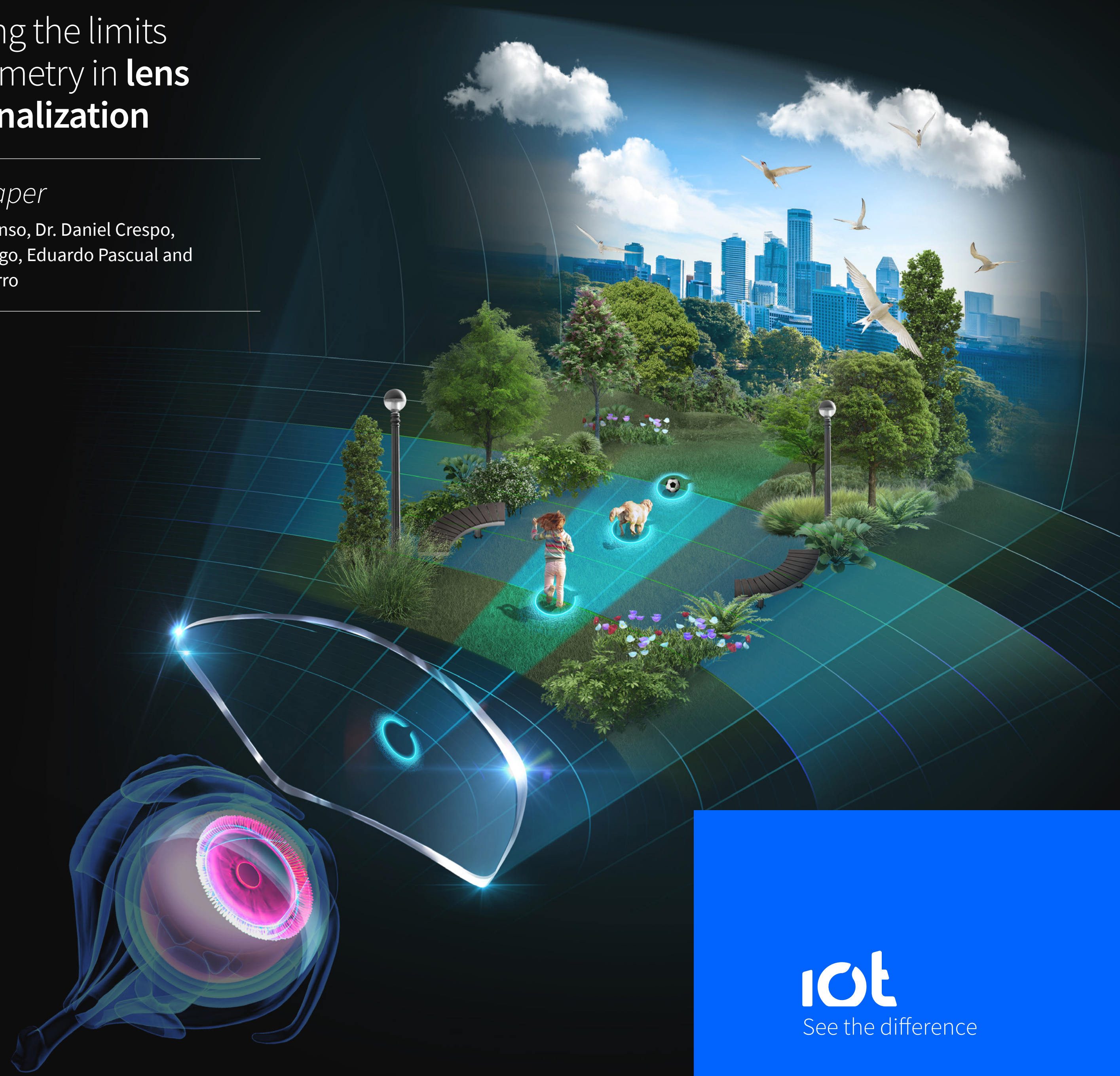
IOT Digital Ray-Path 2

Pushing the limits of geometry in **lens personalization**

Whitepaper

Dr. José alonso, Dr. Daniel Crespo, Carolina Gago, Eduardo Pascual and Eva Chamorro



iot
See the difference

IOT Digital Ray-Path 2

IOT Digital Ray-Path 2 is IOT's foundational technology for minimizing oblique aberrations in personalized and compensated free-form lenses.

In addition to mathematically compensating for oblique aberrations, **IOT Digital Ray-Path 2** adds the intelligent use of the wearer's accommodation: the small power adjustments the eyes naturally make to view objects at different distances.

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Introduction

In recent years, the rise of customized lenses has resulted in substantial improvement of the optical quality of millions of lenses that are prescribed worldwide. More and more professionals offer customized lenses to their patients, implying that they increasingly trust the technology behind them.

Since the introduction of IOT Digital Ray-Path Technology in 2008, the research and development carried out at IOT has led to significant improvements in both the mathematical algorithms and the optical, physiological and clinical principles used to customize ophthalmic lenses. Many of these improvements are now bundled in IOT Digital Ray-Path 2, the second generation of the already mature previous technology. In this paper, we explain the features of this new technology.

IOT Digital Ray-Path has been IOT's key tool to minimize oblique aberrations in a customized way, in both single vision and progressive lenses. IOT Digital Ray-Path 2 Technology embodies its natural evolution. **It adds the smart use of the wearer's accommodation to the traditional minimization of oblique aberrations to get a customized lens in which the compensation of these aberrations provides unnoticeable blur** on most of the lens area and across a vast range of prescriptions and frame typologies. To put it simply, IOT Digital Ray-Path 2 offers wearers an unprecedented level of visual quality.

IOT Digital Ray-Path 2 Technology includes:

Minimization of the effect of full field oblique aberrations by considering the ability of the human visual system to make small focus adjustments via accommodation.

Optimization in an accommodative object space.

Overall improvements of the merit functions that provide an extremely smooth distribution of the residual aberrations.

The results are:

Optimal customization for all working distances and focal ranges.

Improved visual quality for any gaze direction.

Precise and comfortable focus.

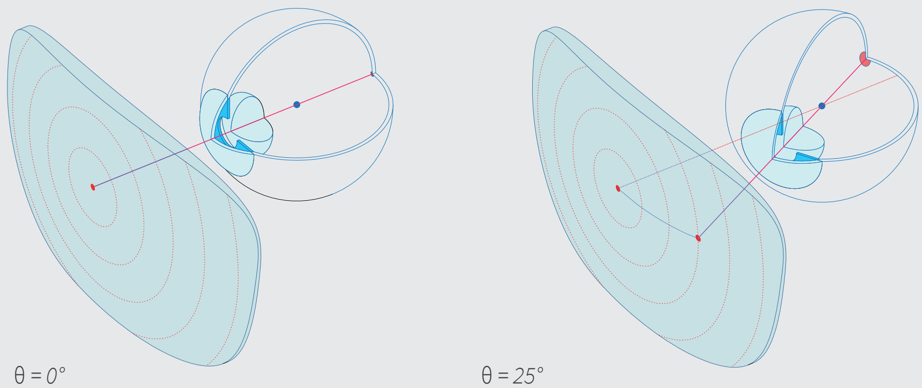
Oblique aberrations and customization

What are oblique aberrations?

Every optical system has aberrations: the eye, a magnifying glass, a peephole, even the best microscopes have some aberrations.

There are different types of aberrations, and their values in a given optical system depend on its design, its manufacturing quality, and especially how it is used.

The optical quality of an ophthalmic lens is primarily affected by oblique aberrations, which is the name given in visual optics to the combination of *oblique astigmatism* and *oblique power error*. Although the calculation of oblique aberrations is complex, their effect is easy to understand: if the lens has been correctly manufactured and provides the right power for the main gaze position, when the wearer views an object at an oblique angle, the power of the lens changes and, consequently, the refractive error is no longer correctly compensated. Figure 1 shows the concept. The prescription can only be matched by the paraxial power of the lens if the gaze direction is perpendicular to its two surfaces. If the lens is tilted, because of the pantoscopic and facial angles of the frame, the lens will be affected by oblique aberration even in the main gaze direction.



θ = 0°
Prescription = [+2.00+1.00x90°]*

θ = 25°
Wearer Perceived Power = [+2.50+1.30x98°]

[Figure 1] Oblique aberrations. To the left, we see a lens that correctly compensates for the wearer's ametropia. Its central back vertex power matches the prescription. However, when the wearer aims with an oblique gaze (see the situation to the right), the power provided by the lens changes, turning into oblique power (or power affected by oblique error).

**For the central gaze, the wearer perceived power matches the prescription*

Visualization of oblique aberrations in dioptric space

Each lens has a target power for each gaze direction.

In the case of single vision lenses, this power is constant, it does not depend on gaze direction, and precisely coincides with the wearer's prescription. For progressive lenses, different gaze directions will have different objective powers. A prescription or target power requires three parameters to be completely defined. Opticians, optometrists, and Rx-laboratories invariably use **the three parameters of the spherocylindrical prescription: sphere, cylinder, and axis, that we may write as *[S,C×α]***. However, there are other ways to describe power having important technical advantages. For example, we may define the parameters M, J_0 and J_{45} as:

$$[1] \quad M = E + \frac{C}{2} \qquad J_0 = -\frac{C}{2}\cos 2\alpha \qquad J_{45} = -\frac{C}{2}\sin 2\alpha$$

The triplet (M, J_0, J_{45}), which is called a *power vector*[1], contains the same information as the spherocylindrical prescription, but it has important clinical and mathematical advantages. It is very useful in understanding the minimization of oblique aberrations. **Component *M* is the well-known mean power, while the components J_0 and J_{45} are the decomposition of the cylindrical power using Jackson's cross-cylinders at 0º and 45º**, respectively.

J_0 stands for astigmatism with horizontal or vertical axis (depending on its sign), while J_{45} stands for astigmatism at ***45º*** or ***135º***. Any other orientation of the cylinder axis requires both J_0 and J_{45} to be nonzero.

