EFFECT OF ATMOSPHERIC CONDITIONS ON ELECTROMAGNETIC DISTANCE MEASUREMENTS

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ABSTRACT

Electromagnetic distance measurement (EDM) has become an important tool, which has been used for modern surveying technology in the last two decades. It is still browsing for more use in civil engineering and urban projects.

This paper is basically devoted to investigate the errors that may arise in EDM due to the change in atmospheric conditions. In order to achieve higher accuracy and best results in that phase, treating such errors by eliminating or minimizing their effect is a must.

For this purpose, a theoretical study on the effect of the change of the refractive index and a limited practical fieldwork were carried out. Also, representation and determination of the elements of atmospheric refraction was highlighted. Moreover, the correlative relations between the atmospheric refraction and the arising systematic errors in EDM observations were illustrated.

Keywords: EDM, Refractive index, Temperature gradient, Wave path height, Errors.

INTRODUCTION

A radio wave that propagates through the earth's atmosphere encounters variations in the atmospheric refractive index along its path. This changes the propagation speed and bends the ray path [1]. These changes cause systematic errors, which are directly proportional to the measured distance. The main external elements, which play a role on the accuracy of EDM observations in this phase, can be summarized as follows:

1- Refractive index
2- Nature of ground surface
3- Height of line of the wave path over the surface
4- Value of temperature gradient

The effect of refractive index will be discussed theoretically, while the effect of the other external elements will be discussed using a limited experimental work, which explain the effect of each component.

DEFINITION AND EFFECT OF REFRACTIVE INDEX

In vacuum, all electromagnetic waves travel with the same velocity, which at the present moment, is taken as [2]:

$C_0 = 299792458 \pm 1.2$ m/s

In the atmosphere, the velocity must be less than this value. The ratio between the two velocities gives the definition of the refractive index of the medium:

Refractive index (n) =

$$\frac{\text{Velocity of electromagnetic wave in vacuum } (C_0)}{\text{Velocity of electromagnetic wave in medium } (C)} \quad (1)$$

For microwave, the formula often used to calculate the refractive index for a given set of meteorological conditions, is that derived by Essen and Froome [3]:

$$(n_M-1)10^6 = \frac{103.49}{(273.15+t)}(P-e) + \frac{86.26}{(273.15+t)}\left(1+\frac{5748}{(273.15+t)}\right)e \quad (2)$$

Where:

n_M = refractive index for microwave
t = dry bulb temperature of air (°C)

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P = pressure of air (mm Hg)
e = partial water vapor pressure (mm Hg)

In case of visible light wave, Barrell and Sears gave the formula which determines the refractive index [3]:

$$n_L = 1 + \frac{n_g - 1}{(1+\alpha t)} \times \frac{P}{760} - \left(\frac{5.5 \times 10^{-8}}{(1+\alpha t)} \right).e \qquad (3)$$

Where: n_L = refractive index for visible light wave
t = dry bulb temperature of air (°C)
P = atmospheric pressure (mm Hg)
e = partial water vapor pressure (mm Hg)
$= \frac{1}{273.15}$
n_g = the group refractive index which can be calculated according to Barrell and Sears formula [3]:

$$(n_g - 1)10^6 = 287.604 + 3 \times \left(\frac{1.6288}{\lambda^2} \right) + 5 \times \left(\frac{0.0136}{\lambda^4} \right) \qquad (4)$$

Where:
= the wavelength of the light in vacuum in microns (μm)

The partial water vapor pressure (e) can be derived from [4]:

$$e = e_S - 0.000662 \times P \times (t - t_W) \qquad (5)$$

Where:
t = dry bulb temperature (°C)
t_W = wet bulb temperature (°C)
e_S = saturation water vapor pressure (mb), (1013.25mb=760 mm Hg)

The value for (e_S) can be calculated from Reference 4:

$$\log_{10}(e_S) = \frac{7.5 t_w}{t_w + 237.3} + 0.7857 \qquad (6)$$

In order to investigate the effects of errors of the variables (p), (t) and (e) on the refractive index (n) partial differential can be carried out for equations (2), (3) with respect to (p), (t) and (e), for microwave, the formula can be rewritten as:

$$n_M = 1 + \left[\frac{Q}{z+t}(P - e) + \frac{y \times e}{z+t} + \frac{y \times w \times e}{(z+t)^2} \right] \times 10^{-6} \qquad (7)$$

