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Foreword

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This document was prepared by Technical Committee ISO/TC 172, *Optics and photonics*, Subcommittee SC 7, *Ophthalmic optics and instruments*.

Ophthalmic optics and instruments — Free form technology — Spectacle lenses and measurement

1 Scope

This document outlines all the steps from refraction to dispensing of spectacles, with particular attention to the benefits added by using free form technology, and provides a collection of relevant terms and descriptions.

This document does not contain the proprietary features of lens designs provided by suppliers.

2 Normative references

There are no normative references in this document.

3 Terms and definitions

No terms and definitions are listed in this document.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

— IEC Electropedia: available at http://www.electropedia.org/

— ISO Online browsing platform: available at http://www.iso.org/obp

4 Technical introduction

4.1 Preliminaries

4.1.1 There are various ways of spelling the term "free form". This document uses two separate words.

4.1.2 There are various terms explaining spectacle lens optical power design which are commonly used such as "optical function", "optical characteristics", "optical properties", or "design property". For purpose of simplicity, this document uses the word "characteristics". The phrase "optical properties" is used simply to describe the optical results of the geometry of the lens, but not an intended design or characteristic.

4.1.3 A typical flowchart including refraction, dispensing and manufacturing is shown in Figure A.1 (see Annex A).

4.1.4 A glossary of terms and their descriptions is provided in Annex C.

4.2 What is free form?

In ophthalmic optics, the term "free form surfacing" refers to a spectacle lens surfacing process that is capable of producing continuous, smooth, non-symmetrical lens surfaces that lack point, axial or plane symmetry and are described by three-dimensional coordinates created by mathematical formulation. This design and surfacing process enables optimization of the lens performance.

Conventional lens surfacing technology which smooths and polishes using hard lap tools can produce only simple spherical or toroidal lens surfaces.

Modern free form lens surfacing methods are now capable of generating surfaces that are much more complex than simple spherical and toroidal surfaces, allowing local optical laboratories to manufacture progressive-power and other lens designs directly onto the lens blank with the required prescription curves. In order to produce these complex surface shapes, free form surfacing utilizes precise, computer-driven control of the cutter with three or more axes of movement. Often, the surface is machined using single-point diamond turning and then polished using flexible lap tools.

A "free form process" can thus be summarized as a lens surfacing process using Computer Numeric Control (CNC) devices capable of producing a free form surface with optical characteristics on either or both side(s) of the lens.

It should be noted that when simpler surfaces that can be manufactured by conventional methods are produced by free form processing, these simpler surfaces should not be termed free form surfaces nor the resulting lenses free form lenses.

4.3   Does free form equal better vision?

As an enabling technology, free form surfacing makes possible the application of optical characteristics, using information specific to the individual wearer, immediately prior to lens manufacture.

The use of free form surfacing as a manufacturing method does not guarantee any visual benefit to the wearer. It is true that the soft lap tool polishing process used during free form surfacing is not subject to the rounding errors of conventional lens surfacing. Conversely, it can maintain an accurately generated free form surface. Hence, soft lap polishing actually relies on more extensive process engineering and quality control in order to achieve high quality lens surfaces.

Free form surfacing provides a powerful vehicle for overcoming the limitations of conventional semi-finished lens manufacturing when utilized in conjunction with sufficiently advanced optical design software by delivering lenses custom-designed for the specific visual requirements of the individual wearer. It becomes possible to optimize the optical design of the lens individually (i.e. upon the exact prescription power and orientation of the fitted lens) before the lens is actually manufactured, in order to preserve the intended optical lens characteristics for each and every wearer.

In addition to preserving the intended optical lens characteristics for any combination of prescription power or as-worn position, it is also possible to customize other features of the lens design for the individual wearer. The lens can be adapted further in order to modify the corridor length for the fitting height in small increments, optimize the viewing zones for occupational demands, and adjust peripheral power gradients for the head-eye movement behaviour, and so on. It is important to note, however, that only custom-designed free form lenses will offer this level of sophistication and design properties for the wearer.

Nevertheless, without the application of real-time optical design to optimize the lens design for the individual wearer, the potential visual advantages of using free form surfacing are relatively small.

4.4   Classification

With free form surfacing, an optical laboratory can surface a variety of lens designs directly onto a semi-finished lens blank in addition to the prescription curves that are normally applied. With two separate surfaces to work with, the optical characteristics, addition power, if any, and prescription components of a free form lens can be applied to the lens blank in a variety of possible lens surface configurations. Each type of free form lens represents a particular combination of factory-moulded and directly-surfaced lens curves. The lens surfaces involved range in complexity from simple spherical surfaces to individually-optimized progressive power surfaces that simultaneously fulfil all of the prescription requirements of the wearer.

When free form surfacing is used to transfer the optical characteristics onto the lens blank, free form progressive-power lenses may be classified by the distribution of the optical characteristics between the front and back surfaces (see Figure 1).

a) *Front surface free form lenses* (A in Figure 1) employ a directly-surfaced progressive surface with the full addition power on the front and conventionally-surfaced prescription curves on the back. The progressive optics are surfaced directly onto the lens. While less common, this configuration may, for instance, be utilized to achieve broader prescription ranges.

b) *Dual-surface free form lenses* (B in Figure 1) employ a factory-moulded (or, in some cases, a directly-surfaced) progressive-like surface with a component of the total addition power on the front and a digitally-surfaced progressive surface with, for instance, the remaining addition power that has been combined with the prescription curves on the back. The progressive-power optics are distributed between both lens surfaces.

c) *Back-surface free form lenses* (C in Figure 1) employ a factory-moulded spherical surface on the front and a directly-surfaced progressive surface that has been combined with the prescription curves on the back. The progressive lens design may be a standard (fixed) design or an optically-optimized design.

For the purpose of simplicity, the rest of this document will refer only to full back surface lenses (C in Figure 1).
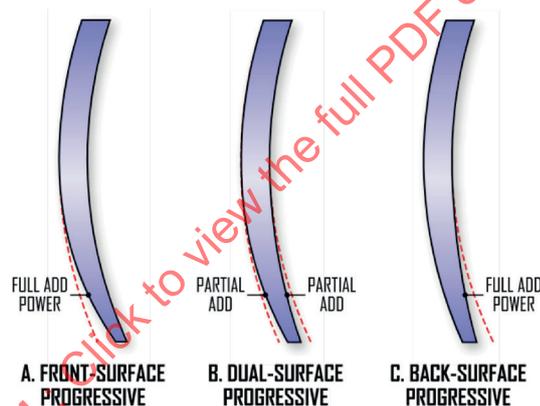
NOTE   Image by Darryl Meister. Reproduced with permission from Carl Zeiss Vision GmbH, USA.

Figure 1 — Classification of free form progressive-power lenses by the distribution of the addition power between the front and back surfaces

5   Manufacturing

5.1   General

Whatever the process used to manufacture the lens, the lens manufacturing cycle is the same. The general lens manufacturing flow is described in Figure 2.

Figure 2 — General lens manufacturing flow with semi-finished lens blanks and surfacing

5.2 Conventional surfacing

Conventional surfacing is a four-step process for finishing the unfinished back surface of a semi-finished lens blank with the required prescription curves (see Figure 3). Semi-finished lens blanks have an optical-quality front surface that has been moulded by a manufacturer.

In the first step termed "blocking", the semi-finished lens blank is mounted by its finished surface on a support to hold it for the next three steps.

In the second step, the unfinished surface of the lens is machined by a generator to approximately the required shape using a grinding, turning or milling process.

In the third step, known as fining or smoothing, the worked surface is ground to the precise surface shape by a toroidal smoothing/polishing machine that rapidly moves the lens surface in a cyclical motion over a hard lap tool fitted with abrasive pads that matches the intended curvature of lens surface. This brings the lens surface to a quality suitable for polishing.

In the fourth and final manufacturing step, known as polishing, the abrasive pad is replaced by a polishing pad. The lens surface is once again cycled over the hard lap tool in a toroidal smoothing/polishing machine, while the pad is soaked with polishing slurry. The lens is then "de-blocked".

See Figure 3 a) and b). In Figure 3 b) the hard lap tool copies the fixed two principal meridians' curvatures to the lens's concave surface.
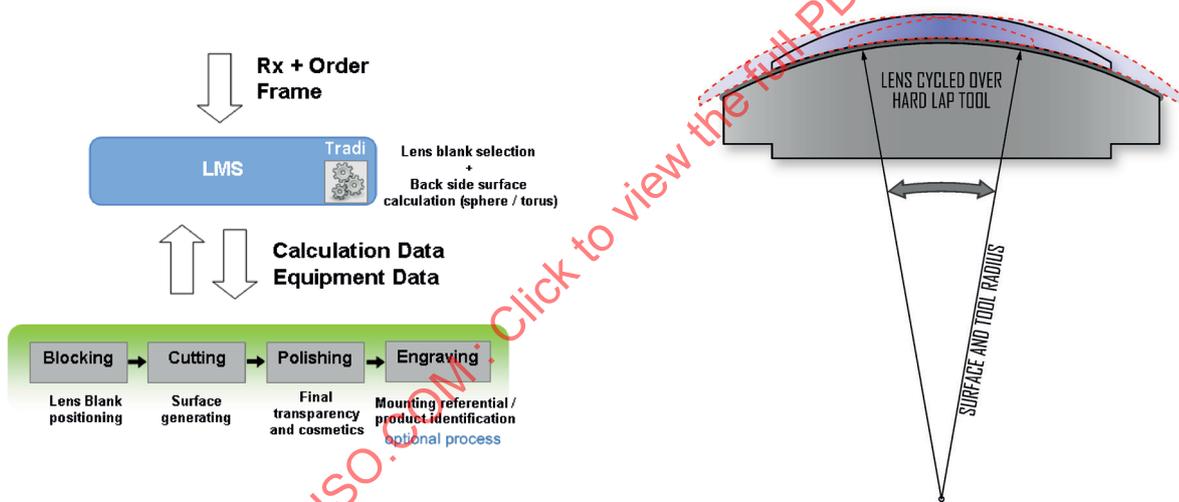
a) Scheme of conventional surfacing process   b) Fining process used in conventional surfacing

