

# Easy-to-use software tools for teaching the basics, design and applications of optical components and systems

Christoph Gerhard\*<sup>a</sup>, Geoff Adams<sup>b</sup>

<sup>a</sup>HAWK - University of Applied Sciences and Arts, Faculty of Natural Sciences and Technology, Von-Ossietzky-Straße 99, 37085 Göttingen, Germany; <sup>b</sup>Optical Software Company, Rothsay, Western Road, Shoreham, BN43 5WD, United Kingdom

## ABSTRACT

Geometric optics is at the heart of optics teaching. Some of us may remember using pins and string to test the simple lens equation at school. Matters get more complex at undergraduate/postgraduate levels as we are introduced to paraxial rays, real rays, wavefronts, aberration theory and much more. Software is essential for the later stages, and the right software can profitably be used even at school. We present two free PC programs, which have been widely used in optics teaching, and have been further developed in close cooperation with lecturers/professors in order to address the current content of the curricula for optics, photonics and lasers in higher education.

PreDesigner is a single thin lens modeller. It illustrates the simple lens law with construction rays and then allows the user to include field size and aperture. Sliders can be used to adjust key values with instant graphical feedback. This tool thus represents a helpful teaching medium for the visualization of basic interrelations in optics.

WinLens3DBasic can model multiple thin or thick lenses with real glasses. It shows the system focii, principal planes, nodal points, gives paraxial ray trace values, details the Seidel aberrations, offers real ray tracing and many forms of analysis. It is simple to reverse lenses and model tilts and decenters. This tool therefore provides a good base for learning lens design fundamentals. Much work has been put into offering these features in ways that are easy to use, and offer opportunities to enhance the student's background understanding.

**Keywords:** educational software, geometric optics, lens equation, basics of optical imaging, visualisation of aberrations, optical system design

## 1. INTRODUCTION

Geometric optics is a key component of several quite different curricula involving optics and photonics. For example, the basics and principles are taught in vocational training schools during the education of skilled labourers, technicians and engineers. At degree level and higher, more advanced geometric optics topics, such as aberration theory, can be important in fields as diverse as pure physics, optical electrical or mechanical engineering, laser sciences, biophotonics, and medical engineering. In addition, a number of upgrade training courses for further education of specialised personnel are offered by commercial institutions and academies.

In this context, appropriate software tools are very useful, even essential, for assisting the basic understanding of optical imaging, the impact of aberrations and the interpretation of the imaging performance of any optical component or system as well as for visualising the various relationships that are key to understanding optical imaging.

At the most basic level - what is known as the thin lens model - a student may wish to know the magnification, image size and distance for an object viewed through a lens of given focal length, without knowing exact design details. These values are connected by simple equations, and it transpires that setting any three of these parameters determines the rest. Even here some permutations can be tricky to solve - cases involving a fixed track [object to image distance] length for instance. The student may then want to alter these parameter values to see the consequences and get a real feel for how they interact. Software which allows the user to change parameters easily, does the repetitious calculations involved and clearly presents the results with real time and even interactive graphics is a valuable pedagogic tool.

\*christoph.gerhard@hawk-hhg.de; phone +49 551 3705 376; hawk-hhg.de

At the next level, the student may want to understand the impact of a finite waveband, e.g. white light as opposed to a laser line. Since the focal length of a lens will vary with wavelength, there are variations in the image distance and size, known as chromatic aberrations. These aberrations are nonlinearly dependant, on the dispersion characteristics of the bulk materials in the lens; the characteristics being described by polynomials with six or more coefficients. Of course, a respectable approximation can be obtained simply knowing the refractive index and dispersion at the middle of the waveband. To model full chromatic effects properly requires non trivial calculations and exact knowledge of the properties of the optical materials - something that software makes viable, especially when rapidly changing glasses.

Such tools can further facilitate the identification and evaluation of a suitable optical system for a given imaging task. Subsequently, the most suitable optical system for the given imaging task (e.g. a single lens, a triplet, a Gauss lens etc.) can be chosen on the basis of theoretical considerations such as the image field diameter-numerical aperture plot as suggested by Towner [1] or the aperture-field plot [2] as provided in PreDesigner.

So far, perfect imaging has been assumed, i.e. a point object has a point image, irrespective of lens f-number. However to any serious camera user, let alone an optical engineer, this is clearly a poor assumption, since it is well known that performance drops off as the aperture is opened due to aberrations such as spherical aberration, coma, astigmatism and field curvature, whilst distortion impact the geometric 'shape' of the image.

