The Effect of Datum Constraints for Terrestrial Laser Scanner Self-Calibration

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Presentation Outlines

- Calibration of TLS.
- Experiment.
- Results.
- Conclusions.

Calibration

- The needs of calibration for TLS:
  i. Similar to other measurement sensors, results from TLS also impaired with errors.
  ii. Standardized calibration routines exist for the traditional geodetic and photogrammetric instruments.
  iii. Requirement of accurate data for surveying applications such as deformation, industrial survey and reverse engineering.

Calibration

- Based on Böhler et al. (2003), Gordon (2005), Schulz (2009), Lichti (2007) and Reshetyuk (2009), error sources can be summarised into two groups as follows:
  i. Internal which consist of errors from instrumental, data and resolution.
  ii. External that might include object related, environmental and georeferencing errors.

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Calibration

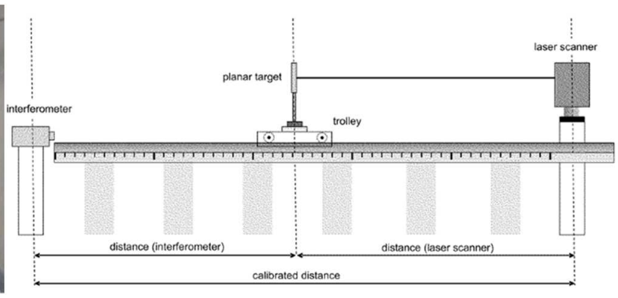
- Two approaches available to investigated those errors in TLS measurement, either separately (component calibration) or simultaneously (system calibration) based on statistical analysis.

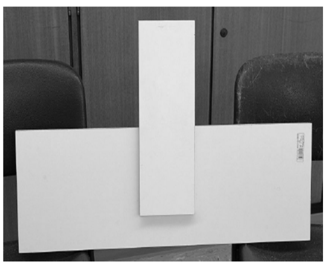
Calibration of Terrestrial Laser Scanner

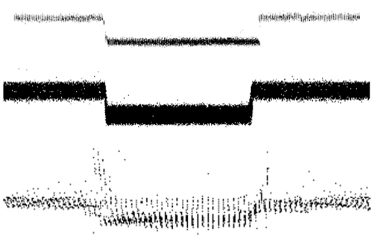
- Component Calibration
  - Intrumental Errors
  - Distance Measurement System
  - Angle Measurement System
  - Others
- System Calibration
  - Self-Calibration
    - Point-Based
    - Feature-Based

Calibration

- Component Calibration.







Calibration

- System Calibration.

Can be carried out either using point-based (a) or feature-based (b) self-calibration.

(a) (b)

Calibration

- Self-Calibration.

The functional model of TLS observation augmented with systemetic error model can be expressed as follows (Lichti, 2007):

$$\text{Range}, r = \sqrt{x^2 + y^2 + z^2} + \Delta r$$

$$\text{Horizontal direction}, \varphi = \tan^{-1}\left(\frac{x}{y}\right) + \Delta\varphi$$

$$\text{Vertical angle}, \theta = \tan^{-1}\left(\frac{z}{\sqrt{x^2 + y^2}}\right) + \Delta\theta$$

Where,

$\Delta r, \Delta\varphi, \Delta\theta$= Respective systematic error model for each observation

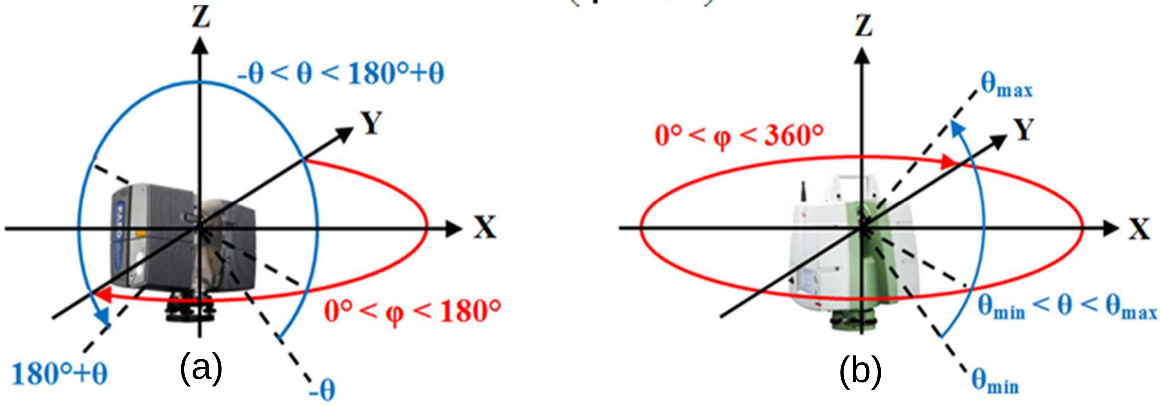
x, y, z = Coordinates of targets in scanner coordinates system

Calibration

- Self-Calibration.