Where:

Q=103.49, z = 273.15 °C, y = 86.26 and w = 5748.

$$\frac{\partial_n}{\partial_t} = \frac{-1}{(z+t)^2} \left[Q \times (P-e) + y \times e + \frac{2y \times w \times e}{(z+t)} \right] \times 10^{-6} \qquad (8)$$

$$\frac{\partial_n}{\partial_p} = \frac{Q}{z+t} \times 10^{-6} \qquad (9)$$

$$\frac{\partial_n}{\partial_e} = \frac{1}{z+t} \left[y - Q + \frac{yw}{z+t} \right] \times 10^{-6} \qquad (10)$$

For light wave, the formula can be rewritten as:

$$n_L = 1 + \frac{(n_g - 1)}{1+\alpha t} \cdot \frac{P}{A} - \frac{B.e}{1+\alpha t} \qquad (11)$$

Where: A = 760, B = 5.5 10^{-8},
n_g = group refractive index

$$\frac{\partial_n}{\partial_t} = \frac{-\alpha.A.(n_g - 1)P}{(A + \alpha.A.t)^2} + \frac{\alpha.B.e}{(1+\alpha.t)^2} \qquad (12)$$

$$\frac{\partial_n}{\partial p} = \frac{(n_g - 1)}{(A + \alpha.A.t)} \qquad (13)$$

$$\frac{\partial_n}{\partial e} = \frac{-B}{(1+\alpha.t)} \qquad (14)$$

For P =755 mm Hg, t = 15 °C, e = 9 mmHg, and n_g = 1.0003045, Table 1 shows the effects of errors dt = 1°C , dp = 1 mmHg and de = 1 mmHg on the refractive index of microwaves and light waves:

Table 1 The effects of errors in atmospheric conditions on the refractive index of microwaves and light waves

	dt =1 °C	dp=1 mmHg	de=1 mmHg	Conditions
dn_M (ppm)	- 1.3122	+ 0.359	+ 5.9118	t = 15 °C , p = 755 mm Hg e= 9 mm Hg, n_g= 1.0003045
dn_L (ppm)	-0.9935	+0.3798	- 0.05214	

It is obvious from Table 1 that, the water vapor pressure is a critical parameter, which has a significant effect on the refractive index determination, in case of microwaves. On the other hand, its effect upon the refractive index of light waves is insignificant and can be neglected.

FIELD OBSERVATIONS

To study the effect of atmospheric refraction on EDM observations, two distances were measured over two different surface covers under different atmospheric conditions, i.e., throughout the day hour. The area, which was chosen for carrying out this experiment, is the front garden of Faculty of Engineering, Alexandria University. The observations were made over two kinds of ground surface (asphaltic road and green land).

The height of the EDM instrument was fixed (h =150 cm), and the heights of the EDM reflectors were varied (h =145cm, 110cm, and 65cm). Observations were carried out in 21 days by RED 2A from SOKKIA, which has accuracy = ±5 mm ±3 ppm (RED 2A/2L), with maximum range of 2.9 km. Two different reflectors were used, one from SOKKIA and the other from ZEISS. The effect of centering has been avoided by making the reflectors fixed all the time during the experiment at two stations (B, C), while the instrument was fixed on a pillar (A) all the time of the experimental work.

The two distances were measured repetitively every hour. The first observation was taken at nine o'clock in the morning, the last observation was obtained at two o'clock in the afternoon. The distance differences were obtained by subtracting the first observed distance (at nine o'clock) from all observed distances that were obtained in the same day. This method was adopted to lessen the sources of errors. The first distance was assumed to be the reference value because the effect of atmospheric refraction was small since it was carried out before a strong sunshine. Therefore, the distance differences were expected to be mainly due to atmospheric refraction since the centering error was kept to be minimum. The temperature were measured using a thermometer with accuracy of 0.1 degree centigrade, temperatures were recorded at the instrument point. The length of the two lines were approximately: AB = 72.962 m, line above green land, and AC = 69.572 m, line above asphaltic road.