Figure 3 — Conventional surfacing process

The simplest generators are two-axis machines that utilize a diamond-impregnated grinding wheel to generate a spherical or toroidal lens surface. The emphasis of a conventional generating process is on throughput and rapid removal of lens material. Any inaccuracy in the shape of the generated lens surface is ultimately corrected during the fining process by the hard lap tool. In particular, the fining process with hard lap tools exploits the rotational or meridional circular symmetry of spherical or toroidal lens surfaces, since these surfaces can be cycled over the hard lap tool using a uniform rocking motion that produces relatively constant fining and polishing pressure over the lens blank [see Figure 3 b)]. The use of hard lap tools during the fining and polishing processes therefore restricts the range of possible lens surface shapes to simple spherical and toroidal surfaces. Moreover, in practice, hard lap tools are only available in discrete increments of surface curvature. Due to the need for reasonable inventory requirements, hard lap tools are often stocked in eighth-dioptre (0,12 D) or tenth-dioptre (0,10 D) steps for the sphere power, although larger laboratories may stock tools in 0,06 D steps. This can potentially result in rounding errors of up to ±0,05 D from the desired surface curvature, which will limit the

accuracy of the prescription power of the surfaced lens and increase the likelihood of failure during a quality inspection.

5.3 Free form surfacing

In conjunction with the Laboratory Management System (LMS), a *Lens Design Server* (LDS; computer and appropriate sophisticated software) is first used to calculate a *surface description file* (SDF) (also known as a "*points file*") from the prescription and lens order parameters. The points file contains surface height (and possibly slope) data [see Axis 1 in Figure 4 b)] that characterize the required three-dimensional geometry of the lens surface to be cut[7]. The required lens surface is then generated from the points file using a CNC cutting process. With three or more axes of precisely controlled movement, the single-point cutting tools of these generators can produce virtually any continuously smooth surface shape with a high degree of accuracy and smoothness that requires minimal polishing.

The machine may also orientate the cutter to be at right angles to the orientation of the lens surface in the immediate area in which it is cutting; hence, there may be three or five axis machines, double that if they can surface the left and right lenses simultaneously.
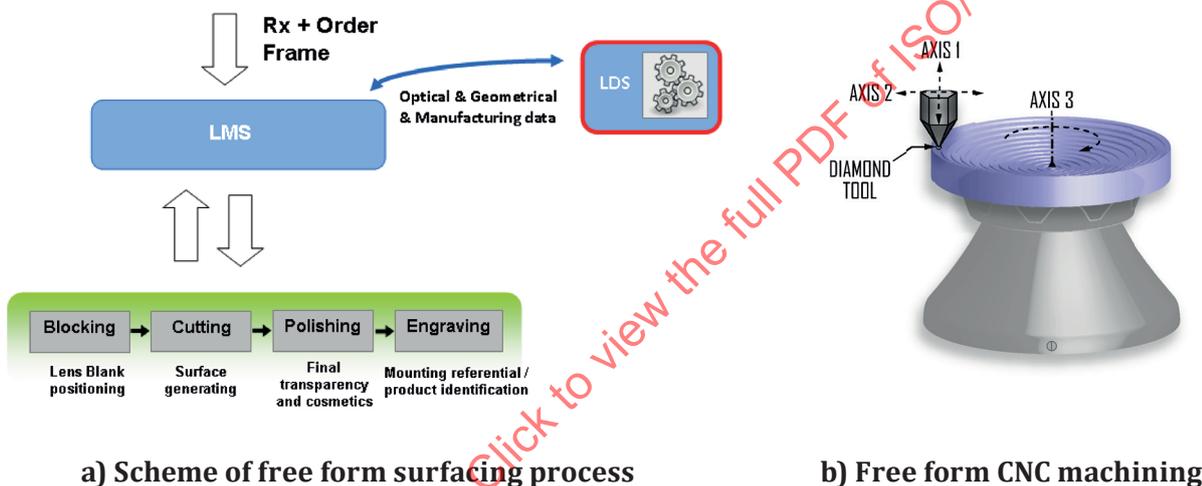

a) Scheme of free form surfacing process   **b) Free form CNC machining**

Figure 4 — Free form surfacing process

With most free form lenses, the prescription powers are combined into the required lens design, and then processed as a single surface onto the back of a semi-finished lens blank, as in Figure 2[8]. This allows the fabrication of a lens design and the prescription curves in a single step. The worked lens surface is then polished by a free form polisher using a soft lap polishing tool that is also dynamically controlled by a computer. Unlike hard lap tools, which are only available in specific increments of surface curvature, soft lap tools can polish a lens surface to within very small increments.

Because this technology allows the laboratory to fabricate complex lens design directly onto the lens blank, free form surfacing is sometimes referred to as *direct surfacing*. Because free form lens surfacing relies on computer (points) files that describe the desired surface shape, free form lens surfacing is also referred to as *digital surfacing*. However, the term "digital surfacing" is often used more generally to refer to any lens surfacing process that utilizes free form surfacing equipment, even when surfacing conventional spherical or toroidal surfaces, which makes the use of this particular term potentially misleading.

In summary, a conventional surfacing process cannot produce the complex surfaces utilized for complicated lens designs like progressive-power lenses due to limitations in both the range of possible surface-shape geometries and the quality of the finished surface produced by conventional generators. Free form surfacing is, however, a more sophisticated surfacing process that is capable of producing virtually any continuously smooth surface, including aspheric, atoroidal, and progressive-power surfaces, in addition to basic spherical and toroidal surfaces. This allows local optical laboratories to

manufacture progressive-power and other complicated continuous surfaces that previously needed moulding using a mass-manufacturing process.

5.4 Comparison of conventional and free form manufacturing

Table 1 — Comparison of steps of conventional and free from manufacturing

Manufacturing step	Conventional process	Free form process
Inputs from order	— **Prescription:** SPH, CYL, Axis, addition, Prism base and value, CD.	— **Prescription:** SPH, CYL, Axis, addition, Prism base and value, CD. — **Fitting and personalised parameters**
Lens blank selection	— The base curve is selected from the prescription according to the Rx range. — The complex surface already exists on the front surface of the lens blank. — **Number of lens blank stock keeping units (SKUs) needed is high** to cover all additions and all prescriptions.	— The base curve is selected from the prescription according to the Rx range. — A part of the complexity may exist on the front surface of the lens blank. — **Number of lens blank SKUs needed can be reduced** in the case of full back surface lenses.
Calculation of the back surface	— **Simple and limited surfaces:** the back surface of the lens can be only spherical or toroidal because of the surfacing tools. — The optical characteristics are managed through the front surface. — The calculation delivers **the radii of curvature and axis of the back surface and its positioning relative to the front surface (thickness and prism).** — **The output of calculation is rounded according to the tooling steps available (e.g. 0,12 D, 0,10 D or 0,06 D).**	— **Free form surfaces:** the surface of the lens can be spherical, toroidal, aspherical or progressive/degressive-power or a combination of both or even more complex. — The optical characteristics are managed through the back surface only (full back) or through both surfaces (dual). — Usually based on **complex ray-tracing algorithms,** the calculation delivers either one **surface that will have to be made and its positioning relative to the other surface or both surfaces.** — **Output of the calculation is the exact lens surface target without any rounding.**
Taping	Use of a plastic film deposited on the front surface both to protect it and to ensure adhesion for blocking (not always needed by alternative method, e.g. water soluble spray).	
Blocking	Mechanical 3D positioning of the blank (centring, axis, tilts, etc.)	
Generating	— **Rough milling.** — Use of **cup wheel introducing elliptical errors.** — Generating of the back surface curvatures. — Generated surface can be approximated as the **final geometry is given by fining/polishing tools.**	— **Rough turning** with a rotating cutter disc. — **Fine turning with a single point diamond tool.** — Cutting machines need **high precision trajectory in high acceleration conditions.** — **Machined surface has the exact final expected shape.**

Table 1 *(continued)*

Manufacturing step	Conventional process	Free form process
Fining	— **Smoothing by abrasive pad on rigid tool.** — **Gives the final expected curve.**	This step is not necessary.
Polishing	— **Respects the fined surface shape.** — **Hard polishing** with **Rigid tool.** — 1 tool = 1 spherical or toroidal surface.	— **Respects the generated shape.** — **Soft polishing** with **flexible tool.** — 1 tool = infinity of surfaces.
Engraving	**Generally put on the front surface of the semi-finished lens blank**	For spherical front surface semi-finished lens blank, **generally done on the back surface** of the finished lens, although some free form lenses uses pre-engraved semi-finished lens blanks.

There has been a steady process in improving conventional surfacing. Lap tools may be cut on reusable or disposable laps, thus avoiding the need to keep such tools in fine steps. More sophisticated lens surface generators can produce more accurate surfaces that do not necessarily require hard lap polishing.

Differences between the two processes also exist in terms of power/prism conformity and integrity of the intended surface (see Table 2). Consequently, a specific process control is needed for a free form process to ensure integrity of the intended surface.

Table 2 — Power/prism conformity and integrity of the intended surface shape

Conventional process	Free form process
Integrity of the intended surface is guaranteed by controlling moulds, inserts and the semi-finished lens manufacturing process **Distance vision and prism reference point (PRP) prism conformity guaranteed by laboratories.**	Integrity of the intended surface also relies on the back side manufacturing phase: **responsibility mostly (fully in case of full back side) transferred to laboratories** — **Distance vision and prism reference point (PRP) prism conformity guaranteed by laboratories**.

