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Accuracy analysis of optical-based measurements considering distance, height, and temperature variations

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ABSTRACT

Refraction is one of the most important factors affecting the accuracy of optical and electromagnetic measurement systems. In this study, the effect of refraction on measurement accuracy was investigated by processing video camera images obtained under different distances, temperatures, and object height conditions. Video camera recordings directed at a fixed target were processed using the Template Matching method in MATLAB. The normalized cross correlation (NCC) algorithm was used to prevent the effects of brightness or contrast differences and to ensure a more reliable comparison. A time series of target position changes (caused by refraction) was obtained, and the results were interpreted using statistical measures such as standard deviation (σ) and the F-test. The findings showed that the σ increased as distance and temperature increased, while the deviation decreased as the target height increased. Furthermore, the deviations of the horizontal component were found to be higher than those of the vertical component. For the first measurement, the deviations varied between ±0.3 and ±4.50 mm, depending on temperature and distance. In the second measurement, the deviation increased to ±6.8 mm when the measured object was 0.50 m above the ground, but decreased to ±2.6 mm at a height of 2.50 m. The deviation values obtained in the current study are not a problem for applications where a few centimeters of precision are sufficient in rough construction work. However, in applications requiring high precision, such as industrial measurements and deformation monitoring, refraction effects must be considered. The pressure factor was not investigated in this study, and future studies are recommended to evaluate the contribution of each parameter to refraction separately.

1. Introduction

Refraction is a significant phenomenon that negatively impacts the measurement accuracy of optical and electromagnetic measuring instruments. The refractive index changes as electromagnetic waves, especially light waves, transmit from one medium to another, affecting the light's direction and speed (Wang and Sun, 2023). This can affect the position, distance, or frequency perceived by optical systems. It is important to consider the effects of refractive index in the positioning of industrial machinery, as even submillimeter errors can cause structural problems (Robson *et al.*, 2016; Summan *et al.*, 2015).

The change in position caused by refraction (a movement that does not actually exist) can be detected using image processing techniques. Many image processing methods are used to determine the movement of the object (Eren and Hoşbaş, 2023). Template matching relies on algorithms to locate a specific object or pattern within a sequence of images. Automated image processing techniques are used in various industrial applications, such as product defect detection systems, to minimize human errors (Babic *et al.*, 2021).

Various methods and techniques have been developed to improve the effectiveness of the template matching algorithm. One of these is normalized cross correlation (NCC), which significantly increases object recognition accuracy (Hashemi *et al.*, 2016). The ability of an optical system to provide accurate measurements depends on many factors, including its ability to account for atmospheric effects such as temperature, pressure, refractive index, and humidity (Nasr *et al.*, 2014). Furthermore, the magnitude of the error due to physical and environmental conditions, the distance between the measurement point and the target, and the height of the measured target above the ground level all influence the accuracy of the measurement.

Changes in air temperature, air density, height, and water vapor have been demonstrated to cause changes in the refractive index of light (Friehe *et al.*, 1975). As posited by Barnett et al. (2022) light rays that undergo refraction due to temperature fluctuations in the ambient environment do not travel in a linear trajectory. This phenomenon, which causes light rays to bend, results in angular errors in measurements and can have a significant impact on positioning accuracy (Holá *et al.*, 2015). Additionally, rising temperatures have been observed to impact the refractive indices of materials utilized in optical measuring instruments, thereby compromising the precision of measurements (Wei *et al.*, 2024).

The effect of measuring distance is that the input signal in optical measurement systems is affected by the ambient air and other physical conditions, leading to different measurement results. Therefore, as the distance increases, the total optical density of the medium through

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which the light travels changes, which can affect the accuracy of the results (Lu *et al.*, 2024).

Another important factor is the height of the measured object above the ground, which can affect changes in the refractive index of the atmosphere by causing light to interact with more atmospheric layers in the measured environment. This is particularly evident in long-distance measurements (Lu *et al.*, 2024).

In this context, the present study aims to determine the refraction effect of video images obtained from different target heights. To achieve this, the temperature effects at different distances are achieved by processing them using the Template Matching algorithm in MATLAB. The study area is located within the Yıldız Technical University campus in Istanbul, Turkey. The effect of distance was investigated with the first measurements taken from 60, 80, 100, and 120 m to the fixed target used in the field studies, and the second measurement was made from different target heights (0.50, 1.50, and 2.50 m) to investigate the effect of the target's height above the ground. In both measurements, hourly measurements were made to consider the temperature increase. The accuracy of the calculations was then evaluated according to the σ error criterion. The equality of variances between measurement sets was examined using the F-test.

While previous studies have examined the effects of parameters such as distance (measurements taken from a few dm away) (Holá *et al.*, 2015) and temperature and pressure (Lu *et al.*, 2024) on optical measurements, these parameters have generally been considered separately. Furthermore, most existing research takes a holistic approach, considering the effects of distance, temperature, and target height on optical systems using video camera measurements. To the author's knowledge, no previous study has simultaneously analyzed the effects of temperature, measurement distance, and target height on video camera-based measurements. The present study aims to address this gap by experimentally investigating these parameters using image processing techniques. The contributions of this study can be summarized as follows:

- Determining the optimal measurement time: Error due to refraction increases with increasing measurement distance and temperature. Therefore, it is recommended to take measurements in the early morning or late evening, when the refractive index is low.
- Impact of target height: As the height of the measured target increases, the error decreases, demonstrating an inversely proportional relationship with height.
- Statistical Assurance: Data sets obtained from different measurements were tested with statistical metrics.