The ground nature of the selected site was sufficient to give all the different parameters affecting the atmospheric refraction such as the ground slope and the kind of surface cover. Some leveling observations were performed by level instrument for the site. The topographic feature of the site is illustrated in Figure 1 using contour lines with contour initial intervals equal to 0.2 m [5]. The profiles as well as the heights of the instrument and the reflectors for the two lines are shown in Figures 2 and 3.

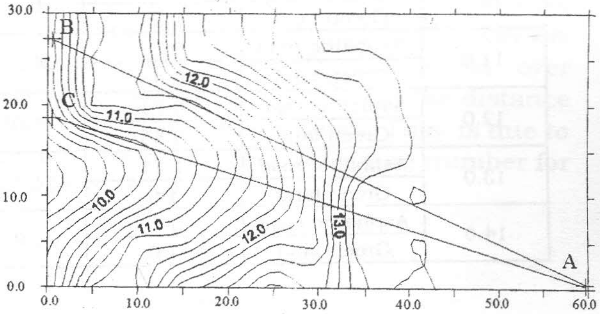

Figure 1 Contour lines with intervals equal to 0.2 m and the two observed lines.

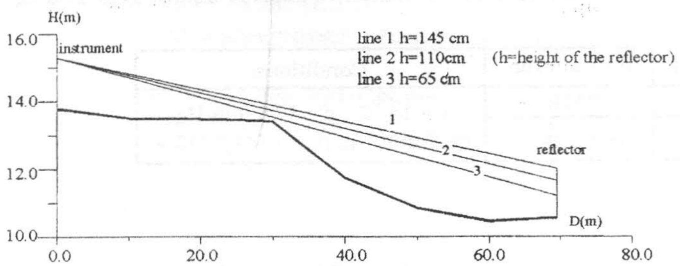

Figure 2 Profile of line AC (asphaltic road)

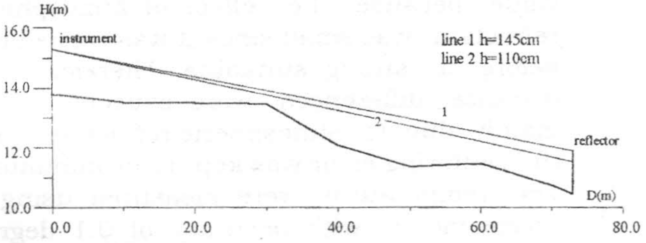

Figure 3 Profile of line AB (green land)

Observations were classified and tabulated according to the different heights of reflectors in Tables 2, 3 and 4. The distance differences (Dis. Diff.) and temperatures (Temp.) were calculated as the mean values for the same hour during the 21 days.

Table 2 The mean values of distance differences and temperatures for h = 145 cm

First case (h = 145 cm)			
Time (hour)	**Ground cover**	**Dis. Diff. (mm)**	**Temp. °C**
9.0	Asphaltic road	0.0	18.2
	Green land	0.0	
10.0	Asphaltic road	0.29	19.3
	Green land	0.29	
11.0	Asphaltic road	0.57	20.5
	Green land	0.43	
12.0	Asphaltic road	0.71	21.0
	Green land	0.86	
13.0	Asphaltic road	1.14	21.7
	Green land	1.0	
14.0	Asphaltic road	1.7	21.8
	Green land	1.0	

Table 3 The mean values of distance differences and temperatures for h = 110 cm

Second case (h = 110 cm)			
Time (hour)	Ground cover	Dis. Diff. (mm)	Temp. °C
9.0	Asphaltic road	0.0	17.8
	Green land	0.0	
10.0	Asphaltic road	0.43	20.3
	Green land	0.14	
11.0	Asphaltic road	1.0	22.2
	Green land	0.43	
12.0	Asphaltic road	1.29	23.7
	Green land	1.0	
13.0	Asphaltic road	1.43	24.5
	Green land	1.14	
14.0	Asphaltic road	2.29	25.0
	Green land	1.14	

Table 4 The mean values of distance differences and temperatures for h = 65 cm

Third case (h = 65 cm)			
Time (hour)	Ground cover	Dis. Diff. (mm)	Temp. °C
9.0	Asphaltic road	0.00	18.2
10.0	Asphaltic road	0.71	20.5
11.0	Asphaltic road	1.00	22.5
12.0	Asphaltic road	1.29	23.5
13.0	Asphaltic road	1.71	24.2
14.0	Asphaltic road	2.00	25.0

RESULTS AND ANALYSIS

Correlation between Temperature Differences and Distance Differences

The correlation coefficients (R) and the formulae of the best fitted lines between temperature differences (x) and distance differences (y) were carried out for the three cases. The results are tabulated in Table 5, while Figure 4 is one of the series of curves illustrating these results. From these curves, it can be noticed that there is a proportional correlation between temperature differences and distance differences in all cases, for the two ground covers.

