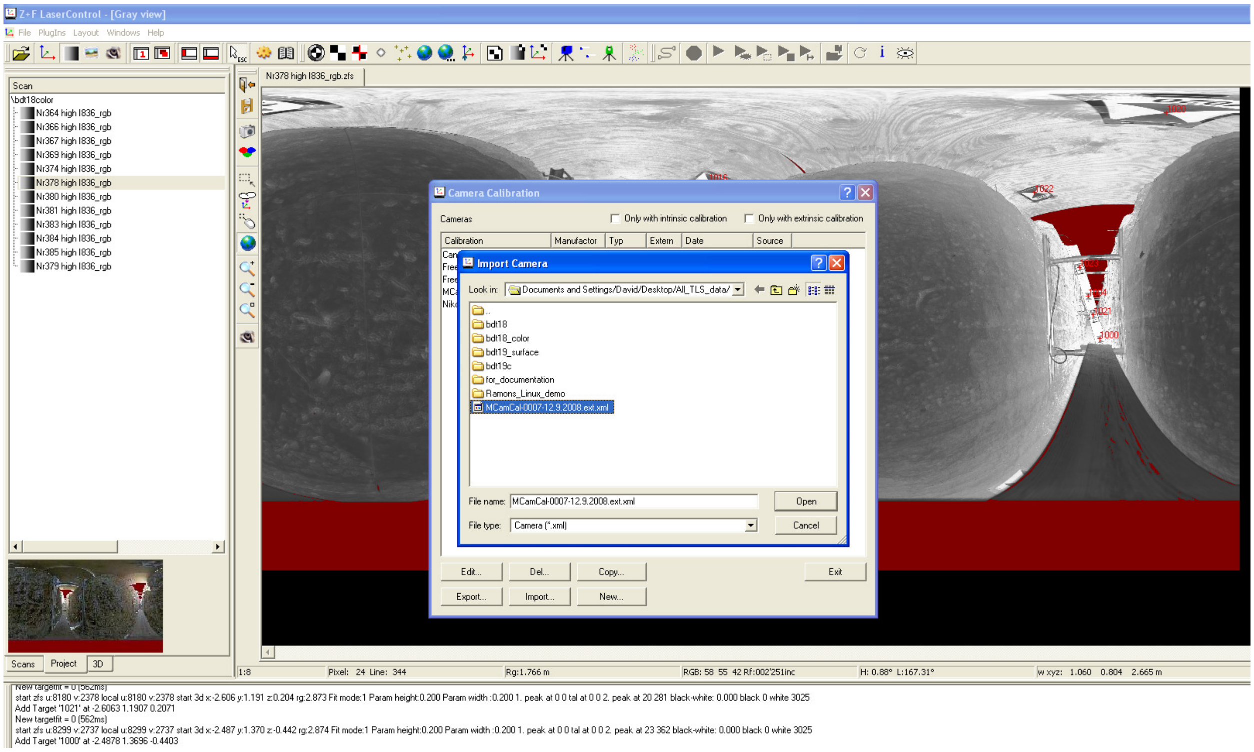
The colored boxes represent scanner locations for each scan.

Color mapping

Color mapping assigns each point in the point cloud a color based on its RGB value from the photographs taken by the scanner's camera. The first step in color mapping it ensuring the camera's calibration file is ready for use by Z+F LaserControl. Go to the PlugIns menu and click Color >> Camera Calibration:

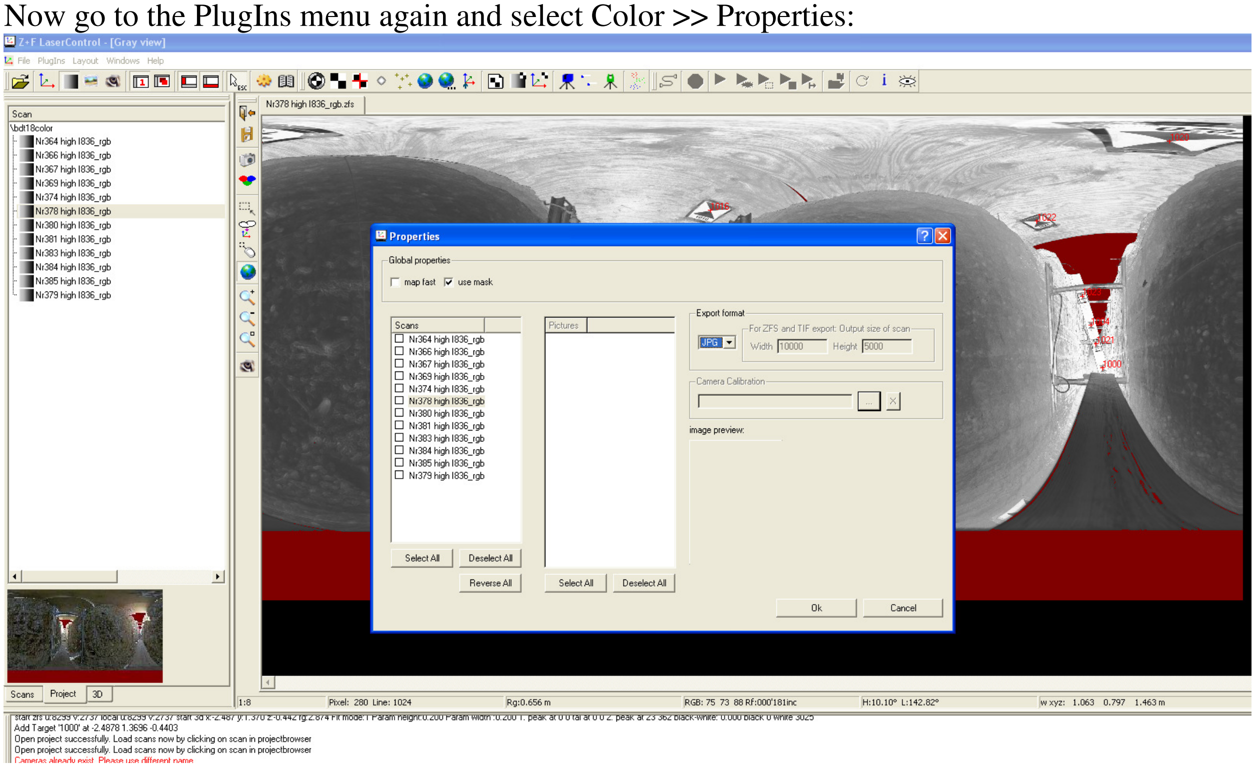


Click "Import…", and navigate to the location of the camera calibration file:



Select the camera and add it to the list of cameras in the "cameracalibration" menu.

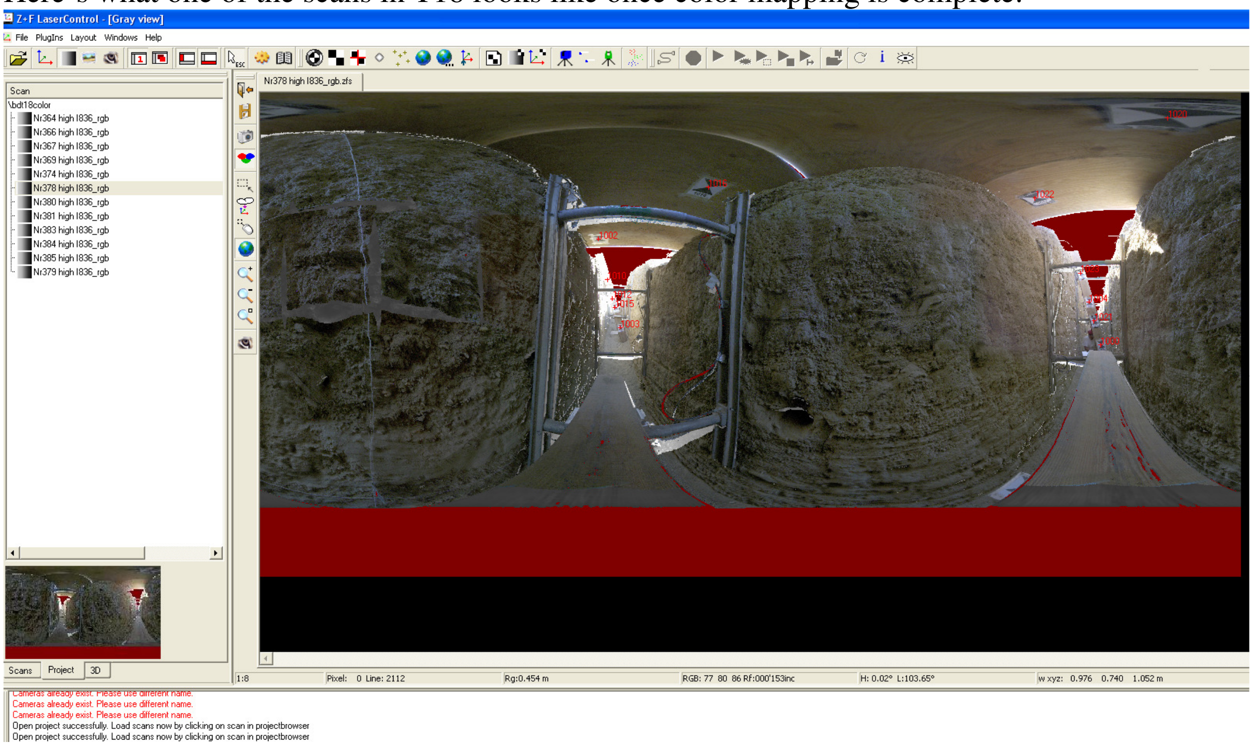
Now go to the PlugIns menu again and select Color >> Properties:



Select all scans to be color mapped, and click the browse button under “Camera Calibration” to select the calibration file you wish to use in the color mapping (this should be the same file you just added in the previous step) and click OK.

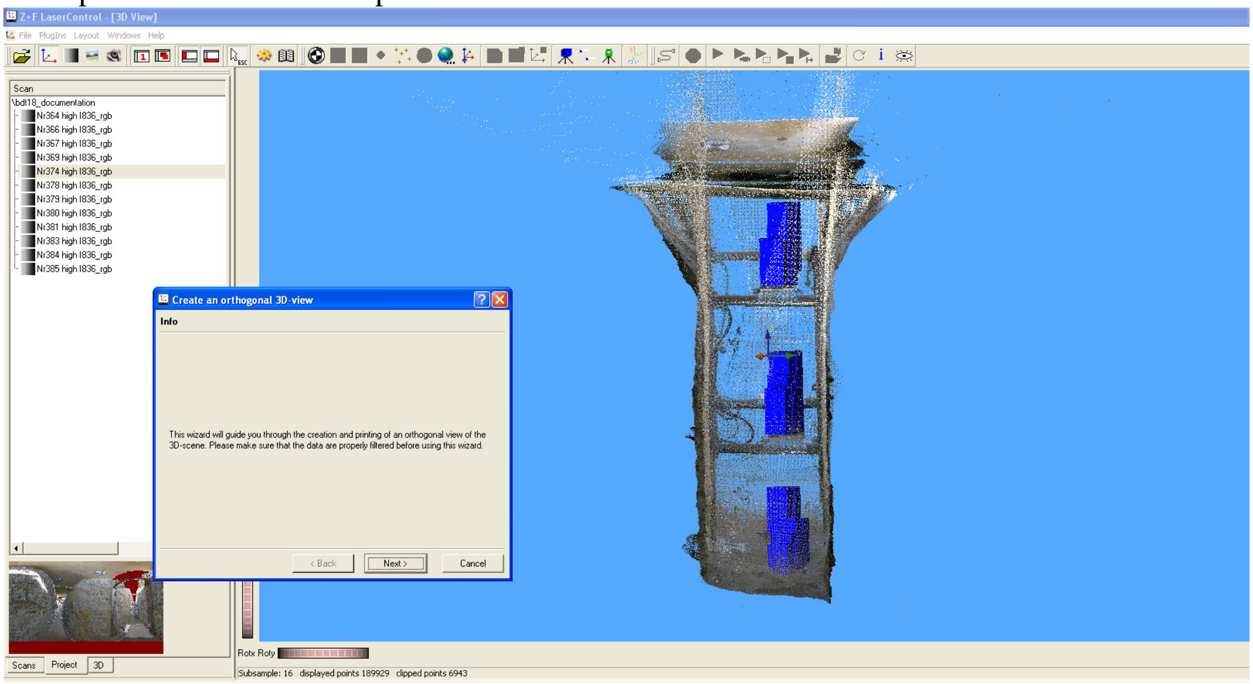
To initiate color mapping, go to PlugIns >> Color >> Generate Color Scan(s). WARNING: this step takes a long time to execute! Make sure Z+F LaserControl is the only program running your machine. If the software crashes, it’s a good indication that the processing power of your machine is not up to par.

