

Investigation of Systematic Errors for the Hybrid and Panoramic Scanners

Mohd Azwan Abbas^a, Halim Setan^b, Zulkepli Majid^b, Albert K. Chong^c, Lau Chong Luh^b, Khairulnizam M. Idris^b, Mohd Farid Mohd Ariff^b

^aFaculty of Architecture, Planning & Surveying, Universiti Teknologi MARA Perlis, 02600 Arau, Perlis, Malaysia

^bFaculty of Geoinformation & Real Estate, Universiti Teknologi Malaysia, 81310 UTM Johor Bahru, Johor, Malaysia

^cSchool of Civil Engineering & Surveying, University of Southern Queensland, Australia.

*Corresponding author: mohdazwanabbas@gmail.com

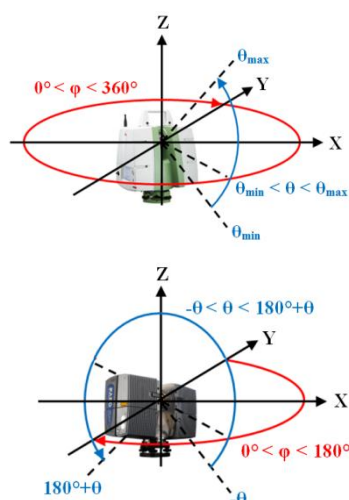
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Graphical abstract



Abstract

The existence of terrestrial laser scanners (TLSs) with capability to provide dense three-dimensional (3D) data in short period of time has made it widely used for the many purposes such as documentation, management and analysis. However, similar to other sensors, data obtained from TLSs also can be impaired by errors coming from different sources. Then, calibration routine is crucial for the TLSs to ensure the quality of the data. Through self-calibration, this study has performed system calibration for hybrid (Leica ScanStation C10) and panoramic (Faro Photon 120) scanner at the laboratory with dimensions 15.5m x 9m x 3m and more than hundred planar targets that were fairly distributed. Four most significant parameters are derived from well-known error sources of geodetic instruments as constant (a_0), collimation axis (b_0), trunnion axis (b_1) and vertical circle index (c_0) errors. Data obtained from seven scan-stations were processed, and statistical analysis (e.g. t-test) has shown significant errors for the calibrated scanners.

Keywords: Terrestrial laser scanner; self-calibration; systematic errors

Abstrak

Kewujudan *terrestrial laser scanners* (TLSs) dengan kemampuan untuk menghasilkan data tiga-dimensi yang padat dalam tempoh masa yang singkat telah menyebabkan ianya digunakan secara meluas bagi pelbagai tujuan seperti dokumentasi, pengurusan dan analisis. Walaubagaimanapun, sama seperti penderia yang lain, data diperoleh dari TLSs juga boleh dipengaruhi oleh selisih yang terhasil dari pelbagai sumber. Oleh itu, rutin kalibrasi adalah penting bagi TLSs bagi memastikan kualiti data. Menggunakan *self-calibration*, kajian ini telah menjalankan kalibrasi sistem bagi alat pengimbas hibrid (Leica ScanStation C10) dan panoramik (Faro Photon 120) di laboratri yang berdimensi 15.5m x 9m x 3m dan lebih daripada seratus target telah digunakan. Empat parameter yang signifikan telah dihasilkan daripada sumber selisih bagi alat geodetik seperti selisish tetap (a_0), paksi kolimasi (b_0), paksi trunnion (b_1) dan indeks sudut pugak (c_0). Data yang dicerap dari tujuh stesen cerapan telah diproses, dan analisis statistik (e.g. t-test) telah menunjukkan selisih yang signifikan terhadap pengimbas yang dikalibrasi.

Kata kunci: *Terrestrial laser scanner; self-calibration; selisih sistematik*

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1.0 INTRODUCTION

An important aspect to ensure the quality of 3D data captured by TLSs is the geometric calibration. As discussed by Reshetyuk [1], there are many error sources can be modeled from TLS measurement. Two approaches available to investigate those errors, either separately (component calibration) or simultaneously (system calibration) based on statistical analyses.

