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Human retina imaging: widening of high resolution area

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In this paper we consider different methods of widening high resolution retinal image area. The first method is based on compensation of an average phase of two beacons formed on human retina within the isoplanatic patch. The second one is based on compensation of external corneal surface refraction with the help of immersion liquid. In both methods we use a single wavefront corrector conjugated to the pupil plane. The immersion method was found to be the most appropriate as it allows one to increase the area of high resolution almost twice without loss of image quality.

Keywords: retinal imaging; adaptive optics; human eye anisoplanatism; isoplanatic patch widening methods

1. Introduction

To get high quality of the human retina image, an adaptive optics approach is often applied [1] and a new generation of fundus-cameras are suggested, equipped with adaptive correctors. But even in the case of an ideal corrector, the retinal image is still degraded by the effect of anisoplanatism [2]. This means we can get high-resolution image quality only within a finite area around the reference source – the isoplanatic patch. In this paper we present the results of measuring the isoplanatic patch of the human eye and discuss possible ways to the enlarge isoplanatic patch size.

To estimate the size of the isoplanatic patch of the human eye we created beacon sources onto human retina. We define the residual mean-square error of correction as

$$\sigma^2(\alpha) = \frac{1}{S}\int_S \varepsilon^2(\alpha, \boldsymbol{r})\, \mathrm{d}^2\boldsymbol{r}\,, \tag{1}$$

where $\varepsilon(\alpha, \boldsymbol{r}) = \varphi(\alpha, \boldsymbol{r}) - \varphi(0, \boldsymbol{r})$, α is angular distance between the beacon position and the imaged point on the retina (we assume the initial angular coordinate of the beacon to be 0°), $\boldsymbol{r}$ is the coordinate vector in the entrance pupil plane, $\varphi(\alpha, \boldsymbol{r})$ is the wavefront from the imaged point on the retina, $\varphi(0, \boldsymbol{r})$ is the beacon wavefront, and S is the pupil area. We define the isoplanatic patch size as the area where the residual mean-square error of

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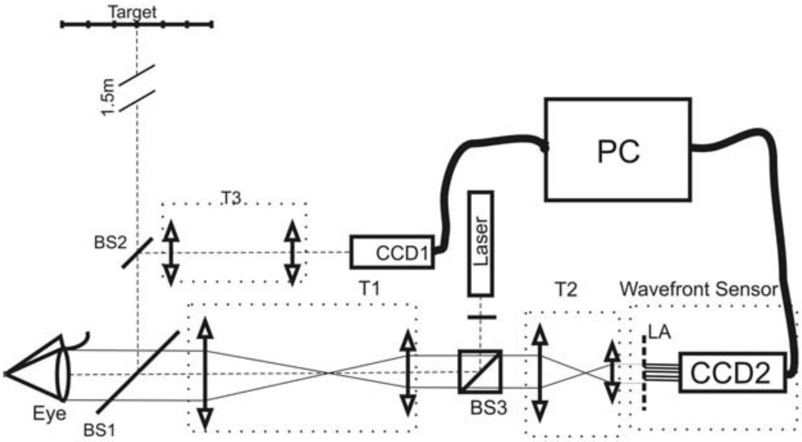

Figure 1. Experimental setup: T1,T2,T3, telescopes; BS1, BS2, pellicle beamsplitters; BS3, beamsplitter cube; LA, lenslet array; CCD1, eye tracking camera; CCD2, camera of the wavefront sensor.

correction by an ideal wavefront corrector (that can ideally compensate the aberrations of the wavefront from the reference source) is less than 1 rad^2. Using that criterion we estimate the size of the isoplanatic patch along the horizontal axes for four subjects.

2. Off-axis and on-axis human eye aberrations measurements

Aberrations of the human eye for different eccentricities were studied with a Shack–Hartmann technique by means of an aberrometer [3] ABDM18C produced by Active Optics Ltd. The principle scheme of the experimental setup is shown in Figure 1. The diode laser (780 nm, power incident on the cornea 50 μW) delivers monochromatic light to the retina, and forms a point source on it. The exit pupil of the eye is optically conjugated with the lenslet array of the Shack–Hartmann wavefront sensor that processes the signal and expands the incoming wavefront into Zernike polynomials up to fourth order. To measure off-axis aberration performance a pellicle beamsplitter BS1 (reflection 8%, transmission 92%) was placed in front of the observer's pupil (we used natural pupil size 4 mm). With the help of the pellicle an examined subject could focus on the different parts of the fixation target, thus rotating his eye in the temporal-nasal direction.