Here’s what one of the scans in T18 looks like once color mapping is complete:

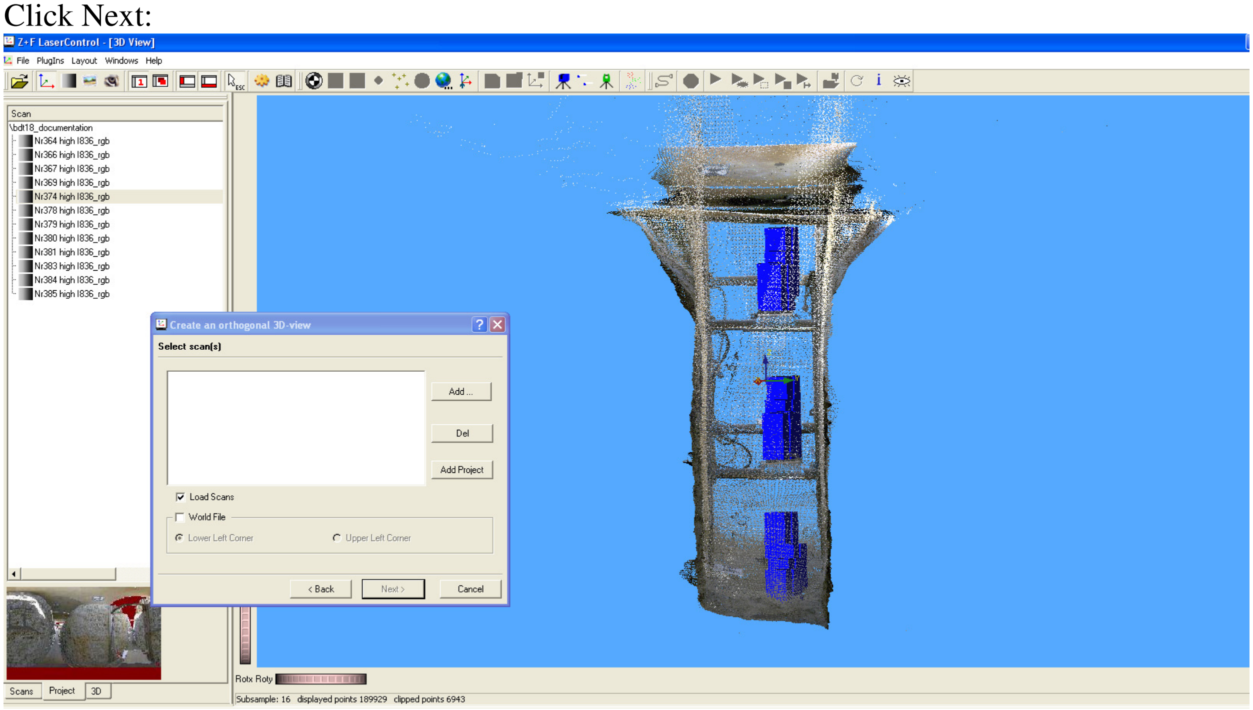


Projecting point clouds onto a plane

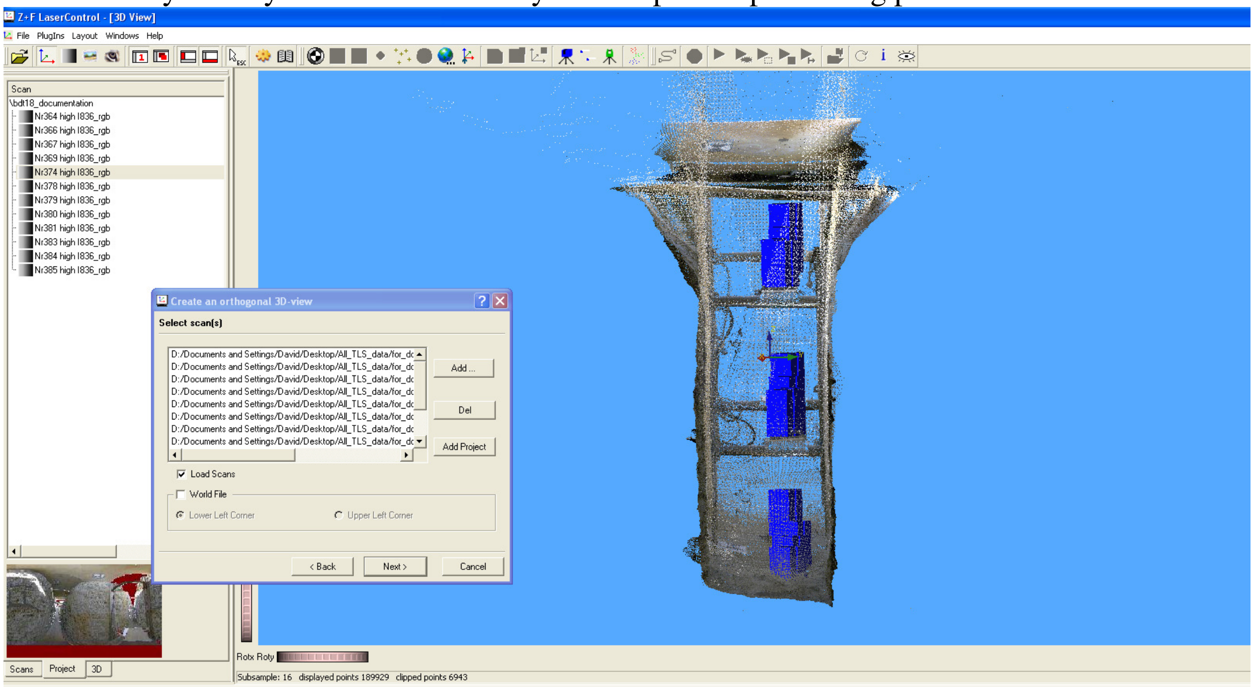
The following steps will demonstrate how Z+F LaserControl can project point clouds onto a user-specified plane. For the case of T18, I will project the channel wall nearest the San Andreas Fault onto a vertical plane to produce a color orthoimage of the trench wall. Go to PlugIns >> Orthophotos >> Create orthophotos:



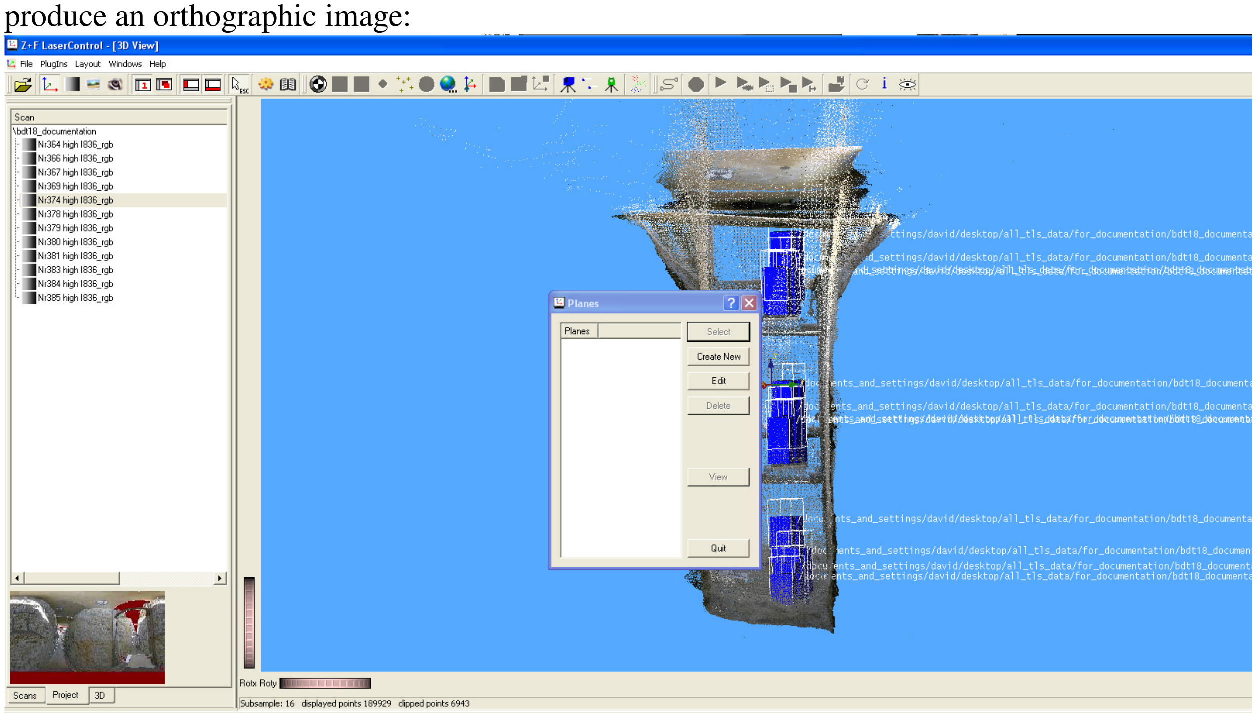
Click Next:



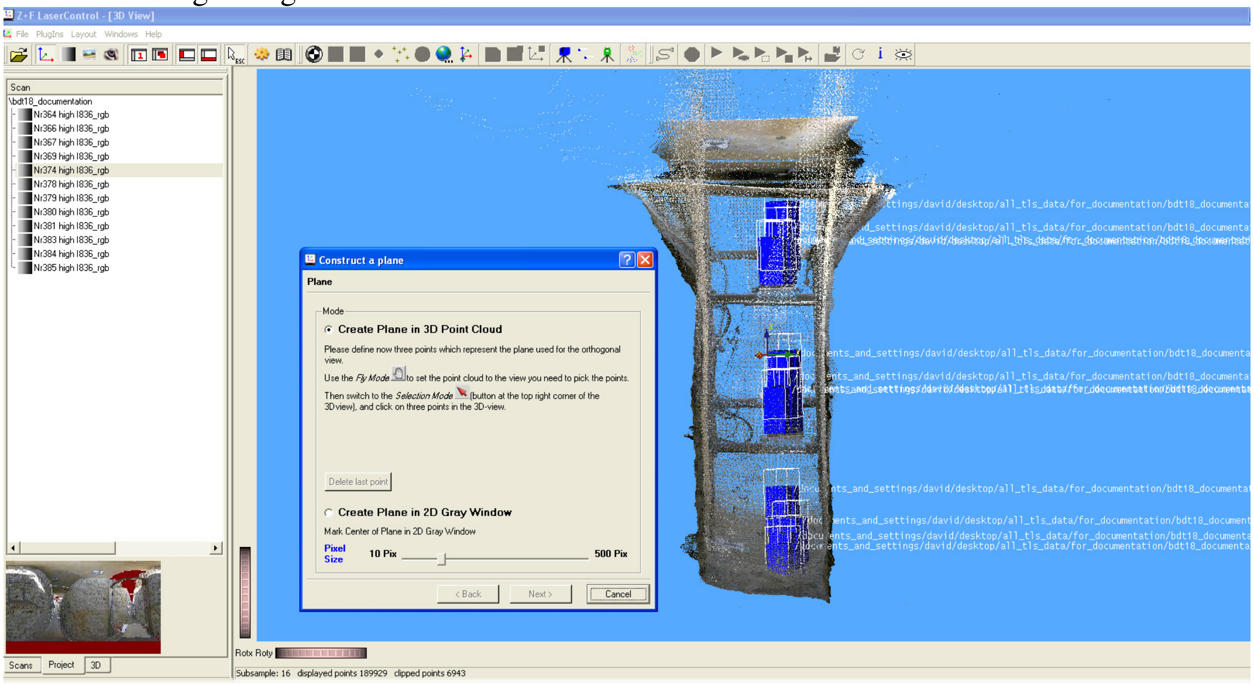
You can either add a selection of scans, or all scans in the project. In the case of T18, I will add all scans in the entire project by clicking Add Project. This step will take some time depending on how many scans you want to add and your computer's processing power:



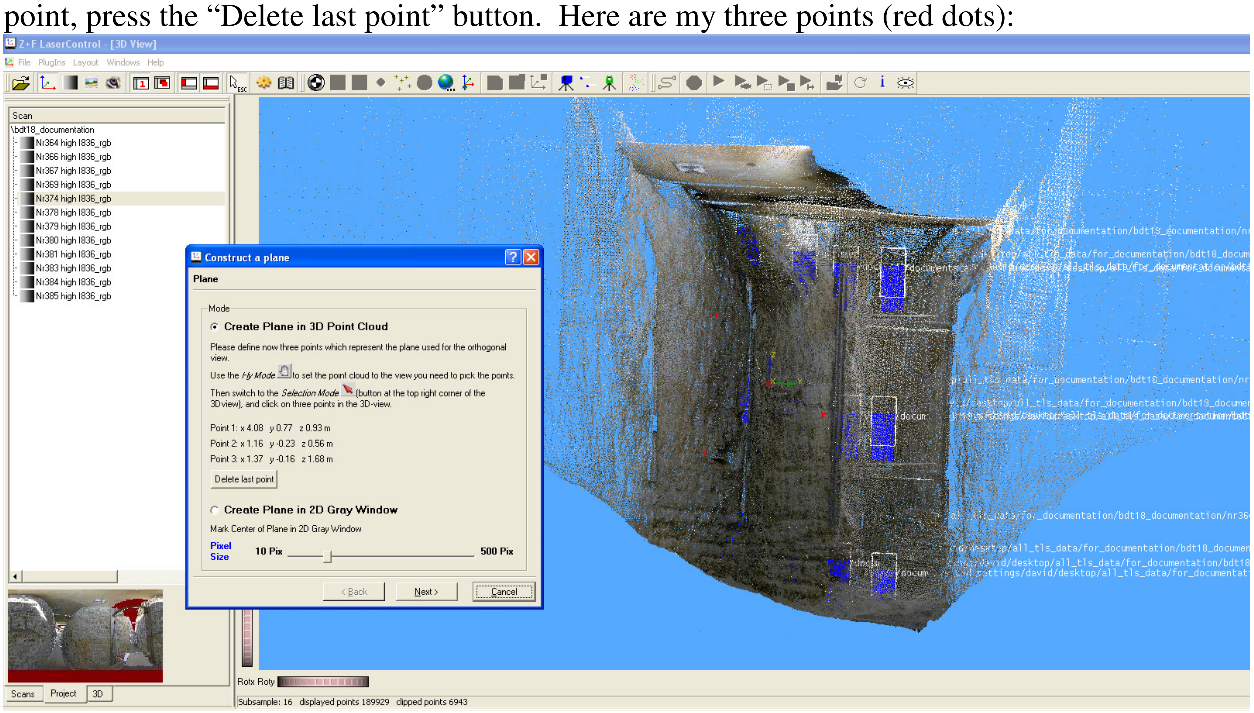
The following dialogue box provides the option to create a new orthoplane or select a predefined orthoplane (or orthoplanes that were created and saved) on which to project the point clouds to produce an orthographic image:



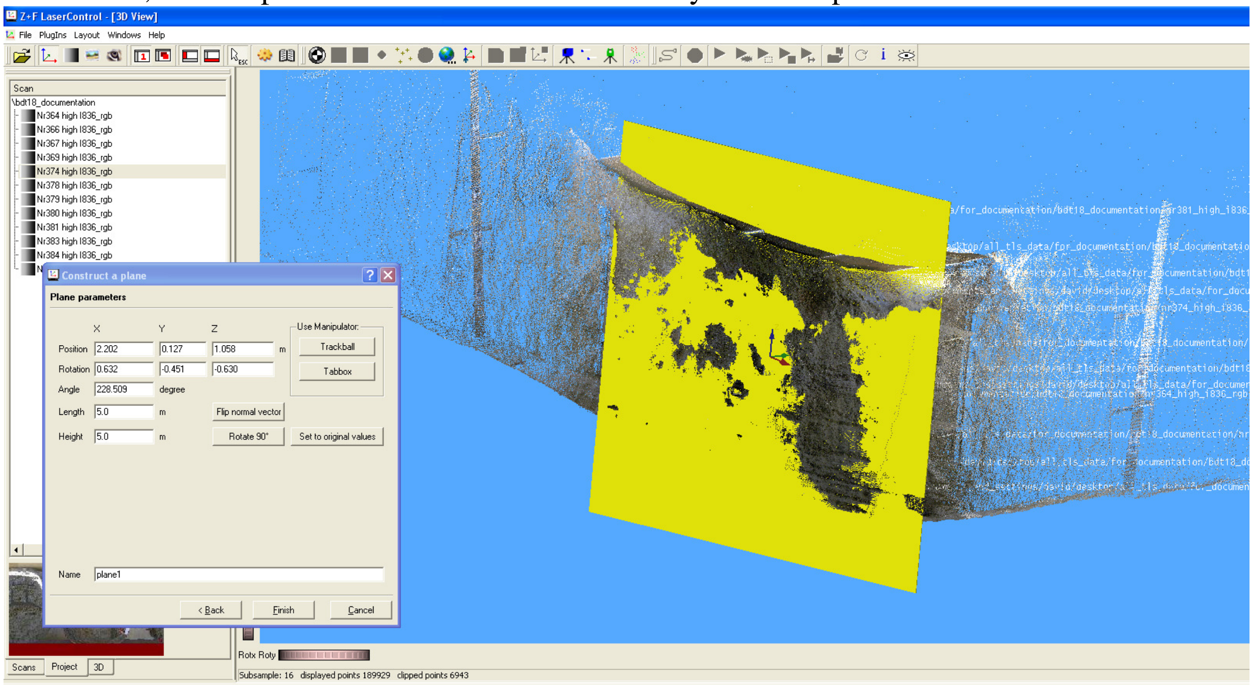
For this case, I'm going to create a new plane by clicking the Create New button. This takes us to the following dialogue box:



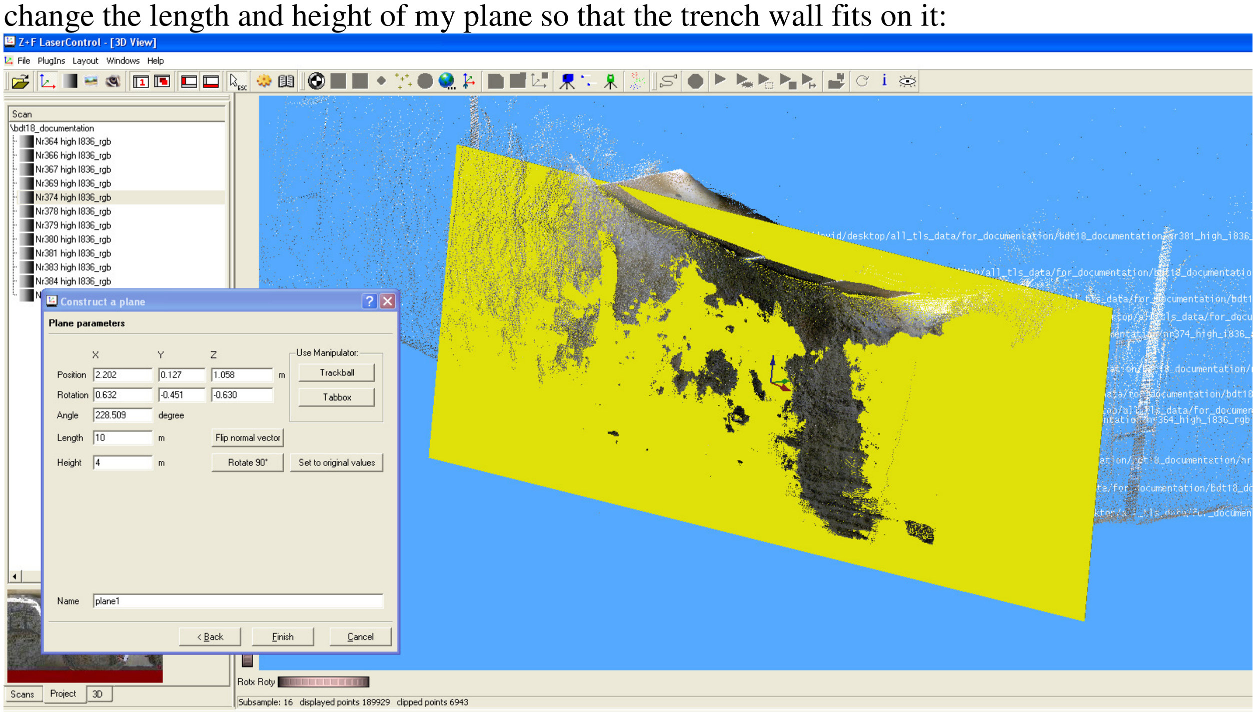
You can create a plane that passes through three points in the point cloud, or you can create a 2D plane in 2D mode. Since I already have my point clouds displayed in 3D, I'm going to choose the first option. Here you will use two tools: the Selection Mode (red pointer) and the Fly Mode (white-gloved hand). Use the Fly Mode to orient the point cloud to a desired view, and the Selection Mode to select a point that the orthoplane will pass through. If you're not happy with a point, press the "Delete last point" button. Here are my three points (red dots):



