Centroid shift analysis of microlens array detector in interference imaging system

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A B S T R A C T

Most CCD imaging detectors integrated microlens arrays (MLAs) to increase fill factor and sensitivity. However, they also introduce spot calibration issues with the inconsistency of spot geometry center and intensity distribution center. We setup theoretical and experimental models to research the problem of centroid shifting. According to the Seidel and Zernike coefficients of the optical model, we analyze main aberrations of microlens. In “Chief Ray” and “Centroid” reference frames, centroid shift numerical value is calculated with Geometric Ensquared Energy (GEE). Based on pentaprism test for 8.4 m mirror segment, we conduct spot imaging experiment in interference system. Spots images are obtained, and two-dimensional centroid algorithm processing is performed on them to get the analog experiment values of centroid movements. The results show that the MLA placed in KAI-16000 imaging detector causes the spot centroid to move. When there is a 14° (or −14°) angle of incident ray, the shifting values are about 1.46 μm in simulation and 2.18 μm in experiment. Our research makes a contribution to the compensation of calibrated error in metrology technology. We also prove that a significant portion of the shift comes from the low order aberration of microlens.

1. Introduction

CCD detector pixels present a trend of decrease in size to improve the resolution [11]. But smaller pixels cause less light rays to be directed to photo sensitive area, which reduce availability ratio of light and enhance potential noise. By integrating a microlens array (MLA) on top of CCD detector, the light that would normally be lost on metal light shield is collected on photoreceptive cell. The main advantage is that the design has higher light collection efficiency and better sensitivity than conventional imaging systems. MLAs have wide application in the areas of infrared focal plane arrays imaging, digital projectors, micro-optics scanner, and CCD imaging detector [2–5].

However, the smaller size of lenses arises unwanted effects. For example, when outer portions of incident beam projected onto the adjacent photodiode, MLAs will result in spot centroid offset in the image [6–8]. It causes an error for optical measurements which are based on spot centroid calibration, such as the scanning pentaprism test.

Scanning pentaprism test was implemented by the University of Arizona as a verification of principal test to guide the fabrication of the off-axis mirror segments for the Giant Magellan Telescope (GMT) [9–11]. 8.4 m segment of GMT is a near paraboloidal surface, the aspherical constant is −0.9983, and the 18-meter primary mirror focal length gives an f/2.1 focal ratio for the segment. In this system, a collimated beam scans across the parabolic mirror surface with a pentaprism. Since the scanning beam is parallel to the axis of parabolic profile, it comes to strikes a detector at the focus. Here, displacement of the spot is proportional to the slope error. Since the detector is integrated MLA, centroid point and geometrical center of the spot may be misaligned, which play a significant role in test precision. Thus it is important to analyze and calibrate the MLAs’ spot centroid shift.

The occurrence of centroid movement in spot’s imaging process may be due to the distortion of the MLA. This paper has dealt with the following respects to verify this assumption: (1) we setup an optical model based on structural features of plano-convex refractive microlenses integrated in Kodak KAI-16000 imaging detector, and then analyzed Seidel aberrations and wave aberrations; (2) we proposed the methods of centroid shift numerical calculation based on GEE; (3) we conducted an experiment of spot imaging, and processed the images captured in detector and validated the centroid shift value of this MLA system. At the end of this paper, we discussed the conclusions and expatiated on the applied value of the model.
2. Model simulation and aberration analysis

A typical microlens placement scheme is illustrated in Fig. 1(a). Tiny optical lens is placed over the metal light shield of a photodiode. It serves to concentrate light onto photodiode surface instead of allowing it to fall on non-photosensitive areas. Our optical model is built based on the analysis of MLA in KAI 16000 imaging detector. This microlens is a single element with one plane surface and one spherical convex surface to refract the light.

2.1. MLA structure and optical model

Kodak KAI-16000 image detector is an array of 4728(H) × 3248(V) with 7.4 μm square pixels. Fig. 1(b) shows micrograph of MLA provided by Eastman Kodak Company. Each microlens is a plano-convex lens with former spherical surface, and the main parameters are illustrated in Fig. 1(c).