Seidel theory provides a reasonable approximation to the size of these aberrations and gives a good conceptual basis to understand what they are and where they arise in a real system. Unfortunately these calculations are non trivial, requiring significant amounts of time if done by hand, even for a simple lens such as an air spaced triplet at one wavelength - the calculations needing to be repeated afresh for multi-wavelength analysis. So again suitable software will take the load enabling the student to make and assess multiple design changes without wasting much time.

For a complete system analysis, there is no substitute for tracing many real rays from many objects points, sampling the lens aperture and thus assessing the image formation quality. A step further on takes into account diffraction effects. This level of analysis would be extremely difficult if attempted manually for any but the simplest mirror system - so efficient software is essential for such calculations, both after any design change and also to offer a range of analysis tools to display the optical effects in ways that provide clear insight.

Given this background we present two free PC programs which address two complimentary sides of teaching geometric optics. PreDesigner is a simple single thin lens modeller, requiring no detailed design information, but providing clear information on the conjugates and field sizes for a conventional light source and for a laser beam - the most fundamental stage of optical engineering. By contrast, WinLens3D Basic is a potent optical design package modelling significant real systems. Over the years, much thought has been put into developing friendly tools for handling 'simple' design tasks, displaying Seidel aberrations and real ray data - all with the aim of assisting those teaching or learning optics.

## **2. PREDESIGNER: SINGLE THIN LENS MODELING**

PreDesigner is an easy-to-use tool for those working with basic geometric optics and laser beam propagation. Starting with geometric optics - at the paraxial level, any compound lens can be reduced to a single thin lens of the same focal length. For a given object, the image location and size are then given by the simple lens equation and magnification. These and other paraxial values, including aperture are displayed in a table and in a drawing. As shown in figure 1, the user can change the key values via text box, slider or by dragging in the drawing - the results being updated immediately.

Different permutations of the key parameter types can be chosen to suit the task in hand, and helpful popup lists of quantities such as image sizes for known sensors and standard f/numbers will 'deliver' the correct values without mistake. The user can choose to model a lens or a mirror, and there are many other nice features and options. Non zero principle plane separation can be defined. Virtual images are clearly shown and impossible cases, for example where the user specifies a lens with a given focal length and a track that is too small, are handled gracefully. PreDesigner also provides an interactive aperture-field plot in the paraxial mode in order to facilitate the choice of an appropriate optical system. The expanded version of this plot even shows typical lens systems for different regions.