We will use bold capital letters to name the whole power vector, so let's give the name $\mathbf{P} = (M, J_0, J_{45})$ to the target power of our lens for a given direction of gaze[2]. Because of oblique aberration, the power perceived by the wearer when gazing in an oblique direction will be different. We call it *user power,* or *oblique power* $\mathbf{P'} = (M, J_0, J_{45})$. The difference between the target and the oblique powers is the *oblique dioptric error*, $\Delta\mathbf{P} = \mathbf{P'} - \mathbf{P} = (M' - M, J'_0 - J_0, J'_{45} - J_{45})$.[3]

For arbitrary powers **P** and **P'**, the length of the vector Δ**P**, is known as the *dioptric distance* between them, which is given by the Pythagorean Theorem,

$$[2] \quad |\Delta\mathbf{P}| = \Delta\mathbf{P} = \sqrt{(M'-M)^2 + (J'_0 - J_0)^2 + (J'_{45} - J_{45})^2}$$

[1] Power refers to optical power. The current form of the power vector was proposed by F.C. Deal and J. Toop in 1993 [1], while the modern notation (M, J_0, J_{45}) is due to L. Thibos in 1997 [2].

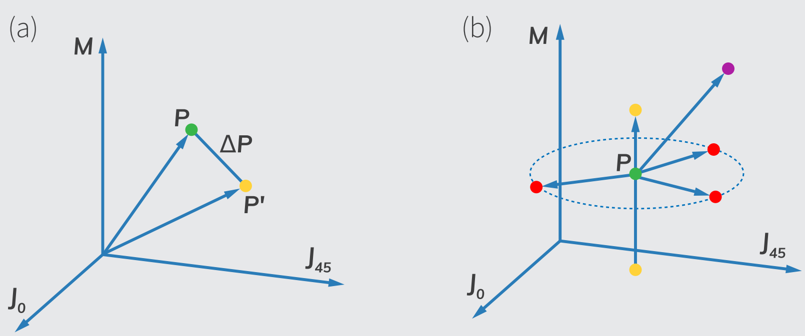
[2] The direction of gaze can be specified by the horizontal and vertical viewing angles, (u, v) . For single vision lenses P will be a constant, independent of u and v. For progressive lenses, the target power will be a function of these two angles, P (u, v).

[3] One of the advantages of using power vectors is that prescriptions can be added or subtracted (which we can also do with the sphere, but not with the cylinder or the axis of the spherocylindrical prescription). Furthermore, the module of a power vector that defines an error is equivalent to the blur perceived by the user (blur strength) [3].

When ***P*** is the wearer's prescription and ***P'*** the corresponding oblique power for a gaze direction, it can be shown that the blur perceived by the wearer (also known as *blur strength*) is proportional to the dioptric distance Δ***P***.[4]

Graphically, we can imagine a three-dimensional space in which each point corresponds to a prescription (see figure 2). One of these points, the one represented by green, will be the target power of our lens for the considered gaze direction. The yellow point represents the power perceived by the wearer, which is the target power affected by oblique error. The distance between the two points is the amount of blur that the wearer will experience. If the lens is single vision, there will be a single target power (a single black point) and a different oblique power for each direction of gaze. These are represented with yellow dots in figure 3. The combination of all gaze directions will produce a cloud of points around the objective power.

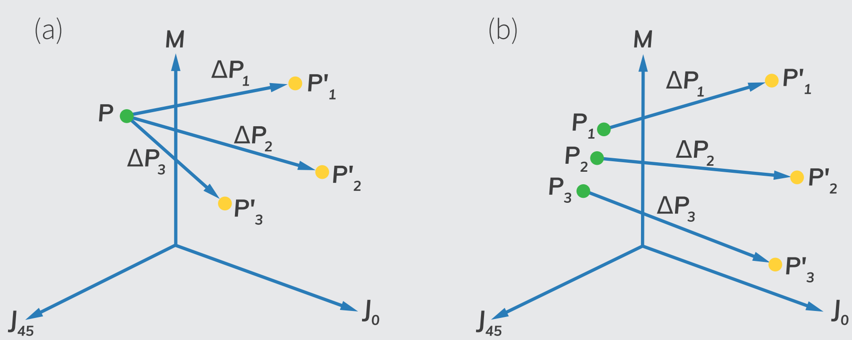
If the lens is a progressive, it has a different target power for each direction of gaze. In figure 3 (b), target powers are represented with green circles, while the yellow color has been kept for the corresponding oblique powers .



[Figure 2] Representation of target power and oblique power in dioptric space.

(a) Target power P and oblique power P'. The distance between the two points is the blur produced by the oblique power.

(b) Points separating from the target along the vertical axis (yellow points) are only affected by mean sphere error, while points separating from the target horizontally (red points on a plane parallel to the J_0 J_{45} plane) are only affected by astigmatic error; for these points, the balance between J_0 and J_{45} determine the axis of this oblique astigmatism. Finally, points away from the target, both along the vertical and horizontal directions (purple point) are affected by both oblique astigmatism and mean sphere error.



[Figure 3] Ophthalmic lens customization.

(a) Target power of a single vision lens (green point) and corresponding oblique powers for three different gaze directions (yellow points).

(b) Target powers of a progressive lens for three different gaze directions (green points) and their corresponding oblique powers (yellow points).

[4] *T.W Raasch, "Spherocylindrical refractive errors and Visual Acuity", Optometry and Vision Science, vol. 72, no 4, pp*

Ophthalmic lens customization

The significance of oblique aberrations depends on the wearer's prescription, the refractive index of the material, the base curve, the pantoscopic and facial angles of the frame, the vertex distance, and the pupillary distances and fitting heights.

If these data are correctly measured and used, it is possible to compute a lens back surface that minimizes oblique aberrations. **This is the principle of** IOT Digital Ray-Path **Technology; the lens calculated with this technology is optimal in the sense that a balanced combination of the oblique aberrations gets the minimum possible value.** It is customized because this optimization depends on the wearer, the frame, and the selected lens material.

Oblique aberrations also depend on the distance to the object that we are looking at, technically speaking, the *object distance*. In the case of progressive lenses, IOT Digital Ray Path optimizes the lens surface by using an object distance associated with the progression profile. It assumes the wearer will be looking at close objects for gaze directions that pass through the near area. For gaze directions passing through the distance zone, it is assumed the wearer is viewing distant objects. It is also assumed that the object distances for gaze directions lying between both zones decreases as the wearer's eyes drop from the distance to the near zone.

Progressive lenses also have aberrations that are not oblique but are associated with the continuous variation of power. When a design of this type of lens is considered, a second form of customization appears: the calculation of power distributions that are optimally adjusted to the visual needs of the wearer, by providing the power that the wearer needs with the best possible ergonomics, and by relegating the aberrations linked to progression to the areas of least use in the lens. While this type of optimization and the subsequent customization are essential and require intelligent strategies, progressive and single vision lenses are naturally affected by oblique aberration. This is why IOT has always considered IOT Digital Ray Path the backbone that supports the design and calculation of high-quality lenses.

Customization limits: surface geometry and curvature

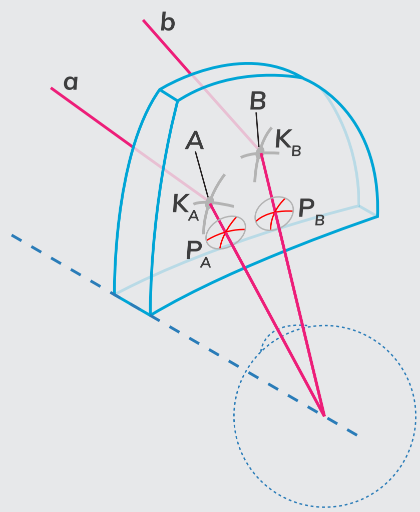
As we have explained, any premium lens should have, as a starting point, a customization based on the minimization of oblique aberrations across the complete dynamic field of view[5].

What exactly does *minimization* mean? Why don't we just say *elimination*?

The implementation of IOT Digital Ray-Path consists of a repetitive process in which, at each step, the cloud of points representing oblique power is calculated, and actions are taken to bring each oblique power closer to its corresponding target power. This is achieved by modifying the parameters defining the free-form surface. If a single direction of gaze was to be considered, oblique aberration would be easy to remove: we can always find a surface with a curvature at the point where the direction of sight intercepts, such that the oblique aberration would be perfectly eliminated. However, this condition cannot be met for all gaze directions because in any smooth surface the curvatures at nearby points are not independent from each other.

[5] *The dynamic field of view is defined as the field of view with high-quality foveal vision attainable by rotating the eyes. When using spectacles, the dynamic field of view is limited by the frame contour.*

Consider the refraction represented in figure 4. Two gaze directions "a" and "b" pass through points A and B on the free-form surface. We can arrange the surface so that its curvature at A, $\boldsymbol{K}_A$, is such that the power $\boldsymbol{P}_A$ is free from oblique error. However, in general, we will not be able to achieve the same cancellation at B. Although the oblique power for a given sight direction is closely related to the curvatures of the surface at the point it passes through, the relations between curvatures at A and B are not the same as the relations between powers $\boldsymbol{P}_A$ and $\boldsymbol{P}_B$, as powers depend not only on curvature but also on the laws of refraction.



[Figure 4] Refraction of light beams along two sight directions passing through points A and B on the back surface of a lens. The relations between K_A and K_B are determined by geometrical constraints. The relations between oblique powers P_A and P_B also depend on the law of refraction, i.e., Snell's law. Snell's law is the reason we cannot cancel oblique power error at full field by controlling the curvature of the free-form surface. The crossed lines in white color at A and B stand for the main meridians at those points. Similarly, the crossed lines in red color down the sight directions, stand for the main meridians of the refracted wavefronts, that is, the oblique powers.

Standard toric lens vs. IOT Digital Ray-Path lens

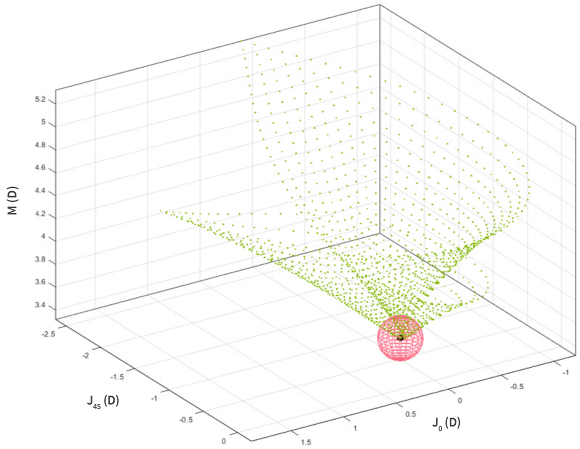
The first approach to the reduction of the oblique aberrations is the use of adequately curved front surfaces (base curves).

