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The Analysis Methodology of Robotic Total Station Data for Determination of Structural Displacements

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ABSTRACT

Monitoring structural deformations and taking measures for building safety are considered almost synonymous with important concepts such as human health, public safety and prevention of economic losses. For this reason, new structural monitoring application techniques are being developed in parallel with the developments in building construction technologies and architecture. In particularly, GNSS satellite-based measurement systems have found wide application areas for determining structural oscillations and deformations. In addition, the direction of the studies in this field has focused on lower cost and more practical measurement systems. One of the alternative measurement devices used for this purpose is angle and distance measurements with the classical total station. Total stations, which have been automated and gained robotic features in recent years, are easily used in the determination of the most critical structural monitoring and deformations with their programmable structure. In this study, angle-distance measurements performed with a robotic total station at a simultaneous and constant sampling interval for 6 hours were processed and analyzed. Coordinate values and position errors were calculated by adjusting according to the least-squares method for each measuring range. Structural displacement values were determined from the coordinate values calculated as a function of time.

1. INTRODUCTION

In structural monitoring, electronic theodolites (ET) or total stations (TS) are commonly used to calculate the time-dependent changes of cartesian coordinates of observation points. These instruments are the most basic geodetic measuring instruments used in engineering measurements and scientific studies. Firstly, with the development of electronic theodolites, TSs emerged and later with automatized robotic total stations (RTS), which allow new generation robotic measurements, have found a wide area of use (Schofield and Breach 2007).

RTS or Robotic theodolites are a modern version of TS. In sampling intervals determined according to the features of the program used, RTS can direct itself to the target point, make measurements and record. Nowadays, by programming RTSs, it has been reached the level of observing with a sampling interval of 5-10 Hz and monitoring moving reflectors. Because of these advantages, it is widely used in many surveying and other engineering projects (Psimoulis and Stiros 2008; Psimoulis and Stiros 2011; Moschas et al. 2012; Lienarth et al. 2016). In addition to general engineering research, it can also be used in more scientific experiments to record oscillations with a high frequency greater than 1 Hz and small amplitude (a few mm). With this capacity, RTS have also be used for monitoring large engineering structures under the influence of wind or traffic load (Psimoulis and Stiros 2007; Pytharouli and Stiros 2008; Pehlivan 2009; Zhou et al. 2019). In addition, studies have been conducted in which they are used as auxiliary sensors in the determination of structural movements and deformations (Psimoulis and Stiros 2012, Pehlivan et. Al. 2013).

In this study, to determine the deformations of a tall structure, horizontal, vertical, and oblique distance measurements were made to model the building movements using total stations with robotic features from long distances. The data were processed and adjusted with the least-squares method to determine the position changes (structural deformations) of the observation point. Positional coordinates and position errors were calculated for each measuring moment, and time-dependent position changes were determined.

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2. MEASUREMENTS WITH TOTAL STATION

The RTS sends laser light to the prism mounted on the observed structure and can record the horizontal distance and the horizontal and zenith angles values using the round trip time of the returning light. Each observation record can be converted into coordinate values and its change over time helps us calculate the direction and trace of motion. Under normal atmospheric conditions, be making angle measurements with 0.5' and distance measurements with 1mm+1ppm accuracy allows us to determine the position with 1mm accuracy. Repeated measurements at regular intervals defined by a total station with automatic target recognition (ATR) system; It automatically performs the process of guiding to the target point, measuring and recording, as programmed. The speed of this automated measurement and recording process is directly proportional to the sampling rate of the measurement process (Psimoulis and Stiros 2011; Moschas et al. 2012; Pehlivan et al. 2013).

2.1. Measurements with Automatized Total Station or Robotic Total Station

Once the RTS is programmed, it automatically performs observations without the need for an operator and can save the data on a memory card. The data recorded during the measurement can be viewed in real-time if the RTS is connected to a computer. It provides instant monitoring of position changes, monitoring of displacement changes and a controlled test environment under loading conditions. These instant data are useful in eliminating system and human-induced errors in load and construction works. It also enables engineers in post-process processes to refine structural analysis or finite element model to examine general structural behavior and model dynamic response when necessary.