Table 5 The correlation coefficient and the best fitted lines for the three cases

Case	R		Formula of fitted line	
	Asphaltic road	**Green land**	***Asphaltic road***	***Green land***
h =145	0.9115	0.9718	y= -7.3036+0.3939 x	y= -5.2441 + 0.2861 x
h =110	0.9440	0.9589	y= -5.0192+ 0.2738 x	y= -3.3373+ 0.1788 x
h = 65	0.9832		y= -2.7563+ 0.1609 x	

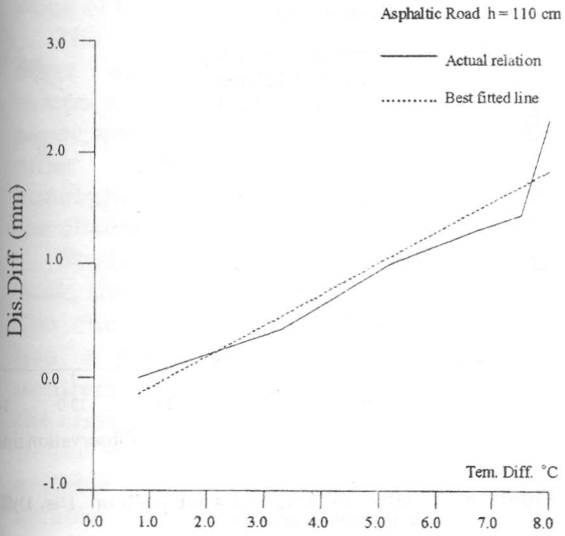

Figure 4 The relationship between Dis. Diff. and the Tem. Diff.

The Standard Deviations of the Distance Differences

The standard deviations (S.D.) of the distance differences for all cases were calculated and the results were grouped in Table 6. To illustrate the relationship of both Dis. Diff. and Temp. Diff. against the observation hours along with the S.D. of the distance differences, several curves had been designed for all cases; Figure 5 represents one of this series.

Table 6 The standard deviations of Dis. Diff. for all cases

Case	Standard Deviation (mm)	
	Asphaltic road	Green land
H=145 cm	1.05	0.78
H=110 cm	1.40	0.90
H =65 cm	1.10	

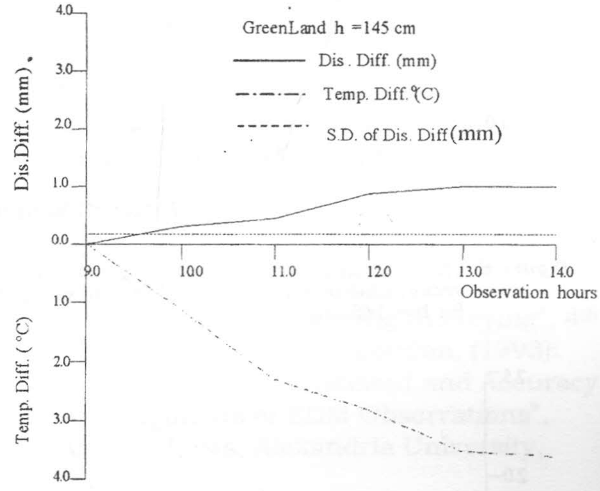

Figure 5 Dis. Diff., Temp. Diff. and S.D. of Dis. Diff. versus observation hours

These curves assure the well known fact that, the best observation hours are either before sunrise or after sunset to avoid the effect of a strong sunshine, since the temperature differences in these two periods are so small.

The Effect of Ground Cover

Figures 6 and 7 show the relation between the distance differences and the observation time for the same height of wave path over different ground covers. Obviously, the distance differences over asphalt road are greater than the distance differences over green land. This is due to the difference in the reflection number for the two ground covers.

