DESIGN OF THE CEMENTED DOUBLET – SOFTWARE APPLICATION

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Abstract: From optical point of view, an imaging application includes the sensor (CCD or CMOS) and the objective. The simplest objective consists of a cemented doublet. The paper proposes a design algorithm of the doublet and describes a software application based on this algorithm. The results provided by the original software are validated by means of a professional application in optical system analysis.
Keywords: optical design, cemented doublet, software application.

1. Introduction

Robotics widely use images provided by different types of cameras. From optical point of view, an imaging application includes the sensor (CCD or CMOS) and the objective. The objective, depending on the required image quality may be an assembly made of one or more basic entities, which are the singlet, the doublet and the triplet.

The image quality can be evaluated in terms of geometrical aberrations, parameters resulted from wavefront analysis and Fourier parameters. There are several software applications, which perform professional analysis of image quality, such as OSLO, Code-V and Zemax [1, 2, 3].

Regarding the design of optical basic entities there are no standards. Different optics schools, world-wide, recommend different algorithms. They are based on minimization of longitudinal spherical aberration and longitudinal/lateral chromatic aberration [4, 5, 6, 7, 8, 9].

The present research refers to the cemented doublet, which is frequently used because it is the simplest assembly, which ensures a good quality of the image.

The cemented doublet consists of a positive lens cemented together with a negative one (Fig. 1).
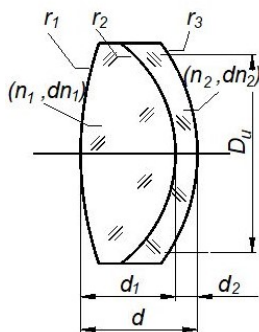

Fig. 1. The cemented doublet.

The three radii allow three mathematical conditions to pose. The first condition refers to the optical power or effective focal length. The second one aims to use an expression of the spherical aberration, which should be minimized. The third condition contains the minimization of the chromatic aberration, defined in different forms.

2. Algorithm for the Design of the Cemented Doublet

The algorithm proposed in this paper is based on the minimization of longitudinal spherical aberration and longitudinal marginal chromatic aberration [3, 10].
The input data for the design is:
- f' (effective focal length)
- D (aperture)
- S (object abscissa)
- n_e, $n_{F'}$, $n_{c'}$ (refractive and diffractive parameters of the glasses).

The steps for the calculus of the doublet are the following:

1. calculus of total curvatures of the lenses, resulted from the condition of axial achromatization:

$$c_a = 1/f'/(\nu_a - \nu_b)/dn_a, \qquad (1)$$

$$c_b = 1/f'/(\nu_a - \nu_b)/dn_b, \qquad (2)$$

where ν_a and ν_b are Abbe numbers, and dn_a and dn_b are the main dispersions of the glasses ($dn = n_{F'} - n_{C'}$).

2. calculus of curvature c_1 ($c_1 = 1/r_1$) from the condition of minimization on primary spherical aberration. The mathematical result is a second degree equation:

$$k_1c_1^2 + k_2c_1 + k_3 = 0, \qquad (3)$$

where the coefficients k_1, k_2 and k_3 are functions of the reference refractive index:

$$k_1 = G_{4a}c_a + G_{4b}c_b, \tag{4}$$

$$k_2 = -G_{2a}c_a^2 - G_{5a}c_a p_a - G_{2b}c_b^2 - 2G_{4b}c_a c_b - G_{5b}c_b p_b, \tag{5}$$

$$k_3 = G_{1a}c_a^3 + G_{3a}c_a^2 p_a + G_{6a}c_a p_a^2 + G_{1b}c_b^3 + G_{2b}c_a c_b^2 +$$
$$+ G_{3b}c_b^2 p_b + G_{4b}c_a^2 c_b + G_{5b}c_a c_b p_b + G_{6b}c_b p_b^2, \tag{6}$$

where so-called G-sums are:

$$G_1 = 1/2 \, n^2 \, (n-1), \tag{7}$$

$$G_2 = 1/2 \, (2n+1)(n-1), \tag{8}$$

$$G_3 = 1/2 \, (3n+1)(n-1), \tag{9}$$

$$G_4 = 1/2n \, (n+2)(n-1), \tag{10}$$
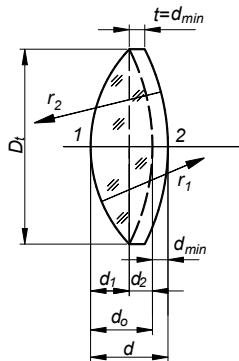
$$G_5 = 2 \, (n^2-1)/n, \tag{11}$$

