Lagrangian-Based Least Squares Criterion in Electro-Optical Distance Measurement (EDM) Instrument Calibration

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Key words: Lagrangian-Based Least Squares; Electro-Optical Distance Measurement (EDM); Instrument Calibration; Accuracy; Geomatics Engineers

SUMMARY

Geomatics instruments frequently encounter continuous and barbarous use in highway construction sites. To measure with high precision, Electro-Optical Distance Measurement (EDM), inherent in Total Station instruments, have to fulfil certain requirements. Whether the EDM is old or new, its constant should be capable of automatically correcting the deviation between the mechanical and electrical centres when measuring distance. This calls for EDM calibration in order to control systematic errors in distance measurement. The least squares method minimizes the sum of squares of weighted disparities between observations to obtain a unique estimates from redundant measurements. As such, this method is applied in analyzing geomatics engineering data. In this contribution, the Lagrangian-based least squares criterion in Electro-Optical Distance Measurement (EDM) instrument calibration is assessed. Distance measurements by tape and EDM collected on a 440-meter (from 0+000.00 to 0+0440.00 meters) stretch are used to evaluate the level of accuracy of Nikon Nivo Total Station. The Lagrangian approach is derived and implemented to compute the residual vectors, a posteriori variance factor and the correlation between the two sets of distance observations. In addition, the paper also establishes the total uncertainty of the measured distance using the distance precision provided in manufacturer's literature for the EDM. Using the proposed approach, the study obtains substantial accuracy from the distances determined by the EDM. The achieved level of accuracy is also found to be within the acceptable tolerances for highway engineering projects in Malawi. As such, geomatics engineers may adopt the method in calibrating EDM instruments.

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1 INTRODUCTION

The advent of Electromagnetic Distance Measuring (EDM) geomatics equipment enables quick and accurate distance measurement regardless of terrain dynamics. At present, EDM devices are incorporated in Total Stations for making linear measurements. Total Stations have been used in both integrated surveys with Global Navigation Satellite System (GNSS) and in scenarios where GNSS is not the only approach to positioning. GNSS is a generic term referring to GPS (Global Positioning System); GLONASS (Global'naya Navigatsionnaya Sputnikkovaya Sistema); Galileo, and BeiDou. More details can be found in Suya (2019c) about GNSS and its application in geomatics engineering.

Ghilani and Wolf (2012) highlighted GNSS as one of the methods for measuring distances alongside tapes and EDM instruments in geomatics engineering. For instance, Suya (2019b) has recently demonstrated the value of the EDM in estimating the distances between electric poles in Malawi.

EDM instruments are affected by five notable errors namely: zero errors, cyclic errors, scale error, phase measurement error, and external errors (Amiri-Simkooei, 2003). This calls for EDM calibration in order to determine the instrument errors which is eventually used to monitor its performance and reliability. As indicated by Schofield and Schofield and Breach (2007), calibration is one of way of controlling systematic errors in observations. To better improve distance measurement by EDM instruments, error corrections are necessary. For example, the application of atmospheric error corrections is pertinent when centimetre-level accuracy is required (Bertacchini *et al.*, 2011). This is particularly true in deformation and displacement surveys. Ježko (2014) verified the efficacy of calibrating geomatics instruments including EDM equipment for improved deformation measurements.

Both checking and calibration of geomatics instrument are useful to verify that the instrument is performing within allowable tolerances. The ambient atmospheric parameters such as pressure, humidity, temperature, and gradients influence distance measurement. For any EDM, the error affecting the final distance is a function of the equipment, operator (geomatics engineer) and the atmosphere. Staiger (2007) expressed the overall EDM error budget (Σ) according to equation [1]:

$$\Sigma = f(\text{Equipment}, \text{Operator}, \text{Atmosphere}) \qquad [1]$$

When calibrating EDM instruments, the atmospheric parameters should be collected at each occupied station. When left uncorrected, Erenoglu (2012) noted that the variation in atmospheric pressure and temperature affects the propagation of electromagnetic signal. An overview of the EDM calibration requirements is presented in Hazelton (2009).

The accuracy of the measured distance by EDM is preferably performed on a certified baseline (Zakari and Aliyu, 2014). Both conventional and satellite-based positioning methods have been used in calibrating EDM parameters. İnal, Şanhoğlu, and Yiğit (2008) employed GNSS survey to estimate EDM scale errors for different geomatics instruments including Topcon GTS701, Topcon GTS 229, Sokkisha SET2, and Sokkia Power SET 2000. Khalil (2005) implemented mirrors on a SOKKIA Total Station SET 600 to determine the EDM zero error. On the other hand, Esteban *et al.* (2015) combined GNSS (Topcon Hiper Lite +, Leica SR500 and Ashtech Z-Xtreme) and EDM (Leica TC-407, Pentax R-326EX and Topcon GTS-236W) to calibrate a 125-meter baseline.