It is well-known, for spherical lenses without tilts, there are two values of the base curve for which the oblique aberration will get smaller. However, the required front surfaces are usually too curved for the typical expectation of practitioners and final wearers. Additionally, lenses with astigmatic prescriptions and/or pantoscopic and wrapping angles cannot be properly corrected from oblique errors.

We can visualize this fact with the example shown in figure 5, where we see the distribution of the oblique powers of a single vision lens with prescription [+3.00+1.00×45°], when computed as a standard sphero-toric lens, with a 6.00 D base curve and refractive index 1.5. We have computed the oblique power of this lens for a 50×50 mm square grid of gaze directions[6]. The power vector corresponding to the prescription is $\boldsymbol{P}$ = (3.50, 0.00, -0.50) D, which is the target for all the gaze directions.

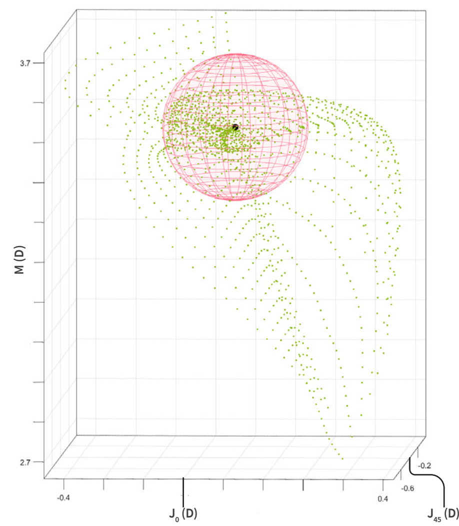
If the oblique power is close enough to the target value so that $\Delta\boldsymbol{P}$ < 0.18 D, then the drop of visual acuity caused by this blur is smaller than 5%, and we can state the blur as unnoticeable. The pink-colored sphere in figure 5 embodies this threshold blur. It is centered at the target prescription and the points inside of it correspond to oblique powers producing unnoticeable blur. We see most of the points are well outside the sphere: 89% of the sight directions to be precise.
As the grid is uniformly distributed, the percentage area of this lens providing undisturbed visual acuity is just 11%. And just by glancing to the scales on the axis, we can see that for many sight directions, the blur is bigger than 1.00 D, actually, 39% out of the total number. Finally, the maximum blur in the grid is 2.80 D. This is a typical example of how poorly performing a standard sphero-toric lens can be.

[6] These type of graphics provide information about the global dispersion of oblique power around the objective, and how this oblique power is distributed among spherical and astigmatic errors. However, the information of the direction of gaze to which each oblique power belongs is lost. A traditional map, in which one optical property at each point on the lens is represented, provides this information. Another advantage of power representation in dioptric space is that the blur (and therefore the VA, broadly speaking) are proportional to the distance from each oblique power to the objective power.



[Figure 5] Oblique powers of a sphero-torical lens with prescription [+3.00+1.00x45°], (corresponding power vector (3.50, 0.00, -0.50) D) manufactured with a base curve of 6.00 D and refractive index 1.5. The sphere represents the region of clear vision (range of powers for which the user would experience a loss of visual acuity less than 5%). The sphere is centered at the point of the dioptric space corresponding to the user's prescription. Gaze directions are uniformly distributed in a 50×50 mm grid, and only 11% of them are within the region of clear vision.

Now let's see how **IOT Digital Ray-Path** can improve on this performance. The oblique powers of the lens with the same prescription, material, and base curve, but with a free-form back surface optimized with **IOT Digital Ray-Path** is shown in figure 6. The cloud of oblique powers is now much more compact, that is, all oblique powers are much closer to the target power. In numbers, no sight direction yields blur values bigger than 1.00 D. Only 8.1% yield blur higher than 0.5%, and 40% of the lens area provides unnoticeable blur. Maximum blur across the whole grid is 0.89 D. All this means is the **overall quality of vision obtained with IOT Digital Ray-Path Technology is far superior to the quality provided by standard single vision lenses**, but still, this technology cannot fully eliminate oblique aberrations.



[Figure 6] Oblique powers of the same lens shown in figure 4, but in this case optimized with IOT Digital Ray-Path Technology. Points are clustered much closer to the prescription: 43% of gaze directions are within the sphere of clear vision.

Standard toric lens vs. IOT Digital Ray-Path lens

As we stated previously, oblique aberrations depend on the object distance.

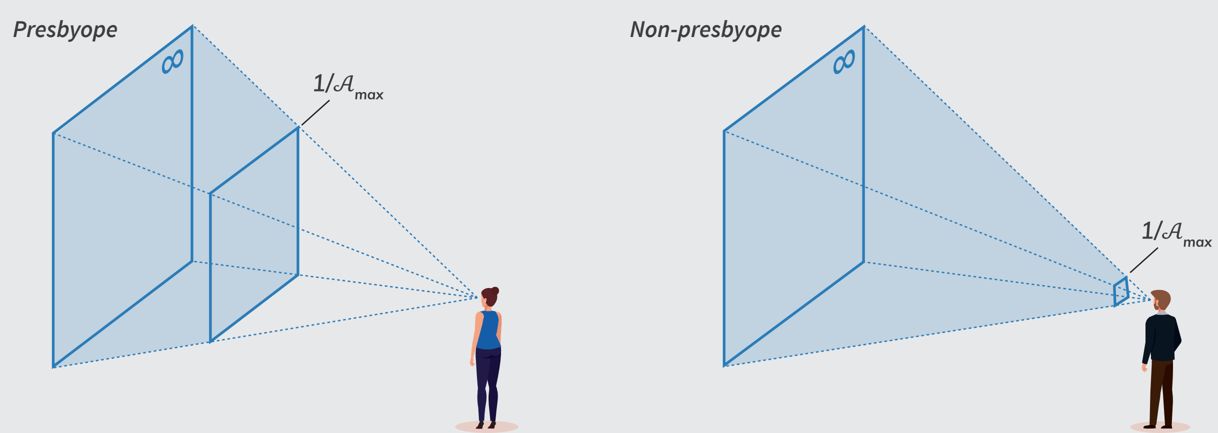
It means both oblique astigmatism and oblique power error will be different, for any given gaze direction, when looking at a distant object, for example, when reading. This fact imposes a new limitation on the correction of oblique aberrations: if we optimize a surface so the lens performance is optimal for viewing distant objects, it will not be optimal at near, and vice-versa. In this section we will review the roles of accommodation and object distance in the compensation of oblique aberrations, both being key ingredients for **IOT Digital Ray-Path 2.**

Accommodation

The eye can focus at different distances by means of accommodation, an increase of the eyes' focusing power by a variable amount ($\mathcal{A}$) that allows focusing on a distant object $-1/\mathcal{A}$.[7]

There are mainly two stimuli that activate accommodation: the retinal blur associated with the variation of the object distance, and the change of convergence of the crystalline lens / visual axis necessary to achieve correct binocular vision for the new fixation distance. The two stimuli trigger an adjustment of the power of the crystalline lens that allows it to focus on the image. Accommodation requires the action of the eye's *ciliary* muscles, and for this reason, high accommodation values sustained for a long time may produce fatigue and visual stress. On the other hand, too large of mismatches between accommodation and convergence also produce visual stress. As we will see, these factors are important in the implementation of the IOT Digital Ray-Path 2 Technology.

The maximum accommodation that a subject can exert is called the *accommodation amplitude,* $\mathcal{A}_{max}$. This amplitude decreases with age at an approximate linear rate and becomes zero sometime in the range from 50 to 60 years of age. **Nevertheless, even when the accommodative capacity seems to be gone as in more advanced stages of presbyopia, a subjective accommodation of about 1.00 D is clinically measured regardless the age.** This subjective accommodation is a manifestation of the depth of focus of the human eye that can be considered as an effective accommodation. The amplitude of accommodation determines a volume in the object space whose points can be focused on. Along the main viewing direction, this volume extends from minus infinity to $-1/\mathcal{A}_{max}$ (see figure 7). We will refer to this volume as the *accommodative space*.



[Figure 7] Representation of the accommodative space, that is, the volume of object space points that can be focused on by means of accommodation. For the non-presbyopic person, with accommodation amplitude above 4.00 D, the accommodative space extends from less than 25 cm to infinity (right). The presbyope, with a reduced accommodation amplitude, will lose this part of the accommodative space corresponding to near or even intermediate viewing distances (left).

[7] *According to the standard sign criterion, distances to the objects in front of the eye are negative.*

The effect of object distance on oblique aberrations

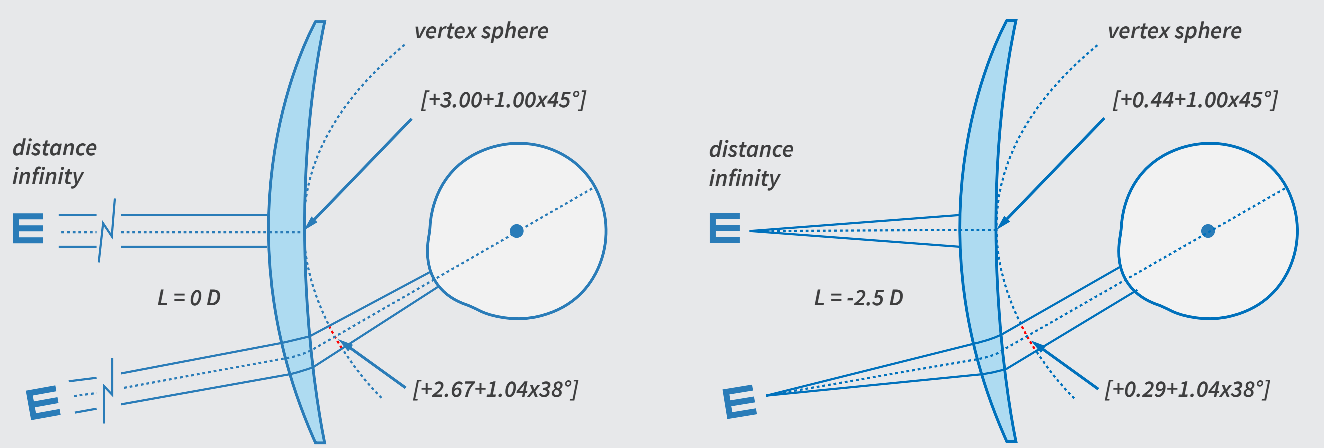
An actual example of how object distance effects oblique aberrations is shown in figure 8.