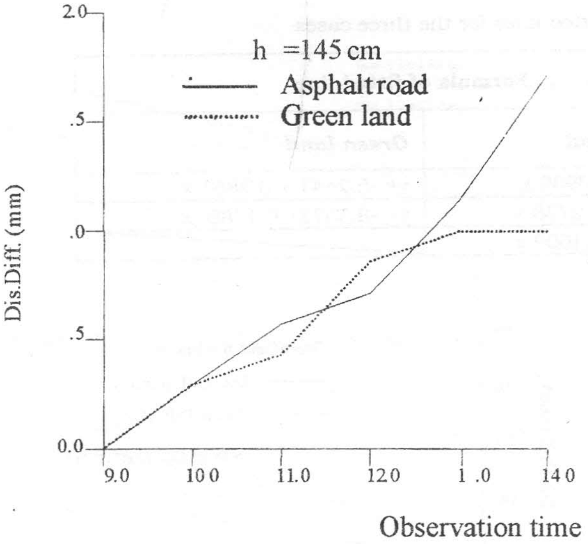

Figure 6 The relation between Dis. Diff. and Observation time over asphalt road and green land for h = 145 cm

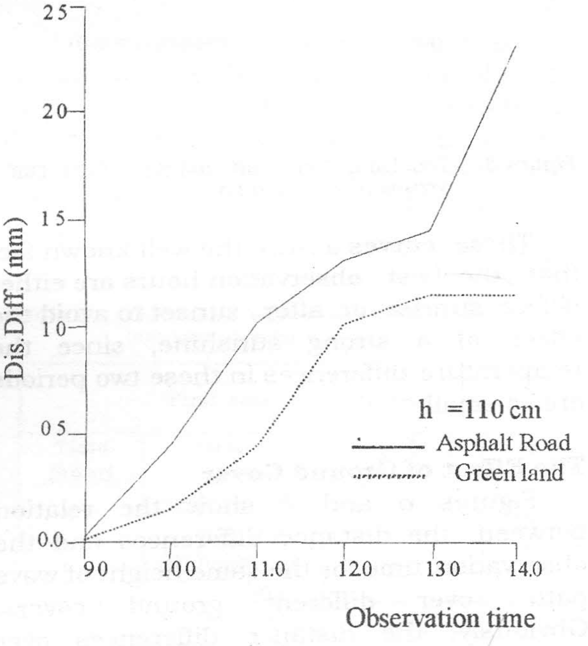

Figure 7 *The relation between Dis. Diff. and Observation time over* asphalt road and green land for h = 110 cm

The Effect of Height of the Wave Path

The effect of height of the wave path, over different ground covers is apparent, the higher the wave path is the lower the distance differences regardless the ground cover. This is clearly noticeable in Figures 8 and 9. They represent the relation between the distance differences and the height of the wave path over the two tested ground covers.