The fixation target consists of tick marks spaced 0.5° from each other along a horizontal line. Measurements are taken at eccentricities ranging from −3° to 3°. Observers are fixated with the help of a chin-rest. Using camera CCD1 we make records of pupil movement that allows us to discard data where the pupil deviation exceeds 50 μm. For such fixation accuracy the error of measurement (root-mean-square deviation of the wavefront) does not exceed 0.005 μm. The size of the image of the point source on the retina (PSF) is an order of magnitude smaller than the estimated isoplanatic patch. For a given characteristics of a lenslet array (0.3 mm pitch, 8 mm focal length) the maximum permissible value of an aberration that could be correctly measured is about 6 μm [4], that is larger than the most severe aberration of the examined observers.

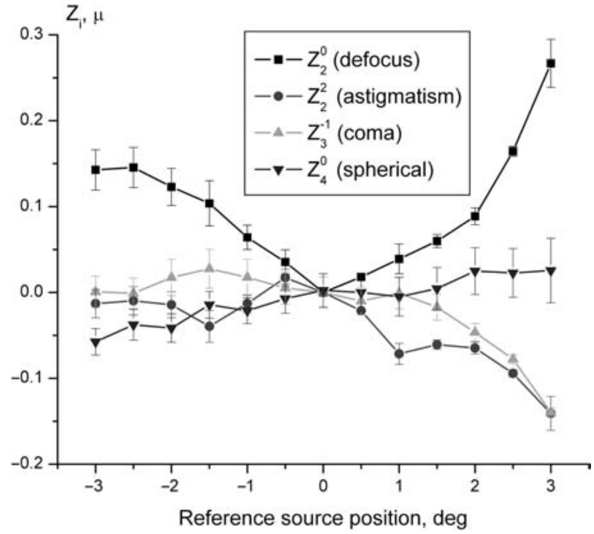

Figure 2. Zernike terms for different beacon eccentricities for subject AD.

Figure 2 demonstrates the results of aberration measurement for different locations of the beacon (from -3° to 3°) for subject AD. For clearness we assume aberrations at 0° beacon position equal to zero. Four Zernike terms Z_2^0, Z_2^2, Z_3^{-1}, Z_4^0 are presented, since variation of other terms is significantly smaller. The magnitude of aberrations is different for all observers, but the total variation of the wavefront is mainly influenced by low-order terms. Astigmatism is the dominant source of phase variation across the visual field for subject AD (0.4 μm amplitude of the aberration), for subject RL (0.5 μ) and AB (0.3 μ), whereas for AK defocus has the largest amplitude of aberration, 0.3 μm. The amplitude of vertical and horizontal coma for all observers does not exceed 0.2 μm. The deviation of defocus for the four subjects, AD, RL, AB, AK, is 0.3, 0.3, 0.2 and 0.3 μm, respectively.

In our experiments we use NIR light, which penetrates deeper behind the photoreceptors and is scattered by the choroids [5]. This means that different retinal thicknesses across the central fovea may affect our measurements. We have estimated possible path-length difference that may be caused by retinal topography and found that an error caused by it is an order of magnitude smaller than, for example, error caused by pupil movements. Consequently measured variation of defocus can not be associated with the retinal profile. The above-mentioned experiment of off-axis aberration measurements was also described in [6].

We then measure the contribution of the corneal surface and the internal eye optics on the total eye aberrations' status. We used the idea of an experiment proposed by Young in 1801 [7]. He measured the contribution of a lens on the total eye astigmatism by immersing the eye in water. The scheme for our measurements is the following. First of all we measure total aberrations of the subject's eyes. Then the subject puts on swimming goggles having high-quality glass. (Aberrations of the glass of the goggles do not exceed $\lambda/10$.) The refractive power of the external corneal surface is neutralized by filling the goggles with saline water and measurements of the aberrations of the internal eye optics are performed. Immersing in water makes the eye hyperopic, thus an additional high-quality lens is placed