An actual example of how object distance effects oblique aberrations is shown in figure 8. We are simulating the same lens shown in figure 6 to compute the vergence of the refracted beam at the vertex sphere. This is a theoretical sphere centered at the rotation center of the eye and passing through the intersection point between the main viewing direction and the back surface of the lens. It is used by lens designers to properly compare any oblique power with the paraxial, back-vertex power. Any vergence considered at the vertex sphere would have, to the rotating eye, the same effect as an identical back-vertex power at the main viewing position. The oblique direction shown in figure 8 is tilted 30° downwards. In the drawing to the left, the object is located at infinity, so the vergences at the vertex sphere are the back-vertex power of the lens for the main viewing direction and the oblique power for the 30° downwards viewing direction. We see that the oblique power presents sphere and cylinder errors of -0.33 D and 0.04 D, respectively, while the cylinder axis is off by 7°. These are pretty good results, achieved by **IOT Digital Ray-Path** Technology.

When a spherical lens is used to look along the main viewing direction to an object located at distance, from which the vergence at the convex surface is L=1/s, the next approximate expression holds,

[3] $$L'-L \cong P$$

where ***L'*** is the output vergence and ***P*** the lens back-vertex power. The thinner the lens, the better the approximation. To focus on the object, the eye should accommodate a vergence ***-L*** at the back-vertex of the lens. Now, let us consider the performance of the former lens when the object is 40 cm in front of the convex surface, the case depicted in figure 8 to the right. As stated, the output vergences at the vertex sphere will reveal both the amount of accommodation needed and the oblique performance. At the main viewing direction, the spherical component of the output vergence is 0.44 D, and the eye will need an accommodation value of $\mathcal{A}$ = 2.56 D. The extra 0.06 of diopter with respect to the 2.50 D expected from equation [3] comes from the lens that is not thin. At the oblique direction, the output vergence is now [+0.29+1.04×38°], so the accommodation required now is 3.29 D, 0.79 D more than at the main viewing direction. The cylinder is again off by 0.04 D and 7°.



[Figure 8] Oblique power and output vergence at the vertex sphere of the same lens shown in Figure 6, at the center of the lens and with an oblique gaze tilted 30° downwards. To the right, the object is located at infinity, so the output vergence will be the wearer-perceived power. To the left, the object is located 40 cm in front of the lens. See the text for a discussion on the vergences obtained in each case.

The conclusion from the previous example is this: if we engineer the surface to compensate for the -0.33 D of spherical error at a distance of infinity, we will have an under correction of -0.46 D at near vision, and vice-versa. **If the surface is optimized to compensate the oblique error at near vision the lens will get an over correction at distance vision.**

Finally, this example hints at another feature that will be of the greatest importance for IOT Digital Ray-Path 2: the oblique error of the spherical component for this lens and for this viewing direction is negative, meaning the error itself can be compensated by extra accommodation from the wearer, whenever this accommodation is available. That is, whenever the total accommodation needed to focus the near object *and* compensate for the oblique error is smaller than the accommodation amplitude.

IOT Digital Ray-Path and object distance with progressive lenses

An important feature of IOT Digital Ray-Path is that each gaze direction is linked to a particular viewing distance that will be used to compute the corresponding oblique aberration.

For general-purpose single vision lenses, the object distance will generally be chosen to be infinity. A single vision reader would be optimized for near viewing distance. For progressive lenses, each gaze direction is paired with a unique object distance which is linked to the progression profile.

When the wearer looks through an arbitrary point on the lens surface with coordinates (x,y), the lens provides a local addition A(x,y). For those values of the x coordinate corresponding to the umbilical line, x_u, the local addition is equal to the power profile of the progressive lens, $A(x_u,y) = p(y)$.[8] The wearer is prescribed an add power A which is related to his/her amplitude of accommodation, $\mathcal{A}_{max}$. This relation can be obtained from statistical data or measured during the refraction and used as a customization parameter. Another important parameter is the preferred working distance, d_{rd}. For this we can use a population average, or an individual value measured by the ECP. The positive power needed to focus an object point at a distance d_{rd} is $1/d_{rd}$. When looking through the lens NRP, the lens provides the nominal add power A, and the wearer complements it with accommodation $\mathcal{A}_{rd} = 1/d_{rd} - A$. The amount of accommodation left unused is named *accommodation in reserve*, $\mathcal{A}_{res} = \mathcal{A}_{max} - \mathcal{A}_{rd}$.

IOT Digital Ray-Path assumes that the amount of accommodation used when looking through any point (x,y) will grow from zero, at points with zero local addition, to the maximum value, A_{rd}, in the same proportion as the local addition grows from zero to the nominal value A. Mathematically,

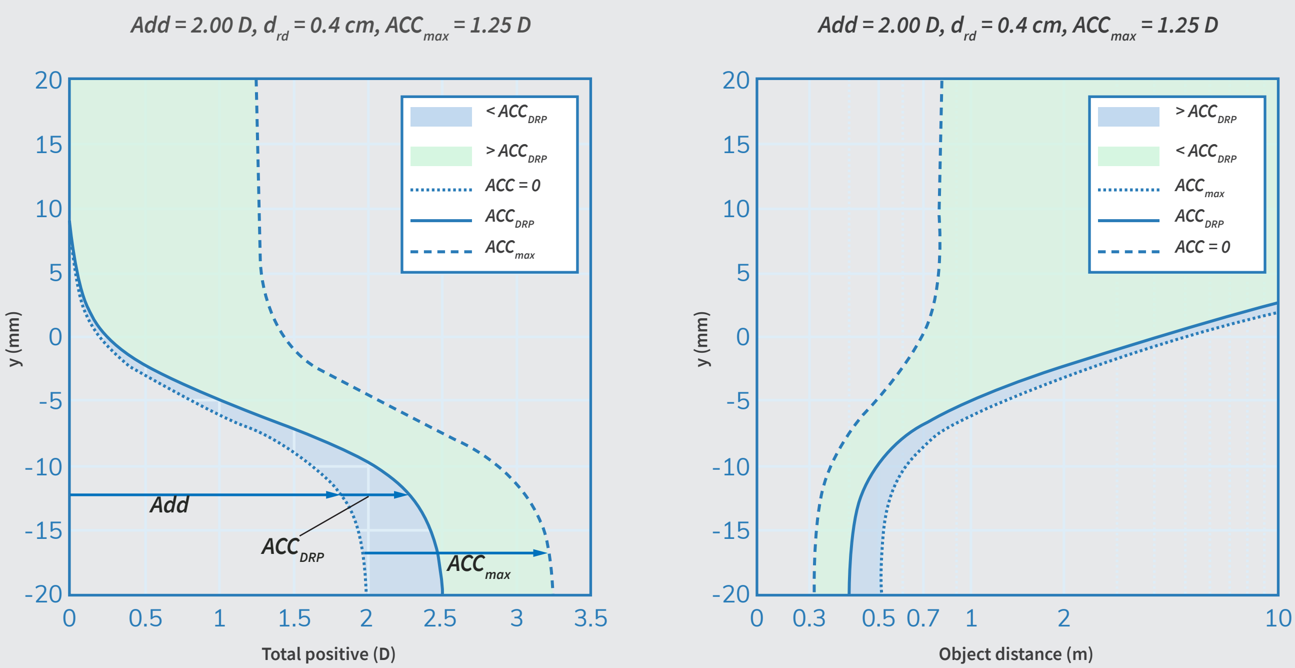
$$\mathcal{A}(x,y) = \begin{cases} \dfrac{A(x,y)}{A}\,\mathcal{A}_{rd} & \text{if} \quad A(x,y) < A \\ \mathcal{A}_{rd} & \text{if} \quad A(x,y) \geq A \end{cases}$$

The maximum accommodation exerted by the wearer will be A_{rd}, even if there are points in the lens with local addition higher than the nominal addition (that some designs may have). Once we have a model for the local accommodation, the local object distance will just be the inverse of the total focusing power (local accommodation plus local addition), $d(x,y) = 1/[\mathcal{A}(x,y) + A(x,y)]$.

Of course, we do not expect that the wearer will always use this local accommodation or will focus on this object distance; we just assume these values are good guesses to be used during lens optimization. Recall that the computation of the oblique aberrations and the amount of blur for any gaze directions requires the selection of the object distance, and d(x,y) seems a good choice. However, we have always been mindful about the fact that in any real case scenario, the wearer can change the accommodation from zero to $\mathcal{A}_{max}$ for any gaze direction, resulting in maximum and minimum focusing distances $d_{max}(x,y) = 1/A(x,y)$ and $d_{min}(x,y) = 1/(\mathcal{A}_{max} + A(x,y))$, respectively. In other words, for any gaze direction passing through point (x,y) on the back surface of the lens, the wearer will be able to focus objects within the range $[d_{min}(x,y), d_{max}(x,y)]$.

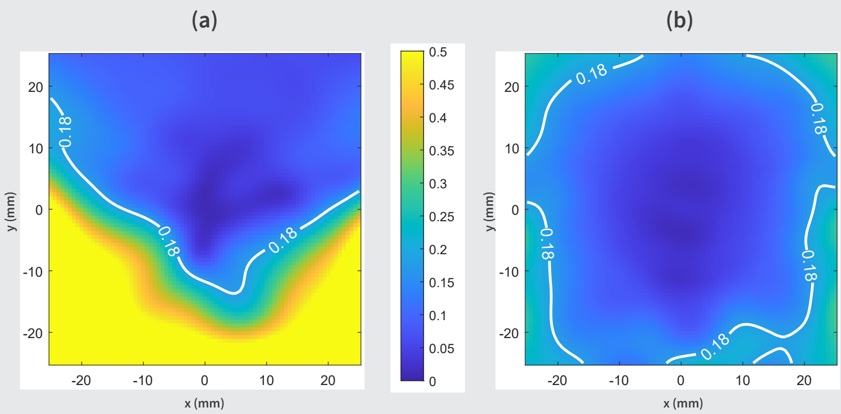
[8] *Modern Ophthalmic Optics*

This reasoning is illustrated in figure 9, where we are presenting a case with A = 2.00 D, d_{rd} = 40 cm and $\mathcal{A}_{max}$ = 1.25 D. In the plot to the left we show the amount of positive power available to the wearer *vs.* the vertical coordinate of the gaze direction. The dotted line is basically the power profile of the lens, the positive power available when no accommodation is used. The solid curve represents the positive power assumed by **IOT Digital Ray-Path**. Its inverse is the object distance that will be used for lens optimization. Finally, the dashed curve stands for maximum positive power available at any point on the lens surface when maximum accommodation is used. According to this, the blue color indicates accommodation smaller than $\mathcal{A}$(x,y), while the green color indicates accommodation bigger than $\mathcal{A}$(x,y). In the plot to the left the range of focusable object distances vs. the vertical coordinate of the gaze direction is shown, using logarithmic scale on the horizontal axis. Once again, the dashed line indicates the amount of maximum accommodation that is used, giving the shortest possible focusing distance, d_{min}(x,y). The dash-dot line signals the case with zero accommodation, yielding a focusing distance d_{max}(x,y). The solid line follows the focusing distance used in **IOT Digital Ray-Path** algorithms to optimize the lens. It grows steadily from d_{rd} at the near reference point toward infinity at the distance reference point and the upper part of the lens (far distance is cropped at 10 m for readability). The colored region represents the range of clear vision for each vertical position of the gaze direction, the green and blue colors representing the same relation between actual accommodation and $\mathcal{A}$(x,y) as shown in the plot on the left.