This dynamic response is closely related to the speed of change in the position of the observation point. Here, the measurement speed of TS, so data sampling recording rate, becomes important. RTS' target orientation, measurement and recording speeds give the total data sampling capacity of the instrument used. As the speed of these three features increases, it will be possible to monitor and record higher frequency dynamic behaviors. As the servo motor properties and software used to develop, it will be possible to monitor the movements even in vibration mode.

Distance and angle values from the observation point to the points to be measured can be measured automatically at certain intervals with RTS. Modern RTSs can measure the angle value with 0.5cc. While angle measurements in the range of 5-10cc can be performed with normal total stations, precise distance measurements can be performed with an accuracy of 0.1 mm and normal distance measurements with an accuracy of 1 mm. With this sampling range and measurement accuracy, RTS will continue to maintain its place as an indispensable measuring instrument in many engineering works as well as in many SHM (Structural Health Monitoring) works (Pehlivan 2019; Zhou et al. 2019).

2.2. Sources of Error in RTS

Total station measurements are affected by instrumental errors and external factors (changes in temperature, pressure and relative humidity). Although these sources of error affect the measurement accuracy, relative position changes can be determined and the direction and magnitude of the movement can be determined. Measurements can be performed with sufficient accuracy in building monitoring studies when instrument errors are minimized and corrections are brought to external factors. With an automated programmable TS, the accuracy of positioning depends on the measured angle and distance measurement accuracy. Angle and distance measurement may also vary depending on the distance made. The type of prism used in measurement may also cause deviations. And therefore it is important to use an appropriate prism depending on the purpose of the measurement.

3. DATA PROCESSING STRATEGY in DETERMINE STRUCTURAL DISPLACEMENTS

Different data processing strategies can be used depending on the expected type of movement in structural motion tracking studies. If slow deformation is expected at a constant rate, the data can be processed in static sessions from a few hours to several days, generally assuming no movement during the session. If the building movement or deformation in question does not pose an imminent threat to the structure or its surroundings or people living in the area, this is usually done after the procedure (Pehlivan 2009).

However, if the movement expected from the structure is expected to be "sudden deformation" for a short period of time and/or "continuous deformation" changes over time, the sampling interval should be increased accordingly. If the deformation could cause the deformed body to fail, a real-time solution is desired to detect the deformation as soon as it occurs and initiate the warning and evacuation processes. In the test study of this work, structural deformations are expected to have a slow character. In normal weather conditions, while the movement is slow, increasing impact loads such as temperature, wind, etc. will cause an increasing effect on the building movements. For these reasons, it is thought that in monitoring the constant and regular motion expected in normal atmospheric conditions, performing our observations with a few minutes sampling interval of RTS measurements will give us the opportunity to capture the expected movements. However, over a relatively short period of time, it can be preferred as a solution in real-time monitoring to detect movements of the structure.

3.1. Determining the Coordinates of the Monitored Point with the Least Squares Method

In the test measurements summarized in Figure 1, simultaneous observations were made at the same observation point (Prism P) by installing two automatic total station instruments at two fixed station points. Two lengths (oblique lengths) and two angle values (horizontal and zenith angles) were recorded over six hours and at equal time intervals. As a function of time, zenith angles and oblique length measurements and horizontal distances S1 and S2 were calculated. Thus, horizontal angles (α1 and α2) and horizontal distances (S1 and S2) have been obtained as time series for each measuring epoch. The linear-angular intersection method was used to determine the coordinates and position accuracies of the P point with these data sets. This is because linear-angular intersection has the advantages of the least-squares method (Ehigiator et al. 2010; Okwuashi et al. 2014).

In these test measurements; the number of observations (S1, S2, α1, α2) is greater than the number of unknowns (Xp, Yp), and the least-squares method can be used to determine the coordinates of the P point. Thus, it is aimed to calculate the balanced coordinate values of the P point and to determine the displacement changes according to time by using the least-squares method. In this section, the formulas for determining the balanced coordinates of the P point by the least-squares method and calculating the displacements are given respectively.