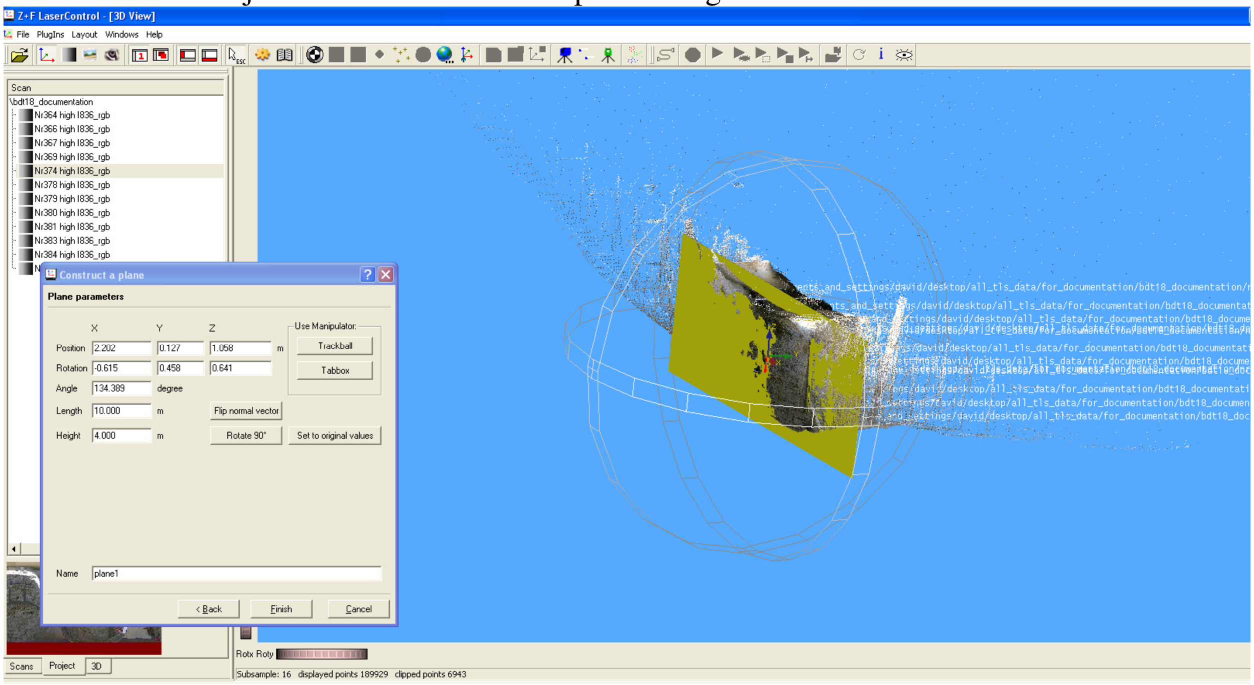
Click Next, and the plane will be created as defined by the three points:



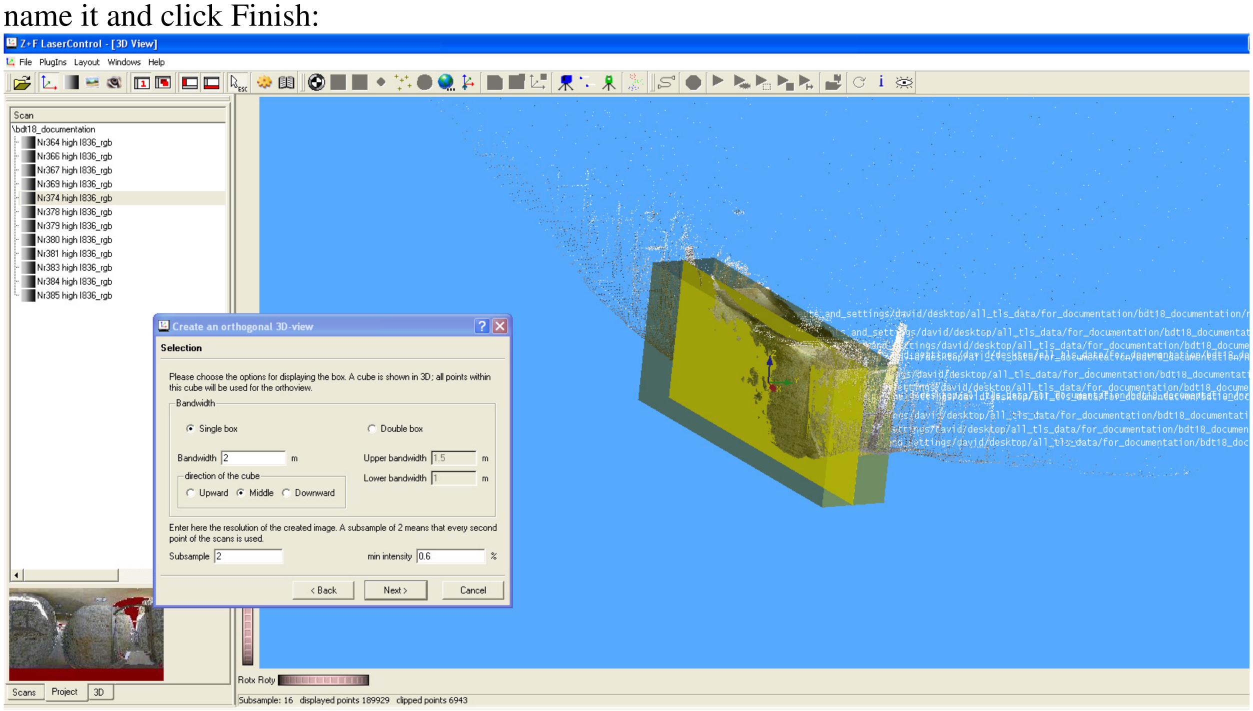
You have the option to tweak the orientation of the plane in this dialogue box. I’m going to change the length and height of my plane so that the trench wall fits on it:



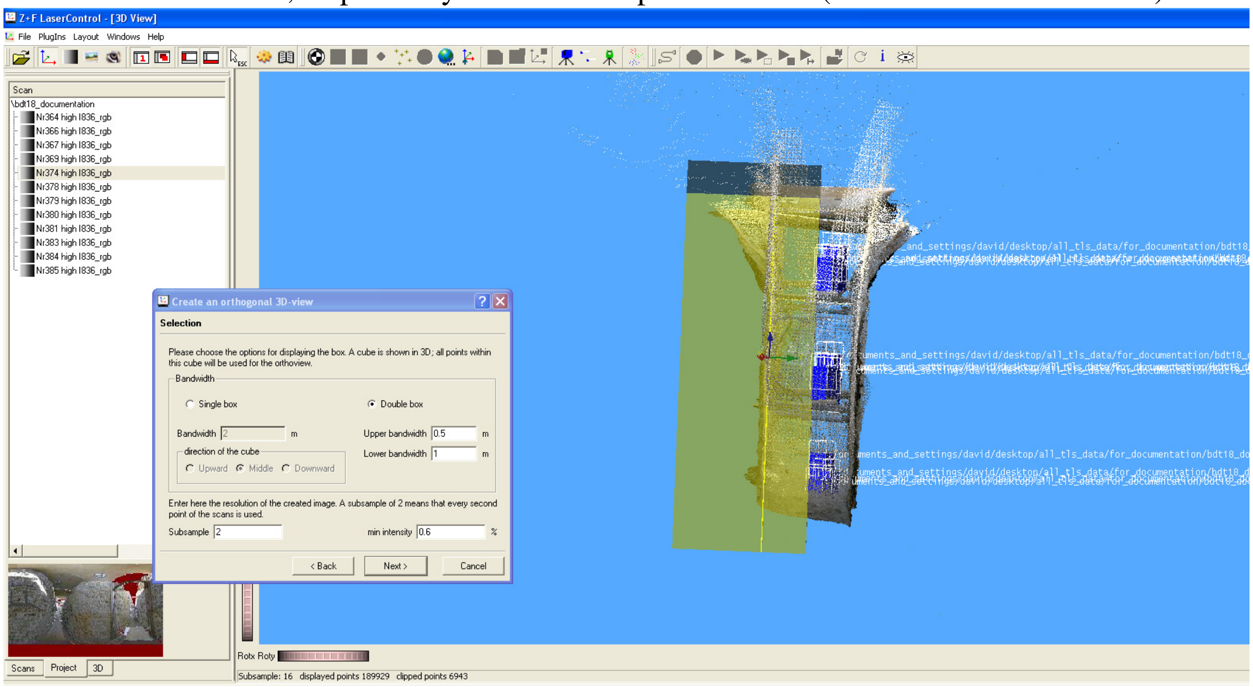
You can further adjust the orientation of the plane using the Trackball:



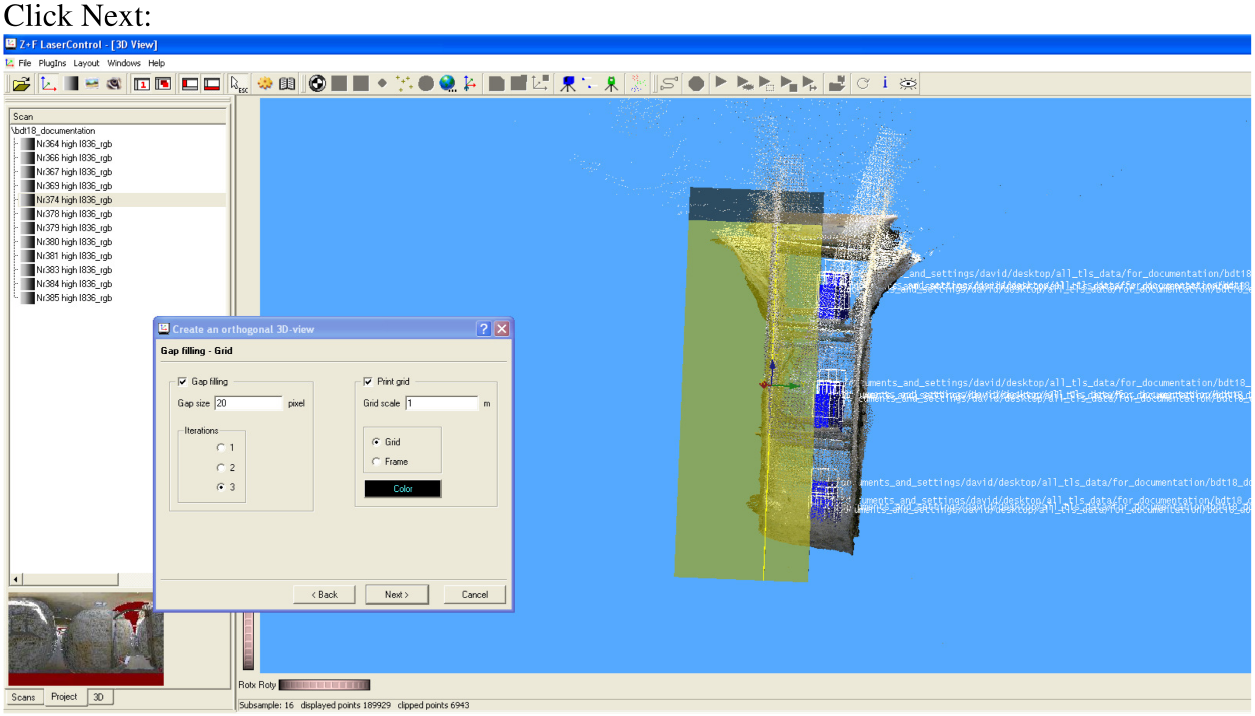
Don't worry if the plane intersects part of the trench wall. The next step will help refine which points in the point cloud will be projected to the orthoplane. Once you're happy with this plane, name it and click Finish:



The above dialogue box will allow you to define a distance from the front (Upper bandwidth) and back (Lower bandwidth) of the plane that points will be selected for the orthoprojection. You can also choose to change the resolution of the orthoimage by reducing the Subsample value (but it will take longer to process!). For the case of T18, I selected 0.5 m and 1 m for the upper and lower bandwidths, respectively and a subsample value of 0 (full resolution of the data):