Practical Contributions: Errors arising from refraction are not a concern for construction work that does not require high precision, such as boundary stake-out and land levelling. However, it is imperative to meticulously plan measurements, taking this effect into account when assessing deformations on critical infrastructure such as dam crests, rail systems, bridges, and viaducts. In addition to these contributions, the originality of the study is that there is no study that considers the effects of temperature, measurement distance, and target height on measurement accuracy in the processing of images obtained with a video camera. A correction can be made by determining the effect of refraction on length (Wei *et al.*, 2016). However, statistical tests, which examine the temperature increase of targets at different distances and heights and the movement caused by light refraction on a fixed target, provide a methodological depth that distinguishes it from similar models in the literature.

2. Materials and Methods

Various methods are used in vision-based motion tracking. This results in apparent displacements induced by fluctuations in ambient intensity along the light propagation path. Some of these methods include feature point matching, optical flow estimation, background subtraction, and template matching.

Optical flow estimation: Optical flow is a method that models the movement of pixel intensities in consecutive video frames (Alfarano *et al.*, 2024). Based on the principle that a pixel's brightness value remains constant over short time intervals, the direction and speed of movement of objects are estimated using algorithms such as Lucas-Kanade or Horn-Schunck.

Feature point matching: It is based on the detection of distinct and recognizable feature points (keypoints) in an image and matching these points across different images. This method is frequently employed in the domain of image processing, leveraging algorithms such as speeded-up robust features (SURF), Scale-Invariant feature transform (SIFT), and Oriented FAST and Rotated BRIEF (ORB).

Background subtraction: Computer vision systems identify moving objects in sequential images by comparing them to the current frame (Garcia *et al.*, 2020). In this approach, the background model of the scene is first created (using Gaussian Mixture Models (GMM) or mean filtering). Subsequently, a comparison is made between the background of sequential frames and the reference frame. Regions that deviate from the reference frame are identified as moving objects.

2.1 Template matching method

Template matching is a widely used computer vision technique. It allows the detection of a specific pattern or object within an image using a small, predefined template (Feng and Feng, 2018). By implementing a region-based search strategy as opposed to a comprehensive image-wide approach, substantial temporal and computational efficiencies can be realized. By searching a selected area within the image against subsequent images, similarities between two images are statistically determined using mathematical algorithms (Hashemi *et al.*, 2016). Using NCC can significantly increase the robustness of the matching process, particularly against changes in illumination and noise (Buniatyan *et al.*, 2017; Chen *et al.*, 2013). By calculating the similarity of patterns at each location, the location with the highest correlation value is identified as the location of the searched object (Sasikala and Kishore, 2020).

Mathematically, the NCC can be defined as follows Eq. (1), where $T_{(x,y)}$ is the target region and $S(x,y)$ is the template image:

$$R(u,v) = \frac{£_{x,y}\left(T_{(x,y)} - \bar{T}_{u,v}\right)\cdot\left(S(x-u,y-v) - \bar{S}\right)}{\sqrt{\left(£_{x,y}\left(T_{(x,y)} - \bar{T}_{u,v}\right)^2\right)\cdot £_{x,y}\left(S(x-u,\ y-v) - \bar{S}\right)^2}} \quad (1)$$

Here, T(x,y) denotes the template image pixels, S(x,y) the search image pixels, and (u,v) the displacement of the template over the search image. $\bar{T}_{u,v}$ represents the mean of the template, while $\bar{S}$ is the mean of the search window. The resulting R(u,v) value ranges from −1 to +1, where values closest to +1 indicate the positions in the search image where the template best matches.

The vertical component of the obtained digital image in the pixel coordinate system takes positive (+) values in the downward direction (Fig. 1). Since the position of this value in the time series (displacement data) is reversed, it is corrected by multiplying it by -1.

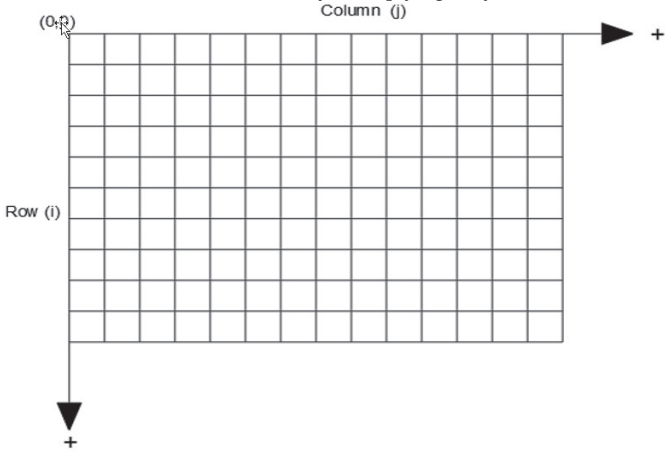


Fig. 1. Pixel coordinate system.