The Least Squares Estimation (LSE) play a worthwhile role in determining EDM calibration parameters. Amiri-Simkooei (2003) deduced a more comprehensive least squares approach for computing EDM zero error. Recently, Erenoglu (2018) compared a total of five robust methods to conventional least squares to identify the best approach for estimating EDM zero errors. Parametric least squares have been implemented in software to detect EDM instrument constant, reflector constant, and scale factor. An example of such software is EDMCAL (EDM CALibration) developed and maintained by the University of New South Wales (UNSW, Janssen and Watson, 2014).

Whether the EDM is old or new, its constant should automatically correct for the shift between electrical and mechanical centres when measuring distance. For calibration purposes, distances measured by EDM are compared to a correctly established pillared baseline. In absence of a baseline, Uren and Price (1985) recommended the use of a three-peg-test to check the EDM zero error.

Determination of zero error is done by distance measurement. The overall magnitude of the residual vectors in distance measurement are performed by the least squares criterion. Schofield and Breach (2007) presented the application of least squares on the checking of instrument constant. Suya (2019a) unveiled the contribution of the least squares approach to the discipline of engineering surveying in Malawi. Wang, Li, and Liu (2016) compared the robust total least squares and general least squares and its application in geodetic science. Nielsen (1998) calibrated nonlinear weighting transducer using Lagrange multipliers. The application of method of Lagrange has not received due attention in EDM instrument calibration in Malawi.

In this contribution, the application of the Lagrangian least squares approach in Electromagnetic Distance Measuring (EDM) instrument calibration is evaluated. The study specifically determines the residual vectors, a posteriori variance factor and the correlation between the two sets of distance observations to establish the threshold of accuracy.

2 TRADITIONAL GEOMATICS TECHNIQUES

Traditional geomatics engineering approaches such as traversing, trilateration and triangulation are used for establishing two-dimensional (2D), horizontal angles and horizontal distances. The relationships expressed by these observations are non-linear. The expressions are in explicit mathematical form and are linearized by Taylor series expansion, usually up to first order. The linearized models are input in the derivation of variation function in least squares method. The least squares approach is presented in most geomatics engineering textbooks such as in Ghilani and Wolf (2006) and in Schofield and Breach (2007). The least squares approach is further expressed by incorporating a vector of correlates (also known as Lagrangian multipliers) to show how the variables change with respect to each other.

2.1 Lagrangian Least Squares Criterion

The Lagrangian approach of the least squares criterion is more conveniently applied in handling linearized models in geomatics engineering. The Lagrangian multipliers have been used to make the weighted total least-squares (WTLS) more rigorous in linear regression and coordinate transformation. A concise description about the Lagrangian approach can be obtained from Gong and Li (2017). In simple terms, the Lagrangian approach is expressed by computing the partial derivatives of the variation function (φ) with respect to the residual error (v), systematic or constant error (δ) and Lagrangian multipliers (k) as presented in [2]:

$$\begin{cases} \dfrac{\partial \varphi}{\partial v} = 2v^T C_\ell^{-1} + 2k^T = 0 \\ \dfrac{\partial \varphi}{\partial \delta} = -2k^T A = 0 \\ \dfrac{\partial \varphi}{\partial k^T} = 2(A\delta + w - v) = 0 \end{cases} \quad [2]$$

In Equation [2], T denotes transpose; C_ℓ^{-1} denotes the inverse of the covariance matrix of observations (ℓ); A denotes the observation equation coefficient matrix $(\partial f / \partial x)$; w denotes vector of misclosure ($w = f\left[x^0\right] - \ell$), and v denotes the vector of observation residuals ($v = w + A\delta$).

