GHOST IMAGE ANALYSIS FOR OPTICAL SYSTEMS

By

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DEDICATION

To my parents and my sons: Karim and Ramy
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ABSTRACT

Ghost images are caused by the inter-reflections of light from optical surfaces that have transmittances less than unity. Ghosts can reduce contrast, provide misleading information, and if severe can veil parts of the nominal image. This dissertation develops several methodologies to simulate ghost effects arising from an even number of light reflections between the surfaces of multi-element lens systems. We present an algorithm to generate the ghost layout that is generated by two, four and up to N (even) reflections. For each possible ghost layout, paraxial ray tracing is performed to calculate the locations of the Gaussian cardinal points, the locations and diameters of the ghost entrance and exit pupils, the locations and diameters of the ghost entrance and exit windows, and the ghost chief and marginal ray heights and angles at each surface in the ghost layout. The paraxial ray trace data is used to estimate the fourth order ghost aberration coefficients. Petzval, tangential, and sagittal ghost image surfaces are introduced. Potential ghosts are formed at the intersection points between the ghost image surfaces and the Gaussian nominal image plane. Paraxial radiometric methodology is developed to estimate the ghost irradiance point spread function at the nominal image plane. Contrast reduction by ghosts can cause a reduction in the depth of field, and a simulation model and experimental technique that can be used to measure the depth of field is presented. Finally, ghost simulation examples are provided and discussed.
1 INTRODUCTION

Ghost images and light scattering are particularly problematic in imaging applications where a large range of light levels exists. In astronomy the problem compounds because of the extreme dynamic range involved in imaging bright and dim objects simultaneously. The light from a bright star can reflect and scatter from multiple surfaces in the imaging systems and cause a faint ghost image that disrupts the imaging of fainter objects. In microscopy a similar problem arises when a bright source is used to illuminate a weakly reflective object through the imaging optics.

In order to compensate for or eliminate ghost images in the design of optical systems, it is important to be able to model ghost images for each design. This chapter will describe the underlying causes of ghost images and some of the current software techniques for identifying them.

1.1 Stray radiation

Stray radiation is any radiation that degrades the performance of the system (i.e., degrades the signal to noise ratio). A useful dichotomy is to consider that two forms of types of electromagnetic radiation are propagating through the system - the "wanted" part and the "unwanted" part. The wanted radiation comes from the objects of interest (the target of observations) which is often imaged on to the image plane. The wanted radiation is controlled by the "idealized" optical system, which contains the optical elements that can be described in a simple optical design model. There is also "unwanted" radiation which is propagated through and generated by the optical system itself. This can include
radiation from an unwanted source (such as sources outside of the field-of-view) or radiation from thermally emissive objects inside or outside of the optical system. Some common sources of stray light are:

- Internal multiple reflections between the lens surfaces
- Reflections from the surfaces of diaphragms and shutter blades.
- Reflections from the detector, windows, or mounting surfaces of the imaging device.
- Scatter from the surfaces of the lens elements due to scratches and other imperfections in the polish, dirt and dust, fingerprints, grease, and poor antireflection coatings.
- Bulk scatter from the interior of the glass and from bubbles.
- Scatter from optical cements.
- Scatter and reflections from the ground edges of the lens elements, from internal lens mounts and from the internal surface of the lens barrel.
- Fluorescence of the glass or optical cements.

All radiation (whether scattered, diffracted, reflected, or self-emitted by the system) reaching the focal plane affects the system performance and is known as veiling glare, flare or stray light. This leads to the premise that the paths of the "unwanted" radiation need as much consideration as the paths of "wanted" radiation through the lenses during the designing stage.

The following subsections (1.1.1, 1.1.2, 1.1.3, 1.1.4, and 1.1.5) give brief examples of how stray light can affect the system [1].
1.1.1 Straight shots

Sometimes stray light rays are not properly blocked by baffles in the system and end up bypassing some of the optical elements to reach the image plane. These “straight shots” can occur for example in a Cassegrain-type system when the central obstruction is too large and/or the telescope tube is too short. Light from outside the field of view can enter the telescope, travel past the secondary mirror, through the hole in the primary mirror, and strike the focal plane directly as stray light. This type of stray light can be a disaster if sunlight is allowed to enter the telescope as shown in Figure 1-1.

![Figure 1-1 Straight shot where the off-axis source shown in green bypasses all the optics and strikes the detector directly [1]. “Reproduced by permission from Rich Pfisterer (Photon Engineering).”](image)

1.1.2 Singly-scattered light

Singly-scattered light occurs when a stray light source such as the sun directly illuminates the optics in the system. Some portion of the light will scatter in a direction
that causes it to reach the focal plane. We say that it scatters into the field of view. Once light has scattered into the field of view, it becomes stray light, and there is no way to eliminate it without also causing vignetting. Thus a basic goal of baffle design is to keep stray light from shining on the optics.

1.1.3 Multiply-scattered light

Even when stray light sources do not illuminate the optics directly, they can still cause stray light scattering indirectly, by first scattering from the baffle surfaces and then illuminating the optics. Stray light of this type will always be smaller light levels than direct scatter, but it may still be large enough to be of concern. Figure 3 shows an excellent demonstration of how an out of field source, shown as green rays in the figure, entering a Cassegrain system can scatter from baffle to baffle inside the system and eventually reach the detector.

Figure 1-2 Rays entering the Cassegrain telescope intersect the main barrel baffle and then split towards the primary and secondary where they reflect to the detector as shown with red and blue rays in the figure [1]. “Reproduced by permission from Rich Pfisterer (Photon Engineering).”
1.1.4 Edge diffraction

When the ratio of aperture diameter to wavelength is relatively small (10^4 or smaller) edge diffraction from the aperture stop from out-of-field sources can be a significant source of stray light.

1.1.5 Self-Emission in Infrared Systems

Thermal infrared or thermal imaging systems can also have stray light caused by blackbody emissions from the instrument itself. These systems work by detecting a small signal superimposed on a large background. At room temperature, the peak of the blackbody emission curve is at about 10µm. Thus the world “glows” at this wavelength, and small variations in this glow indicate differences in temperature or emissivity. Thermal imaging systems normally subtract the background to enhance the contrast of the variations in the infrared scene. When the background is not uniform, as in the presence of narcissus, a stray signal is produced. Specifically, when an image of the cooled detector is imaged back on itself, a locally strong absence of background occurs. This typically appears as a dark spot in the center of the image. One might call this “stray dark” instead of stray light. In infrared radiometers that measure absolute radiance instead of a relative signal, any background radiation is unacceptable. In such an instrument it may be necessary to cool the entire instrument to cryogenic temperatures to eliminate the stray light caused by self emission.
1.2 Ghost images

Ghost images are one of the manifestations of stray light and they are called so because they are in general out of focus or ghostly looking images of bright sources [1]. A bright source causes ghost images at the image plane if it is inside or near the nominal field of view. The sun causes ghost images in a photograph if it is in or near the field of view of the object being photographed. Automobile headlights and streetlights cause stray light ghosts in a nighttime photograph. If the bright source is small, the ghost image in general takes the shape of the system aperture stop. However, if the ghost image plane coincides with the nominal image plane, the ghost image will have the same shape as the bright source.
Ghost images are caused by the inter-reflections of light from optical surfaces that have non-zero reflection and transmission coefficients as illustrated in Figure 1-4. The non-zero reflection and transmission is due to the difference in the refractive index on either side of the interface. Some of the incident light is transmitted at the surface of the element while some is reflected at the same time. The reflected light propagates back to another element surface, is reflected there, and eventually propagates to the image plane resulting in a ghost image. The magnitude of ghost power depends upon the surface reflectivity and transmissivity.

![Figure 1-4 Ghost images formation by a thick lens. Odd and even ghost orders are shown.](image)

Ghost images are classified according to the number of reflections encountered along the ghost ray path. Only even order ghosts may reach the nominal image plane. In this dissertation we are concerned only with ghosts that may reach the detector. However, in high power laser applications, analysts are concerned with even and odd ghosts because both can contribute to surface damage.
For a system that consists of M refractive surfaces, the number of second order ghosts \( C_{2R} \) and fourth order ghosts \( C_{4R} \) are given by Eq.(1-1) and Eq.(1-2), respectively[2]. A plot of \( C_{2R} \) and \( C_{4R} \) as a function of the number of surfaces is shown in Figure 1-5.

\[
C_{2R} = M \frac{(M - 1)}{2} 
\]

\[
C_{4R} = M^2 \frac{(M - 1)^2}{4} - \frac{(M - 2)(M - 1)M(M + 1)}{4!} 
\]

Figure 1-5 second and fourth order ghosts as a function in the number of surfaces.

1.3 Ghost image analysis with optical engineering software

Ghosts are simulated with deterministic or with Monte-Carlo techniques. In the deterministic mode, the ray is split at each surface that has non-zero reflection and transmission coefficients as illustrated in Figure 1-6 and non-sequential ray tracing is performed [3].
In the Monte-Carlo technique; such as is used in the software programs like ASAP Optical Software (Breault Research Organization, Tucson, AZ) and FRED Optical Engineering Software (Photon Engineering, Tucson, AZ); the incident ray is not split into components! Instead the coating reflection and transmission coefficients are used as probability functions and the incident ray becomes a transmitted ray or a reflected ray on a statistical basis. The total number of rays remains the same. This technique is faster because no new rays are generated at each surface.

ASAP has a powerful visualization technique as illustrated in Figure 1-7, where a ghost image of the sun is manifested as the apodization of the aperture stop of the optical system [3].

"Reproduced by permission from Breault Research Organization (ASAP Optical Software by Breault Research Organization)."
1.4 Cooke triplet incoherent ghost image analysis with FRED

The Cooke triplet lens is imported from ZEMAX Optical Design Software (ZEMAX Development Corporation, Bellevue, WA) and its prescription is shown in Table 1-1[4]. The object is a point source at infinity. The lens’ surfaces are uncoated and the ray control in FRED is assigned to “Allow all” at each lens surface, which means: that rays may either specularly reflect or transmit at each surface. Non sequential ray tracing is performed and the rendered layout is shown in Figure 1-8.
Table 1-1 Cooke triplet lens prescription.

