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Precision Comparison and Analysis of Reflector-less Total Station Observations

تحليل ومقارنة دقة أرصاد جهاز المحطة المتكاملة بدون عاكس

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الملخص:

الهدف من هذا البحث هو تحديد مدى دقة ارصاد جهاز محطة الرصد المتكاملة بدون عاكس خلال عملية رصد المنشات الهندسية , كما تهدف ايضا لدراسة تأثير زاوية ميل السطح العاكس و لونة و نوع مادتةه على دقة القياسات. و من خلال هذة الدراسة تم تطوير معادلة لتمثيل مدى تاثير هذة العوامل على القياسات , و قد تم تحويل نتائج هذا البحث الى مجموعة من الجداول و المنحنيات .

وقد تم استنتاج ان السطح العاكس ذو اللون الابيض له نسبة انعكاس اكثر من باقى الالوان , و ايضا تم استنتاج ان السطح المعدنى الغير مطلى له اقل تاثير .

Abstract:

In order to achieve the results that meet the specifications of given project, such as setting out and monitoring the structural deformation, the knowledge of reliability and accuracy of surveying equipment is inevitable. Reflector-less total station are widely used nowadays for several applications in geodetic engineering due to its highly accurate and fast measurements. A shortcoming is that it gives less accurate measurements in some cases of observations. The point position determination using reflector-less total station is subjected to some uncertainty due to angle of observation, incidence angle of signal to the surface, distance from the instrument to the point, instrument precision and material of reflecting surfaces.

This paper investigates the accuracy of reflector-less total station observations during the process of monitoring and setting out of engineering structures. This paper is performed also to find out the effect of inclined angle of reflecting surface, its color and type on the accuracy of reflector- less total station measurements. It has been converted to a group of charts that assure the accuracy required in determining the point coordinates. A formula is developed to represent the effect of these parameters on the uncertainty of the observations. The results of the practical measurements, adjustment and analysis of the observations are also presented.

From the results, It can be concluded that the white reflector surface have stronger reflectivity than any other surface. The unpainted metal target was the worst reflecting surface and the brick target was the best surface.

Keywords
Reflector-less total station, monitoring, setting out, accuracy and structural deformation.

1. Introduction:

The deformation of structures needs to be measured precisely in order to determine the structure's stability and safety. Monitoring surveys for deformation measurements of deformable bodies has been used for the verification of material parameters, determination of causative factors, and determination of deformation mechanisms [6]. Therefore monitoring of such geometric imperfection is important for decisions concerning the structure maintenance or its liability to be service

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[1]. Ground surveying is a viable method that can be used to determine the structural deformation [5]. The precision of the measured deformation depends on the accuracy of the applied surveying observations technique, the precision of the instrument used and the adjustment technique.

One of the advanced available accurate surveying instruments is the reflector-less (also known as prism-less) total station. Unlike conventional total stations or electronic theodolites, which require a prism to return the distance measuring signal, the reflector-less signal does not require a prism but can simply reflect off almost anything. The main advantage of such reflector-less instruments is the ability to measure inaccessible points [3]. There could be any number of reasons that points are inaccessible, including safety concerns, detail surveys of busy road intersections where traffic control is undesirable or impossible and simply finding locations of jetty piles where access simply isn't possible. The problem arises then, of the accuracy that is given by such technological techniques. Whereas most survey measurements either are or at least can be checked for errors, reflector-less measurements, by their very nature of being inaccessible, are very hard to check. How then, can we rely upon such measurements, especially when high accuracy results are essential, and even simple checks like using a tape measure between two distinct points is impossible.

The main object of this paper is to develop guiding charts to relate the main parameters that affect the accuracy of reflector-less total station observations during the process of structure deformation monitoring and setting out.

The principle of work of reflectorless total station is determining the position of any point B in three dimension coordinates (X, Y and Z) from its basic measurements (horizontal and vertical angles together with slope distances) without using reflectors (prisms).The coordinates of point (B) can be determined as following [2]:

$$\left.\begin{aligned} X_B &= X_A + S\cos\gamma\sin\alpha \\ Y_B &= Y_A + S\cos\gamma\cos\alpha \\ Z_B &= Z_A + S\sin\gamma \end{aligned}\right\} \qquad (1)$$

Where: X_B, Y_B, X_B – the coordinates of observed point B; X_A, Y_A, Z_A – the coordinates of the occupied station A; γ, α, S – the vertical, horizontal angles and inclined distance respectively.

Equations (1) have three unknown parameters (X_B, Y_B, X_B) and three observations. So there is no redundancy of observations, then the multivariate propagation technique (Jacobean method) will be used to determine the accuracy of coordinates of point B [7]:

$$C_{X_{(3,3)}} = J_{(3,3)} \cdot C_{l_{(3,3)}} \cdot J^T_{(3,3)} \qquad (2)$$

Where: C_X – variance-covariance matrix of unknowns, J- Coefficient matrix (Jacobean coefficient), C_L – variance-covariance matrix of unknowns.

