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**Aberdeen Proving Ground M-Range Survey Report**

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## Table of Contents

<b>Introduction.....</b>	<b>3</b>
Survey Execution Overview .....	4
<b>Process .....</b>	<b>7</b>
Photogrammetry Data.....	7
LiDAR Scans.....	7
Man and Machine Hours .....	9
<b>Correlation Test Results .....</b>	<b>12</b>
<b>Best Practices .....</b>	<b>14</b>
Overview .....	14
Marker Placement.....	15
GPS Surveys.....	15
Terrestrial Laser Scans.....	15
Ground Survey and Aerial Surveys: Automatically Generated Survey Reports .....	19
M-Range 5-3-18 Ground Survey.....	19
M-Range, Combined 5-3-18 Aerial Surveys, Section 1 of 3.....	28
M-Range, Combined 5-3-18 Aerial Surveys, Section 2 of 3.....	35
M-Range, Combined 5-3-18 Aerial Surveys, Section 3 of 3.....	44
<b>Summary .....</b>	<b>57</b>
<b>Appendix A.....</b>	<b>58</b>
<b>List of Abbreviations .....</b>	<b>65</b>

## Introduction

During the execution of the “Embedded Training Research and Development for Current and Future Live Training Environments” Cooperative Agreement, the Institute for Simulation and Training (IST) performed a multi-layer survey of the Aberdeen Proving Grounds (APG) M-Range training area. The reason for this highly precise scan was to build a virtual environment to support high precision round-flyout algorithms that represent the foundation of the E-Bullet training system concept.

An E-Bullet training system can improve on an imperfect laser-based training system and its associated dirty-blanks. Nevertheless, subject matter experts have expressed that the width of a North Atlantic Treaty Organization (NATO) 5.56 round, or 5.7 mm, is the desired maximum error for the platform’s effective range. Thus, the E-Bullet training system needs to be highly precise, in terms of both terrain representation of a local training area and modelling of realistic flyout trajectories, to insure proper occlusion and intersection of an E-Bullet flyout ultimately.

IST performed three different collection processes of the APG M-RANGE to form an accurate representation of one section of the small arms firing range. The first collection involved a novel man wearable system that used a real-time kinematic (RTK) global positioning system (GPS) and ground-based photogrammetry to reconstruct a segment of the APG M-RANGE. The second collection involved a drone-based aerial survey that leveraged RTK GPS and photogrammetric software as the basis for reconstruction. The third and final collection involved LiDAR data stemming from a FARO S-70 sensor and used a variety of point-cloud-based reconstruction software packages to build a mesh from a dense point cloud.

This report will briefly outline the three processes involved, provide accuracy metrics, and provide estimated man-hours spent to perform the collection process.

## Survey Execution Overview

An overview of the survey execution is shown in Table 1. Elaboration on each survey type and its related aspect of the execution is given. Scenes of the final M-Range, as visualized in Unity, are shown in Figure 1. See Appendix A for supplemental images taken from the survey execution.

Table 1. Overview of M-Range survey execution across survey types and related survey aspects

Survey aspect	Survey type	Elaboration
Survey control	Ground	<ul style="list-style-type: none"> <li>• Setup GPS base station and a rover unit was attached to a camera on a gimbal suit</li> </ul>
	Aerial	<ul style="list-style-type: none"> <li>• Placed checkerboard ground control points (GCPs) in a grid layout over the area of the range to be captured</li> <li>• Setup a GPS base station and used a rover unit on the quadcopter and over each GCP</li> </ul>
	Laser	<ul style="list-style-type: none"> <li>• Conducted GPS surveys and scanned next to each one to include the surveyed points in the laser-scan point cloud</li> </ul>
Data collection	Ground	<ul style="list-style-type: none"> <li>• Took photos (1242 photos and 750 photos used in the project)</li> </ul>
	Aerial	<ul style="list-style-type: none"> <li>• Took photos (690 used in the project)</li> <li>• Used 16 GCPs and 1 base station</li> </ul>
	Laser	<ul style="list-style-type: none"> <li>• Took 80 scans (63 in June 2019 and 17 in October 2019)</li> </ul>
Collection processes	Ground	<ul style="list-style-type: none"> <li>• Used man-wearable system that has a camera and rover GPS unit to timestamp and add GPS data from the base station</li> </ul>
	Aerial	<ul style="list-style-type: none"> <li>• Used drone flights at two elevations to capture imagery and pre-placed geo-located markers</li> </ul>
	Laser	<ul style="list-style-type: none"> <li>• Used LiDAR scanner to generate a colored point cloud of the environment</li> </ul>
Output	Mixed: orthographic image	<ul style="list-style-type: none"> <li>• Exported from MetaShape RealityCapture</li> <li>• Merged with orthographic images from various surveys in Photoshop to create orthomosaic imagery</li> <li>• Imported into Global Mapper or custom Unity tool; tiled into 20 x 20 4096 pixel (px) images</li> </ul>
	Mixed: Digital Surface Model (DSM)	<ul style="list-style-type: none"> <li>• Exported from MetaShape or RealityCapture</li> <li>• Merged with DSMs from various surveys in Photoshop</li> <li>• Imported into Global Mapper or custom Unity tool; tiled into 20 x 20 4097 px heightmaps (see Figure 2 for DSM example)</li> </ul>

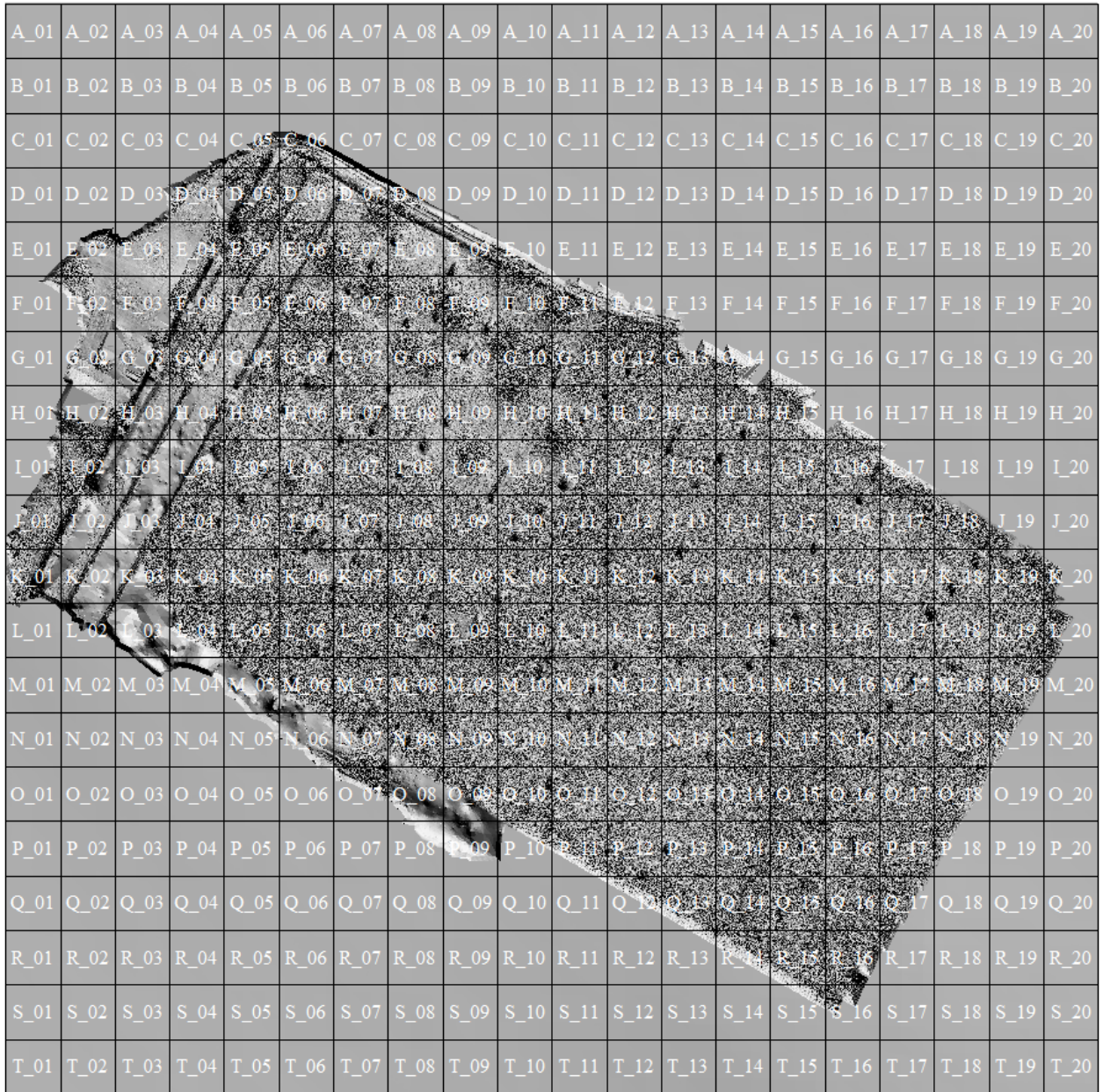
Figure 1. Final M-Range scenes, as visualized in the Unity game engine



To complement the overview in Table 1, we provide a stepwise summary view. Sixteen GCPs were placed in a grid layout across the section of the range we wanted to capture, with a GPS base station nearby. Also, we used a survey pole with both a digital camera and a rover GPS unit attached. Each GCP had their location captured using the rover unit. A rover unit was attached to a quadcopter, and a flight path was constructed using open-source software. The quadcopter was set to take photographs of the ground at set intervals, including the pre-placed ground control points. Several quadcopter flights were conducted over a two-day period. Once the data collection was finished, the GPS points were processed using Receiver Independent Exchange Format (RINEX) and Online Positioning User Service (OPUS).

The photos were used to create a high-resolution mesh and corresponding textures using photogrammetric techniques. The data output was geo-referenced using the GCPs.

Figure 2. High-resolution DSM 20 x 20 tile scheme with the removal of above-ground objects



## Process

### Photogrammetry Data

There are two main methods of processing data: using photogrammetry without other data and using photogrammetry with laser-scan data. The steps per each of these processing approaches are shown in Table 2.

Table 2. Steps for two different methods of processing data

Photogrammetry without other data	Photogrammetry with laser scan data
<ol style="list-style-type: none"> <li>1. Import survey photos, camera positions and surveyed reference points (GCPs) into MetaShape.</li> <li>2. Align photos, using proper projection (State Plane or Universal Transverse Mercator [UTM]).</li> <li>3. Generate sparse point cloud.</li> <li>4. Generate dense point cloud.</li> <li>5. Generate DSM elevation data.</li> <li>6. Generate orthomosaic imagery.</li> <li>7. Export DSM and orthomosaic imagery.</li> <li>8. Tile the DSM and imagery to desired tile scheme using Global Mapper.</li> <li>9. Import tiled data into Unity.</li> </ol>	<ol style="list-style-type: none"> <li>1. Import laser scan data into FARO Scene.</li> <li>2. Align scans together.</li> <li>3. Geo-reference point cloud using OPUS solutions of GPS surveys</li> <li>4. Export geo-referenced scans.</li> <li>5. Import scan data in RealityCapture.</li> <li>6. Import aerial photo data.</li> <li>7. Align the aerial and laser scan point clouds.</li> <li>8. Generate DSM elevation.</li> <li>9. Generate ortho imagery mosaic.</li> <li>10. Export DSM and orthomosaic imagery.</li> <li>11. Tile the DSM and imagery to desired tile scheme using Global Mapper.</li> <li>12. Import tiled data into Unity.</li> </ol>

### LiDAR Scans

As mentioned, a total of 80 scans were completed. These scans covered two survey dates differing in scan specifications, as shown in Table 3.

Table 3. Specifications of laser scans based on the survey date

Survey date	Amount	Scan duration	Resolution	Quality	Distance between scans	Marker type
June 2019	63 scans	00:04:11	¼": 10240 pt/360 degrees	3x	Farther apart	Checkerboards on buildings
October 2019	17 scans	00:14:56	½": 20480 pt/360 degrees	3x	Closer together	Checkerboards on buildings; spheres outside

For the laser scans, seven V-Map GPS Surveys and three EMLID GPS Surveys of the M-Range area-of-interest (AOI) were post-processed to receive OPUS solutions for each position. Please refer to the “Overall OPUS RMS (m)” column in Table 4 for OPUS solution results. Longer GPS observation times usually result in lower root mean square (RMS) values, and lower RMS values equate to a more accurate position solution. Whereas the EMLID GPS Surveys resulted in an average RMS value of 1.6 cm, 5 select V-MAP GPS surveys resulted in an average of 2 cm (the two shortest surveys, of about 90 and 60 minutes, are deselected due to high RMS values, which were from low observation duration).

Table 4. OPUS Solution Results for M-Range, V-Map, and EMLID GPS surveys

Position	X (UTM Zone 18N NAD83)	Y (UTM Zone 18N NAD83)	Z (At Ground)	Location	Overall OPUS RMS (m)
BS_001	399608.64	4365245.33	5.149	~ 4hr. 20min. V-MAP Base station survey in parking lot, close to range (from 6-19-19 FARO Laser Scan Surveys)	0.02
BS_002	399621.304	4365221.433	5.363	~ 4hr. V-MAP Base station survey on metal grate/sewer cover (from 6-19-19 FARO Laser Scan Surveys)	0.023
BS_003	399643.399	4365266.233	4.809	~ 4hr. 7min. V-MAP Base station survey near shoot house (from 6-20-19 FARO Laser Scan Surveys)	0.021
BS_004	399674.011	4365214.728	5.516	~ 90 min. V-MAP Base station survey on range (from 6-20-19 FARO Laser Scan Surveys)	0.565
BS_005	399701.317	4365278.414	4.398	04:19:32 Duration. V-Map Base station survey on Range ("V-Map Survey_01" from 10-15-19 FARO Laser Scan Surveys)	0.018
BS_006	399765.759	4365244.843	5.456	03:59:32 Duration. V-Map Base station survey on Range ("V-Map Survey_02" from 10-15-19 FARO Laser Scan Surveys)	0.018
BS_007	399822.679	4365219.503	5.451	01:01:22 Duration. V-Map Base station survey on Range ("V-Map Survey_03" from 10-16-19 FARO Laser Scan Surveys)	0.47
BS_008	399644.236	4365266.031	4.846	~ 04:02:00 Duration. EMLID Base station survey on Range ("EMLID 4Hour.pos1" from 10-15-19 FARO Laser Scan Surveys)	0.017
BS_009	399707.038	4365225.813	5.39	~ 14:38:00 Duration. EMLID Base station survey on Range ("EMLID 14Hour.pos2" from 10-15-19 FARO Laser Scan Surveys)	0.014
BS_010	399766.243	4365193.294	4.839	~ 03:40:00 Duration. EMLID Base station survey on Range ("EMLID 4Hour.pos3" from 10-16-19 FARO Laser Scan Surveys)	0.019

Once all 80 laser scans were complete, they were imported into FARO Scene for alignment, and then geo-registration. Finally, a correlation test was performed. The steps taken are broken down in Table 5. The following section details the correlation test results.

Table 5. Steps per activity: alignment, geo-registration, and correlation test

FARO Scene for alignment of Laser Scan Point Clouds	
1. Performed top-down registration.	5. Re-ran initial top-down and cloud-to-cloud registration on any clusters with newly added scans.
2. Performed cloud-to-cloud registration.	6. After all the clusters had an initial successful registration, re-ran cloud-to-cloud registration several times on each cluster using different settings in order to achieve the most accurate cloud to cloud alignment possible.
3. Performed marker-based registration and/or manual registration as needed to register scans that were difficult to register due to poor overlap or lack of spheres and/or markers within close proximity to scanner positions.	7. Inspected the registration report of each cluster. Attempted to further improve cloud
4. Inspected scans that failed to register and were not automatically added to a cluster. Moved problematic scan(s) into clusters	

<p>which had other scans that overlap the area captured in the problematic scan(s).</p>	<p>to cloud registration by combining scans from clusters with similar registration error results into a single cluster to provide more scan overlap for registration. Visually inspected registered point clouds including measurement and scale checks.</p>
<p>Geo-registration of point clouds</p>	
<ol style="list-style-type: none"> <li>1. Copied the UTM coordinates and elevation values from the EMLID and V-MAP OPUS Solutions into a Comma Separated Values (CSV) file for import into FARO Scene.</li> <li>2. Imported EMLID and V-MAP surveyed reference points into FARO Scene.</li> </ol>	<ol style="list-style-type: none"> <li>3. In FARO Scene, we manually added corresponding point markers at each GPS surveyed position.</li> <li>4. Moved master cluster into a new cluster titled "Survey_Control" and ran target-based registration on the "Survey_Control" cluster using the "Force correspondences by target names" option.</li> </ol>
<p>Correlation test</p>	
<ol style="list-style-type: none"> <li>1. Exported GPS marker positions from FARO Scene.</li> <li>2. Imported FARO Scene GPS marker positions and corresponding surveyed reference point positions into Global Mapper and performed correlation test by measuring offsets. Documented correlation test results and sent report to supervisor.</li> </ol>	<ol style="list-style-type: none"> <li>3. Exported each geo-registered scan to the E57 format. Imported scans nearest GPS markers into Global Mapper to perform correlation test of point clouds.</li> </ol>

**Man and Machine Hours**

From an objective view, consideration is given to the time spent for execution, by personnel or equipment. Table 6 shows man-hours for survey activities, and Table 7 shows machine times.