$$G_6 = 1/2n \, (3n+2)(n-1), \tag{12}$$

and p, p' are notations for the invers of object/image abscissas of the lenses:

$$p = 1/s, \; p' = 1/s'. \tag{13}$$

   3.   calculus of center thickness of the lenses, d:

$$d = d_0 + d_{min}, \text{ for positive lenses (fig. 2)} \tag{14}$$

Fig. 2. Geometry of the positive lens ($r_{1,2}$ – radii, D_t – total diamter (aperture), d_0 – basic center thickness, $d_{min} = t$ – minimum marginal thickness.

The basic center thickness d_0 is computed depending on the shape of the lens (bi-convex, plano-convex, meniscus).

   4.   calculus of the curvature c_3 from the condition of marginal achromatization:

$$(D_a - d_a)dn_a - (D_b - d_b)dn_b = 0, \tag{15}$$

where $D_{a,b}$ are the lengths of the marginal rays through the lenses and $d_{a,b}$ are the paraxial rays, approximated through the center thicknesses.

The following intermediate data is necessary:

$$x_i = r_i [1 - \cos(\sigma'_i - \varepsilon'_i), \; i = 1, 2 \tag{16}$$

$$y_i = r_i \sin(\sigma'_i - \varepsilon'_i), \; i = 1, 2, \tag{17}$$

where σ' is the angle of the image ray and the optical axis and ε' is the emergence angle.

The coordinates of the third incidence point provide r_3:

$$r_3 = (x_3^2 + y_3^2)/2/x_3. \tag{18}$$

   5.   check of the reference optical characteristics and residual aberration.

3. Software Application

The algorithm was written within the software development environment Python. The interface of the application (fig. 3) allows the user to type the input data (effective focal length, aperture and object abscissa) and to read the results (r_1, r_2, r_3, d_1, d_2, effective focal length and image abscissa) for two solutions (the second degree equation (3) provides two solutions for c_1).

The program ran for the input data:
- f' = 100
- D = 15
- s = - ∞
- glass sorts: N-LAK7 and N-LASF45 from the catalogue Schott

and displayed two solutions, of which is chosen the one with global bi-convex shape:
- r_1 = 148.99
- r_2 = -32.44
- r_3 = -77.96
- d_1 = 1.7
- d_2 = 1.5.

The resulting doublet was verified regarding the reference optical characteristic and the image quality with the program OSLO EDU.

Figure 4 shows the window Surface data, displaying the input data, the effective focal length and image abscissa:
- f' = 99.79
- s'_F' = 99.37.

Figures 5, 6 and 7 summarize the results of analysis from geometrical, wave theory and Fourier optics point of view.

Figure 5 displays the geometric aberrations. One can notice the insignificant spherical residual aberration, as well as the residual lateral color.

Figure 6 shows the results of the wavefront analysis. The parameters P-V OPD < 0.25λ and RMS OPD < 0.07λ qualify the system as diffraction limited.

Figure 7 prints the modulation transfer function and foresees the behavior of the doublet regarding the resolution. MTF is ~0.8 up to approximately 40 cycles/mm, which recommends the use of the assembly in applications both traditional (the human eye is the image receptor) and imaging (a physical sensor captures the image).