6   Potential benefits of free form lens calculation

6.1   Oblique astigmatism

When the line of sight passes through the lens at an angle to the optical axis of the lens, an optical aberration known as *oblique astigmatism* is produced due to the oblique refraction of light rays through the lens. Oblique astigmatism results in unwanted spherical and cylindrical power errors that are perceived by the wearer as deviations from the desired prescription. Oblique astigmatism is introduced when either the lens is tilted with respect to the wearer due to the fit of the frame or the wearer views an object through the periphery of the lens. In either case, the line of sight forms an angle to the optical axis of the lens that can result in an astigmatic focus that departs from the intended focus, if the lens design does not adequately account for this effect (see Figure 5).
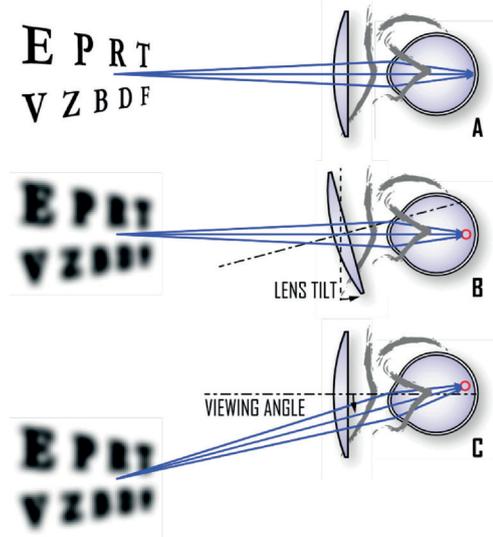
Figure 5 — Degradation of the image because the line of sight is not along the optical axis of the lens

Oblique astigmatism does not occur when the line of sight coincides with the optical axis of the lens and the object is seen clearly (see Figure 5):

a)   line of sight aligned to the optical axis of the lens gives a good image (A in Figure 5);

b)   blurred image with tilted lens (B in Figure 5);

c)   blurred image with oblique line of sight (C in Figure 5).

For spherical prescriptions, oblique astigmatism introduced during off-axis vision can be eliminated by selecting a spherical front curve that corresponds to a Tscherning's ellipse for a given set of lens design parameters. See the example in Figure 6[9] which represents the power of the lens's convex surface needed in distance vision to eliminate oblique astigmatism when the line of sight is rotated 30° to the optical axis. For a prescription of −5,00 D, the power of the convex surface will need to be about either +3,50 D or +17,00 D.

This results in a *best form* lens design. Alternatively, an aspheric lens design can be utilized, which frees the lens designer from the relatively steep lens form requirements of Tscherning's ellipse in order to provide flatter, thinner lenses. However, as with best form lenses, each spherical power requires a separate aspheric lens design.

Values in dioptres
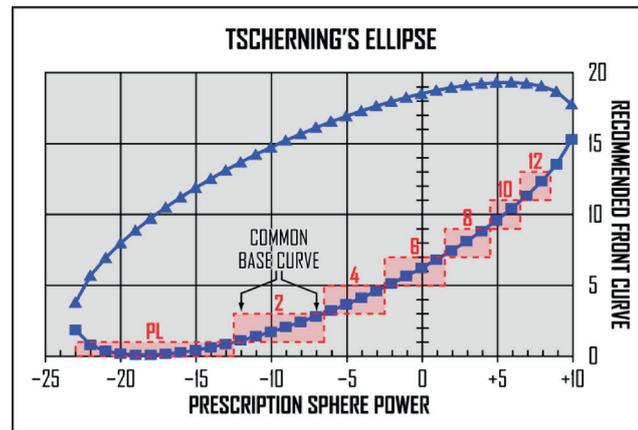
NOTE   Image by Darryl Meister. Reproduced with permission from Carl Zeiss Vision GmbH, USA.

Figure 6 — Tscherning's ellipse

Best form and aspheric lenses are rotationally-symmetrical lens designs that can correct for oblique astigmatism fully only when the lens design precisely matches the design required for the sphere power of the prescription and the prescription does not require cylindrical power. In order to correct the oblique astigmatism in sphero-cylindrical lenses with prescribed cylindrical power, an *atoroidal* lens design should be utilized, which has asphericity that differs in the two principal meridians of the lens[10]. Over 75 % of prescriptions in the USA include cylindrical power[11]. Lenses with prism, progressive-power, addition power, as-worn pantoscopic or face form angles, or other optical variables can require designs of even greater complexity[12].

6.2   Limitations of conventional lenses

An optical laboratory fabricates conventional spectacle lenses from *semi-finished* lens blanks that have been mass-produced at a lens factory. The front surface of a semi-finished lens blank has been moulded by the lens manufacturer with the intended optical characteristics and nominal surface curvature, typically identified by a *base curve* value. Unfortunately, the economics of offering a unique front curve design for every prescription combination, as indicated by Tscherning's ellipse, are extremely prohibitive for both lens manufacturers and optical laboratories due to the costs associated with mould making and to the excessive inventory requirements that would be involved.

Consequently, in each lens material, conventional semi-finished spectacle lens blanks are typically made available in only a few-base curves, which are each intended to cover a range of prescription powers. For example, these lens blanks are typically offered in a limited range of different front or *base* curves, such as 0,50 D, 2,00 D, 4,00 D, 6,00 D, 8,00 D, and 10,00 D. A single set of average frame fitting values should also be assumed. The lens design associated with each base curve should therefore work sufficiently well for a relatively broad range of possible combinations of prescription powers and fitting parameters. Consequently, while some wearers may enjoy the intended optical characteristics with conventional lenses, many wearers must tolerate less than perfect correction because their parameters differ from those assumed for the lens design.

With semi-finished progressive-power lenses, the base curve restrictions become even more critical, because of the number of additional design permutations required. For each base curve, there are typically 12 addition powers (from +0,75 D to +3,50 D) and separate right and left lens designs. If five base curves are made available, this results in 5 × 12 × 2 = 120 different lens blanks for each lens material. Any new lens design options, such as a short-corridor design or a design with a different viewing zone balance, would double the number of unique lens blanks needed. The inventory requirements and product development costs associated with introducing a new progressive-power lens design therefore limit the range of possible lens designs that are made available.

The unwanted effects of uncorrected optical aberrations are also exacerbated in progressive-power lenses, which are already subject to optical limitations imposed by the surface astigmatism in the lateral blending regions of the lens design. As the prescription deviates from the ideal prescription associated with a given base curve design, the effects of cylindrical power ordered at an oblique axis increase. This oblique cylindrical power interacts optically with the surface astigmatism of the progressive-power design, causing the zones of the lens to contract and can also cause the zones of a progressive-power to shift or become distorted from their ideal shape as the combination of oblique and surface astigmatism combine to increase or decrease the total power (see Figure 7). This effect can differ between the right and left lenses and disrupt binocular vision.
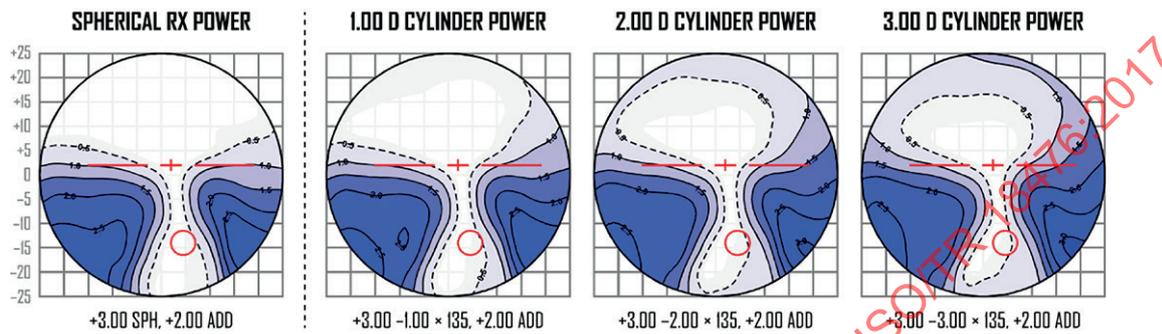
NOTE 1   Values determined by ray tracing. Power values given in dioptres. Linear dimensions given in millimetres.
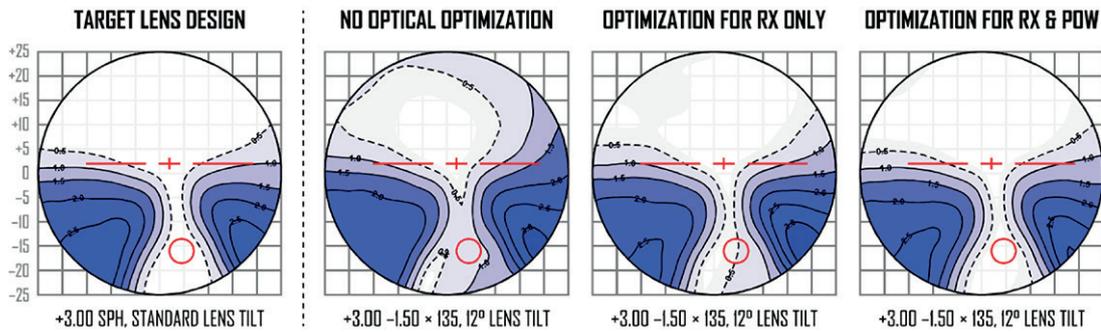
NOTE 2   Image by Darryl Meister. Reproduced with permission from Carl Zeiss Vision GmbH, USA.