Table 6. Tasks and associated man-hours for survey activities

Task	Time
Process four base station surveys	12 hours
Process GCP Survey	4 hours
<p>Process aerial photogrammetry survey (in MetaShape) using pre-processed base station surveys and GCPs: 8-16 hours depending on size and alignment issues encountered. Estimate is based on four survey runs.</p> <ul style="list-style-type: none"> <li>• Importing aerial photos with geo-referencing, GCPs and base station reference points</li> <li>• Setting up the project, including entering projection info and camera offsets</li> </ul>	8-16 hours

<ul style="list-style-type: none"> <li>• Aligning cameras</li> <li>• Proofing camera alignments</li> <li>• Manually marking photos and re-aligning photos to improve camera alignment if necessary</li> <li>• Optimizing camera alignment</li> <li>• Generate sparse point cloud</li> <li>• Filter out noise from sparse point cloud, crop in on main area of interest</li> <li>• Generate dense point cloud</li> <li>• Generate DSM elevation data</li> <li>• Generate orthomosaic imagery</li> <li>• Export DSM orthomosaic imagery to GeoTiff</li> </ul>	
<p>Process ground photogrammetry survey (in MetaShape) using pre-processed base station surveys and GCPs: 16-24 hours depending on size and alignment issues encountered. Estimate is based on four survey runs.</p> <ul style="list-style-type: none"> <li>• Importing aerial photos with geo-referencing, GCPs and base station reference points</li> <li>• Setting up project, including entering projection info and camera offsets</li> <li>• Aligning cameras</li> <li>• Proofing camera alignments</li> <li>• Manually marking photos and re-aligning photos to improve camera alignment if necessary</li> <li>• Optimizing camera alignment</li> <li>• Generate sparse point cloud</li> <li>• Filter out noise from sparse point cloud, crop in on main area of interest</li> <li>• Generate dense point cloud</li> <li>• Generate DSM elevation data</li> <li>• Generate orthomosaic imagery</li> <li>• Export DSM and orthomosaic imagery to GeoTiff</li> </ul>	16-24 hours
<p>Manually merging and blending DSM outputs from two ground surveys, one aerial survey and one laser scan survey.</p>	16-24 hours
<p>Manually merging and blending orthomosaic imagery from two ground surveys, one aerial survey and one laser scan survey.</p>	16-24 hours
<p>Process and geo-reference 63 terrestrial laser scans that have enough external targets and proper overlap</p> <ul style="list-style-type: none"> <li>• Importing raw scan data into FARO Scene</li> <li>• Processing scans and coloring points</li> <li>• Registering scans into one point cloud</li> <li>• Manually adding marks to aid in registration</li> <li>• Re-running various registrations to obtain best results</li> <li>• Verify proper alignments</li> <li>• Adding point to registered point cloud that correspond to survey points</li> <li>• Import survey references</li> <li>• Geo-reference points</li> <li>• Verify results</li> </ul>	4-6 days
<p>Create Unity project (manual process) with 100 terrain tiles</p>	8-12 hours

<ul style="list-style-type: none"> <li>Importing, sizing, and translating elevation and applying textures</li> </ul>	
Create Unity project (custom automated process) with 100 terrain tiles	1 hour
<ul style="list-style-type: none"> <li>Importing, sizing, and translating elevation and applying textures</li> </ul>	
Smoothing terrain transitions in Unity and removing any remaining elevation spikes	3 days
Add trees to Unity scene	1 day
Add models of buildings, light poles, and other environment elements	1-2 days
Bake lighting and optimize scene	2-3 days

Table 7. Tasks and associated machine times for survey activities

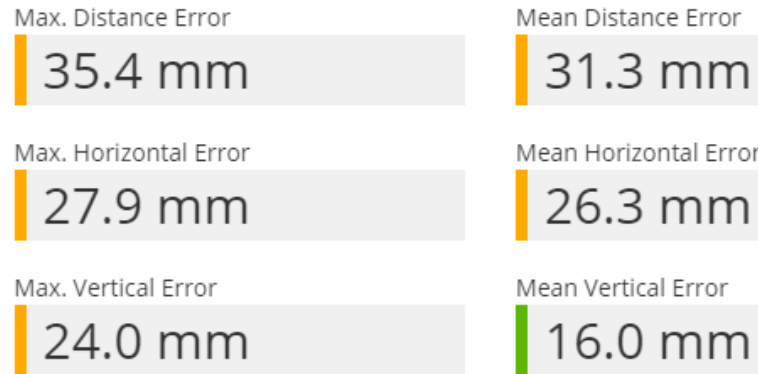
<b>Task</b>	<b>Time</b>
Create dense point cloud from photos in MetaShape (1200 photos)	9 days
Create dense point cloud from photos in RealityCapture (1200 photos)	1 day
Create textured mesh from laser scans in RealityCapture (63 scans)* <ul style="list-style-type: none"> <li>Created a mesh with 970 triangles</li> <li>784 – 4096 x 4096 px textures</li> </ul>	9.5 hours

\*Note: not supported in MetaShape as of October 2020.

### Correlation Test Results

In this section, the correlation test results are given for the M-Range’s geo-registered laser-scan point clouds. In Figure 3, the FARO Scene marker-based registration results are shown.

Figure 3. FARO Scene marker-based registration results



To get the best results during geo-registration, we only used the four surveyed reference points that are highlighted yellow in Table 8, below. Those four points form the translucent yellow area that is depicted in Figure 4, below; this area has the most accurate correlation.

We measured the offsets between the surveyed reference points (UTM coordinates from OPUS solutions) and their corresponding markers in FARO Scene, after geo-registration. We also imported the surveyed reference points (from OPUS) and the markers (from FARO Scene) into Global Mapper, and measured total (X and Y) offsets. The correlation test results are shown in the bottom-right of Table 8: in the yellow area, the average X offset is 2.11 cm, the average Y offset is 1.39 cm, and the average Z offset is 1.59 cm. These values appear to be in line with the OPUS RMS values (that is, 0.02, 0.018, 0.018 and 0.019) for each of the four points used during geo-registration.

Table 8. Reference points used for correlations results

Marker Name	OPUS RMS	Surveyed X Coordinate	Surveyed Y Coordinate	Surveyed Z Value	FARO Scene X Coordinate	FARO Scene Y Coordinate	FARO Scene Z Value	X Offset (m)	Y Offset (m)	Z Offset (m)	XY Linear Offset Measured in GM (m)
BS_001	0.02	399608.64	4365245.33	5.149	399608.620322	4365245.310215	5.156948	0.019678	0.019785	0.007948	0.02791
BS_005	0.018	399701.317	4365278.414	4.398	399701.334081	4365278.435371	4.378500	0.017081	0.021371	0.019500	0.02737
BS_006	0.018	399765.759	4365244.843	5.456	399765.784172	4365244.849612	5.479954	0.025172	0.006612	0.023954	0.02603
BS_010 (EMLID)	0.019	399766.243	4365193.294	4.839	399766.220425	4365193.285803	4.826598	0.022575	0.008197	0.012402	0.02402
BS_002	0.023	399621.304000	4365221.433000	5.363000	399621.270749	4365221.406164	5.449791	0.033251	0.026836	0.086791	0.04274
BS_003	0.021	399643.399300	4365266.233000	4.809000	399643.391850	4365266.244389	4.699496	0.007450	0.011389	0.109504	0.01345
BS_009 (EMLID)	0.014	399707.038	4365225.813	5.39	399707.106266	4365225.881391	5.394675	0.068266	0.068391	0.004675	0.0967
										Total Average Offsets	
								Average X Offset	Average Y Offset	Average Z Offset	Average XY Linear Offset
								0.027639	0.023226	0.037825	0.03688571
Average Offsets of just the 4 points [highlighted in yellow] that were used during registration											
								Average X Offset	Average Y Offset	Average Z Offset	Average XY Linear Offset
								0.021127	0.013991	0.015951	0.0263325

Even though points 2, 3, and 9 were not used during registration, they may be included to test overall correlation: adding these three points into the correlation test, the average X offset increased to 2.76 cm, the average Y offset increased to 2.32 cm, and the average Z offset increased to 3.78 cm. The BS\_008 (i.e., base station 8) value was not used during geo-registration and was not included in the correlation test because it had a much higher offset than the other points; it appears to be an outlier.

Figure 4. Base station locations used for the most accurate correlation, shown as vertices



## Best Practices

A range of best practices related to the survey study are described in this section. Both an overview and granular view of best practices are discussed, to inform future survey activities.

### Overview

Both GCP and checkerboard markers should be placed before photogrammetric and laser-scan surveys. Further, these markers should remain stationary throughout all surveying, so that the same markers can be seen in all photogrammetric and laser-scan surveys. Keeping markers stationary reduces the amount of time it takes to register (or align) various datasets together, increases alignment accuracy, and might allow automatic registration/alignment in FARO Scene, RealityCapture and Metashape processing.

The capture context dictated the best collection method. Aerial photogrammetric surveys should be performed to capture terrain imagery and elevation since these surveys result in superior terrain imagery and can be used to improve the visual texture component correlating to the elevation data derived from laser scanning. Terrestrial laser-scan surveys should be used to capture important terrain objects, key buildings, and other above-ground objects. These surveys excel at precisely capturing surfaces of manmade, above-ground objects and can be used to generate accurate building meshes and topography. However, laser-scan surveys should not be relied upon to generate adequate terrain imagery or textures. To provide better imagery and texture data, ground photogrammetric surveys, or high-resolution panoramic photography could be used to supplement terrestrial laser scans. During post-processing, the laser-scan point clouds can be used during the meshing phase, whereas the photogrammetric or panoramic photos could be used during the texturing phase, to generate the most accurate 3-Dimensional (3D) mesh possible.

When aerial and ground photogrammetric surveys and terrestrial laser-scan surveys have mismatched marker locations between datasets, a preferred option is to (1) register/align and process each survey separately, before (2) merging the output DSM elevation datasets and orthomosaic imagery

datasets together, perhaps through the Global Mapper tool, to create a DSM mosaic and an orthomosaic imagery. This option is preferred, as it reduces time and effort trying to align photogrammetric and laser scan surveys together with mismatched markers. The issue of mismatched markers may arise if the collection is iterated at different times.

## **Marker Placement**

Marker placement should follow various guidelines. For aerial surveys, large checkerboard GCP markers should be evenly spaced across a terrain in the form of a grid; this grid includes the periphery and inner parts of an AOI. Markers should also be attached to vertical objects, such as walls, that will be captured during ground and laser scan surveys. For terrestrial laser scans, a sphere traversing technique can be employed for adding markers to areas with little to no vertical features, such as fields. With this method, a series of alignment spheres are moved around as the scanning positions change ensuring that two scan positions see at least three of the same spheres as they are traversed. Having a scan plan that includes the traversing sequence is beneficial in time savings and sequence errors in the field.

## **GPS Surveys**

When completing GPS base station surveys, a minimum of four GPS surveys should be performed, each from outside one of the four corners of the AOI. Ideally, each corner used in the survey should be set up on the corresponding GCP marker from each AOI corner. Longer surveys are typically better, with a minimum recommendation of 4 hours. To supplement the 4+ hour surveys, consider capturing GCPs with the rover at GCP marker positions to create a regular grid of GCP observations. This capture may be done during one of the base station surveys.

## **Terrestrial Laser Scans**

The best settings for terrestrial laser scans comprised a scan duration of 15 – 20 minutes, a quality of 3x (or 4x if more range is needed outdoors on a sunny day or in inclement weather ), a resolution of

$\frac{1}{2}$  (20480 pt/360 degrees) for best overlap and detail, and a resolution up to  $\frac{1}{4}$  (10240 pt with 6.1 mm point distance at 10 m) for additional scans meant to reduce occlusion areas.

Terrestrial laser scans should be performed outside the four corners of the AOI. The scans should be set next to the four GPS-observed GCP markers, with the GCP marker captured in the scan. One should promote proper registration through overlap when using spheres: scanner locations should not be set over 20 m apart at  $\frac{1}{4}$  resolution. This distance can increase if the resolution setting is increased.

When performing outdoor scans in large fields, sphere targets are beneficial. The distance a sphere can be from the scanner is determined by resolution, and the scanner needs a minimum of 80 points on a sphere for accurate and reliable detection. For a 145 mm sphere, the farthest a sphere should be from a scanner at  $\frac{1}{4}$  resolution is 15 m.

When traversing spheres during the capture process, three of the six spheres should be seen by two scan positions; as traversal continues, one should move through three of the six spheres, confirming that between each scan the same three spheres are captured. A traversing strategy should be formed, as it can be difficult to remember where to place spheres.

Checkerboard markers on walls should be captured by two or more laser scans. The scanner is best when facing perpendicular to a marker and should not exceed an oblique angle of 45 degrees.

Consideration should be given to increasing the height of the scanner by raising its tripod. By increasing height, the angle of incidence becomes greater, and therefore the quality falloff happens further out. Although the increase is especially significant in outdoor fields (where grass can degrade scan points), a compromise is made due to increased occlusion areas below the scanner.

### **Aerial Photogrammetric Surveys**

Planning before aerial photogrammetric surveys include using flight-planning software to ensure overlap; coverage should extend up to two rows beyond the AOI to capture the AOI periphery. Further, ensured placement and visibility of checkerboard GCP markers are needed. To form a dense grid of photos per two directions, both a row and column survey should be implemented. To achieve the best

ortho imagery and texture resolution possible in post-processing, the drone should be flown as low as possible, without sacrificing safety. Finally, photos should be quality-checked for crispness and clarity after every survey.

A number of considerations are given to the camera. Using a standard camera lens seems to produce the most consistently clear and crisp textures in post-processing. Altering the pitch, or angle, of the camera may lead to better capture of buildings and other above-ground objects; trial and error may be involved, and the final pitch settings should be documented for each survey. If the camera cannot be angled in these cases, ensure to collect complete photos of the objects (even if you can't fly over them); or, use a wide-angle or fisheye lens for such shots. This may allow you to tie into a ground survey and/or scan surveys in the absence of common GCPs. This is especially true if you have areas that have been scanned or have ground survey photos taken, but the aerial survey does not overlap this area. Having a wide-angle or fisheye lens may allow some overlap even if they datasets do not overlap.

### **Ground Photogrammetric Surveys**

As is typical with other surveys, markers will need to be in place, here on building walls and other above-ground objects. The best times to capture photos are around noon (when the sun is straight above) or with enough cloud cover to achieve diffused lighting. To remove shadows (e.g., from equipment or personnel) introduced into the survey, manual or automatic post-processing methods may be used. Similar to aerial photogrammetry practices, photos should be collected in a row-and-column method. Also, all buildings and above-ground objects should be thoroughly captured by gathering data from every angle – by walking clockwise and counter-clockwise – to avoid occlusion spots. Confirm each side of a building, above-ground object, or other desired terrain features are captured. Concave objects might need for the camera to be taken off its gimbal mount, but ultimately demand attention, so no occluded areas are missed.

Other camera aspects are also considered. A fisheye lens provides the benefit of needing less photo overlap, but also compromises image quality (i.e., parts of the imagery are crisp and other parts are blurry) and demands post-processing to generate object textures without warping. The camera should be pitched

at 30 degrees towards the ground. The camera should not be pointed directly ahead of the surveyor while walking; instead, the camera should have a fixed rotation of -90 or +90 degrees as the surveyor walks forward.

### **Capture Photos for Textures**

As a method for generating textures for object modeling, a high-resolution camera with a standard lens may be used for taking orthographic photos of buildings and other above-ground objects. This step is additional and not required for surveying.

### **Processing Aerial Photogrammetry**

Two software programs are recommended for processing aerial photogrammetry: Agisoft Metashape and RealityCapture. MetaShape is useful for generating orthomosaic imagery best when high-detail settings are applied, resulting in crisper, better-looking terrain imagery. RealityCapture is useful for generating 3D meshes and DSM elevation best when high-detail settings are applied.

### **Processing Ground Photogrammetry**

Upon completion of ground photogrammetry collection, processing follows. Using Photoshop, any shadows inadvertently added during collection should be removed. RealityCapture is ideal for aligning photos, and one ground survey should be aligned at a time. Based on the camera lens used, follow the appropriate camera distortion model, such as for a fisheye lens, to reduce warping effects. After generating a high-detail mesh using a 100% texture resolution setting, generate orthomosaic imagery and DSM from the mesh at 100% texture resolution, as well. If needed, decimate the high-detail mesh. As an advanced process, consider cropping out buildings and decimating them separately from the terrain.

## **Registering Laser Scan Point Clouds**

Recommendations on registering laser-scan point clouds break down into testing through experimentation and running a linear procedure. One exterior scan and an interior scan may be temporarily imported for registration into FARO Scene: tweaking the default settings can help not over-filter points (e.g., grass or leaves), although default settings may work best for interior scans. Tweaking dark-point settings can also help not automatically removing points in shadow areas or needed dark surfaces; disabling the setting may be best.

## **Ground Survey and Aerial Surveys: Automatically Generated Survey Reports**

The following sections contain survey reports generated primarily by one of the software tools used to produce the M-Range Unity scene: MetaShape. The four reports cover three segments of the range that were captured by a drone and an additional segment that was captured by the man-wearable ground system. First, the ground survey will be covered; second, the aerial surveys will be covered. The processing parameters for the three aerial surveys have also been consolidated for comparison, in Table 35.

### **M-Range 5-3-18 Ground Survey**

The M-Range ground survey was carried out on 5-3-18. The MetaShape processing report was produced on 7-10-18. Figure 4 shows an aerial view of the ground survey area.

Figure 5. Aerial view of the ground-based survey area.