[Figure 9] The plot on the left is the positive power available for focusing at near or intermediate objects vs. the vertical position of the gaze direction. The solid line represents the lens local addition plus the accommodation assumed by the optimization algorithms in IOT Digital Ray-Path. The dashed-dotted line stands for the case with zero accommodation (only lens addition) and the dashed line stands for maximum accommodation. The plot on the right shows the ranges of clear vision vs. the vertical position of the gaze direction. These ranges are delimited by the dashed curve (maximum accommodation) and the dotted curve (zero accommodation). The solid curve gives the object distance used by IOT Digital Ray-Path to compute the lens.

Power plots in dioptric space are very useful, but without previous experience, they can be difficult to grasp, especially for progressive lenses. We use blur maps to see the dioptric distance between the lensometer and wearer-perceived power for the Basic H40 / Everyday B design, while plot (b) shows the difference between the target and the wearer-perceived power of the Alpha H45 / Ultimate B design. It is important to clarify why each lens uses a different comparison .



[Figure 12] Maps of dioptric distance between the target and the wearer-perceived power. The left map corresponds to a Basic H40 / Everyday B progressive lens design, while the one on the right corresponds to an Alpha H45 / Ultimate B design. The target for both lenses are similar, well balanced, general purpose PALs. However, the wearer-perceived power is heavily affected by oblique aberrations in the Basic / Everyday design, with dioptric errors up to 1.00 D, especially in the near region and the astigmatic lobes. The performance of the Alpha / Ultimate design is much better, the area with dioptric error smaller than 0.18 D (interior of the red iso-curve) stretching most of the useful region of the lens.

In both cases we start optimizing a distribution of curvature (or surface power) that will define the design: the shape of the power profile along the corridor, the inset, the distribution of mean sphere and astigmatism at either side of the umbilical line, etc. For a Basic / Everyday design, this distribution of curvature provides the power we would measure with a standard lensometer, and that is it: the lens is manufactured, and the power the wearer will perceive is different because of oblique aberration. In the case of the Alpha / Ultimate line of progressive lenses, we use the surface power of the design as a target. Then we look for the surface yielding the wearer-perceived power that better matches the target, and the lens is manufactured with this surface. According to this, the plots in figure 12 do not show the "areas of clear vision" of the respective progressive lenses, and we will avoid the term "blur" as these plots do not represent blur perceived by the wearer. They represent the dioptric distance between the intended design and its actual performance. In other words, the plots show the lens performances related to oblique aberrations, but say nothing on the performance of the progressive designs.

The red contour line identifies points with dioptric distance equal to 0.18 D. In the Basic / Everyday lens all points above the red line have a dioptric distance smaller than 0.18 D, and they amount to 51% of the lens area. Below the red line all points have dioptric distance bigger than 0.18 D, and the maximum for this quantity is 0.95 D (the color map saturates at 0.50 D to present identical color scales for both lenses). In the Alpha / Ultimate lens all the points inside the red perimeter have dioptric distance smaller than 0.18 D, amounting to 79% of the lens area. The performance of this Basic / Everyday lens in the far region is quite good, as obliquity at the distance reference point is small, and the power to base curve ratio is good. However, performance rapidly degrades towards the near region because of the two very same reasons: near power is 4.00 D, now too close to the base curve, and obliquity of the gaze directions at the near reference point is much larger. Both factors combined make oblique aberrations grow. **IOT Digital Ray-Path does a very good job with this progressive lens, the actual performance of the design matches the desired target within 0.18 D for all the critical regions (far and near) within the whole field of view.**

IOT Digital Ray-Path 2

Since the creation of the **IOT Digital Ray-Path** Technology in 2008, IOT has continued researching alternatives to overcome the limitations imposed by the geometry of the free-form surfaces and thus achieve lenses with even better compensation of the oblique errors. The key ingredient that will allow us to surpass the performance of **IOT Digital Ray-Path** Technology is not in the geometry of the free-form surfaces, but in the smart use of the wearer's accommodation and a more balanced optimization process which considers all points in the accommodative space.

To understand how **IOT Digital Ray-Path 2** works, we must first understand the optimization process of the previous technology. **The optimization of any optical system requires the formulation of a mathematical object known as *merit function*. This function depends on the parameters describing both the optical system and the way it is used.** Some of these parameters are fixed, and some are free. The objective of the optical designer is to find the values of the free parameters that provide the best possible system performance. As the value of the merit function is typically given by a weighted sum of the optical aberrations of the system, the objective of the optical designer (which is achieving best performance) is usually coincides with the merit function having the least possible value. Optimization of the optical system means finding the values of the free parameters that make the value of the merit function minimal.

Regarding the workings of **IOT Digital Ray-Path**, let us assume we have received the lens parameters: prescription, lens design (values of the target power for all the considered gaze directions), refractive index, base curve, minimum thickness, etc. We have also received the customization parameters: frame size, tilts, pupil position data, vertex distance, working distance, etc. All these parameters are fixed (for the lens we are about to compute) and there remain the parameters describing the lens free-form surface, which are free. The first step is giving starting values to these free parameters. For example, for a single vision lens, we may compute the toric surface to meet the required paraxial lens power; then, the starting values of the free parameters would be set to describe this toric surface. For a progressive lens we could start with a basic analytical model of a progressive surface complying with the set of fixed parameters, but with suboptimal optical performance.

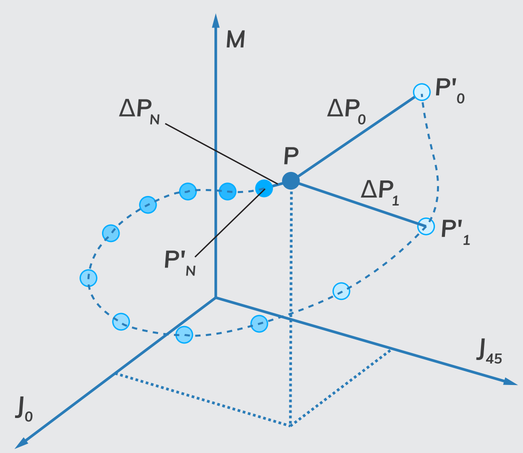
With these starting values of the parameters describing the free-form surface, we create a computer model of the lens-eye system which include a viewing distance per gaze direction. This model allows the computation of the oblique (wearer-perceived) powers by means of ray tracing or wavefront tracing.

IOT Digital Ray-Path *minimizes oblique aberrations to provide improved visual quality at a specific distance associated with each direction of gaze.*

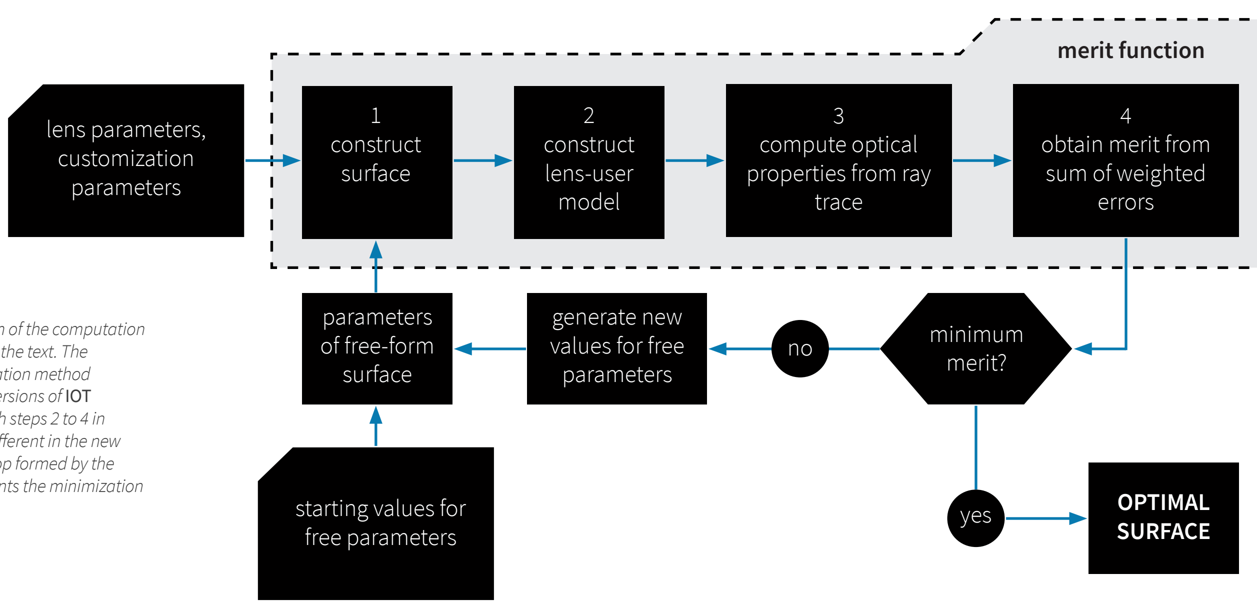
IOT Digital Ray-Path 2 *analyzes oblique aberrations at various focal distances for each direction of gaze. Minimization of oblique aberrations is balanced throughout the accommodative object space, providing extremely clear vision and precise focus.*

One of these oblique powers, $\boldsymbol{P'_0}$, is shown in dioptric space in figure 9, along with its corresponding target power, $\boldsymbol{P}$. The distance between the two points is the oblique dioptric error, $\Delta \boldsymbol{P_0}$, and the merit function is then constituted as a weighted sum of these errors for all the viewing directions. Next, an optimization algorithm will look for the set of parameters describing the free-form surface that will make the merit function minimal. To do so, the merit function will be evaluated a large number of times, let us say, *N*. Each time, the optimization algorithm will compute new oblique powers, $\boldsymbol{P'_i}$; it will evaluate the merit function, and will modify the free parameters to bring the next set of oblique powers, $\boldsymbol{P'_{i+1}}$, closer to the target power. If there were a unique gaze direction, this problem would have a perfect solution. However, as we want to improve the optical quality all over the lens, we must distribute a large number of viewing directions across the visual field, and as we have seen before, equating all the oblique powers with all the corresponding target powers is not possible. In the last step we will obtain reduced oblique errors, $\Delta \boldsymbol{P_N}$, but not zero, as shown in figure 13. The sequence of oblique powers $\boldsymbol{P'_0},\cdots,\boldsymbol{P'_N}$ will follow a path in dioptric space that will end close to the target power. The paths may differ from one gaze direction to another, and they may follow complex trajectories in dioptric space.