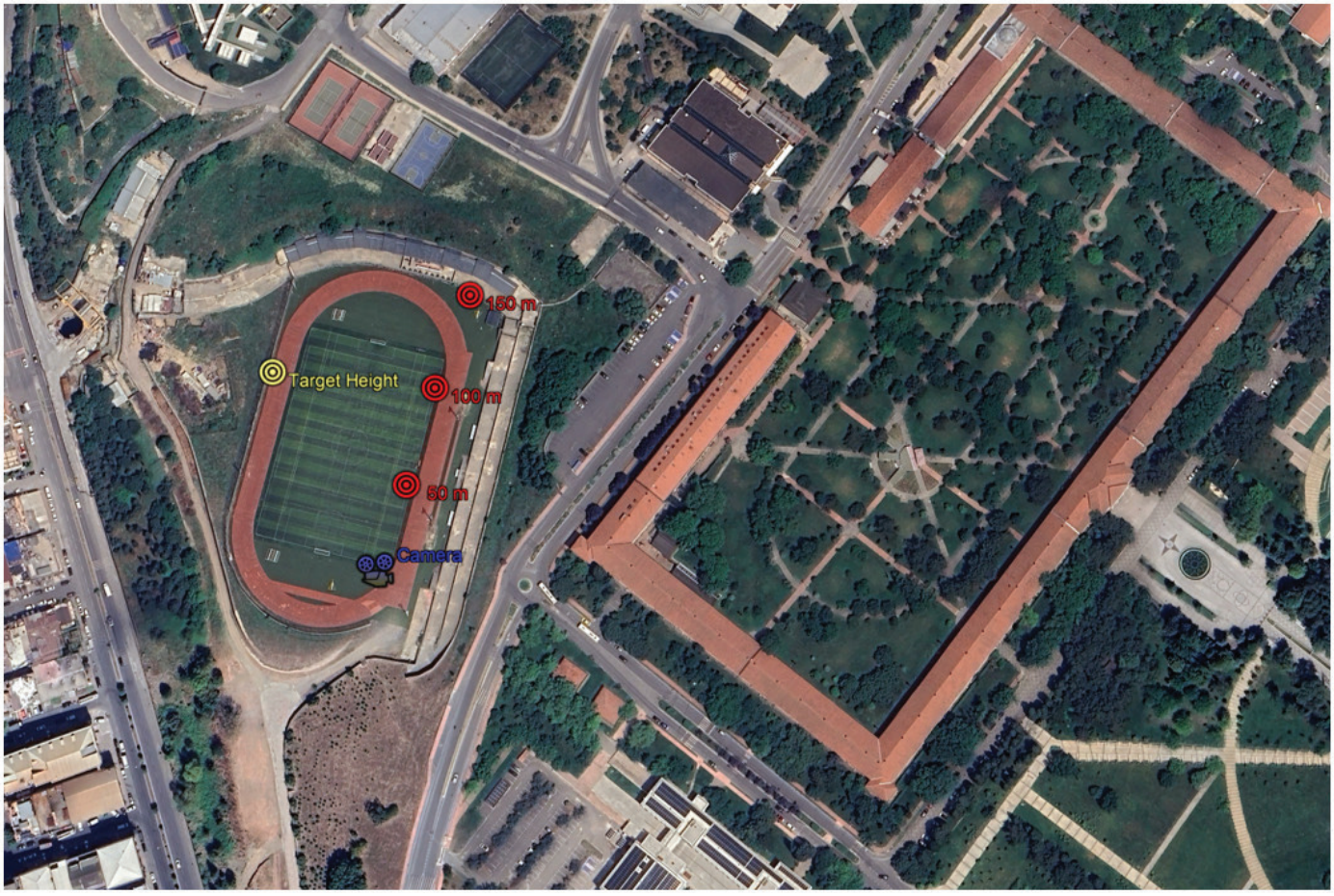


Fig. 2. Map showing the area where the measurements were carried out.

In this study, using the template matching method, the position of a fixed target was determined under different temperature, distance, and altitude conditions, and the effects of image shifts caused by refraction were examined. Thus, the effects of atmospheric refraction on measurement accuracy were quantitatively analyzed.

3. Implementation

3.1 Data and analysis

The study area was the sports field located on the Yıldız technical university campus in Istanbul (Fig. 2). The first measurements were conducted on May 23, 2025, by recording artificial targets placed at distances of 50, 100, and 150 m with a video camera between 9:00 and 13:00, in hourly intervals (5 sets in total) (red targets). The second measurements were performed on June 4, 2025, targeting an artificial object positioned at heights of 0.50, 1.50, and 2.50 m above the ground, recorded between 10:00 and 12:00, again in hourly intervals, as 3 sets in total (yellow target). Since it provided more precise results, the measurements were conducted on a high-contrast artificial target (black on a white background) (Busca *et al.*, 2013). All videos were recorded with a duration of 2 min each.

The data obtained were processed in MATLAB 2018a using image processing codes. In this study, the position of the fixed target was determined under varying temperature, distance, and height conditions by using the Template Matching method, thereby revealing the effects of refraction-induced image displacements. Subsequently, a time series of displacement data was generated. The time series obtained at different hours was combined into a single time series, facilitating visual comparison.

3.2 Criteria used in interpreting results

3.2.1 Standard deviation (σ)

Standard deviation is a fundamental metric used in statistics to evaluate the dispersion of data sets. It expresses the distribution of a dataset around its mean and provides essential information about the consistency of measurements (Biau, 2011). A low σ indicates that the data points are closer to the mean, resulting in more consistent results. A high σ indicates greater scatter and instability in the data set (Lee *et al.*, 2015). The standard deviation, denoted as σ, is calculated using Eq. (2).

$$\tilde{\mathbf{A}} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(x_i - ¼\right)^2} \tag{2}$$

where N represents the number of data; x_i represents each data point, and μ represents the mean of the data set.

This metric can be used to assess the reliability of results obtained in image processing, object tracking, or sensor-based measurements. Comparing standard deviations from measurements taken at different distances or under different environmental conditions can determine which conditions yield more stable results. The displacement data obtained were statistically interpreted by calculating their standard deviations. In this way, the effect of atmospheric refraction on measurement accuracy was quantitatively analyzed.