Survey Data

Figure 6. Survey camera locations and image overlap

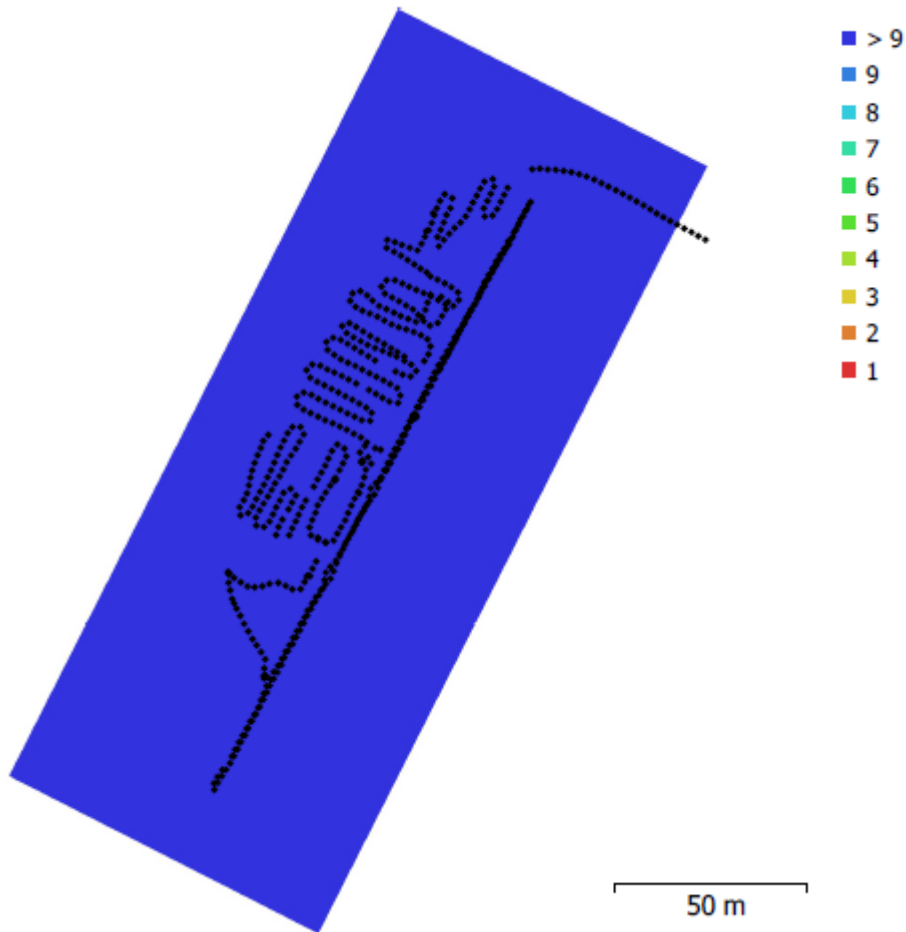


Table 9. Ground survey overview

Number of images:	605	Camera stations:	582
Flying altitude:	52.2 m	Tie points:	161,863
Ground resolution:	1.73 mm/px	Projections:	412,214
Coverage area:	0.0201 km <sup>2</sup>	Reprojection error:	0.588 px

Table 10. Ground survey cameras

Camera Model	Resolution	Focal Length	Pixel Size	Precalibrated
ILCE-7RM2	7952 x 5304	Unknown	Unknown	No

### Camera Calibration

Figure 7. Image residuals for ILCE-7RM2

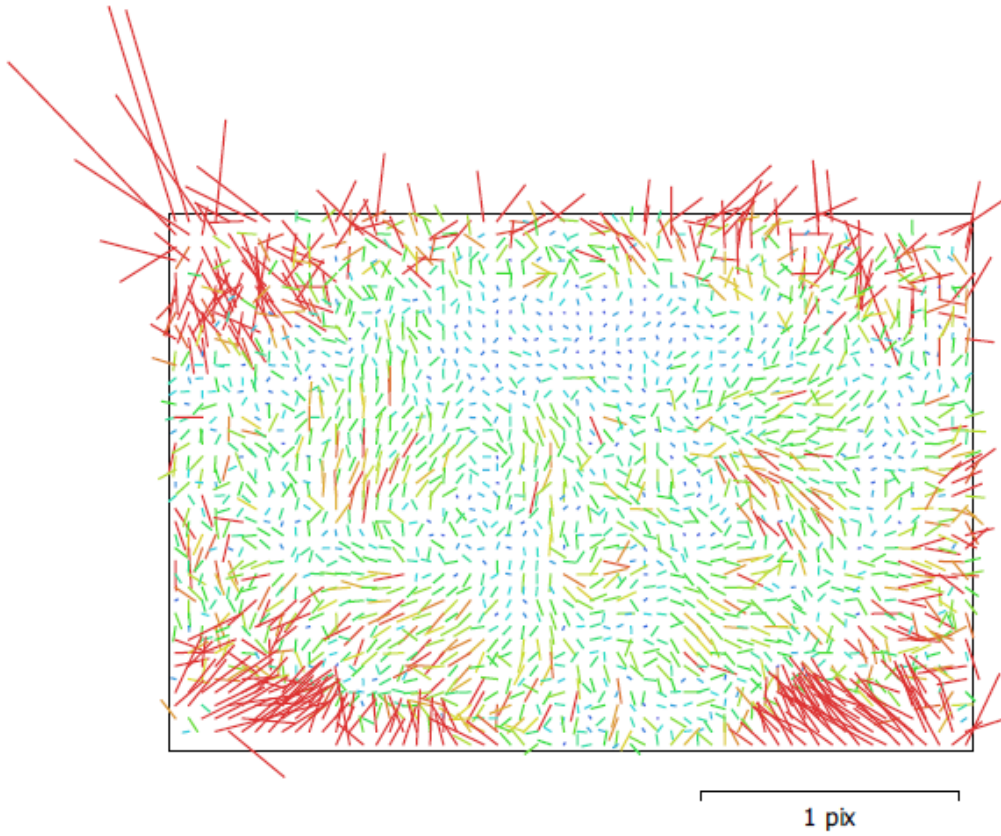


Table 11. Ground survey camera calibration aspects

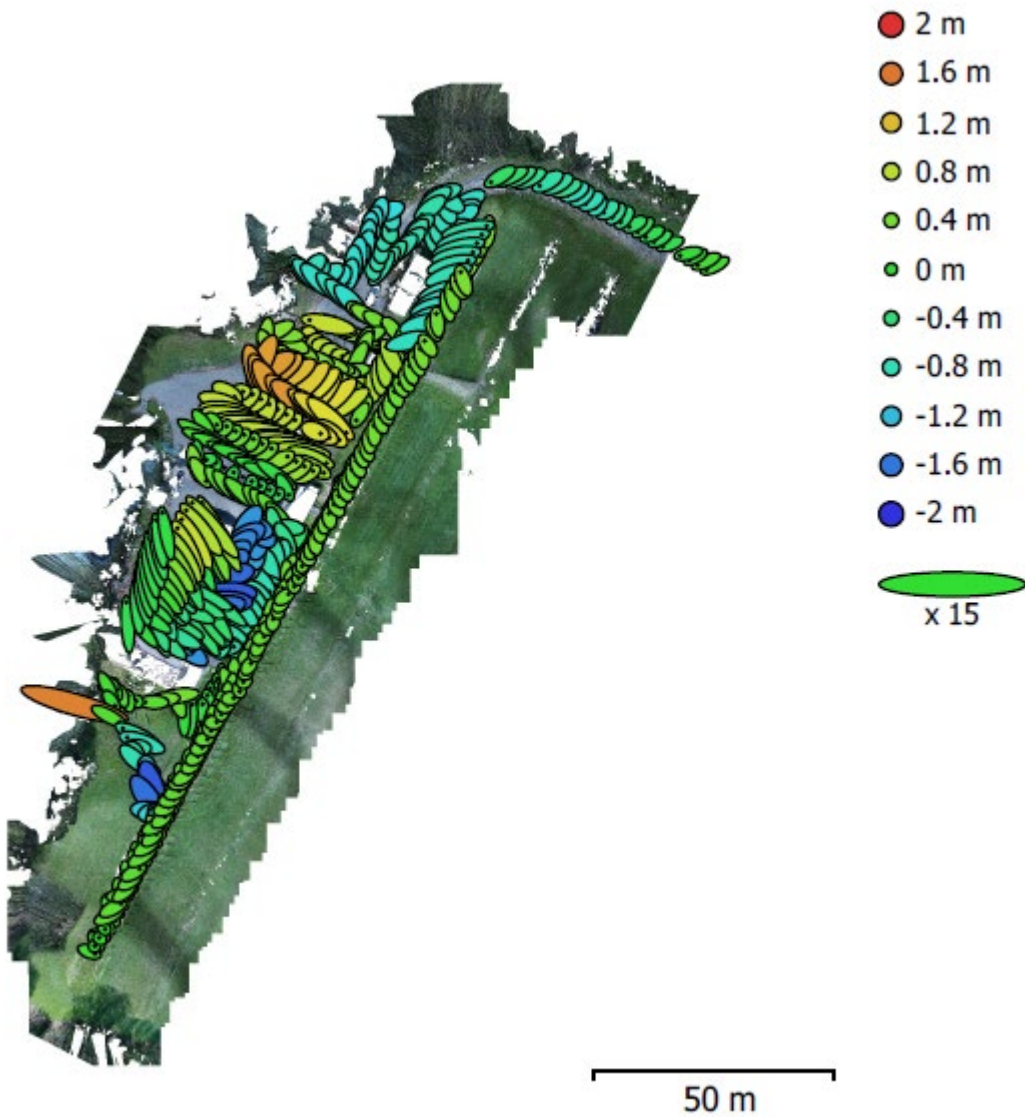
<b>ILCE-7RM2</b>	<b>Type</b>	<b>Resolution</b>	<b>Focal Length</b>	<b>Pixel Size</b>
605 images	Fisheye	7952 x 5304	Unknown	Unknown

Table 12. Calibration coefficients and correlation matrix for ground survey

	<b>Value</b>	<b>Error</b>	<b>F</b>	<b>Cx</b>	<b>Cy</b>	<b>B1</b>	<b>B2</b>	<b>K1</b>	<b>K2</b>	<b>K3</b>	<b>P1</b>	<b>P2</b>	<b>P3</b>	<b>P4</b>
<b>F</b>	<b>2794.06</b>	0.054	1.00	-0.06	0.29	-0.77	0.04	-0.49	0.46	-0.42	0.18	-0.36	0.36	-0.30
<b>Cx</b>	<b>-14.2363</b>	0.054		1.00	-0.09	0.11	-0.48	-0.02	0.03	-0.04	0.51	0.02	-0.13	0.08
<b>Cy</b>	<b>5.12971</b>	0.062			1.00	-0.65	0.02	-0.03	0.11	-0.11	0.19	-0.59	0.34	-0.29
<b>B1</b>	<b>-3.0195</b>	0.057				1.00	-0.03	0.06	-0.13	0.13	-0.21	0.68	-0.39	0.32
<b>B2</b>	<b>-0.61221</b>	0.038					1.00	-0.02	0.00	0.01	-0.66	0.09	0.17	-0.12
<b>K1</b>	<b>0.0366354</b>	2.8e-05						1.00	-0.96	0.91	-0.03	-0.00	-0.13	0.16
<b>K2</b>	<b>0.00826958</b>	2.8e-05							1.00	-0.98	0.05	-0.10	0.14	-0.17
<b>K3</b>	<b>-0.000345665</b>	8.5e-06								1.00	-0.05	0.10	-0.12	0.16
<b>P1</b>	<b>-0.000270766</b>	5.3e-06									1.00	0.06	0.39	-0.32
<b>P2</b>	<b>-0.000766092</b>	9.4e-06										1.00	0.17	-0.11
<b>P3</b>	<b>-0.626102</b>	0.0087											1.00	-0.95
<b>P4</b>	<b>0.213144</b>	0.0034												1.00

### Camera Locations

Figure 8. Camera locations and error estimates



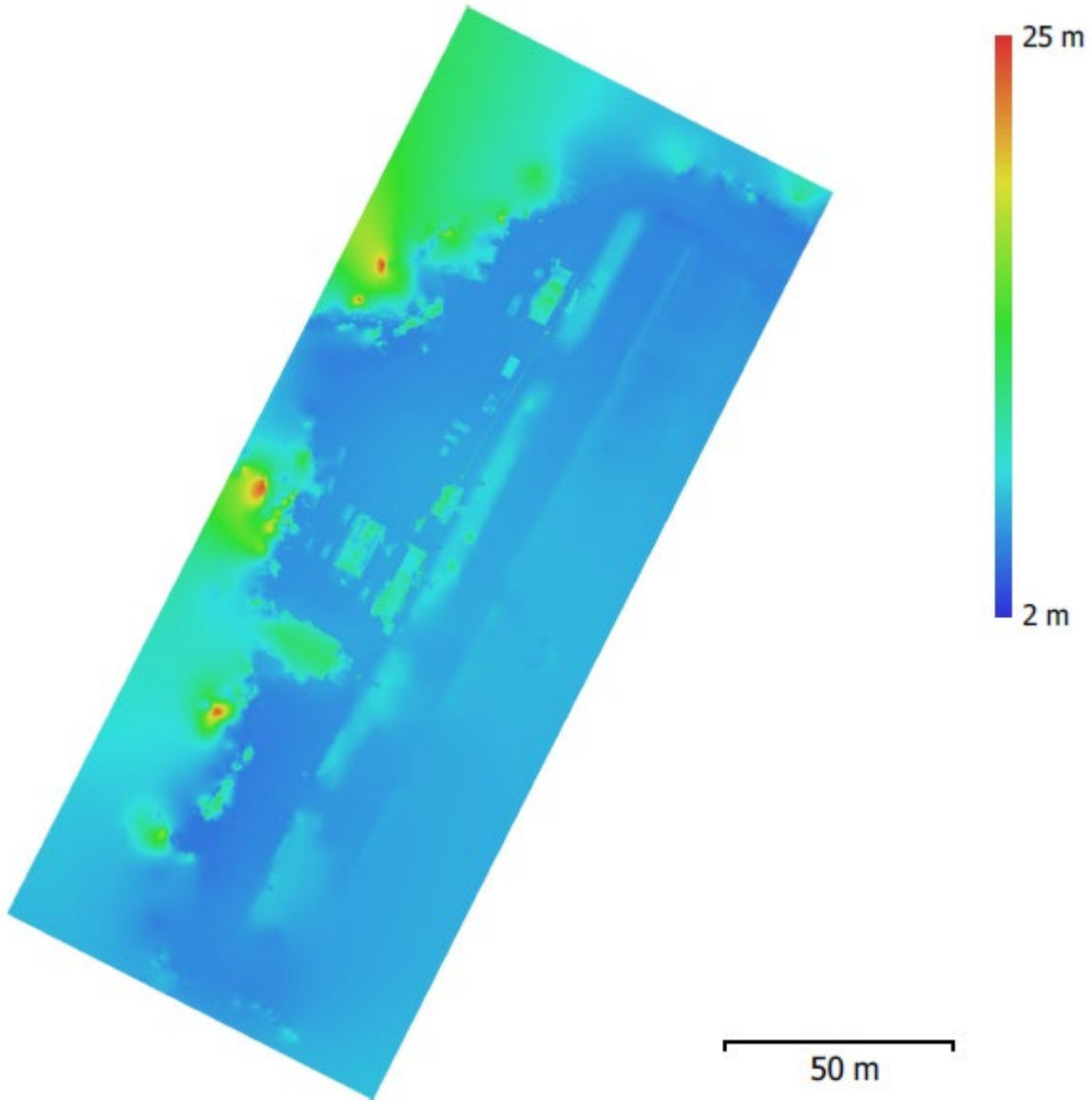
Note: Z error is represented by ellipse color. X,Y errors are represented by ellipse shape.  
 Estimated camera locations are marked with a black dot.

Table 13. Average camera location error for X (longitude), Y (latitude), and Z (altitude)

X error (cm)	Y error (cm)	Z error (cm)	XY error (cm)	Total error (cm)
22.5225	23.5954	62.4808	32.6191	70.483

### Digital Elevation Model

Figure 9. Reconstructed digital elevation model



Note: resolution was 3.46 mm/px, and point density was 834 points/cm<sup>2</sup>.

#### Processing Parameters (Ground Section)

##### General

Cameras	605
Aligned cameras	582
Coordinate system	World Geodetic System (WGS) 84 (European Petroleum Survey Group [EPSG]::4326)
Rotation angles	Yaw, Pitch, Roll
<b>Point Cloud</b>	
Points	161,863 of 293,453
RMS reprojection error	0.136178 (0.587711 px)
Max reprojection error	0.802527 (13.7933 px)
Mean key point size	3.69913 px
Point colors	3 bands, uint8

Key points	No
Average tie point multiplicity	2.92614
<b>Alignment parameters</b>	
Accuracy	High
Generic preselection	No
Reference preselection	Yes
Key point limit	40,000
Tie point limit	10,000
Adaptive camera model fitting	Yes
Matching time	56 minutes 44 seconds
Alignment time	14 minutes 41 seconds
<b>Optimization parameters</b>	
Parameters	f, b1, b2, cx, cy, k1-k3, p1-p4
Adaptive camera model fitting	No
Optimization time	39 seconds
<b>Dense Point Cloud</b>	
Points	225,638,919
Point colors	3 bands, uint8
<b>Reconstruction parameters</b>	
Quality	High
Depth filtering	Aggressive
Depth maps generation time	4 hours 1 minutes
Dense cloud generation time	2 days 4 hours
<b>Model</b>	
Faces	45,127,779
Vertices	22,663,879
Vertex colors	3 bands, uint8
Texture	8,192 x 8,192 x 39, 4 bands, uint8
<b>Reconstruction parameters</b>	
Surface type	Arbitrary
Source data	Dense
Interpolation	Enabled
Quality	High
Depth filtering	Aggressive
Face count	45,127,780
Processing time	3 hours 57 minutes
<b>Texturing parameters</b>	
Mapping mode	Generic
Blending mode	Mosaic
Texture size	8,192 x 8,192
Enable hole filling	Yes
Enable ghosting filter	No
UV mapping time	28 minutes 56 seconds
Blending time	4 hours 27 minutes
<b>Digital Elevation Model (DEM)</b>	
Size	52,447 x 69,316
Coordinate system	WGS 84 (EPSG::4326)
<b>Reconstruction parameters</b>	
Source data	Dense cloud
Interpolation	Enabled
Processing time	28 minutes 38 seconds
<b>Orthomosaic</b>	
Size	104,873 x 138,590
Coordinate system	WGS 84 (EPSG::4326)
Colors	3 bands, uint8