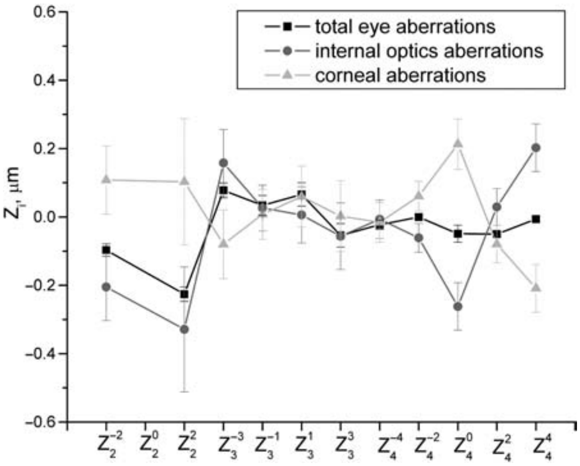

Figure 3. Magnitude of Zernike coefficients for different eye elements (subject AB).

in front of the eye in order to compensate for hyperopia of the eye. Each subject's pupil is considered to be centered with respect to the optical axis of the aberrometer when the signal from the eye coincided with the reference hartmannogram. The value of the measured defocus is very sensitive to the distance to the eye thus defocus is not included in the results of the experiment. The refractive index of the immersion liquid ($n \approx 1.34$) slightly differs from that of the cornea ($n = 1.37$). This leads to an additional error in the determination of the internal eye optics aberrations of about 10%. Corneal aberrations are determined by subtracting the internal optics aberrations from the total eye's aberrations.

Figure 3 shows values of Zernike coefficients for different elements of the eye for subject AB. It can be seen that aberrations of the cornea and the internal eye optics are greater than the total eye aberrations. Similar results are obtained for subjects AD and GL. For subject RL the same result is observed mostly for high-order aberrations. So for most cases the value of the total eye aberrations lies between the corneal and internal optics aberrations' values. This result is in good agreement with results obtained in [8].

We calculated the Strehl ratio by computation of the exponent of the residual mean-square error of correction (see Figure 4). This figure makes possible the estimation of the isoplanatic area of the human eye as a Strehl ratio value of 0.37 corresponds to the limits of the isoplanatic area. Figure 4 also shows the isoplanatic patch size of the modified Gullstrand eye model [9], with asphericities of the cornea and the lens surfaces introduced as suggested by Navarro co-workers [10, 11]. The value of the isoplanatic angle of the Gullstrand–Navarro model eye is 3.4° which is larger than the values obtained experimentally for real eyes.

3. Human eye modeling

To investigate possible ways of isoplanatic patch widening we first developed human eye models reproducing correctly on-axis and off-axis eye aberrations and their distribution

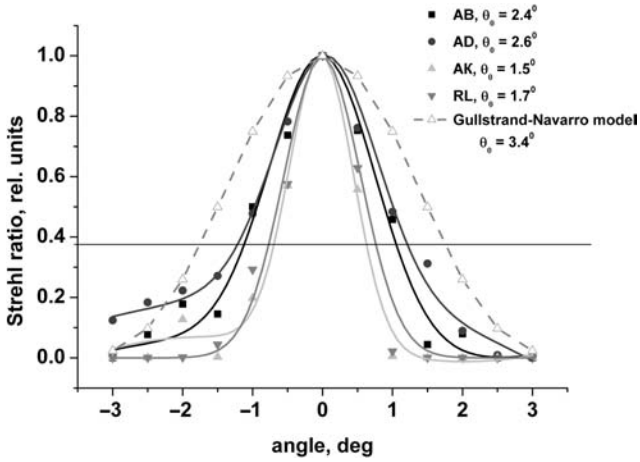

Figure 4. Relative Strehl ratio (in the case of an ideal corrector directed to the beacon at the center of the fovea). The horizontal line corresponds to a Strehl ratio of 0.37 (mean-square error of one square radian).

between optical elements of the eye as measured in our experiments. First of all we altered the Gullstrand–Navarro model by misaligning its main components – lens and cornea. For example, shifting the lens 0.2 mm leads to the isoplanatic angle decreasing up to 1.9°. Varying the parameters of the Gullstrand–Navarro eye model, for example decentering the pupil, changing the values of the conic constants and the curvature radii of surfaces, we managed to obtain the same off-axis performance as we observed for each subject in the experiment. Optical parameters of the eye models are shown in Table 1.