Then, by differentiate equations (1) and substitute in equation (3), the following formulae can be deduced;

$$m_X^2 = (\sin\alpha\cos\gamma)^2 m_S^2 + (S\cos\alpha\cos\gamma)^2 m_\alpha^2 + (-S\sin\alpha\sin\gamma)^2 m_\gamma^2$$

$$m_Y^2 = (\cos\alpha\cos\gamma)^2 m_S^2 + (-S\sin\alpha\cos\gamma)^2 m_\alpha^2 + (-S\cos\alpha\sin\gamma)^2 m_\gamma^2$$

$$m_Z^2 = (\sin\gamma)^2 m_S^2 + (S\cos\gamma)^2 m_\gamma^2 \qquad (3)$$

Where: m_S, m_α, m_γ – standard deviation (accuracy) of inclined distance, vertical and horizontal angles of the used instrument respectively.

The values m_S, m_α, m_γ can be taken from the specifications of the instrument or experimental tests. In structural deformation monitoring, it is recommended that these values must be calculated experimentally.

From the laws of reflection, the incident ray emitted from reflector-less total station and the normal to the reflection surface at the point of the incidence lie in the same plane and the angle which the incident ray makes with the normal is equal to the angle which the reflected ray makes to the same normal [8]. Therefore, the incidence angle, type and color of the reflecting surface will substantially affect the energy of reflected ray from this surface to total station and consequently the accuracy of instrument observations. So, it is necessary to investigate the effect of inclined reflecting surfaces which are made from different materials and painted in different colors on total station observations.

2. Comparison the accuracy of total station observations with reflector and reflector-less ability

To study practically the accuracy of total station for measuring distance with the ability of reflector less and compare the accuracy of observations, base line is chosen between two fixed points with the length not less than 200 meters. The line was divided into 6 sections with unequal length. Total station is fixed at first station of the base line and six marks will be established at different distances from the instrument 10 m, 25 m, 50 m, 100 m, 150 m and 220 m. At each mark position, the inclined distance from the instrument to the mark was measured 25 times with reflectorless ability. After finishing reflectorless observations the software of the instrument was changed to reflector observations and the same procedure will be done for all marks. The same procedure of practical work was repeated several different times of the day for prism and non-prism observations. For each position of marks, the mean square error will be calculated by using formula [4].

$$m_D = \sqrt{\frac{\sum_{i=1}^{n} v_i^2}{n-1}} = \sqrt{\frac{\sum_{i=1}^{n} (D_i - \bar{D})^2}{n-1}} \qquad (4)$$

Where: m_D - mean square error of observations, n - number of measurements, V_i - the difference between observations distance (i) and the mean of all observations.

Based on the results of experimental work, graphical representation is constructed where X-axis express the distance between instrument and the target and Y-axis express the mean square error of the measured inclined distance .

From Fig.1, it is seen that increasing the distance between total station and the observed target increases the errors in measurements and the accuracy of observations with reflector ability is better by 23.7 % than observations with reflectorless ability.

Based on the results of the experimental study, formula for determining the errors of the observation resulted from reflectorless total station can be established. The derived equation of mean square errors are formed and satisfied by the method of least square technique, depending on the distance from total station to the target for different conditions of observation, as shown in Table (1).

3. Studying the influence of incident angle variation on the accuracy of reflector less total station observations

To find out the effect of inclination of the incident laser beam on the laser spot size as shown in figure (3), two different positions is preformed:

(a) When the laser ray emitted from total station fall down perpendicular on the reflecting plane (θ)) i.e. the incidence angle equal zero), the laser spot will be circle (fig. 3).

(b) When the laser ray is falling with inclined angle (or is falling in inclined surface), the laser spot of this ray will have ellipse figure. Parameters of this ellipse depend mainly on the inclination angle and the distance from instrument to the monitored object.

This section is carried out to study the effect of incidence angle (In horizontal and vertical projection) on the accuracy of slope distance measured by total station with the ability of reflectorless observations .To achieve this goal, two tests have been done:

a) Effect of horizontal angle variation on total station observations accuracy

The first test was performed to investigate the effect of horizontal angle variation and consequently the incidence angle of laser beam in horizontal projection on the accuracy of measured slope distance measured by total station with reflectorless ability. The used total station is Geomax, which has the following abilities [3]:

- Least count of vertical and horizontal angles = $1^{//}$
- Specified accuracy for measuring distance (with reflector ability) = 2 mm ± 2 ppm
- Specified accuracy for measuring distance (with reflector ability) = 3 mm ± 3 ppm (up to 250 m)

In this test, total station was fixed at distance (D) from the monitoring object and the telescope was aimed to the object with different horizontal angles (varied from 0˚to 60˚, gradually each 5^o) (Fig. 4). At each horizontal angle, the slope distance from the instrument to the object was measured 25 times. The test was repeated at three different distances from total station to the object (20, 55, 72 m), the mean square error of slope distance observations for all observations epochs was calculated.

Based on the results of experimental work, graphical representation is constructed, where the X-axis expresses the horizontal angle from instrument to the observed object and the Y-axis expresses the mean square error of the measured inclined distance (Fig. 5).

The results show that increasing the horizontal angle leads to increase the errors of slope distance measured by reflector less total station at any distance.

b) Effect of vertical angle variation on total station observations accuracy

The second test is performed to find out the effect of vertical angle variation on the accuracy of slope distance measured by total station with reflectorless ability. As shown in Fig. 3, the vertical angle was varied several times from 0˚to 40˚by 5˚ gradually. At each angle the slope distance was measured 25 times at several distances from the object and the mean square error was determined for each angle variations. Based on the results of experimental work, graphical representation is constructed (Fig. 6).