The computation method just described is represented in figure 14. The merit function involves the four steps bordered by the dashed line. The blue connectors form the loop known as the *minimization algorithm*.



[Figure 13] Workings of IOT Digital Ray-Path. Optimization path followed by the oblique power corresponding to a single gaze direction. Each oblique power corresponds to one step of the optimization algorithm. The optimization of the whole lens requires hundreds of these paths, one per gaze direction.



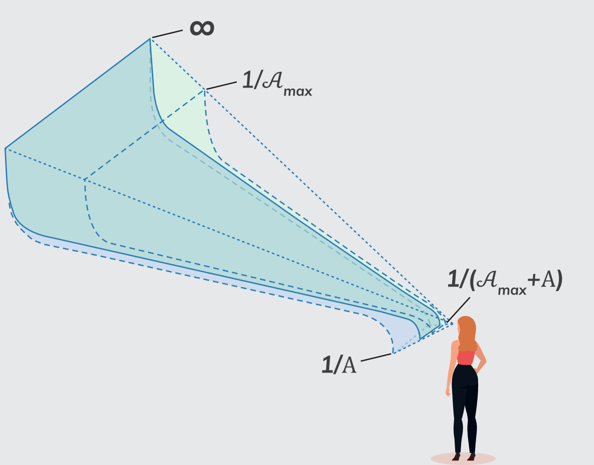
[Figure 14] Flow diagram of the computation method, as described in the text. The structure of the computation method is identical for the two versions of IOT Digital Ray-Path*, though steps 2 to 4 in the merit function are different in the new implementation. The loop formed by the blue connectors represents the minimization algorithm.*

The optimization process of a IOT Digital Ray-Path 2 lens

IOT Digital Ray-Path 2 is an optimization technology for ophthalmic lenses based on customization parameters that, compared to its predecessor, incorporates two new characteristics:

1 It takes advantage of the wearer's accommodative ability to reduce the oblique error in a more effective way. *Physiological* merit functions that incorporate accommodation as a way to partially compensate for the mean power error have been known in the ophthalmic sector for a long time. However, their practical implementation has been reduced due to the mathematical difficulties associated with the use of accommodation in merit functions. IOT has achieved an especially effective implementation of this concept by incorporating accommodation in the dioptric power space and by using *blur strength* or *dioptric error* with weight functions that give continuity to the merit function. In addition, **IOT Digital Ray-Path 2** limits the use of accommodation depending on the object distance and amplitude of accommodation of the individual.

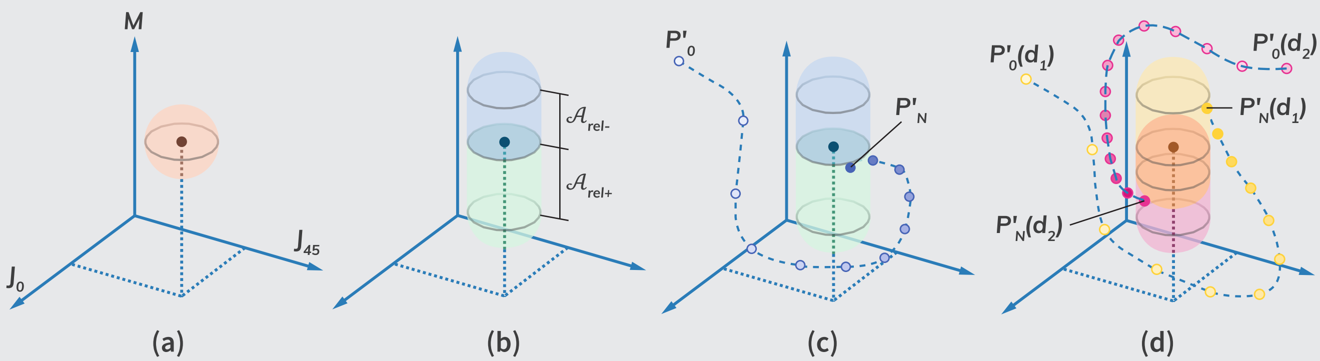
2 Since oblique aberrations depend on the object vergence, **IOT Digital Ray-Path 2** works in the wearer's accommodative space. Once again, IOT progresses on well-established technologies. According to the classical theory of spherical lens design, the compromise solution to reduce oblique errors, both for distance and near vision, consists on the reduction of the oblique error in just one of the main values of the oblique power.[9] However, this solution is only valid for lenses with revolution symmetry (without astigmatic prescription) and when there are no significant pantoscopic and/or facial angles. This classic idea is enhanced in **IOT Digital Ray-Path 2.**
For each gaze direction there is a range of object vergences accessible to the wearer and defined by their accommodative space , which is represented in figure 15. **IOT Digital Ray-Path 2** searches for the optimal free-form surface configurations for the entire range of vergences, using, at least, the object vergences that limit the interval and considering the visual acuity needs for each one.



[Figure 15] The solid line represents the location of objects which are brought into focus with the accommodation level assumed by **IOT Digital Ray Path 2**. *The surfaces edged with dash-dotted and dashed lines represent the farthest and closest boundaries of the accommodative space, that can be reached without accommodation and with maximum accommodation, respectively.*

[9] The oblique power of a spherical lens is, in general, an astigmatic power. Its two corresponding main powers are called tangential and sagittal. The lenses for which the tangential power equals the prescription at some viewing direction are said to be free from tangential error and provides a good balance for the correction of oblique aberrations at both near and far vision [M. Jalie, "The principles of Opthalmic Lenses, 4th edition", The Association of British Dispensing Opticians, London].

The way these two features are implemented in the merit function used by IOT Digital Ray-Path 2 is represented in figure 16. First, we start by defining a threshold for both blur and oblique dioptric error, as we already showed in figures 5, 6, 10, and 11. Let us recall that when the target power is a prescription, the oblique dioptric error can be interpreted as blur. However, in progressive lenses, there are many gaze directions for which the target power already contains Minkwitz aberrations. In those cases, the oblique dioptric error does not translate into blur, but into a change in the amount of blur. A threshold value for the oblique dioptric error, $\Delta \boldsymbol{P}$, is chosen in the interval from 0.18 to 0.25 D. Let us plot a spherical surface centered on the target power with radius equal to the selected threshold, as shown in figure 16 (a). IOT Digital Ray-Path 2 will consider any oblique power inside this sphere as *acceptable*[10], and we may call the set of points inside the sphere the *region of unnoticeable oblique power errors*.



[Figure 16] Key elements of the merit function in IOT Digital Ray-Path 2.

Now, for any given viewing direction and object distance, let us consider the sign of the mean sphere error. If $\Delta \boldsymbol{M}$ is negative, the lens is providing less mean sphere than necessary; as the ***M-axis*** in dioptric space lays along the vertical direction, oblique power will be represented by a point *below* the target power. In optical terms, the circle of least confusion produced by the lens-eye system will be located behind the retina, and this stimulus will trigger eye accommodation that will compensate for the error, if enough accommodation is available. On the other hand, if the gaze direction involves intermediate or near vision requiring some accommodation from the wearer, and the mean error for this gaze direction turns out to be positive, the circle of least confusion of the lens-eye system will be located in front of the retina. The stimulus would trigger a relaxation of the accommodation that would reduce, or even cancel, this positive mean sphere error.

For a given interpupillary distance, the convergence and accommodation levels needed for proper binocular fixation are determined by the object distance. However, the human visual system is flexible enough to tolerate deviations from this relationship. Lenses may produce prismatic effects and power shifts that would change convergence for a given accommodation, and the other way around. The maximum accommodation that can be relaxed with respect to the convergence-determined value is known as *negative relative accommodation (NRA)*. Similarly, the maximum accommodation that can be exerted with respect to the convergence-determined value is called *positive relative accommodation (PRA)*. Typical values for these two parameters in non-presbyopic persons without convergence or accommodation disorders are 2.50 D for the former and 3.50 D for the latter. We can therefore assume that **most wearers can comfortably shift their accommodation up or down with respect to the convergence-determined accommodation** inasmuch as the shift is small compared to the typical PRA and NRA values. As IOT Digital Ray-Path 2 will make use of these shifts, we establish two boundaries for the maximum amount of accommodation shift that the technology will use, and we call them $\mathcal{A}_{0+}$ for the positive shifts and $\mathcal{A}_{0-}$ for the negative ones.

