BEACON AVIATION INC.

Aerial Triangulation Accuracy Assessment

Prepared by

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Endorsed by

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ASPRS Certified Photogrammetrist

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Letter of Endorsement

GMail by Google

Endorsement

Jolyon D Thurgood <jolyon@gisimage.com> Mon, Oct 24, 2016 at 11:21
To: Marty Gould <marty@beaconaviationinc.com>
Cc: Taylor Gould <Taylor@beaconaviationinc.com>

Marty,
Having reviewed the report "Aerial Triangulation Accuracy Assessment" prepared by Beacon Aviation and being familiar with the hardware and software components being used in your aerial mapping activities, I can fully endorse the findings of the report with regard to providing highly precise sub-pixel levels of accuracy through both conventional aerial triangulation methods, utilizing ground control points, and direct georeferencing, which can eliminate the need for ground control points. The level of accuracy reported indicates a highly robust photogrammetric model which is the basis for mapping products produced from such aerial imagery, and also reflects the attention to detail throughout the full workflow, including flight operations and ground processing, which is necessary to maintain such accuracies.

Sincerely,
Jolyon D Thurgood PhD
ASPRS Certified Photogrammetrist / Mapping Scientist / Remote Sensing Scientist

Principal, gisIMAGE
San Francisco

1. Introduction

This document describes an aerial triangulation accuracy assessment of Beacon Aviation, Inc.'s Airborne Mapping System. The assessment was conducted by Taylor Gould, Beacon Aviation's GeoTech, with the use of an independent surveying company, Stanger Surveying, LLC.

2. Method

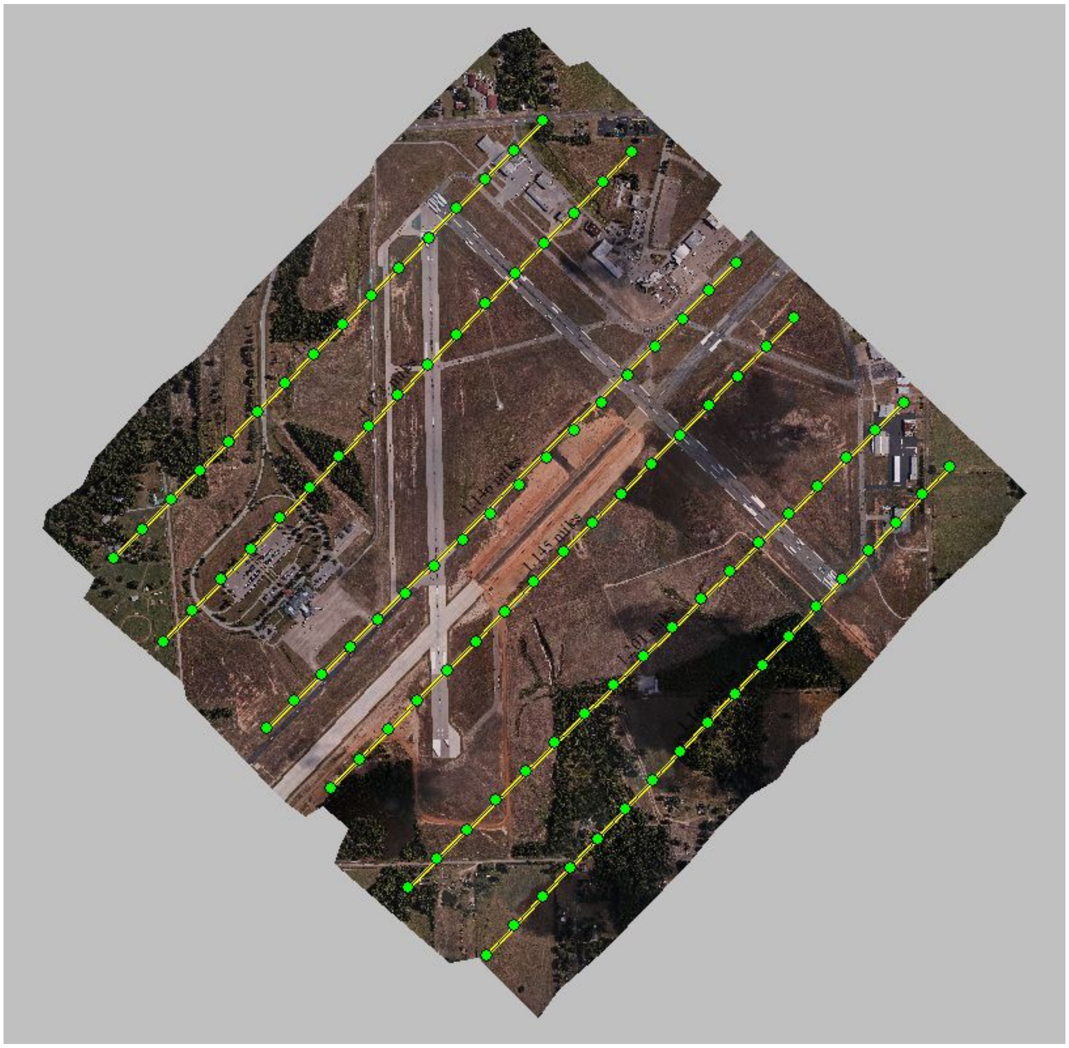
The assessment took place between July and August 2016 and included the following steps:

- Location of a suitable test area
- Flight planning
- Two independent Metric ground calibrations for the Aerial Mapping camera
- Measurement of ground control points and check control points
- Flight and image/EO capturing
- Processing EO Data
- Processing RAW images to TIFFs
- Aerial triangulation
- Accuracy assessment

2.1. Selection of Test Area

The test area that was selected is a flat Airport, urban area. It was selected for operational flight reasons, ease of generating ground control points and check control points, as well as additional data used in the KTYR Airport Runway Extension. Figure 1 – Flight lines and image locations show an overlay of the flight lines and image locations on the ground. The area elevation is between 490 to 575 Feet with an average of 540 feet above ground level. The flight was planned such that there would be 60% minimum forward overlap and 30% minimum sidelap between the images.

Figure 1: Flight lines and image locations



2.2. Flight Planning

The flight was planned with the following values:

• Flight height: 1,300 feet above the ellipsoid to ensure a GSD of 2 Inch(5 cm) for the entire area

• Aircraft speed: 120 knots

• Time between exposures: about two seconds

• Flight line direction: NE – SW

2.3. Metric Ground Calibration of Camera

The camera was calibrated by Phase One Industrial using the standard Phase One calibration protocol, as well as, Beacon Aviation's In-House Calibration System.

Both Calibration reports available as attachments:
"PhaseOne_08-04-15_BAI_Distortion_Table" - "iXA-R Calibration Certificate_Phase_One_Oodi".

3. Measurement of Control Points

Twenty-Four control points (CPs) were measured with real-time kinematics (RTK) GNSS by Stanger Surveying LLC with an accuracy of 8 mm in X, Y and 15 mm in Z. Some were used as ground control points (GCPs) and some as check control points (CCPs).

The GCP distribution over the block was planned to serve the block accuracy and to achieve flexibility in switching between GCPs and CCPs during the block accuracy assessment. Switching control points to check control points was used in evaluation of the stability of the aerial triangulation. It was also used in solution of models and small blocks.

CCPs were measured on flat areas, usually on street markings or well-defined marks.