According to Schulz [2], component calibration is mainly based on knowledge-based modelling of the instrument and its

instrumental errors, and each single error is investigated separately in a specific experimental setup. All of those errors will be identified separately in component calibration. In order to carry out this type of calibration, special facilities and devices are required, and these may not be readily available to the users (Figure 1). Other than being used for calibration purposes, component calibration also performed to compare the performance of scanners from different models and manufacturers. Many studies regarding component calibration have been made by Brian et al. [3], Kersten and Mechelke [4] and Schulz [2].

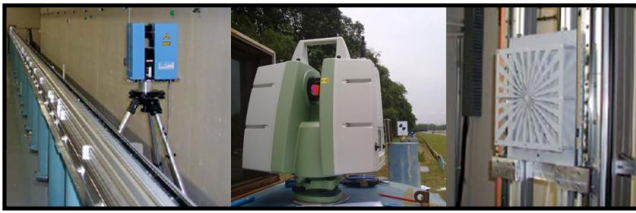


Figure 1 Facilities and devices required for component calibration [3, 5]

System calibration is generally used for the determination of all geometric parameters of a complete measurement system, and it includes including interior (calibration parameters) and exterior orientation parameters of the entire system component [2]. This calibration can be performed through self-calibration. Compared to component calibration, system calibration doesn't require any knowledge of the scanner error model. Thus, least square adjustment technique is used to derive the error model in the system calibration [1]. In contrast to the component calibration, performing self-calibration doesn't require for special facilities or devices, only a room with appropriate targeting is required as depicted in Figure 2. In order to de-correlate model variables and also to maximise the accuracy of the estimated systematic error parameters, the network used for the calibration should be designed carefully as discussed in Lichti [6].



Figure 2 Self-calibration of the panoramic (a) and hybrid scanners (b).

2.0 HYBRID AND PANORAMIC SCANNERS

Terrestrial laser scanner is a non-contact sensor, optics-based instrument technology that collects three-dimensional (3D) data of a defined region of an object surface automatically and in a systematic pattern with a high data collecting rate. This capability has made TLS widely applied for robust 3D reconstruction. In order to provide 3D point clouds that cover its entire field of view, laser source direction should be changed during scanning process. This can be performed either by rotating the laser source itself, or by using a system of rotating mirrors. The latter method is commonly used because mirrors are much lighter, faster and have greater accuracy. This method may consist of either two scanning mirrors or one scanning mirror and a servomechanism. There are three different types of beam deflection units used in TLSs as follows (Figure 3):

- i. Oscillating mirrors (Figure 3a).
- ii. Rotating polygonal mirrors (Figure 3b).
- iii. Monogon (flat) rotating mirrors (Figure 3c).

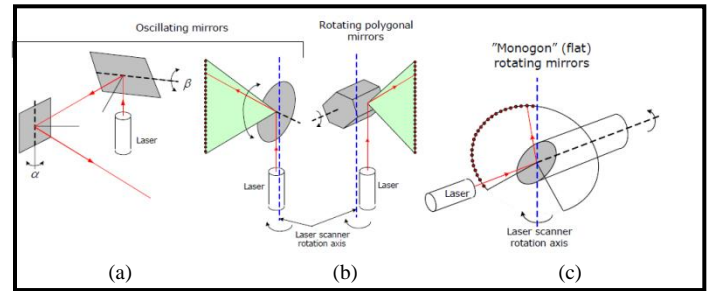


Figure 3 Beam deflection units used in TLSs [1].

Figure 3 shows that the type of laser beam deflection unit which represents the field of view (FOV) of the TLS. According to Staiger [7] and Reshetyuk [1], there are three classifications of TLS based on FOV as follows (Figure 4):

- i. Camera scanner (Figure 4a).
- ii. Hybrid scanner (Figure 4b).
- iii. Panoramic scanner (Figure 4c).

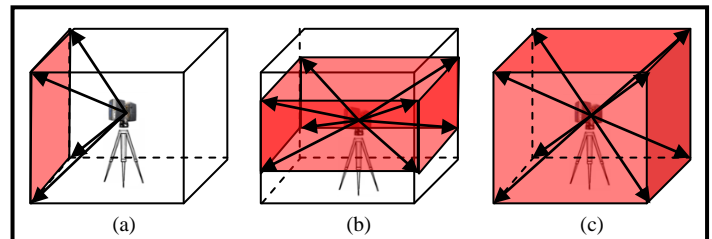


Figure 4 Classification of TLS based on field of view, camera scanner (a), hybrid scanner (b) and panoramic scanner (c).