**Reconstruction parameters**

Blending mode  
Surface  
Enable hole filling  
Processing time

Mosaic  
DEM  
Yes  
5 hours 48 minutes

**Software**

Version  
Platform

1.4.2 build 6205  
Windows 64

### M-Range, Combined 5-3-18 Aerial Surveys, Section 1 of 3

#### Survey Data

Figure 10. Camera locations and image overlap

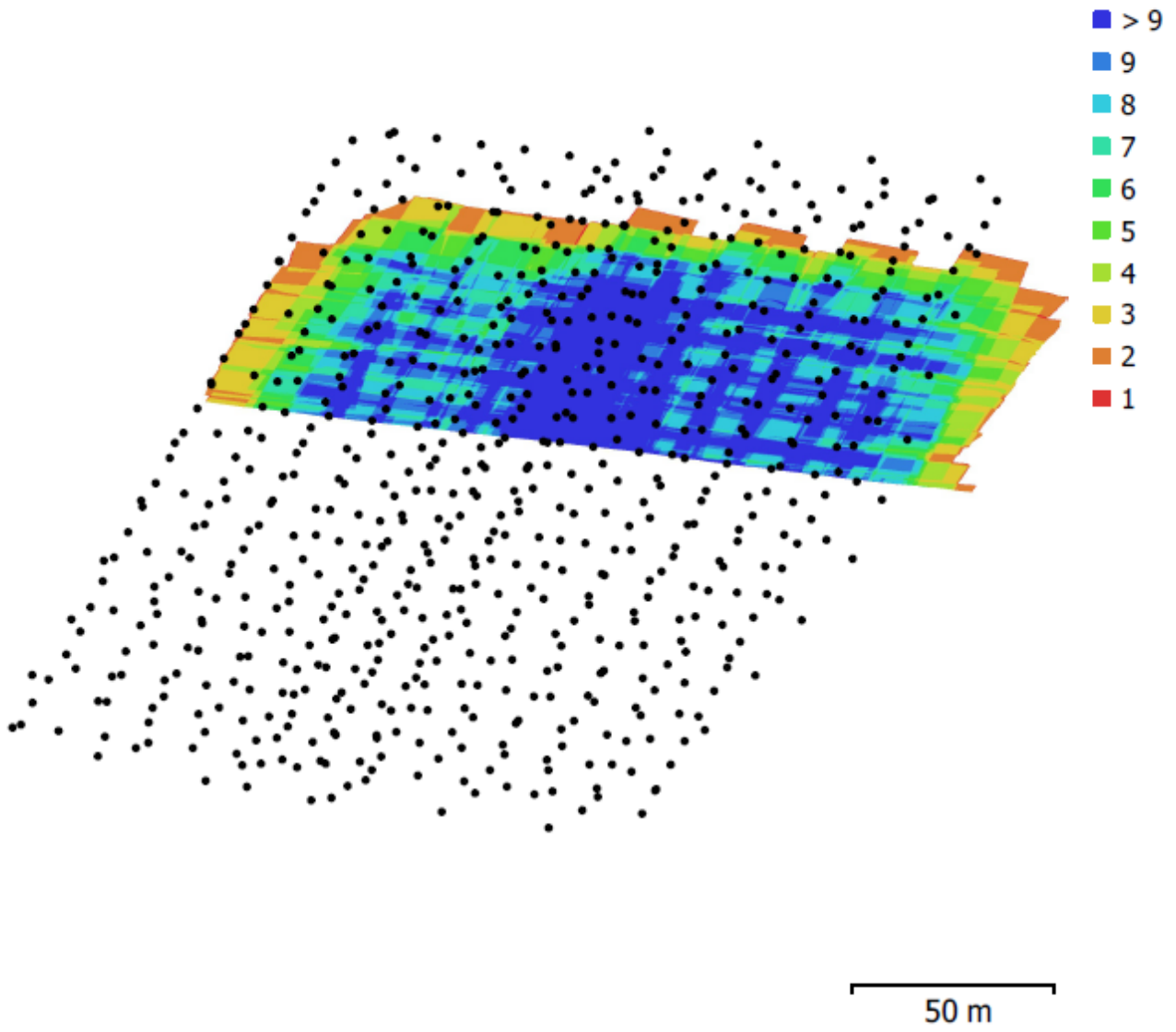


Table 14. Aerial survey overview (for section one of three)

Number of images:	690	Camera stations:	690
Flying altitude:	30.6 m	Tie points:	1,275,831
Ground resolution:	5.47 mm/px	Projections:	3,074,940
Coverage area:	0.0104 km <sup>2</sup>	Reprojection error:	0.521 px

Table 15. Aerial survey cameras (for section one of three)

Camera Model	Resolution	Focal Length	Pixel Size	Precalibrated
ILCE-6000 (20 mm)	6000 x 4000	20 mm	4 x 4 μm	No

**Camera Calibration**

Figure 11. Image residuals for ILCE-6000 (20 mm)

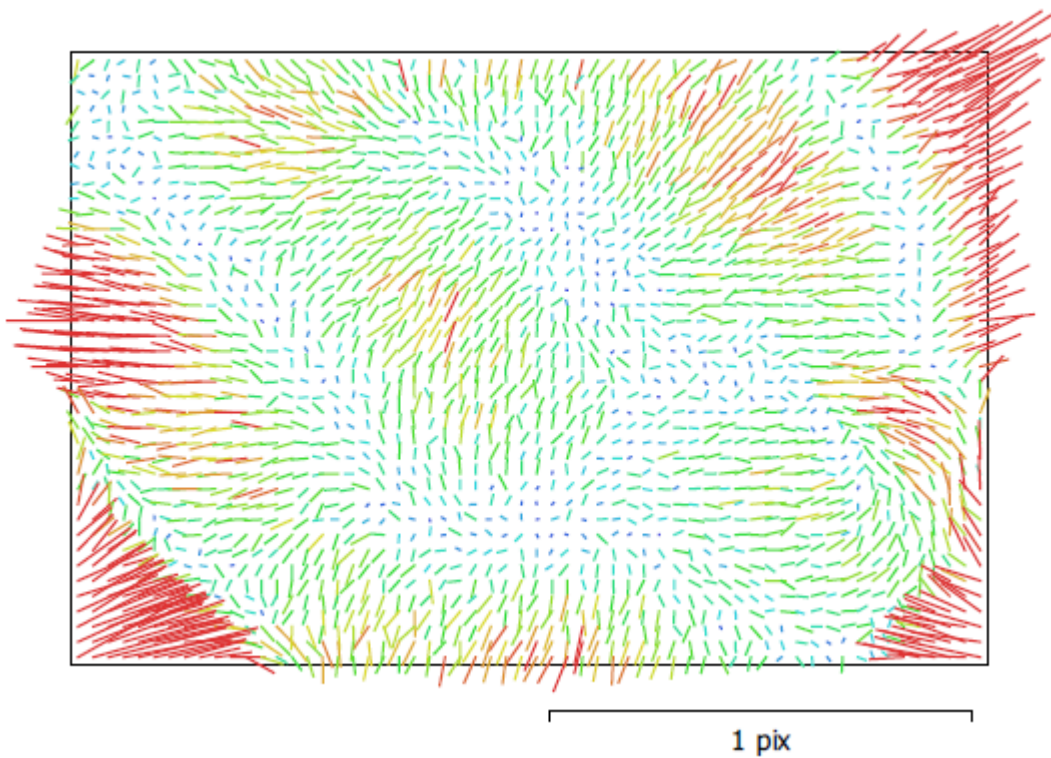


Table 16. Aerial survey camera calibration aspects (for section one of three)

ILCE-6000 (20 mm)	Type	Resolution	Focal Length	Pixel Size
690 images	Frame	6000 x 4000	20 mm	4 x 4 μm

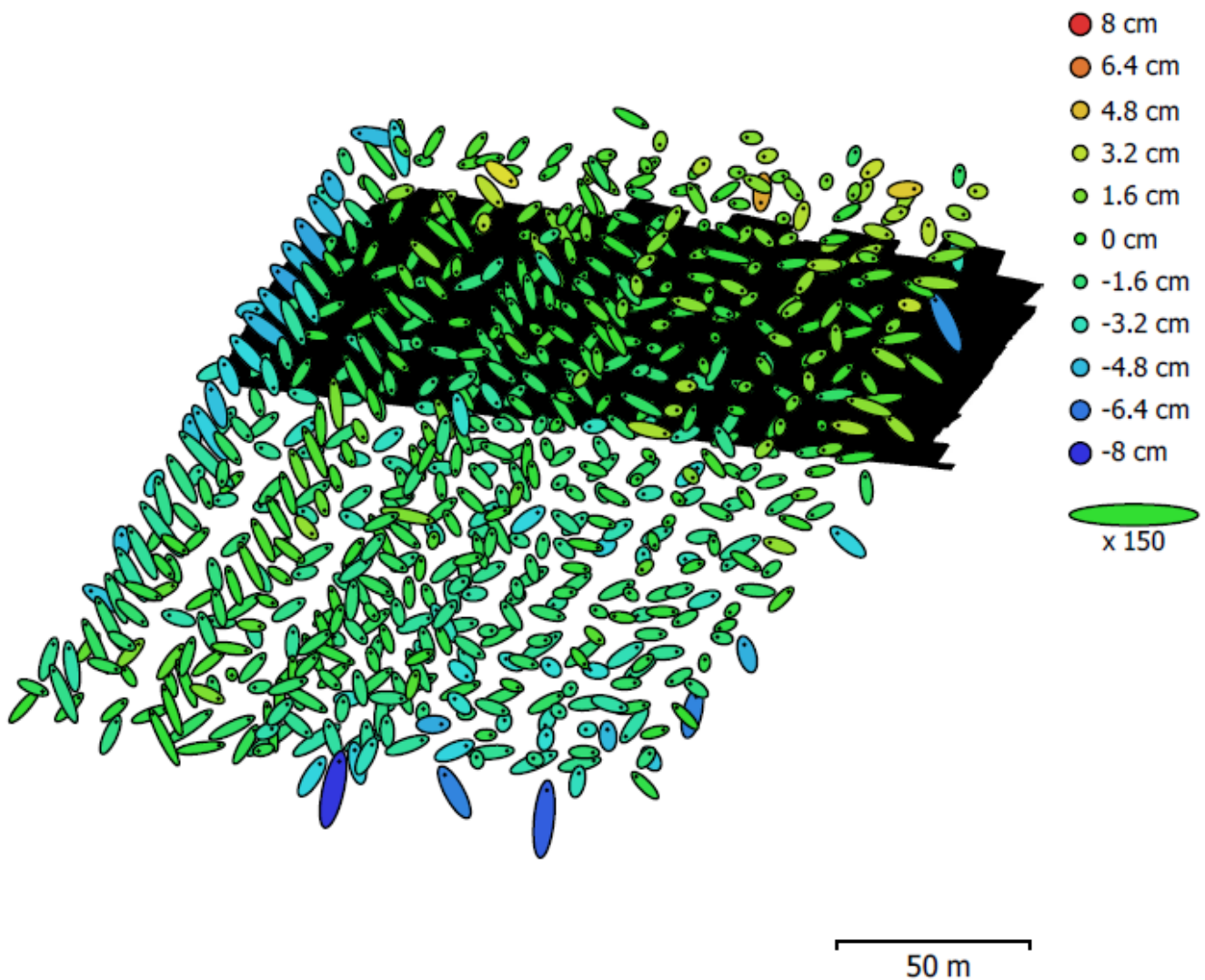
Table 17. Calibration coefficients and correlation matrix for aerial survey (for section one of three)

	Value	Error	F	Cx	Cy	B1	B2	K1	K2	K3	K4	P1	P2
<b>F</b>	<b>5230.19</b>	0.083	1.00	0.03	0.20	-0.01	-0.02	-0.22	0.13	-0.09	0.08	-0.04	-0.12
<b>Cx</b>	<b>-48.0248</b>	0.039		1.00	0.03	-0.12	-0.62	-0.04	0.04	-0.04	0.05	-0.09	-0.02
<b>Cy</b>	<b>24.2162</b>	0.039			1.00	0.55	-0.18	-0.00	-0.01	0.02	-0.02	-0.01	-0.32

<b>B1</b>	<b>-2.72019</b>	0.0047				1.00	-0.03	0.04	-0.05	0.05	-0.05	0.05	-0.43
<b>B2</b>	<b>-0.189867</b>	0.0043					1.00	0.02	-0.02	0.02	-0.03	0.35	0.11
<b>K1</b>	<b>-0.157654</b>	5e-05						1.00	-0.97	0.92	-0.88	0.02	0.02
<b>K2</b>	<b>0.115099</b>	0.00038							1.00	-0.99	0.96	-0.02	0.00
<b>K3</b>	<b>0.103301</b>	0.0011								1.00	-0.99	0.02	-0.01
<b>K4</b>	<b>-0.110454</b>	0.0011									1.00	-0.03	0.01
<b>P1</b>	<b>-0.001308</b>	1.2e-06										1.00	0.03
<b>P2</b>	<b>0.000952256</b>	1.2e-06											1.00

**Camera Locations**

Figure 12. Camera locations and error estimates



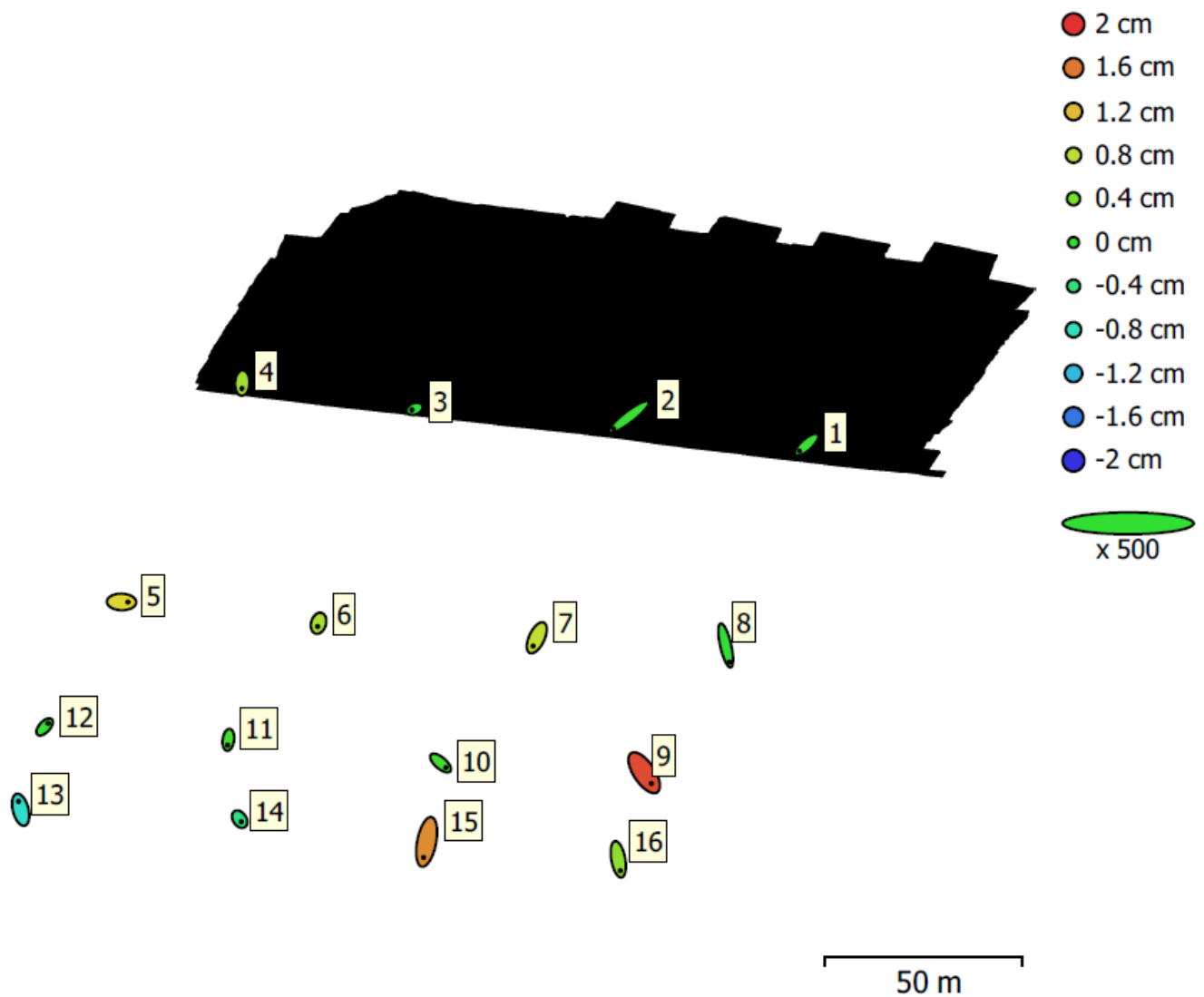
Note: Z error is represented by ellipse color. X,Y errors are represented by ellipse shape. Estimated camera locations are marked with a black dot.

Table 18. Average camera location error for X (longitude), Y (latitude), and Z (altitude)

X error (cm)	Y error (cm)	Z error (cm)	XY error (cm)	Total error (cm)
2.69735	2.81113	1.93111	3.89591	4.34826

**Ground Control Points**

Figure 13. GCP locations and error estimates



Note: Z error is represented by ellipse color. X,Y errors are represented by ellipse shape. Estimated GCP locations are marked with a dot or crossing.

Table 19. Control points root mean square error (RMSE) for X (longitude), Y (latitude), and Z (altitude)

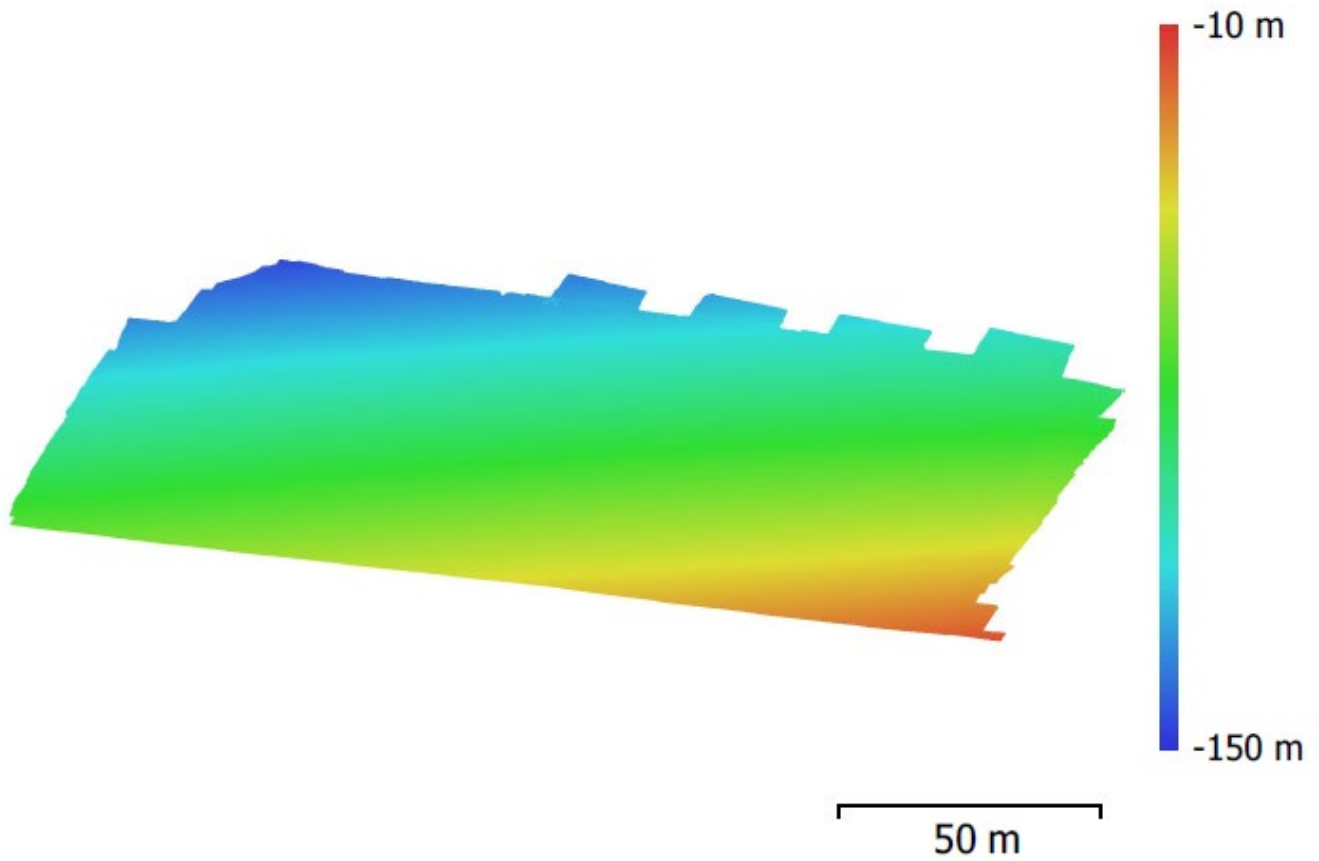
Count	X error (cm)	Y error (cm)	Z error (cm)	XY error (cm)	Total (cm)
16	0.555387	0.878758	0.775237	1.03955	1.29679

Table 20. Control points for X (longitude), Y (latitude), and Z (altitude)

Label	X error (cm)	Y error (cm)	Z error (cm)	Total (cm)	Image (px)
1	-0.715582	-0.648694	0.0522246	0.967258	0.114 (9)
2	-1.56125	-1.20519	0.0448036	1.97281	0.424 (12)
3	-0.27031	-0.108976	-0.0623116	0.298036	0.162 (10)
4	-0.0252293	-0.555632	0.657231	0.860997	0.068 (3)
5	0.650496	-0.0159973	1.03816	1.22522	0.256 (6)
6	-0.0954972	-0.339393	0.710526	0.793192	0.230 (10)
7	-0.386295	-0.832355	0.837761	1.24253	0.319 (9)
8	0.388929	-1.69458	-0.0238428	1.7388	0.313 (8)
9	0.737248	-1.10069	1.86172	2.28496	0.206 (8)
10	0.547023	-0.467956	0.102936	0.727196	0.345 (10)
11	-0.0696401	-0.541037	0.100731	0.554723	0.163 (10)
12	0.347558	0.378186	-0.0144203	0.513837	0.220 (5)
13	-0.217111	0.850907	-0.878648	1.24226	0.149 (4)
14	0.163826	-0.250443	-0.435077	0.528065	0.362 (11)
15	-0.306309	-1.58122	1.46274	2.17571	0.390 (10)
16	0.207486	-1.15256	0.549908	1.29377	0.189 (8)
<b>Total</b>	<b>0.555387</b>	<b>0.878758</b>	<b>0.775237</b>	<b>1.29679</b>	<b>0.282</b>

### Digital Elevation Model

Figure 14. Reconstructed digital elevation model



Note: resolution was 1.09 cm/px, and point density was 83.4 points/cm<sup>2</sup>.