Modified model for Panoramic scanner.

$$\varphi = \tan^{-1}\left(\frac{x}{y}\right) - 180^\circ \qquad \theta = 180^\circ - \tan^{-1}\left(\frac{z}{\sqrt{x^2+y^2}}\right)$$



Angular observation ranges for (a) Panoramic scanner and (b) Hybrid scanner.

Calibration

- Self-Calibration.

x, y, z from previous equation are the coordinates of target (i) from object space to scanner space (j), which are related to object space through the rigid body transformation (Lichti, 2007):

$$\begin{bmatrix} x_{ij} \\ y_{ij} \\ z_{ij} \end{bmatrix} = R(\omega_j, \phi_j, \kappa_j)\left\{\begin{bmatrix} X_i \\ Y_i \\ Z_i \end{bmatrix} - \begin{bmatrix} X_{sj} \\ Y_{sj} \\ Z_{sj} \end{bmatrix}\right\}$$

Where,

$[X_{sj}, Y_{sj}, Z_{sj}]$ = Translation parameters

$R(\omega_j, \phi_j, \kappa_j)$ = Rotation matrix

$[X_i, Y_i, Z_i]$ = Coordinate of targets based on global system

$[x_{ij}, y_{ij}, z_{ij}]$ = Coordinate of targets based on scanner system

Calibration

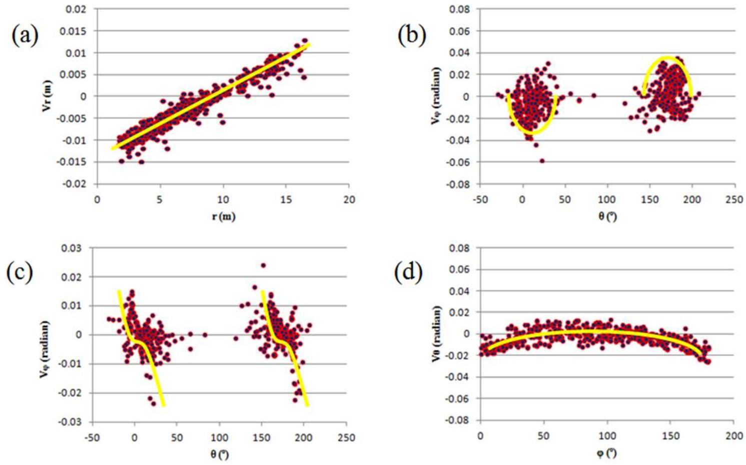
- Self-Calibration.

Systematic error models

$$\Delta r = a_0$$

$$\Delta\varphi = b_0 \sec\theta + b_1 \tan\theta$$

$$\Delta\theta = c_0$$



Where,

a_0 = Constant error
b_0 = Collimation axis error
b_1 = Trunnion axis error
c_0 = Vertical circle index error

Calibration

- Self-Calibration.

As a result, this study implemented the statistical test to investigate the significant of the parameter to the scanner observations. Known as t-test, the analysis is carried out using formula :

$$t = \frac{X}{\sigma_X}$$

Where,

X = Parameter to be evaluate
σ_X = Standard deviation of parameter

The hypothesis of the test is:

- H_0 : The parameter is not significant to the scanner observation.
- H_A : The parameter is significant to the scanner observation.

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Calibration

- Self-Calibration.

Datum defects (minimum constraints)

Removing matrix element for minimum constraints can be expressed as follows:

Removed

$$ {}_nA_u = \begin{bmatrix} A_{EO} & A_{CP} & A_{TG} \end{bmatrix} = \begin{bmatrix} A_{EO_1} & 0 & 0 & A_{CP} & A_{TG} \\ 0 & A_{EO_2} & 0 & A_{CP} & A_{TG} \\ 0 & 0 & A_{EO_n} & A_{CP} & A_{TG} \end{bmatrix} $$

New design matrix A without EO parameters for first scanner station will look as:

$$ {}_nA_u = \begin{bmatrix} 0 & 0 & A_{CP} & A_{TG} \\ A_{EO_2} & 0 & A_{CP} & A_{TG} \\ 0 & A_{EO_n} & A_{CP} & A_{TG} \end{bmatrix} $$

Calibration

- Self-Calibration.