Height at the vertex $h_L$ is about 2.6 μm as measured by a microscope, and $r=D/2=3.7$ μm. Then, the radius of curvature at the vertex can be given by:

$$R = h_L + \frac{r^2}{2h_L}$$

(1)

The vertex focal length $f$ of the plano-spherical refractive lens is:

$$f = \frac{R}{n(\lambda) - 1} = \frac{h_L + r^2/h_L}{2(n(\lambda) - 1)}$$

(2)

The focal length $f$ is a function of the wavelength $\lambda$, due to material dispersion. Refractive index of fused silica microlens is $n(\lambda=632.8 \text{ nm}) \approx 1.46$. The lens profile $h(r)$ is a function of the $R$, $r$ and aspherical constant $K$. As $h(r)$ is spherical here, $K=0$, the lens profile is generally described by:

$$h(r) = \frac{1}{R} + \frac{r^2}{1 + \sqrt{1 - r^2/R^2}}$$

(3)

We developed a single microlens model of Kodak KAI-16,000 image detector based on Fig. 1. Wavelength of light is set to 632.8 nm in Zemax, and incident angles are set to $+14^\circ$, $0^\circ$ and $-14^\circ$ as the GMT has an f/2.1 focal ratio for 8.4 m segmented mirror. Aperture type of MLA is “Entrance Pupil Diameter” and its value is 7.4 μm. According to Kodak KAI-16,000 CCD product description [14], results of Eq. (1–3) and photomicrograph, the parameters of MLA are determined. Key parameters are listed in Table 1. Non-sequential model is shown in Fig. 2(a).

2.2. Aberration analysis

We analyze the MLA aberration with Zemax software. This effort aims to explore the connection between MLA aberrations and spot centroid movement.

2.2.1. Seidel aberrations of MLA

Microlens aberration can be expressed in various forms. Seidel aberration is researched, as it breaks down the microlens aberrations into five quantities and they can be manipulated arithmetically. If we neglect the higher order terms, the approximate function of microlens aberration can be expressed in terms of Seidel coefficients as [15]:

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lens diameter ($D$)</td>
<td>7.4 μm</td>
</tr>
<tr>
<td>Height at the vertex ($h_L$)</td>
<td>2.6 μm</td>
</tr>
<tr>
<td>Radius of curvature at the vertex ($R$)</td>
<td>3.9 μm</td>
</tr>
<tr>
<td>Vertex focal length ($f$)</td>
<td>≈ 8.5 μm</td>
</tr>
<tr>
<td>Aspherical constant ($K$)</td>
<td>0</td>
</tr>
<tr>
<td>Refractive index, $n(\lambda=632.8 \text{ nm})$</td>
<td>1.46</td>
</tr>
</tbody>
</table>

Fig. 1. (a) Typical microlens placement scheme. (b) Micrograph of microlens array, each microlens unit is plano-convex lens with former spherical surface and corresponds to one pixel. (c) A plano-convex microlens is described by the lens diameter $D$, the height at the vertex $h_L$, the radius of curvature $R$, the refractive index $n$ and the contact angle $\theta$. 

Fig. 2. KAI-16000 microlens optical system. Plane 1 represents the incident light source, STO is the aperture stop, planes 3–5 respectively represent the rear surface of spherical lens, front and rear surface of substrate, and SUM is the image plane. (a) Non-sequential model. (b) Seidel diagram.
S, C, A, F, and D are Seidel coefficients of spherical aberration, coma, astigmatism, field curvature, and distortion, respectively. \( \alpha \) is field angle, \( d \) is nominal pupil radius, \( \rho \) is relative height (0 to 1) in pupil, \( \phi \) is height in pupil, and \( \theta \) is pupil angle.

Fig. 2(b) is a Seidel diagram which shows the five third-order coefficients as a bar plot for each MLA surface. Effects of various aberrations that influence the image quality are visible in this bar plot. Different colors denote different types of aberration, from red to yellow are spherical aberration, coma, astigmatism, field curvature, and distortion, in that order. To facilitate the theoretical analysis, only a single wavelength of light source is selected in Zemax, so that there are no axial and lateral chromatic aberrations. Result shows that spherical aberration is the main aberration.

Table 2 lists Seidel coefficients in Zemax. The total value of S is \( 7.35 \times 10^{-4} \), larger than other coefficients obviously. This table yields the same conclusion as Fig. 2(b) that spherical aberration is the major composition of aberration. It is worth noting that C has the same order of magnitude as S. Consequently, spherical aberration and coma are selected as the research objects in this paper.