### Processing Parameters (Aerial Section 1 of 3)

#### General

Cameras	690
Aligned cameras	690
Markers	16
Coordinate system	WGS 84 (EPSG::4326)
Rotation angles	Yaw, Pitch, Roll

#### Point Cloud

Points	1,275,831 of 1,443,858
Point colors	3 bands, uint8
RMS reprojection error	0.155823 (0.521424 px)
Max reprojection error	0.711538 (6.49469 px)
Mean key point size	3.19951 px
Effective overlap	2.44644

**Alignment parameters**

Accuracy	High
Generic preselection	No
Reference preselection	Yes
Key point limit	40,000
Tie point limit	10,000
Adaptive camera model fitting	Yes
Matching time	36 minutes 59 seconds
Alignment time	8 minutes 0 seconds

**Optimization parameters**

Parameters	f, b1, b2, cx, cy, k1-k4, p1, p2
Adaptive camera model fitting	No
Optimization time	11 seconds

**Dense Point Cloud**

Points	613,402,039
Point colors	3 bands, uint8

**Reconstruction parameters**

Quality	High
Depth filtering	Aggressive
Depth maps generation time	3 hours 5 minutes
Dense cloud generation time	1 hours 49 minutes

**Model**

Faces	37,833,608
Vertices	18,926,192
Vertex colors	3 bands, uint8

**Reconstruction parameters**

Surface type	Arbitrary
Source data	Dense
Interpolation	Enabled
Quality	High
Depth filtering	Aggressive
Face count	37,833,608
Processing time	8 hours 37 minutes

**DEM**

Size	18,162 x 21,645
Coordinate system	WGS 84 (EPSG::4326)

**Reconstruction parameters**

Source data	Dense cloud
Interpolation	Enabled
Processing time	5 minutes 44 seconds

**Orthomosaic**

Size	32,736 x 39,510
Coordinate system	WGS 84 (EPSG::4326)
Colors	3 bands, uint8

**Reconstruction parameters**

Blending mode	Mosaic
Surface	DEM
Enable hole filling	Yes
Processing time	23 minutes 26 seconds

**Software**

Version	1.4.1 build 5925
Platform	Windows 64

### M-Range, Combined 5-3-18 Aerial Surveys, Section 2 of 3

Figure 15. Aerial view of aerial survey area



Survey Data

Figure 16. Camera locations and image overlap

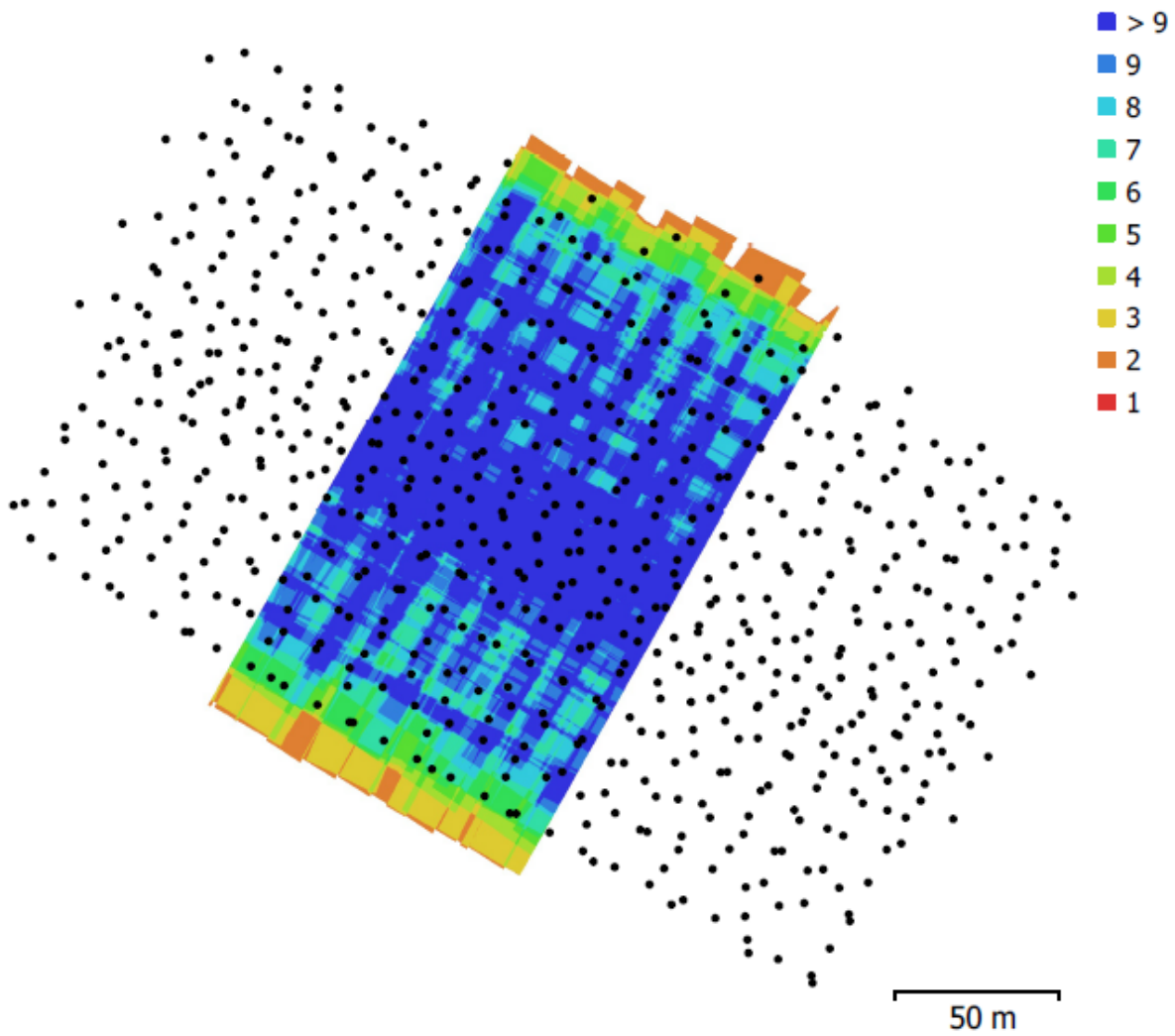


Table 21. Aerial survey overview (for section two of three)

Number of images:	690	Camera stations:	690
Flying altitude:	30.6 m	Tie points:	1,275,831
Ground resolution:	5.47 mm/px	Projections:	3,074,940
Coverage area:	0.0219 km <sup>2</sup>	Reprojection error:	0.521 px

Table 22. Aerial survey cameras (for section two of three)

Camera Model	Resolution	Focal Length	Pixel Size	Precalibrated
ILCE-6000 (20 mm)	6000 x 4000	20 mm	4 x 4 μm	No

### Camera Calibration

Figure 17. Image residuals for ILCE-6000 (20 mm)

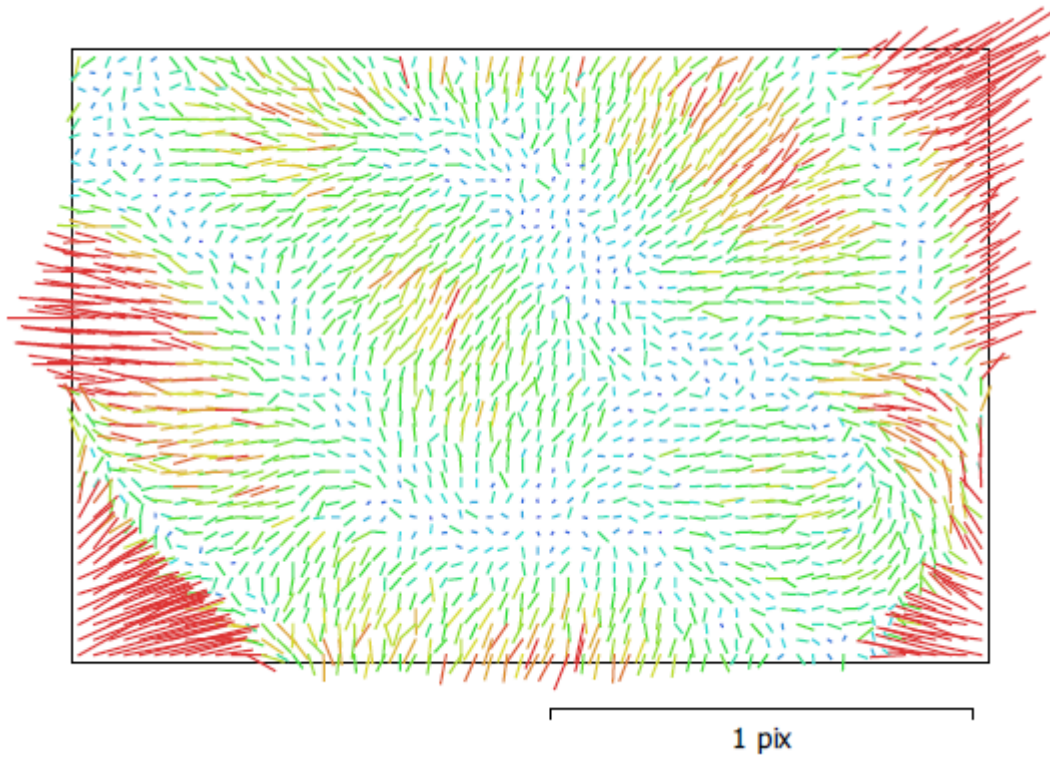


Table 23. Aerial survey camera calibration aspects (for section two of three)

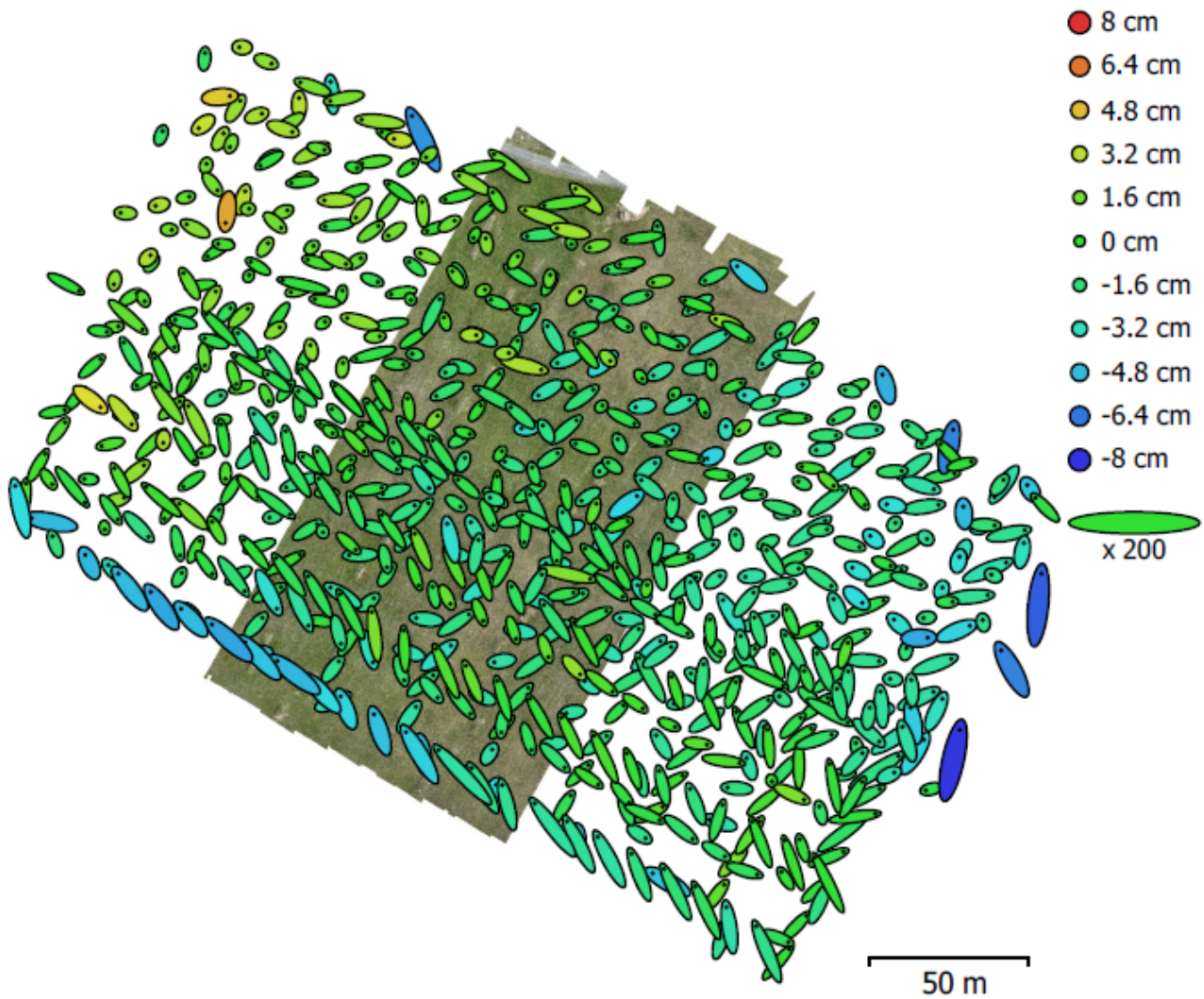
ILCE-6000 (20 mm)	Type	Resolution	Focal Length	Pixel Size
690 images	Frame	6000 x 4000	20 mm	4 x 4 μm

Table 24. Calibration coefficients and correlation matrix for aerial survey (for section two of three)

	Value	Error	F	Cx	Cy	B1	B2	K1	K2	K3	K4	P1	P2
<b>F</b>	<b>5230.19</b>	0.083	1.00	0.03	0.20	-0.01	-0.02	-0.22	0.13	-0.09	0.08	-0.04	-0.12
<b>Cx</b>	<b>-48.0248</b>	0.039		1.00	0.03	-0.12	-0.62	-0.04	0.04	-0.04	0.05	-0.09	-0.02
<b>Cy</b>	<b>24.2162</b>	0.039			1.00	0.55	-0.18	-0.00	-0.01	0.02	-0.02	-0.01	-0.32
<b>B1</b>	<b>-2.72019</b>	0.0047				1.00	-0.03	0.04	-0.05	0.05	-0.05	0.05	-0.43
<b>B2</b>	<b>-0.189867</b>	0.0043					1.00	0.02	-0.02	0.02	-0.03	0.35	0.11
<b>K1</b>	<b>-0.157654</b>	5e-05						1.00	-0.97	0.92	-0.88	0.02	0.02
<b>K2</b>	<b>0.115099</b>	0.00038							1.00	-0.99	0.96	-0.02	0.00
<b>K3</b>	<b>0.103301</b>	0.0011								1.00	-0.99	0.02	-0.01
<b>K4</b>	<b>-0.110454</b>	0.0011									1.00	-0.03	0.01
<b>P1</b>	<b>-0.001308</b>	1.2e-06										1.00	0.03
<b>P2</b>	<b>0.000952256</b>	1.2e-06											1.00