The equations in [2] can be simplified to the least squares normal equations based on the Lagrangian approach according to [3]:

$$v^T C_l^{-1} + k^T = 0 \quad [3]$$
$$k^T A = 0 \quad [4]$$
$$A\delta + w - v = 0 \quad [5]$$

To obtain the least squares solution, simultaneously solve for δ from the Lagrangian normal equations in [3] to [5]. By post-multiplying $V^T C_\ell^{-1} + k^T = 0$ by the matrix of observations A and substituting $k^T A$, Equation [6] is obtained.

$$v^T C_\ell^{-1} + A = 0 \qquad [6]$$

Transpose Equation [6] to obtain [7]:

$$A^T C_\ell^{-1} + v = 0 \qquad [7]$$

Substitute v, from Equation [5], into Equation [7] to obtain the normal equation based on Lagrangian criterion expressed in [8]:

$$A^T C_\ell^{-1} A\delta + A^T C_\ell^{-1} w = 0 \qquad [8]$$

Solve for δ to obtain the solution for Equation [8] as expressed in Equation [9]:

$$\delta = -\left(A^T C_\ell^{-1} A\right)^{-1} A^T C_\ell^{-1} w \qquad [9]$$

2.2 Parameters and Observations

The precision of the adjusted quantities such as parameters and observations is given by Equations [10] and [11]:

$$\hat{x} = x^0 + \delta \qquad [10]$$
$$\hat{\ell} = \ell + v \qquad [11]$$

In equations [10] and [11], $\hat{x}$ and $\hat{\ell}$ are the vector of adjusted parameters and vector of adjusted observations, respectively.

2.3 Precision in Geomatics Engineering

Adjustment is meaningful when observations are redundant (Mikhail, 1976). Redundancy is described as the number of degrees of freedom, for example in Ghilani and Wolf (2012). It simply means the number of independent observations made minus the number of unknown parameters involved in the equations.

For both weighted and unweighted adjustments, the a posteriori variance factor of unit weight is expressed as [12]:

$$s_0^2 = \frac{v^T C_\ell^{-1} v}{r} \qquad [12]$$

where r is the number of observations minus the number of parameters.

For the unweighted case, it is just a matter of removing C_ℓ^{-1} from Equation [12]. The product of the standard deviation of unit weight s_0^2 and $A^T C_\ell^{-1} A$ leads to the covariance matrix of parameters [13].

$$C_{\hat{x}} = s_0^2 \left(A^T C_\ell^{-1} A \right) \qquad [13]$$

3 MATERIALS AND METHODS

3.1 Geomatics Instruments Experimented

In this study, two sets of distance observations were made using two different instruments on Lilongwe Western Bypass Road. In the first set, design distances were set out on the road using a measuring tape in a joint construction survey between the client and contractor survey teams. In the second set, the same distances were measured with a newly bought Nikon Nivo Total Station by the same teams.

The distance was measured at twenty-meter interval from 0+000.00 to 0+440.00 meters. The distances measured with a tape were taken as control and accepted by the consultants as per the design. For each section, the distance was measured five-times within four days and an average was taken for each. Five redundant observations for each section were recorded with the Total Station (TS). Similarly, an average was taken for each section.
The control and experimental distances together with the approved TS standard deviations of the measurements are presented in Table 1.

__Table 1:__ Tape and Total Station distances (Source: David Consultants).

	Chainages				
SN.:	From	To	Tape	Total Station	Standard Deviation
1	0+000	0+020	19.999	19.9999	0.0020
2	0+020	0+040	19.997	19.9999	0.0025
3	0+040	0+060	19.997	20.0000	0.0030
4	0+060	0+080	19.999	19.9999	0.0010
5	0+080	0+100	20.000	20.0009	0.0005
6	0+100	0+120	19.999	19.9999	0.0002
7	0+120	0+140	19.999	19.9999	0.0001
8	0+140	0+160	19.999	20.0000	0.0002
9	0+160	0+180	19.998	19.9999	0.0010
10	0+180	0+200	19.999	19.9999	0.0003
11	0+200	0+220	19.999	19.9999	0.0003
12	0+220	0+240	19.997	19.9999	0.0020
13	0+240	0+260	19.999	19.9999	0.0005
14	0+260	0+280	20.001	20.0010	0.0004
15	0+280	0+300	19.999	19.9999	0.0007
16	0+300	0+320	19.999	19.9999	0.0008
17	0+320	0+340	19.998	19.9999	0.0009
18	0+340	0+360	19.998	19.9999	0.0011
19	0+360	0+380	19.999	20.0002	0.0012
20	0+380	0+400	19.998	19.9994	0.0013
21	0+400	0+420	19.998	19.9998	0.0014
22	0+420	0+440	19.998	19.9999	0.0015

Key: The distances measured with a tape and Total Station fall in the columns of 'Tape' and'Total Station', respectively.