### 2.2.2. Zernike aberrations of MLA

According to [16], Zernike aberrations coefficients of MLA are converted to Seidel and higher-order power-series aberration coefficients. The results are listed in Table 3, which also prove that the spherical aberration and coma are two of the most significant aberrations. In addition, the "displacement-free" Zernike modes is a useful method of aberration correction [17]. In this method, a proportionate amount of the tip, tilt, or defocus mode is added to each applied Zernike mode to remove the displacement effects. The procedure of "displacement-free" Zernike modes provides valuable information for the further study of aberration correction. This is one of the main reasons why we analyze the Zernike aberrations of MLA.

### 2.2.3. Wave aberrations of MLA

Using polar coordinates, the wavefront expansion of microlens can be written in terms of wavefront aberration coefficients:

\[
W_{(x,y)} = -\frac{S}{4\rho d^4} + C_{1}(\rho d)^3 \cos \theta - A_{1}(\rho d)^2 \cos^2 \theta - \frac{(F_2a^2 \rho d^2) + D_4(\rho d) \cos \theta}{4}
\]

(4)

\( W_{(x,y)} \) is wavefront expansion of microlens in which wavefront coefficients \( W_{00}, W_{11}, W_{22}, W_{20}, W_{12}, W_{10}, W_{31}, W_{30} \), and \( W_{33} \) corresponds to spherical aberration, coma, astigmatism, field curvature, and distortion. They can be obtained from Seidel aberration coefficients in waves, as listed in Table 4.

#### 2.2.4. Geometrical aberration of MLA

The significance of geometrical aberration is that it provides a lateral displacement value of light ray, which makes possible direct analysis of combined effect of two or more aberrations with the centroid shift. According to [18], wavefront distribution in exit pupil can be expressed by Eq. (6), and Eq. (7) can be further derived based on angular aberration of the light ray:

\[
W_{(x,y)} = \frac{x^2 + y^2}{2R_w} - \frac{\delta x x^2}{4R_w^3} - \delta y y^2 - \frac{\delta x y}{R_w^2}
\]

(6)

\[
\delta_x = -\frac{R_w \partial W}{h \partial x} \text{ and } \delta_y = -\frac{R_w \partial W}{h \partial y}
\]

(7)

\( R_w \) is the radius of wavefront. Eq. (8) puts the wavefront aberration in a direct relationship with geometrical aberration [18]:

\[
\begin{align*}
\delta_{SA} \quad & = \frac{4R_W h^3}{W_{00}} \\
\delta_{C} \quad & = -\frac{W_{13} h^3 \sin 2\theta}{h} \quad \delta_{C} = -\frac{R_h W_{13} h^3 (2 + \cos 2\theta)}{h} \\
\end{align*}
\]

(8)

in which \( \delta_{SA} \) and \( \delta_{C} \) are aberrations on sagittal and meridional plane. Field coordinate \( x_0 = 1 \). Normalizing factor \( h = 0.345989 \). Based on Eq. (8), the numerical computing results of MLA geometrical aberrations are shown in Table 5.

For the reason of CCD detector rotating in horizontal direction in experiment (subsection 4.2), we only need to study the sagittal aberration. According to aberration theory that the maximum deviation (residual spherical aberration) is in zone 0.707 [19], we select the sum of spherical aberration and coma \( \delta_s = \delta_{SA} + \delta_{C} = -1.65 \mu m \) at \( \rho = 0.707 \) as the reference value of microlens' sagittal aberration, which is used to validate the assumption that the inconsistency of spot geometry center and light intensity distribution center comes from the spherical aberration and the coma of microlenses.

### 3. Centroid shift theoretical calculation

#### 3.1. Principle

In general, the spot centroid can be shifted by a gradient in detector sensitivity across the spot. When the detector integrated...
with MLA, it may also be shifted by optical distortion through the lens. The possible reason is that marginal rays will be shifted laterally in the presence of aberrations. Aberrations of microlens will lead the marginal rays to strike the ‘wrong’ detector pixel (axial rays are unaffected). This would introduce variations of intensity distribution, resulting in the centroids shift of focus spots. Therefore, the shift in spot centroid might be produced by various aberrations contributed by the MLA which is transmitted through by light beam.