### Camera Locations

Figure 18. Camera locations and error estimates



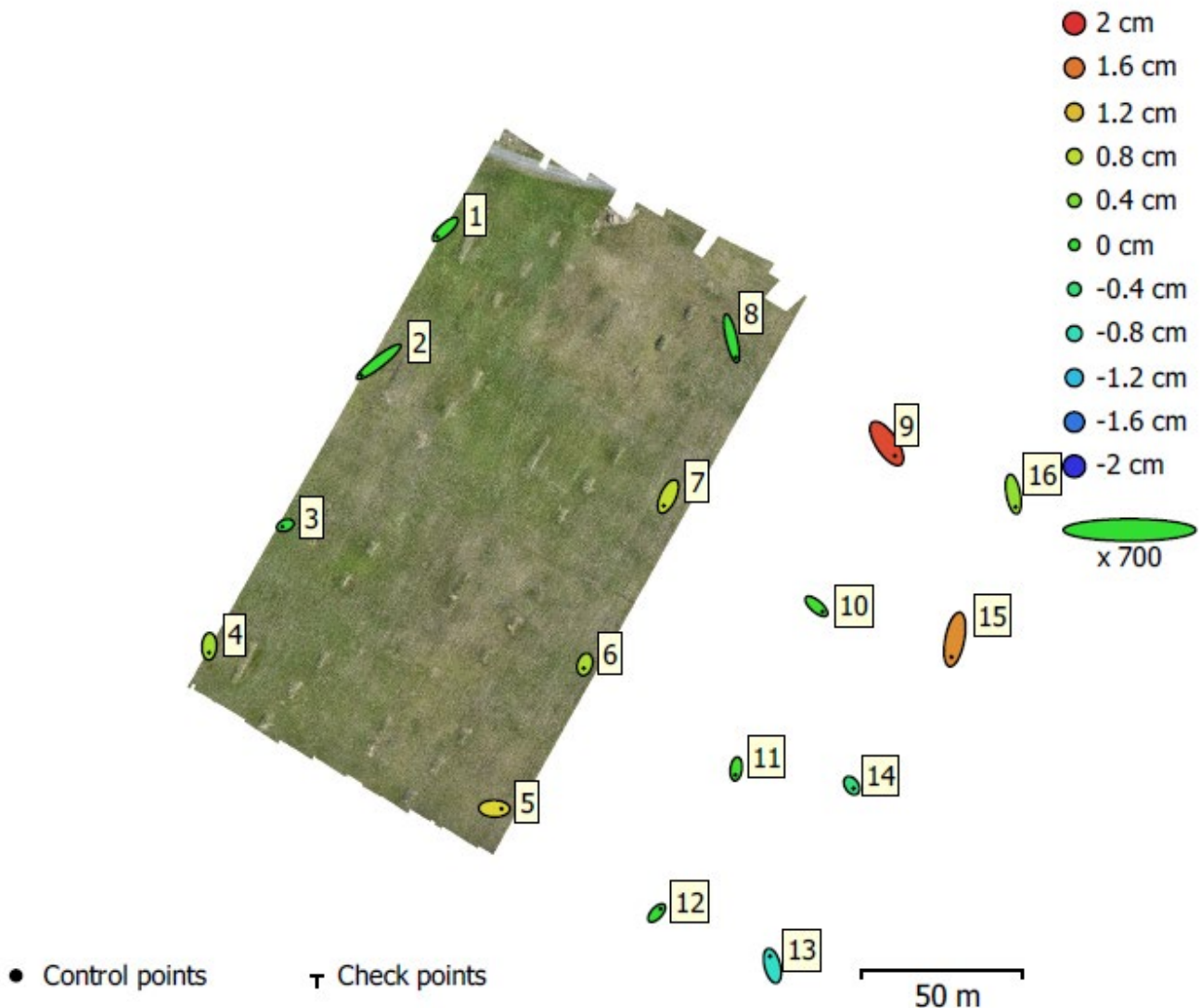
Note: Z error is represented by ellipse color. X,Y errors are represented by ellipse shape.  
 Estimated camera locations are marked with a black dot.

Table 25. Average camera location error for X (longitude), Y (latitude), and Z (altitude)

X error (cm)	Y error (cm)	Z error (cm)	XY error (cm)	Total error (cm)
2.69735	2.81113	1.93111	3.89591	4.34826

### Ground Control Points

Figure 19. GCP locations and error estimates



Note: Z error is represented by ellipse color. X,Y errors are represented by ellipse shape. Estimated GCP locations are marked with a dot or crossing.

Table 26. Control points RMSE for X (longitude), Y (latitude), and Z (altitude)

Count	X error (cm)	Y error (cm)	Z error (cm)	XY error (cm)	Total (cm)
16	0.555387	0.878758	0.775237	1.03955	1.29679

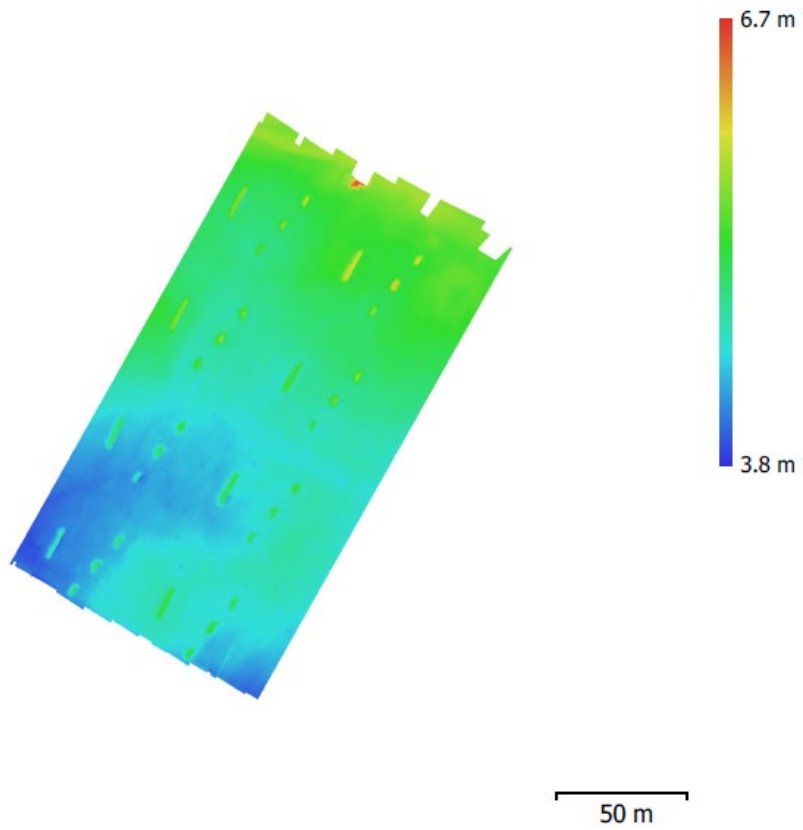
Table 27. Control points for X (longitude), Y (latitude), and Z (altitude)

Label	X error (cm)	Y error (cm)	Z error (cm)	Total (cm)	Image (px)
1	-0.715582	-0.648694	0.0522246	0.967258	0.114 (9)
2	-1.56125	-1.20519	0.0448036	1.97281	0.424 (12)

3	-0.27031	-0.108976	-0.0623116	0.298036	0.162 (10)
4	-0.0252293	-0.555632	0.657231	0.860997	0.068 (3)
5	0.650496	-0.0159973	1.03816	1.22522	0.256 (6)
6	-0.0954972	-0.339393	0.710526	0.793192	0.230 (10)
7	-0.386295	-0.832355	0.837761	1.24253	0.319 (9)
8	0.388929	-1.69458	-0.0238428	1.7388	0.313 (8)
9	0.737248	-1.10069	1.86172	2.28496	0.206 (8)
10	0.547023	-0.467956	0.102936	0.727196	0.345 (10)
11	-0.0696401	-0.541037	0.100731	0.554723	0.163 (10)
12	0.347558	0.378186	-0.0144203	0.513837	0.220 (5)
13	-0.217111	0.850907	-0.878648	1.24226	0.149 (4)
14	0.163826	-0.250443	-0.435077	0.528065	0.362 (11)
15	-0.306309	-1.58122	1.46274	2.17571	0.390 (10)
16	0.207486	-1.15256	0.549908	1.29377	0.189 (8)
<b>Total</b>	<b>0.555387</b>	<b>0.878758</b>	<b>0.775237</b>	<b>1.29679</b>	<b>0.282</b>

### Digital Elevation Model

Figure 20. Reconstructed digital elevation model



Note: resolution was 1.09 cm/px, and point density was 83.4 points/cm<sup>2</sup>.

## Processing Parameters (Aerial Section 2 of 3)

### General

Cameras	690
Aligned cameras	690
Markers	16
Coordinate system	WGS 84 (EPSG::4326)
Rotation angles	Yaw, Pitch, Roll

### Point Cloud

Points	1,275,831 of 1,443,858
RMS reprojection error	0.155823 (0.521424 px)
Max reprojection error	0.711538 (6.49469 px)
Mean key point size	3.19951 px
Point colors	3 bands, uint8
Key points	No
Average tie point multiplicity	2.44644

### Alignment parameters

Accuracy	High
Generic preselection	No
Reference preselection	Yes
Key point limit	40,000
Tie point limit	10,000
Adaptive camera model fitting	Yes
Matching time	36 minutes 59 seconds
Alignment time	8 minutes 0 seconds

### Optimization parameters

Parameters	f, b1, b2, cx, cy, k1-k4, p1, p2
Adaptive camera model fitting	No
Optimization time	11 seconds

### Dense Point Cloud

Points	613,402,039
Point colors	3 bands, uint8

### Reconstruction parameters

Quality	High
Depth filtering	Aggressive
Depth maps generation time	3 hours 5 minutes
Dense cloud generation time	1 hours 49 minutes

### Model

Faces	43,268,724
Vertices	21,643,112
Vertex colors	3 bands, uint8
Texture	4,096 x 4,096 x 88, 4 bands, uint8

### Reconstruction parameters

Surface type	Arbitrary
Source data	Dense
Interpolation	Enabled
Quality	High
Depth filtering	Aggressive
Face count	43,268,724
Processing time	4 hours 32 minutes

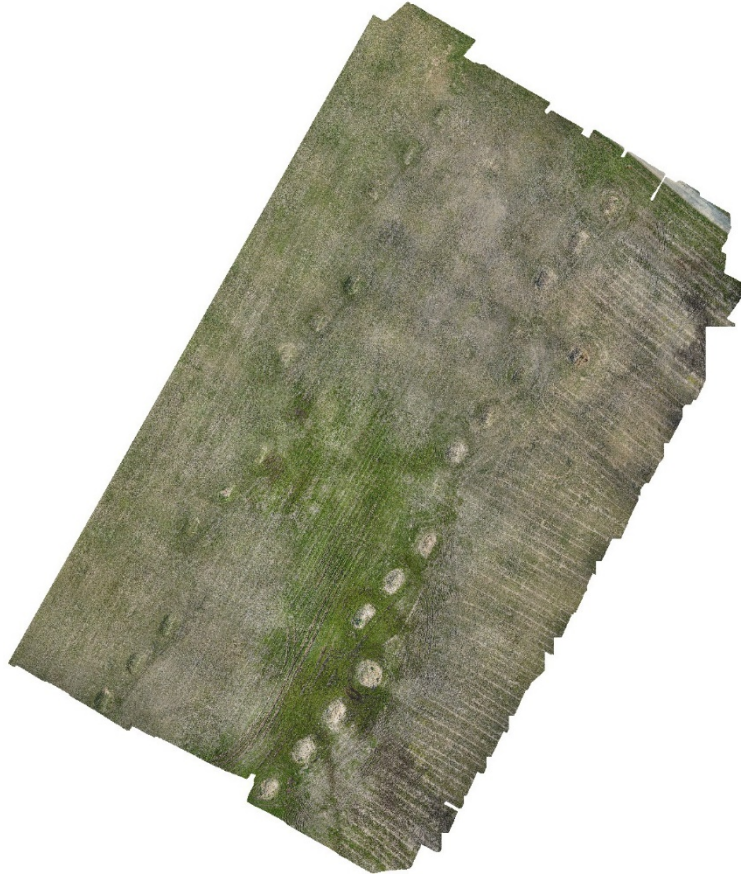
### Texturing parameters

Mapping mode	Generic
Blending mode	Mosaic
Texture size	4,096 x 4,096
Enable hole filling	Yes
Enable ghosting filter	No
UV mapping time	1 hours 10 minutes

Blending time	32 minutes 13 seconds
<b>DEM</b>	
Size	18,265 x 21,896
Coordinate system	WGS 84 (EPSG::4326)
<b>Reconstruction parameters</b>	
Source data	Mesh
Interpolation	Enabled
Processing time	4 minutes 30 seconds
<b>Orthomosaic</b>	
Size	35,438 x 41,464
Coordinate system	WGS 84 (EPSG::4326)
Colors	3 bands, uint8
<b>Reconstruction parameters</b>	
Blending mode	Mosaic
Surface	DEM
Enable hole filling	Yes
Processing time	14 minutes 0 seconds
<b>Software</b>	
Version	1.4.2 build 6205
Platform	Windows 64

**M-Range, Combined 5-3-18 Aerial Surveys, Section 3 of 3**

Figure 21. Aerial view of aerial survey area



### Survey Data

Figure 22. Camera locations and image overlap

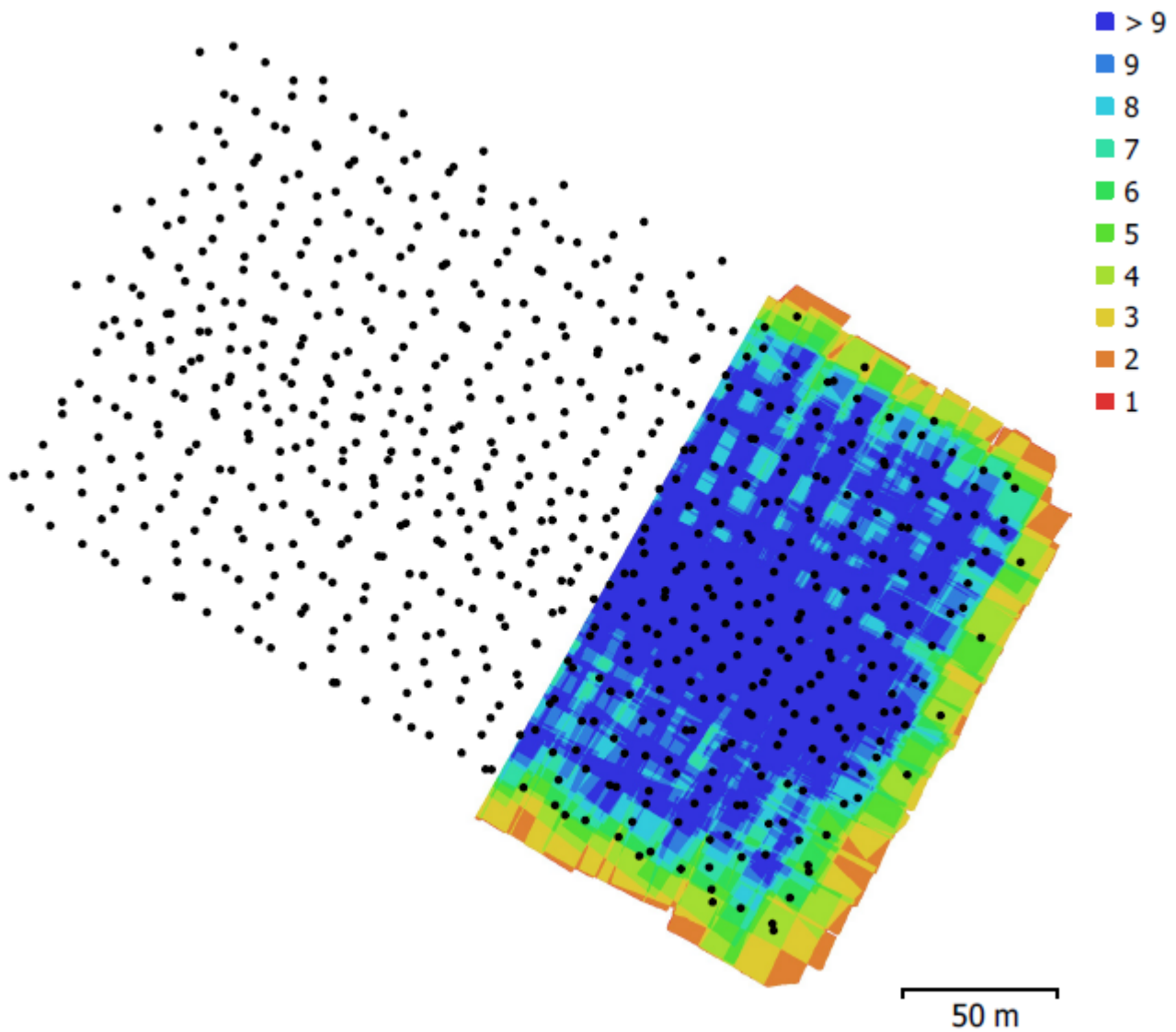


Table 28. Aerial survey overview (for section three of three)

Number of images:	690	Camera stations:	690
Flying altitude:	30.6 m	Tie points:	1,275,831
Ground resolution:	5.47 mm/px	Projections:	3,074,940
Coverage area:	0.0235 km <sup>2</sup>	Reprojection error:	0.521 px

Table 29. Aerial survey cameras (for section three of three)

Camera Model	Resolution	Focal Length	Pixel Size	Precalibrated
ILCE-6000 (20 mm)	6000 x 4000	20 mm	4 x 4 μm	No

### Camera Calibration

Figure 23. Image residuals for ILCE-6000 (20 mm)

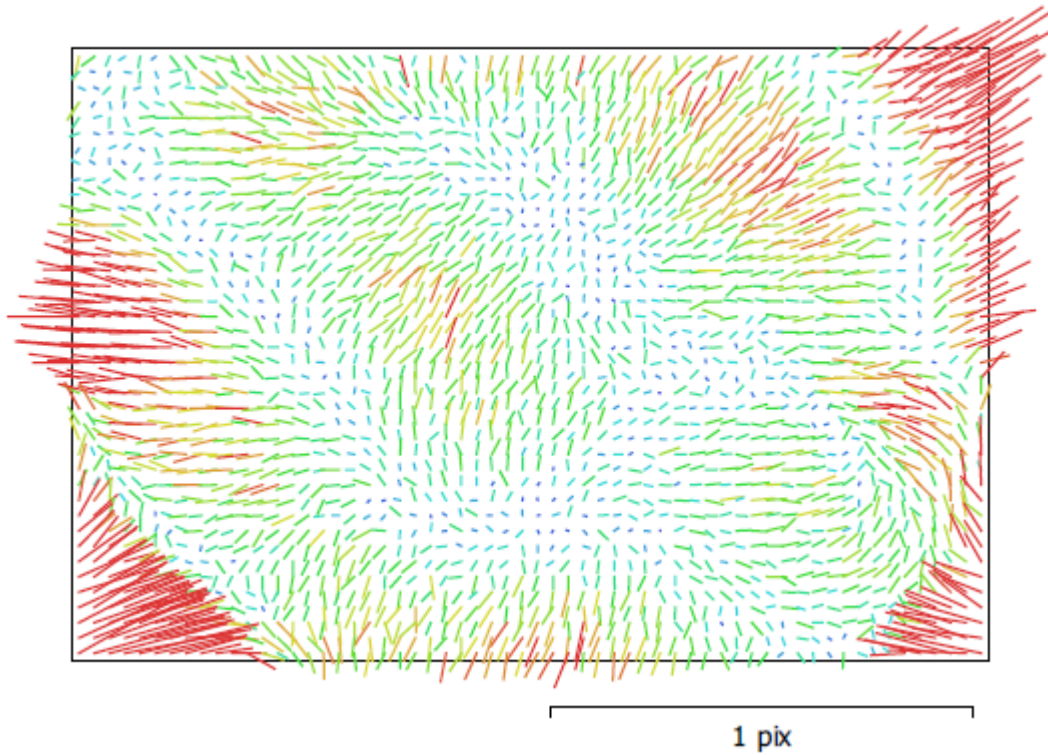


Table 30. Aerial survey camera calibration aspects (for section three of three)