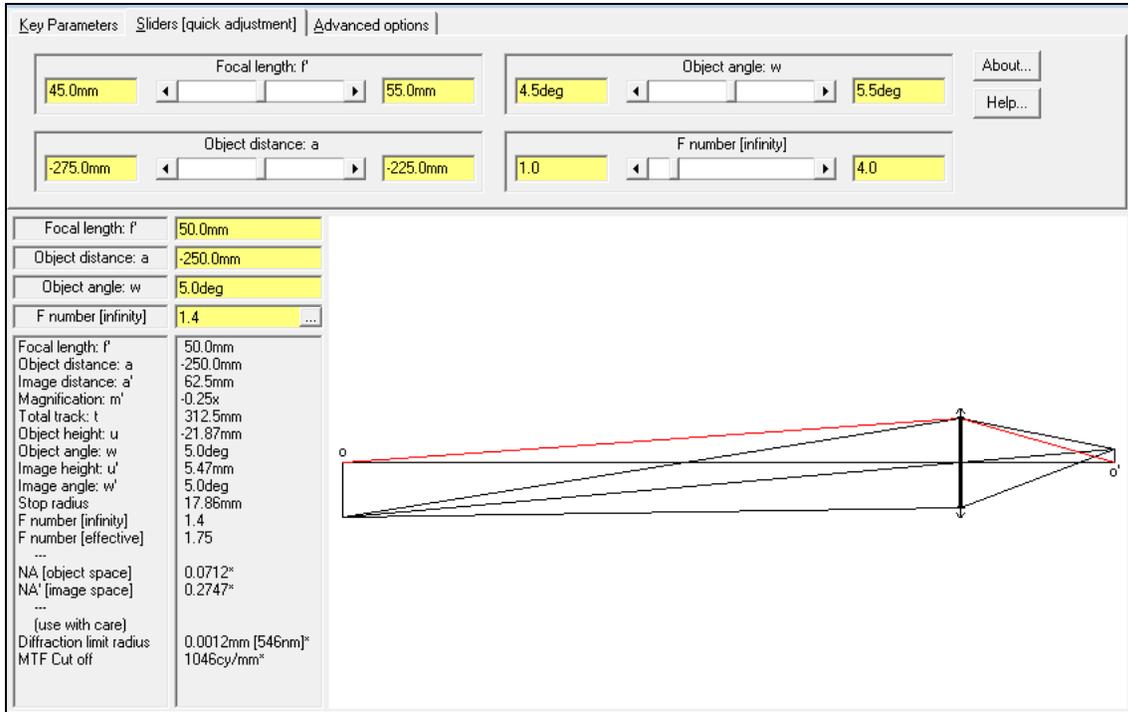


Figure 1. Paraxial thin lens analysis in PreDesigner, showing sliders for quick key parameter adjustment

As an example, consider the case where there is an object with a height of  $u = 175$  mm, at a distance of  $a = -1,000$  mm is to be imaged on a  $2/3''$  detector, i.e. an image height of  $u' = -5.5$  mm.

The three conjugate and field values set the other parameters, such as the focal length  $f'$  and the image distance  $a'$ . The magnification  $m$ , is given by simple equation:

$$m = \frac{u'}{u} = \frac{a'}{a}, \quad (1)$$

The magnification is therefore is approximately  $-0.0314$ , and the focal length  $f' \approx 30.5$  mm, as can be shown using:

$$f' = \frac{a}{\left(1 - \frac{1}{m}\right)}. \quad (2)$$

Reusing equation (1), the image distance  $a'$  is then approx. 31.4 mm. By applying such simple equations, a number of dependant parameters such as the object and image angle,  $w$  and  $w'$ , and the total track (object-image distance),  $t = a + a'$  can also be determined. This seems trivial, but other cases are not. Moreover manually re-running the calculations to show the effects of many changes in object or focal length would become tedious very quickly. PreDesigner takes away the calculation overhead. So using the sliders to make continual adjustments allows the student to get an instinctive feel for how the image distance or track would change as the object distance is altered, or the impact of requiring a fixed track, or other such situations.

As noted above, PreDesigner can help suggest the type of lens needed in a given situation. Once an aperture size or f/number is defined, then the field angle/aperture plot becomes available. This shows the location current 'design' - given by red cross hairs - in the sea of islands of standard solution families. So for the case above, and an aperture of  $f/3.5$ , shown in fig 2, a simple triplet is indicated.