Camera scanner uses oscillating mirrors to deflect the laser beam about the horizontal and vertical axes of the scanner. The scanning head remains stationary during scanning process. They carry out their distance and angle measurement over a much more limited angular range and within a specific FOV (Figure 4a) of e.g. $40 \times 40^\circ$, comparable to a photogrammetric camera [7]. Hybrid scanner has the horizontal FOV of 360° and limited vertical FOV (Figure 4b). This scanner employs the oscillating or rotating polygonal mirrors (Figure 3b) to deflect the laser beam in vertical and horizontal axes. With aid of servomotor, hybrid scanner is capable to be rotated by a small step around the vertical axis (horizontally). It works by scanning the vertical profile using the mirror, and this step is repeated around the vertical axis until the scanner rotates for 360° . Monogon mirror used in panoramic scanner has improved the vertical FOV compared to hybrid scanner (Figure 4c). Using the same mechanism as hybrid scanner which is based on servomotor, this scanner is also capable of providing 360° horizontal FOV. These advantages (360° horizontal FOV and nearly the same for vertical FOV) has made panoramic scanner very useful for indoors scanning.

3.0 GEOMETRIC MODEL FOR SELF-CALIBRATION

Due to the very limited knowledge regarding inner functioning of modern terrestrial laser scanners, thus, most of the researcher have make assumptions about the suitable error models for TLSs based on errors involve in reflectorless total stations [6].

Since the data measured by TLS are range, horizontal and vertical angle, thus, the equation for each measurement are augmented with systematic error correction model as follows [8]:

$$\text{Range, } r = \sqrt{x^2 + y^2 + z^2} + \Delta r \quad (1)$$

$$\text{Horizontal direction, } \varphi = \tan^{-1}\left(\frac{x}{y}\right) + \Delta\varphi \quad (2)$$

$$\text{Vertical angle, } \theta = \tan^{-1}\left(\frac{z}{\sqrt{x^2 + y^2}}\right) + \Delta\theta \quad (3)$$

Where,

x, y, z = Cartesian coordinates of point in scanner space.

$\Delta r, \Delta\varphi, \Delta\theta$ = Systematic error models for range, horizontal direction and vertical angle, respectively.

Since this study also employed panoramic scanners (Faro Photon 120), the angular observations computed using Eq. 2 and Eq. 3 must be modified. This is due to the scanning process applied by panoramic scanner, which is rotated only at 180° to provide 360° information for horizontal and vertical angles as depicted in Figure 5.

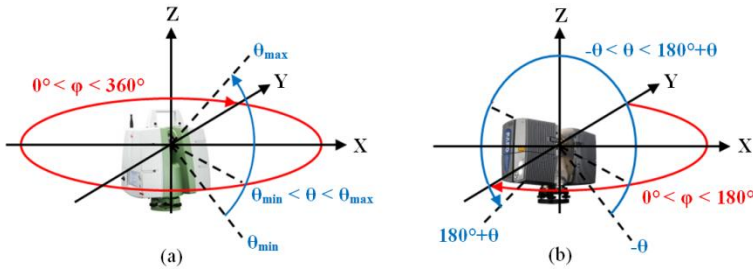


Figure 5 Angular observation ranges for hybrid scanner (a) and panoramic scanner (b).

Based on Lichti [9], modified mathematical model for a panoramic scanner can be presented as follows:

$$\text{Horizontal direction, } \varphi = \tan^{-1}\left(\frac{x}{y}\right) - 180^\circ \quad (4)$$

$$\text{Vertical angle, } \theta = 180^\circ - \tan^{-1}\left(\frac{z}{\sqrt{x^2 + y^2}}\right) \quad (5)$$

The modified models above (Eq. 4 and Eq. 5) are only applicable when horizontal angle is more than 180° as shown in Figure 4b. Otherwise, Eq. 2 and Eq. 3 will be used, which means that panoramic scanner has two equations for both angular observations.