Figure (6) shows that increasing the vertical angle leads to increasing the errors of slope distance measured by reflector less total station at any distance.

4. Studying the influence of the reflecting surface color and type on the accuracy of reflectorless total station observations

The laser beam emanates from the emitter of reflectorless total station and is reflected from the surface of the object and returns to the instrument. The angle of laser beam reflection equals the angle of depression; therefore the type and color of the reflecting surface will substantially affect the energy of the reflection of the laser beam. So, setting out and monitoring the deformation of cylindrical structures and domes with reflectorless total station requires investigating the effect of inclined surfaces which are made from different materials and painted in different colors. This section is performed to find out the effect of type of reflecting surface and its colors on the accuracy of slope distance measured by reflectorless total station. To achieve this goal, two tests have been done.

The first test is performed to study the effect of reflecting surface color on the accuracy of measured slope distance. To simulate the reflecting surface of structures with different colors, six rectangular targets with different colors were selected (white, red, black, brown, grey and yellow). For field data collection, the following procedure has been developed.

Colored targets were set at different distances in increments of approximately 20 meters. The inclined angle of the targets at all positions was equal to zero. For each color, 25 measurements of slope distance were taken at each target position for each color. Based on the results of experimental work, graphical representation is constructed, where the X-axis expresses the distance from instrument to the target and the Y-axis expresses the mean square error of the measured slope distance. The graph is constructed for all target colors as shown in Fig. (7).

As seen in figure 7, increasing the distance between the total station and the target leads to increase the errors in measuring the slope distances of all colors. The resulting accuracy of measured slope distance for the white surface is higher than the accuracy of any other surface color; hence this surface has the strongest reflectivity for reflectorless total station ray as compared with any other surface. The surface of the black target has a very low-reflectivity, so it absorbs more energy.

The second test was carried out to investigate the influence of the type of reflecting surface material on the accuracy of slope distance measured by reflectorless total station. To simulate the different types of reflecting surface materials, eight different targets made from different materials were selected (brick, reinforced concrete, wood, gypsum board, plastic, ceramics, painted metal and unpainted metal targets).

All the targets are fixed in the same position at distance 11.296 m from total station. The inclined angle for all targets is kept to equal zero. For each target, the observations of slope distances were measured 25 times. The mean square error is calculated for each material type and listed in table. It is deduced that the surface material type has a great influence on the accuracy of reflector less total station observations, for example the unpainted metal target was the worst reflecting surface and the brick target was the best.

It is deduced that the surface material type has a great influence on the accuracy of reflectorless total station observations, for example the unpainted metal target was the worst reflecting surface and the brick target was the best.

5. Study the accuracy of reflectorless total station for deformation monitoring

An important step in process of setting out and monitoring the structural deformation of engineering structures is the selection of used instrument and its accuracy (Beshr, 2012). The manufacturer’s specifications of the accuracy of reflectorless total station nowadays are not very high which ranges about 2 mm ± 2 ppm for distance measurements up to 300 m without reflector. So some experiments must be done to determine the performance of the reflectorless total station under conditions comparable to those expected during construction of the actual detectors. These tests measure the accuracy of the instrument within a reference frame established with a set of highly accurate control measurements.

Between each two epochs of structural deformation observations of any structure, the expected vertical and horizontal movement of monitoring points was a few millimeters or centimeters. To detect point movement successfully and with confidence, it was imperative that the sensitivity of the reflectorless total station in detecting the motion of deforming targets was assessed. In this section, a subsiding object was simulated to examine the reflectorless total station aptitude at detecting the motion of two targets.

Four targets were fixed on vertical wall. The distances between marks are shown in figure (8). The distance between targets was measured with high accurate instrument before the test. For all sensitivity analysis tests, the tested reflectorless total station was positioned approximately 5 meters away from the wall. The two marks A and B will be fixed during all observation epochs. These two fixed targets were included as a measure of control against the two deforming targets.

The main idea of the experiment that the two targets at points C, D (Fig. (8) ill move by known distance in the directions X, Y by different values while the two marks A, B will be fixed without movements. Point C will be moved in vertical direction but point D will be moved in horizontal (Fig. 8). The vertical and horizontal displacements must be measured by high accurate instrument (for example vernier with accuracy less than 0.1 mm). The first deformation sensitivity analysis involved lowering the targets by large increments approximately 100 mm, 80 mm, 50 mm, and 30 mm for point C (as vertical movement) and approximately 90 mm, 75 mm, 60 mm, and 35 mm for point D (horizontal movement). On the other hand, the targets were lowered by small increments 20 mm, 15 mm, 8 mm, 5 mm for point C and by 18 mm, 14 mm, 7 mm and 4 mm for point D. for each targets movement, the four targets were observed by vernier and reflectorless total station.

The first observations epochs the four targets were observed where all were held fixed in position. The remaining epochs were acquired with the targets changed (moved).

The accuracy of total station with reflectorless ability during the process of setting out and monitoring can be determined by comparing the accuracy of the calculated distance between reflective targets resulted from coordinates measured by total station and the calculated distance from other accurate instrument (vernier with accuracy 25*0.01 mm).