3.2.2 F-test

The F-test is a statistical test used to check whether the variances of two populations or two measurements are equal (Rayat, 2018). This test uses the F-statistic to compare two variances by taking their

ratio Eq. (3). In this statistic, it is assumed that the observations are independent and normally distributed. The hypothesis of the test is as follows:

$$H_0 : \sigma_1^2 = \sigma_2^2$$

$$H_1 : \sigma_1^2 \neq \sigma_2^2$$

It is defined as follows. Here, σ_1^2 and σ_2^2 represent the true population variances of each group. However, since the population variances cannot be known directly, the variance estimates obtained from the samples, S_1^2 and S_2^2, are used instead Eq. (3).

$$F = \frac{S_1^2}{S_2^2} \tag{3}$$

where S_1^2 is the first sample variance (assumed to be the largest value), S_2^2 is the second sample variance. It is evaluated under the F-distribution. If the obtained p value is greater than ($p > \alpha$) the selected significance level ($\alpha = 0.05$), H_0 is accepted; otherwise ($p < \alpha$), it is concluded that the variances of the groups are different. The term "reject" used in the tables indicates that hypothesis H_0 is not accepted.

4. Results

The image data for each measurement were processed in MATLAB 2018 software, and displacement data were obtained. For all measurements conducted on two different dates, σ values were calculated separately. In the first measurements, where the effect of temperature was considered, the influence of distance on σ was examined, while in the second measurements, the effect of the height between the target and the ground on σ was analyzed.

For the measurements on May 23, 2025, σ values were calculated for each dataset (Table 1, Figs. 3 and 4). The results show that deviations in the horizontal direction are consistently larger than those in the vertical direction. In addition, σ values increase with both distance and temperature rise during the day. The time series for the vertical and horizontal components have been shown in Fig. 3. When the overall data is examined;

Table 1.
Horizontal and vertical σ values calculated for measurements made at the beginning of the hour (all values are in mm).

Distances	50 m		100 m		150 m	
Time/σ	σx	σy	σx	σy	σx	σy
09:00	0.09	0.08	0.53	0.48	0.96	0.94
10:00	0.24	0.21	0.53	0.48	1.12	1.02
11:00	0.28	0.25	0.82	0.70	1.37	1.22
12:00	0.30	0.28	0.95	0.85	1.47	1.36
13:00	0.34	0.29	1.10	0.96	1.57	1.44

- For the measurements taken at 50 m at 9:00, the deviation values ranged between 0.32 and -0.36 mm, while at 13:00, these values ranged from 1.30 to -1.30 mm.
- For the measurements taken at 100 m at 9:00, the deviation values ranged between 2.34 and -1.84 mm, whereas at 13:00, the values ranged from 3.23 to -3.69 mm.
- For the measurements taken at 150 m at 9:00, the deviation values ranged between 2.96 and -3.32 mm, while at 13:00, they ranged from 4.50 to -4.50 mm.

When both Table 1 and Fig. 5 are examined, it is seen that as distance increases, displacement increases, and therefore the σ value increases. For example, at 9:00 am, the σx value is 0.09 for 50 m, while it becomes 0.96 for 150 m. These values increase with σy from 0.08 to 0.94. This finding demonstrates that measurement error tends to increase with increasing measurement distance. On the other hand, the σ value increases as the day progresses (with increasing temperature). These values are as follows: at 100 m distance, the σx value increases from 0.53 to 1.10 mm at 13:00, while the σy value increases from 0.48 mm to 0.96 mm.

The F-test showed a statistically significant difference between the variances of the 09:00 and 13:00 measurements ($p < 0.05$). This