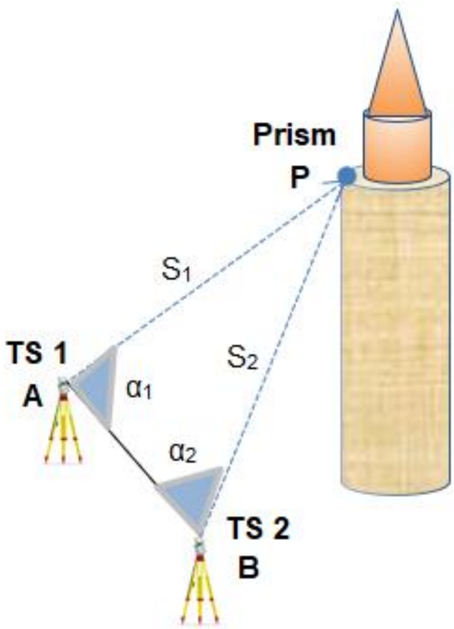

Figure 1. Test measurements and the geometry of angular-linear intersection.

All calculations were made with algorithms developed in the Matlab program. An adjusting model, which can be applied iteratively for each measurement epoch, has been applied in the triangle ABP formed by points A B and P. Since it is assumed that the weights of all measurements are equal, W = I is accepted.

Firstly; The approximate coordinates of the P point are calculated. The coordinates of point P are (Xp, Yp), the coordinates of fixed station points A and B are (XA, YA) and (XB, YB), respectively. The adjusting of these calculated coordinates was done by using the observation equation method. In this correction model (observational least square), the number of equations is equal to the number of observations (n = 4), each equation contains one observation and one or more unknowns. In this case, observations are S1, S2, α1, α2 and unknowns are Xp, Yp.

The two lengths (S1, S2) of the lines in the horizontal projection can be written in a coordinate form as follows:

$$S_1 = \sqrt{(X_P - X_A)^2 + (Y_P - Y_A)^2}$$

$$S_2 = \sqrt{(X_P - X_B)^2 + (Y_P - Y_B)^2} \qquad (1)$$

The horizontal angles (α_1 and α_2) from figure 1 can be calculated as follows:

$$\alpha_1 = cos^{-1}\left(\frac{\overline{AP}^2 + \overline{AB}^2 - \overline{PB}^2}{2\,\overline{AP}\,\overline{AB}}\right)$$

$$\alpha_2 = cos^{-1}\left(\frac{\overline{BA}^2 + \overline{BP}^2 - \overline{AP}^2}{2\,\overline{BA}\,\overline{BP}}\right) \qquad (2)$$

Using the coordinates of the points, we can write equations 2 as follows:

$$\alpha_1 = cos^{-1}\left[\frac{(X_P-X_A)^2+(Y_P-Y_A)^2+AB^2-(X_P-X_B)^2+(Y_P-Y_B)^2}{2\,AB\,\sqrt{(X_P-X_A)^2+(Y_P-Y_A)^2}}\right]$$

$$\alpha_2 = cos^{-1}\left[\frac{(X_P-X_B)^2+(Y_P-Y_B)^2+\overline{AB}^2-(X_P-X_A)^2+(Y_P-Y_A)^2}{2\,\overline{AB}\,\sqrt{(X_P-X_B)^2+(Y_P-Y_B)^2}}\right] \quad (3)$$

The four observational equations given in equations 1 and 3 are nonlinear functions of both parameters and observations; they can be processed by the least-squares adjustment technique. Before starting the solution, approximate values of unknown parameters are calculated. Approximate values of the coordinates of the P point are calculated using the angular intersection according to the following formulas (Ehigiator 2005, Ehigiator et al. 2010):

$$X_P^0 = \frac{X_A\,cot\,\alpha_2 + X_B\,cot\,\alpha_1 - Y_A + Y_B}{cot\,\alpha_1 + cot\,\alpha_2}$$

$$Y_P^0 = \frac{Y_A\,cot\,\alpha_2 + Y_B\,cot\,\alpha_1 - X_A + X_B}{cot\,\alpha_1 + cot\,\alpha_2} \qquad (4)$$

Using these X_P and Y_P values, the approximate values of the observation equations (Lo) are calculated. Then the misclosure vector (L) is calculated as:

$$L = L^0 - L_{abs} \qquad (5)$$

We can express the linearized model in matrix form as follows:

$$V_{4\times1} = A_{4\times2} \;.\; X_{2\times1} + L_{4\times1} \qquad (6)$$

Where; A: the coefficients matrix of parameters, L: the misclosure vector, V: the residuals vector. Matrix A may be computed by differentiation of the four equations with respect to the two unknowns and can be written in the form:

$$A_{(4\times2)} = \begin{bmatrix} \frac{\partial S_1}{\partial X_P} & \frac{\partial S_1}{\partial Y_P} \\ \frac{\partial S_2}{\partial X_P} & \frac{\partial S_2}{\partial Y_P} \\ \frac{\partial \alpha_1}{\partial X_P} & \frac{\partial \alpha_1}{\partial Y_P} \\ \frac{\partial \alpha_2}{\partial X_P} & \frac{\partial \alpha_2}{\partial Y_P} \end{bmatrix} \tag{7}$$