All three figures resulted from analysis confirm the high quality of the assembly, thus validating the proposed algorithm and software.
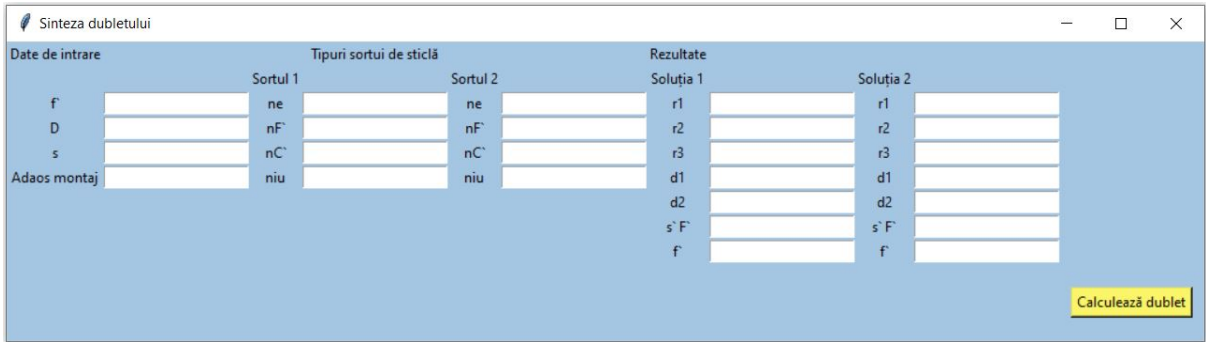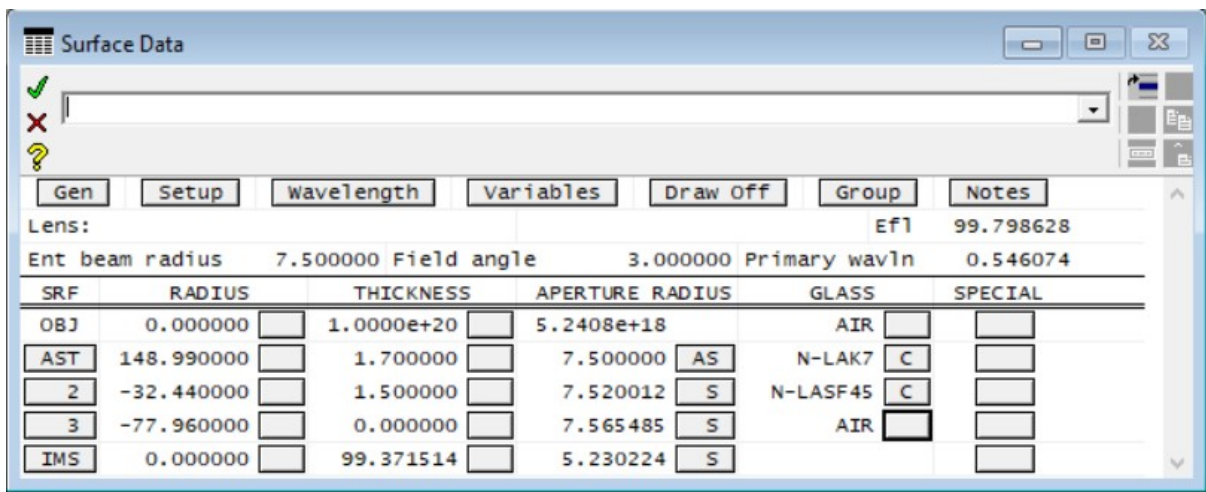
Fig. 3. Interface of the program.

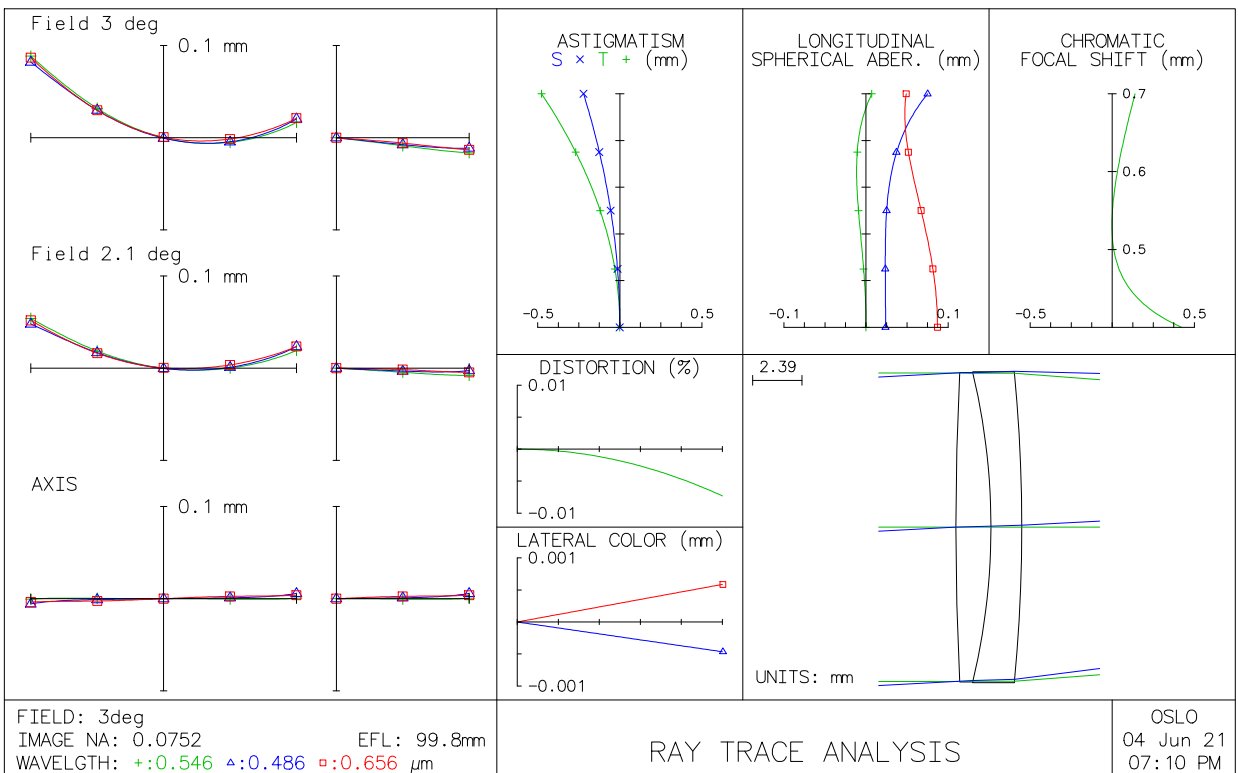**Fig. 4.** The window Surface data (OSLO).