Figure 2: Ground control points

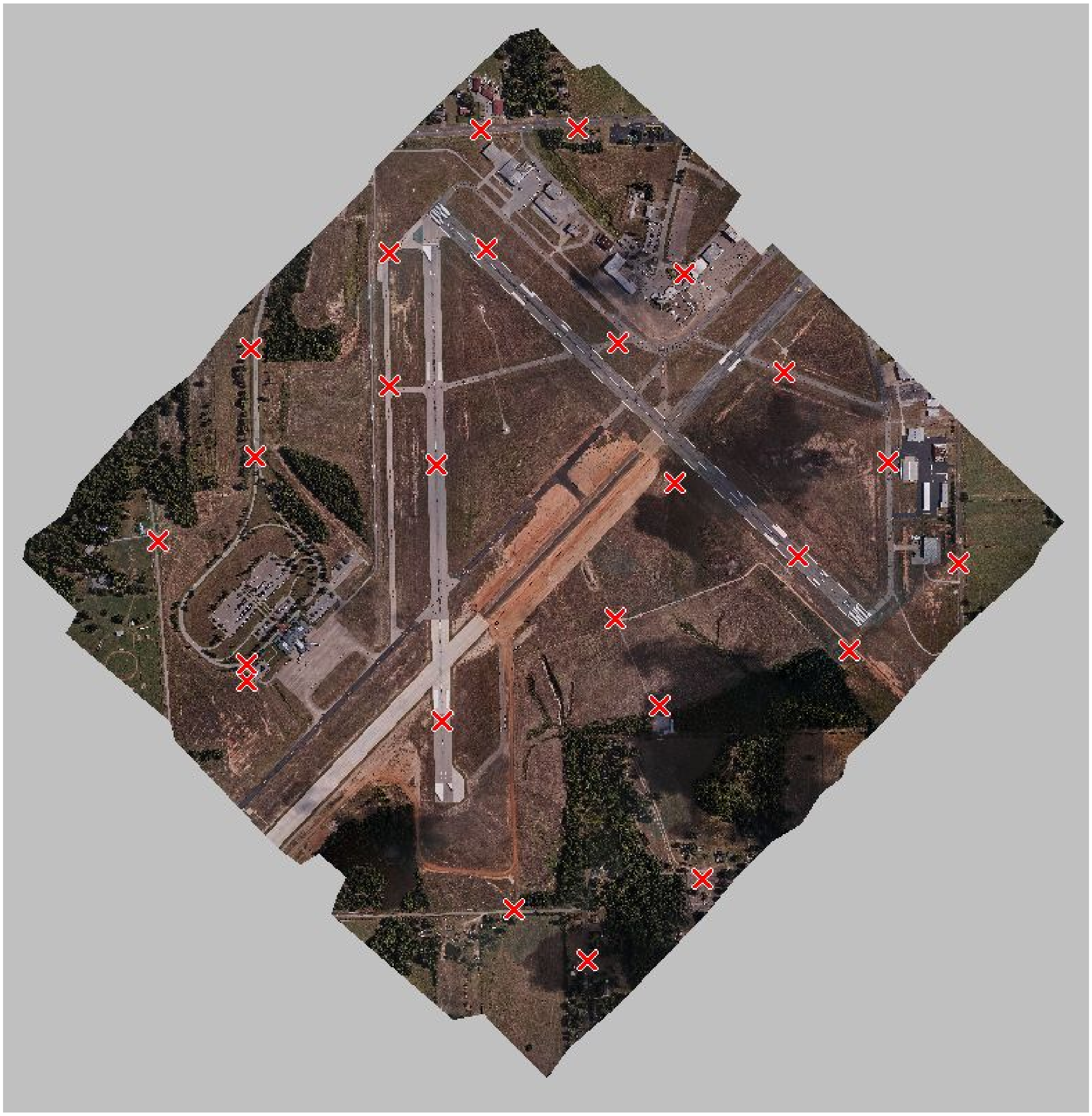


Figure 3: Control and checkpoints spread on images footprint

GCPs = X, CheckPoints = X

3.1. Photogrammetric Processing

A full aerial triangulation was performed using Beacon Aviation's in house photogrammetric software.

• The Australis values were used in the calibration of the digital camera model.

• The EO data was processed and each capture point linked to its corresponding image.

• The GCPs were identified on the images and the block was solved in a few iterations.

• A comparison of checkpoints between the models was done.

• A small block was solved and checkpoints accuracy was evaluated.

• The aerial triangulation was done using a set of GCPs, testing the accuracy with a set of CCPs.

• Several GCPs were changed into CCPs and the accuracy was reevaluated to check the stability of the aerial triangulation.

• In the final scenario all GCPs were changed into CCPs and the accuracy was once again reevaluated to check stability of the enhanced Direct GeoReferenced Data through the aerial triangulation software.