With the Matlab program, the elements of the matrix A (a_{ij}) can be found by differentiating the four observation equations. Then the normal equation system is written like this:

$$N_{2\times2}\ .\ \hat{X}_{2\times1} + U_{2\times1} = 0 \tag{8}$$

Where,

$$N_{2\times2} = A^T_{2\times4}\ .\ W_{4\times4}\ .\ A_{4\times2} \tag{9}$$

And,

$$U_{2\times1} = A^T_{2\times4}\ .\ W_{4\times4}\ .\ L_{4\times1} \tag{10}$$

The solution for the normal equation system (8) is as follows;

$$\hat{X}_{2\times1} = -N^{-1}_{2\times2}\ .\ U_{2\times1} \tag{11}$$

After this, the adjusted unknown parameters can be estimated as follows:

$$\bar{X}_{2\times1} = \hat{X}_{2\times1} + X^0_{2\times1} \tag{12}$$

The vector of adjusted observations can be estimated as follow:

$$\bar{L}_{4\times1} = \hat{V}_{4\times1} + L_{4\times1} \tag{13}$$

The estimated variance factor is:

$$\sigma_0^2 = \frac{V^T.W.V}{r} = \frac{V^T.W.V}{2} \tag{14}$$

The estimated variance-covariance matrix of the parameters is as follows:

$$C_X = \sigma_0^2\ .N^{-1} \tag{15}$$

And as a result, the variance-covariance matrix of adjusted observations are computed follow as:

$$C_L = A\ .C_X\ .A^T \tag{16}$$

Like the other operations above, this normal equation (16) can be solved using the Matlab program too. The positional error at point P can be calculated using the following equation (Allan 1988):

$$M_P = \frac{b\ m''_\alpha}{\rho''\sin\gamma}\sqrt{sin^2_{\alpha_1} + sin^2_{\alpha_2}} \tag{17}$$

Where; b: base line (the distance between total stations) (b=AB length in figure 1); m_α'': mean square error of measured horizontal angles (taken from specifications of the used total stations); α_1: the horizontal angle at point A, α_2: the horizontal angle at point B, γ: the horizontal angle at point P and ρ''=206265 "from the small angle formula" (Ehigiator et al. 2010).

In order to accept the observations of the point P from the triangle ABP and its adjusted coordinates to be sufficiently accurate, the coordinates must satisfy the following condition (Ashraf 2010).

$$r_P = \sqrt{\Delta_x^2 + \Delta_y^2} \leq 3\ M_t \tag{18}$$

Where;

$$\Delta_X = X_i^P - X_k^P\ ,\ \Delta_Y = Y_i^P - Y_k^P \text{ ve } M_t = \sqrt{M_i^2 - M_k^2}\ ,$$

X_i^P , Y_k^P: the adjusted coordinates of the point P at the time i of measurement; X_i^P, Y_k^P: the adjusted coordinates of the point P at the time k of measurement; M_i and M_k : the position errors of the point P at the time i and k of measurement (Ashraf 2010).

3.2. Determining the displacement vectors of the observed point

If we consider the position changes in 2 dimensions, let's assume that two coordinate values x_i,y_i and x_k,y_k are recorded at an observation point at times i and k. The displacements of the observation point between the time i and k will be dn (Δx, Δy).
The coordinate displacements from the coordinates obtained at time i and k in the time interval $\Delta_t = t_k - t_i$;

Δx = x_k - x_i, displacement on the x-axis
Δy = y_k - y_i, displacement on the y-axis
Δt = t_k - t_i, time difference between measurements.