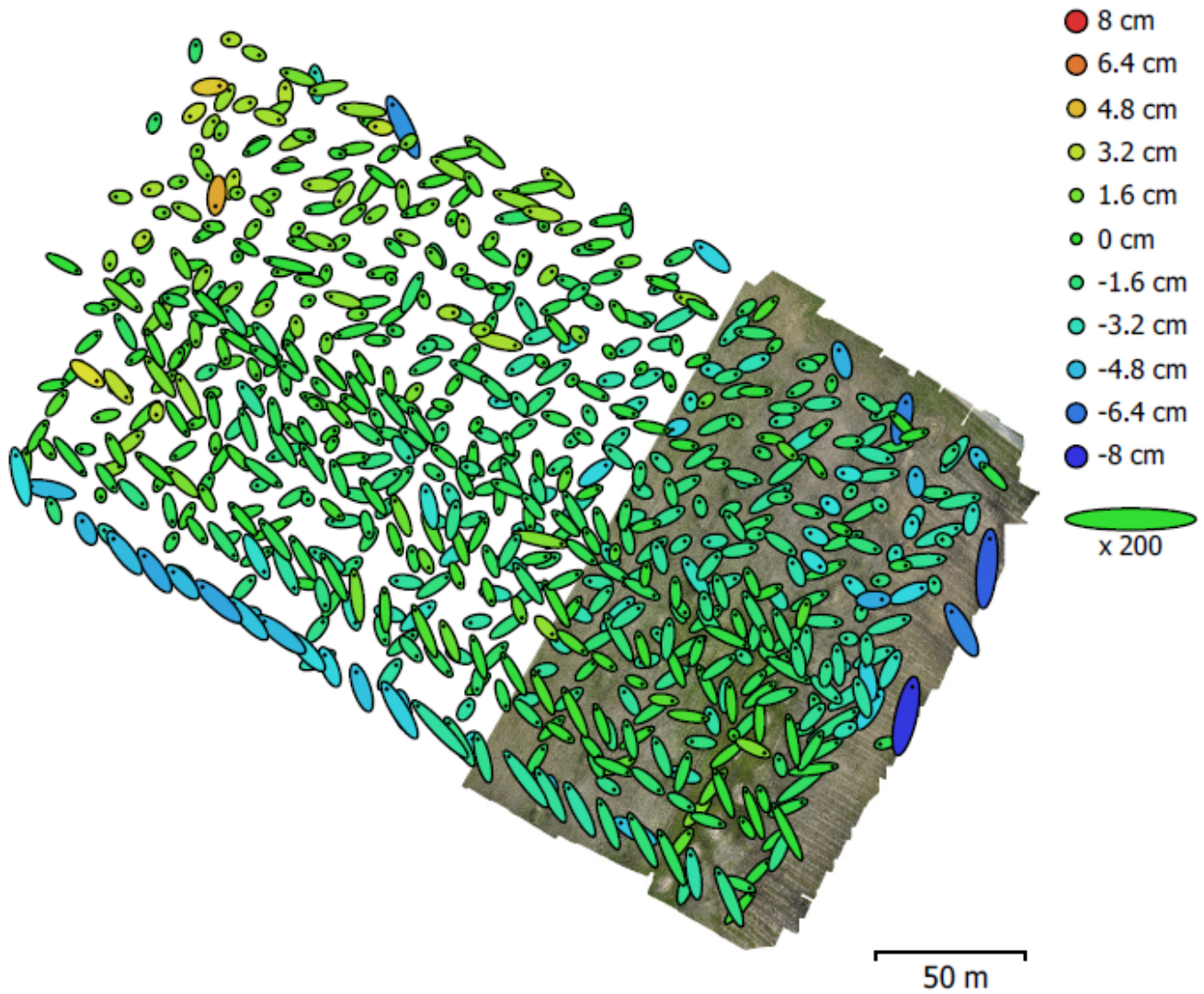
ILCE-6000 (20 mm)	Type	Resolution	Focal Length	Pixel Size
690 images	Frame	6000 x 4000	20 mm	4 x 4 $\mu$ m

Table 31. Calibration coefficients and correlation matrix for aerial survey (for section three of three)

	Value	Error	F	Cx	Cy	B1	B2	K1	K2	K3	K4	P1	P2
<b>F</b>	<b>5230.19</b>	0.083	1.00	0.03	0.20	-0.01	-0.02	-0.22	0.13	-0.09	0.08	-0.04	-0.12
<b>Cx</b>	<b>-48.0248</b>	0.039		1.00	0.03	-0.12	-0.62	-0.04	0.04	-0.04	0.05	-0.09	-0.02
<b>Cy</b>	<b>24.2162</b>	0.039			1.00	0.55	-0.18	-0.00	-0.01	0.02	-0.02	-0.01	-0.32
<b>B1</b>	<b>-2.72019</b>	0.0047				1.00	-0.03	0.04	-0.05	0.05	-0.05	0.05	-0.43
<b>B2</b>	<b>-0.189867</b>	0.0043					1.00	0.02	-0.02	0.02	-0.03	0.35	0.11
<b>K1</b>	<b>-0.157654</b>	5e-05						1.00	-0.97	0.92	-0.88	0.02	0.02
<b>K2</b>	<b>0.115099</b>	0.00038							1.00	-0.99	0.96	-0.02	0.00
<b>K3</b>	<b>0.103301</b>	0.0011								1.00	-0.99	0.02	-0.01
<b>K4</b>	<b>-0.110454</b>	0.0011									1.00	-0.03	0.01
<b>P1</b>	<b>-0.001308</b>	1.2e-06										1.00	0.03
<b>P2</b>	<b>0.000952256</b>	1.2e-06											1.00

### Camera Locations

Figure 24. Camera locations and error estimates



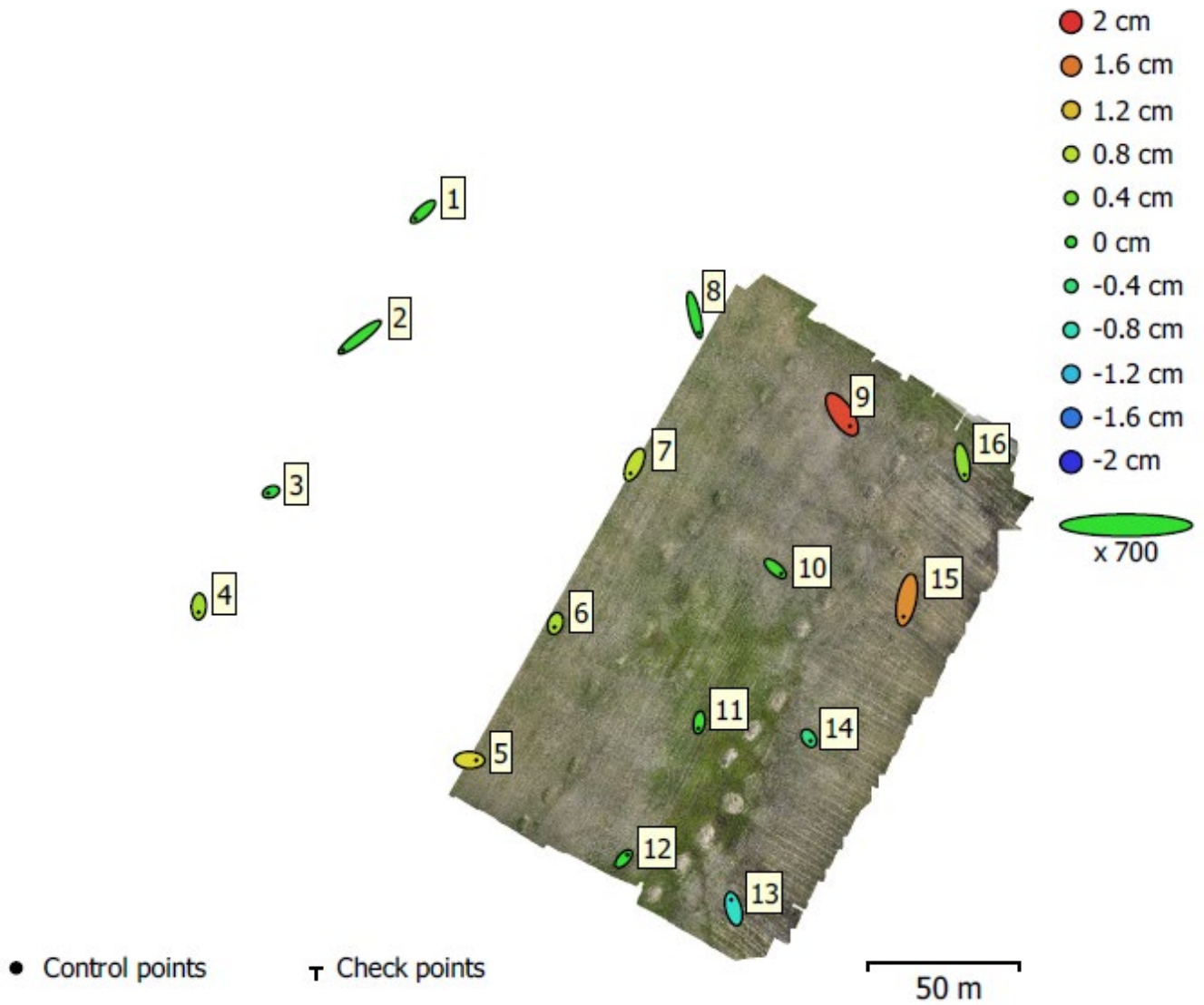
Note: Z error is represented by ellipse color. X,Y errors are represented by ellipse shape.  
 Estimated camera locations are marked with a black dot.

Table 32. Average camera location error for X (longitude), Y (latitude), and Z (altitude)

X error (cm)	Y error (cm)	Z error (cm)	XY error (cm)	Total error (cm)
2.69735	2.81113	1.93111	3.89591	4.34826

### Ground Control Points

Figure 25. GCP locations and error estimates



Note: Z error is represented by ellipse color. X,Y errors are represented by ellipse shape.  
 Estimated GCP locations are marked with a dot or crossing.

Table 33. Control points RMSE for X (longitude), Y (latitude), and Z (altitude)

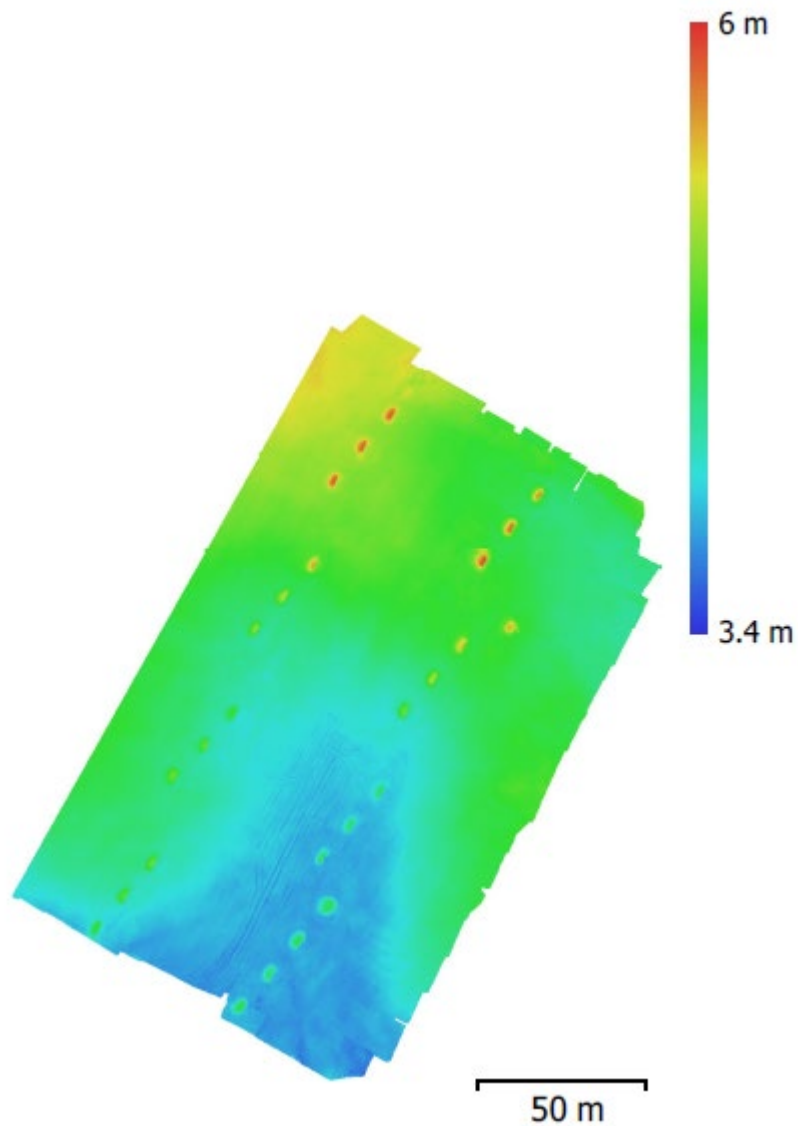
Count	X error (cm)	Y error (cm)	Z error (cm)	XY error (cm)	Total (cm)
16	0.555387	0.878758	0.775237	1.03955	1.29679

Table 34. Control points for X (longitude), Y (latitude), and Z (altitude)

<b>Label</b>	<b>X error (cm)</b>	<b>Y error (cm)</b>	<b>Z error (cm)</b>	<b>Total (cm)</b>	<b>Image (px)</b>
1	-0.715582	-0.648694	0.0522246	0.967258	0.114 (9)
2	-1.56125	-1.20519	0.0448036	1.97281	0.424 (12)
3	-0.27031	-0.108976	-0.0623116	0.298036	0.162 (10)
4	-0.0252293	-0.555632	0.657231	0.860997	0.068 (3)
5	0.650496	-0.0159973	1.03816	1.22522	0.256 (6)
6	-0.0954972	-0.339393	0.710526	0.793192	0.230 (10)
7	-0.386295	-0.832355	0.837761	1.24253	0.319 (9)
8	0.388929	-1.69458	-0.0238428	1.7388	0.313 (8)
9	0.737248	-1.10069	1.86172	2.28496	0.206 (8)
10	0.547023	-0.467956	0.102936	0.727196	0.345 (10)
11	-0.0696401	-0.541037	0.100731	0.554723	0.163 (10)
12	0.347558	0.378186	-0.0144203	0.513837	0.220 (5)
13	-0.217111	0.850907	-0.878648	1.24226	0.149 (4)
14	0.163826	-0.250443	-0.435077	0.528065	0.362 (11)
15	-0.306309	-1.58122	1.46274	2.17571	0.390 (10)
16	0.207486	-1.15256	0.549908	1.29377	0.189 (8)
<b>Total</b>	<b>0.555387</b>	<b>0.878758</b>	<b>0.775237</b>	<b>1.29679</b>	<b>0.282</b>

### Digital Elevation Model

Figure 26. Reconstructed digital elevation model



Note: resolution was 1.09 cm/px, and point density was 83.4 points/cm<sup>2</sup>.

### Processing Parameters (Aerial Section 3 of 3)

**General**

Cameras	690
Aligned cameras	690
Markers	16
Coordinate system	WGS 84 (EPSG::4326)
Rotation angles	Yaw, Pitch, Roll

**Point Cloud**

Points	1,275,831 of 1,443,858
RMS reprojection error	0.155823 (0.521424 px)
Max reprojection error	0.711538 (6.49469 px)
Mean key point size	3.19951 px
Point colors	3 bands, uint8
Key points	No
Average tie point multiplicity	2.44644

**Alignment parameters**

Accuracy	High
Generic preselection	No
Reference preselection	Yes
Key point limit	40,000
Tie point limit	10,000
Adaptive camera model fitting	Yes
Matching time	36 minutes 59 seconds
Alignment time	8 minutes 0 seconds

**Optimization parameters**

Parameters	f, b1, b2, cx, cy, k1-k4, p1, p2
Adaptive camera model fitting	No
Optimization time	11 seconds

**Dense Point Cloud**

Points	613,402,039
Point colors	3 bands, uint8

**Reconstruction parameters**

Quality	High
Depth filtering	Aggressive
Depth maps generation time	3 hours 5 minutes
Dense cloud generation time	1 hours 49 minutes

**Model**

Faces	45,818,065
Vertices	22,917,190
Vertex colors	3 bands, uint8
Texture	4,096 x 4,096 x 87, 4 bands, uint8

**Reconstruction parameters**

Surface type	Arbitrary
Source data	Dense
Interpolation	Enabled
Quality	High
Depth filtering	Aggressive
Face count	45,818,065
Processing time	5 hours 16 minutes

**Texturing parameters**

Mapping mode	Generic
Blending mode	Mosaic
Texture size	4,096 x 4,096
Enable hole filling	Yes
Enable ghosting filter	No
UV mapping time	1 hours 51 minutes

Blending time	33 minutes 32 seconds
<b>Orthomosaic</b>	
Size	35,147 x 41,413
Coordinate system	WGS 84 (EPSG::4326)
Colors	3 bands, uint8
<b>Reconstruction parameters</b>	
Blending mode	Mosaic
Surface	Mesh
Enable hole filling	Yes
Processing time	58 minutes 46 seconds
<b>Software</b>	
Version	1.4.2 build 6205
Platform	Windows 64

Table 35. Processing parameters for all three aerial survey sections. If all surveys were identical in their report, the parameter is in the “All surveys” column, in blue cells. Otherwise, each section parameter definition is given, in yellow cells.