Figure 7 — Comparison of the size and position of the clear zones of a progressive-power lens with increased amounts of oblique cylindrical power

6.3   Potential benefit of free form lens design

The advent of free form technology has freed lens designers from the constraints of conventional mass lens production by enabling an optical laboratory to deliver spectacle lenses that have been designed and manufactured for the specific details of the actual lens order. Free form surfacing makes possible the production of complicated lens designs in a small-scale production environment, on demand[8]. When used in conjunction with sufficiently advanced optical design software, often referred to as a *lens design server*, free form surfacing can be utilized to deliver custom-designed single-vision and progressive-power lens designs that have been individually optimized using parameters specific to each wearer, prior to production.

For free form surfacing processes that deliver custom-designed lenses, the optical characteristics of each lens is calculated by the lens design server in order to optimize the optical characteristics individually for factors that can include the wearer's prescription, fitting parameters, frame information and so on. The final optical characteristics of the lens will depend upon the number of parameters that are taken into account during this optical optimization (see Figure 8). The most advanced optical optimization routines will manipulate the free form surface on a point-by-point basis, using complex aspherization algorithms, until the calculated optical characteristics of the lens comes as close as possible to the ideal optical characteristics of the *target* lens design.

NOTE 1   The diagrams show the target design, a lens with no optimization, and the improvements with optimization for the prescription and even better, also with position of wear. Values determined by ray tracing. Power values given in dioptres. Linear dimensions given in millimetres.

NOTE 2   Image by Darryl Meister. Reproduced with permission from Carl Zeiss Vision GmbH, USA.

Figure 8 — Comparison of the size and position of the clear zones of a progressive-power lens with oblique astigmatism

6.4   Optimization for prescription

With sufficiently advanced software and a free form surfacing system, it becomes possible to optimize the optical characteristics of the lens based upon the specific prescription requirements of each wearer, prior to production. In one application of free form technology, a lens design server individually optimizes each optical characteristic for the specific prescription requirements of the wearer by manipulating the free form surface on a point-by-point basis, using complex aspherization, until the differences between the optical characteristics of the calculated lens and the ideal target lens have been minimized. This optical optimization ensures that the intended optical characteristics of the lens design are preserved, regardless of prescription. See Figure 9.
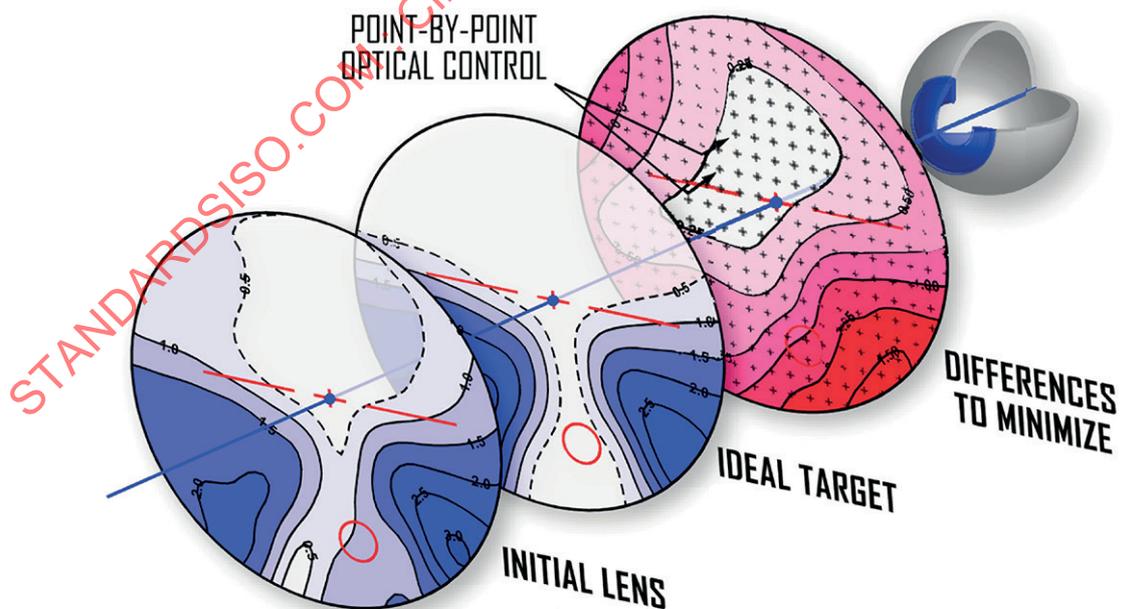
NOTE   Image by Darryl Meister. Reproduced with permission from Carl Zeiss Vision GmbH, USA.

**Figure 9 — Optimization for prescription**

For instance, it is possible to minimize differences between the actual and intended characteristics in order to eliminate residual aberrations. Wearers can therefore enjoy the widest possible fields of clear vision, regardless of prescription. Furthermore, for progressive-power lenses, the binocular function of the wearer can be preserved by maintaining more symmetrical fields of view and by varying the inset of the near zone based upon the optical effects of the prescription.

6.5 Customization for the as-worn position

6.5.1 Explaining the as-worn position

The *as-worn position* is the location and orientation of the fitted lens relative to the actual wearer and includes the as-worn pantoscopic angle, face-form (wrap) angle and vertex distance of the lens. Spectacle prescriptions are typically determined using refractor-head or trial-frame lenses that are positioned perpendicular to the lines of sight of the wearer. Once fitted to the wearer's face, however, spectacle frames generally hold the lenses tilted with respect to the lines of sight. Lens tilt introduces oblique astigmatism, which results in changes from the required spherical power and unwanted cylindrical power that vary over the lens. These unwanted power changes can modify the optical characteristics of both single-vision and progressive-power lenses.

Although preformed progressive-power lenses assumed a default fixed position of wear, with sufficiently advanced software, it is possible to customize the single-vision or progressive-power lens design based upon the unique fitting parameters of each wearer. If the wearer's pantoscopic angle, face-form angle, and vertex distance are supplied, the as-worn position of the fitted lens can be modelled using ray tracing in order to apply the necessary optical corrections across the lens surface during the optical optimization process. Wearers can therefore enjoy the best optical characteristics possible, regardless of their unique fitting requirements. See Figure 10.
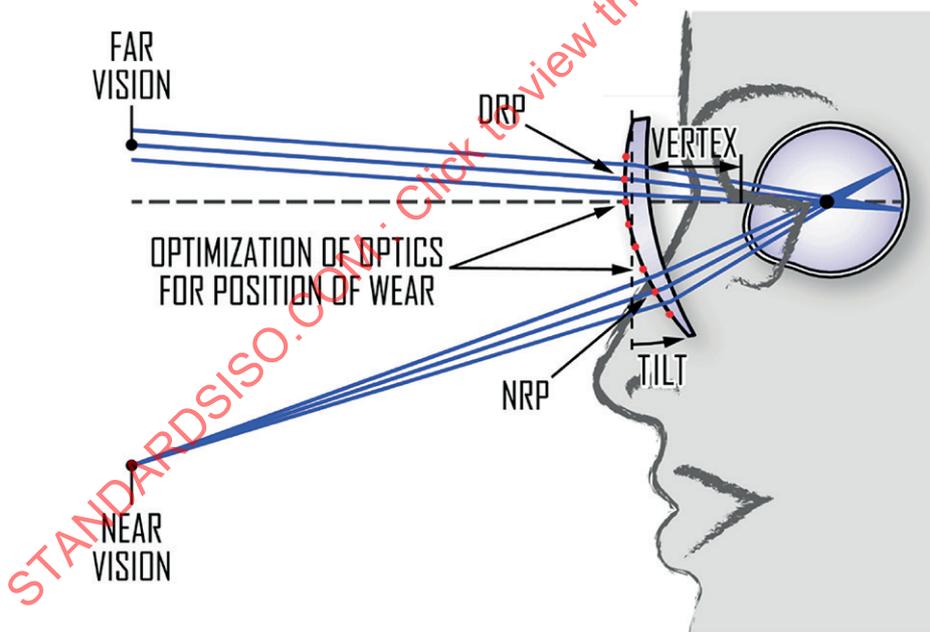
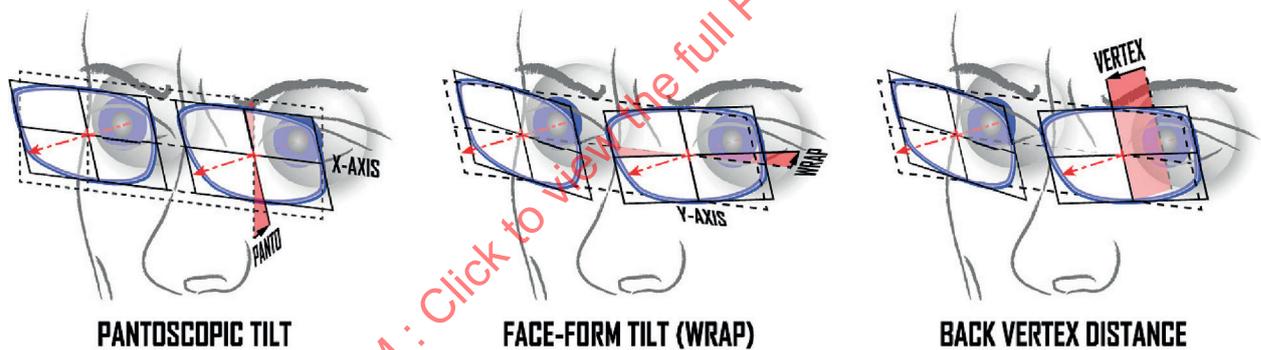NOTE   Image by Darryl Meister. Reproduced with permission from Carl Zeiss Vision GmbH, USA.