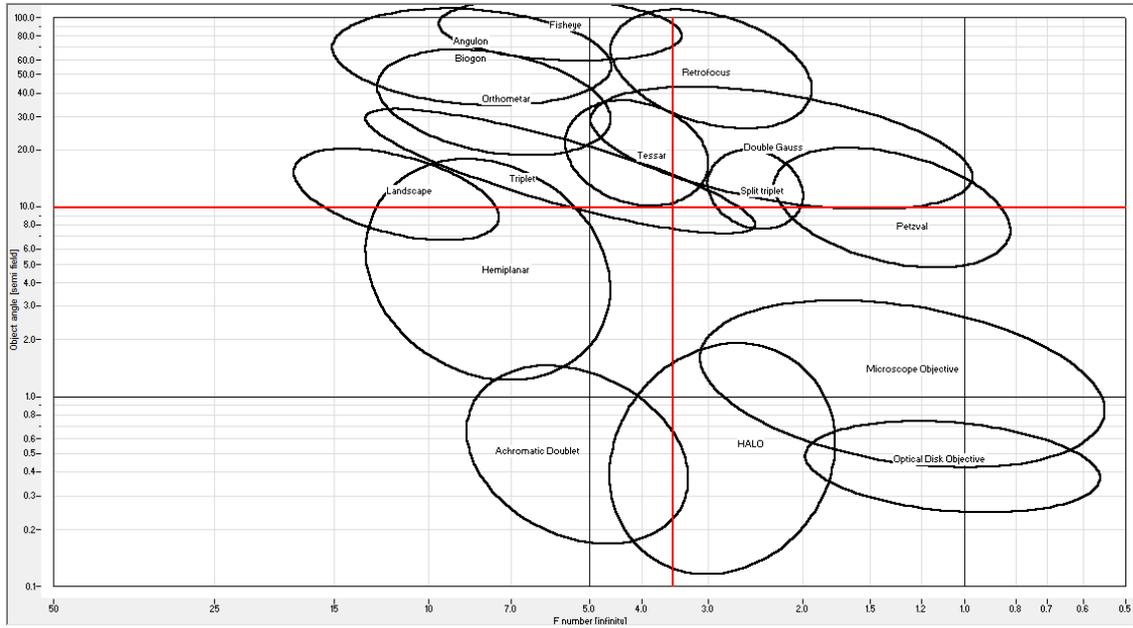


Figure 2.  $f/\#$  vs. field angle for solution, showing different lens families

When dealing with a laser or Gaussian beam, the key parameters are somewhat different from those used in geometric optics and the basic equations governing beam waist size, location and divergence are more complex. When modelling a Gaussian beam source, the beam diverges from a waist inside the laser case and is focused by the lens into image space, where another waist is formed. The location of the waist may be the same as the geometric optics image or it may be quite different - depending upon the beam properties.

PreDesigner, in Gaussian mode, offers a new range of key parameters, to suite the task in hand as shown in figure 3. All beam parameters are displayed in a table and the beam profile is shown in the drawing, along with other sub plots of interest. When selecting the laser wavelength a popup list of key laser and spectral values is at hand. Using this popup helps ensure the correct wavelength value is entered.

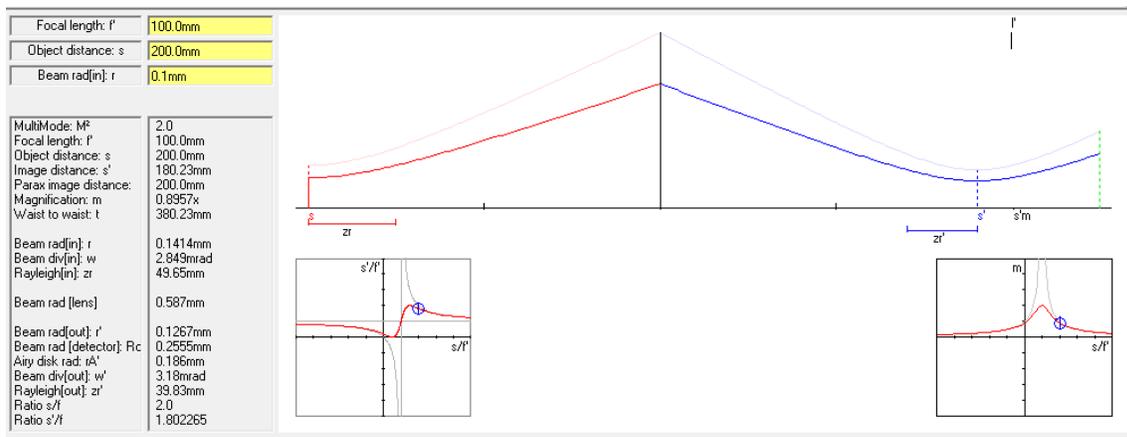


Figure 3. Laser mode: Gaussian beam profile and beam propagation factor effect

The beam propagation factor  $M^2$  of a laser beam can also be considered, shown by the fainter beam profile in figure 3. By default, the laser is assumed to have a circularly symmetric beam, but diode lasers with rectangular symmetry can easily be modelled. Different beam characteristics for the two cross sections can be specified, data for both is tabulated and the graphics are doubled. There are other interesting features that will be of use to teachers, students and engineers alike.

Thus far only conceptual lenses with perfect imagery have been considered. However, the second software tool allows users to setup and analyse the imaging performance and optical aberrations of real systems.

### 3. WINLENS3D BASIC: RAYTRACING AND SYSTEM ANALYSIS

The ray tracing and system analysis software WinLens3DBasic is a powerful tool for the simulation of either on-axis or folded optical systems. It offers a simple and easy-to-use menu structure, spreadsheet editors, a toolbar for quick access to the features, multiple resizable graphs and tables for results, which are updated in real time when applying any change to the current optical system, as well as a full windows help with extensive background notes on optics.