Parameter Type	Parameter Definition			
	All surveys	Section 1 of 3	Section 2 of 3	Section 3 of 3
<b>General</b>				
Cameras	690	-	-	-
Aligned cameras	690	-	-	-
Markers	16	-	-	-
Coordinate system	WGS 84 (EPSG::4326)	-	-	-
Rotation angles	Yaw, Pitch, Roll	-	-	-
<b>Point cloud: general</b>				
Points	1,275,831 of 1,443,858	-	-	-
RMS reprojection error	0.155823 (0.521424 px)	-	-	-

Max reprojection error	0.711538 (6.49469 px)	-	-	-
Mean key point size	3.19951 px	-	-	-
Point colors	3 bands, uint8	-	-	-
Key points	-	N/A	No	No
Average tie point multiplicity	-	N/A	2.44644	2.44644
Effective overlap	-	2.44644	N/A	N/A
<b>Point cloud: alignment parameters</b>				
Accuracy	High	-	-	-
Generic preselection	No	-	-	-
Reference preselection	Yes	-	-	-
Key point limit	40,000	-	-	-
Tie point limit	10,000	-	-	-
Adaptive camera model fitting	Yes	-	-	-
Matching time	36 minutes 59 seconds	-	-	-
Alignment time	8 minutes 0 seconds	-	-	-
<b>Point cloud: optimization parameters</b>				
Parameters	f, b1, b2, cx, cy, k1-k4, p1, p2	-	-	-

Adaptive camera model fitting	No	-	-	-
Optimization time	11 seconds	-	-	-
<b>Dense point cloud: general</b>				
Points	613,402,039	-	-	-
Point colors	3 bands, uint8	-	-	-
<b>Dense point cloud: reconstruction parameters</b>				
Quality	High	-	-	-
Depth filtering	Aggressive	-	-	-
Depth maps generation time	3 hours 5 minutes	-	-	-
Dense cloud generation time	1 hours 49 minutes	-	-	-
<b>Model: general</b>				
Faces	-	37,833,608	43,268,724	45,818,065
Vertices	-	18,926,192	21,643,112	22,917,190
Vertex colors	3 bands, uint8	-	-	-
Texture	-	N/A	4,096 x 4,096 x 88, 4 bands, uint8	4,096 x 4,096 x 87, 4 bands, uint8
<b>Model: reconstruction parameters</b>				
Surface type	Arbitrary	-	-	-
Source data	Dense	-	-	-

Interpolation	Enabled	-	-	-
Quality	High	-	-	-
Depth filtering	Aggressive	-	-	-
Face count	-	37,833,608	43,268,724	45,818,065
Processing time	-	8 hours 37 minutes	4 hours 32 minutes	5 hours 16 minutes
<b>Model: texturing parameters</b>				
Mapping mode	-	N/A	Generic	Generic
Blending mode	-	N/A	Mosaic	Mosaic
Texture size	-	N/A	4,096 x 4,096	4,096 x 4,096
Enable hole filling	-	N/A	Yes	Yes
Enable ghosting filter	-	N/A	No	No
UV mapping time	-	N/A	1 hours 10 minutes	1 hours 51 minutes
Blending time	-	N/A	32 minutes 13 seconds	33 minutes 32 seconds
<b>DEM: general</b>				
Size	-	18,162 x 21,645	18,265 x 21,896	N/A
Coordinate system	-	WGS 84 (EPSG::4326)	WGS 84 (EPSG::4326)	N/A
<b>DEM: reconstruction parameters</b>				

Source data	-	Dense cloud	Mesh	N/A
Interpolation	-	Enabled	Enabled	N/A
Processing time	-	5 minutes 44 seconds	4 minutes 30 seconds	N/A
<b>Orthomosaic: general</b>				
Size	-	32,736 x 39,510	35,438 x 41,464	35,147 x 41,413
Coordinate system	WGS 84 (EPSG::4326)	-	-	-
Colors	3 bands, uint8	-	-	-
<b>Orthomosaic: reconstruction parameters</b>				
Blending mode	Mosaic	-	-	-
Surface	-	DEM	DEM	Mesh
Enable hole filling	Yes	-	-	-
Processing time	-	23 minutes 26 seconds	14 minutes 0 seconds	58 minutes 46 seconds
<b>Software</b>				
Version	-	1.4.1 build 5925	1.4.2 build 6205	1.4.2 build 6205
Platform	Windows 64	-	-	-

## Summary

This report described procedures, the estimated level of effort for the M-Range survey, and supporting data to provide foundational survey accuracies. We merged data sets gathered at the ground level with drone-based aerial survey techniques. In addition, we demonstrated the capability to merge point clouds derived from both photogrammetry and LiDAR systems.

IST developed tools to ingest the high-quality source data from the M-Range into the Unity game engine to render a realistic virtual environment. This report outlines some of the best practices and lessons that were learned during the M-Range data collection and processing effort.

If future opportunities arise, IST would employ a superior GPS system such as our TopCon Hyper-VR system which is capable of finer GNSS precision and would lend itself toward higher-quality terrain accuracy. Additional capabilities have arisen that allow the LiDAR to be collected on the move, which reduces time constraints while on-site. Furthermore, we should explore alternative rendering systems that support the One World Terrain objectives.

## Appendix A

Appendix A provides images taken from the survey execution.

Figure 27. Point cloud produced using laser scans and photos taken from a quadcopter

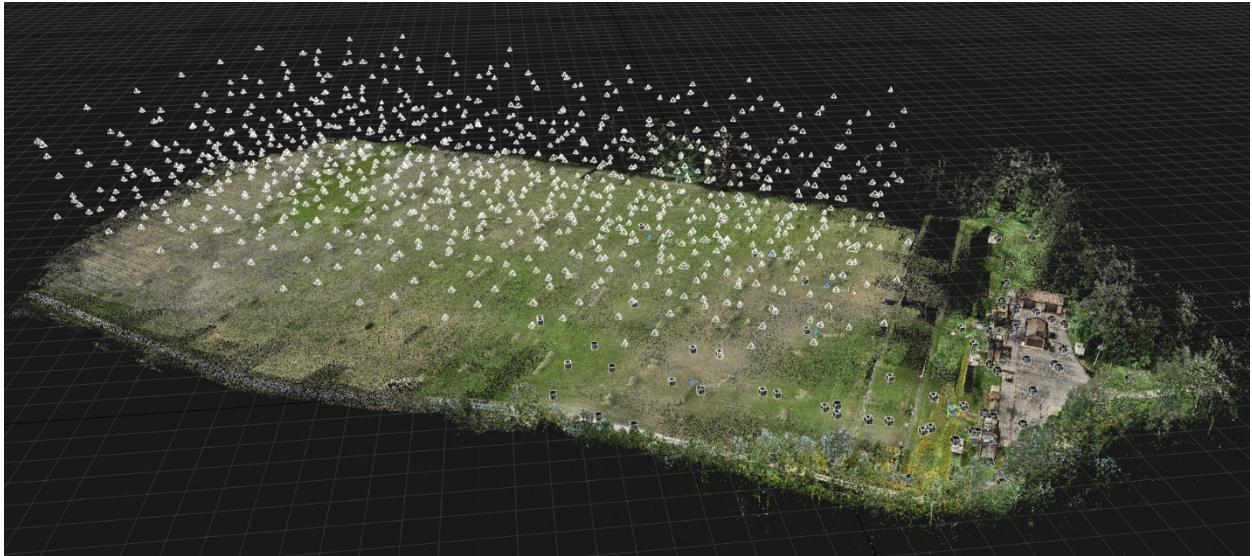


Figure 28. Final M-Range scene, as visualized in the Unity game engine



Figure 29. Close-up showing detail of DSM created from aerial photogrammetry



Figure 30. DSM and orthographic imagery derived from aerial photogrammetry

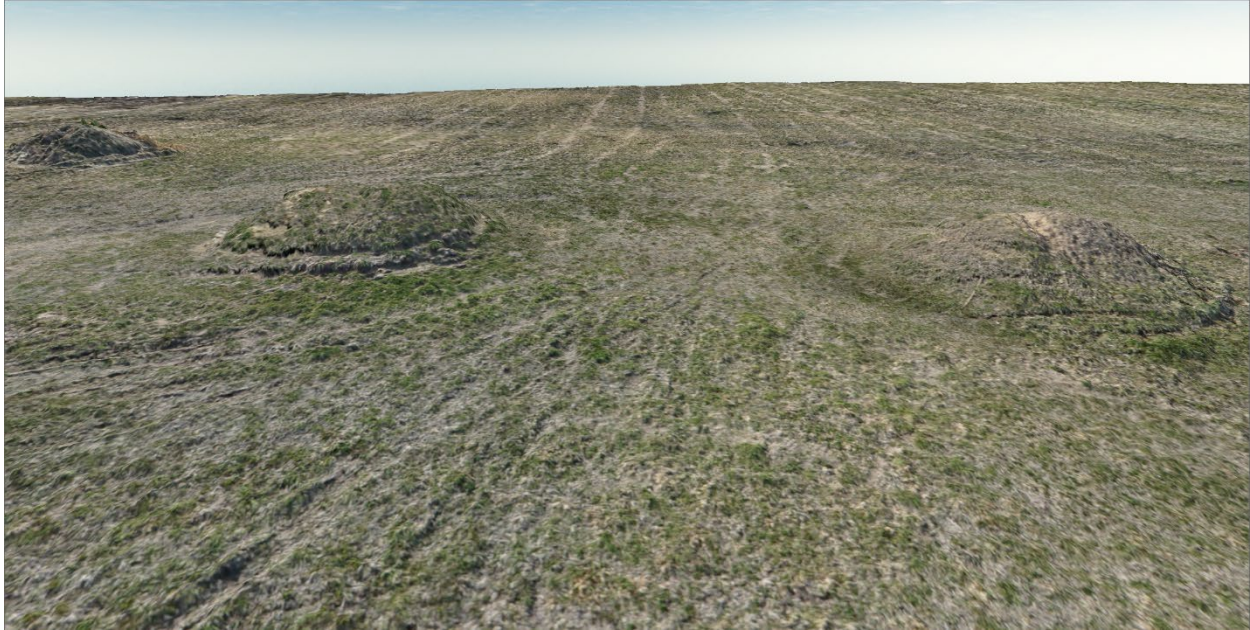


Figure 31. Example GCP captured from quadcopter



Figure 32. Example of DSM created from ground survey photogrammetry

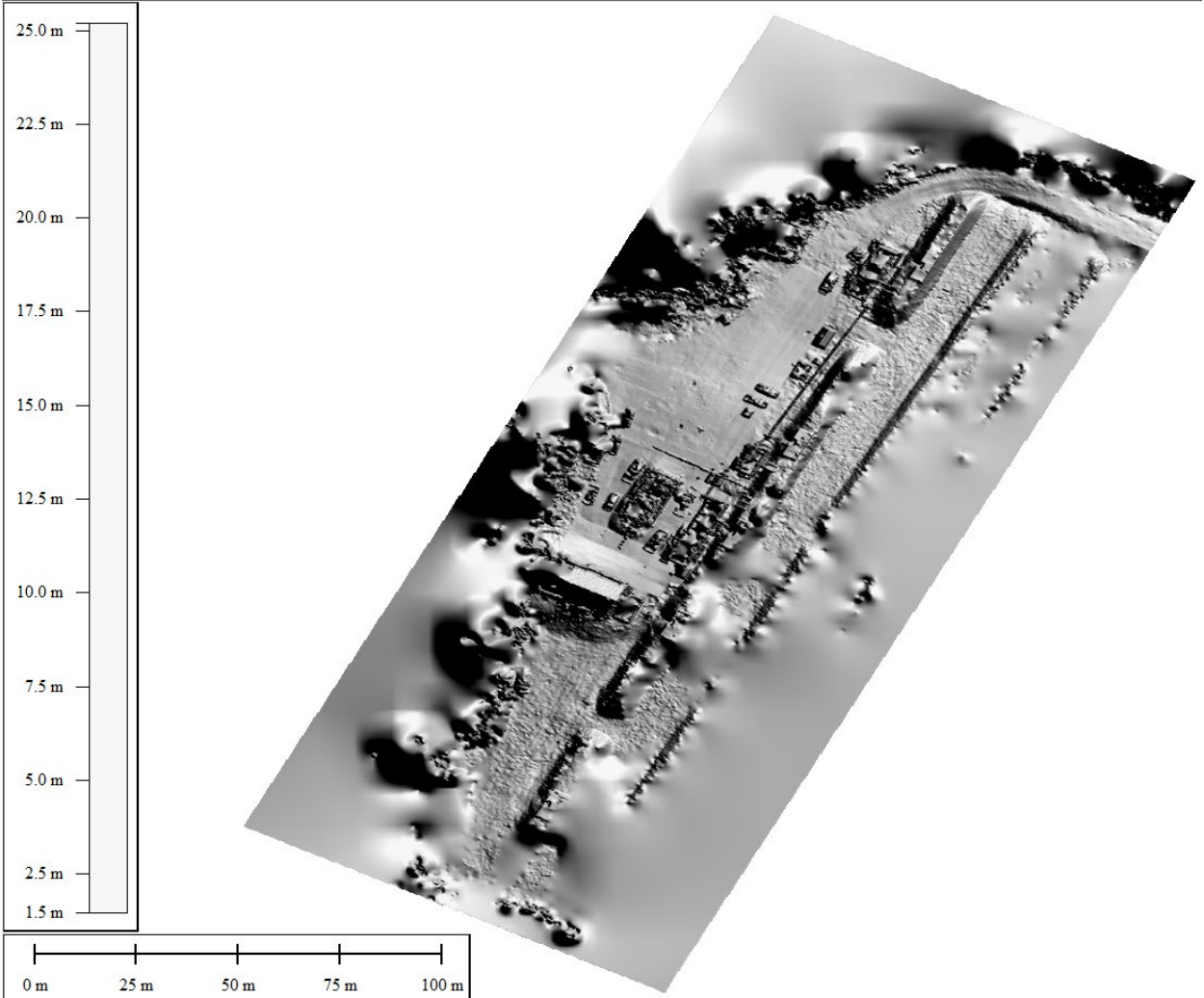
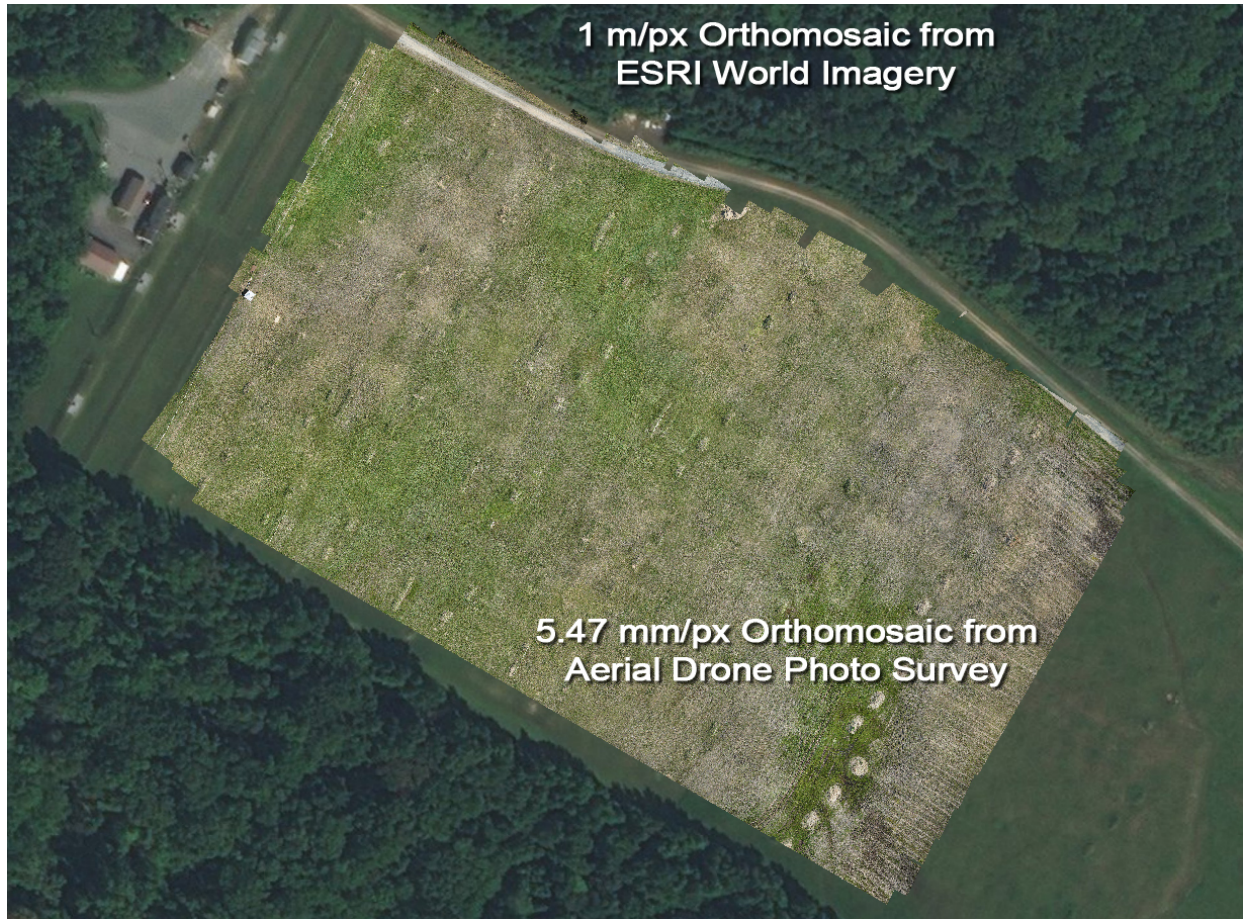


Figure 33. Comparison of aerial drone survey vs. orthomosaic available from United States Geological Survey (USGS)



Figure 34. Comparison of aerial drone survey vs. orthomosaic available from Environmental Systems Research Institute (ESRI) World Imagery



**List of Abbreviations**

3D	3-Dimensional
AOI	Area Of Interest
APG	Aberdeen Proving Grounds
CSV	Comma Separated Values
DEM	Digital Elevation Model
DSM	Digital Surface Model
EPSG	European Petroleum Survey Group
ESRI	Environmental Systems Research Institute
GCP	Ground Control Point
GPS	Global Positioning System
IST	Institute for Simulation and Training
OPUS	Online Positioning User Service
px	Pixel
RINEX	Receiver Independent Exchange Format
NATO	North Atlantic Treaty Organization
RINEX	Receiver Independent Exchange Format
RMS	Root Mean Square
RMSE	Root Mean Square Error
RTK	Real-Time Kinematic
USGS	United States Geological Survey
UTM	Universal Transverse Mercator

WGS

World Geodetic System