Datum defects (inner constraints)

Application of inner constraints for this study has been adopted based on Lichti (2007).

$$ G_o^T = \left(\begin{array}{ccc|ccc|ccc} 1 & 0 & 0 & 1 & 0 & 0 & 1 & 0 & 0 \\ 0 & 1 & 0 & 0 & 1 & 0 & 0 & 1 & 0 \\ 0 & 0 & 1 & 0 & 0 & 1 & 0 & 0 & 1 \\ 0 & Z_1 & -Y_1 & 0 & Z_2 & -Y_2 & 0 & Z_n & -Y_n \\ -Z_1 & 0 & X_1 & -Z_2 & 0 & X_2 & -Z_n & 0 & X_n \\ Y_1 & -X_1 & 0 & Y_2 & -X_2 & 0 & Y_n & -X_n & 0 \end{array} \right) $$

The bordered system of normal equation follows from standard parametric least square is given by:

$$ N \quad \hat{X} \quad + \quad U \quad = \quad 0 $$

$$ \begin{bmatrix} A^TPA & G_o^T \\ G_o & 0 \end{bmatrix} \begin{bmatrix} \hat{X}_{EO} \\ \hat{X}_{CP} \\ \hat{X}_{TG} \\ k_c \end{bmatrix} + \begin{bmatrix} A^TPL \\ 0 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix} $$

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Calibration

- Self-Calibration.

Computation of least square adjustment using parametric equation for non-linear model.

$$A = \left.\frac{\delta F}{\delta \hat{X}^a}\right|_{\hat{X}^a = X^0}$$

$$L = L^0 - L^b$$

$$N = A^T P A$$

$$U = A^T P L$$

$$P = \sigma_0^2 \Sigma_L^{-1}$$

$$\hat{X} = -N^{-1}U = -(A^T P A)^{-1}.A^T P L$$

$$\hat{X}^a = X^0 + \hat{X}$$

$$\hat{V} = A\hat{X} + L$$

$$\hat{L}^a = L^b + \hat{V}$$

$$\hat{\sigma}_0^2 = \frac{V^T P V}{n - u}$$

$$\Sigma_{\hat{X}^a} = \sigma_0^2 (A^T P A)^{-1}$$

$$\Sigma_{\hat{L}^a} = \sigma_0^2 A (A^T P A)^{-1} A^T$$

$$\Sigma_V = \sigma_0^2 \left[P^{-1} - A(A^T P A)^{-1} A^T\right]$$

Where,

V = Residual

A = Design matrix

L^0 = Approximate observation (calculated from approximate parameters)

L^b = Observation values

$\hat{X}$ = Correction to the approximate parameters = $\hat{X}^a - X^0$

X^0 = Approximate parameters

N = Coefficient matrix

$\hat{X}^a$ = Adjusted parameters

$\hat{\sigma}_0^2$ = A posteriori variance factor

$\Sigma_{\hat{X}^a}$ = Cofactor matrix for adjusted parameters

$\Sigma_{\hat{L}^a}$ = Cofactor matrix for adjusted observations

Σ_V = Cofactor matrix for residual

Calibration

- Self-Calibration.

According to Lichti (2007), requirement for network design are as follows:

i. Need large elevation angle range:
   - Floor and ceiling points for trunnion axis error.
   - Points in front and behind the scanner for collimation axis error.

ii. Need at least two locations and a variety of ranges for rangefinder offset and cyclic errors.

iii. High redundancy (therefore many targets) needed so that during the exploratory data analyses trends in residual could be safely assumed to be due to unmodelled systematic errors.

iv. Orthogonal scans from same nominal location as an additional measure to de-correlate EO and APs, a technique borrowed from photogrammetric camera calibration.