<table>
<thead>
<tr>
<th>Flags</th>
<th>Radius</th>
<th>Thickness</th>
<th>Material</th>
<th>Semi-Aperture</th>
<th>Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>16.20</td>
<td>0</td>
<td>Air</td>
<td>3.868e+19</td>
<td>Object</td>
</tr>
<tr>
<td>1</td>
<td>27.3</td>
<td>6</td>
<td>NLAF3</td>
<td>13.156e8</td>
<td>tripletL</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>0.75</td>
<td>Air</td>
<td>11.99e9</td>
<td>tripletS</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
<td>12</td>
<td>Air</td>
<td>7.050e11</td>
<td>tripletL</td>
</tr>
<tr>
<td>4</td>
<td>48.536</td>
<td>4</td>
<td>NLAF1</td>
<td>B.11045.265</td>
<td>tripletL</td>
</tr>
<tr>
<td>5</td>
<td>78.269</td>
<td>0</td>
<td>Air</td>
<td>13.95e14</td>
<td>tripletL</td>
</tr>
<tr>
<td>6</td>
<td>&lt;52.116</td>
<td>47.99e5</td>
<td>Air</td>
<td>14.85179e</td>
<td>tripletL</td>
</tr>
<tr>
<td>7</td>
<td>0</td>
<td>0.18e2</td>
<td>Air</td>
<td>6.99e2</td>
<td>tripletL</td>
</tr>
<tr>
<td>8</td>
<td>0</td>
<td>0</td>
<td>Air</td>
<td>7.06e11</td>
<td>tripletL</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Wavelength (nm)</th>
<th>Focal Length</th>
<th>Front Principal Plane</th>
<th>Back Principal Plane</th>
</tr>
</thead>
<tbody>
<tr>
<td>587.681 d (He)</td>
<td>62.999934325</td>
<td>18.69030593</td>
<td>62.91417915</td>
</tr>
</tbody>
</table>

Figure 1-8 Cooke triplet with bare surfaces which creates ghosts due to Fresnel losses (two splits are allowed). Dotted lines correspond to rays that couldn’t reach the detector.

Irradiance colour chart, Irradiance profile, the estimated percentage error and the number of rays are shown in Figure 1-9 through Figure 1-12, respectively. The ray trace path summaries report manipulates the amount of power in each path and the number of reflections. Path 0 is a specular path because there are no reflections counted as shown in Table 1-2. This path contains 80.5 % of the initial source power. All other paths involve
two reflections because that’s what “Allow All” ray trace control permits by default. The amount of power that each path contains is shown in Table 1-2. It is also possible to take any ray trace path and copy it to a user defined path list (select the path, right mouse click on the path and then select the option to copy this path to the user-defined path list). This path will now show up as an optional path in the advanced ray trace as one of the ray methods to use. It is then possible to do spot diagrams irradiance spread functions on only this path.

Table 1-2 Ray trace paths summary for Cooke triplet. For path # 19 the first surface is the last entity.
The specular reflection counts being greater than two because possibly some of the rays are experiencing total Internal Reflection within a lens element. TIR is not treated as splitting so this does not violate the ancestry of the two. This path has 580 rays, and 6 surface intersections.

<table>
<thead>
<tr>
<th>Path</th>
<th>Total Power</th>
<th>Ray Count</th>
<th>Event Count</th>
<th>Spec Refl Count</th>
<th>Spec Tran Count</th>
<th>Spec Abs Count</th>
<th>Spec Diff Count</th>
<th>Spec Ancestry</th>
<th>First Entity</th>
<th>Last Entity</th>
<th>Previous Entity</th>
</tr>
</thead>
</table>
Figure 1-9 Irradiance point spread function grey chart for cooke triplet.

Figure 1-10 Irradiance profile across the image plane of the Cooke triplet.

Figure 1-11 Estimated error across the image of the Cooke triplet.
Figure 1-12 Number of rays is larger in the middle giving rise to less error in the central structure.

The same information also can be obtained in another way. For example, if we would like to see ghost rays that are generated by reflections from surfaces #7 and 5, we need to insert manually the intervening surfaces and assign a reflection property to surfaces #7 and 5, this is illustrated in Table 1-3. The rendered image of the Cooke triplet with light reflected only from surfaces 5 and 7 and the formation of a hot spot are shown in Figure 1-13 and Figure 1-14, respectively. Irradiance grey chart, Irradiance profile, the estimated percentage error and the number of rays for this particular ghost $G_{7,5}$ are shown in Figure 1-15 through Figure 1-18, respectively.
Table 1-3 Inserting surfaces manually to get ghost $G_{7,5}$

<table>
<thead>
<tr>
<th>Non Seq</th>
<th>Surface (or entity)</th>
<th>Ray Control</th>
<th>Diffract Order</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>triplet.Lens 1.2.Surface 2   (Axix)</td>
<td>Transmit</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>triplet.Surface 3.Surface 3 (Plane)</td>
<td>Transmit</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>triplet.Lens 4.5.Surface 4   (Axix)</td>
<td>Transmit</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>triplet.Lens 4.6.Surface 5   (Axix)</td>
<td>Transmit</td>
<td>0</td>
</tr>
<tr>
<td>6</td>
<td>triplet.Lens 6.7.Surface 6   (Axix)</td>
<td>Transmit</td>
<td>0</td>
</tr>
<tr>
<td>7</td>
<td>triplet.Lens 6.7.Surface 7   (Axix)</td>
<td>Reflect</td>
<td>0</td>
</tr>
<tr>
<td>8</td>
<td>triplet.Lens 6.7.Surface 8   (Axix)</td>
<td>Transmit</td>
<td>0</td>
</tr>
<tr>
<td>9</td>
<td>triplet.Lens 6.7.Surface 7   (Axix)</td>
<td>Transmit</td>
<td>0</td>
</tr>
<tr>
<td>10</td>
<td>triplet.Lens 6.7.Surface 8   (Axix)</td>
<td>Transmit</td>
<td>0</td>
</tr>
<tr>
<td>11</td>
<td>triplet.Lens 6.7.Surface 7   (Axix)</td>
<td>Transmit</td>
<td>0</td>
</tr>
<tr>
<td>12</td>
<td>triplet.Surface 8.Surface 8 (Plane)</td>
<td>Transmit</td>
<td>0</td>
</tr>
<tr>
<td>13</td>
<td>triplet.Surface 8.Surface 8 (Plane)</td>
<td>Transmit</td>
<td>0</td>
</tr>
</tbody>
</table>

Figure 1-13 Ghost rays that are generated by reflections from surface 7 and 5 only.
Figure 1-14 Intermediate ghost image is formed between surfaces # 5 and 6.

Figure 1-15 Grey chart of the irradiance point spread function for $G_{7,5}$

Figure 1-16 Irradiance profile due to ghost that is generated by surfaces 7 and 5.
1.5 Historical background

Several researchers have contributed to the understanding of stray light and ghost images. Tuckerman [5] has evaluated reflections from a pile of parallel plates, and Murray [6] has discussed the number of potentially distinct ghost imaging configurations within an optical system. The first use of ray tracing to find the size of the ghost image and the irradiance distribution within it was by Naylor [7]. He traced finite rays through the refracting system and estimated the size and irradiance distribution from the ray densities. Ghost imaging was investigated more simply by Smith [8]. He used paraxial
ray tracing to determine which surfaces, if any, are likely to cause a significant contribution to the veiling glare.

During the development of a miniature microscope for detection of precancer, ghost images and reflections were determined to severely limit the useful application of the device by Descour et al. [9]. A novel solution to problematic ghost images was implemented by using tilted lens elements with polynomial surfaces by Rogers et al. [10]. Tilting the lens surfaces sends reflections out of the imaging path. Aberrations can be eliminated by using nonrotationally symmetric lens surfaces that correct the wavefront error at each surface. The complex lens surfaces are fabricated by using gray-scale lithographic patterning of hybrid solgel glass.

In this dissertation we present algorithms to generate the ghost layouts. We develop a paraxial ghost image analysis methodology. We discuss how to estimate the ghost fourth order aberrations. Paraxial radiometric methodology is developed to estimate the ghost irradiance point spread function at the nominal image plane. A measurement technique for the depth of field is presented and ghost effects on the depth of field are discussed. Ghost simulation examples are provided and discussed.

**Outline of this dissertation**

This dissertation is organized in the following way. In chapter two we present algorithms that can be used to generate the 2\textsuperscript{nd} and 4\textsuperscript{th} order ghost layouts with generalization through the N\textsuperscript{th} (even) order layout.
Chapter three develops the paraxial ghost image analysis methodology. The paraxial ray tracing equations are reviewed and used to trace ghost rays through each possible ghost layout. Thereby, the estimation of ghost entrance and exit pupils locations and diameters, ghost entrance and exit windows pupils locations and diameters, ghost marginal and chief ray heights at each surface can be obtained. Anomalous ghost layouts are discussed separately and examples are provided.

Paraxial radiometric analysis is developed in chapter four. The basic equations for imaging point and extended objects are reviewed. The ghost irradiance at the nominal image plane of an extended object is derived. We propose two approaches to calculate the ghost irradiance at the nominal image plane due to a point object. The paraxial ghost point spread function is obtained by adding up the contributions of all ghosts. Qualitative examples for the paraxial irradiance point spread function are provided.

In chapter five we extend the geometric and radiometric analysis by including fourth order aberrations. We present the Ghost Petzval image surface. The consequence of nominal and ghost Petzval image surfaces intersection is discussed.

In chapter six, we present a depth of field simulation and measurement technique. Theoretical model, optical set up, and results are provided.

In chapter seven, ghost simulation examples are presented and the conclusion and suggestions for future work are discussed in chapter nine.