Figure 10 — Customization for the as-worn position

Recall that the *as-worn position* can be defined as the position and orientation of the fitted spectacle lens relative to the eye in primary gaze. The *orientation* of the spectacle lens is most consistently defined by the orientation of the plane of the lens shape, i.e. the lens aperture of the frame that contains the lens, with respect to a frontal reference plane that is perpendicular to the line of sight in primary gaze. In the absence of pantoscopic tilt and any face-form angle, the plane of the spectacle front, passing through the vertical midline of each boxed lens aperture, will coincide with this frontal reference plane. Further,

if the horizontal and vertical midlines of the boxed lens aperture of the frame are treated as *vectors*, an equation of the plane of the lens aperture relative to this frontal reference plane can be deduced mathematically[13].

The *position* of the spectacle lens relative to the eye is also typically defined by the *back vertex distance* of the lens, which is the horizontal distance from the apex of the cornea to the back surface of the lens. The previous definition of vertex distance was the longitudinal distance along the line of sight perpendicular to the plane of the frame front to the back surface of the lens. Depending upon the requirements of the lens designer, either of these definitions can be used. The as-worn position is therefore described by three fitting parameters associated with the tilt of the frame and the location of the lens (see Figure 11). Lens designers frequently use definitions for these parameters that are consistent with ISO 13666, a glossary of standardized terminology for spectacle lenses:

— as-worn pantoscopic angle represents the vertical angle between the plane of the frame front and a vertical plane perpendicular to the line of sight in primary gaze, which results from a rotation of the plane of the frame front around the horizontal X-axis.

— face form angle represents the horizontal angle between the horizontal centreline of the lens aperture and the plane of the spectacle front, which results from a rotation of the lens aperture around a "vertical" Y-axis in the plane of the spectacle front.

— back vertex distance represents the longitudinal distance from the apex of the cornea to the back surface of the lens with the line of sight in primary gaze (or, alternatively, perpendicular to the plane of the spectacle front).

PANTOSCOPIC TILT   **FACE-FORM TILT (WRAP)**   **BACK VERTEX DISTANCE**

NOTE   Image by Darryl Meister. Reproduced with permission from Carl Zeiss Vision GmbH, USA.

Figure 11 — Defining the as-worn position

6.5.2   As-worn position and verification power

Spectacle corrections are typically determined using thin refractor-head or trial-frame lenses that are held perpendicular, or nearly so, to the line of sight and centred in front of the eye. The line of sight is therefore coincident with the optical axis of the lens, avoiding any optical effects associated with oblique refraction. The eye care practitioner determines the combination of sphere and cylindrical powers that will neutralize the refractive error of the eye at the plane of the refractor-head or trial-frame lens, roughly 13,5 mm from the apex of the cornea. This represents the *vertex distance during refraction*.

The spectacle wearer, on the other hand, experiences the optics of a spectacle lens with the lens mounted in a frame worn on the face in the *as-worn position*. The orientation of the fitted spectacle lens will typically involve both pantoscopic and face-form tilt relative to the wearer. Additionally, the *vertex distance* of the *fitted* spectacle lens in the as-worn position will often differ from the original refraction vertex distance.

If the orientation of the fitted lens is tilted in the as-worn position, astigmatism due to oblique central refraction will result in a change from the required spherical power and the introduction of

13

unwanted cylindrical power. Additionally, if the position of the fitted lens differs from the refraction vertex distance, a change in effective power due to vertex distance will also result in changes from the required prescription powers. In order to provide the wearer with the intended prescription when actually wearing the spectacle lenses, these prescription changes should be essentially reversed from the original prescription. Neutralizing the optical effects of these prescription changes will require a new, verification power to provide the wearer with the intended power during straight-ahead vision when the lenses are in the as-worn position.

Additional optical effects are associated with the near addition power of multifocal and power-variation lenses in the as-worn position. The near refraction to determine the addition power is conducted using trial lenses that are thin, flat, and centred. Spectacle lenses, on the other hand, have non-negligible thickness and curvature, resulting in potentially significant differences in optical vergence for near objects relative to trial lenses of the same back vertex power. This difference in vergence is referred to as the *near vision effectivity* error. Furthermore, because the near zone of a progressive-power lens is located at a significant distance below the centre of the lens, the line of sight assumes a significant angle of ocular depression while reading. As a result of oblique astigmatism, optical power errors are often produced at this off-axis viewing angle during near vision that will also influence the effective addition power of the lens[14].
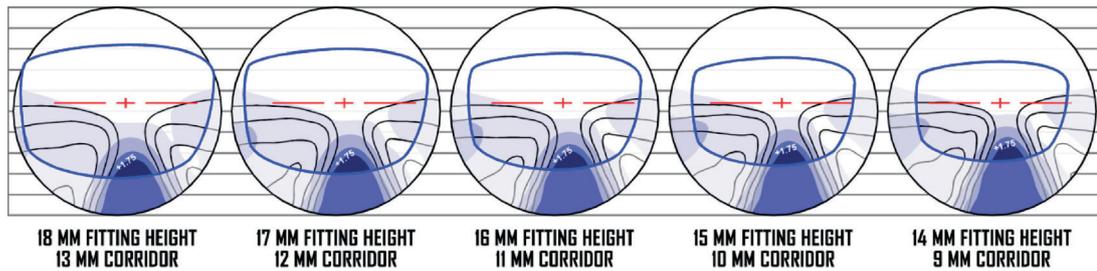
Due to these optical interactions, the addition power of a progressive-power lens will typically differ from the ray-traced or as-worn addition power observed by the actual wearer with the lens in the as-worn position. For free form progressive-power lenses that have been optically optimized for a default as-worn position or customized for the wearer's measured as-worn position, the compensated addition power, provided as the verification addition power or near prescription, can therefore differ from the original near refraction value by a significant amount.

With the introduction of free form lenses, verification power has become increasingly common. For the most advanced free form progressive-power lenses that are optically optimized for an assumed as-worn position, the net optical effect produced by the combination of oblique astigmatism due to off-axis viewing and surface astigmatism due to the progressive-power optics is corrected at numerous points over the lens design by ray tracing the eye-and-lens model. Afterward, the compensated verification and addition powers are calculated at the distance and near reference points of the lens for power verification using a conventional focimeter. The laboratory will then supply these verification values with the free form lenses for correct power verification.

6.6 Customization for the frame size

The optical characteristics of progressive-power lenses are significantly influenced by the length of the progressive-power corridor that connects the distance zone to the near zone. If the corridor is too long for a given frame size, reading utility is reduced, because the lower or whole part of near zone is cut away. If, on the other hand, the corridor is too short, the optics of the lens design must be "compressed." Due to the mathematical constraints of progressive-power surfaces, the rate of change in unwanted astigmatism across a progressive-power lens must increase as the corridor length decreases, resulting in narrower viewing zones and reduced intermediate utility[15].

The corridor length of a progressive-power lens design should therefore be no shorter than necessary, and should place the near zone within the spectacle frame. Nevertheless, the corridor lengths of *standard* progressive-power lenses generally offer insufficient reading utility at shorter fitting heights. *Short-corridor* progressive-power lens designs are frequently designed to work at extremely short fitting heights, often resulting in significant optical compromises in all but the smallest frame styles. Consequently, unless the corridor length of the lens design happens to coincide with the optimal length required by the size of the frame, the wearer must tolerate unnecessary optical compromises and reduced comfort (see Figure 12).

18 MM FITTING HEIGHT 13 MM CORRIDOR | 17 MM FITTING HEIGHT 12 MM CORRIDOR | 16 MM FITTING HEIGHT 11 MM CORRIDOR | 15 MM FITTING HEIGHT 10 MM CORRIDOR | 14 MM FITTING HEIGHT 9 MM CORRIDOR

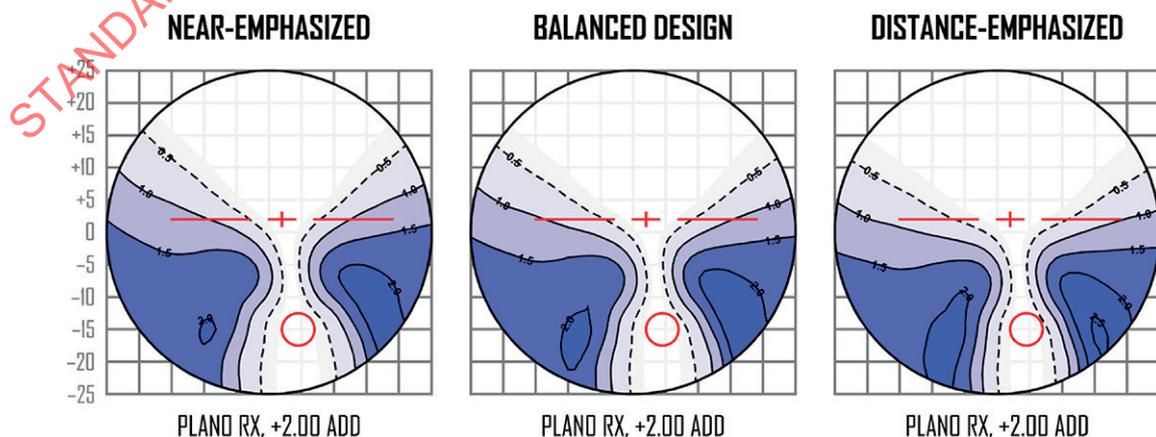NOTE   Image by Darryl Meister. Reproduced with permission from Carl Zeiss Vision GmbH, USA.