[10] *More precisely,* IOT Digital Ray-Path 2 *always considers nonzero errors, but the weight given to them is rapidly reduced when their values get smaller than the threshold.*

The actual shifts may be further reduced with respect to the boundaries $\mathcal{A}_{0-}$ and $\mathcal{A}_{0+}$ when the available accommodation that can be relaxed or increased is smaller than the corresponding boundary. For example, if the viewing distance is infinite, accommodation $\mathcal{A}$ will already be zero, and there is no way to relax it anymore. Similarly, if the viewing distance demands maximum accommodation $\mathcal{A}_{max}$, then there is no way to increase it any further. In any given situation, the actual available shifts, $\mathcal{A}_{rel-}$ and $\mathcal{A}_{rel+}$ will be given by:

$$[4] \quad \mathcal{A}_{rel-} = \begin{cases} \mathcal{A}_{0-} & \text{if} \quad \mathcal{A} \geq \mathcal{A}_{0-} \\ \mathcal{A} & \text{if} \quad \mathcal{A} < \mathcal{A}_{0-} \end{cases}$$

and

$$[5] \quad \mathcal{A}_{rel+} = \begin{cases} \mathcal{A}_{0+} & \text{if} \quad \mathcal{A}_{max} \geq \mathcal{A}_{0+} \\ \mathcal{A} & \text{if} \quad \mathcal{A}_{max} < \mathcal{A}_{0+} \end{cases}$$

If the object distance demands accommodation bigger than $\mathcal{A}_{rel-}$, and the mean power error, $\Delta\boldsymbol{M}$, is positive and smaller than $\mathcal{A}_{rel-}$, the wearer will be able to compensate the error by relaxing accommodation. Similarly, if $\Delta\boldsymbol{M}$ is negative and its absolute value is smaller than $\mathcal{A}_{rel+}$, the wearer will be able to compensate it by increasing accommodation.

This effect can be nicely represented in dioptric space as stretches of the region of tol erable oblique errors along the vertical direction. The wearer's accommodation relaxing up to $\mathcal{A}_{rel-}$ diopters and compensating for errors above the sphere shown in figure 16 (a), is equivalent to the sphere being stretched upward by an amount $\mathcal{A}_{rel-}$. Similarly, the wearer's accommodation increasing up to $\mathcal{A}_{rel+}$ and compensating for errors below the sphere is equivalent to the sphere being stretched downward by an amount $\mathcal{A}_{rel+}$. This is shown in figure 16 (b). The colors chosen are the same as those used in figure 9: blue for relaxation of accommodation, green for increase of accommodation, though either action may happen at any point of the accommodative space represented in figures 9 and 15. We will still name the stretched region shown in figure 16 (b), including both the green and blue portions, the *region of unnoticeable oblique error*.

The merit function and the optimization algorithm implemented in IOT Digital Ray-Path 2 will seek that the oblique powers get as close as possible to the region of tolerable oblique error; once the optimization loop gets the oblique power into the region, its contribution to the merit drops very rapidly[11] and the optimization algorithm does not need to further modify the surface to bring this oblique power closer to its target. The sequence of oblique powers obtained in each step of the optimization loop, $\boldsymbol{P'}_i$, follow a path in dioptric space, and as we saw with IOT Digital Ray-Path, the trajectories may be complex and may differ among different gaze directions. One of these paths is represented in figure 16 (c).

Finally, the merit function in IOT Digital Ray-Path 2 will deal with more than one object distance for each gaze direction to balance the lens performance across the desired portion of the accommodative space. That means the lens-eye system must be traced as many times as object distances are considered per gaze direction. For example, if we want to design a lens optimized for the whole accommodative space, we will use the working distances associated with accommodation levels zero and $\mathcal{A}_{max}$, as shown in figure 15. Each object distance has a pair of related values $\mathcal{A}_{rel+}$ and $\mathcal{A}_{rel-}$, from this point on, each object distance will also have a characteristic region of unnoticeable oblique error and each step of the optimization algorithm will seek to bring the oblique power corresponding to each object distance as close as possible to the corresponding region of unnoticeable oblique error. The procedure is represented in figure 16 (d). Here we have two object distances, d_1 and d_2. Each one produces its own sequence of oblique powers, $\{\boldsymbol{P'}_i(d_1)\}$ and $\{\boldsymbol{P'}_i(d_2)\}$, where $\boldsymbol{i}$ goes from *1*, for the power obtained with the first set of parameters of the free-form surface, to *N*, the last iteration of the optimization loop where all the oblique powers will be inside the corresponding regions of unnoticeable oblique error (or as close as possible). IOT Digital Ray-Path 2 will use two object distances for most lens designs but depending on the details of the design and its intended use, three or more object distances could be used.

[11] *An important feature of IOT Digital Ray-Path 2 is that the weight its merit function gives to each oblique error changes smoothly as the oblique error crosses into the region of unnoticeable oblique error.*

Unprecedented results

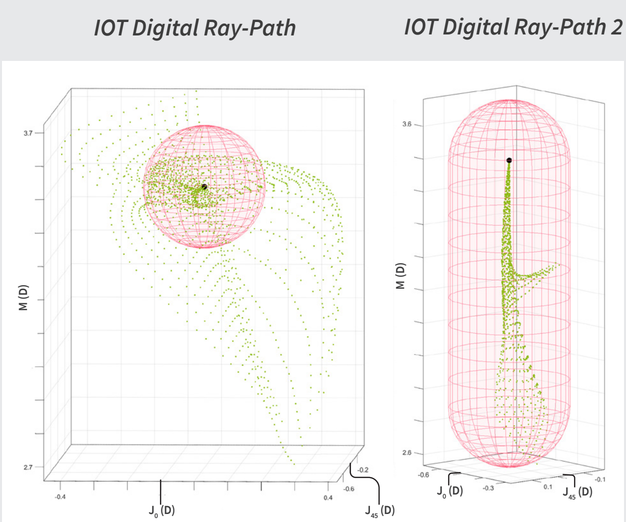
→

Single vision lenses

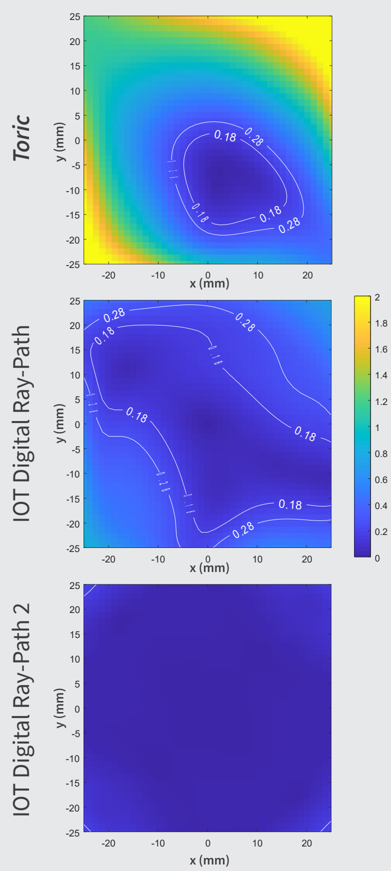
IOT Digital Ray-Path 2 obtains unprecedented results when it comes to controlling oblique aberrations.

Extensive numerical research indicates that for a wide range of prescriptions, base curves, and personalization parameters, the oblique aberrations will be imperceptible in a large percentage of the field of view. We will present next the comparison between IOT Digital Ray-Path and IOT Digital Ray-Path 2 for the same single vision lens we previously analyzed. Figure 17 shows the complete oblique performance of the lens previously analyzed: [+3.00+1.00×45°], base curve 6.00 D, and refractive index 1.5. The graphic on the left corresponds with IOT Digital Ray-Path optimization, while the graphic on the right was obtained using IOT Digital Ray-Path 2. The left plot is the same as in figure 6 and is repeated here to easily show the comparison between both technologies. **We see how the new technology allows total control of the oblique error, since basically all the oblique powers are well contained within the region of unnoticeable oblique error (which in this case means unnoticeable blur).** Consider the oblique astigmatism that we can observe in the plot on the left, as points spreading out horizontally from the sphere of unnoticeable blur. IOT Digital Ray-Path 2 has swapped it by mean sphere error, with a span smaller than 0.75 D. The optimization was done for a single object distance, infinity in this case, which makes the sphere of unnoticeable blur stretch downward.

The effectiveness of the new technology can also be noticed by using conventional maps, in which we show the value of an optical property as a function of the point of the lens through which we see. If we represent the *blur strength* of the oblique error, we obtain the maps in figure 18.



[Figure 17] Comparison between IOT Digital Ray-Path *(left-hand graph) and* IOT Digital Ray-Path 2 *(right-hand graph) for the same lens with prescription [+3.00+1.00×45°] from figure 6. While* IOT Digital Ray-Path *achieved a significant improvement compared to a standard lens (figure 5), the new technology manages to get the oblique powers for all gaze directions inside the region of unnoticeable blur, with a vertical stretch (mean power error) smaller than 0.75 D. With the new optimization, the amount of astigmatism is negligible across the entire surface.*

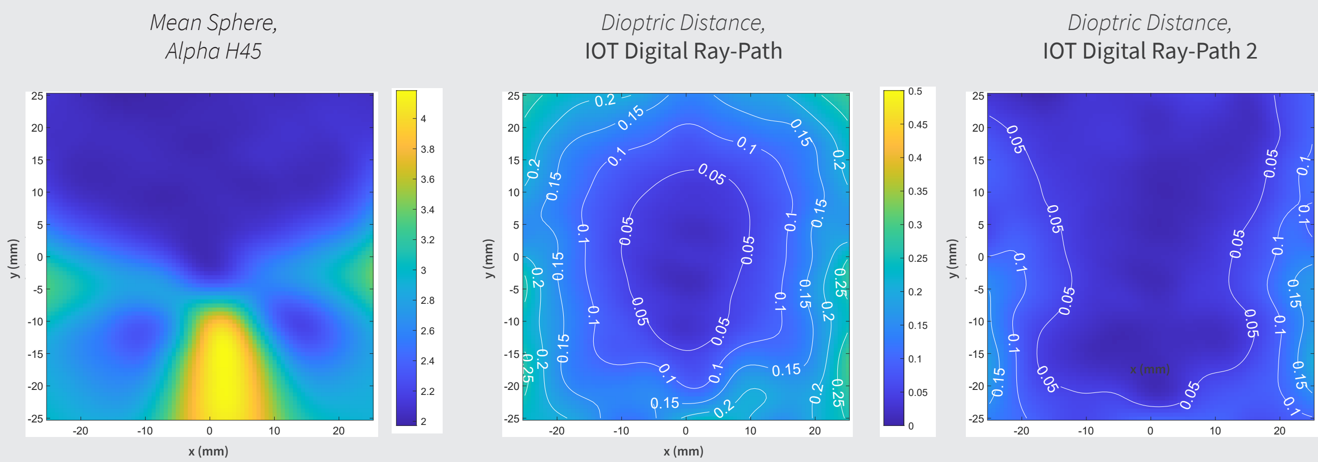


[Figure 18] Blur maps of the single vision lens showed on figures 5, 6, and 17. Each point of the map is proportional to the wearer's angle of minimum resolution (MAR), which in turn is inversely proportional to visual acuity. The result obtained with IOT Digital Ray-Path *is already very good, but* IOT Digital Ray-Path 2 *achieves unnoticeable levels of blur through the entire surface of the lens (this fact implies that the lens would not alter the wearer's visual acuity at any point on it).*

Progressive lenses

The dioptric space representation was useful to show the difference between a non-compensated progressive lens (figure 10) and a similar design optimized with **IOT Digital Ray-Path** (figure 11).