Then we performed further modifications of the eye models taking into account the cornea and the internal optics contribution on the total eye aberrations. The profile of the cornea surface was changed in order to have the same on-axis aberrations as the real subject eye's cornea. We consider internal optics aberrations to be introduced mainly by the lens so we also changed the lens surface profile to match the internal optics aberrations of the real eye. After changing the surface profiles according to the results of the experiment, the off-axis performance of the eye models is only slightly changed for all subjects (so we corrected it by slightly misaligning of Gullstrand–Navarro eye elements). Thus, the off-axis eye performance is mainly determined by misalignment of the eye elements. Figure 5 shows the resulting off-axis performance for the real eye (subject AD) and the model eye reproducing the behavior of the real one.

4. Methods of isoplanatic patch widening

4.1 *Average phase correction method*

The idea of using several wavefront correctors conjugate to different layers of the turbulent medium was suggested in 1988 by Beckers [12]. The results of investigation of the potential of multi-conjugate adaptive optics (MCAO) systems for correction of atmospheric turbulence are presented in many papers. For example in [13] the performance of

Table 1. Optical parameters of model eyes. Refractive indices are the same for all models. Also decentering of the pupil aperture with respect to the optical axis is pointed out for each model.

Surface	Radius (mm)	Conic constant	Thickness (mm)	Refractive index
Subject AD (right eye)				
1	7.7	−0.4	0.5	1.376
2	6.8	0	3.1	1.336
Pupil	Infinity	0	0	–
4	10	−3.13	0.546	1.386
5	7.91	0	2.419	1.406
6	−5.76	0	0.635	1.386
7	−6	−1	17.4	1.34
Retina	−11.8	0	–	–
Pupil decentering: 0.5 mm nasally				
Subject AB (left eye)				
1	7.7	−0.33	0.5	
2	6.8	0	3.1	
Pupil	Infinity	0	0	
4	10	−3.13	0.546	
5	7.91	0	2.419	
6	−5.76	0	0.635	
7	−6	−1	17.4	
Retina	−11.5	0	–	
Pupil decentering: 0.5 mm nasally				
Subject RL (right eye)				
1	7.6	−0.28	0.5	
2	6.8	0	3.1	
Pupil	Infinity	0	0	
4	11	−3.13	0.546	
5	7.91	0	2.419	
6	−5.7	0	0.635	
7	−5.8	−1	17.2	
Retina	−11	0	–	
Pupil decentering: 0.6 mm nasally				

MCAO with two and three correctors is investigated. It is shown that using two correctors allows increasing isoplanatic patch size by a factor of 5.5–6.5. Using three correctors gives isoplanatic patch size increasing by a factor of 7–10. In a recent paper written by Bedgood et al. [14] application of this technique to human eye aberrations correction is considered. The authors use the Liou and Brennan schematic eye [15] and model the performance of the MCAO system for the human eye aberrations correction using the ZEMAX software. It is shown that using a MCAO system with five deformable mirrors and five reference sources, a significant increase of the isoplanatic patch size (by a factor of 2.44) can be obtained. However, there are several limiting factors for the development of the MCAO technique. First of all the cost of such a system may be prohibitive as several wavefront sensors and several correctors are required. This is why we consider methods of isoplanatic patch widening that require only one corrector and one wavefront sensor.

Widening the size of isoplanatic patch is possible when several beacon sources are used. In this method the average phase coming from different sources is calculated and applied

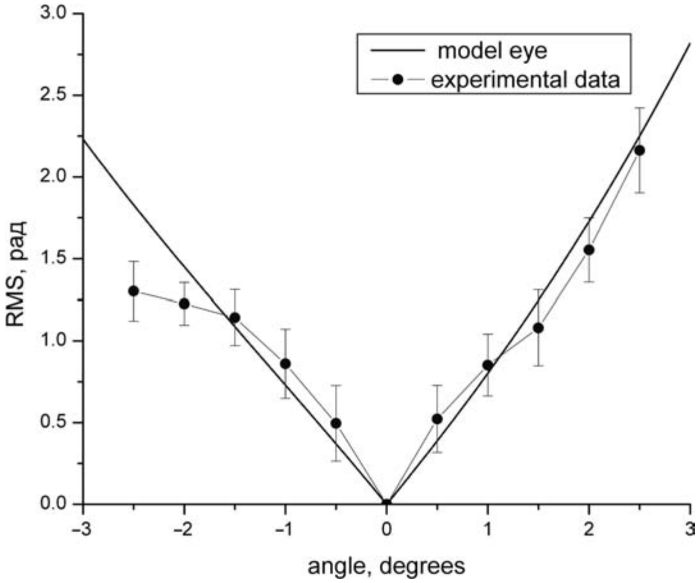

Figure 5. Result of the calculation of the RMS value for different beacon positions for the real eye of subject AD and the modified model eye. The direction of correction is 0°.