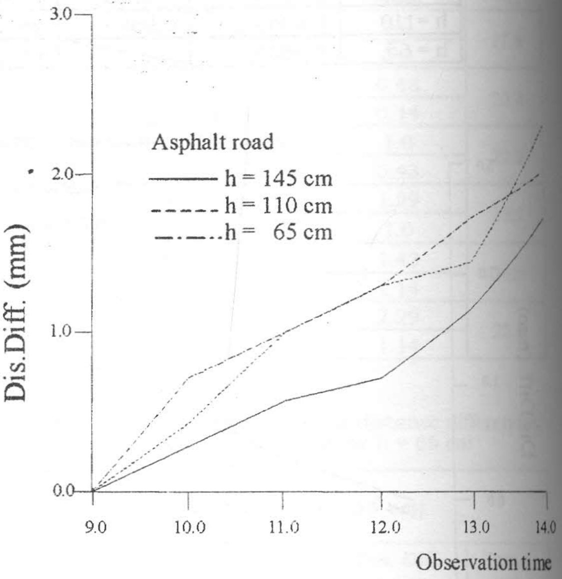

Figure 8 The effect of height of wave path on Dis. Diff. over the asphalt road

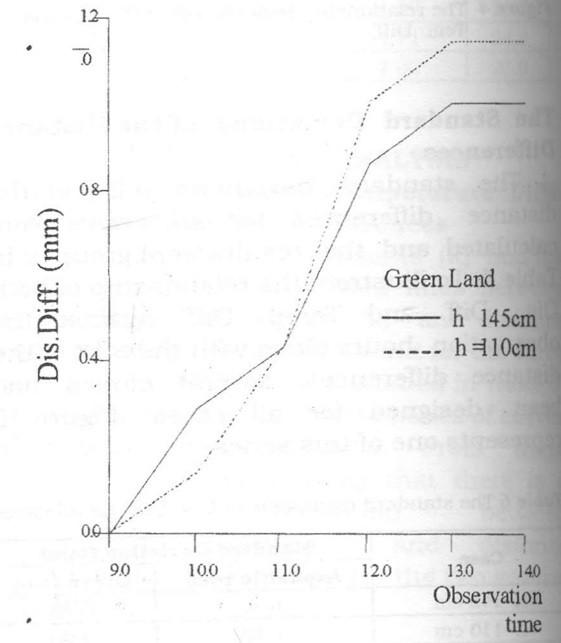

Figure 9 The effect of height of wave path on Dis. Diff. over the green land

CONCLUSION

The atmospheric refraction strongly affects the accuracy of all EDM observations. If high accuracy is desired, a number of external factors must be taken into consideration to eliminate its effect totally or partially. The refractive index, the temperature, the observation hours, the ground cover and the wave path height are some of these factors.

The theoretical study illustrated the effect of the refractive index and its components. The experimental work in this paper was devoted to extract the effect of the other mentioned factors upon the atmospheric refraction, which in turn affects the observation accuracy.

Studying the results of the experimental work, the following can be concluded:
The change in temperature during the day has a direct proportional effect upon the accuracy of measured distances. Therefore, the choice of observation hours is important. Before sunrise and after sunset are the most suitable times for EDM observations, to achieve high accuracy. The refraction number of the ground cover is also a very important factor, which directly affects the observation accuracy. The higher the refraction number is the higher the atmospheric refraction. Moreover, the height of the wave path above the ground surface has a noticeable inversely proportional effect upon the accuracy of observations.

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تأثير العوامل الجوية على القياس الإلكتروني للمسافات

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ملخص البحث

أصبح القياس الإلكتروني للمسافات من الوسائل الهامة و السريعة حيث يستخدم في الأعمال المساحية الحديثة وذلك فى العقدين الأخريين وما زالت الدراسات قائمة لتعميم هذه الأجهزة فى الهندسة المدنية والمشروعات العمرانية الحديثة . والغرض الأساسي من هذا البحث هو إيجاد الأخطاء ومصادرها التى قد تظهر عند القياس الإلكتروني وذلك نتيجة تغير الظروف المناخية حيث يتم التحكم فيها بإزالتها أو تقليلها للوصول إلى أقصى دقة ممكنة فى القياس ومن أجل تحقيق هذا الغرض تم عمل البحوث النظرية على تأثير تغير معامل الانكسار **(Refractive index)** وكذلك أجريت أبحاث حقلية محدودة . تم توضيح عناصر الانكسار الجوى وتمثيلها بيانيا بالإضافة إلى ذلك تم أيجاد العلاقة التبادلية بين الانكسار الجوى والأخطاء المنتظمة التى قد تحدث فى القياس الإلكتروني للمسافات نتيجة للظروف الجوية المختلفة .

وفى نهاية البحث وجد أن الانكسار الجوى يؤثر بقوة على دقة القياس الإلكتروني حيث يتسبب عنه أخطاء منتظمة . ومن هنا يجب أن يؤخذ فى الاعتبار عدد من العوامل الخارجية مثل معامل الانكسار ودرجة الحرارة وقت الرصد وطبيعة التربة وارتفاع خط النظر حتى يمكن الحصول على دقة عالية وذلك بتحديد الأخطاء المنتظمة الناتجة من القياس على النتائج التى تم الحصول عليها حيث وجد أن معدل التغير الحرارى له أكبر تأثير لذلك يجب اختيار الوقت المناسب للرصد وهو قبل الشروق أو بعد الغروب .

وقد أنتهى البحث إلى أن رقم الانكسار لسطح الأرض له علاقة طردية بدقة القياس بالإضافة إلى ذلك فإن خط النظر له تأثير عكسى على دقة الأرصاد .