The oblique errors, especially at the near region, are so large in the non-compensated lens that they are easily spotted in the cloud of oblique powers in dioptric space. However, the differences between the lenses optimized with **IOT Digital Ray-Path** and **IOT Digital Ray-Path 2** are not easily identified in dioptric space. The difference between the two technologies are much smaller than the typical dispersion of target powers due to progression and its accompanying Minkwitz aberrations. Nevertheless, we can see the differences between the two technologies in dioptric distance blur maps like those shown in figure 12.

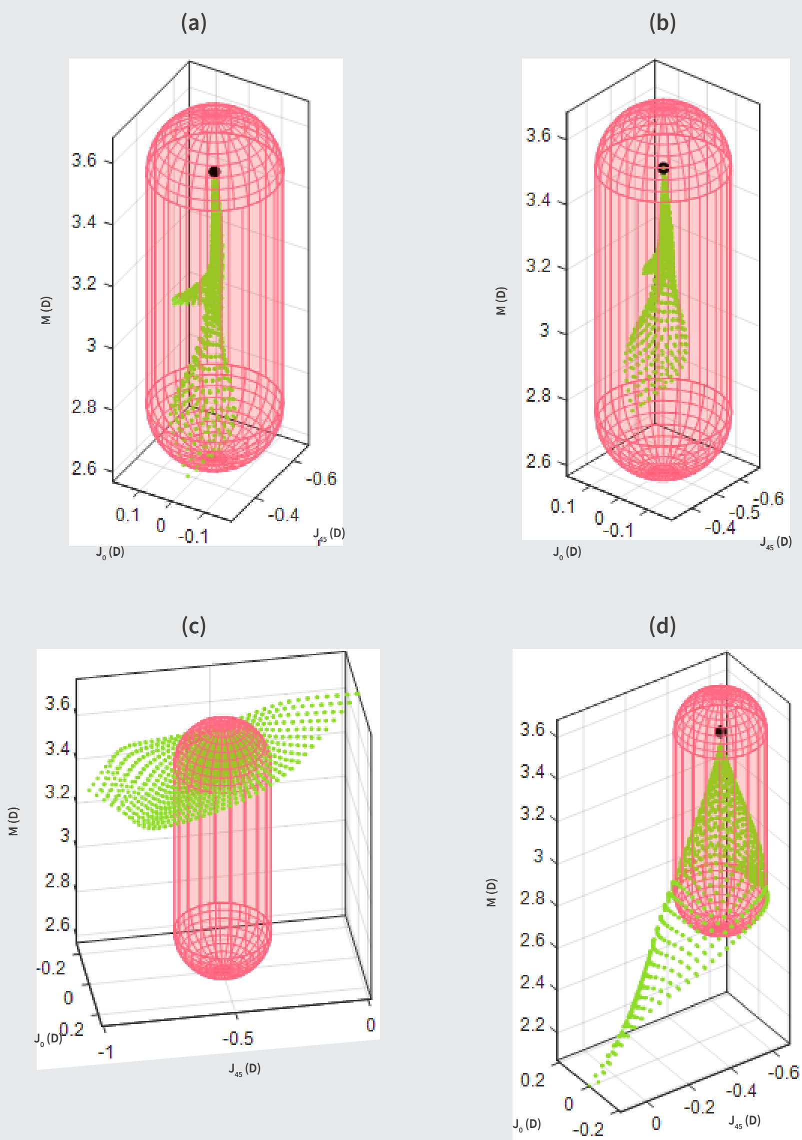


[Figure 19] The map on the left show the mean sphere of the target power of a well-balanced progressive design. The maps to the center and to the right shows the module of oblique error obtained with IOT Digital Ray-Path *and* IOT Digital Ray-Path 2*, respectively.*

The comparison is shown in figure 19. The map on the left is the standard mean sphere map of the target power distribution in a balanced, general purpose progressive lens with power +2.00 D, addition +2.00 D and manufactured with a 5.00 D base curve. The central map represents the dioptric distance from the target to the oblique powers achieved with **IOT Digital Ray-Path**. The map to the right shows the same dioptric distance from the target to the oblique powers obtained with **IOT Digital Ray-Path 2**.

The magnitude of the oblique error does not exceed 0.30 D for the lens optimized with **IOT Digital Ray-Path**, but the boundary is reduced to 0.20 D for the lens optimized with the new technology. We can see that the improvement in the reduction of oblique error is especially important in the lens corridor, where **IOT Digital Ray-Path** get the highest values of oblique error. In general, **IOT Digital Ray-Path 2** achieves a clean umbilical line, smaller oblique error at the periphery of the far region, and astigmatism lobes closer to the target than the previous technology.

We will finish this review on **IOT Digital Ray-Path 2** with an analysis of the importance of the optimization in the accommodative space. To visualize the effect of the object distance in lens optimization and performance, we will choose the same prescription and lens geometry that we used in the previous examples: [+3.00+1.00×45°], base curve 6.00 D, and index 1.5. First, we will show how the object distance used for the optimization of the lens affects lens performance at other distances. In figure 20 we show the cloud of oblique powers for the lens optimized with **IOT Digital Ray-Path 2** but at just one single object distance. Figure 20 (a) corresponds with the lens optimized for far vision and traced at far vision, with zero object vergence. Figure 20 (b) corresponds with the optimization being made at 50 cm, equivalent to an object vergence of 2.00 D, and the resulting lens being traced at the same distance. The structure of the cloud of oblique powers is very similar in both cases: virtually all the oblique power inside the region of unnoticeable blur. In figure 20 (c) and (d) below, we show the performance of the same lenses but traced at the opposite object distances: in (c) the lens optimized for far vision is traced at 50 cm, and in (d), the lens optimized at 50 cm is traced at infinite object distance. We clearly see that performance rapidly decreases when the lens is used at an object distance different than the one for which it was optimized.



[Figure 20] Oblique powers of the lens [3.10×45°].

(a) Lens optimized for distance vision, performance at distance vision.

(b) Lens optimized at 50 cm, performance at 50 cm.

(c) Lens optimized at distance vision, performance at 50 cm.

(d) Lens optimized at 50 cm, performance at distance vision.

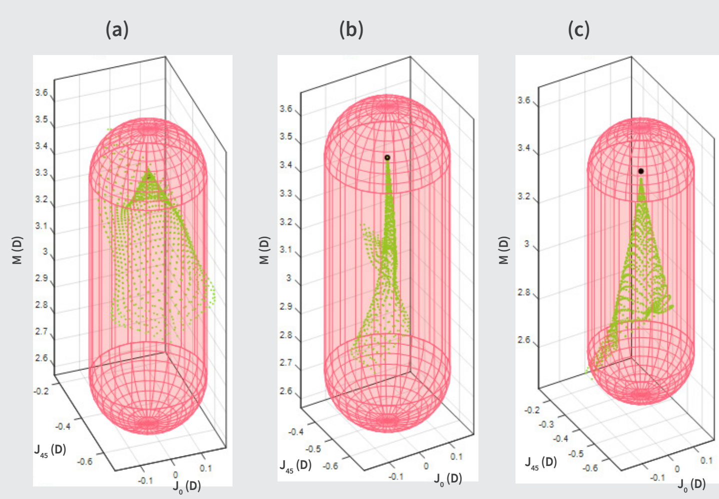
More quantitative results can be read in table 1. Here we provide the percentage of the field of view for which the blur is below three levels: 0.40 D, 0.25 D, and 0.18 D. As stated before, **the performance of the lens when used at the same distance for which it was optimized is almost perfect**, with virtually all the fields of view presenting blur smaller than 0.18 D. However, when the lens optimized for distance vision is used at 50 cm, blur will be noticeable in 29% of the field of view, and visual acuity will be affected in 23% of the field of view. For the lens optimized at 50 cm and used for distance vision, 49% of the field of view will present noticeable blur and visual acuity will be affected in 29% of the field of view.

Optimization Vergence (D)	Tracing Vergence (D)	Blur < 0.4 D (%)	Blur < 0.25 D (%)	Blur < 0.18 D(%)
0	0	100	100	99
2	2	100	100	100
0	2	90	83	71
2	0	95	71	51
0, 2	0	100	99	92
0, 2	1	100	100	99
0, 2	2	99	95	91

[Table 1] Performance of IOT Digital Ray-Path 2 *lenses at different object distances.*

Finally, in figure 21 we show the results when the capacity of IOT Digital Ray-Path 2 to optimize the lens at more than one object distance is enabled. We have optimized the same job (same prescription, same wearer parameters) for two different vergences, zero and 2.00 D, which is the infinite object distance and 50 cm. Figure 21 (a), (b), and (c) present the clouds of oblique powers when this lens is used at infinite object distance (a), one meter (b), and 50 cm (c). Though the compactness of the cloud is not as good as the ones in figure 20 (a) and (b), most of the gaze directions have oblique power within the region of unnoticeable blur for any object distance in the object space, in particular the three distances represented in figure 21. The numerical data in table 1 demonstrates the superiority of the technology.

In figure 21 we see the lens optimized with the IOT Digital Ray-Path 2 Technology in the accommodative space. **Lens characteristics are now virtually optimal across the entire object distance range.**



[Figure 21] Oblique powers of the lens [+3.00+1.00×45°] optimized at two different object distances, infinity, and 50 cm.

(a) Performance at far vision.

(b) Performance at 100 cm.

(c) Performance at 50 cm.

Features and benefits

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Lenses with **IOT Digital Ray-Path 2** give eyecare professionals the ability to offer their patients the latest in lens personalization technology from IOT. A unique technology to help them differentiate their businesses.

1

Minimizes the effect of oblique aberrations

By considering the wearer's natural accommodation.

2

Optimized for the wearer's

Entire accommodative object space.

3

Precise and comfortable focus

At all working distances in any direction of gaze.

4

Virtual elimination

Of peripheral blur.

5

Automatic centering

For thickness reduction.

6

Customized for the individual parameters

Of each wearer, material, base curve, and frame.

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