In order to perform self-calibration bundle adjustment, values of x, y, z have to be substituted by the rigid-body transformation equation in order to express the original laser scanner observations as function of the position and orientation of the laser scanner in a global coordinate system [10].

$$\begin{aligned} x &= R_{11}(X - X_s) + R_{21}(Y - Y_s) + R_{31}(Z - Z_s) \\ y &= R_{12}(X - X_s) + R_{22}(Y - Y_s) + R_{32}(Z - Z_s) \\ z &= R_{13}(X - X_s) + R_{23}(Y - Y_s) + R_{33}(Z - Z_s) \end{aligned} \quad (6)$$

Where,

$[x \ y \ z]$ = Coordinates of the targets in the scanner coordinate system.

${}_3R_3$ = Components of rotation matrix between the two coordinate systems of the scanner stations.

$[X \ Y \ Z]$ = Coordinates of the targets in the global coordinate system.

$[X_s \ Y_s \ Z_s]$ = Coordinates of the scanner station in the global coordinate system.

4.0 SYSTEMATIC ERROR MODELS

According to Lichti [9], error models which are consisted in TLSs can be classified into two groups, either physical or empirical parameters. The first group can be considered as basic calibration parameters which have been derived from the total station systematic error models. This group includes the constant, cyclic, collimation, vertical circle index errors and others as described by Lichti and Licht [11]. The other group of error model may appear due to the geometric defects in construction or electrical cross-talk and may be system dependent. These are inferred from systematic trends visible in the residuals of a highly-redundant and geometrically strong, minimally-constrained least-square adjustment.

Due to the use of two different types of scanners, hybrid and panoramic scanners then this study focuses on the most significant systematic error models as follows:

- i. Systematic error model for range.

$$\Delta r = a_0 \quad (7)$$
- ii. Systematic error model for horizontal direction.

$$\Delta\varphi = b_0 \sec\theta + b_1 \tan\theta \quad (8)$$
- iii. Systematic error model for vertical angle.

$$\Delta\theta = c_0 \quad (9)$$

Where,

a_0 = Constant error.

b_0 = Collimation axis error.

b_1 = Trunnion axis error.

c_0 = Vertical circle index error.

Lichti et al. [8] have mentioned that systematic error models for panoramic scanner can be recognised based on the trends in the residuals from a bundle adjustment that excludes the relevant calibration parameters. Most of the cases, the trend of unmodelled systematic error closely resembles the analytical form of the corresponding correction model. Figure 6 shows the trend of residuals for systematic error model for both panoramic and hybrid scanners. However, this approach not suitable for the hybrid scanner due to the measurement procedure between hybrid and panoramic scanners are quite different as shown in Figure 5. It only applicable to defined systematic errors in range and vertical angle measurement as illustrated in Figure 6b and Figure 6h but not for horizontal direction (Figure 6d and Figure 6f).

Based on Figure 6, all systematic error models are identified by plotting a graph of adjusted observations against residuals. For panoramic scanner, the residual trends are

presented at the left side of Figure 6. The graph of adjusted range against its residuals (for panoramic scanner) will indicate a constant error (a_0) if the trend seems like an inclining line (Figure 6a). When residuals of horizontal observations against adjusted vertical angles shows the trend like secant function, which means that the scanner has collimation axis error (Figure 6c). Trunnion axis error can be identified by having a trend like tangent function as shown in Figure 6e. For vertical circle index error, by plotting graph of adjusted vertical angles against its residuals, this systematic error model considers exist when the trend looks like the big curve as depicted in Figure 6g. For hybrid scanner, those indicator only applicable for range measurement (Figure 6b), however for vertical angle measurement, the trend quite similar but due to the different measurement procedure, thus two curves with different direction appear (Figure 6h). For horizontal direction, there are no significant trends indicate any existence of systematic errors as shown in Figure 6d and Figure 6f.

Since identification of those systematic errors are based on residual pattern only suitable for panoramic scanner, then this study has implement 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 [12]:

$$t = \frac{X}{\sigma_x} \quad (10)$$

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.

The null hypothesis (H_0) will be rejected if the calculated t value (equation 10) is higher than the critical t value (predicted from the t-distribution table) with selected level of significant (confidence level 95% equal to 0.05 of significant level). With the rejection of H_0 , the test parameters is statistically significant (accept H_A).

