Calculation of contrast for computer simulated resolution chart image

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Abstract. The work is devoted to the analysis of the resolution chart image created with the Image Simulation mode of ZEMAX software. The changes in image quality are simulated using the model of Helios-44M-4 photographic objective lens. The research is conducted for monochromatic light conditions and computer simulated resolution test chart as an object for the lens with different chart positions. An axial beam and an off-axis beam that corresponds to the maximum object space field angle are analyzed. The calculation of contrast of the simulated resolution chart images is made modeling different spatial frequencies of the chart lines. The contrast is calculated in three ways. The first way uses the maximum and minimum values of the image illumination, and the second and third ways are based on the integral values of the illumination of black and white lines, calculated with the method of rectangles and the method of trapeziums, respectively. Having been calculated the values of contrast are compared with the theoretical values of the diffraction modulation transfer function obtained with ZEMAX.

1. Introduction
Optical system design is now closely connected with usage of computer-aided software such as ZEMAX, Code V, OSLO, OPAL, etc. Obviously, the most informative criteria to assess image quality for specialists in optical system design are modulation transfer function (MTF) [1], encircled energy function, point spread function (PSF), etc., which are available in modern special software, in particular ZEMAX [2]. On the other hand, software producers create and develop new functions and modes connected with the visualization of images that can be formed by an optical system being analyzed [3-6]. Computer simulation of images with modeling of an aberrational degradation of their quality is performed in ZEMAX using the Image Simulation mode [2]. The simulation is provided for a graphic image of an object saved as a file and loaded into the program by its user. This mode may be useful to present the results of researches to a customer and to demonstrate the expected image quality without explaining complex technical terms and details [6].

In this regard, the authors consider it interesting to study the correlation between the results of two ZEMAX modes: diffraction MTF mode and Image Simulation mode. The results of the first one are taken as reference and correspond to MTF graphs as "theoretical" values of contrast for different spatial frequencies, while the results of the second mode produce the images of the resolution chart to calculate the "practical" values of contrast. Therefore, section 2 is devoted to the description of different contrast calculation methods and defines input data connected with a resolution chart, an optical system and Image simulation mode settings. Section 3 gives the results of contrast calculation and estimates correlation of results of two ZEMAX modes for different input conditions.
2. Description of contrast calculation methods and input data

2.1. Resolution test chart and its settings

An estimation of the photographic objective lens "visual resolution" is based on the visual observation of the images of special test charts formed with an optical system being tested [1]. The most frequently used chart in Russian Federation (RF) is a "mira" resolution chart shown in figure 1. The resolution test chart layout and the size of its elements are regulated with RF standards such as GOST 15114-78.

In general, there is a set of similar charts and every chart consists of 25 elements (see figure 1) as well as each element contains a system of horizontal, vertical and inclined black and white lines. Thus, the chart is an ideal 100% contrast object with a set of different spatial frequencies in the tangential, sagittal and inclined sections.

Working with the Image Simulation subprogram it is not necessary to use all the chart shown in figure 1. It is rather more convenient to use a region of interest (ROI), consisting of 10 line pairs where one pair is a set of single black and white lines as shown in figure 2.

Using ZEMAX Image Simulation settings window shown in figure 3 it is possible to adjust specific parameters of chart ROI: wavelength, tangential or sagittal section, axial or off-axis position, etc. For example, it can be seen in figure 3 that ROI spatial frequency and line orientation are set with the Field Height and Rotate Source fields, respectively.

![Figure 1. Resolution test chart.](image1.png)  
![Figure 2. Resolution chart region of interest.](image2.png)  

![Figure 3. Image Simulation settings window.](image3.png)
The interface of the Image Simulation mode also allows to adjust pupil and image sampling connected with calculation accuracy and to take into account diffraction effects and aberrations.

2.2. Optical system model
The transmittances of the black and white lines of the resolution chart do not depend on the spatial frequency and the chart is considered to be an ideal test object with 100% contrast. The changes in the intensity of the lines of chart images are connected with the parameters of the optical system, such as its aberration correction, diffraction, etc.