When the light passes through the MLA and refracted to photoactive, the geometrical center position of spot is \( x_C \), however the centroid of spot is shifting to \( x'_C \). They can be illustrated by Fig. 3 based on the following conclusions from the fact:

- Without MLA, point of \( x_C \) (chief ray) is coincides with the theoretical centroid \( x_C \);
- When integrating MLA, the new centroid point \( x'_C \) may be shifted away from \( x_C \).

Definition of light intensity centroid of planar array CCD in two-dimension can be expressed as:

\[
\chi_C = \frac{\sum_{j=1}^{m} \sum_{i=1}^{n} (y_i \cdot I_{ij})}{\sum_{j=1}^{m} \sum_{i=1}^{n} I_{ij}}, \quad \chi'_C = \frac{\sum_{j=1}^{m} \sum_{i=1}^{n} (y_i' \cdot I_{ij})}{\sum_{j=1}^{m} \sum_{i=1}^{n} I_{ij}}
\]

in which \( x_C (y_C) \) is spot centroid, \( x_j (y_j) \) and \( I_{ij} \) are coordinate and gray of the \( i^{th} \times j^{th} \) pixel. From the above formula we can see that the spot centroid is determined by coordinate \( x_j (y_j) \) and gray \( I_{ij} \) of each pixel. We only analyze \( x_C \) since the calculation results are the same in both \( x \) and \( y \) directions.

Our study is predicated on the assumption that all of the microlens single elements have the same effect on spot centroid. Thus if \( x_{ij} \) of each coordinate has a variation \( \Delta x \), and \( I_j \) has a variation \( \Delta I_j = t \cdot I_j \) centroid shift value \( \Delta x_C \) is:

\[
\Delta x_C = x_C - x'_C = x_C - \chi_C = \sum_{j=1}^{m} \sum_{i=1}^{n} \left( (x_j + \Delta x)(y_j + \Delta I_j) \right) / \sum_{j=1}^{m} \sum_{i=1}^{n} I_{ij}
\]

in which \( t \) is the ratio of light intensity variation and total light of the spot. Since the error in position coordinate is thought not to exist in almost all the test, therefore the \( \Delta x \) is usually considered as zero. Predigested calculation was applied to find the simple formula meeting the request of approximate theoretical analyses:

\[
\Delta x_C = x_C - x'_C = \pm t \cdot x_C
\]

The deductions of \( \Delta x_C \) are the same in \( \Delta y_C \).

In this paper, we present numerical calculation of centroid shift. Set variation \( \Delta x \) to a zero value, and so the shift value \( \Delta x_C \) is \( \pm t \cdot x_C \) according to Eq. (11). The \( \Delta x_C \) is analyzed with GEE.

### 3.2. Centroid shift calculation using GEE

We’ve defined \( \Delta l = t \cdot l \) or \( \Delta l = l / l \). \( l / l \) can be approximately calculated by \( \Delta l = l_{\text{centroid}} - l_{\text{center}} \), \( l_{\text{center}} \) is the total light within a square aperture of a pixel length with the geometric center of the spot, and \( l_{\text{centroid}} \) is that with the intensity center. We can get the relationships between \( l_{\text{center}} (l_{\text{centroid}}) \) and \( l \) based on GEE in Zemax. The encircled energy is the fraction of total light from a point source that is contained within a circular aperture of a given radius. The center of square region can be geometric center of chief ray or spot centroid. Since detectors have nominally square pixels, we consider that it is more convenient to evaluate the energy falling within a certain number of pixels (“ensquared energy”) instead of the encircled energy, which requires interpolation to account for the fractional pixels intercepted by a circular aperture.

Fig. 4 illustrates the GEE of microlens when the incident light at an angle of 14 degrees. The tow curves are plotted by “half width from chief ray/centroid” on the horizontal axis and “fraction of enclosed energy” on the vertical axis. It shows that if we select different centers of square imaging region, we’ll get different GEE curves. The differences between them imply the energy changes caused by aberrations of microlens.