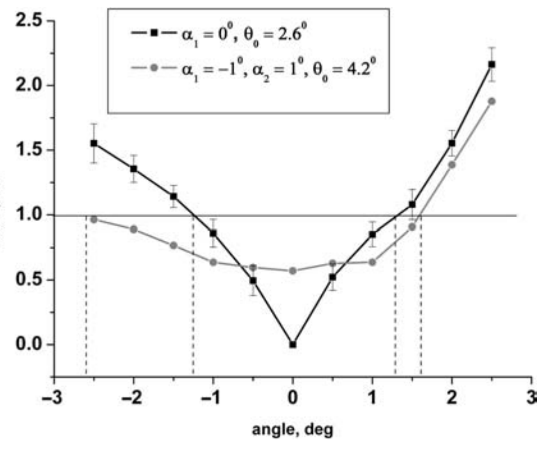

Figure 6. Result of aberration correction for subject AD. The black line represents data for conventional correction using one beacon. The grey one illustrates the result of the correction for average phase of two beacons placed at $-1°$ and $1°$.

to one corrector, conjugated to the pupil plane. In this case one corrector is able to decrease the amplitude of the aberrations emerging from a region larger than the isoplanatic patch.

Figure 6 demonstrates the residual RMS error of correction versus angular distance between beacon and the point being imaged for subject AD. The pupil size is 4 mm.

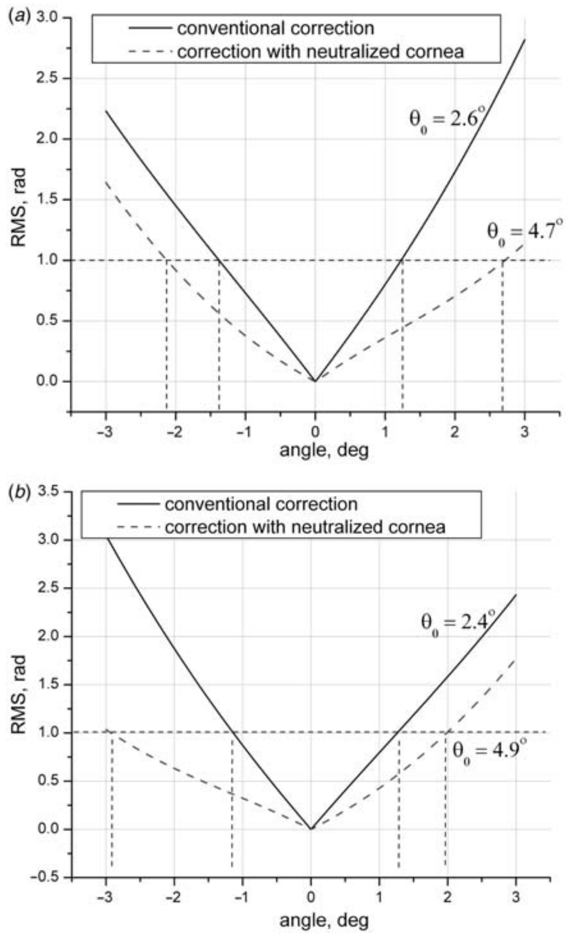

Figure 7. Results of correction with neutralized refraction of the exterior cornea surface: (*a*) subject AD, (*b*) subject AB, (*c*) subject RL and (*d*) Gullstrand–Navarro model.

The results indicate that the average phase correction leads to an increasing isoplanatic patch size from 2.6° to 4.2°. Similar results are achieved for the other subjects (isoplanatic patch enlargement from 2.4° to 3° for subject AB and from 1.7° to 2.3° for subject RL). It is seen that the residual error of correction between the beacons increases when this method is applied. This is the main disadvantage of the method.

4.2 *Immersion method*

In this section we suggest an immersion method for isoplanatic patch widening as described in Section 2. We expect that the cornea refraction neutralization leads to reducing the anisoplanatism effect as it would be caused only by off-axis aberrations of the internal optics of the eye. We used the ZEMAX® software to model the experiment.