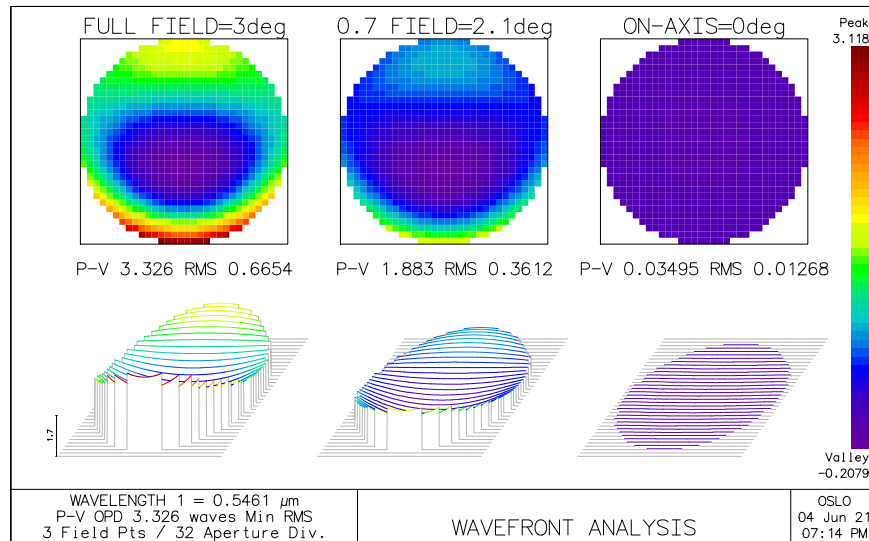**Fig. 5.** Geometrical and chromatic residual aberration (OSLO).
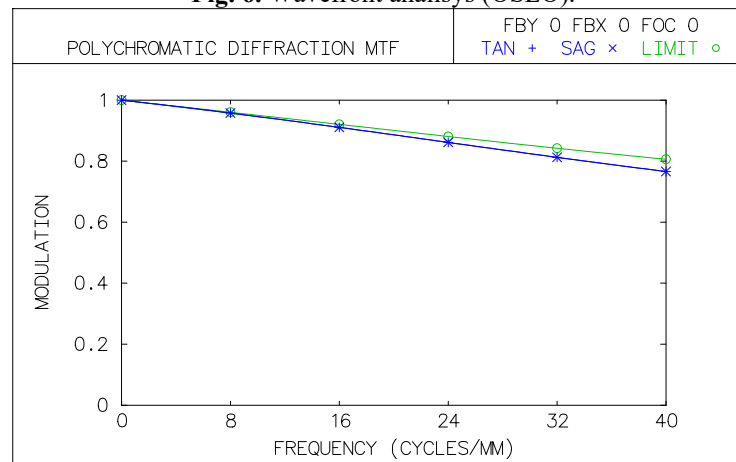
Fig. 6. Wavefront analisys (OSLO).

Fig. 7. MTF (OSLO).

4. Conclusions

The design of an optical entity, such as the cemented doublet, which is the subject of this paper requires an elaborate mathematical algorithm. The algorithm uses expressions of the primary longitudinal spherical aberration, longitudinal chromatic aberration and paraxial/ extra-axial ray tracing.

The original software application is conceived in the environment Python. The numerical results were validated with the analysis program OSLO EDU, which provided very high image quality parameters.

5. References

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