Resolution chart image simulation is made for "Helios-44M-4" objective lens [7]. The optical layout of the lens shown in figure 4 contains 6 elements in 4 groups and may be classified as an optical system of "Planar" (Biotar) type.

![Figure 4. Layout of "Helios-44M-4" objective lens.](image)

2.3. Image simulation and contrast calculation algorithms
The results of the Image Simulation mode [2] can be represented in graphical or text windows shown in figure 5. The text window contains information about the intensity values at different points of the image for red, green and blue colors. The intensity values for each wavelength can change from 0 to 255 that corresponds to 8-bit image. In addition, the windows contain the value of the image size that makes it possible to calculate the spatial frequency of the chart in image plane. Since the resolution chart ROI has 10 pairs of lines, the spatial frequency of the image can be calculated as the ratio of 10 linepairs to the image size in mm. For the image simulation results shown in figure 5 the image size is 1 mm so the spatial frequency is 10 linepairs/mm. Changing the size of the object it is possible to get the necessary values of spatial frequencies as 10, 20, 50, 75, 100, 150 and 200 (for the axial position of the test chart only) linepairs per mm.

![Figure 5. Image Simulation results.](image)
Different methods of MTF measurements are described in [8, 9]. Our research is based on the resolution chart image analysis, contrast calculation for the images with different values of spatial frequencies and building MTF graphs.

The calculation of contrast of the resolution chart ROI images is performed in three different ways. **Method 1** is based on calculating the contrast \( K \) using the maximum \( I_{\text{max}} \) and minimum \( I_{\text{min}} \) peak values of the image intensities. The contrast \( K \) is expressed as follows:

\[
K = \frac{I_{\text{max}} - I_{\text{min}}}{I_{\text{max}} + I_{\text{min}}}.
\]  

**Method 2** uses integral maximum and minimum values of the image intensities calculated by the method of rectangles. In that case the contrast \( K \) can be found as

\[
K = \frac{\sum_{m=1}^{M/2} I_{\text{max}} - \sum_{m=1}^{M/2} I_{\text{min}}}{\sum_{m=1}^{M/2} I_{\text{max}} + \sum_{m=1}^{M/2} I_{\text{min}}},
\]

where \( M \) is the number of points in the image period that is a single pair of black and white lines.

**Method 3** uses integral maximum and minimum values of the image intensities calculated by the method of trapezium. In that case the contrast \( K \) is

\[
K = \frac{\sum_{m=1}^{M/2} I_{\text{max}} + I_{\text{max}} + I_{\text{min}} + I_{\text{min}}}{2} - \frac{\sum_{m=1}^{M/2} I_{\text{min}} + I_{\text{min}} + I_{\text{max}} + I_{\text{max}}}{2}.
\]

### 3. Calculation of contrast for resolution chart simulated images

#### 3.1. Calculation of contrast for the axial position of resolution chart ROI

The results of analysis of resolution chart images formed with Helios-44M-4 objective lens for the axial position of the chart are shown in Table 1. The values of contrast \( K \) are calculated for the spatial frequencies defined in subsection 2.3. Three methods of contrast calculation described in subsection 2.3 are used. The theoretical values of contrast are obtained as a result of ZEMAX diffraction MTF mode.

| Frequency (linepairs/mm) | Contrast \( K \) | Method 1 | Method 2 | Method 3 | Theoretical value |
|-------------------------|------------------|---------|---------|---------|------------------|
| 10                      | 1.000000         | 0.843369| 0.887139| 0.919384 |
| 20                      | 0.961089         | 0.725185| 0.774221| 0.770136 |
| 50                      | 0.486238         | 0.337813| 0.365456| 0.355784 |
| 75                      | 0.301333         | 0.193600| 0.210074| 0.198003 |
| 100                     | 0.200000         | 0.121144| 0.131579| 0.130819 |
| 150                     | 0.087248         | 0.057111| 0.061458| 0.063578 |
| 200                     | 0.006237         | 0.001663| 0.001616| 0.016804 |
Figure 6 shows four MTF graphs. Theoretical graph corresponds to the diffraction MTF calculated with ZEMAX software. The other graphs are built based on the values of contrast in table 1, obtained with the methods of contrast calculation described in subsection 2.3. Figure 6 also shows simulated images of the resolution chart ROI for the spatial frequencies indicated in table 1.