GCPs = X, CheckPoints = X

4. Results

4.1. Accuracy with 24 GCPs

Using 24 ground control points shown in figure 4: Control points spread on image footprints. The accuracy results are shown below.

Figure 4: Triangulation summary - 24 GCP's

GCPs = X, CheckPoints = X

```
                              GCP Summary
=====================================================================
Total number of GCPs:                                              24
Number of used GCPs:                                               24
Number of discarded GCPs:                                           0
Minimum (non-zero) number of observations per GCP:                  3
Average number of observations per GCP:                           6.0
Maximum number of observations per GCP:                             8
Min, max pixel residual error:                           [0.00, 2.36]
RMS pixel residual error:                                        0.43
Average pixel residual error:                                    0.28
Standard deviation of pixel residual error:                      0.15
Min, max XYZ residual error:                           [0.009, 0.205]
RMS XYZ residual error:                                         0.073
Average XYZ residual error:                                     0.053
Standard deviation of XYZ residual error:                       0.050
Average correction (bias):                   (-0.000, -0.008, -0.031)
---------------------------------------------------------------------
```

Note: All values are in U.S. Feet unless specified as pixels.

24 GCP Residuals:

RMSx= 0.20 Inch (0.52 cm)

RMSy= 0.43 Inch (1.11 cm)

RMSz= 0.73 Inch (1.86 cm)

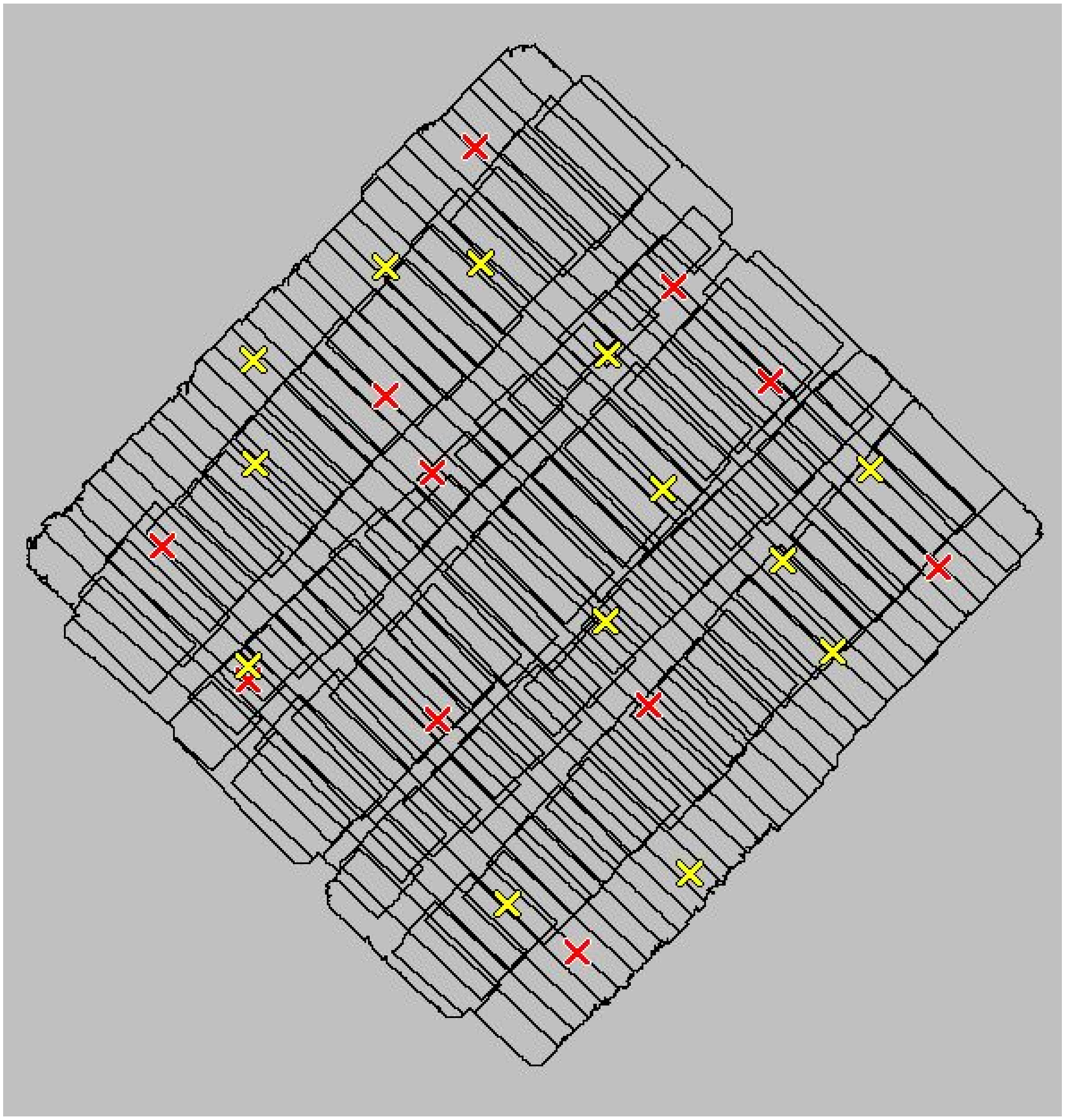
For a GSD of 2 Inch(5 cm) this result is better than half a pixel.