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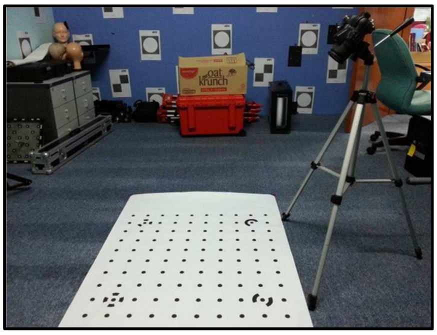
Experiments

- According to Reshetyuk (2009), in camera self-calibration, the used of inner constraints has an unfavourable property of increasing the correlations between calibration and exterior orientation parameters. While employing minimum constraints tends to cause high correlation between calibration parameters and object points.



Experiments

- With intention to investigate the effect of datum constraints in TLS self-calibration, this study has performed calibration for Faro Focus 3D.
- To ensure the quality of results obtained, optimise network configuration (Lichti, 2007) was adopted during data collection.
- Self-calibration bundle adjustment was carried out using both datum constraints and parameter correlations were extracted for further evaluation and analysis.

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Experiments

1. Self-Calibration

   - Self-calibration has been performed using Faro Focus 3D at FGRE laboratory with dimensions 9m (length) x 7m (width) x 2.6m (height).
   - There are 123 planar targets being distributed to the four walls and ceiling based on condition as stated by Lichti (2007).
   - Seven scan stations have been used to capture the targets.
   - Bundle adjustment has been performed with precision setting based on the accuracy of each scanner.
   - After four iterations, bundle adjustment process has converged.

Experiments

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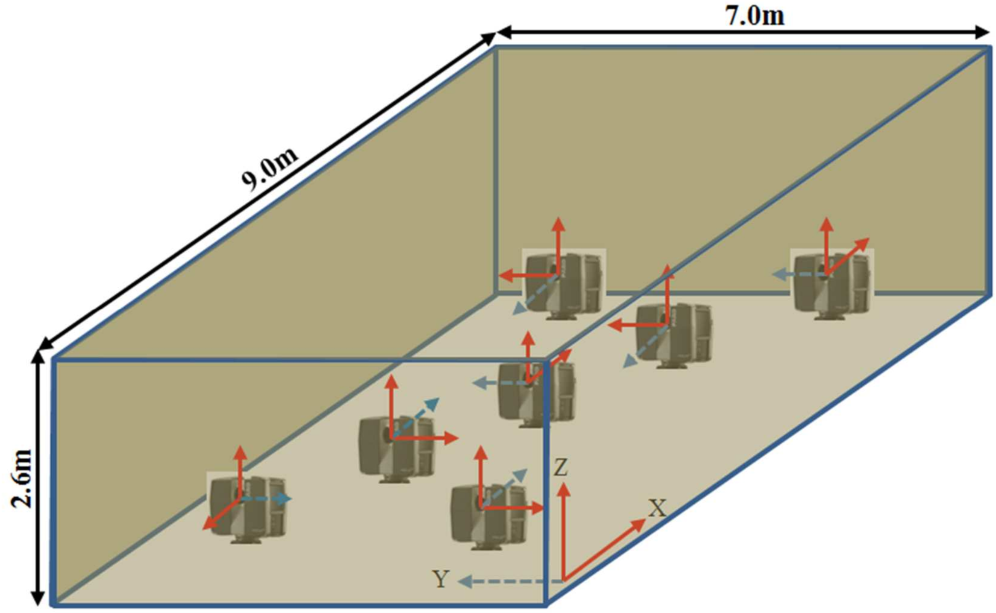
Experiments

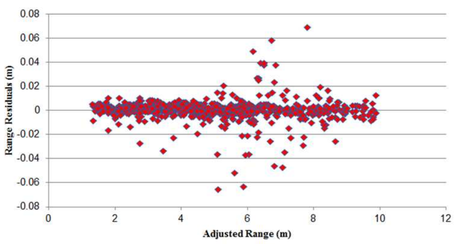
- Network Configuration

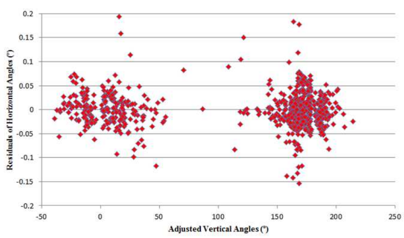


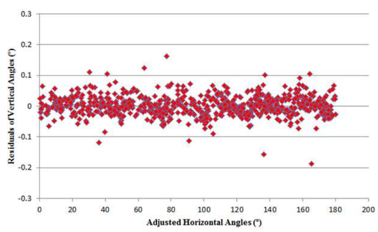
Results

1. Self-Calibration
   - Calibration parameters and their standard deviations (obtained using both datum constraints).

Calibration Parameters	$a_0 \pm \sigma_{a_0}$	$b_0 \pm \sigma_{b_0}$	$b_1 \pm \sigma_{b_1}$	$c_0 \pm \sigma_{c_0}$
Panoramic (mm/")	-1.3 ± 0.9	-14.3 ± 2.5	-35.2 ± 7.5	-24.1 ± 3.2