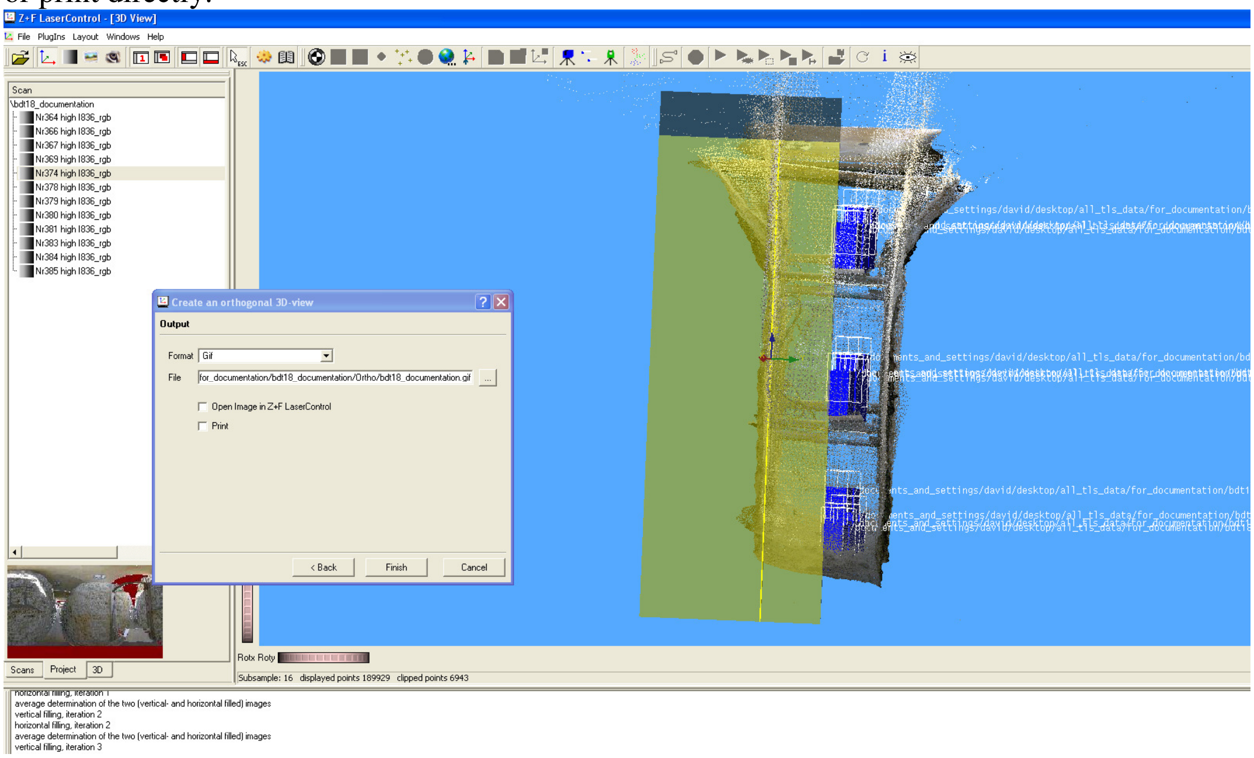


Click Next:

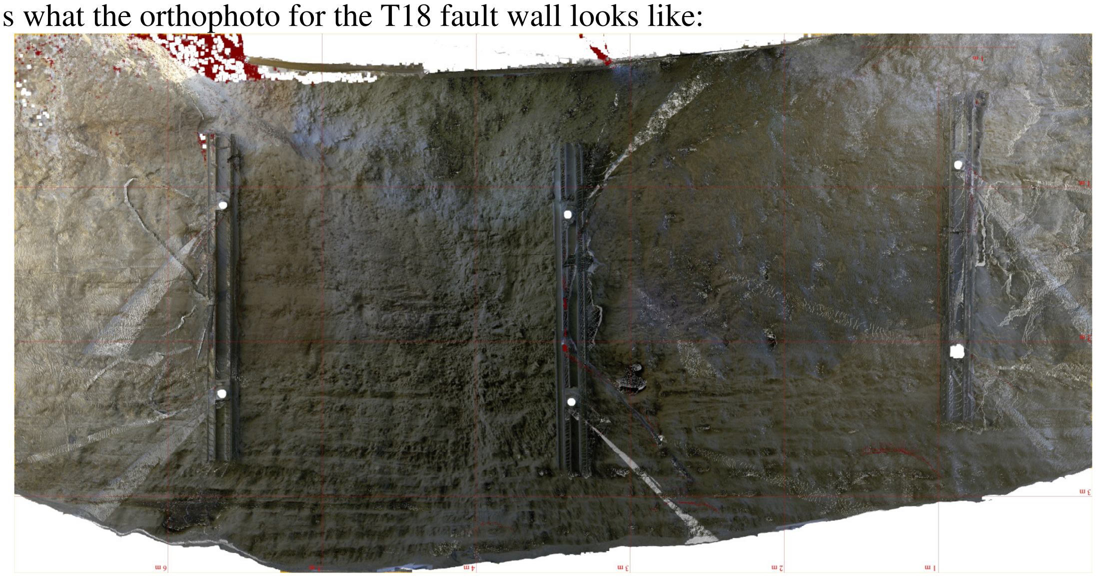


This is the final dialogue box before the orthoprojection process begins. Here you have the option to fill in any gaps in the pointcloud that may be projected onto the orthoplane. Larger pixel sizes will fill in most gaps but take longer to process. You also have the option to define the number of times L+F LaserControl iterates gap filling. The final option allows you to set the grid scale and color that will be printed on the final orthoimage. Click the next button to begin orthoimage processing. WARNING: depending on the settings you choose and your computer's processing power, this process may take some time to execute!

When orthoprojection is complete, you have the option to either save the image (as a .gif or .jpg) or print directly:

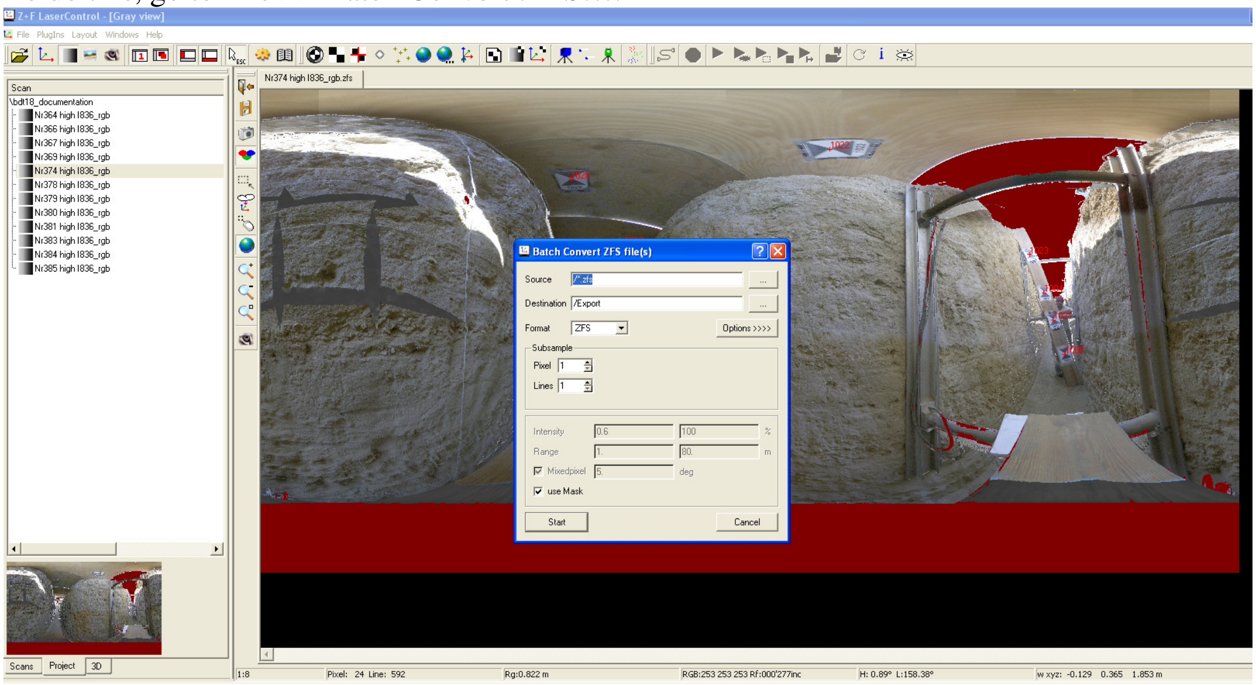


Here's what the orthophoto for the T18 fault wall looks like:



Exporting point clouds as xyz ASCII files

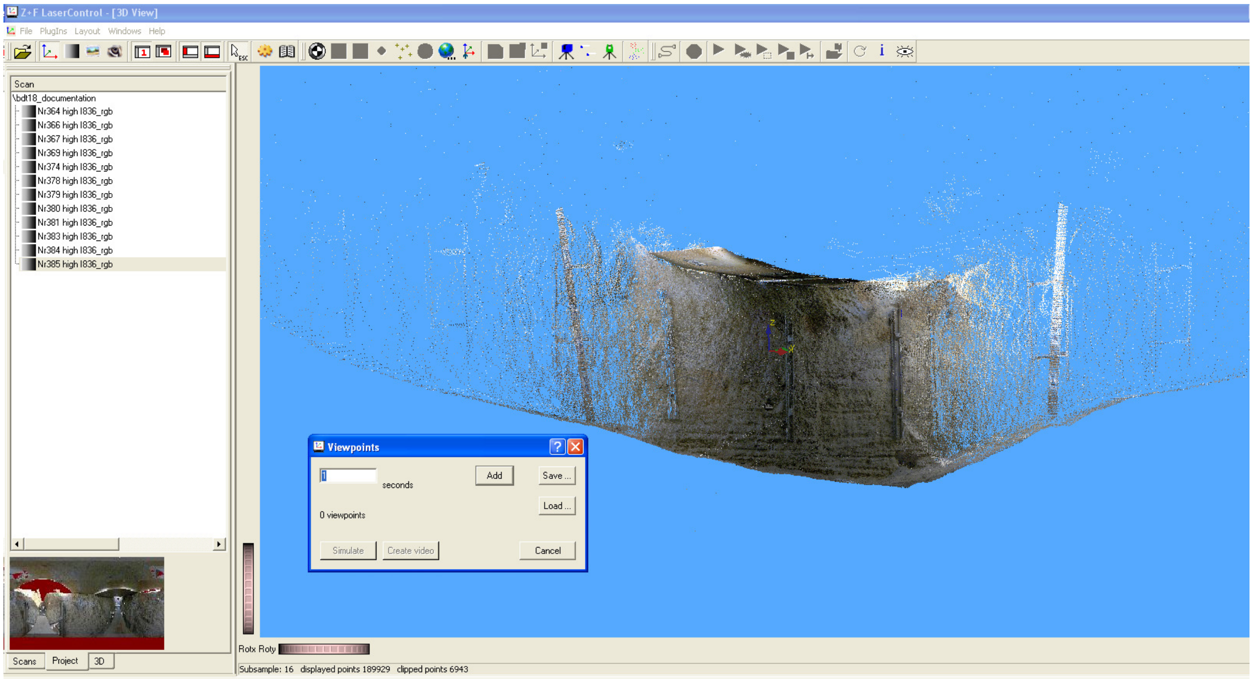
Converting and exporting .zfs scans as xyz ASCII files is best done in batch for multiple scans. To do this, go to File >> Batch Convert .ZFS…:



Browse to the source directory of the scan files you wish to convert and select a destination directory. Select a file format, and click start. This process may take some time depending on your computer's processing power and the number of scans you want to export.

Creating videos of point clouds

Z+F LaserControl has the capability to create .avi (video) files of user-defined fly-bys. Videos will be created for point clouds that are currently displayed in the 3D view. Go to PlugIns >> Video Generation:



The "Add" button adds the current view to the video. The "Time" value specifies the travel time between each view. The shorter the time, the faster the transition from one viewpoint to the next (and the smaller the final .avi file size). Using the "Fly" tool (white-gloved hand), orient the point cloud to the starting position of the video, click the Add button, then orient the point cloud to the next position in sequence, click Add, and so on. At any time during the addition of viewpoints, you can click the Simulate button to simulate what the video will play like. Once you're happy with the simulation (if not, either cancel or keep adding more viewpoints), click the Create button. Specify where you want to save the video, then select the compression format for the video (or leave it uncompressed for maximum compatibility with your computer's media player).