The distances determined from the TS were taken as experimental part in order to check the level of agreement between the two sets of distances. This was done to assess the precision of the new TS against the manufacturer's specification.

3.2 Total Station Specifications

The TS distance specifications are presented in Table 2. The measurements mode for the employed TS are described in the key. Using the descriptions provided for distance measurement with or without a reflector, the uncertainty of the TS was estimated for the given distance.

Table 2: *Distance precision for Nikon Nivo 3.C*

	Distance Precision
1	**Precise Mode**
Prism/Reflectorless	± (3 + 2 ppm × D) mm (–10 °C to +40 °C) ± (3 + 3 ppm × D) mm (–20 °C to –10 °C, +40 °C to +50 °C)
2	**Normal Mode**
Prism	Prism ± (10 + 5 ppm × D) mm
Reflectorless	Reflectorless ± (10 + 5 ppm × D) mm

Key: In precise mode with the prism and without (reflectorless), the Total Station takes 1.5 seconds and 1.8 seconds to compute distance, respectively. In normal mode, 0.8 seconds and 1.0 second to measure, respectively.

3.3 Uncertainty in Measured Distance

Uncertainty in the measured distance with the TS was determined using the distance precision. In Table 2, distance precision is presented in manufacturer's literature as (3 + 2 ppm x D) mm and (10 + 5 ppm x D) in precise and normal mode, respectively.

For this TS, 3 and 10 denote the zero error and phase measurement whereas 2 ppm and 5 ppm are the resultant errors in the modulation frequency and in the group refractive index. The two values (2 ppm and 5 ppm) are proportional to the distance (D) measured. The abbreviation *ppm* denotes *parts per million* in which 1 ppm equates to 1 mm per km. More details EDM precision are discussed in Ghilani and Wolf (2012).

The total uncertainty was estimated for the twenty (20)-meter distance using Equation [14] as given in Schofield and Breach (2007):

$$\sigma = \left[a^2 + \left(\mathrm{bL}.10^{-6}\right)^2\right]^{\frac{1}{2}} mm \qquad [14]$$

where L denotes the distance in kilometres.

This was done to check the threshold of the measured distance on the ground using the TS.

3.4 Design Matrix Formulation

The Lagrangian approach, Equation [9], was employed in order to compute the least squares solution. A design matrix involving twenty-two (22) tape observations (A_{Tape}) was developed. This is simply a 2 by 22 matrix, i.e., ${}_{22}A^{2}_{Tape}$ as summarised in Equation [15]:

$$ {}_{22}A^{2}_{Tape} = \begin{bmatrix} 1 & 19.999 \\ 1 & 19.997 \\ 1 & 19.997 \\ \vdots & \vdots \\ \vdots & \vdots \\ 1 & 22^{\text{nd}} \end{bmatrix} \quad [15] $$

3.5 Vector of Misclosure

The misclosure vector was determined by simply subtracting the TS distance measurements from the control observations. This was computed using w as described in Section 1.2 above. This is simply a one by 22 matrix (${}_{22}w^{1}$), as summarised in Equation [16]:

$$ {}_{22}w^{1} = f\left[x^{0}\right] - \ell = \begin{bmatrix} 19.999 & - & 19.9999 \\ 19.997 & - & 19.9999 \\ 19.997 & - & 20.0000 \\ \vdots & \vdots & \vdots \\ \vdots & \vdots & \vdots \\ 22^{\text{nd}} & - & 22^{\text{nd}} \end{bmatrix} = \begin{bmatrix} w_1 \\ w_2 \\ w_3 \\ \vdots \\ \vdots \\ 22^{\text{nd}} \end{bmatrix} $$

[16]

3.6 Covariance Matrix of Observations

Using the standard deviations for the TS observations, the covariance matrix was formulated. A weight matrix of measurements with squares of the inverses of the standard deviations was developed. Since there were twenty-two observations, then a 22 by 22 diagonal matrix was developed ${}_{22}C^{22}_{\ell}$ as presented in Equation [17].

$$
{}_{22}C_{\ell}^{22(-)} = \begin{bmatrix} \sigma_1^{-2} & & & & & \\ & \sigma_2^{-2} & & & & \\ & & \sigma_3^{-2} & & & \\ & & & \vdots & & \\ & & & & \vdots & \\ & & & & & \sigma_{22^{nd}}^{-2} \end{bmatrix} \qquad [17]
$$

3.7 Least Squares Solution

The least squares solution was obtained using equation [9], i.e.: $\delta = -\left(A^T C_\ell^{-1} A\right)^{-1} A^T C_\ell^{-1} w.$ equations [15], [16] and [17] were plugged in equation [9] to obtain the least squares solution. The vector of residuals was determined using $v = w + A\delta$. This was done by simply summing up the vector of misclosure and the product of the design matrix and the least squares solution. This was performed to quantify the degree of disparity between the standard and experimental distances.