After entering the given parameters and conjugate values (determined with the aid of the above-mentioned PreDesigner tool) in the System Parameter Editor, optical systems can easily be setup using different methods. First, different components types, i.e. thin lenses, thick lenses, mirrors, blocks, prisms and coordinate breaks can be inserted into the System Data Editor by a simple drag and drop function. Each new component is then specified in more detail by entering the appropriate parameters, e.g. lens surface forms (spherical, aspherical, cylindrical etc.), radii of curvature, aperture, thickness, diameter and material, or the prism type and key dimensions and material etc.

The second option for adding optical components is via the integrated lens database which includes all sorts of spherical and cylindrical lenses, cemented and air-spaced achromats as well as laser monochromats. The required components with predefined design data can be found easily with the database's search function. Prisms and wedges are notoriously tricky to setup. However in WinLens3D they can be dragged in from a prism database containing many standard prism types, or created using an easy prism wizard. Another database provides a number of diffraction gratings.

Once created or inserted, a component can be easily modified manually or via temporarily assigned sliders, while materials can be changed by tapping on the interactive glass map, dragging from the glass database or using the glass search function.

More complex optical systems can be taken from the lens library - a separate free database. The library contains a number of system files ready for use in WinLens3DBasic such as aspheres, ball lenses, beam expanders, condenser systems, eyepieces, microscopic lenses, HALOs (high aperture laser objectives), double Gauss lenses, Petzval lenses, retrofocus lenses, scan lenses, split triplets, tele lenses, telecentric lenses, telescopes, Tessars, triplets, and zoom lenses. Finally, existing optical designs can be imported from and exported to other lens design software, e.g. Zemax or Code V. While the optical system being built or edited, the design and set of rays can be displayed in the lens drawing as shown in figure 4.

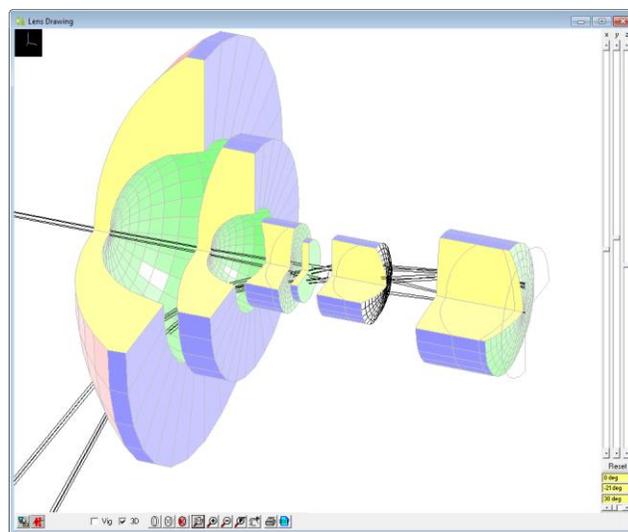


Figure 4. Lens drawing in WinLens3D Basic - 3D mode

A lens drawing, while informative, does not offer qualitative information. So the drawing can be supplemented by a whole range of tables and graphs such as surface by surface design data, paraxial values and rays, Seidel aberrations and Seidel surface contributions, optical path difference (OPD), field aberrations (i.e. astigmatism, distortion and colour), longitudinal aberrations, transverse ray aberrations (TRA), the modulation transfer function (MTF), chromatic aberration, full field distortion, 3D wavefront plots and more. Engineering tasks such as edge thickness calculations and transmission losses, including polarisation effects, can be modelled. Figure 5 shows a selection of these diagrams.