4.2. Stability Analysis

4.2.1. Reduction of Thirteen Ground Control Points

Ground control points tying flight line one to two and flight line five to six were removed from the photogrammetric process, leaving only one common ground control point between five and six lines and two common ground control points between one and two lines. Figure 5 shows the ground control points and Checkpoints.

Figure 5 - Thirteen GCP's converted to CheckPoints for stability evaluation



GCPs = **X**, CheckPoints = **X**

Using 11 ground control points and 13 checkpoints as shown in Figure 5, the accuracy results are:

```
                         Check Point Summary
======================================================================
Total number of check points:                                       13
Number of used check points:                                        13
Number of discarded check points:                                    0
Minimum (non-zero) number of observations per check point:           4
Average number of observations per check point:                    6.2
Maximum number of observations per check point:                      8
Min, max pixel residual error:                           [0.11, 4.09]
RMS pixel residual error:                                         1.12
Average pixel residual error:                                     0.93
Standard deviation of pixel residual error:                       0.49
Min, max XYZ residual error:                           [0.039, 0.418]
RMS XYZ residual error:                                          0.194
Average XYZ residual error:                                      0.166
Standard deviation of XYZ residual error:                        0.101
----------------------------------------------------------------------
```

Note: All values are in U.S. Feet unless specified as pixels.