Send me an e-mail (address on front page of report) if you're interested in viewing some of the videos I created for T18, T19 amd T19c, or check out our videos library at http://lidar.asu.edu.

Preliminary Results

This section describes preliminary results from our summer 2009 TLS efforts on the Bidart fan site in the Carrizo Plain, CA (i.e. this is where the 12-hour, 117° days' work pay off). The T19 surface colored point cloud was projected onto a horizontal plane to produce a color orthophoto (Fig. 7). The resulting image is a poorly colored orthophoto, primarily due to the large contrast of the photos acquired by the Z+F Imager 5006i scanner's mounted camera. We produced the same orthophoto but without the use of color mapping to produce a grayscale orthoimage of T19's surface (Fig. 8).

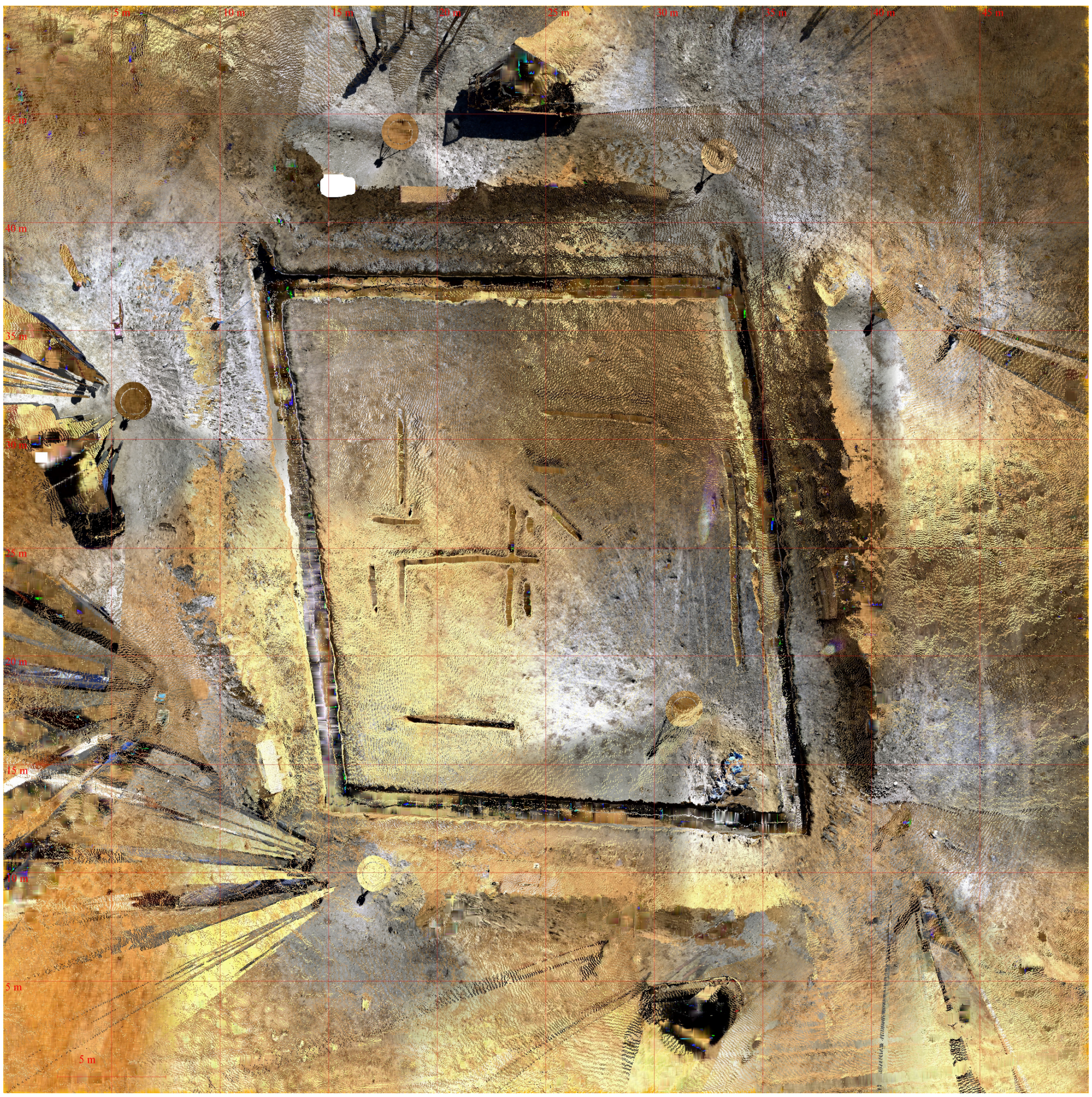


Figure 7. Orthophoto of T19's surface. The poor color quality of the image is due to the large contrast difference of each photo acquired by the scanner's mounted camera. Red grid lines represent 5-m spacing.

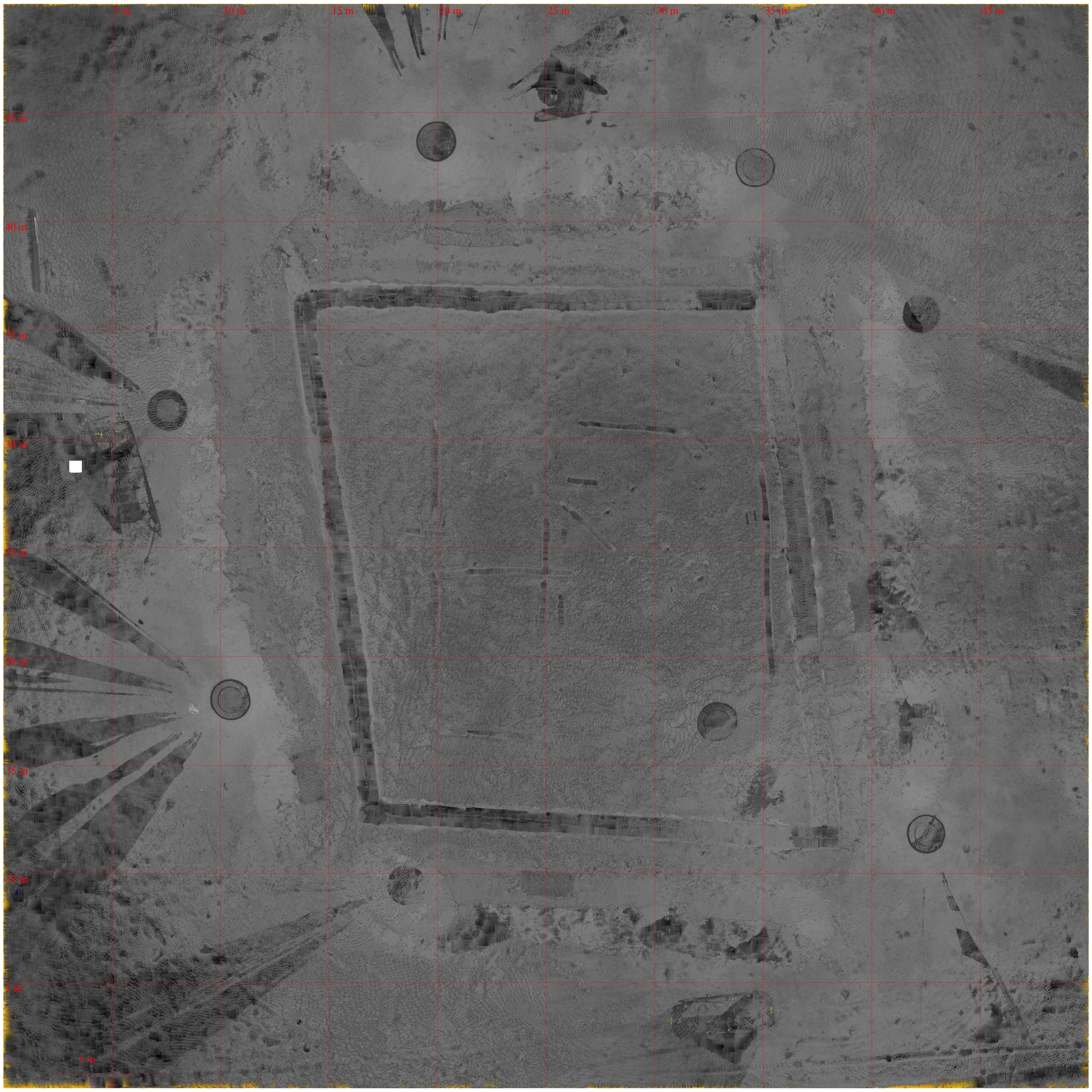


Figure 8. Grayscale image of T19's surface orthophoto. Red grid lines represent 5-m spacing.

The image below (Fig. 9) is a perspective view of T19's surface that was generated using LViz. LViz is a lightweight 3D visualization tool that was developed by Jeffrey Conner in the Active Tectonics, Quantitative Structural Geology and Geomorphology research group at Arizona State University (Jeff is now with HPC at ASU). It is designed to quickly visualize large LiDAR datasets in 3D, but can also be used to visualize any 3D dataset.

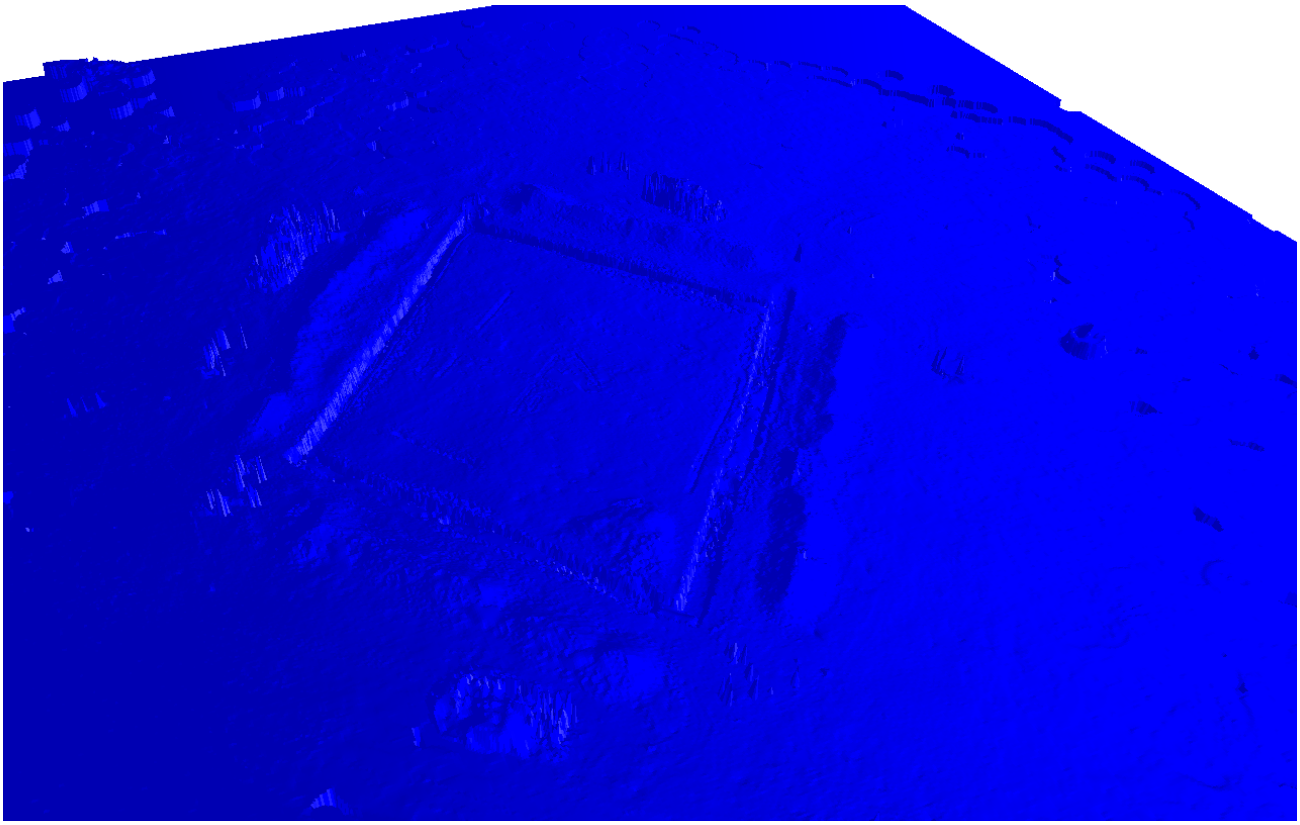


Figure 9. LViz visualization of the T19 surface dataset.