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Results

- Statistical Analysis

Number of scanner station		7
Critical value for 't' (95%)		1.645
Calibration Parameters	**Calc. 't'**	**Results**
Constant error (a_0)	1.44	Not Significant
Collimation axis error (b_0)	5.72	Significant
Trunnion axis error (b_1)	4.69	Significant
Vertical circle index error (c_0)	7.53	Significant

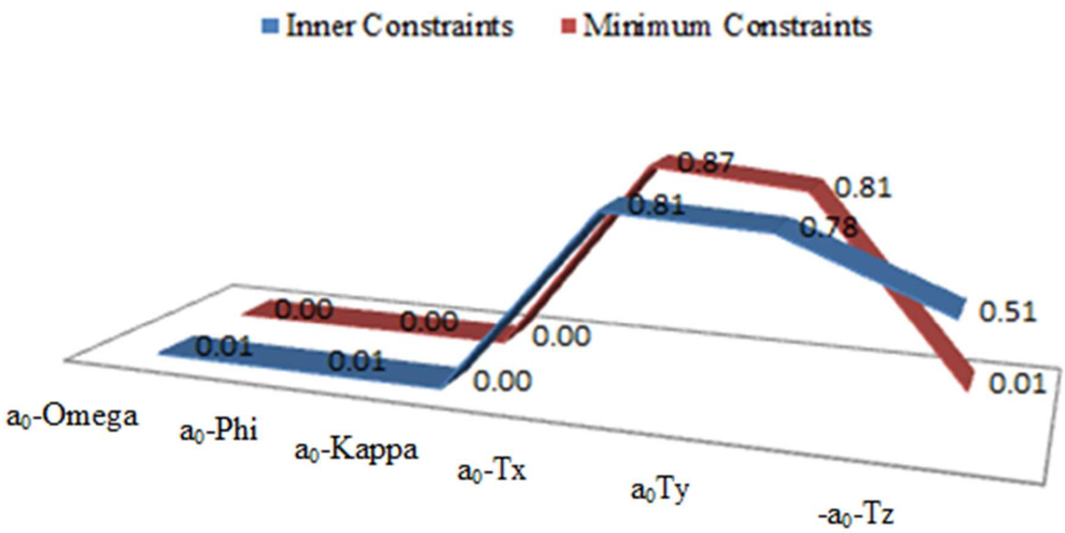
Results

2. Datum Constraints Analysis

   - Due to the different correlations effect caused by datum constraints in camera self-calibration, thus, further investigation is necessary to ensure that similar trends are applied to TLS self-calibration.
   - For that purpose, five graphs have been plotted to visually illustrated the parameter correlations between calibration parameters, exterior orientation and object points.