Expressed as the coordinate differences of point displacements, each of Δx, Δy denotes a motion vector. And and each of them has a magnitude and direction. Collectively, these vectors define the field of displacement in a given time interval.
Comparison of the magnitude of the calculated displacement and the associated measurement accuracy indicates whether the detected motion is more likely due to measurement error:

$$|\ dn\ | < (pn) \tag{19}$$

Where; dn is the magnitude of the displacement (for point n), (pn) = maximum size of the combined 95% confidence ellipse for point n = (1.96).

$\text{pn} = \sqrt{\sigma f^2 + \sigma i^2}$ and σf (next) or standard error in position for the last measurement, σi (previous) or standard error in position for reference measurement.

4. EVALUATION of EXPERIMENTAL TESTS RESULTS

Test data were collected with the measuring setup given in Figure 1 using two automatized total stations installed at points A and B. Horizontal-zenith angle observations and oblique distance measurements, from points A and B whose coordinates are known to the monitoring point P on the tower, was recorded with a measurement recording period of 2 minutes. The data sets obtained as time series were pre-audited and each observation data set was inspected within itself. The time series consisting of 2 angles and 2 lengths were resampled with a sampling interval of 30 minutes. In other words, 30-minute new data sets were created by taking the average of 15 measurement values recorded every 30 minutes. Thus, it was aimed to determine the change of total displacement according to time with the observation sets created during the measurement period and providing also ease of operation.

For this purpose, adjusted coordinate values (Xp, Yp) and position errors (Mp: equation 17) of the observation point P were calculated for each half-hour time between 11:00 and 17:00 using the least-squares equations model (given in section 3.1). The adjusted coordinates calculated from the observations obtained during the observation period are presented in Table 1. Measurements that started at 11 o'clock were completed at 17:00 and coordinate values were calculated every 30 minutes. Since the position errors for each epoch depend on approximately the same parameters, approximately the same values were calculated (Mp=∓3.825 mm).

To test the accuracy of the adjusted coordinate values; The rp and Mt values given in equation 18 were calculated using the position errors calculated for each measurement period of the P point (Mt= 5.41 and 3*Mt= 16.23). As a result of the comparison and evaluation; It has been accepted that the observations made to point P in triangle ABP and its adjusted coordinates are sufficiently accurate. The corrected coordinates calculated from the data recorded during the observation period and their accuracy test results are presented in Table 1. The measurements that started at 11 o'clock were completed at 17:00 and the raw and corrected coordinate values calculated every 30 minutes and the differences between them are shown in Table 1.

Table 1. The adjusted coordinates and position errors of the observed point P

Time	$X_{adjusted}$	X_{raw}	$Y_{adjusted}$	Y_{raw}	dx	dy	$r_P \leq 3 * M_t$
11:00	914.2165	914.2132	449.4410	449.4440	-3.30	3.00	4.46
11:30	914.2163	914.2129	449.4381	449.4430	-3.40	4.90	5.97
12:00	914.2162	914.2123	449.4350	449.4364	-3.90	1.40	4.14
12:30	914.2162	914.2119	449.4324	449.4303	-4.30	-2.10	4.79
13:00	914.2159	914.2107	449.4311	449.4272	-5.20	-3.90	6.50
13:30	914.2161	914.2116	449.4297	449.4239	-4.50	-5.80	7.34
14.00	914.2174	914.2172	449.4297	449.4242	-0.20	-5.50	5.50
14:30	914.2171	914.2162	449.4302	449.4257	-0.90	-4.50	4.59
15:00	914.2170	914.2154	449.4314	449.4282	-1.60	-3.20	3.58
15:30	914.2182	914.2203	449.4336	449.4328	2.10	-0.80	2.25
16:00	914.2189	914.2232	449.4373	449.4407	4.30	3.40	5.48
16:30	914.2200	914.2280	449.4390	449.4454	7.99	6.40	10.24
17:00	914.2204	914.2299	449.4408	449.4494	9.57	8.60	12.87

In order to determine the structural displacements between the data that passed the accuracy-test and the measurement epochs, the coordinate differences for the periodic times were calculated separately for the X and Y directions (Table 2). The magnitude of the displacement (dn) at each periodic n point was calculated and tested by equation 19 and the results are presented in Table 2. According to Table 2, the displacements between the measurement epochs remained within the 95% confidence ellipse in magnitude. The displacements of the P point in the X and Y directions are presented in Figure 2. Accordingly, the total is the magnitude of the displacement from the adjusted coordinates of the P observation point were calculated as 24.60 mm. According to these calculated results, it has been determined that the structural displacement was approximately 2.5 cm from the six-hour measurements performed with the RTS. The representation of position changes with respect to time on the X/Y plane is presented in Figure 3.