Figure 12 — Customization of the corridor length in small increments for the frame size and, hence, fitting height

6.7   Personalization of the lens design

Modern progressive-power lens designs work quite well for the majority of wearers, with acceptance rates of 90 % or more. Nevertheless, the visual requirements of spectacle lens wearers vary from person to person, and it has long been understood that conventional, "one-size-fits-all" progressive-power lenses will not be the ideal solution for *every* progressive-power lens wearer[16]. Yet the constraints of conventional semi-finished lens manufacturing often necessitate the production of progressive-power lens designs that appeal to the broadest class of wearers. For any given wearer, this progressive-power lens design may not provide the optimum balance of distance, intermediate, and near viewing zones or the optimum balance between central viewing zone size and peripheral power gradients.

Furthermore, the lens can be optimized by taking into account individual ocular physiological effects like pupil size, high order aberrations or near-view astigmatism.

In addition to preserving the intended optical lens characteristics, it is also possible to customize the desired characteristics of the lens design for special uses. *Personalizing* the lens design seeks to modify the distribution of addition power and astigmatism in order to provide the individual wearer with the progressive-power lens geometry that is more suitable to his or her particular visual requirements. For instance, several lens manufacturers offer free form progressive-power lenses that have the balance between the central viewing zones alterable based upon the visual lifestyle requirements of the wearer in order to emphasize near vision, distance vision, active vision, or some other viewing task (see Figure 13). It is also possible to alter the balance between the size of the central viewing zones and gradients of power and astigmatism in the lens periphery in order to account for the head-eye movement propensity of the wearer[17]. Furthermore, the position for designated viewing areas can be adjusted by the manufacturer for individual physiological parameters (for example, individual convergence). Additional forms of personalization are also possible.

NEAR-EMPHASIZED | BALANCED DESIGN | DISTANCE-EMPHASIZED

PLANO RX, +2.00 ADD | PLANO RX, +2.00 ADD | PLANO RX, +2.00 ADD

NOTE 1   Power values given in dioptres. Linear dimensions given in millimetres.

NOTE 2   Image by Darryl Meister. Reproduced with permission from Carl Zeiss Vision GmbH, USA.

Figure 13 — Personalization of the lens design depending upon the visual requirements of the wearer

7   Measurement and quality control

7.1   Lens performance

The performance of a lens is a complex interaction between the lens, the eye and the brain of the wearer. Assessment and comparison of performance can only be made with all these aspects taken into account (called wearer tests). Measurement of lenses for specific parameter quantities and the comparison of such data are useful for production process monitoring and control. These data alone however, are usually insufficient to make overall judgments on lens performance.

7.2   Conformity with standards

Free form is just a new process for lens manufacturing. Consequently, there is no need to change the relevant standards. The conformity to standards (including tolerances) has to be performed as for any other lens, with focimeters (complying with ISO 8598-1) at the specified reference points. The control of the conformity confirms that the lenses delivered to the customer conform to the order.

For verification of conformity to standards and to ensure proper mounting in the cases where specific compensations have been made during product manufacture, such as compensating for positional influences of a lens in the as-worn position, it is necessary to provide the verification powers (calculated by the manufacturer), in addition to the ordered powers and the ordered parameters.

As it is not possible to measure the power in the as-worn position with current focimeter technology, compensated values should be provided. The requirements and tolerances in the relevant standards are then applied to the variation between the actual measured values and the verification power supplied.

Measurement and verification should be made only with respect to the reference points obtained from the permanent alignment reference marks as specified by the manufacturer. These positions should not be determined automatically by the measurement instrument based on the measured power distribution. The criteria used by such instruments may not necessarily reflect the design criteria used by the manufacturer. Furthermore, optical defects can influence the results of such automatic algorithms.

It is important to remember even for normal focimeter use, the following factors and their effect on results need to be considered:

— back vertex power measurement versus front vertex power measurement;

— instrument design type, i.e. Infinite on Axis (IOA) or Focal point on Axis (FOA);

— measurement aperture and design.

For more details, see Annex B, ISO/TR 28980 and ISO 8598-1.

Other properties of the lens such as transmittance, material index, thickness, etc. can be measured, but are not relevant to this document.

7.3 Design integrity and process control

7.3.1 General

As explained in Table 2, with free form processing, a part or all the responsibility for the design integrity is given to the surfacing laboratory. Consequently, the lens designer has to give the surfacing laboratory the tools to assume this responsibility.

Therefore, specific process controls have been developed and remain proprietary, but they are all based on the same principle, i.e. comparison between the actual lens and the target at multiple points.

Two main approaches exist today:

— surface shape measurement, see 7.3.2;

— through power measurement (i.e. by transmission, or refractive power), see 7.3.3.

7.3.2 Surface shape measurement

For surface topography measurement and interpretation, there is a requirement for extreme instrument accuracy and a thorough understanding of the computation of measured data.

The measurement of the lens surfaces allows a comparison between the intended and the produced surfaces. This data can indicate surface irregularities that are likely to impact on the lens's optics but these data alone are unable to "quantify" the effects on optical characteristics.

Coordinate machine measurements of a surface topography show the deviation from the surface design data over the entire lens diameter.

Surface measurements performed optically (e.g. deflectometry) are sensitive to small local variations of optical properties.

For more details, refer to B.1.

7.3.3 Through power measurement

Two approaches are used today:

a) Discrete point measurement by instruments and methodology as defined in ISO 8598-1 to satisfy the requirements of ISO 21987, ISO 8980-1 and ISO 8980-2.

   As mentioned in 7.2, the same limitations and influences have to be considered (refer to B.2 and ISO/TR 28980).

b) Global transmission measurement to create global power distribution maps.

Instruments which are able to show a distribution of optical properties across an extended portion or possibly the whole lens are often referred to as transmission mapping devices.

Transmission mapping devices[18] show the deviation between the optical properties of the manufactured lens and of the target (power error maps). On the error maps, patterns specific to defects are visible, such as centre dot or rings which come from the spiral surface generating lathe process (locus at centre results in a dot while further out in the spiral results in a ring). From the error maps, different criteria are calculated and the tolerances are defined by the manufacturer. A trouble shooting routine is proposed to the laboratory to correct the process if the deviation is out of tolerance. The selection of the measured criteria, the definition of the tolerances and the troubleshooting are proprietary.

Consequently, these devices enable the laboratory to control the process by checking indirectly the manufactured surface since they do not measure the surface directly.

Moreover, these devices cannot be used to compare products because the power they deliver significantly depends on the kind and direction of the incoming wavefront. Therefore the results of measurements with different devices differ from each other and also from the power in the as-worn position. This could lead to confusion or misinterpretation of measuring results.

7.4 Measuring the as-worn position

The prescription powers of spectacle lenses are typically verified using a *focimeter*, such as a lensometer or automatic lensmeter. Focimeters measure the focus of a spectacle lens while holding the centre of the lens flat against the lens support of the instrument, which ensures that the optical axis of the lens coincides, or very nearly coincides, with the optical axis of the instrument in the absence of prism (see Figure 14)[19].
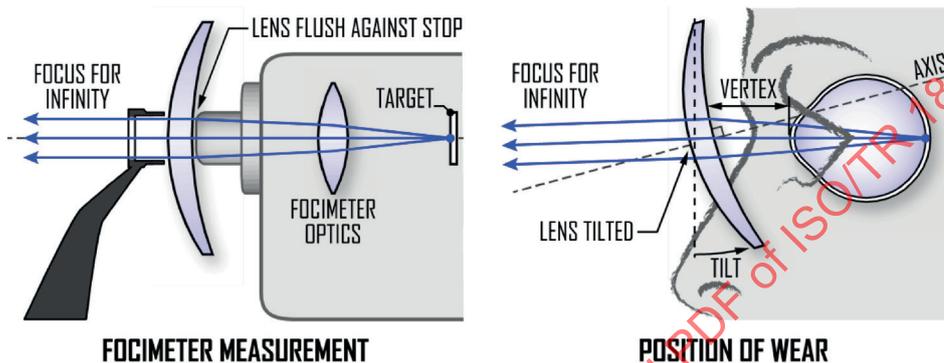
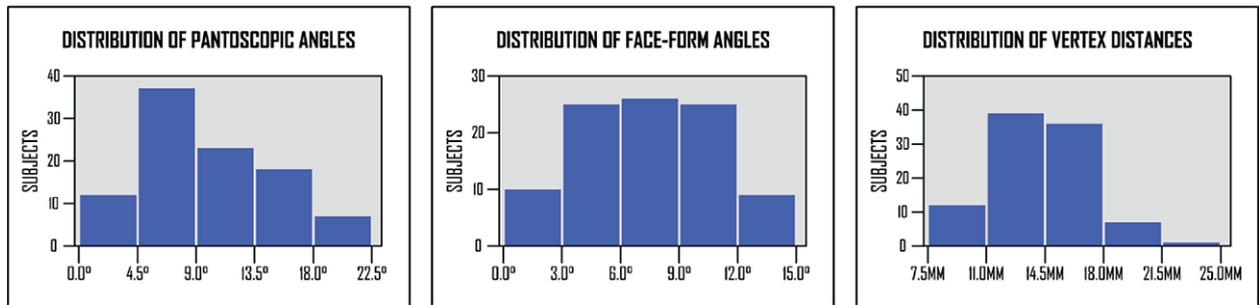NOTE   Image by Darryl Meister. Reproduced with permission from Carl Zeiss Vision GmbH, USA.

Figure 14 — Comparison of the lens position during measurement on a focimeter with that in the as-worn position

A focimeter therefore closely replicates the measurement conditions associated with the original refraction using trial lenses, in which the optical axis is collinear with the line of sight. Hence, spectacle lenses have conventionally been designed and fabricated to provide the correct power readings for a focimeter, not necessarily for the actual spectacle wearer, under the assumption that the results would be consistent with the original refraction values.