In Appendix A1 and A2, the macros that are used to generate the ghost layouts that arise by two and four reflections are provided.
2 GENERATION OF GHOST LAYOUTS

2.1 Introduction

In this chapter we present an algorithm that can be used to generate the ghost layouts that are generated by two, four and up to N (even) reflections. The generation algorithm is based on the extraction of the ghost layout from the nominal layout.

2.2 Generation of second order ghost layouts

In this section we present an algorithm to generate ghost layouts that are formed by two reflections and we provide an example to illustrate its use. The generation algorithm is based on the extraction of the ghost layout from the nominal layout. The macro that generates the 2\textsuperscript{nd} ghost layout is shown in Appendix A1. The basic steps of the process are outlined in a flow chart as shown in Figure 2-1 and described in words below:

- Consider a lens system that consists of M refractive surfaces.
- The object and image planes are at surfaces 0 and M+1, respectively.
- The first surface where reflection to be considered is labeled as $k_1$ while the second reflection surface is labeled as $k_2$. The corresponding ghost is labeled as $G_{k_2,k_1}$.
- The allowed values for $k_1$ and $k_2$ are, $k_1 = 2,3,\ldots,M$ and $k_2 = 1,\ldots,k_1 - 1$. 
- Light is transmitted in the forward direction until it reaches $k_1$, at which it will reflect and be transmitted in the backward direction until it reaches $k_2$. The light is reflected again at $k_2$ and will be transmitted in the forward direction towards the detector.

Figure 2-1 Ghost second order layout generation flow chart.
• The ghost layout now consists of three sub-layouts: transmission in the forward direction TF<sub>1</sub>, transmission in the backward direction TB<sub>1</sub>, and finally transmission in the forward direction TF<sub>2</sub>, again.

• The prescription of the forward transmission sub-layout TF<sub>1</sub> is the same as the nominal layout starting from the first surface and up until surface k<sub>1</sub>.

• The backward transmission sub-layout TB<sub>1</sub> prescription has the same prescription of the nominal layout, starting from k<sub>1</sub> and up until surface k<sub>2</sub> but with negative sign for the refractive index and thicknesses.

• The prescription of the forward transmission TF<sub>2</sub> is the same as the nominal layout starting from k<sub>2</sub> and up until image surface M+1.

• Table 2-1 gives the 2<sup>nd</sup> order ghost lens prescription: the refractive index n<sub>g</sub>, the thickness t<sub>g</sub>, the radius of curvature R<sub>g</sub>, and the semidiameter a<sub>g</sub>. The suffix g is used as an abbreviation for the ghost prescription parameters.
2.2.1 Example

Consider a lens that consists of three surfaces imaging an object at infinity. The three possible 2\textsuperscript{nd} order ghosts are: $G_{2,1}$, $G_{3,1}$, and $G_{3,2}$ as shown in Figure 2-2, Figure 2-3, and Figure 2-4, respectively. The ghost lens systems for $G_{2,1}$, $G_{3,2}$, and $G_{3,1}$ are given in Table 2-2, Table 2-3, Table 2-4, respectively.

### Table 2-1: Second order ghost layout prescription for $G_{k_2,k_1}$ ghost.

<table>
<thead>
<tr>
<th>Sub-layout</th>
<th>$n_g$</th>
<th>$t_g$</th>
<th>$R_g$</th>
<th>$a_g$</th>
</tr>
</thead>
<tbody>
<tr>
<td>TF\textsubscript{1}</td>
<td>$n_0$</td>
<td>$t_0$</td>
<td>$R_1$</td>
<td>$a_1$</td>
</tr>
<tr>
<td>TB\textsubscript{1}</td>
<td>$n_{k_1-1}$</td>
<td>$t_{k_1-1}$</td>
<td>$R_{k_1}$</td>
<td>$a_{k_1}$</td>
</tr>
<tr>
<td>TF\textsubscript{2}</td>
<td>$n_{k_2}$</td>
<td>$t_{k_2}$</td>
<td>$R_{k_2}$</td>
<td>$a_{k_2}$</td>
</tr>
<tr>
<td>$n_{M}$</td>
<td>$t_{M}$</td>
<td>$R_{M+1}$</td>
<td>$a_{M+1}$</td>
<td></td>
</tr>
</tbody>
</table>
Figure 2-2 Nominal and ghost $G_{2,1}$ layouts for a lens with three surfaces.

<table>
<thead>
<tr>
<th>Sub-layout</th>
<th>$n_g$</th>
<th>$t_g$</th>
<th>$R_g$</th>
<th>$a_g$</th>
</tr>
</thead>
<tbody>
<tr>
<td>TF$_1$</td>
<td>$n_0$</td>
<td>$t_0$</td>
<td>$R_1$</td>
<td>$a_1$</td>
</tr>
<tr>
<td>TB$_1$</td>
<td>$-n_1$</td>
<td>$-t_1$</td>
<td>$R_2$</td>
<td>$a_2$</td>
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<tr>
<td>TF$_2$</td>
<td>$n_1$</td>
<td>$t_1$</td>
<td>$R_2$</td>
<td>$a_2$</td>
</tr>
<tr>
<td></td>
<td>$n_2$</td>
<td>$t_2$</td>
<td>$R_3$</td>
<td>$a_3$</td>
</tr>
<tr>
<td></td>
<td>$n'$</td>
<td>$t_3$</td>
<td>$R_4$</td>
<td>$a_4$</td>
</tr>
</tbody>
</table>
Figure 2-3 Nominal and ghost $G_{3,1}$ layout for a lens with three surfaces.

Table 2-3 The prescription for the ghost lens system $G_{3,1}$

<table>
<thead>
<tr>
<th>Sub-layout</th>
<th>$n_g$</th>
<th>$t_g$</th>
<th>$R_g$</th>
<th>$a_g$</th>
</tr>
</thead>
<tbody>
<tr>
<td>TF1</td>
<td>$n_0$</td>
<td>$t_0$</td>
<td>$R_1$</td>
<td>$a_1$</td>
</tr>
<tr>
<td>TF1</td>
<td>$n_1$</td>
<td>$t_1$</td>
<td>$R_2$</td>
<td>$a_2$</td>
</tr>
<tr>
<td>TF1</td>
<td>$n_2$</td>
<td>$t_2$</td>
<td>$R_3$</td>
<td>$a_3$</td>
</tr>
<tr>
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<td>$-n_2$</td>
<td>$-t_2$</td>
<td>$R_2$</td>
<td>$a_2$</td>
</tr>
<tr>
<td>TB</td>
<td>$-n_1$</td>
<td>$-t_1$</td>
<td>$R_1$</td>
<td>$a_1$</td>
</tr>
<tr>
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<td>$t_1$</td>
<td>$R_2$</td>
<td>$a_2$</td>
</tr>
<tr>
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<td>$n_2$</td>
<td>$t_2$</td>
<td>$R_3$</td>
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</tr>
<tr>
<td>TF2</td>
<td>$n'$</td>
<td>$t_3$</td>
<td>$R_4$</td>
<td>$a_4$</td>
</tr>
</tbody>
</table>
Once the ghost layouts are mapped for each scenario, the attributes of the ghost image can then be determined by ray tracing the layout, as described in later chapters.

### 2.3 Generation of fourth order ghost layouts

In this section, the presented algorithm in section 2.2 is extended to generate the 4th order ghost layouts. The macro that generates the 4th order ghost layout is shown in

![Figure 2-4 The ghost $G_{3,2}$ and nominal layouts.](image)

![Table 2-4 The prescription for the ghost lens system $G_{3,2}$](table)

<table>
<thead>
<tr>
<th>Sub-layout</th>
<th>$n_g$</th>
<th>$t_g$</th>
<th>$R_g$</th>
<th>$a_g$</th>
</tr>
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<tbody>
<tr>
<td>TF1</td>
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<td>$t_0$</td>
<td>$R_1$</td>
<td>$a_1$</td>
</tr>
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<td>$t_1$</td>
<td>$R_2$</td>
<td>$a_2$</td>
</tr>
<tr>
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<td>$-t_1$</td>
<td>$R_2$</td>
<td>$a_2$</td>
</tr>
<tr>
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<td>$t_2$</td>
<td>$R_3$</td>
<td>$a_3$</td>
</tr>
<tr>
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<td>$n_3$</td>
<td>$t_3$</td>
<td>$R_4$</td>
<td>$a_4$</td>
</tr>
</tbody>
</table>
Appendix A2.

Figure 2-5 Fourth order ghost layout generation flowchart.

- The surfaces that give rise to the first, second, third, and fourth reflections are $k_1$, $k_2$, $k_3$, and $k_4$, respectively.
• Light is transmitted in the forward direction until it reaches $k_1$, at which it will reflect and be transmitted in the backward direction until it reaches $k_2$. The light then reflects and is transmitted in the forward direction until it reaches $k_3$, at which it will be reflected again and be transmitted in the backward direction until it reaches $k_4$. At surface $k_4$ light makes its final reflection and is transmitted in the forward direction until it reaches the detector.

• The ghost layout consists of five sub-layouts: transmission in the forward direction $TF_1$, transmission in the backward direction $TB_1$, transmission in the forward direction $TF_2$, transmission in the backward direction $TB_2$, and the final transmission in the forward direction $TF_3$.

• The prescription of sub-layout $TF_1$ is the same as the nominal layout starting from the first surface and up until surface $k_1$.

• The backward transmission sub-layout prescription has the same prescription as the nominal layout, starting from $k_1$ and up until surface $k_2$ but with a negative sign for the refractive index and thicknesses.

• The prescription of the forward transmission $TF_2$ is the same as the nominal layout starting from $k_2$ and up until surface $k_3$.

• The prescription of the backward transmission $TB_2$ is the same as the nominal layout starting from $k_3$ and up until surface $k_4$ but with a negative sign for the refractive indices and thicknesses.
The prescription of the forward transmission $TF_3$ is the same as the nominal layout starting from $k_4$ and up until the image surface $M+1$.