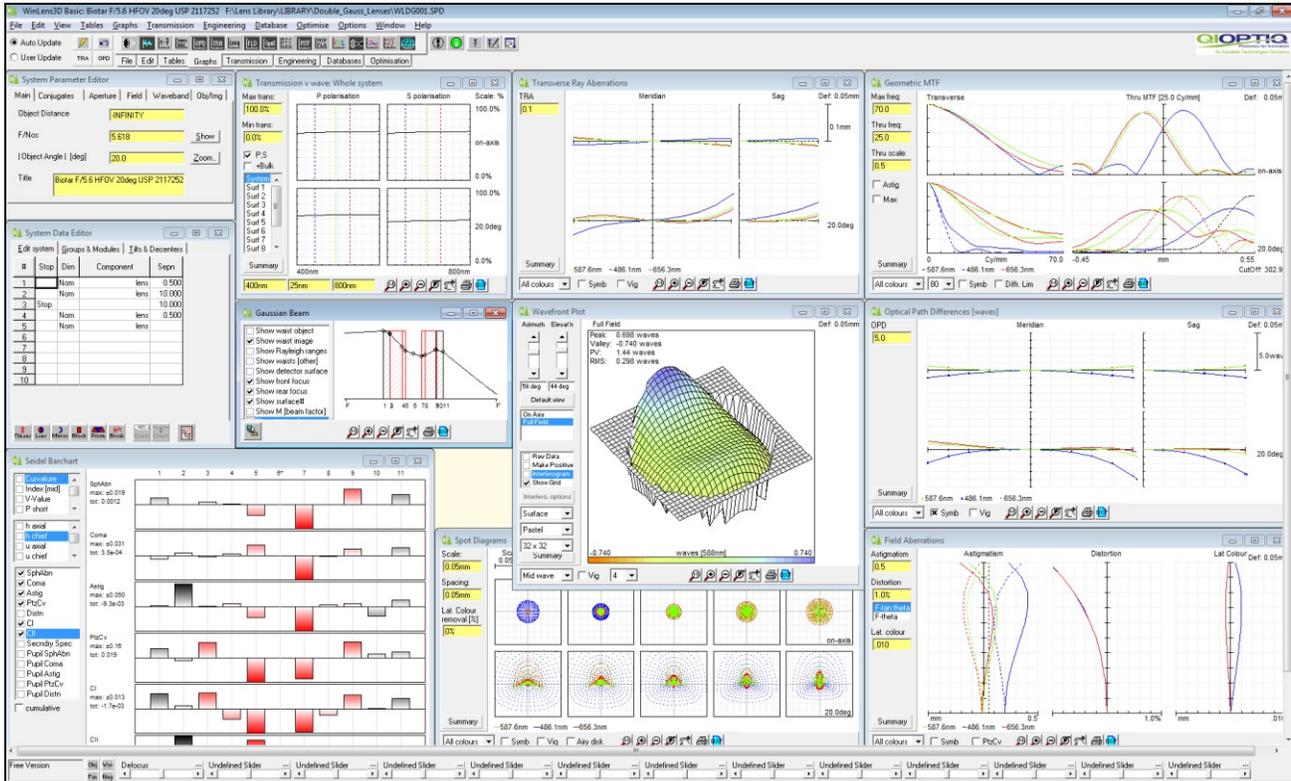


Figure 5. Some of the available diagrams showing system performance: Seidels, OPD, TRA, MTF, wavefront and more

For laser beam analysis, WinLens3DBasic also provides a Gaussian beam table and graph showing the resulting beam waist radii and Rayleigh lengths. The graphs (and the lens drawing) are zoom friendly, showing one, some or all zooms, overlaid in separate frames. Multiple copies of most graphs and tables can be created, while individual graphs or tables can be frozen to provide an audit trail. All these capabilities positively encourage the visualisation of the dependency of aberrations on the materials, orientations and surface forms of optical components and systems in real time and are thus very useful in teaching optics.

Finally WinLens3D offers a powerful tilt and decenter capability. This makes it easy to model folded systems. It is also easy to rotate whole components without changing the global location of subsequent elements (if so desired) - which is helpful when assessing manufacturing errors (tolerancing) and also when demonstrating the importance of proper alignment of optical setups used in practical training in educational labs.

#### 4. SUMMARY

Two free programs have been presented. These provide valuable aids to those teaching and learning geometric optics, both at a simple level and for degree, postgraduate and professional training. With the programs, users can gain insight into basic principles and attempt typical design tasks using optical components and systems. PreDesigner is valuable in that initial 'back of envelope' situation when gaining insight into a design task, showing what key values - focal length, conjugate and field sizes - may be required. Moving into actual design and analysis, WinLens3D Basic makes it easy to

build up and 'edit' systems from different types of components, and to apply tilts and decenters if so needed. Various well planned tools - graphs and tables - enable the user to inspect the optical imaging in these real systems and help elucidate the quantities and causes of the various aberrations.

Both tools are free of charge and can be downloaded from [www.winlens.de](http://www.winlens.de), where further information and manuals can also be found. Tutorials and commented screen casts on how to use the programs are further provided on [www.opticalsoftware.net](http://www.opticalsoftware.net). PreDesigner is also available as a free app for Android mobile phones and tablets and can be found in the Google play store - though this version does not include Gaussian beam tools. Additional discussions on the software, including theory, and some specific applications such as the ray tracing of spectrometers or the design of achromatic lenses is found in [3-13].

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