The ten scans of T19's surface afforded us a dense 3D point cloud to generate a high-resolution digital elevation model (DEM) of the T19 trenches and suspect 5-m offset channel. We used the GEON LiDAR Workflow (GLW; http://www.opentopography.org/) to produce a 0.25 m DEM of the Bidart fan paleoseismic site using the B4 airborne LiDAR dataset, and a 0.1 m DEM of the T19 trenches and surface using our terrestrial LiDAR dataset. Both DEMs were produced using the local binning inverse distance weighting algorithm in GLW's Points2Grid (P2G) utility and 1 m search radii. The TLS-generated DEM was then nested in the B4-generated DEM (Fig. 10).

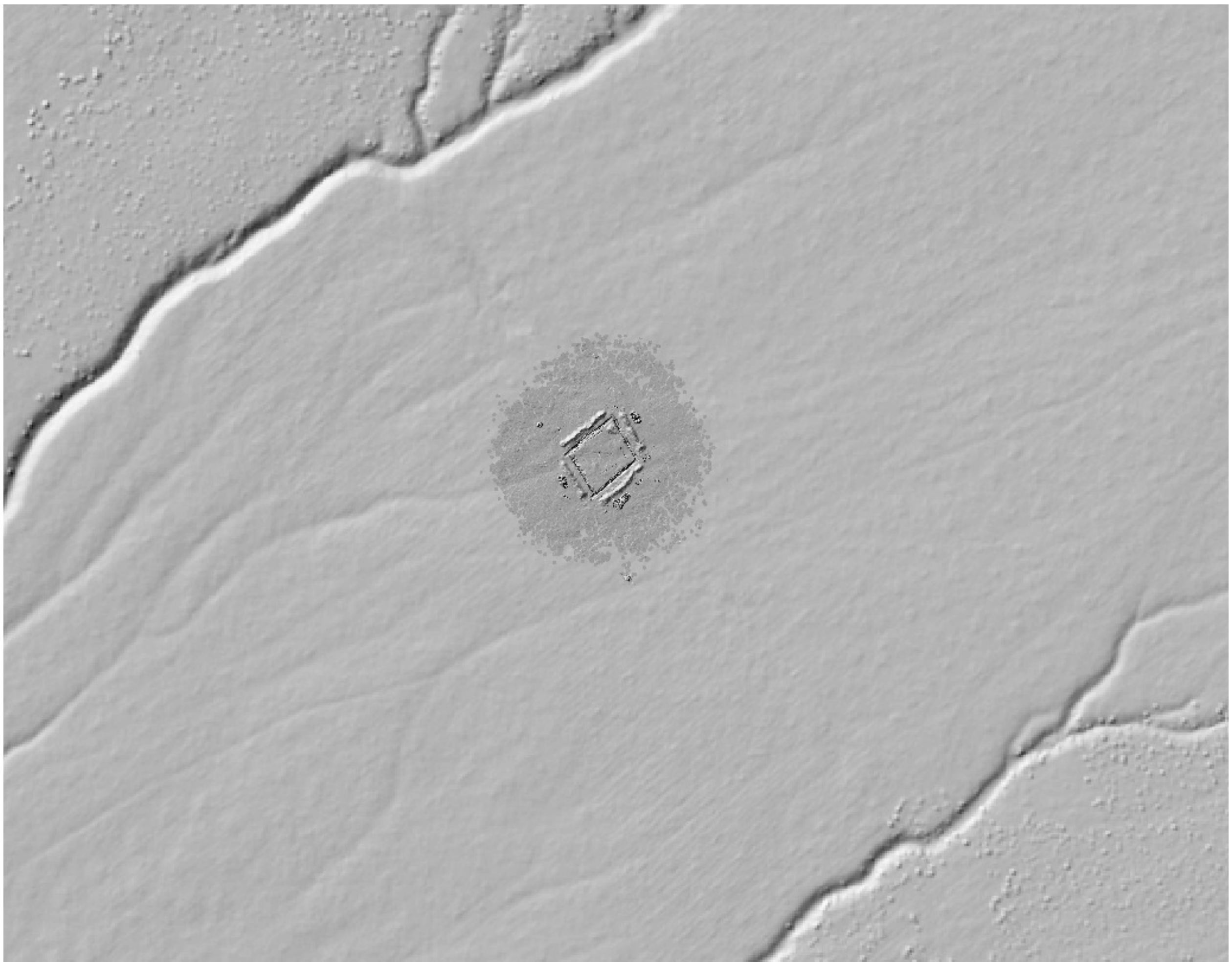


Figure 10. Overview hillshades of a 0.1 m digital elevation model (DEM) produced from the combined point clouds of T19's surface nested in a 0.25 m DEM that was generated using the B4 LiDAR dataset. Both DEMs were created using the GEON LiDAR Workflow's Points2Grid (P2G) utility.

Figure 11. Zoomed-in image of the 0.1 m TLS DEM nested in the 0.25 m B4 DEM. The suspect 5 m offset channel is now clearly visible in the 0.1 m DEM that was produced using the TLS point clouds.

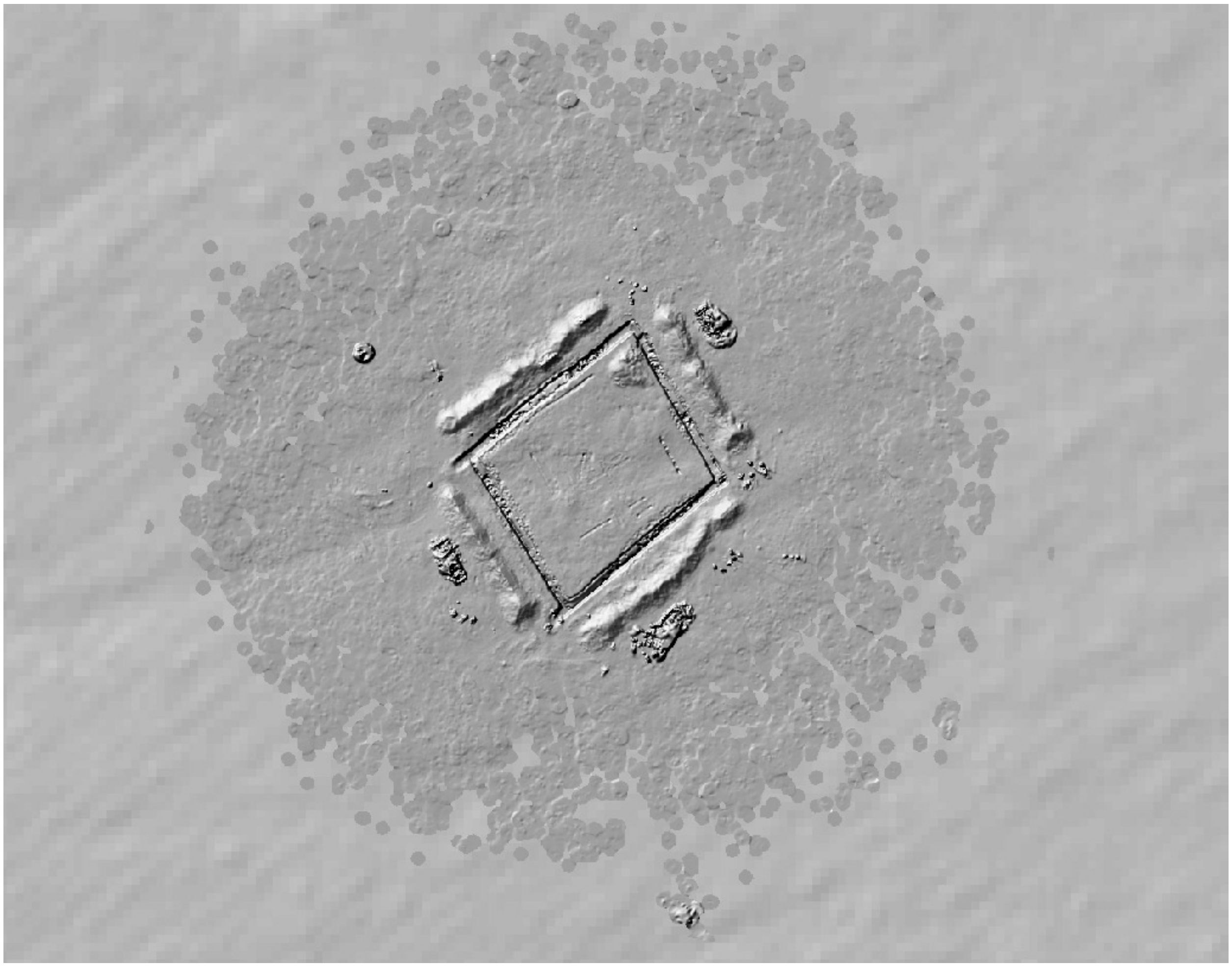


Figure 12. Zoomed in some more. Ahh that's better! Now we can really see the channel and the hand-dug trenches that attempt to hunt down the illusive "pea gravel".