Table 2-5 The ghost lens system prescription for $G_{k1,k2,k3,k4}$

<table>
<thead>
<tr>
<th>Ghost sub-layouts</th>
<th>$n_g$</th>
<th>$t_g$</th>
<th>$R_g$</th>
<th>$a_g$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$TF_1$</td>
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<td>$t_0$</td>
<td>$R_1$</td>
<td>$a_1$</td>
</tr>
<tr>
<td></td>
<td>$n_1$</td>
<td>$t_1$</td>
<td>$R_2$</td>
<td>$a_2$</td>
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<td>$t_{k1-1}$</td>
<td>$R_{k1}$</td>
<td>$a_{k1}$</td>
</tr>
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<td>$-n_{k1-1}$</td>
<td>$-t_{k1-1}$</td>
<td>$R_{k1-1}$</td>
<td>$a_{k1-1}$</td>
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<td></td>
<td>$-n_{k2}$</td>
<td>$-t_{k2}$</td>
<td>$R_{k2}$</td>
<td>$a_{k2}$</td>
</tr>
<tr>
<td>$TF_2$</td>
<td>$n_{k2}$</td>
<td>$t_{k2}$</td>
<td>$R_{k2+1}$</td>
<td>$a_{k2+1}$</td>
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<td></td>
<td>$n_{k3-1}$</td>
<td>$t_{k3-1}$</td>
<td>$R_{k3}$</td>
<td>$a_{k3}$</td>
</tr>
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<td>$-t_{k3-1}$</td>
<td>$R_{k3-1}$</td>
<td>$a_{k3-1}$</td>
</tr>
<tr>
<td></td>
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<td>$-t_{k3-2}$</td>
<td>$R_{k3-2}$</td>
<td>$a_{k3-2}$</td>
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<td>$R_{k4}$</td>
<td>$a_{k4}$</td>
</tr>
<tr>
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<td>$t_{k4}$</td>
<td>$R_{k4+1}$</td>
<td>$a_{k4+1}$</td>
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<td></td>
<td>$n_{k4+1}$</td>
<td>$t_{k4}$</td>
<td>$R_{k4+2}$</td>
<td>$a_{k4+2}$</td>
</tr>
<tr>
<td></td>
<td>$n'$</td>
<td>$t_M$</td>
<td>$R_{M+1}$</td>
<td>$a_{M+1}$</td>
</tr>
</tbody>
</table>

2.4 Generation of the $N^{th}$ order ghost layouts

Because there is a great deal of repetition as demonstrated in the above described generation of $2^{nd}$ and $4^{th}$ order ghost layouts, the possible reflection surfaces configurations can be generated by “for loops” for the $N^{th}$ order ghost layout. The
allowed values for \( k_1, k_2, k_3, k_4 \ldots \ldots k_N \) are shown below. There will be N+1 ghost sub-layouts that are generated from the nominal prescription data and they are labeled as TF_1, TB_1, TF_2, TB_2, \ldots , TF_{N+1}

First loop \( k_1 = 2, 3 \ldots , M \)

Second loop \( k_2 = 1, 2 \ldots , k_1 - 1 \)

Third loop \( k_3 = k_2 + 1, k_2 + 2 \ldots , M \)

Fourth loop \( k_4 = 1, 2 \ldots , k_3 - 1 \)

Fifth loop \( k_5 = k_4 + 1, k_4 + 2 \ldots , M \)

\( i^{th} \) loop \( k_i = k_{i-1} + 1, k_{i-1} + 2 \ldots , M \)

\( (i+1)^{th} \) loop \( k_{i+1} = 1, 2 \ldots , k_i - 1 \)

\( (N-1)^{th} \) loop \( k_{N-1} = k_{N-2} + 1, k_{N-2} + 2 \ldots , M \)

\( N^{th} \) loop \( k_N = 1, 2 \ldots , k_{N-1} - 1 \)
2.4.1 Example

Consider a biconvex lens, The $N^{th}$ order ghost layout that consists of $(N+1)$ sub-layouts are shown in Table 2-6.

Table 2-6 $N^{th}$ order ghost layout of a biconvex lens.

<table>
<thead>
<tr>
<th>Ghost sub-layouts</th>
<th>$n_g$</th>
<th>$t_g$</th>
<th>$R_g$</th>
<th>$a_g$</th>
</tr>
</thead>
<tbody>
<tr>
<td>TF$_1$</td>
<td>$n_0$</td>
<td>$t_0$</td>
<td>$R_1$</td>
<td>$a_1$</td>
</tr>
<tr>
<td>TB$_1$</td>
<td>$-n_1$</td>
<td>$-t_1$</td>
<td>$R_1$</td>
<td>$a_1$</td>
</tr>
<tr>
<td>TB$_2$</td>
<td>$n_1$</td>
<td>$t_1$</td>
<td>$R_2$</td>
<td>$a_2$</td>
</tr>
<tr>
<td>TF$_3$</td>
<td>$-n_1$</td>
<td>$-t_1$</td>
<td>$R_1$</td>
<td>$a_1$</td>
</tr>
<tr>
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<td>$n_1$</td>
<td>$t_1$</td>
<td>$R_1$</td>
<td>$a_1$</td>
</tr>
<tr>
<td>TB$_{(i+1)}$</td>
<td>$-n_1$</td>
<td>$-t_1$</td>
<td>$R_1$</td>
<td>$a_1$</td>
</tr>
<tr>
<td>TF$_N$</td>
<td>$n_1$</td>
<td>$t_1$</td>
<td>$R_2$</td>
<td>$a_2$</td>
</tr>
<tr>
<td>TB$_{(N+1)}$</td>
<td>$-n_1$</td>
<td>$-t_1$</td>
<td>$R_1$</td>
<td>$a_1$</td>
</tr>
</tbody>
</table>

2.5 Ghost layouts for lens systems with physical stops

So far we have presented algorithms to generate the ghost layouts for lens systems that don’t have the same media at both sides of a physical stop. If the lens system contains a physical stop with same media on both sides of the stop, all possible reflection surfaces pairs are generated so that the physical stop surface is excluded. The second order ghost layout flow chart for a lens system with physical stop is shown in Figure 2-6.
Figure 2-6 Second order ghost layouts generation for lens systems that have physical stops. S is the physical stop surface number in the nominal layout.
3 GAUSSIAN (SECOND ORDER) GHOST IMAGING ANALYSIS

3.1 Introduction

In this chapter we discuss Gaussian calculations in ghost lens systems. The 2\textsuperscript{nd}, 4\textsuperscript{th} and generalized through the N\textsuperscript{th} (even) order ghost layout generation algorithms for a nominal lens system with M elements have been previously discussed in Chapter two. The second-order analysis developed in this chapter will be used extensively throughout this dissertation as a fundamental diagnostic tool. This tool will help in identifying the surfaces that are responsible for seriously degrading the nominal image by ghost effects and later on as a design aid to eliminate or reduce ghost effects. Second-order imaging properties for each ghost lens system are in general different from those found in the nominal lens system, since the nominal and ghost systems have generally different layouts. However, the same equations that are used to determine the nominal system second-order properties are also used to determine the ghost system properties.

Some second-order properties for the ghost lens system that are necessary to know are:

- Ghost aperture stop location and size
- Ghost entrance and exit pupil sizes and locations
- Ghost field stop location and size
- Ghost entrance and exit window sizes and locations
- Ghost object and image spaces fields of view
- Ghost chief and marginal ray heights and angles at each surface
Throughout this dissertation we will assume the aperture stop for the nominal system is the aperture stop for all ghost systems. This assumption simplifies the analysis. However, for some systems this assumption might not hold, and a ghost aperture stop must be identified. These systems are considered as anomalous systems and the techniques that can be used to identify the surface that serves as the aperture stop will be discussed. Knowledge of the ghost aperture stop is required to calculate marginal ray heights and angles at each surface. Locations and diameters of ghost entrance and exit pupils are determined by imaging the ghost stop in object and image spaces, respectively. Ghost entrance and exit pupils determine the ghost lens system object and image space numerical apertures respectively. Object and image space numerical apertures help in determining the radiometric properties for each ghost lens system.

Throughout this dissertation, it is assumed that all ghost systems and the nominal system have the same object space field of view as measured by the object height. However, because of the different path lengths of the ghost layouts, they might have different angular object space fields of view. The Ghost field stop determines the object and image fields of view. Knowledge of the ghost field of view is required to
calculate the ghost chief ray heights and angles at each surface in the ghost layout. Ghost marginal and chief ray heights and angles at each surface are used to calculate the second and fourth order ghost imaging properties.

Gaussian nominal and ghost image planes are in general displaced from each other. Therefore, a blurred ghost image is projected at the nominal Gaussian image plane. The amount of blurring depends on the separation between these two planes. If the separation is smaller than the ghost depth of focus (where the nominal image plane falls inside the depth of focus of the ghost lens system), a considerably sharp ghost image is formed at the nominal image plane. The larger the depth of focus of the ghost lens system, the more probable the formation of sharp ghost images at the nominal plane.

3.2 Paraxial ray tracing through the ghost layout

The paraxial region of an optical system is a thin threadlike region about the optical axis which is so small that all angles made by the rays (i.e. the slope angles and the angles of incidence and refraction) may be set equal to their sine’s and tangents.

For each generated ghost layout, paraxial ray tracing is applied repetitively until the ghost ray reaches the detector as shown in Figure 3-1. Same paraxial equations that are used to trace a ray in the nominal layout are used to trace a ray in the ghost layout[11].
Figure 3-1 An arbitrary ray originating from the object and traced through the reduced ghost layout to the image plane. The ray height and optical angles \((y_g, \omega_g)\) are shown at each surface \(S_g\).