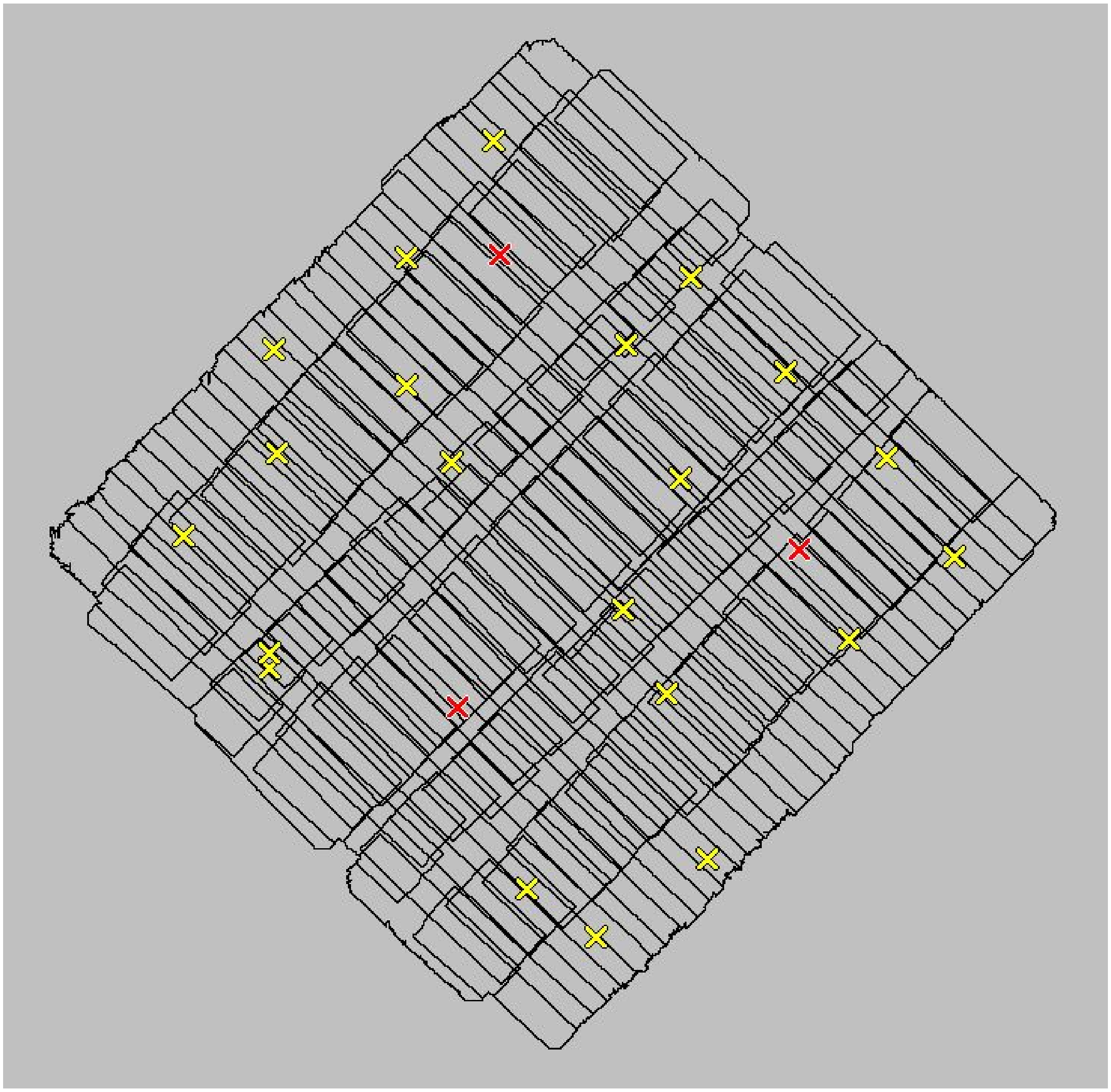
11 GCPôs RMS Residual	**13 Checkpointôs RMS Residual**
RMSx= 0.39 Inch (0.98 cm)	**RMSx= 0.07 Inch (0.17 cm)**
RMSy= 0.02 Inch (0.04 cm)	**RMSy= 1.57 Inch (3.10 cm)**
RMSz= 0.04 Inch (0.10 cm)	**RMSz= 0.18 Inch (0.46 cm)**

After converting 13 GCPs to check points the RMS accuracy for X,Y, and Z remains sub-pixel.

4.2.2. Reduction of Twenty-One Ground Control Points

To further check the stability of the solution, Only 3 Control Points were used to tie the entire project together. Figure 6 shows the ground control points and the Checkpoints being used.

Figure 6: Six GCPs canceled for stability evaluation



GCPs = **X**, CheckPoints = **X**

Using 3 ground control points and 21 checkpoints as shown in Figure 7: Triangulation summary — 3 GCP's are:

```
                     Check Point Summary
======================================================================
Total number of check points:                                       21
Number of used check points:                                        21
Number of discarded check points:                                    0
Minimum (non-zero) number of observations per check point:           3
Average number of observations per check point:                    5.9
Maximum number of observations per check point:                      8
Min, max pixel residual error:                            [0.03, 3.66]
RMS pixel residual error:                                         1.22
Average pixel residual error:                                     1.07
Standard deviation of pixel residual error:                       0.35
Min, max XYZ residual error:                            [0.051, 0.381]
RMS XYZ residual error:                                          0.239
Average XYZ residual error:                                      0.227
Standard deviation of XYZ residual error:                        0.074
----------------------------------------------------------------------
```

Note: All values are in U.S. Feet unless specified as pixels.