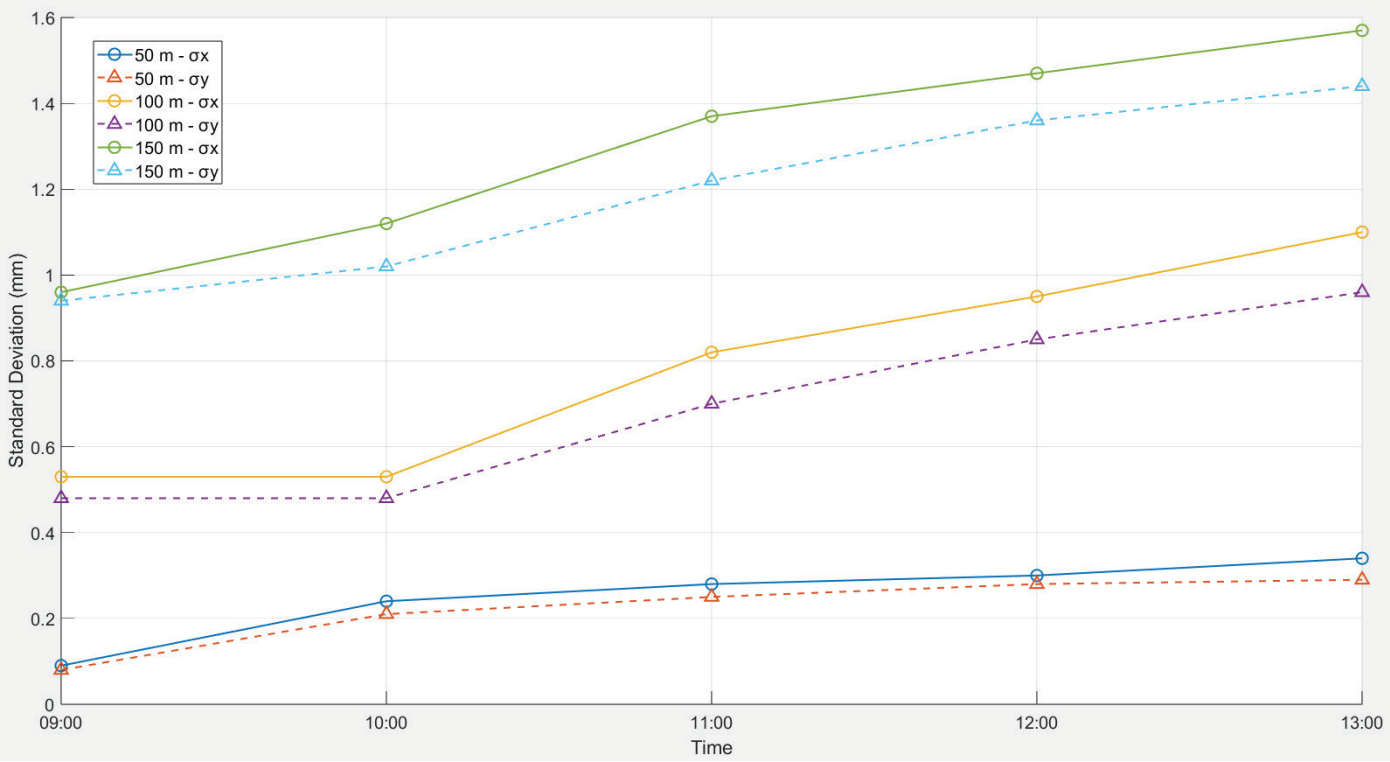


Fig. 3. Pairwise comparison table based on σ values. It is clearly seen that σ values increase as temperature increases.

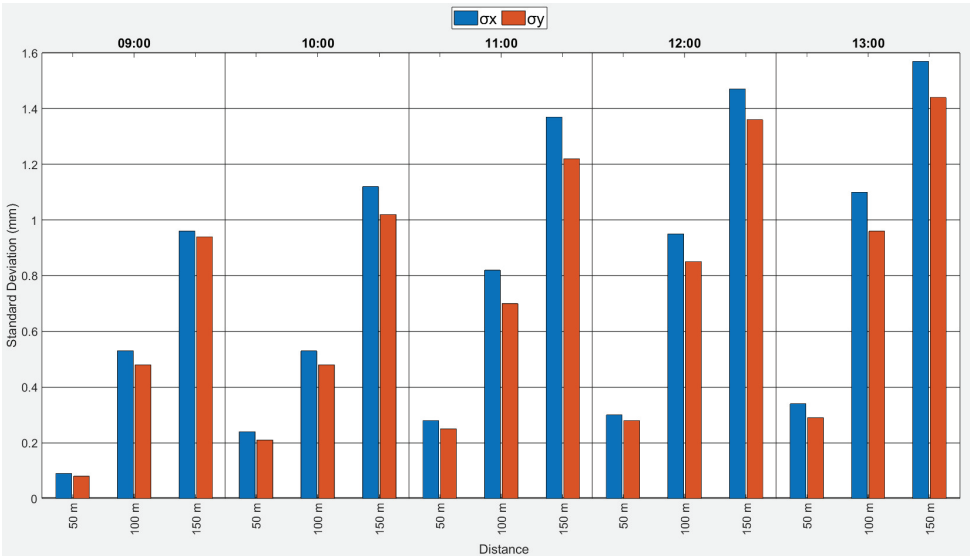


Fig. 4. Pairwise comparison of horizontal (blue) and vertical (red) σ values obtained at different hours of the day for measurement distances of 50 m, 100 m, and 150 m. The results show that σ values increase with both temperature and distance. Furthermore, horizontal deviations are consistently higher than vertical deviations.

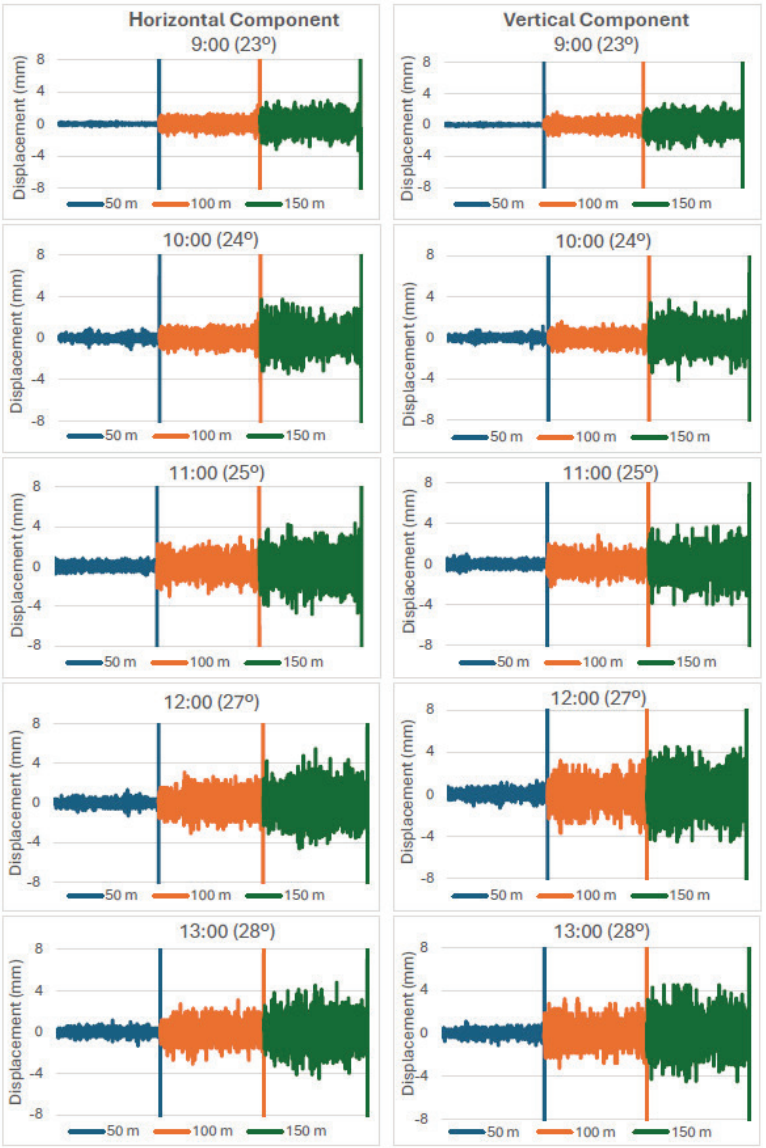


Fig. 5. Hourly time series based on data obtained from three different distances.