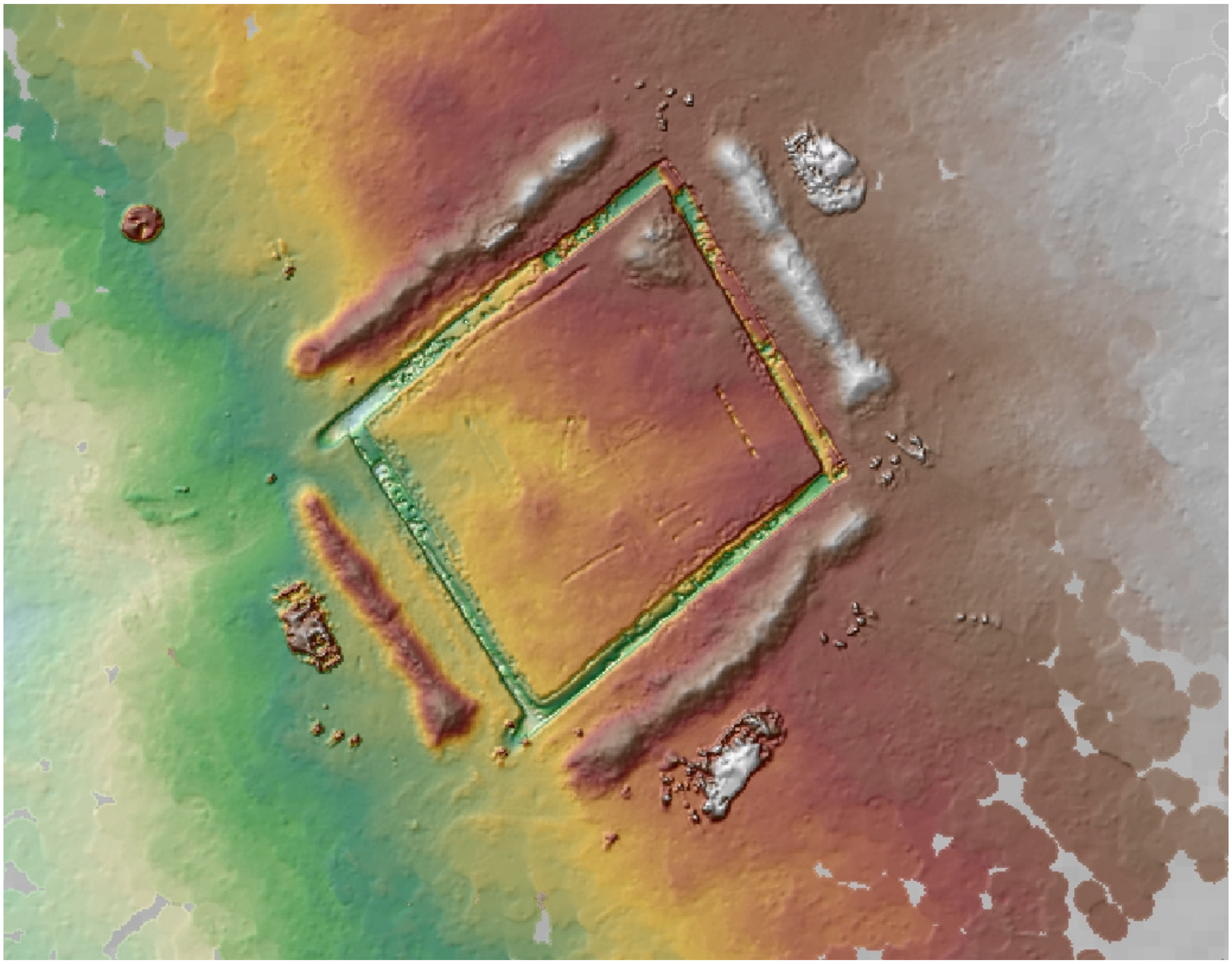


Figure 13. We took low-altitude aerial photographs using the Arrowsmith Balloon Aerial Photography Setup. The aerial photo was georeferenced to the 0.1 m DEM of T19.

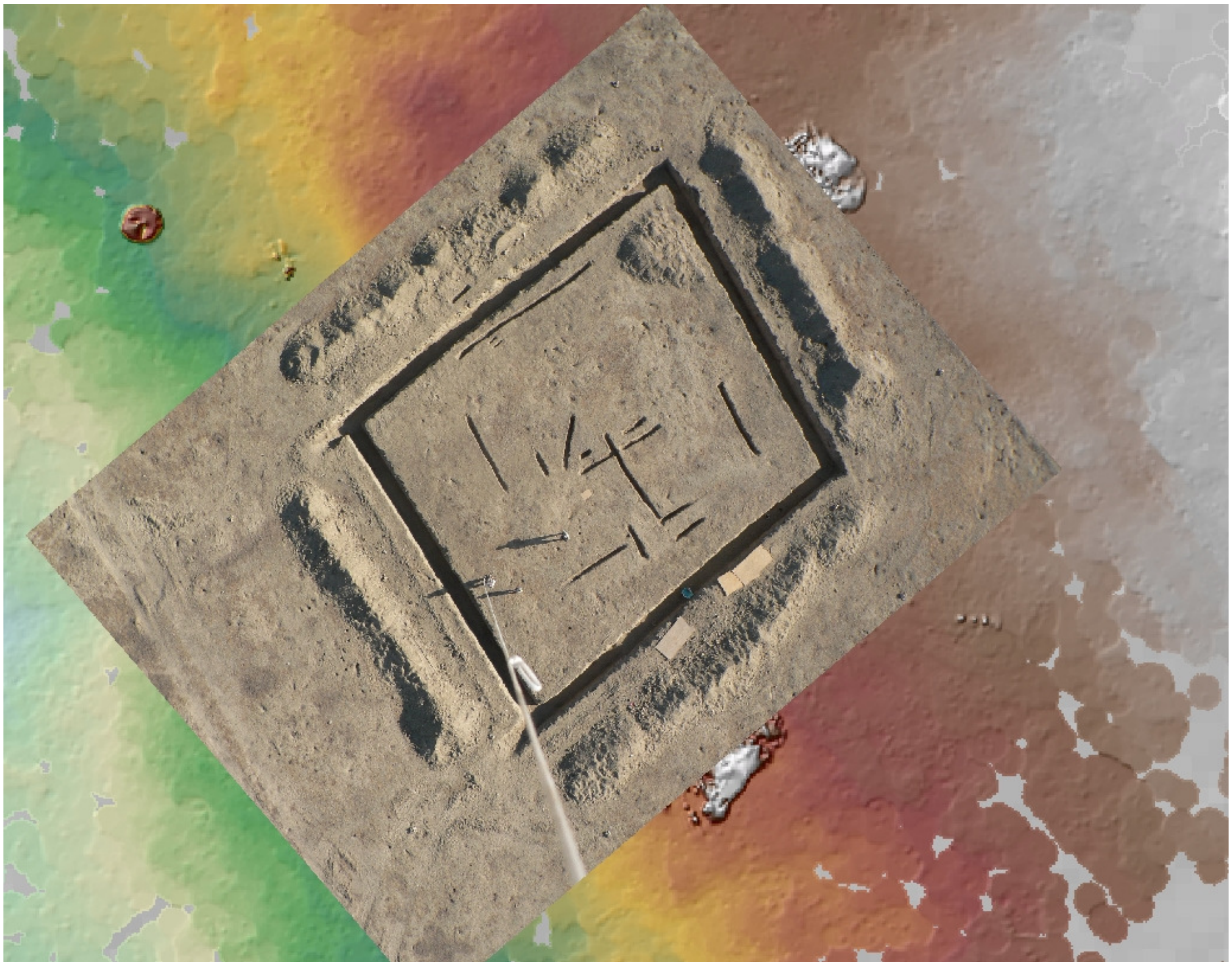


Figure 14a. 3D view of the balloon photograph draped over the 0.1 m DEM of T19 in ArcScene.

Figure 14b. Another 3D view.

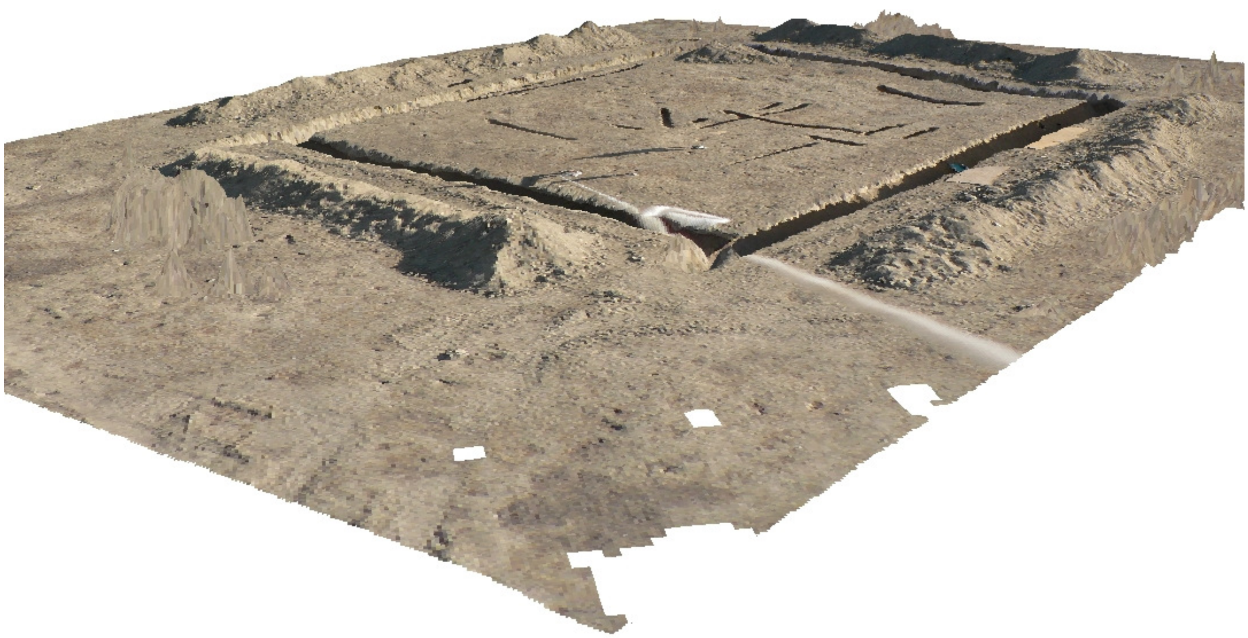


Figure 14c. And another.

Figure 14d. And one last view for good measure.

Figure 15. Comparison of a basemap produced using the Trench-o-Matic setup and an orthophoto generated using the Z+F Imager 5006i point cloud, photos and software. White and red grid lines represent 1-m grids.

The upper panel in Figure 15 shows a photomosaic of the T18 trench wall produced using the Trench-o-Matic setup and used as a base image to log the trench wall. The bottom panel shows an orthoimage of the same wall that was produced using the colored point clouds of T18 projected onto a trench-parallel vertical plane. We can see that the nearly seamless and orthorectified image produced from the point clouds and TLS photographs produces a far superior base map for trench logging. Zones of “no data” (white streaks) in the orthoimage are a result of scarce scan coverage behind the shores’ pistons; they essentially represent the pistons shadows in the point clouds. Careful planning of scanner position can easily eliminate such zones of “no data” in the future. Similarly, the contrast of the orthoimage can easily be enhanced in an image processing software (e.g., Adobe Photoshop) to improve the delineation of sedimentary packages.

Summary and Conclusions

We used the Zoller+Fröhlich (Z+F) Imager 5006i terrestrial laser scanner to scan two paleoseismic trenches and one offset channel in the Bidart fan paleoseismic site, Carrizo Plain, CA, during the summer of 2009. A total of thirty four scans were conducted to acquire 3D point clouds of the trenches and channel. The Z+F LaserControl software was used to process the scans and photographs captured by the scanner’s mounted camera. Orthophotographs and videos were then generated for all datasets. The raw point clouds for T19 surface (5 m suspect offset channel) were used to generate a 0.1 m digital elevation model (DEM). This DEM was then nested in a 0.25 m DEM that was produced from the B4 LiDAR dataset. A low-altitude balloon aerial photograph was then georeferenced to and draped over the 0.1 m DEM and displayed in 3D.

Overall, our innovative TLS efforts for this paleoseismic investigation were very successful. Despite our inability to produce useful color orthophotos of T19c and the 5-m suspect offset channel, we were able to determine that with careful considerations regarding scanner setup and lighting conditions, a short-range terrestrial laser scanner such as the Z+F Imager 5006i is a very effective tool for imaging the walls of paleoseismic trenches and subtle tectonic geomorphic features.

Is using a terrestrial laser scanner cost-effective, or is it overkill? We believe that the high quality of images and DEMs produced from the point clouds make TLS a very effective tool for imaging trench walls and subtle tectonic geomorphic features in a paleoseismic investigation. Since the Z+F Imager 5006i scanner acquires data in 360° laser swaths (rotating about the vertical and horizontal axes simultaneously), the production time of base maps for trench logging can be significantly reduced when compared to the time is takes to manually collect photographs using the Trench-o-Matic system (because the scanner scans the two trench walls simultaneously). Similarly, producing the orthoimage base map using the TLS data is far more efficient than manually stitching the Trench-o-Matic photographs in an image-processing software (e.g., Adobe Photoshop). Additionally, TLS allows us to image the suspect 5-m offset channel with great detail that is otherwise unresolved by the B4 data. This will complement our detailed surveys of the “pea gravel” to understand the relationship between the 5-m offset channel and the 1857 earthquake. Furthermore, the high-resolution DEM allows us to perform decimeter-scale morphometric calculations for the channel’s geomorphic situation across the SAF, which will thus allow us to delineate meter-scale surface manifestations of the fault zone structure across T19’s surface.

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