The length of side, from its end coordinates can be calculation by

$$S = \sqrt{(X_j - X_i)^2 + (Y_j - Y_i)^2 + (Z_j - Z_i)^2} \quad (5)$$

By differentiation equation (5) and by using propagation law, the accuracy of the side length between two points can be determined by using the following formula:

$$m_S^2 = \left(\frac{X_j - X_i}{D}\right)^2 m_{X_j}^2 + \left(\frac{X_i - X_j}{D}\right)^2 m_{X_i}^2 + \left(\frac{Y_j - Y_i}{D}\right)^2 m_{Y_j}^2 + \left(\frac{Y_i - Y_j}{D}\right)^2 m_{Y_i}^2 + \left(\frac{Z_j - Z_i}{D}\right)^2 m_{Z_j}^2 + \left(\frac{Z_i - Z_j}{D}\right)^2 m_{Z_i}^2 \quad (6)$$

The deformations of each point (C and D) for all epochs are calculated using the formulae (5), and the accuracy is determined by equation (6). The final results can be shown table (3).

From table (2), it is deduced that the difference of measured distance between two points (deformation value) resulted from vernier and total station with the ability of reflectorless is small. Maximum difference value is 1.1 mm and minimum value 0.05 mm.

Conclusions

Based on the analysis of the theoretical and experimental study, the following conclusions can be summarized:

1. Total station can perform reflector-less slope distance on different surface made from different material and painted with different colors with satisfied accuracy. The accuracy of slope distance and angles measurements by this instrument is less than the specified value of accuracy in its specifications.

2. Accuracy of reflector less total station observation depends mainly on the power of the signal, which is reflected from the reflecting surface. The intensity of the returning signal depends on the distance from total station, and reflectivity of reflecting surfaces which have different color and made from various materials. It is found that the white reflecting surfaces have a stronger reflectivity surface than any other surface. Increasing the horizontal angle and vertical angle also provides an increase in measurement errors.

3. Achieving the required accuracy for geodetic monitoring technique of Highway Bridge is based on the following factors:

a. The used instruments specifications (Instrument resolution, data collection options and the proper operating instructions).

b. The field observing and modeling procedures. Measurements and adjustment techniques of the network have direct influence on the detection of monitoring point’s displacements;

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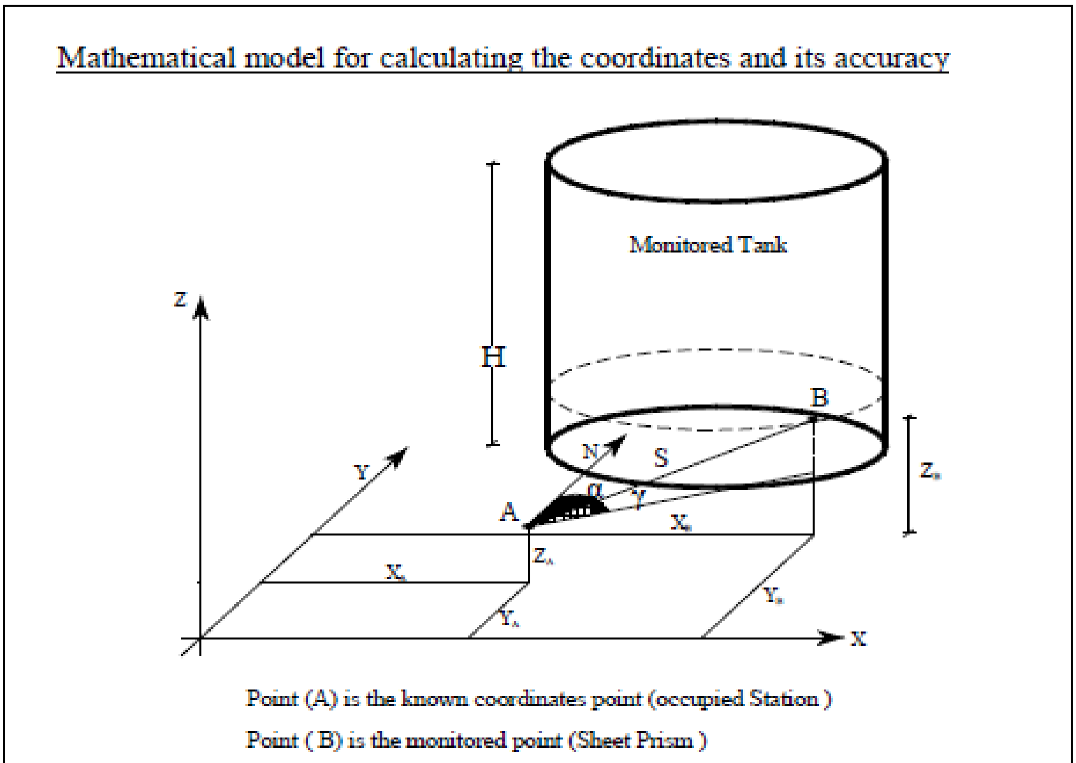