Table 2.
Results of the f-test for measurements taken hourly at a distance of 50 meters (the situation is similar at other distances). p-values indicate statistical significance; where $p < 0.05$ means that the variance values between two data sets are statistically different.

Measurement pair	Horizontal component		Vertical component	
	p-value	Decision	*p*-value	Decision
09:00 - 10:00	0.00	Reject	0.00	Reject
10:00 - 11:00	0.03	Reject	0.00	Reject
11:00 - 12:00	0.01	Reject	0.00	Reject
12:00 - 13:00	0.00	Reject	0.04	Reject

Table 3.
F-test results obtained with measurements taken at 13:00 with varying distances.

Measurement pair	Horizontal component		Vertical component	
	p-value	Decision	*p*-value	Decision
50 m - 100 m	0.00	Reject	0.00	Reject
100 m - 150 m	0.00	Reject	0.00	Reject
50 m - 150 m	0.00	Reject	0.00	Reject

indicates that the dispersion in the measurements varies depending on the time conditions (Table 2). Similarly, it was observed that changes in distance lead to statistically significant differences in measurement variances (and consequently standard deviations) (Table 3). The differences in variances suggest that environmental conditions (temperature increase and distance) affect measurement accuracy and show that sequential measurements taken between 09:00 and 13:00 exhibit different dispersion patterns.

On the other hand, hourly combined time series were plotted for each distance (Fig. 6). When Fig. 6 is examined, it is clearly observed that the data obtained from the same distance increases with the rise in temperature. Looking at the time series plotted on the same scale, the deviation values also increase with distance. When the heat map in Fig. 7 is examined, a clear increase from the top-left corner to the bottom-right corner can be observed.

In the second measurement, the relationship between the height of the object above the ground and the displacement values was investigated. The calculations showed that the deviation decreased as the target height increased. For instance, at 10:00, the σ value was found to be 1.18 mm at 0.50 m, 0.95 mm at 1.50 m, and 0.90 mm at 2.50 m, which aligns with expectations (see Fig. 8). This is because higher heights lead to a more homogenized air layer, providing a more stable environment. In Fig. 9 shows a clear increase in the heat map from the top-right corner to the bottom-left corner. In short, the decrease in σ with increasing measurement height indicates an inverse relationship between these two parameters.

Furthermore, based on the F-test results for the calculated variances, the alternative hypothesis (H_1) was accepted. In other words, the F-test results reveal that there is a statistically significant difference between the variances of measurements taken at target heights of 0.50, 1.50, and 2.50 m. This indicates that the dispersion in measurements varies depending on the height conditions (Table 4).