Table 2. Displacement magnitudes of the observation point P

Time	Δx (mm)	Δy (mm)	|dn| < (pn=16.23)
11:30	-0.25	-2.90	2.91
12:00	-0.13	-3.19	3.19
12:30	-0.07	-2.57	2.57
13:00	-0.28	-1.28	1.31
13:30	0.23	-1.458	1.47
14.00	1.29	0.09	1.29
14:30	-0.29	0.43	0.52
15:00	-0.16	1.19	1.20
15:30	1.21	2.20	2.50
16:00	0.75	3.71	3.79
16:30	1.06	1.76	2.06
17:00	0.46	1.74	1.80

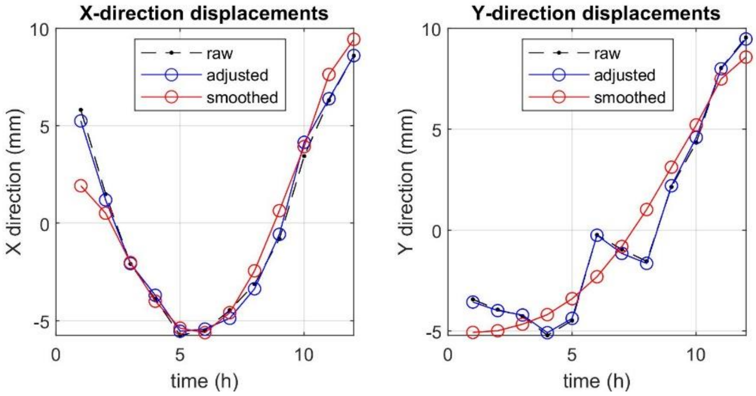

Figure 2. Displacements in X and Y directions with recorded raw data, adjusted and corrected coordinates.

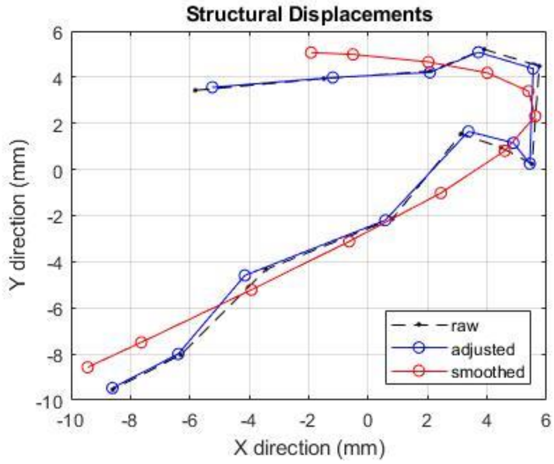

Figure 3. For observation point P, plotted positional displacements with recorded raw data, adjusted and corrected coordinates.

5. CONCLUSION

Continuous or periodic monitoring of buildings and determining their deformation characteristics will provide an important foresight for building health and life safety. Achieving the desired performance in structural monitoring depends on the use of correct measurement systems and correct analysis methods. It is a known fact that incorrect analysis of measurement data prevents some deformations from being noticed. The monitoring period and the most appropriate measurement system should be selected, taking into account the structural features, and should be evaluated with the most appropriate analysis methods.

Total stations with robotic features are proven instruments in structural deformation measurements. Although it has some handicaps during measurement, it is one of the first devices that comes to mind in structural deformation studies due to its measurement precision and practical measurement possibilities. The analysis process of the data recorded with RTS is also an important issue in order to make an accurate deformation estimation.

Within the scope of this study, structural monitoring data recorded for 6 hours under normal meteorological conditions were analyzed. The displacement vectors of each measurement time were calculated by calculating the coordinate values and mean errors balanced by the least-squares method. As a result of analysis and evaluation; It was concluded that the movement of the structure was within the known and predicted limits and the measurements were made with sufficient accuracy

Author contributions

All contributions belong to the author in this paper.

Conflicts of interest

The author declare no conflicts of interest.

Statement of Research and Publication Ethics

The author declare that this study complies with Research and Publication Ethics

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