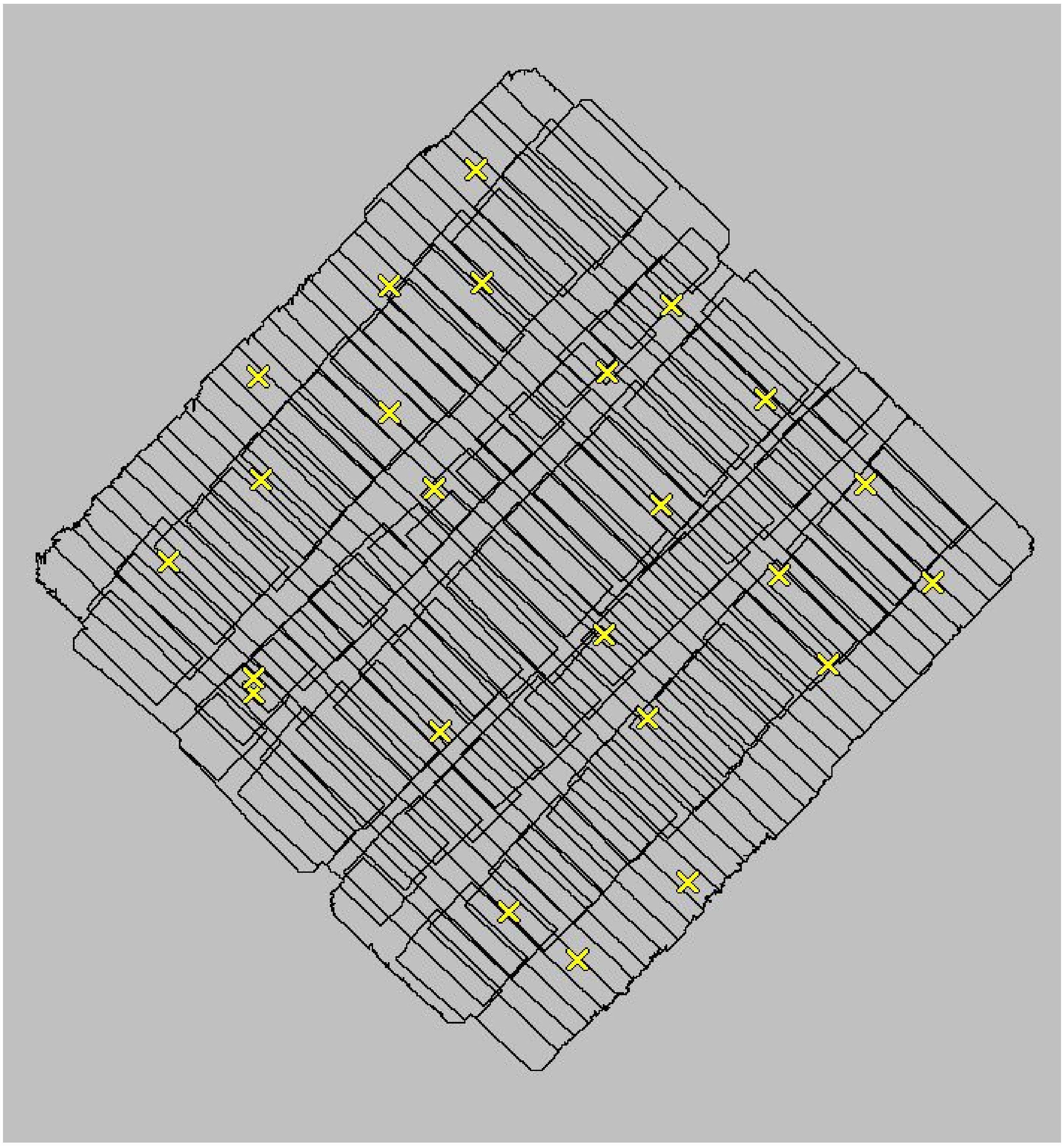
3 GCP's RMS Residual	**21 Checkpoint's RMS Residual**
RMSx= 0.36 Inch (0.91 cm)	**RMSx= 1.22 Inch (3.11 cm)**
RMSy= 0.04 Inch (0.11 cm)	**RMSy= 1.64 Inch (4.18 cm)**
RMSz= 0.36 Inch (0.84 cm)	**RMSz= 2.01 Inch (5.09 cm)**