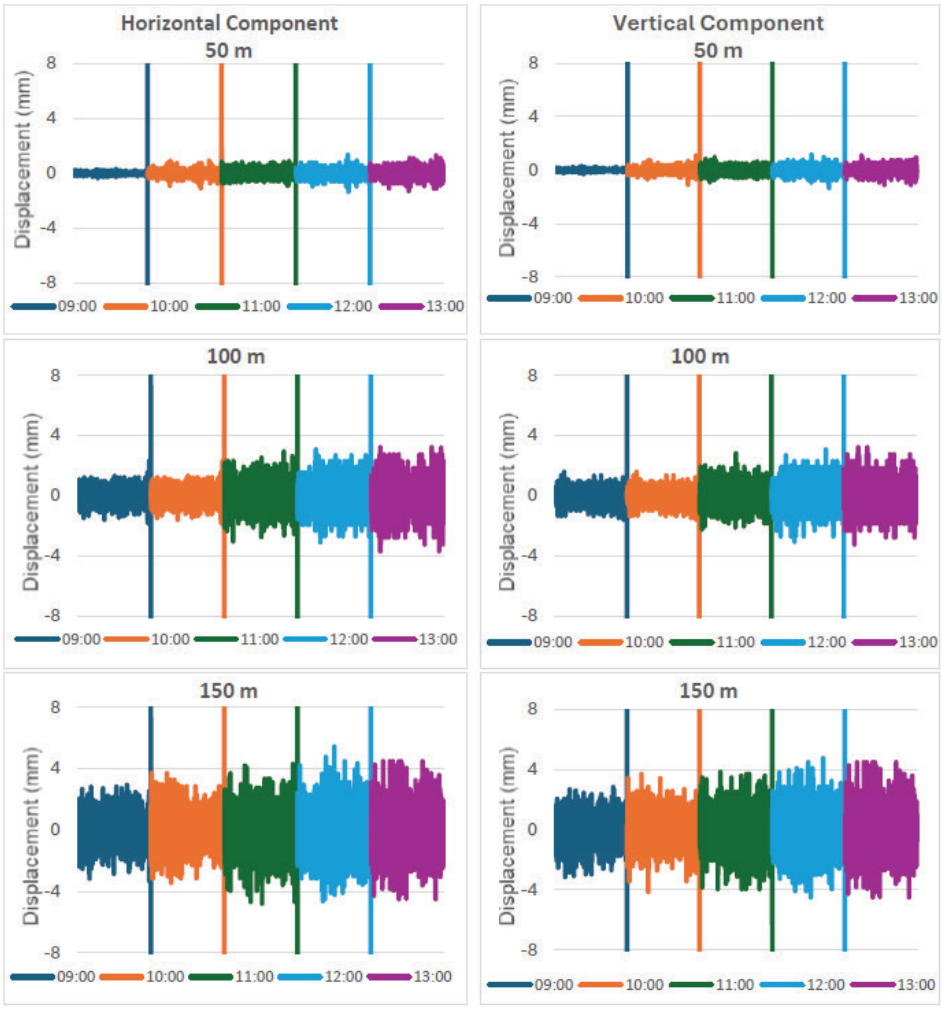


Fig. 6. Displacement data from the same distance and different times of the day.

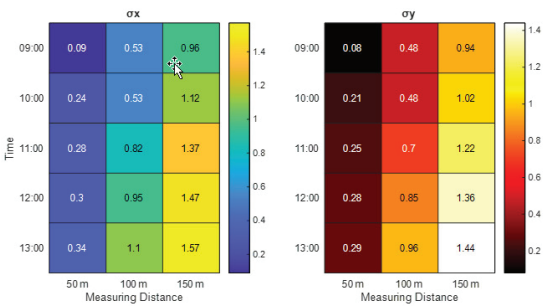


Fig. 7. Heat map for σ values derived from displacement data of varying distances and different hours.

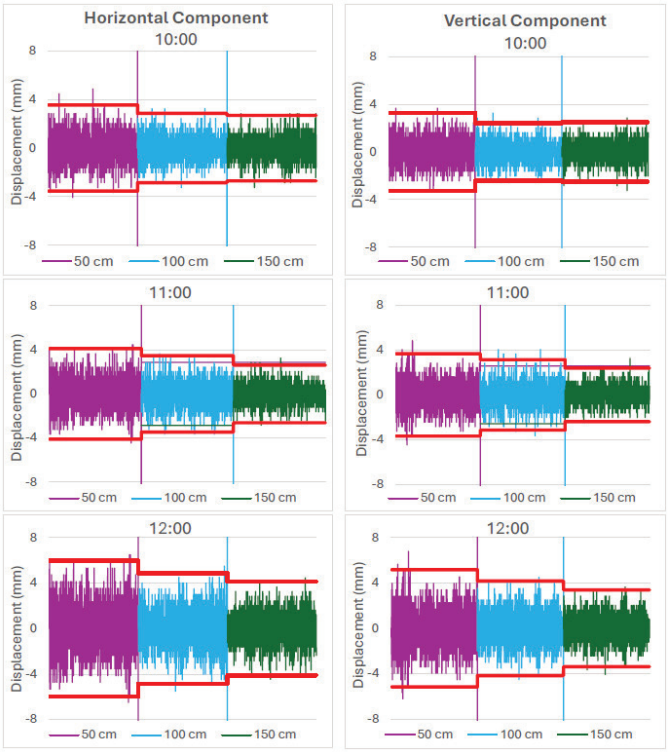


Fig. 8. Target displacement versus height above ground. The red horizontal lines represent 3σ values. Each time series contains 4500 data points. Data exceeding 3σ is relatively small and has no impact on the results.

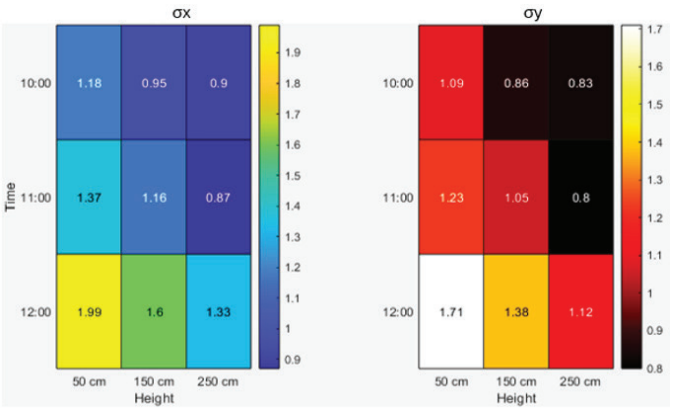


Fig. 9. Heat map showing the effect of different target heights on the change in σ.

Additionally, the maximum and minimum displacement values for different target heights are shown in Fig. 10. At 10:00, for a height of 0.50 m, the maximum and minimum values were 4.9 mm and -4.1 mm, respectively; for 1.50 m, 3.2 mm and -3.2 mm; and for 2.50 m, 2.8 mm and -2.7 mm. At 12:00, these values were calculated as 6.8 mm and -6.5 mm for 0.50 m, 5.5 mm and -5.5 mm for 1.50 m, and 4.5 mm and -4.6 mm for 2.50 m. This indicates that the error caused by changes in target height is inversely related to the measurement height.

Table 4.
F-test results obtained by changing the height of the object measured at 12:00.