The paraxial ray tracing equations are given by,

\[
\omega'_g = \omega_g - y_g \phi_g \quad \text{and} \quad y'_g = y_g + \omega_g' \tau_g
\]  

Where, \(\omega_g\), and \(\omega'_g\) are the incident and refracted optical slope angles at surface \(S_g\). The slope angles are given by,

\[
\omega_g = n_g u_g = n_g \tan U_g \quad \text{and} \quad \omega'_g = n'_g u'_g = n'_g \tan U'_g
\]  

Where, \(U_g\) and \(U'_g\) are the ghost ray incidence and refracted angles measured with respect to the optical axis at surface \(S_g\), respectively. The object and image spaces refractive indices for surface \(S_g\) are \(n_g\) and \(n'_g\), respectively. The optical power of surface \(S_g\) is a function of the curvature \(C_g\) and is given by:

\[
\phi_g = (n'_g - n_g)C_g
\]  

The ghost reduced thickness \(\tau_g\) and is given by:
\[ \tau_g = \frac{t_g}{n_g} \]  

3.3 Ghost cardinal points

Each ghost lens system can be reduced into its cardinal points as shown in Figure 3-2. The ghost cardinal points are: the ghost front and back focal points \((F_{g,F}, F'_{g,R})\), the ghost front and back principle points \((P_{g,F}, P'_{g,R})\), and the ghost front and back nodal points \((N_{g,F}, N'_{g,R})\). The same equations that are used to determine the locations of the nominal cardinal points [11] are used to determine the locations of the ghost cardinal points.

Accordingly, the ghost system power \(\phi_g\), the ghost effective focal length \(f_{E,g}\), the ghost rear and front focal distances \((f'_{g,R}, f'_{g,F})\), the back and front focal distances \((BFD_g, FFD_g)\), the location of the rear principle plane with respect to the rear vertex \(d'_{g}\), the location of the front principle plane with respect to the front vertex \(d_{g}\), and the distance from the ghost principle plane to the ghost nodal plane \(Z_{PN,g}\) are given by:

\[
\phi_g = -\frac{\omega'_{g}}{y_{1,g}} \quad \text{and} \quad f_{E,g} = \frac{1}{\phi_g} \tag{3-5}
\]

\[
f'_{g,R} = \frac{n'_{g}}{\phi_g} \quad \text{and} \quad f'_{g,F} = -\frac{n_{g}}{\phi_g} \tag{3-6}
\]
$BFD_g = -\frac{n'y_{M,g}}{\omega_g'}$ and $FFD_g = -\frac{ny_{1,g}}{\omega_{1,g}}$  \hspace{1cm} 3-7

$d'_g = BFD_g - f_{R,g}$ and $d_g = FFD_g - f_{F,g}$ \hspace{1cm} 3-8

$Z_{PN,g} = Z_{PN',g} = f_{F,g} + f_{R,g}$ \hspace{1cm} 3-9

Where, $y_{M,g}$ is the height of an on-axis ray traced in the forward direction at the last lens surface, and $y_{1,g}$ is the height of an on-axis ray at the first lens surface traced in the reverse direction.

3.4 Ghost aperture and field stops

Ghost image analysis requires the identification of the surfaces that act as the ghost aperture and field stops. The ghost aperture stop defines the on-axis ghost cone while ghost field stop defines the ghost field of view. In general, the ghost aperture and field stops are different from the nominal aperture and field stops.
Throughout this dissertation it will be assumed that the ghost lens system stop is the stop for all ghost lens systems. To validate this assumption, the ratio between the ghost preliminarily marginal ray height and the aperture stop radius is calculated at each surface. If this ratio doesn’t have its largest value at the nominal stop, then this assumption is not valid. Techniques that can be used to perform ghost analysis for such anomalous systems are discussed separately.

Object space ghost and nominal fields of view are in general different in diameters. This explains the appearance of an object that lies outside the nominal field of view but inside one of the ghost systems field of view. Our main concern is to consider ghost images that arise from the nominal object only. Therefore, it will be assumed that the object space ghost and nominal fields of view are both defined by the same object height.

3.5 Ghost marginal and chief rays

Each ghost layout has its own chief and ghost marginal rays. The preliminary ghost marginal ray is obtained by tracing an on axis ray with an arbitrary slope angle. The ghost marginal ray height and the angles at each surface in the ghost layout are obtained by scaling the preliminary marginal ray by the proper scaling factor. The scaling factor is given in terms of the semidiameter of the ghost aperture stop $a_{s,g}$ and the preliminary ghost marginal ray height at the ghost stop $\tilde{y}_s$:
The preliminary ghost chief ray is obtained by tracing a ray with a height of zero and an arbitrary angle from the aperture stop in the forward and backward directions through the ghost layout. Then, the ghost chief ray is obtained by scaling the angles and heights of preliminary ghost chief ray by the proper scaling factor so that the unvignetted condition is satisfied. The scaling factor is given by:

\[
s_{\text{ghost}} = \min\left(\frac{a_{k,g}}{\bar{y}_{k,g}}, \frac{y_{s,g}}{a_{s,g}}\right)
\]

Here, \(a_{k,g}\) is the semi-diameter of surface \(k\) and \(\bar{y}_{k,g}\) is the preliminary ghost chief ray height at surface \(k\).

### 3.6 Ghost pupils and windows

Ghost entrance and exit pupils have generally different locations and sizes than those found in the nominal system. Ghost entrance and exit pupil locations are determined by the locations where the ghost chief ray extensions intersect the optical axis. The diameters of the ghost entrance and exit pupils are defined by the ghost marginal ray heights at the locations of the ghost entrance and exit pupils.

Similarly, ghost entrance and exit windows have different locations and sizes than those of the nominal system. Ghost entrance and exit windows are the images of the
ghost field stop in object and image space, respectively. The diameters of the entrance and exit windows are defined by the corresponding chief ray heights.

3.7 Ghost image location and size

The Gaussian image plane for a given ghost layout can be determined by tracing an on-axis ray through the ghost layout. The point of intersection of the ray with the optic axis defines the Gaussian ghost image location. In general, the ghost image plane is separated from the nominal image plane by an amount $\Delta Z_{g,n}$.

In general, the ghost image of an on-axis point object at the nominal plane is a blurred image that has a width of $2y_{g,n}$ as shown in Figure 3-3. The ghost image for an off-axis point object at the nominal image plane is a blurred image centered on the ghost chief ray $\bar{y}_{g,n}$ with a width $2y_{g,n}$ as illustrated on Figure 3-4.
3.8 Ghost image features

In general ghost images of a bright point object that falls within the object space ghost field of view forms a blurred image. The blurred image of the point object has the same shape as the ghost aperture stop. This is explained graphically in Figure 3-5.
Figure 3-5 ghost image of a point object. The ghost image takes the shape of the ghost AS. (a) the ghost point image is in front of the detector. (b) the ghost point image is behind the detector.
3.9 Ghost depth of focus

A reasonably focused ghost image is formed at the nominal image plane if the nominal image plane lies within the ghost depth of focus. The smaller the ghost depth of focus, the less probable the appearance of focused ghost images on the nominal image plane. This can become a very useful design tool when considering a system that is normally prone to ghosts. Let the accepted blur diameter criterion at the nominal image plane be represented by $B'$. From Figure 3-6 the geometrical $DOF_g$ is given by:

$$DOF_g = \pm b_g$$  \hspace{1cm} (3-12)

$$\frac{B'}{b'_g} = \frac{D_{sp,g}}{L'_g}$$  \hspace{1cm} (3-13)

The working ghost $f/\#_{w,g}$ is given by:

$$f/\#_{w,g} = \frac{L'_g}{D_{sp,g}}$$  \hspace{1cm} (3-14)

Substituting Eq. (3-13) and Eq. (3-14) into Eq. (3-12) gives:

$$DOF_g = \pm B' f/\#_{w,g}$$  \hspace{1cm} (3-15)
3.10 Vignetting

Not all ghosts can reach the nominal plane due to vignetting. The three vignetting conditions are listed below [11],

Unvignetted: \( a_g \geq |y_g| + |y_g| \) \hspace{1cm} 3-16

Fully vignetted \( a_g \geq |y_g| - |y_g| \) and \( a_g \geq |y_g| \) \hspace{1cm} 3-17

Half vignetted \( a_g = |y_g| \) and \( a_g \geq |y_g| \) \hspace{1cm} 3-18

Where: \( a_g \) is the surface semi-diameter for the ghost layout and \( y_g \) is the marginal ray height and \( -\bar{y}_g \) is the chief ray height at the corresponding surface.
3.11 Anomalous ghost lens systems

Anomalous ghost lens systems are systems that have a different aperture stop and/or a different object space field of view than that of the nominal system. To identify these systems, an on-axis ray with an arbitrary angle is traced paraxially throughout the ghost layout. The ratio $\left| y_{k,g} / a_{k,g} \right|$ is calculated at each surface. If this ratio at the nominal stop doesn’t have its highest value compared to the ratios at other surfaces, then the nominal aperture stop is not the ghost lens system aperture stop. To determine the ghost object space field of view, the ghost field stop needs to be identified. This is done by tracing a preliminary ghost chief ray through the ghost layout in the backward direction. The surface that has the largest ratio of $\left| y_{k,g} / (a_{k,g} - y_{k,g}) \right|$ will serve as the ghost field stop. This ray is scaled: $s_{\text{chief, ghost}} = \min((a_{k,g} - y_{k,g})/y_{k,g})$ so that, the fully unvignetted condition is satisfied at the field stop. Therefore, ensure that the unvignetting condition is satisfied at the other surfaces. The ghost angular field of view is the angular subtense of the ghost chief ray with the optical axis at the ghost entrance pupil. To get a better perception of anomalous ghost lens systems, four examples are discussed.