When the powers of a spectacle lens have been compensated for the as-worn position, however, legitimate differences should now be expected between the fabricated lens powers measured in a focimeter and the original power values. When evaluating optical characteristics against industry standards such as ANSI Z80.1[20], ISO 8980-2 and ISO 21987, the powers of the spectacle lens should be verified against the verification powers when these have been supplied. A spectacle lens that exhibits the correct verification power (including the addition power) in a focimeter will provide the actual wearer with the correct ordered or prescribed powers once the lens is in the as-worn position that was specified on the order.

Figure 15, from one study[21] with a digital dispensing measuring equipment (*n* = 100), shows that the as-worn position of the fitted spectacle frame can vary significantly from frame to frame and from wearer to wearer. Indeed, the range of possible measurement values associated with each fitting parameter underscores the potential importance and benefits of customizing the lens design for the as-worn position.

Because frame adjustments will influence the as-worn position, the frame should, of course, be properly fitted to the wearer prior to any measurements.

NOTE   Image by Darryl Meister. Reproduced with permission from Carl Zeiss Vision GmbH, USA.

Figure 15 — Variation of the parameters of the as-worn position of the fitted spectacle frame

Face-form angle or "wrap" is often measured independently of the wearer using an inexpensive protractor (see Figure 16). The horizontal angle formed between the horizontal midline of the lens aperture and the plane of the spectacle front is determined by measuring the angle that a line joining the nasal and temporal edges of the lens box across the midline makes with a plane parallel to the spectacle front. The lower edge of the frame front should be held directly over the upper rim to eliminate the influence of any vertical tilt on the face-form angle measurement. The face-form angle should also be verified on the wearer in order to ensure that the spectacle front does not exhibit unwanted *bowing* as a result of the forces exerted between the skull and the frame sides (temples). Many three-dimensional electronic frame tracers measure the face-form angle of the frame. Some of the modern digital dispensing measuring equipment also captures the face-form angle of the frame in the as-worn position.
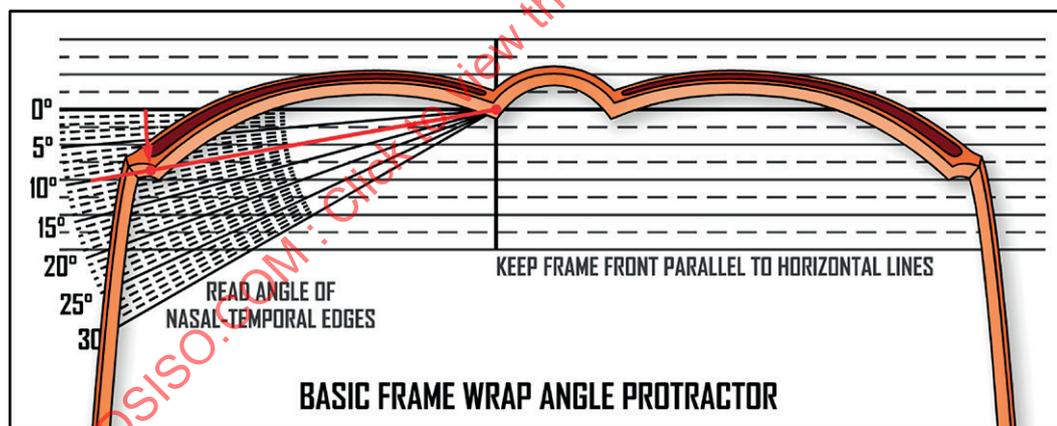
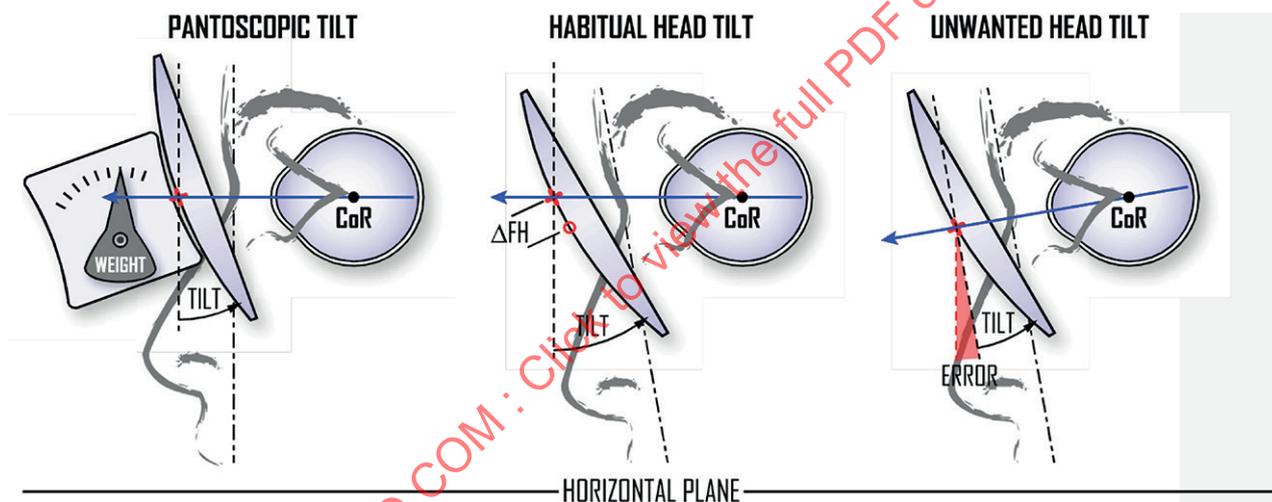NOTE   Image by Darryl Meister. Reproduced with permission from Carl Zeiss Vision GmbH, USA.

Figure 16 — Measurement of the face-form angle using a simple "wrap protractor"

Since it is assumed that primary gaze is parallel to the ground, the force of gravity is often used to measure the as-worn pantoscopic angle of the frame on the wearer by determining the vertical angle between the plane of the spectacle front and the frontal plane that is orthogonal to the line of sight. Using an inclinometer or similar tool that makes use of a plumb line or spirit level, the vertical plane perpendicular to the ground is determined using gravity, while the tool is positioned against the upper and lower rims of the frame or the dummy or demonstration lens at the vertical midline of the lens aperture. Note that this angle will generally not be equal to the angle of side or frame pantoscopic angle (i.e. the angle between the plane of the spectacle front relative to the centreline of the sides), because the as-worn pantoscopic angle will vary with the fit of the frame on the wearer. Some digital dispensing measuring equipment can also capture the as-worn pantoscopic angle using edge detection algorithms, registration markers mounted to the frame, or other methods. The measurement of the as-worn pantoscopic angle will be sensitive to the tilt of the head, whether habitual or random. Although the

plane that is perpendicular to the line of sight in primary gaze will often be parallel to the frontal plane of the skull, this may not necessarily be the case when the wearer has a habitual head tilt. Consequently, the as-worn pantoscopic angle is not necessarily associated with the plane of face, if the person has a *habitual* head tilt. Figure 17 illustrates measurement by positioning an inclinometer against the vertical centreline of the boxed lens aperture. If there is an habitual head tilt, as shown in the central diagram, then there will be a valid change in pantoscopic angle, although the fitting height will need to be modified accordingly to maintain the fitting point at the line of sight (by ΔFH). However, if the person exhibits *unwanted* head tilt during the measurement, as the result of a random or atypical postural adjustment, this will result in an error in the measured angle. See the right-hand diagram in Figure 17.

Therefore, when measuring the as-worn pantoscopic angle, the following recommendations should be met.

— The wearer should be looking straight ahead, preferably fixating a distant object at the correct height, in order to ensure that the line of sight remains in primary gaze, parallel to the ground.

— The spectacle frame should be correctly adjusted to fit the face so that the fitting point of the lens to be ordered will aligned properly with the centre of the wearer's pupil to ensure that the line of sight intersects the fitting point of the mounted lens during primary gaze.

— The wearer should assume his or her habitual posture, while minimizing any unwanted head tilt, in order to arrive at a truly representative measurement of the as-worn pantoscopic angle.

Key

CoR   ocular centre of rotation

NOTE   Image by Darryl Meister. Reproduced with permission from Carl Zeiss Vision GmbH, USA.

Figure 17 — Measuring the as-worn position

The back vertex distance is frequently measured manually using a ruler, pupilometer (held against the side of the face and spectacles), vertex distance gauge, or other tool to determine the distance from the apex of the cornea to the back surface of the dummy lens.

Thus the vertex distance is measured with the line of sight intersecting the intended location of the fitting point when the wearer is looking straight ahead. Because of the previous definition of vertex distance being the distance from the cornea measured perpendicular to the back surface of the lens, the lens manufacturer should be consulted when in doubt regarding which measurement method to use for a given lens design. As with face-form and as-worn pantoscopic angles, some digital dispensing measuring equipment can also capture the back vertex distance. Note that, depending upon the specific surface design calculations, the final lens surface produced may not be located precisely at the measured vertex distance, once the finished lens has been mounted in the frame.

7.5   Inspection gates of the manufacturing process

Measurement and control may occur at the following inspection gates during the manufacturing process using various types of instruments (see Table 3).