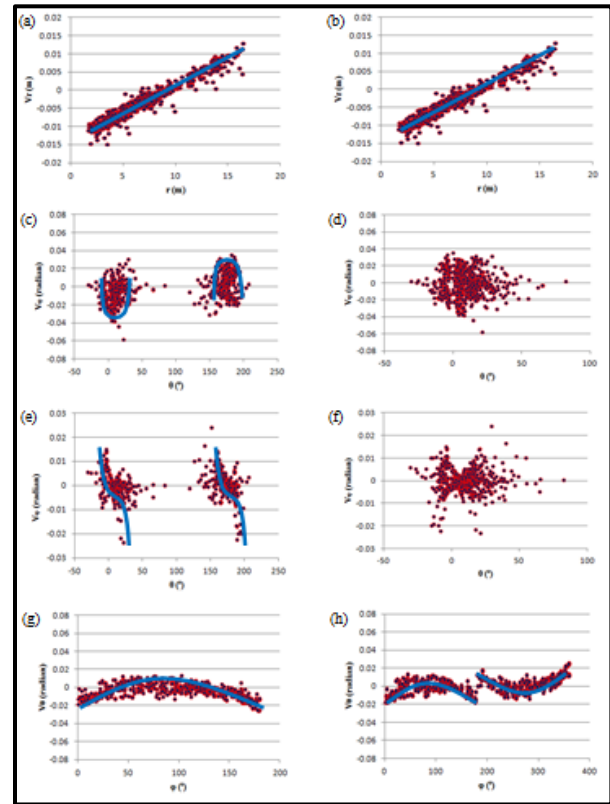


Figure 6 Simulation residuals for panoramic (constant error (a), collimation axis error (c), trunnion axis error (e) and vertical circle index errors (g)) and hybrid scanners (constant error (b), collimation axis error (d), trunnion axis error (f) and vertical circle index errors (h)).

5.0 EXPERIMENT DESCRIPTION

As shown in Figure 7, self-calibration for both panoramic (Faro Photon 120) and hybrid (Leica ScanStation C10) scanners have been performed in a laboratory with dimensions 15.5m (length) x 9m (width) x 3m (height). There were 138 planar targets distributed evenly on the four walls and ceiling as depicted in Figure 2, which based on conditions as stated by Lichti (2007).

Seven scan-stations have been used to capture the targets. Based on Figure 7, five scan-stations were located at the each corner and centre of the room. The other two were positioned close to the two corners and the scanner orientation were manually rotated 90° from scanner orientation at the same corner. In all cases the height of the scanner was set midway between floor and ceiling.

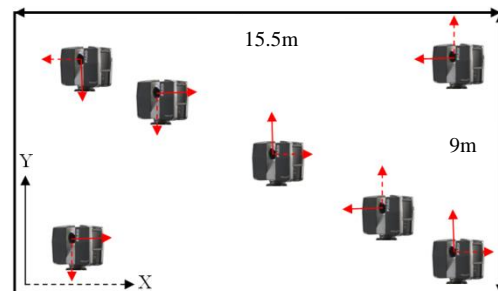


Figure 7 Scanner locations during self-calibration.

In this experiment, the scan resolution was set to the 1/4 setting for panoramic scanner which is equivalent to the medium resolution for hybrid scanner. Higher resolution scans were not captured due to the longer time required to complete the scanning. Furthermore, medium resolution also was sufficient for the commercial software (FaroScene for Faro Photon 120 and Cyclone for Leica ScanStation C10) to extract all targets except for those which have high incidence angle.

After the scanning and target measurement processes were completed, self-calibration bundle adjustment was performed with precision settings based on the manufacturer's specification, which were 2mm for distance and 0.009° for both angle measurements. After two iterations, the bundle adjustment process converged.

6.0 SELF-CALIBRATION RESULTS

Even though the panoramic scanner was used in this study, due to the limitation of hybrid scanner, thus, the agreement has been made to only implement statistical analysis to investigate the significant of the calculated systematic errors. As a result, the residual patterns are not employed. To investigate the improvement in quality of the data, least square adjustment was performed with and without systematic error models. Table 1 has indicated the improvement of root mean square (RMS) of residuals for both scanners. For panoramic scanner, the results of RMS have shown the improvement in accuracy for up to 29% by implementing self-calibration procedure. In contrast, hybrid scanner only has 1% improvement for vertical angle while the others measurement have no improvement.