Based on the data of figure 6 and table 1 it can be concluded that there is a high correlation between the theoretical values of contrast and the values calculated with integral methods of intensity analysis (methods 2 and 3). It should be noticed that method 3 provides the best approximation to the theoretical graph.

3.2. Calculation of contrast for the off-axis position of resolution chart ROI

The calculation of contrast for the off-axis position of the resolution chart ROI is performed for the horizontal and vertical orientation of the ROI lines, that makes it possible to calculate the tangential and sagittal MTFs. Figure 7 shows a cross-sectional profile of the intensities in the image of ROI horizontal lines.
As can be seen from figure 7 the resulting profile is not symmetric relative to the maximum and minimum intensity values (peak values). As a result, it leads to ambiguity in the interpretation of the line boundaries in the image plane [10]. Therefore, two approaches were considered in determining the line boundaries, that is important in contrast calculation with integral methods (methods 2 and 3):

- **approach 1** illustrated in figure 8 defines that to calculate the integral maximum intensity value, $M/2$ following one by one $I_{\text{imax}}$ intensity values are taken and every $I_{\text{imax}}$ value must be greater than every $I_{\text{imin}}$ intensity value of the remaining $M/2$ number of values; these remaining $M/2$ number of $I_{\text{imin}}$ values are taken to calculate the integral minimum intensity value;

- **approach 2** illustrated in figure 9 defines that to calculate the integral maximum intensity value, $M/2$ $I_{\text{imax}}$ values are taken and these values are equidistant from the maximum intensity peak value; to calculate the integral minimum intensity value $M/2$ $I_{\text{imin}}$ values are taken and these values are equidistant from the minimum intensity peak value.

![Figure 8. Line boundary interpretation based on approach 1.](image)

![Figure 9. Line boundary interpretation based on approach 2.](image)

Tables 2 and 3 contain the contrast values calculated with the described above approaches 1 and 2, respectively. The structure of the tables is similar to table 1.

### Table 2. Calculation of contrast based on approach 1 for the off-axis position of resolution chart ROI and horizontal line orientation (tangential MTF).

| Frequency (linepairs/mm) | Method 1 | Method 2 | Method 3 | Theoretical value |
|--------------------------|----------|----------|----------|-------------------|
| 10                       | 0.976285 | 0.708289 | 0.736822 | 0.690300          |
| 20                       | 0.776173 | 0.509577 | 0.514695 | 0.482279          |
| 50                       | 0.282322 | 0.156269 | 0.163969 | 0.132025          |
| 75                       | 0.127962 | 0.055335 | 0.057950 | 0.108413          |
| 100                      | 0.151807 | 0.087662 | 0.092520 | 0.059784          |
| 150                      | 0.107551 | 0.066900 | 0.069789 | 0.032996          |
| 200                      | 0.006237 | 0.001663 | 0.001616 | 0.016804          |

Figure 10 shows four MTF graphs based on the contrast values according to table 3. Theoretical graph corresponds to the diffraction tangential MTF calculated with ZEMAX software. The other three graphs obtained with approach 2 correspond to the values of contrast calculated with methods 1-3, respectively (see table 3). Figure 10 also shows simulated images of the resolution chart ROI for the spatial frequencies given in table 3.
Table 3. Calculation of contrast based on approach 2 for the off-axis position of resolution chart ROI and horizontal line orientation (tangential MTF).