Figure (1) Geometry of observations using one total station technique

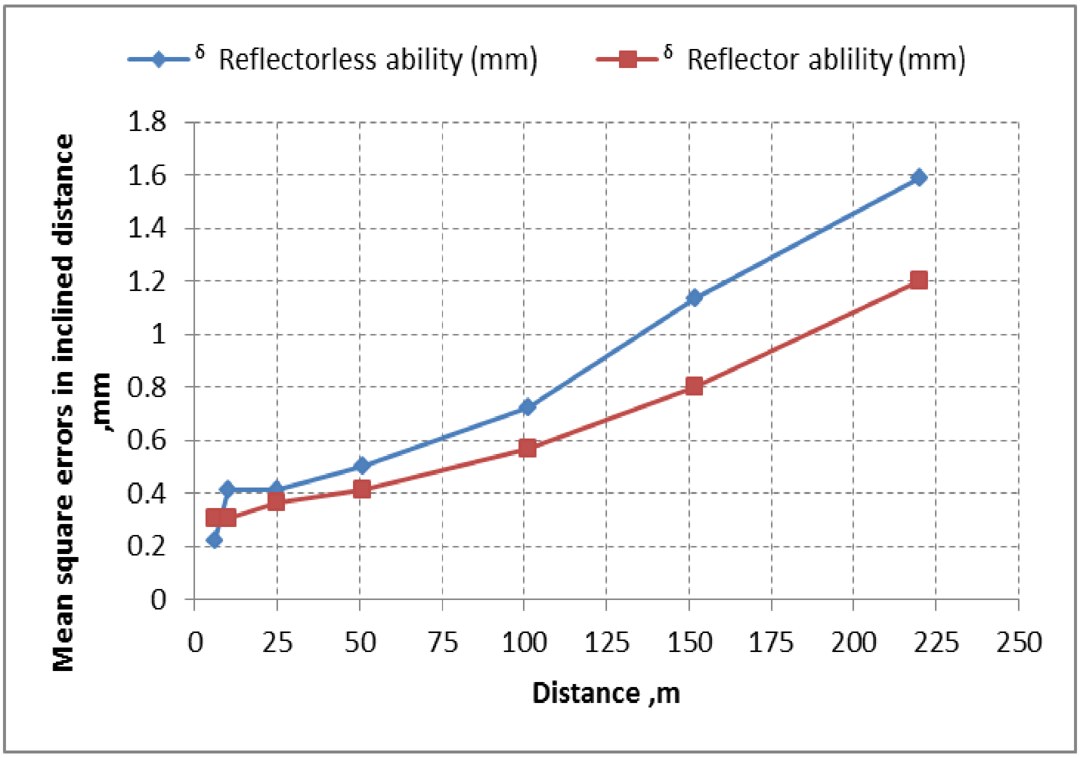


Figure (2) Comparing the accuracy of total station observations for measuring distance with reflector and reflector-less ability

Table (1) The equation of mean square errors resulted from reflectorless total station based on the distance to the target.

Measurement conditions	Derived equation of errors ,where D in m	Correlation factor (R)
Observation with reflector ability	$m_D = 0.004\ D + 0.2421$	0.9854
Observation with reflector less ability	$m_D = 0.0059\ D + 0.237$	0.9776