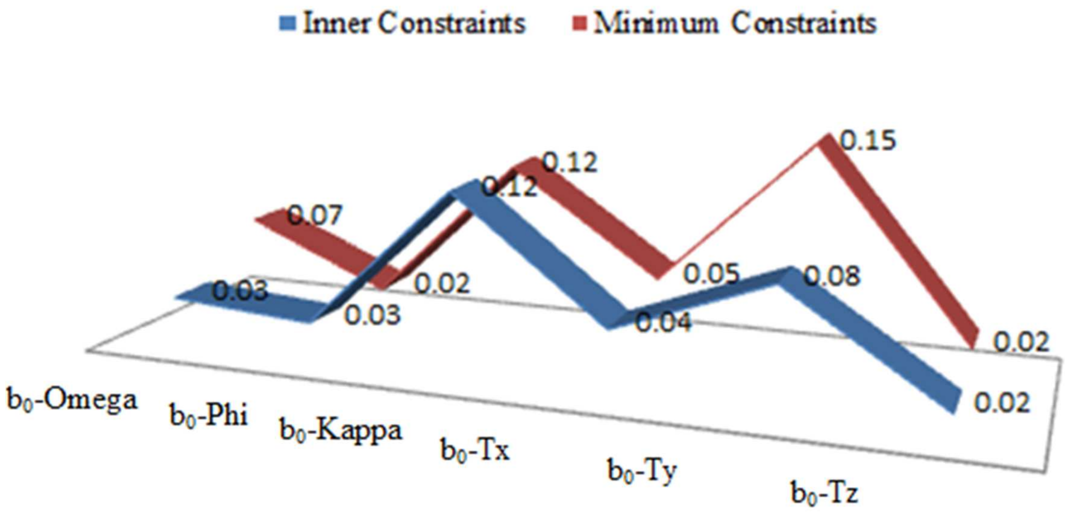
Results

Graph01: Correlation of Calibration Parameters and Exterior Orientation (Constant Error, a_0)



Results

Graph02: Correlation of Calibration Parameters and Exterior Orientation (Collimation Axis Error, b_0)



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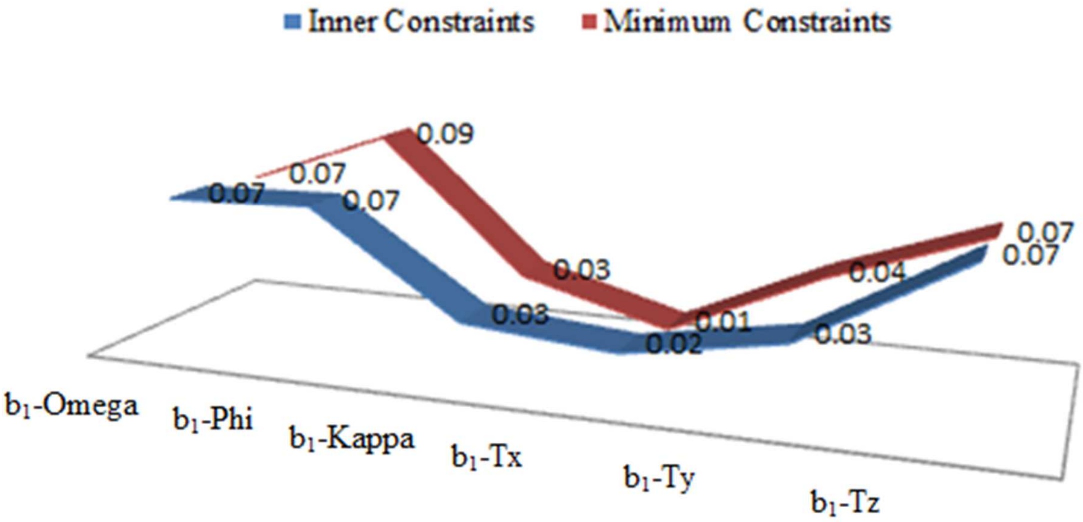
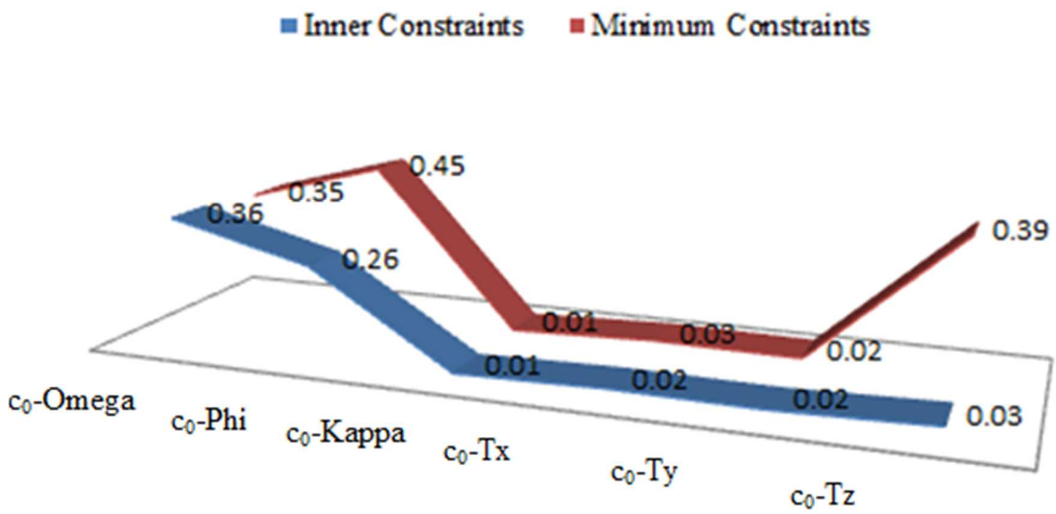
Results