Table 1 RMS of residuals from the least square adjustment without and with systematic error models for panoramic and hybrid scanners.

Scanner	Panoramic (Faro Photon 120)		Hybrid (Leica C10)	
	Without	With	Without	With
Observable				
Range (mm)	5.6	4.0	2.3	2.3
Horizontal Direction (°)	41.0	37.1	47.5	47.5
Vertical Angle (°)	24.0	22.4	18.4	18.2

According to the results of the calibration parameters (a_0 , b_0 , b_1 and c_0) shown in Table 2 for hybrid and panoramic scanners, the magnitude of the calculated parameters are quite small except constant error for panoramic scanner and vertical circle index error for hybrid scanner. These outcomes have shown the cause of the small improvement for the hybrid scanner compared to the panoramic scanner. Comparing between angle and range measurement, usually the errors in range will give more effect to the accuracy of data. As depicted in Figure 7, the length of the room is 15.5m which indicate the 1° error in angle measurement just cause 3mm discrepancy. Comparing the results of constant error for both calibrated scanners, panoramic has 9.3mm error while hybrid has only 0.7mm error. Neglecting the other calibration parameters, conclusion can be made that the Leica ScanStation C10 scanner is more accurate the Faro Photon 120.

Table 2 Calibration parameters and standard deviations for panoramic and hybrid scanners.

Calibration Parameters	Panoramic scanner (mm/°)	Hybrid scanner (mm/°)
$a_0 \pm \sigma_{a_0}$	9.3 ± 0.2	0.7 ± 0.2
$b_0 \pm \sigma_{b_0}$	-1.1 ± 2.1	-2.9 ± 43.7
$b_1 \pm \sigma_{b_1}$	2.9 ± 8.0	10.7 ± 17.8
$c_0 \pm \sigma_{c_0}$	9.4 ± 2.8	-45.4 ± 12.9

In order to have a reliable solution regarding the significant of the calculated systematic error models acquired from self-calibration bundle adjustment, then, statistical test was performed. All calibration parameters yielded for both calibrated scanners were statistically tested to investigate the significant of the calibration parameters to the observations (Table 3).

Table 3 Statistical test performed for the calibration parameters.

Calibration Parameters	Critical 't' (95%)	Calculated 't' (Panoramic)	Calculated 't' (Hybrid)
a_0	1.645	46.5	3.5
b_0	1.645	0.524	0.066
b_1	1.645	0.363	0.601
c_0	1.645	3.357	3.519

*Red – Significant; Blue – Not Significant

Based on the data in Table 3, for both calibrated scanners, null hypothesis has been rejected for constant and vertical circle index errors which mean that those parameters are significant. On the contrary, collimation and trunnion axis errors are not significant for both scanners. According to the results obtained in Table 2, magnitudes for both insignificant parameters for both scanners are very small and these have also contributed to the outcomes obtained from the significant test.

7.0 SUMMARY

This study has employed Faro Photon 120 and Leica ScanStation C10 represent panoramic and hybrid scanners, respectively, to discussed and investigate the different between those scanners. Begin with the measurement procedure, discussion also has been made regarding the limitation of hybrid scanner to investigate the significant systematic errors through residual trends. Recommendations were given to resolve this issue with the aid of statistical analysis, which is applicable for both types of scanners. Having 138 planar targets distributed evenly on the four walls and ceiling, self-calibration has been carried out from 7 scanner-stations. By using appropriate a priori standard deviations for the observations, calibration parameters yielded from the adjustment have been evaluated through statistical analysis. The evaluations of RMS of residuals have indicated that calibrated panoramic scanner has improved up to 29% compared to hybrid scanner that only has 1% improvement. However, this does not describe that self-calibration is failed to improve the accuracy hybrid scanner but according to the error in range measurement, conclusion can be made that calibrated hybrid scanner has a very good accuracy. Nevertheless the results obtained from statistical analyses have

indicate that for both calibrated hybrid and panoramic scanners, the constant and vertical circle index errors are significant.

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