A posteriori variance (s_0^2) of factor of unit weight was computed to express the precision as discussed in section 2.3. Since there were twenty-two observations, then the degrees of freedom (r) was twenty (i.e., 22 observations minus two unknowns). The vector of residuals, covariance matrix, and the degrees of freedom were used to calculate s_0^2. The covariance matrix was computed to determine whether the two sets of measurements were correlated or not. This was deduced from Equation [13], presented in section 2.3.

4 RESULTS AND DISCUSSIONS

Processing the experimental datasets using the approach discussed in the methodology, the findings to the Lagrangian-based least squares criterion EDM calibration are presented in the following sub-sections.

4.1 Output on Vector of Residuals

In consideration to section 3.7, the computed vector of residuals is presented Equation [18]:

$$v = w + A\delta = \begin{bmatrix} 0.0000 \\ -0.0009 \\ -0.0010 \\ 0.0000 \\ -0.0005 \\ 0.0000 \\ 0.0000 \\ -0.0001 \\ -0.0005 \\ 0.0000 \\ 0.0000 \\ -0.0009 \\ 0.0000 \\ -0.0001 \\ 0.0000 \\ 0.0000 \\ -0.0005 \\ -0.0005 \\ -0.0003 \\ 0.0000 \\ -0.0004 \\ -0.0005 \end{bmatrix} \quad [18]$$

The disparity between the Tape and TS distance measurements was satisfying. As can be seen in Equation [18], all the residuals were very small (millimeter-level). The differences in distances agree to within a few millimetres.

4.2 A posteriori Variance Factor

The residual values, the covariance matrix, and the degrees of freedom were plugged in Equation [12] to obtain the a posteriori variance factor. The solution is presented in Equation [19]:

$$s_0^2 = \frac{v^T C_\ell^{-1} v}{r} = 0.1283 \quad [19]$$

4.3 Correlation Between Observations

The covariance matrix was computed according to Equation [13]. The calculated correlation between the Tape and TS distance measurements are presented in Equation [20]:

$$C_{\hat{x}} = s_0^2\left(A^T C_\ell^{-1} A\right) = \begin{bmatrix} 1.4621 & -0.0731 \\ -0.0731 & 0.0037 \end{bmatrix} \qquad [20]$$

As can be seen from Equation [19], the off-diagonal elements are equal to -0.073 m. This means that the calculated values for the tape and EDM were correlated. The diagonal values are the associated variances. The standard deviations of the tape and EDM observations are simply the square-roots of the diagonal elements of the matrix in Equation [20]. This follows that the tape and EDM measurements were determined with standard errors of 1.209 m and 0.061 m, respectively. This follows that the EDM measurements were about twenty-times better than those of the tape. The accuracy (about 6 cm) of the measured distances by EDM was within acceptable tolerance in highway engineering surveys in Malawi as highlighted by Suya (2019a).

4.4 Instrument Uncertainty

The TS uncertainty was determined using equation [14] presented in section 3.3. For the precise and normal mode, the estimated uncertainty for the 20-meter distance was about 3 mm and 10 mm, respectively. This means better precision can be obtained when this TS is used in precise mode.

5 CONCLUSIONS

In this paper, the Lagrangian-based least squares criterion in Electro-Optical Distance Measurement (EDM) instrument calibration was evaluated. Distance measurements by tape and EDM collected on a 440-meter stretch were used to assess the level of accuracy of Nikon Nivo TS. The Lagrangian approach was derived and implemented to compute the residual vectors, a posteriori variance factor and the correlation between the two sets of distance observations. The uncertainty of the measured distance was estimated using the provided distance precision for the EDM.

Using the proposed approach, substantial accuracy was obtained from the distances determined by the EDM. The level of accuracy estimated was also within the acceptable tolerances in highway engineering surveys in Malawi. As such, geomatics engineers need to be adopting the method in calibrating EDM instruments in Malawi.

The implemented datasets were not determined from a pillared baseline. Moreover, the tape used in distance measurement may have errors due to lack of standardization. Therefore, a similar study has to be performed taking these factors into consideration.

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BIOGRAPHICAL NOTES

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