3.11.1 Example one

The purpose of this example is to show that the nominal stop is not the ghost system stop in some lens systems. For simplicity, a simple lens system is considered. The lens system consists of two positive thin lenses. The nominal aperture stop is $L_1$ as shown in Figure 3-7.
In this example only ghosts formed by two reflections from the surfaces of the lenses are considered. As a result, there will be only one possible ghost layout that arises from reflection with the reflection from $L_2$ towards $L_1$ and then back reflected from $L_1$. This ghost will be labeled as $G_{2,1}$. The aperture stop (AS) for this ghost lens system can’t be $L_1$ as illustrated in Figure 3-8.
To generate the ghost layout, the ghost lens system in Figure 3-9 is unfolded. The resulting ghost layout has four elements as shown in Figure 3-10. The ghost layout consists of five elements: L₁, L₂, L₁, L₂ and the detector.
An on-axis ghost ray with an arbitrary angle is traced paraxially as shown in Figure 3-10. The ratio $|a_{k,g}/y_{k,g}|$ is calculated at each element in the ghost layout. The surface that serves as the ghost aperture stop corresponds to the minimum ratio. The potential ghost marginal ray is scaled so that it passes through the edge of the ghost AS. The resulting ray is the ghost marginal ray. The ghost marginal ray is shown in Figure 3-11 and Figure 3-12.
3.11.2 Example two

The purpose of this example is to show that the ghost system aperture stop floats with the associated ghost reflection pair. In this example, the lens system consists of three positive thin lenses. The nominal aperture stop is $L_1$. An intermediate nominal image is formed at an intermediate image plane as shown in Figure 3-13.
Ghosts formed by two reflections only are considered here. The three possible ghost systems $G_{3,1}$, $G_{2,1}$ and $G_{3,2}$ are shown in Figure 3-14, Figure 3-15, and Figure 3-16, respectively. The unfolded layout for each possible ghost system consists of six elements, including the detector.

The same algorithm that is discussed in example one is applied here to identify the ghost aperture stop for each possible ghost layout. For $G_{3,1}$, the ghost AS is the fourth element in the unfolded ghost layout. For $G_{2,1}$, the ghost AS is the fourth element in the unfolded ghost layout. For $G_{3,2}$, the ghost AS is the fifth element in the unfolded ghost layout.

Figure 3-13 Nominal lens system
Figure 3-14 Ghost marginal ray for the ghost system $G_{2,1}$

Figure 3-15 Ghost marginal ray for the ghost system $G_{3,2}$
3.11.3 Example three

This example illustrates an anomalous system in which the object space ghost field of view is smaller in diameter than the object space nominal field of view. The nominal lens system is in focus with an object of height $h_o$. The object fills the nominal field of view. The object consists of three sections: black, green, and blue. The nominal lens system consists of two thin positive lenses. The nominal aperture is $L_1$ and the nominal field stop is $L_2$. This is shown in Figure 3-17.
Only ghosts formed by two reflections between the lens surfaces are considered here, so, in this system one ghost is possible. This ghost arises from a reflection from \( L_2 \) and then \( L_1 \) and will be labeled \( G_{2,1} \). The AS for this ghost lens system is \( L_1 \) as illustrated in Figure 3-18.

Figure 3-18 The nominal field of view is larger than the ghost field of view.

To identify the ghost field stop (FS), a preliminary ghost chief ray is traced from the center of the ghost aperture stop in the forward and reverse directions. The ratio 

\[
\frac{(a_{k,g} - |y_{k,g}|)}{a_{k,g}}
\]

is calculated at each element, so five ratios (including the detector) are estimated. The element that serves as the ghost FS corresponds to the maximum ratio.

The preliminary ghost chief ray is scaled so that the unvignetted condition is satisfied at the ghost FS. This is the ghost chief ray and its height at the nominal object plane is the object space ghost half field of view in diameter. A simple sketch (Figure 3-19) shows that the object space ghost field of view is smaller than the nominal field of view. The ghost lens system sees only a portion of the nominal object. The ghost AS and
FS are the first and third elements, respectively in the unfolded ghost layouts as shown in Figure 3-20. In this example, the ghost FS is at the intermediate ghost image plane.

Figure 3-19 Ghost object space field of view

Figure 3-20 The ghost marginal and chief rays traced through the unfolded ghost layout.
3.11.4 Example four

This example illustrates an anomalous system in which the object space ghost field of view is larger in diameter than the object space nominal field of view. The nominal lens system consists of: two thin positive lenses. The nominal AS is $L_1$ as shown in Figure 3-21. The detector is the nominal field stop. The ghost field of view is larger in diameter than the nominal field of view as shown in Figure 3-22. The ghost AS and FS are the fourth element and second element, respectively in the unfolded ghost layout as shown in Figure 3-23. A blurred ghost image is formed at the nominal image plane along with objects that are outside the nominal field of view but inside the ghost field of view.

![Figure 3-21 Nominal lens system. The size of the nominal field of view is defined by the arrow.](image-url)
Figure 3-22 Ghost lens system with a field of view larger than the nominal field of view.

Figure 3-23 The ghost marginal and chief rays traced through the unfolded ghost layout.

3.12 Ghosts by a plane parallel plate

In this section we demonstrate the effect of thickness and refractive index on the separation between the ghost and the nominal images.
Consider the case of a multi-lens element before the glass plate so that the ghost marginal ray makes an angle $u_{1p}$ with the first surface of the plate. We are concerned only with the second order ghost that is formed by the plate. The nominal ray exits the glass plate with height $y_{2p}$ and angle $u_{1p}$ as shown in Figure 3-24. The ghost ray exits the plate at a height of $y_{4p}$ and with the same angle as the nominal ray. The height $y_{4p}$ is given by:

$$y_{4p} = y_{2p} + 2u'_{1p} t_p$$  \hspace{1cm} 3-19$$

The nominal and ghost marginal rays intersect the z axis in the image space at distance $t_g$, $t_n$ with respect to the second surface of the plate, according to:
\[ 0 = y_{4p} + u_{1p} t_g \quad \text{and} \]
\[ 0 = y_{2p} + u_{1p} t_n \]

Equating Eq. (3-20) in Eq. (3-21) gives:
\[ y_{4p} + u_{1p} t_g = y_{2p} + u_{1p} t_n \]
\[ 2u'_{1p} t_p = u_{1p} (t_n - t_g) \]
\[ (t_n - t_g) = 2 \frac{u'_{1p}}{u_{1p}} t_p \]

The separation between the ghost and nominal images is inversely proportional to the parallel plate refractive index, and directly proportional to both the thickness of the plate and the object space refractive index for the plate. This result is illustrated in Figure 3-25 for two different glass plates in air. The ghost – nominal separation is directly proportional to the wavelength as shown in Figure 3-26. The ghost image is considered to be reasonably focused if \( (t_n - t_g) \leq DOF_g = B f / \#_{w,g} \)
Figure 3-25 The ghost –nominal image separation for crown glass (N-BK7) and flint glass (SF5).

Figure 3-26 Ghost –nominal images separation as a function of wavelength for crown (N-BK7) and flint (SF5) glasses.
4 GHOST PARAXIAL RADIOMETRIC ANALYSIS

4.1 Introduction

The main purpose of ghost image analysis is to develop techniques to simulate all possible combinations of ghost effects at the nominal image plane. This analysis will consequently help in minimizing ghost effects by giving the designer the tools to help reduce the total ghost light at the nominal image plane. Ghost image analysis includes geometric and radiometric analysis. Geometric analysis for ghost images has been discussed in chapter three and is essential for the paraxial ghost radiometric analysis that is developed in this chapter.

In this chapter, we will start by reviewing the basic principles of radiometric analysis, particularly, the radiometry of point and extended sources (Lambertian disc) [12]. The cosine-third law of irradiance for a point source and the cosine fourth law of irradiance for an extended source are discussed. The results thus obtained are used to discuss the radiometry of nominal optical imaging systems.

Ghost radiometric analysis is then developed by using the results obtained from the radiometry of nominal optical imaging systems. This analysis is applicable for ghost systems in which attenuation of optical power is only due to Fresnel reflection and transmission losses. Two expressions for the individual ghost irradiance at the nominal image plane resulting from imaging a point object are derived. An expression for the individual ghost irradiance at the nominal image plane resulting from imaging a Lambertian disc is also derived. For incoherent illumination, the total ghost irradiance at
the nominal image plane is obtained by summing the individual irradiance contributions of all possible ghosts.

4.2 Point source radiometry

Consider a point source with intensity $I_o$ irradiating a screen. The screen is placed at a distance $R$ from the point source as shown in Figure 4-1. The irradiance on surface element $dA_2$ at the screen is given by [12]:

$$E = E_o \cos^3 \theta = \frac{I_o}{R^2 \cos^3 \theta}$$

Where $E_o$ is the on-axis irradiance, $\theta$ is the angle in degrees between the screen normal and line joining the source point with the center of $dA_2$.

![Figure 4-1 Irradiance of surface elements irradiated by a point source.](image)

The on-axis screen irradiance is directly proportional to the source intensity and inversely proportional to the square of the distance between the screen and the source. As we go further from the on-axis position, the irradiance drops with $\cos^3 \theta$. 
4.3 Lambertian disc radiometry

Consider a screen at a distance R from a Lambertian disc of radius a and radiance B, the screen and the disc are parallel to each other as shown in Figure 4-2.