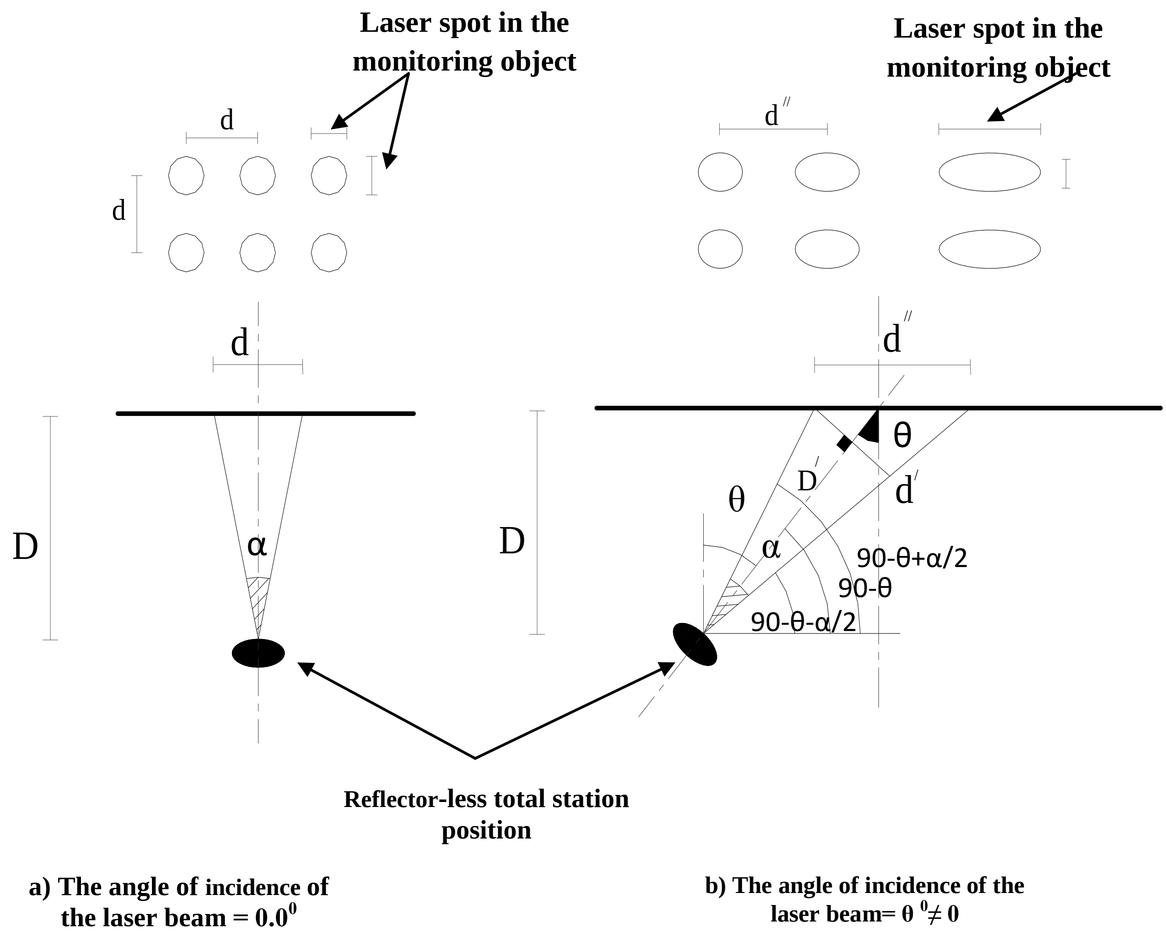
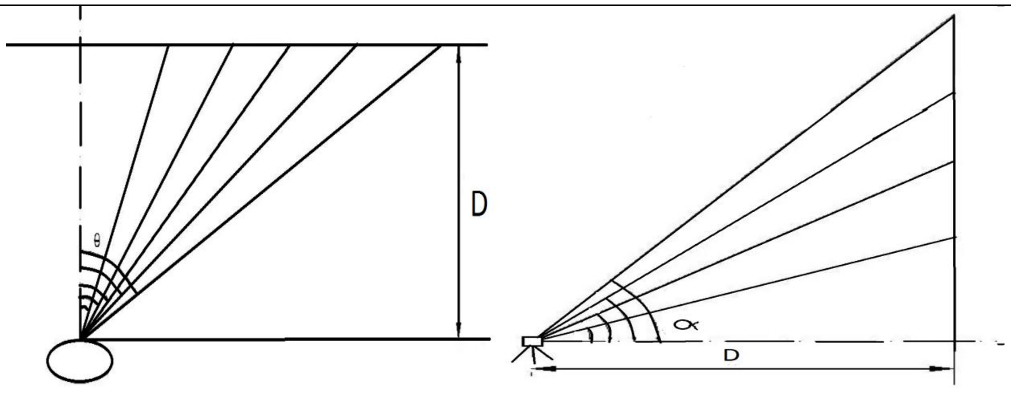


Figure (3) Effect of inclination of the incident laser beam on the laser spot size on the monitoring object



(a) Horizontal angle **(b) Vertical angle**

Figure (4) Effect of incidence angle (horizontal and vertical angles) at different distances (D) on the accuracy reflectorless total station observations

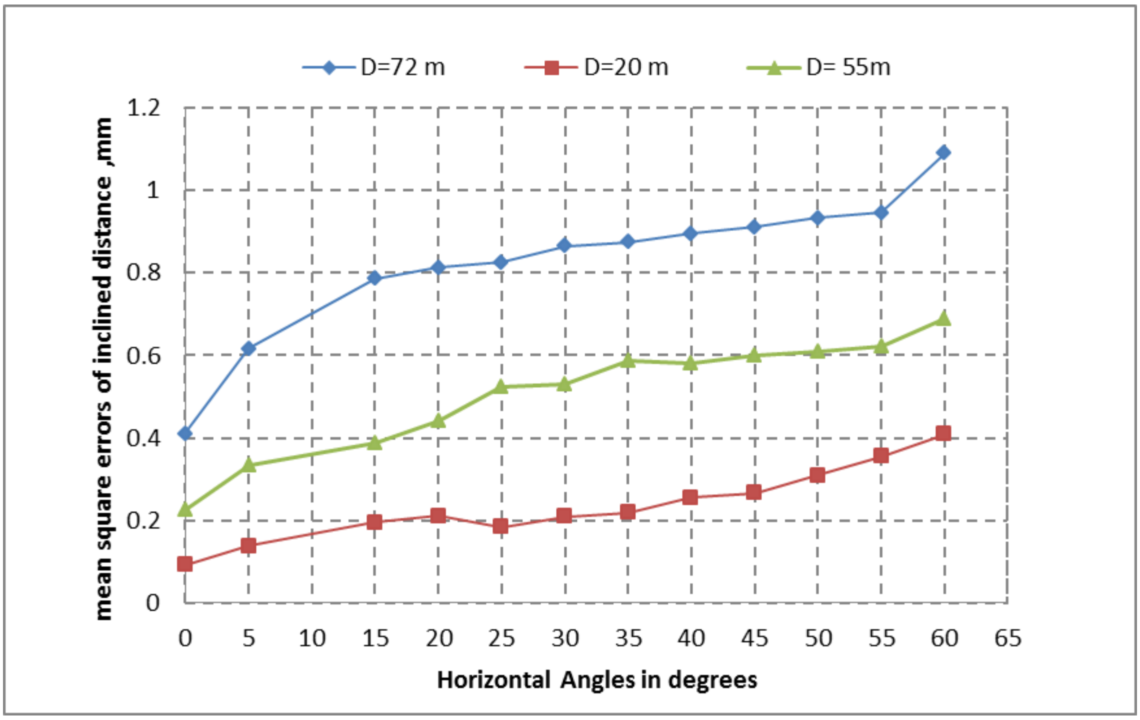


Figure (5) Effect of horizontal angle on the accuracy of reflector less total station