The unit pixel size in this detector has fallen to approximately 3.4 μm, so we read the fraction value when half width is 1.7 μm. According to Fig. 4, we can obtain the theoretical calculation of parameter \( t = (l_{\text{centroid}} - l_{\text{center}}) / l = (96.85\% - 96.43\%) / l = 0.42\% \). However, the initial centroid coordinates \( x_C \) is an unknown quantity. To obtain a theoretical approximation of centroid shift, experimental data is solved for \( x_C \) (Table 6), and the average of three centroid \( x \)-coordinates \( x_C \approx 347.86 \) μm is substituted in \( \Delta x_C \approx \pm t \cdot x_C \). The calculating result shows that \( \Delta x_C \approx 1.46 \) μm.
In this method, only $t$ is calculated by GEE. The centroid value of $x_c$ is obtained from spot imaging experiment. Our theoretical approximate calculation of centroid shift is completed by the help of Zemax model and experiment, which needs further development in the future research.

Centroid variation is got from this method only for one microlens. However, the $\Delta x_c$ will be different for every microlens, so there is a certain principle error with this method.

4. Centroid shift experiment

4.1. Pentaprism test introduction

Fig. 5 illustrates the concept of pentaprism test. This paraboloid test utilizes the property that incidence rays parallel to the optical axis will go through the focal point. It uses a narrow collimated laser beam to scan the surface of Giant Magellan Telescope (GMT) 8.4 m segment mirror, and the centroid position of spot is measured with a CCD detector at the focus. Slope errors of the mirror are proportional to the displacement of the spot. A second pentaprism is fixed to produce reference spot and compensate the changes in system alignment [9–11].

The collimated source for the GMT pentaprism tests is fed with 635 nm light from a laser diode. Incoming beam strikes a stationary reference pentaprism which has a built-in beamsplitter. Half of the light is deflected 90° down toward the test surface. The other half travels to another pentaprism and also deflects the light by 90°. Output beams from both prisms approach the mirror are parallel to the parent axis and have an angle of 28° between them. Since the GMT primary is an ellipsoid with $K = -0.998286$, the spots from reference and scanning prisms will be separated by as much as 900 μm. Slopes on the mirror are found by comparing the observed positions of the spots to the expected positions [9–11]. In theory, geometric center and light intensity distribution center (centroid) of spot are the same point, thus the observed position is calculated from its centroid. However, in actual test, the inconsistency of spot geometry center and centroid is discovered which will introduce measurement error.

4.2. Experiment design

The simulation experiment study based on pentaprism test model is conducted to detect the centroid shift value and to explore its source.

The experiment equipments mainly include laser interferometer, focusing lens, pinhole diaphragm, rotating platform and CCD camera integrated with MLA. The laser interferometer is an

<table>
<thead>
<tr>
<th>$U$</th>
<th>Center coordinates</th>
<th>Centroid coordinates</th>
<th>Centroid shift</th>
<th>Centroid shift average value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$-14^\circ$</td>
<td>(348.2100, 159.3898)</td>
<td>(348.5119, 159.2554)</td>
<td>2.2341 μm</td>
<td>2.1771 μm</td>
</tr>
<tr>
<td>$0^\circ$</td>
<td>(349.4835, 159.6000)</td>
<td>(349.9421, 159.4678)</td>
<td>0 μm</td>
<td></td>
</tr>
<tr>
<td>$+14^\circ$</td>
<td>(345.4263, 159.7313)</td>
<td>(345.1398, 159.6490)</td>
<td>2.1201 μm</td>
<td></td>
</tr>
</tbody>
</table>
The circular window radius.

The core of this method is to determine the spot center coordinate and circle window to separate the target spot from original image. The troid with window of circular region. The basic idea is using a 4.4. Center/centroid shift computing

Changing of spot centroid will be analyzed and computed with mathematical software.

4.3. Spots imaging

Two spots are formed by a beam splitter in the actual process to simulate the imaging result of scanning pentaprism test. One of the beam used as scanning beam, the other one represents the reference beam. We choose a window from detector whose size is 3.61 mm × 3.4 μm pixel size. Fig. 6(a) is schematic diagram of experimental setup. Using the lens and diaphragm, laser beam from interferometer is focalized and converted into a slow beam. Diameter of diaphragm is 1 mm, and 150 mm from the CCD, that the F number of our system is 150. CCD is supported by rotating platform, and rotation axis at the plane of the detector. The detector is rotated from +20° to −20° in the Z axis to ensure that the measure angles are included in the variation range as shown in Fig. 6(b). The facula imaged on detector will be recorded every 2°. Finally, the position changes of spot centroid will be analyzed and computed with mathematical software.