Table 3 — Typical inspection gates of the manufacturing process

Mould/Semi finished lens blank	Cutting	Polishing	Finished lens
Inspection: — Local curvature measurement — Surface	Inspection: — Surface for the purpose of process (grinding) control	Inspection: — Surface for the purpose of process and quality control (pass/fail) — Through power for the purpose of quality control (pass/fail)	Inspection: — Through power (D) for the purpose of quality control (pass/fail), mix ups, deformation, cosmetics, edging and mounting — Global transmission power measurements
Instruments/methods used: — Focimeter by reflection — Coordinate measuring machine (CMM) — Deflectometry	Instruments/methods used: — Coordinate measuring machine (CMM)	Instruments/methods used: — Coordinate measuring machine (CMM) — Deflectometry — Focimeter by reflection	Instruments/methods used: — Deflectometry — Conventional focimeter — Cosmetic inspection station
Result: — Local surface power — Topography map $Z(x, y)$ — Surface slope map $dX(x, y)$, $dY(x, y)$	*Result:* — Topography map $Z(x, y)$	*Result:* — Topography map $Z(x, y)$ — Surface slope map $dX(x, y)$, $dY(x, y)$ — Through power map "D"(x, y) — Local through power [D]	*Result:* — Through power map "D"(x, y) — Local through power [D]

Annex A
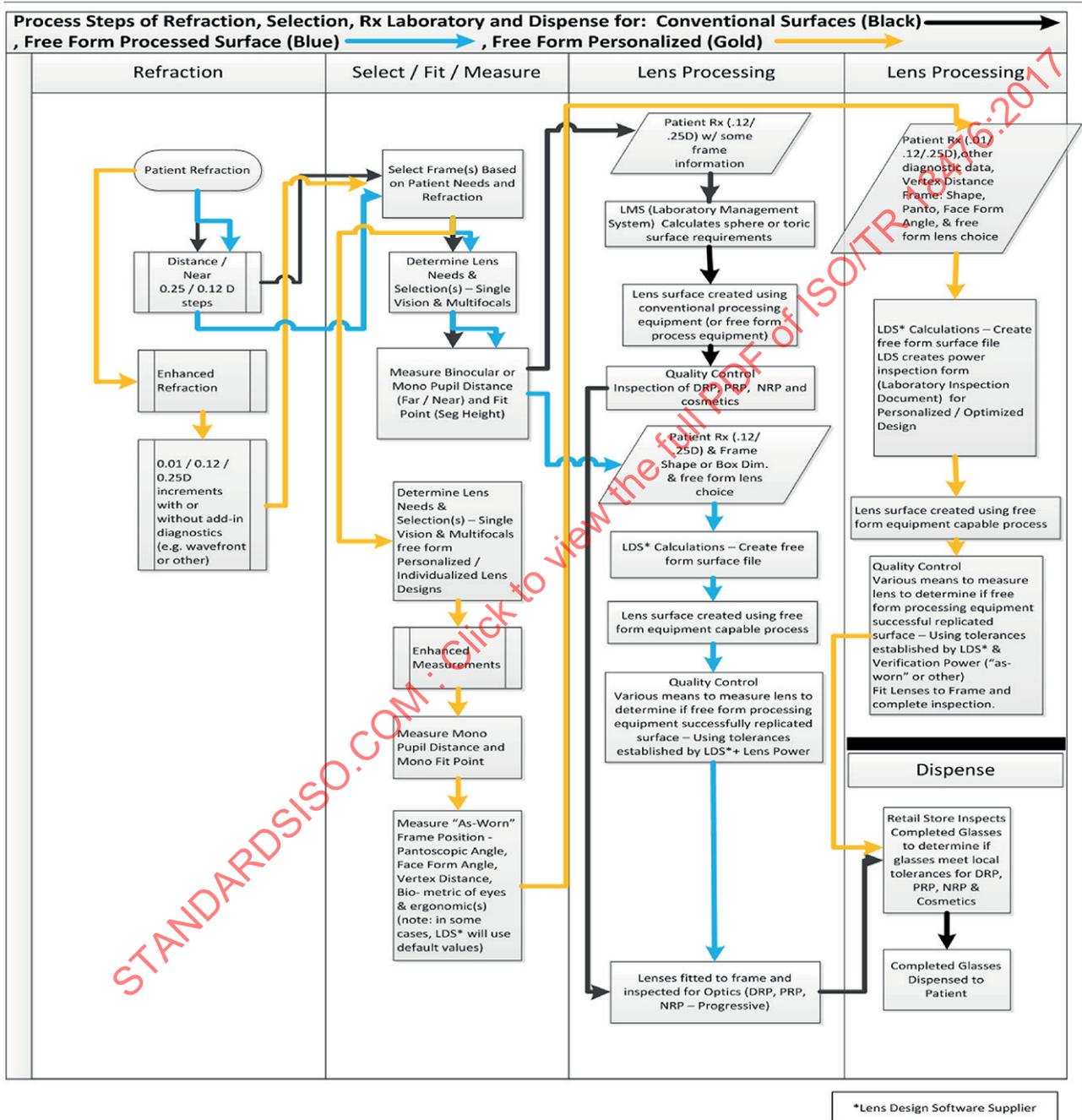## (informative)

Typical dispensing flowchart

Figure A.1 — Typical flowchart including refraction, dispensing and manufacturing

Annex B
(informative)

Measurement technology

B.1 Surface shape measurements

B.1.1 General

For a free form lens, manufacturers calculate an individual surface topography and translate it into a format suitable for generators and polishers. Such surface topography can be expressed in terms of x, y, z.

The requirements on measuring surface topographies are:

— topography in terms of x, y, z;

— max. slope on surface 45°;

— accuracy in x, $y \leq 1$ µm, in $z \leq 0,7$ µm;

— surface quality: milled, turned, polished;

— applicable on all lens materials, organic and mineral;

— actual to target value comparison;

— determination and control of tooling and machine parameters.

B.1.2 Measurements by means of coordinate measuring machines

For decades, the accurate measurement of surface topography has been done by means of coordinate measuring machines (CMM) (see Figure B.1) While touching the surface with a stylus mechanically or probing optically by means of an, e.g. confocal sensor, the machine records its position in x, y, z.
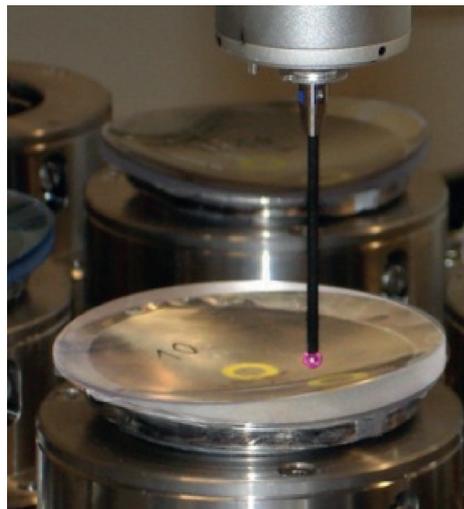

Figure B.1 — Stylus of a CMM touching the lens sample

The characteristics, pros and cons and challenges with measurement by CMM are summarized in Table B.1.

Table B.1 — Summary of characteristics, pros and cons and challenges with measurement by CMM

Characteristics and pros:	— Well established
	— High accuracy
	— (Almost) independent of the material to be measured
	— Independent of the surface quality
	— (Almost) direct actual to target value comparison
Cons:	— Measurement time up to hours (dependent on number of points)
	— Investment
	— Robustness (environmental conditions)
	— Due to contact by the stylus, polished lenses might be damaged
Challenges	a) Measurement tells us only the coordinates of the black dots and every dot has its inherent measurement errors (in x, y, z). There is no real information about the surface between the dots.
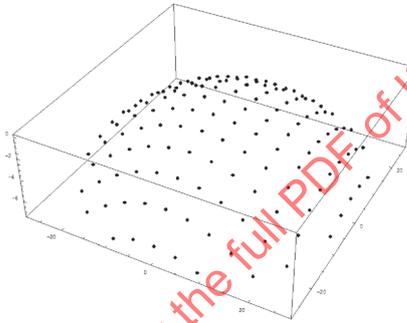
Figure B.2 — Point cloud from CMM measurement

b) Impact of topography deviations on the optical effects imposed on the wearer is a very complex one.

For example, see the two trivial cases in Figures B.3 and B.4, where difference to design, in millimetres, is shown.

Dimensions in millimetres
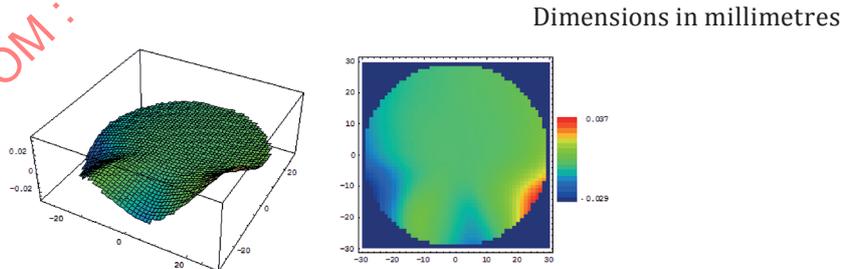
Figure B.3 — Rotated during measurement by only 1°

Dimensions in millimetres
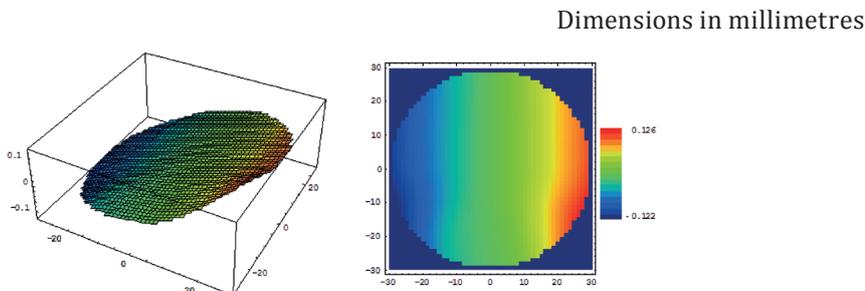
Figure B.4 — Rotated during measurement by only 1° + tilt of 0,1 mm

c) Any positional error of the whole surface (e.g. caused by clamping error during measurement) has to be compensated.