![Figure 4-2 Irradiance by a Lambertian disc.](image)

When \( R \gg a \), the irradiance \( E \) at \( dA_2 \) is given by [12]:

\[
E = E_o \cos^4 \theta
\]

Where: the angles \( \theta \) and \( \alpha \), and the axial \( E_o \) are given by:

\[
\alpha = \tan^{-1}\left(\frac{a}{R}\right)
\]

\[
\theta = \cos^{-1}\left(\frac{R}{d}\right)
\]

\[
E_o = \pi B \tan^2 \alpha = \pi B \frac{a^2}{R^2}
\]
4.4 Radiometry of object point imaging

In this section, the radiometric equations for imaging a point object are reviewed. The entrance pupil of the lens system is at a distance \( L \) from the source and has an area \( A_{en} \). The exit pupil of the lens system is at distance \( L' \) from the image plane and has an area \( A_{xp} \). The off axis point object \( O \) is at a height \( h \) from the optic axis and has an intensity \( I_o \). The nominal image point height is \( h' \) and has an intensity \( I' \). The flux accepted by the nominal lens system is \( \phi_{en} \) and the solid angle subtended by the entrance pupil at the point object is \( \Omega_{en} \). The flux emerging from the exit pupil is \( \phi_{xp} \) and the solid angle subtended by the exit pupil at the image point is \( \Omega_{xp} \). The geometry is shown in Figure 4-3.

\[
I_o = \frac{\phi_{ep}}{\Omega_{ep}} \quad \text{and} \quad I' = \frac{\phi_{xp}}{\Omega_{xp}}
\]
Consider the system transmittance $T$ is, then \( \phi_{xp} = T \phi_{ep} \) and \( \phi_{ep} \) is given by:

\[
\phi_{ep} = I_o \frac{A_{ep}}{L^2} \cos^3 \bar{U} \quad \text{4-8}
\]

\[
\phi_{xp} = I' \frac{A_{xp}}{L'^2} \cos^3 \bar{U}' \quad \text{4-9}
\]

Substituting Eq.(4-10) in Eq.(4-9) yields:

\[
I' = TI_o \frac{A_{ep} L'^2 \cos^3 \bar{U}}{A_{xp} L^2 \cos^3 \bar{U}'} \quad \text{4-11}
\]

Since we are interested in the paraxial radiometric analysis, we can make the approximation \( \cos \bar{U} \simeq \cos^3 \bar{U}' \simeq 1 \), and Eq.(4-11)becomes:

\[
I' = TI_o \frac{A_{ep} L'^2}{A_{xp} L^2} \quad \text{4-12}
\]

### 4.5 Radiometry of Lambertian disc imaging

For a small exit pupil of radius \( a_{xp} \) and radiance \( B' \), the irradiance at the image plane due to a Lambertian disc is given by [12]:
\[ E = E_0 \cos^4 \theta_d \]  
\[ \text{Where:} \]
\[ E_0 = \pi B' \tan^2 \theta_d \]
\[ E_0 = \pi B \frac{n^2}{n^2} \frac{a_{xp}^2}{L^2} \]
\[ \theta_d = \tan^{-1}\left(\frac{y_d}{L}\right) \]

Again, in the paraxial regime, Eq.(4-13) becomes:
\[ E \approx \pi B \frac{n^2}{n^2} \frac{a_{xp}^2}{L^2} \]

**Figure 4-4 Radiometry of extended object imaging.**

**4.6 Ghost image irradiance of a point object**

The purpose of this section is to derive an expression for the ghost irradiance at the nominal image plane due to a point object. For each nominal lens system there are
several ghost lens systems that are associated with it. Two approaches are used to get the individual ghost irradiance at the nominal image plane. The total ghost irradiance at the nominal image plane is obtained by adding up the individual irradiance contributions from all possible ghosts.

4.6.1 Individual ghost image irradiance (first approach)

In this approach, the derivation of the individual ghost irradiance expression is done in two steps. The first step is to get the intensity of the ghost point image $O_g'$ at the ghost image plane. The second step is to consider the ghost point image $O_g'$ as a point source illuminating the nominal image plane.

**First step:**

The intensity of the ghost image point at the ghost image plane is given by:

$$I_g = T_g I_o$$
Where: it is assumed that the loss in the ghost system is only result of imperfect Fresnel ghost system transmittance $T_g$.

**Second step:**

The ghost irradiance on the nominal image plane due to the object point $O_g$ is $E_{g,n}$. Using equation 4-1 and the paraxial approximation yields,

$$E_{g,n} = \frac{I_g}{Z_{g,n}} \text{rect}\left[\frac{y_d - y_{g,n}'}{2y_{g,n}'}\right]$$

4-19

Where: $y_d$ is the height of an observation point at the nominal image plane and $\theta_d$ is the angle subtended by $y_d$ from the center of the ghost exit pupil.

**Figure 4-6 Ghost image of an off-axis point object at the nominal image plane.**
Substituting equation 4-12 into equation 4-19 gives:

\[ E_{g,n} = T_g \frac{I_o}{Z_{g,n}} \text{rect} \left( \frac{y_o - y_{g,n}}{2y_{g,n}} \right) \quad 4-20 \]

Equation 4-20 shows that the individual ghost irradiance is directly proportional to the ghost system transmittance and the point object intensity and is inversely proportional to the distance squared between the nominal and the ghost image planes. The paraxial ghost irradiance as a function of the ghost-nominal image planes separation is shown in Figure 4-7.

![Figure 4-7 Ghost irradiance at the nominal image plane as a function of the separation between the ghost and nominal image planes.](image)

4.6.2 Individual ghost image irradiance (second approach)

In this approach, the power accepted by the ghost entrance pupil is determined and is used to derive the power exiting the system through the ghost exit pupil. The ghost image irradiance is the ratio of the exiting ghost power to the area of the ghost image at
the nominal image plane \( A'_{g,n} \). The power accepted by the ghost entrance pupil \( \phi_{en,g} \) is given by:

\[
\phi_{en,g} = I_o \Omega_{en,g}
\]

\[
\phi_{en,g} = I_o \frac{A_{en,g}}{L_g^2}
\]

The power exiting the ghost system through the ghost exit pupil \( \phi_{xp} \) is given by:

\[
\phi_{xp,g} = T_g \phi_{en,g} = T_g I_o \frac{A_{en}}{L_g^2}
\]

Individual ghost image irradiance at the nominal image plane \( E_{g,n} \) is given by:

\[
E_{g,n} \approx T_g I_o \frac{A_{en,g}}{L_g^2 A'_{g,n}} \text{rect}\left(\frac{y'_{d} - y'_{g,n}}{2y'_{g,n}}\right)
\]

4.7 Ghost image irradiance of a Lambertian disc (extended source)

In this section, we derive an equation for the individual ghost image irradiances at the nominal image plane due to a Lambertian extended disc. This analysis assumes that the losses are due to Fresnel losses only. The net incoherent ghost irradiance at the nominal image plane is obtained by adding up the individual irradiance contributions from all possible ghosts.
Figure 4-8  Ghost radiometry of Lambertian disc.

Applying the approximation \( \cos^4 \theta_d \cong 1 \) and using Eq.(4-17), the individual ghost irradiance at the ghost image plane is given by:

\[
E_g \cong \pi BT_g \frac{n^2 a_{sp,g}^2}{L_g^{'2}}.
\]

The ghost power exiting the ghost system \( \phi_{sp,g} \) is obtained by multiplying Eq. (4-2) by the area of the ghost image at the ghost image plane \( A'_g \), i.e.:

\[
\phi_{sp,g} \cong \pi BT_g \frac{n^2 a_{sp,g}^2}{L_g^{'2}} A'_g.
\]

Individual ghost image irradiance at the nominal image plane \( E_{g,n} \) is obtained by dividing the ghost power by the ghost image area at the nominal image plane \( A'_{g,n} \).

\[
E_{g,n} = \pi BT_g \frac{n^2 A'_g a_{sp,g}^2}{n^2 A'_{g,n} L_g^{'2}} \text{rect} \frac{y_d - y'_{g,n}}{2y'_{g,n}}.
\]
The total incoherent ghost irradiance $E_g^T$ is obtained by adding up the contributions of all possible ghosts and is given by:

$$E_g^T = \sum_g \pi B T_g \frac{n^2}{n^2} A_g' \frac{A_{sp,g}^2}{A_{g,n}^2} \frac{A_g}{L_g^2} \frac{\text{rect} \left( \frac{y_d - y_{g,n}'}{2y_{g,n}'} \right)}{4-28}$$

### 4.8 Paraxial incoherent ghost irradiance point spread function

A ghost point spread function at the nominal image plane is defined as the cumulative ghost image irradiance distribution resulting from imaging an on-axis point object. The function $PSF_{g,n}$ is given by:

$$PSF_{g,n} = \sum_g E_{g,n} \quad 4-29$$

Substituting Eq. 4-20 in Eq. 4-29 gives the paraxial ghost irradiance point spread function at the nominal image plane:

$$PSF_{g,n} = \sum_g T_g I_o \frac{1}{Z_{g,n}} \frac{\text{rect} \left( \frac{y_d - y_{g,n}'}{2y_{g,n}'} \right)}{4-30}$$

Another form of the ghost point spread function is obtained by using Eq. 4-24 for the individual ghost contributions at the nominal image plane.

$$E_{g,n} = \sum_g T_g I_o \frac{A_{m,g}^2}{L_g^2 A_g'} \frac{\text{rect} \left( \frac{y_d - y_{g,n}'}{2y_{g,n}'} \right)}{4-31}$$
4.8.1 Example one

The following example will qualitatively elucidate the second order ghost irradiance paraxial point spread function. Assume an on-axis object point is imaged by a lens system that consists of three surfaces. The image plane irradiances distributions of the three ghosts are shown in Figure 4-9 and the paraxial ghost irradiance point spread function is shown in Figure 4-10.

![Figure 4-9 Individual ghost irradiances at the detector](image_url)
4.8.2 Example two

In this example an off-axis object point is imaged with the same lens system as in example one. Figure 4-11 illustrates the individual ghost irradiances while Figure 4-12 illustrates the off axis ghost irradiance at the detector.
Figure 4-11 Individual ghost irradiances at the detector.

Figure 4-12 Ghost irradiance distribution at the detector.
5 GHOST OPTICAL ABERRATIONS

5.1 Introduction

In general, the nominal lens system is designed to have minimum aberrations. Therefore, ghosts are expected to be highly aberrated in well corrected nominal systems. In this chapter, we review the formulas that are used to calculate the fourth order and the defocus aberration coefficients. These formulas are used to construct the ghost aberration function at the nominal image plane.

Ghost image surfaces: the Petzval, sagittal and tangential are presented. The curved ghost image surface leads to potential sharp focusing at the nominal image plane. For ghost systems that are dominated by astigmatism and field curvature, an expression for the points of intersection of the tangential and sagital ghost image surfaces with the nominal image plane is derived.