Graph03:Correlation of Calibration Parameters and Exterior Orientation (Trunnion Axis Error, b_1)



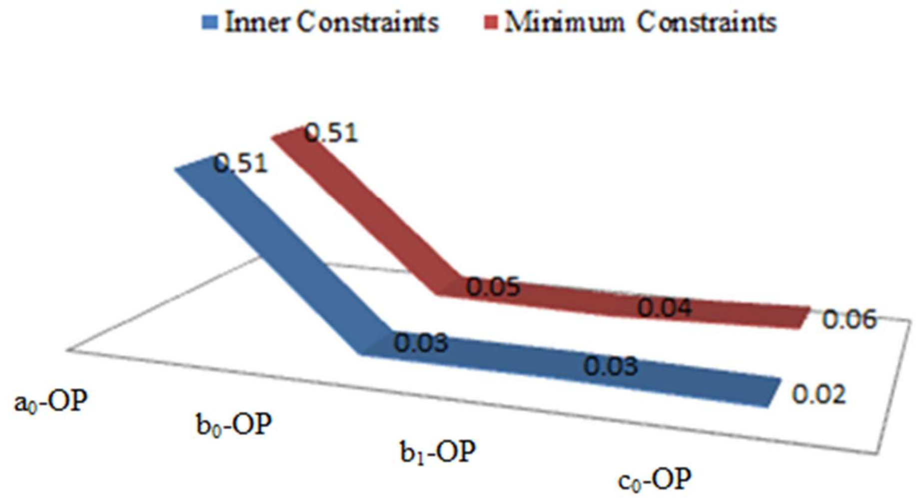
Results

Graph04:Correlation of Calibration Parameters and Exterior Orientation (Vertical Circle Index Error, c_0)



Results

Graph05:Correlation of Calibration Parameters and Object Points



Results

- Referring to the photogrammetry principle, the results of the inner constraints (blue colour) in Graph01 until Graph04 should be larger compared to the minimum constraints (red colour).
- However, the comparison between the results obtained show the opposite trends and can be considered as significantly similar.
- Through graphical evaluation, initial assumption can be made that the selection of datum constraints does not significantly affect the parameter correlations.

Results

- For a concrete conclusion, this study has employed the statistical analysis to prove that photogrammetry principal regarding datum constraints selection is not applicable for TLS self-calibration.
- In this analysis, ANOVA test was used to statistically verify that the selection of datum constraints for TLS self-calibration bundle adjustment does not affect the parameter correlations.
- Results of the F-variance ratio test with 95% confidence level showed that the difference between the means for all tables were not significant.
- In all cases, the calculated F are smaller than critical F (Table below) and p-values are gathered from the test were larger than level of significance (0.05), thus, the null hypothesis (H_0) were accepted.

Results

- With acceptance of the null hypothesis, a conclusion can be made that both datum constraints contribute similar parameter correlations. In other words, the selection of inner or minimum datum constraint does not affect the calculated calibration parameters and the parameter correlations.

Tested Parameters	Calculated F	>/<	Critical F	p-value	>/<	Level of Significance
a_0 – Exterior Orientations	0.09	<	5.05	0.77	>	0.05
b_0 – Exterior Orientations	0.42	<	5.05	0.53	>	0.05
b_1 – Exterior Orientations	0.01	<	5.05	0.91	>	0.05
c_0 – Exterior Orientations	0.69	<	5.05	0.42	>	0.05
a_0, b_0, b_1, c_0 – Object points	0.01	<	9.28	0.92	>	0.05

Conclusions

- A self-calibration procedure used to investigate systematic errors in TLS is a method adapted from photogrammetry approach.
- There are several considerations need to take into account, in order to perform this calibration method, especially regarding network design.
- Based on photogrammetry principal, selection of datum constraints can affect the parameter correlations.
- However, the implementation of self-calibration for TLS has different requirement for network configuration compared to photogrammetry approach.
- Therefore, this study carried out several experiments to investigate the effect of datum constraints selection for TLS self-calibration.
- The results verify that both inner and minimum datum constraints can provide similar parameter correlations, which mean that principle of photogrammetry self-calibration techniques are not applicable for TLS application.

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THANK YOU