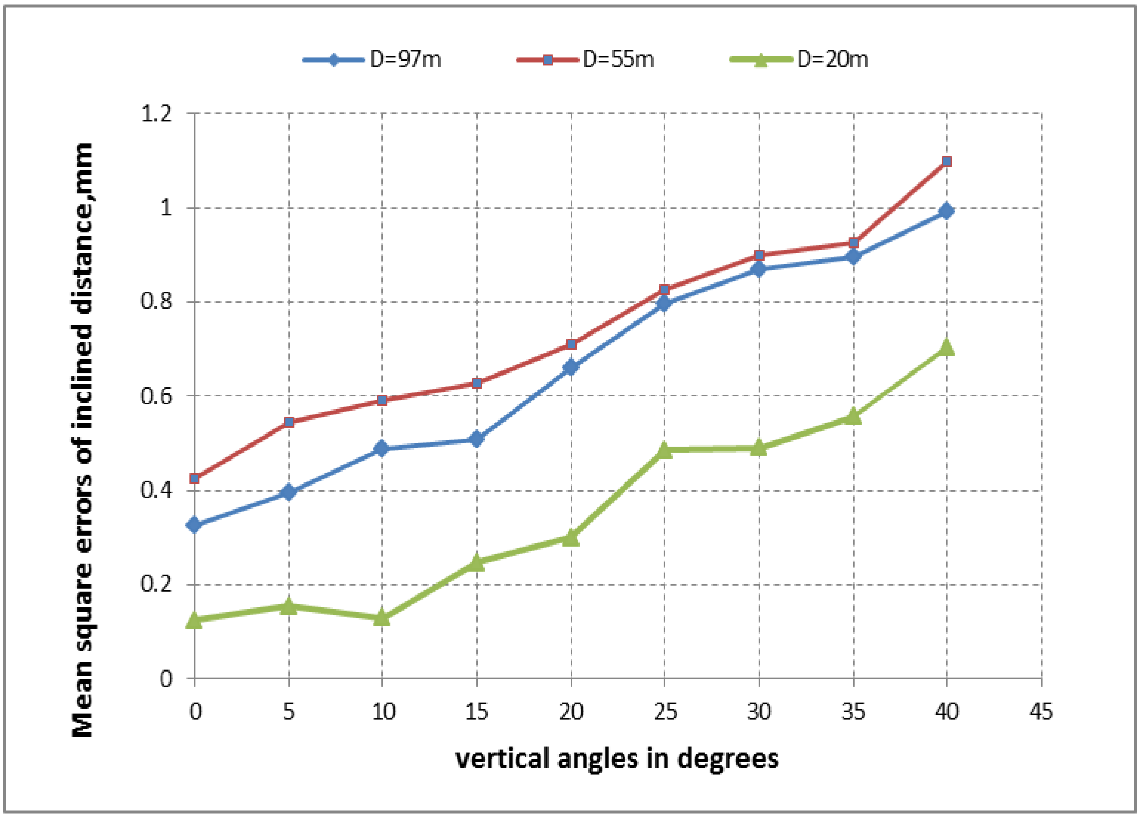


Figure (6) Effect of vertical angles variation on the accuracy of reflectorless total