4.4. Center/centroid shift computing

We propose a method for calculating single spot center/centroid with window of circular region. The basic idea is using a circle window to separate the target spot from original image. The core of this method is to determine the spot center coordinate and the circular window radius.

Spot center location can be obtained using function of regionprops in Matlab. Regionprops measures a variety of image quantities and features in a black and white image. One of these particular properties is the ‘centroid’. Here, the ‘centroid’ means ‘geometry center’, which represents the center of mass. After image binarization processing, we can write a procedure to call the regionprops function and indicate (X, Y) location of the center of target spot.

Different sizes of circular window can result in different effects of centroid computing. Fortunately, it does not affect spot centroid much, as shown in Fig. 8. So in the three original images (Fig. 7), we choose the minimum radius which does not contain side-lobe as the window radius. According to subsequent analysis of cross-section optical intensity distribution, we finally select 48 pixels as window radius.

Center/centroid of single spot calculation can be summarized in Fig. 9(a):

1. Image collection and binarization: Matlab reads a grayscale original image from detector. Using minimum error method, which belongs the global threshold, to attain binary image, so that background and object are distinguished.

2. Spot center calibration and circular window setting: Determining target spots’ centers \((X_{14}’, Y_{14}’)\), \((X_0, Y_0)\), and \((X_{14}, Y_{14})\) and assistant spot’s center \((X_{10}’, Y_{10})\), \((X_0, Y_0)\), and \((X_{14}, Y_{14})\) with regionprops function. Then we set a circular window with the center points and radius of 48 pixels (Fig. 9(c)).

3. Target spot image formation and centroid calculation: Zeroing the gray value of background outside the window area which determined in step (2), we can form a new single spot images (Fig. 9(d)). Centroid location of target spot is calculated separately (Fig. 9(e)). Repeat the steps above to get all centroid locations of the target spots in Fig. 8. Here, the

Fig. 6. Schematic diagram of experimental setup. (a) Laser beam illuminates from Intellium™ H2000 Interferometer and passes through a pinhole, and received by Kodak KAI-16000 imaging detector. (b) The rotation angle from +20° to −20°. Spot images are gathered through CCD camera every 1°. Dealing with the figures of spot by Matlab, the shift of centroid can be presented.

Fig. 7. Results of centroid shift experiment: (a), (b) and (c) are spots images when \(U=+14°, 0°\) and \(-14°\).
The centroid shift also exists in the y direction, which is considered that it comes from coma of microlens and vertical axis deviation of rotating platform.

According to the analysis in Section 2.2.4, reference aberration of microlens is about 1.65 μm. The comparison between values of aberrations and centroid shift indicates that, a significant portion of the shift mainly caused by the low order aberration of MLA system.

5. Conclusion

In this paper, combining with the structural characteristics and parameters of MLA, we established the optical model of microlens integrated in detector. Seidel and wave aberrations were analyzed, and microlens sagittal aberration $\delta_s = 1.65 \, \mu m$ was selected as the reference value, whose relative height in pupil $\rho = 0.707$. A theoretical calculation method for centroid shift was presented with Geometric Ensquared Energy, and it pointed out that the centroid movement from spot geometric center was about 1.46 μm. Employing laser interferometer, pinhole diaphragm, and CCD camera integrated with MLA, we designed a spot imaging experiment to simulate pentaprism test. The results were shown that when the beam imaging at detector with a certain angle, the spot centroid on image plane has been shifted. The actual centroid shift average value was 2.18 μm when the incidence angle was $\pm 14^\circ$. From the aspects of theory calculate and experiment, the low order aberration of MLA that made the spot centroid shifted was proved. The improvement of lens-array alignment accuracy may be a good way to enhance the imaging quality in MLA system, which will be verified in further study.

Our study proposes the theoretical and experimental methods to research the spot centroid shift value of a CCD detector, and proves that it mainly comes from the low order aberration of MLA. The results of this paper will be used as the error compensation in actual spot calibration.

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