| Frequency (linepairs/mm) | Method 1  | Method 2  | Method 3  | Theoretical value |
|--------------------------|-----------|-----------|-----------|-------------------|
| 10                       | 0.976285  | 0.708289  | 0.736822  | 0.690300          |
| 20                       | 0.776173  | 0.501984  | 0.523740  | 0.482279          |
| 50                       | 0.282322  | 0.143850  | 0.149994  | 0.132025          |
| 75                       | 0.127962  | 0.053812  | 0.055079  | 0.108413          |
| 100                      | 0.151807  | 0.083215  | 0.087216  | 0.059784          |
| 150                      | 0.107551  | 0.060957  | 0.063468  | 0.032996          |
| 200                      | 0.006237  | 0.001663  | 0.001616  | 0.016804          |

Figure 10. Tangential MTF graphs and resolution chart images for off-axis position of the chart ROI with horizontal line orientation.

Comparing the data of tables 2 and 3 it can be concluded that there is a high correlation between the theoretical values of contrast and the values calculated with integral methods of intensity analysis (methods 2 and 3) and approach 2 in determining the boundaries of the line image for the given set of spatial frequencies. As can be seen from table 3 and figure 10 the best approximation to the theoretical values is obtained when method 2 is used to calculate the contrast.

The values of contrast presented in table 4 are obtained with the off-axis position of the resolution chart ROI and vertical orientation of the ROI lines. The theoretical contrast values correspond to the sagittal MTF.
Table 4. Calculation of contrast for the off-axis position of resolution chart ROI and vertical ROI line orientation (sagittal MTF).

| Frequency (linepairs/mm) | Contrast K | Method 1 | Method 2 | Method 3 | Theoretical value |
|--------------------------|------------|----------|----------|----------|-------------------|
| 10                       | 1.000000   | 0.707241 | 0.736928 | 0.845609 |
| 20                       | 0.627242   | 0.421963 | 0.440655 | 0.519443 |
| 50                       | 0.209877   | 0.106264 | 0.112215 | 0.012131 |
| 75                       | 0.048458   | 0.004971 | 0.004631 | 0.160242 |
| 100                      | 0.078947   | 0.032187 | 0.035654 | 0.030425 |
| 150                      | 0.065169   | 0.023772 | 0.026847 | 0.061431 |

Figure 11 shows four MTF graphs based on the contrast values according to table 4. Theoretical graph corresponds to the diffraction sagittal MTF calculated with ZEMAX software. The other three graphs correspond to the values of contrast calculated with methods 1-3, respectively (see table 4). Figure 11 also shows simulated images of the resolution chart ROI for the spatial frequencies given in table 4.

Analyzing the data of table 4 and figure 11 it can be concluded that the correlation between theoretical and calculated values of contrast is very low.

4. Conclusion
According to the research simulated images of the resolution test chart for its axial and off-axis positions have been obtained with Image Simulation mode in ZEMAX software. To calculate the contrast of the resolution chart ROI images three different methods of maximum and minimum intensity estimation have
been analysed. The first method uses peak intensity values for the images of black and white lines whereas the second and the third methods use integral maximum and minimum intensity values, calculated with the methods of rectangles and trapeziums, respectively. Calculated values of contrast have been compared with the theoretical contrast values that were taken from ZEMAX diffraction MTF graphs.

A high correlation between the calculated and theoretical contrast values is observed for the axial position of the resolution chart ROI. The best results are obtained when using the integral maximum and minimum values of the image intensity, calculated using the trapezium method.

As for the off-axis position of the resolution chart ROI very low correlation can be found for sagittal MTF curves. High correlation of the calculated and theoretical contrast values is observed for the tangential MTF graph in the area of low and high spatial frequencies. The maximum deviation between the values can be seen in the area of medium spatial frequencies and reaches 15%. In this case, the best result was obtained when using the contrast estimation with the integral maximum and minimum image intensity values, calculated with the method of rectangles.

Future researches may be conducted for the practical measurements of contrast for resolution chart images formed with a real "Helios-44M-4" objective lens and comparison of the results with ones obtained in the current study.

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