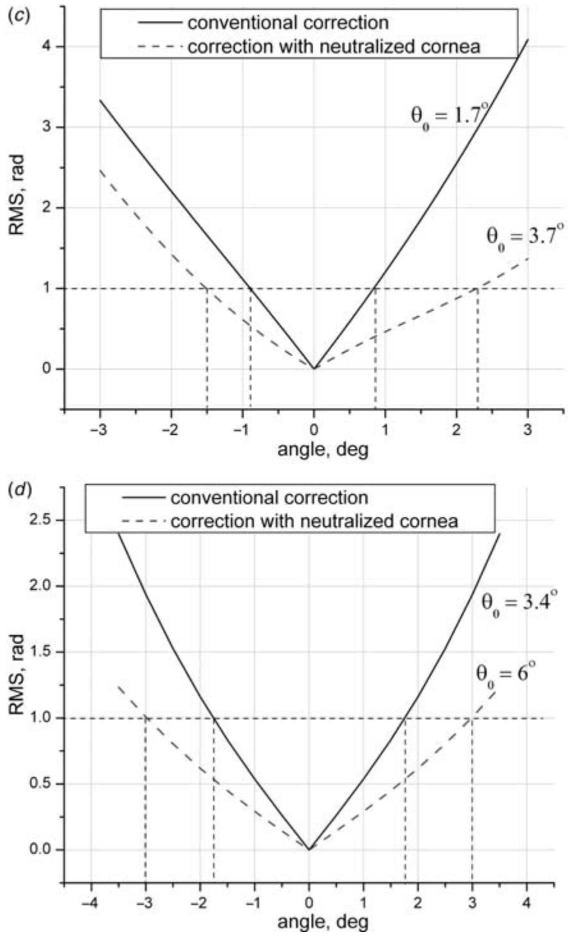

Figure 7. Continued.

The immersion liquid was placed in front of the cornea and an additional corrector was placed in front of the model eye to compensate for the eye's hyperopia. It is essential that this corrector should not introduce off-axis aberrations. In the model experiment we used the ZEMAX® ideal paraxial focusing surface as an additional hyperopia corrector.

Results presented in Figure 7 are obtained for three eye models representing the eyes of three measured subjects. The pupil size was 4 mm. The wavefront corrector was conjugated to the pupil plane. You can see the dependency of the RMS error of correction on the angular distance between the beacon and the imaged point of the retina. The reference beacon is placed at 0° (on the visual axis of the eye). Results are shown both for an eye with and without neutralization of the cornea refraction. It can be seen that application of the immersion method leads to significant isoplanatic patch widening for all three eye models. The obtained isoplanatic patch size for subjects AB, AD and RL equals 4.7°, 4.9°

and 3.7°, respectively. For the ideal Gullstrand–Navarro model the isoplanatic angle increases from 3.4° to 6°.

It is significant that application of this method does not result in increasing RMS error of correction near the reference source as in the average phase correction method. Thus, the proposed method can be used for fundus-camera high-resolution image size widening since application of this method significantly increases the isoplanatic patch size without image quality degradation near the reference source.

5. Conclusions

In this paper results of investigations of the anisoplanatism effect of the human eye are reported. The value of the isoplanatic patch defined as an area where the residual mean-square error of correction by an ideal wavefront corrector is less than 1 rad^2 varied among subjects and for the examined observers it was found to lie in the range 1.5°–2.6°. We demonstrate that the value of the isoplanatic angle for the Gullstrand–Navarro model is 3.4°. Modifying the Gullstrand–Navarro eye model we have been able to reproduce on-axis and off-axis aberration performance of the subject's eyes. We investigated possible ways to enlarge the isoplanatic patch of the human eye using such modified eye models. We consider the average phase correction method when the phase, averaged over two beacons within one isoplanatic patch, is compensated by one corrector. Applying this method the portion of retina imaged with high resolution could be increased by a factor of 1.25–1.7 for the measured subjects. However, using this method leads to image quality degradation within the isoplanatic patch. Then we suggested applying the immersion method for isoplanatic patch widening. This method allows us to obtain isoplanatic patch enlargement by a factor of 1.6 ± 0.3 for models of real eyes and by a factor of 1.8 for the ideal Gullstrand–Navarro eye model without any image quality loss near the beacon position. Results of the paper can be used to widen the area of high-resolution of the retinal image obtained by fundus-cameras equipped with adaptive optics.

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