Measurement pair	Horizontal component		Vertical component	
	p-value	Decision	*p*-value	Decision
0.50 m – 1.50 m	0.00	Reject	0.00	Reject
1.50 m – 2.50 m	0.00	Reject	0.00	Reject
0.50 m – 2.50 m	0.00	Reject	0.00	Reject

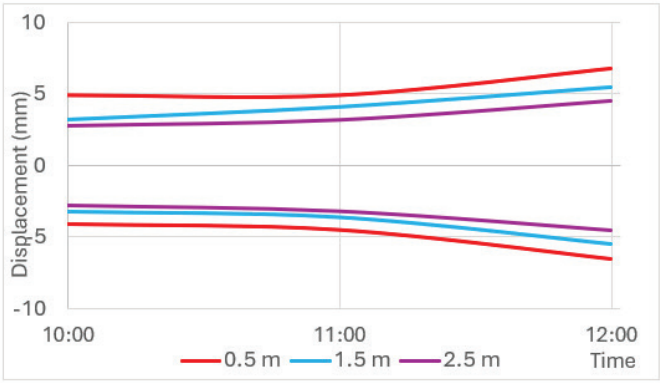


Fig. 10. Maximum and minimum displacement values calculated for hourly measurements of changing target height.

Table 5.
Change in σ value with increasing distance, temperature, and target height (The σ value increases when the arrow points upward and decreases when it points downward)

Effect	σ Trend	Description
Distance	↑	Light undergoes greater refraction over long distances.
Temperature	↑	Refraction increases with rising temperature.
Target height	↓	Proximity to the ground increases refraction.

In summary, increases in distance and temperature lead to higher σ values, whereas an increase in target height reduces the σ values (Table 5). On the other hand, the σ in the horizontal component is larger than in the vertical component, indicating that light undergoes greater refraction in the horizontal direction.

When all data are examined, displacement values caused by refraction are affected by increasing temperature, increasing measurement distance, and changing the height of the measured object. The effect increases with rising temperature and measurement distance, while it decreases as the target height increases. In current applications, this can lead to errors of up to 6.81 mm. Considering the measurement time (when the temperature is not high, 23–28°C, and the humidity is low, around 40%), this effect is estimated to reach several centimeters. With the current measurements, significant errors may occur in industrial surveying and deformation monitoring studies. Therefore, various precautions should be taken depending on measurement timing, distance, and the height of the measured object above the ground; otherwise, these errors will reduce measurement accuracy.

5. Discussion

The findings from this study indicate that atmospheric refraction, along with variations in distance, temperature, and target height, has a significant impact on the precision of optical measurements. The increase in σ at longer measurement distances and higher temperatures is consistent with the findings of Holá *et al.* (2015) and Lu *et al.* (2024), who emphasized the sensitivity of optical systems to environmental

changes. Furthermore, a decrease in measured deviations is observed with an increase in target height, further supporting the hypothesis that ground-level temperature gradients play a significant role in amplifying refraction effects. This finding is consistent with the pioneering work of Friehe *et al.* (1975).

The novelty of this study lies in its quantitative examination of the effect of refraction under real-world conditions, utilizing a video-based measurement method for three distinct parameters. Moreover, statistical validation employing the F-test serves to reinforce the interpretation of the results. The findings of the study demonstrate that variance values vary with changing distance, time, and height parameters.

Despite the aforementioned contributions, the study also has limitations. The inability to test atmospheric pressure and humidity, which are among the factors affecting the refractive index, in the experiment makes it difficult to generalize the effect caused by meteorological conditions. The findings emphasize that error due to refraction is not a significant concern in rough construction work, where centimeter-level accuracy is sufficient. However, applications requiring millimeter-level precision, such as deformation monitoring of dams, bridges, or railway systems, require a measurement plan that takes refraction effects into account. Therefore, it is recommended that high-precision optical measurements be conducted in the early morning or evening hours, when temperature gradients are minimal.

Future studies are recommended to determine the individual contributions of temperature, pressure, humidity, and distance under varying environmental conditions.

6. Conclusions

In this study, the effect of refraction on video camera-based measurements was analyzed with respect to distance, temperature, and target height. According to the F-test results, varying measurement times, distances, and target heights resulted in statistically significant differences between the variances of the measurements ($p < 0.05$). This suggests that the scatter in the measurements varies depending on the measurement time, distance, and height. The findings that were obtained can be summarized as follows:

1. Effect of distance: Refraction-induced errors increase as the measurement distance grows, due to the longer path of light through the atmosphere.
2. Effect of temperature: As temperatures rise later in the day, the σ values increase, indicating that changes in the optical density of the atmosphere have a negative effect on measurement accuracy.
3. Effect of Target Height: As the height of the measured target above the ground increases, the deviation values decrease, resulting in more stable measurements. This is attributed to stronger temperature gradients near the ground.
4. Component Differences: Deviations in the horizontal component were larger than those in the vertical component, indicating that light undergoes greater refraction in the horizontal direction.

In conclusion, this study presents an experimental approach that considers the effect of refraction in optical measurements. It is particularly recommended that measurements in deformation monitoring and industrial applications requiring high accuracy be conducted in the morning or evening. The study provides a novel contribution to the literature by simultaneously evaluating distance, temperature, and target height parameters in video-based measurements. Furthermore, it highlights the overall effects of these parameters on refraction. However, the individual contribution of each parameter to refraction was not quantified, and the effect of atmospheric pressure was not considered. It is anticipated that future studies will yield more comprehensive results by analyzing the individual contributions of these parameters. Furthermore, pressure fluctuations will impact measurement accuracy through changes in the refractive index. Therefore, we conclude that incorporating the pressure parameter into the model will facilitate a more comprehensive assessment of refractive effects.

CRediT authorship contribution statement

Mehmet Eren: Conceptualization; methodology; software; validation; formal analysis; investigation; resources; data acquisition; writing-original draft preparation; writing-review and editing; visualization; supervision.

Declaration of competing interest

The author declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Declaration of generative AI and AI-assisted technologies in the writing process

The authors confirm that there was no use of artificial intelligence (AI)-assisted technology for assisting in the writing or editing of the manuscript and no images were manipulated using AI.

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