When converting Twenty-One control points to Checkpoints that tie between the flight lines, the RMS error in Z increased to one pixel, while the RMS error in X and Y remained well below a pixel.

4.2.3 Direct GeoReferencing (Converting All Control Points To Checkpoints)

In our final stability test we converted all the Control points to Checkpoints. This left the build with Zero Ground Control Points and Twenty-Four Checkpoints. Figure 8 shows the locations of the Checkpoints and that there were Zero Ground Control Points used in the Direct GeoReferencing Triangulation.

Figure 7: Zero GCPs and Twenty-Four Checkpoints



GCPs = X, CheckPoints = X

Using Direct Geo-referencing, meaning zero ground control points and 24 checkpoints as shown in Figure 7: Triangulation summary:

```
                          Check Point Summary
======================================================================
Total number of check points:                                       24
Number of used check points:                                        24
Number of discarded check points:                                    0
Minimum (non-zero) number of observations per check point:           3
Average number of observations per check point:                    6.0
Maximum number of observations per check point:                      8
Min, max pixel residual error:                            [0.03, 4.42]
RMS pixel residual error:                                         1.28
Average pixel residual error:                                     1.10
Standard deviation of pixel residual error:                       0.47
Min, max XYZ residual error:                            [0.066, 0.494]
RMS XYZ residual error:                                          0.251
Average XYZ residual error:                                      0.231
Standard deviation of XYZ residual error:                        0.097
----------------------------------------------------------------------
```

Note: All values are in U.S. Feet unless specified as pixels.

GCP’s RMS Residual:	**24 Checkpoint’s RMS Residual:**
RMSx= N/A	**RMSx= 1.17 Inch (2.97 cm)**
RMSy= N/A	**RMSy= 2.00 Inch (5.09 cm)**
RMSz= N/A	**RMSz= 2.23 Inch (5.67 cm)**

By removing all Ground Control Points from the Triangulation and converting them to check points, the system was forced to rely solely on airborne data (External Orientation, Internal Orientation, and Relative Orientation). And in this rigorous test the residuals grew only slightly above a pixel level accuracy in the ‘Z’ while the ‘X’ and ‘Y’ remained within a pixel.

5. Conclusion

The aerial triangulation accuracy results of Beacon Aviation, Inc.'s Airborne Mapping System are displayed in the Matrix below.

Matrix of Assessment Scenario Results:

	4.1	4.2.1	4.2.2	4.2.3
	24 GCP/0 CCP	**11 GCP/13 CCP**	**3 GCP/21 CCP**	**0 GCP/24 CCP**
RMSx	0.20 Inch (0.52 cm)	0.07 Inch (0.17 cm)	1.22 Inch (3.11 cm)	1.17 Inch (2.97 cm)
RMSy	0.43 Inch (1.11 cm)	1.57 Inch (3.10 cm)	1.64 Inch (4.18 cm)	2.00 Inch (5.09 cm)
RMSz	0.73 Inch (1.86 cm)	0.18 Inch (0.46 cm)	2.01 Inch (5.09 cm)	2.23 Inch (5.67 cm)

Note: All RMS values are based on Checkpoint, except for scenario 4.1.

The 24 GCP Block result is better than a 0.3 pixel accuracy and shows that Beacon Aviation, Inc.'s Airborne Mapping System is suitable for accurate mapping work.

The aerial triangulation results show that reducing or completely removing the GCPs can be done in the aerial triangulation with minimal influence on the block accuracy results.

Figure 8: 3D view of Capture Points, Flight Lines, GCPs, and DTM