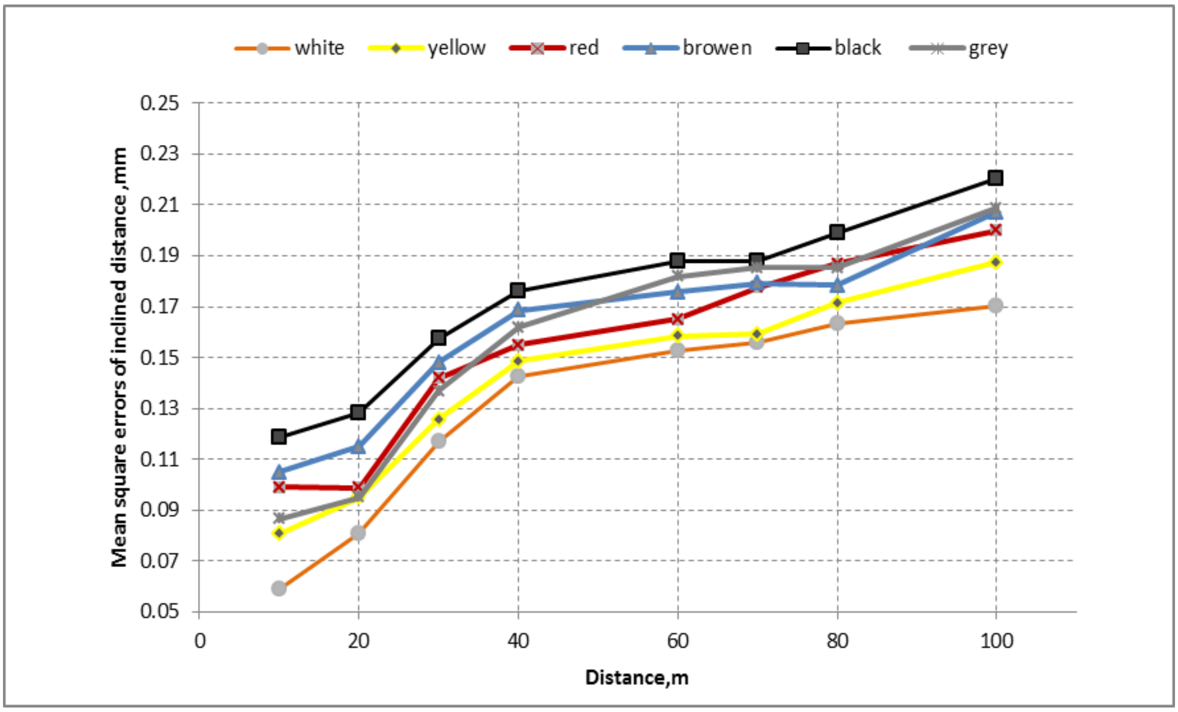


Figure (7) Comparing the mean square errors of inclined distance by reflectorless total station for different colored targets.

Table (2) The mean square errors of slope distance measured by reflector less total station for different materials

Type of target material	Mean square error, mm
Brick target	±0.198
Reinforced concrete target	±0.306
Wood target	±0.268
Gypsum board target	±0.251
Plastic target	±0.262
Ceramics target	±0.232
Painted metal target	±0.357
Unpainted metal target	±0.406

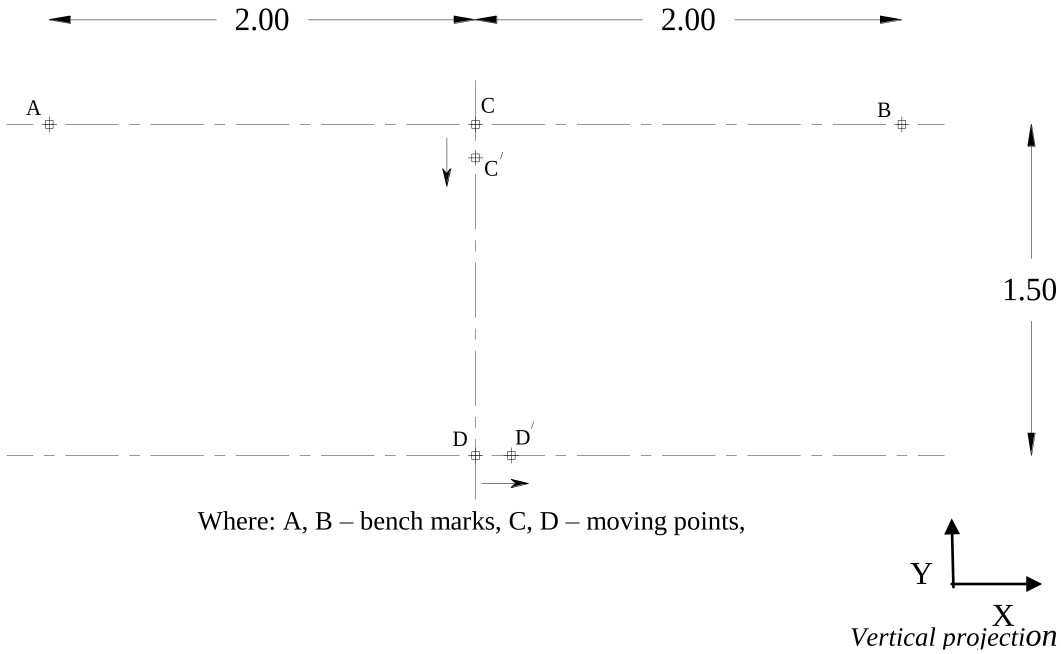


Figure (8) The distribution of marks for testing reflectorless total station for deformation monitoring

Table (3) Comparison the deformation values resulted from reflectorless totals station and vernier

Distance		Proposed movements, mm	Distance from Vernier, mm	Calculated distance from coordinates, mm	Difference of distance between vernier and coordinates, mm
C – C/ Vertical movement	**large increments**	**100**	**100.19**	**100.5**	**0.31**
		80	**79.82**	**80.2**	**0.38**
		50	**50.04**	**51.1**	**1.06**
		30	**30.25**	**30.6**	**0.35**
	small increments	**20**	**19.90**	**20.2**	**0.3**
		15	**15.21**	**15.5**	**0.29**
		8	**8.10**	**8.8**	**0.7**
		5	**4.84**	**5.7**	**0.86**
D – D/ Horizontal movement	**large increments**	**90**	**90.52**	**90.8**	**0.28**
		75	**74.85**	**75.1**	**0.25**
		60	**60.10**	**61.3**	**1.2**
		35	**35.8**	**36.2**	**0.4**
	small increments	**18**	**18.15**	**17.8**	**-0.35**
		14	**13.92**	**14.0**	**0.08**
		7	**7.15**	**7.2**	**0.05**
		4	**4.20**	**5.1**	**0.9**