5.2 Ghost Petzval image surface

In Gaussian imaging, the object distance of any point in a certain object plane is treated as equal to the distance of the axial point. Therefore, there is a slight error in locating the image of an off-axis point object by an imaging surface. It has the consequence that the actual image of a planner object by a multi-surface imaging system is generally spherical, called the Petzval surface. The radius of curvature of the $R_p$ of the Petzval image surface is defined by [12]:

\[ R_p \]
\[
\frac{1}{R_p} = n_M \sum_{j=1}^{M} \frac{1}{R_j} \left( \frac{1}{n_j} - \frac{1}{n_{j-1}} \right)
\]

Where, \(n_{j-1}\) is the object space refractive index of surface \(\# j\), \(n_j\) is the image space refractive index of surface \(\# j\), \(R_j\) is radius of curvature of surface \(\# j\), and \(M\) is the number of surfaces in the nominal layout.

Similarly, the ghost Petzval radius of curvature \(R_{p,g}\) can be defined by,

\[
\frac{1}{R_{p,g}} = n_{Mg} \sum_{j=1}^{Mg} \frac{1}{R_{j,g}} \left( \frac{1}{n_{j,g}} - \frac{1}{n_{j-1,g}} \right)
\]

Where, \(n_{j-1,g}\) is the object space refractive index of surface \(\# j\) in the ghost layout, \(n_{j,g}\) is the image space refractive index of surface \(\# j\), \(R_{j,g}\) is radius of curvature of surface \(\# j\) in the ghost layout, and \(Mg\) is the number of surfaces in the ghost layout.
Two illustrations for the ghost and nominal paraxial image surfaces are shown in Figure 5-2. In Figure 5-2a: the ghost Petzval image surface doesn’t intersect the nominal Gaussian image surface. In Figure 5-2b: the ghost Petzval image surface and the nominal Gaussian image plane intersect at two points. At each intersection point, a potential ghost image is formed at the nominal Gaussian image surface.

Figure 5-2 Ghost (dotted) and nominal(solid) Petzval image surfaces. (a) Ghost Petzval image plane intersects the nominal Gaussian image plane at two points.
5.3 Defocus aberration coefficient

The defocus phase aberration of the optical wavefront at a point in the plane of the exit pupil with radial position $\rho$ measured with respect to a reference sphere of radius of curvature $L'$ is given by \[12\]:

$$\Phi_d(\rho) = \frac{2\pi}{\lambda} W_{020} \rho^2$$ \hspace{1cm} 5-3

Where: $W_{020}$ is the defocus wavefront aberration coefficient and is given by \[12\]:

$$W_{020} = \frac{1}{2} \left( \frac{1}{L'_d} - \frac{1}{L'} \right) a_{xp}^2$$ \hspace{1cm} 5-4

Figure 5-3 Schematic showing the various planes, object, exit pupil, defocused and nominal image planes.

5.4 Fourth order monochromatic aberration coefficients

Consider an optical system consisting of a series of rotationally symmetric coaxial refracting and/or reflecting surfaces imaging a point $p$ lying at a height $h$ from
the optical axis. Assume, without loss of generality that the point object lies along the y axis, and the Z axis is the optical axis of the system.

Figure 5-4 Object, exit pupil and image planes. The optical axis of the system is along the Z axis.

For optical systems with circular exit pupil of radius $a_{xp}$, the aberration function takes the form [13]:

$$W(\rho, \theta; H) = W_{040} \rho^4 + W_{131} H^3 \rho^3 \cos \theta + W_{222} H^2 \rho^2 \cos^2 \theta + W_{220} H^2 \rho^2 + W_{311} H^3 \rho \cos \theta$$

5-5

Where: the normalized coordinates $(\rho, H, \theta)$ are given by $\rho = r_p / a_{xp}$, $H = \frac{y'}{h'}$, and $-1 \leq \rho \leq 1$, $0 \leq \theta \leq 2\pi$. The fourth order aberration coefficients are: spherical $W_{040}$, coma $W_{131}$, astigmatism $W_{222}$, field curvature $W_{220}$, and distortion $W_{311}$. 
The fourth order monochromatic aberration coefficients are calculated by using first order ray tracing data. A summary of the aberration coefficients formulas are given in the following table [13]:

<table>
<thead>
<tr>
<th>Spherical aberration coefficient</th>
<th>$W_{640} = \frac{1}{8} S_I$</th>
<th>$S_I = -\sum A^2 y \Delta \left(\frac{u}{n}\right)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coma aberration coefficient</td>
<td>$W_{131} = \frac{1}{2} S_{II}$</td>
<td>$S_{II} = -\sum AB y \Delta \left(\frac{u}{n}\right)$</td>
</tr>
<tr>
<td>Astigmatism aberration coefficient</td>
<td>$W_{222} = \frac{1}{2} S_{III}$</td>
<td>$S_{III} = -\sum B^2 y \Delta \left(\frac{u}{n}\right)$</td>
</tr>
<tr>
<td>Field curvature aberration coefficient</td>
<td>$W_{220} = \frac{1}{4} S_{IV}$</td>
<td>$S_{IV} = -\sum C \Delta \left(\frac{1}{n}\right)$</td>
</tr>
<tr>
<td>Distortion aberration coefficient</td>
<td>$W_{311} = \frac{1}{8} S_{V}$</td>
<td>$S_{V} = -\sum \frac{B^2}{A} y \Delta \left(\frac{u}{n}\right) - C \sum \frac{B}{A} \Delta \left(\frac{1}{n}\right)$</td>
</tr>
</tbody>
</table>

Where, $A = ni = n(u + yC)$, $B = ni = n(u + yC)$, $\Sigma = n(u y - u y)$, $A = n'u' = n'(u' + yC)$, $B = n'u' = n(u' + yC)$, $\Sigma = n'(u' y - u' y)$, and $\Delta \left(\frac{u}{n}\right) = \left[\frac{u'}{n'} - \frac{u}{n}\right]$.

Here, $i$, $i'$ and $\Sigma$ are the angle of incidence measured with respect to the, the angle of refraction and the Lagrange invariant, respectively.
5.5 Ghost aberration function

In general the ghost image plane is defocused from the nominal image plane by a distance $\Delta Z_{g,n}$. The ghost aberration with respect to the reference sphere centered at a ghost defocused point lying at distance $L'_{g,n}$ from the plane of the ghost exit pupil may be written as:

$$W_g' (\rho, \theta, H) = W_g (\rho, \theta, H) + W_{020,g} (\rho)$$

Where, $W_g (\rho, \theta; H)$ and $W_{020,g} (\rho)$ are the ghost fourth order and defocus aberration functions, respectively.

The ghost fourth order functions includes the ghost aberration coefficients: spherical $W_{040,g}$, coma $W_{131,g}$, astigmatism $W_{222,g}$, field curvature $W_{220,g}$, and distortion $W_{311,g}$. Same formulas that are used to calculate the nominal fourth order aberration coefficients are used to calculate the ghost fourth order aberration coefficients, but with the substitution of the ghost parameters.

![Figure 5-5 Ghost and nominal image planes with respect to the ghost exit pupil.](image-url)
The ghost defocus aberration coefficient $W_{020,g}$ is obtained by the substitution of $L'$ by $L'_g$, $L'_d$ by $L'_{g,n}$ and $a_{sp}$ by $a_{sp,g}$ in equation (5-4). Thus, the ghost defocus aberration coefficient is given by:

$$W_{020,g} = \frac{1}{2} \left( \frac{1}{L'_{g,n}} - \frac{1}{L'_g} \right) a_{sp,g}^2$$  \hspace{1cm} (5-7)$$

For ghosts that are focused very near to the nominal image plane, the defocus aberration coefficient is given by:

$$W_{020,g} \approx \frac{1}{2} \frac{\Delta Z_{g,n}}{L'_g^2} a_{sp,g}^2$$  \hspace{1cm} (5-8)$$

$$W_{020,g} \approx \frac{1}{2} \frac{\Delta Z_{g,n}}{f' / \#_{w,g}}$$  \hspace{1cm} (5-9)$$

For ghost systems that form ghosts very near to the nominal image plane, the defocus aberration coefficient is inversely proportional to square of the ghost working f number $f' / \#_{w,g}$ and directly proportional the ghost-nominal image planes separation $\Delta Z_{g,n}$.

### 5.6 Points of intersection between the ghost image surfaces and the nominal Gaussian image plane

For a ghost lens system that is dominated by astigmatism and field curvature, the ghost sagittal and tangential image surfaces are parabolas and the ghost wavefront aberration function is given by:
The tangential ghost ray aberration is given by:

\[ \varepsilon_{y,g} = -2(f/#_{w,g})^2[W_{020,g}x_{y,g}^2 + 2W_{220,g}y_{y,g}H_g^2 + 2W_{222,g}y_{y,g}H_g^2] \]  

The tangential ghost image surface corresponds to \( \varepsilon_{y,g} = 0 \), therefore:

\[ W_{020,g} = -W_{220,g}H_g^2 - W_{222,g}H_g^2 \]  

\[ W_{020,g} \cong \frac{\delta Z_g}{8(f/#_{w,g})^2} \]  

The tangential ghost image surface is represented by:

\[ \delta Z_{t,g} \cong -8(f/#_{w,g})^2[W_{220,g}H_g^2 + W_{222,g}H_g^2] \]  

The ray aberration along x axis is given by:

\[ \varepsilon_{x,g} = -8(f/#_{w,g})^2[W_{020,g}x_{x,g}^2 + 2W_{220,g}x_{x,g}H_g^2] \]  

The sagittal image surface corresponds to \( \varepsilon_{x,g} = 0 \), therefore:

\[ W_{020,g} = -W_{220,g}H_g^2 \]  

The sagittal ghost image surface is represented by:

\[ \delta Z_{s,g} \cong -8(f/#_{w,g})^2W_{220,g}H_g^2 \]  

To find the points of intersection between the tangential ghost image surface and the Gaussian nominal image plane (\( \Delta Z_{g,n} = \delta Z_g \)), we solve the following equation:
\[ \Delta Z_{g,n} \approx -8 (f / \#_{w,g})^2 \left[ W_{220,g} H_g^2 + W_{222,g} H_g^2 \right] \]

Thus, the points of intersection \((\Delta Z_{g,n}, H_{g,t})\), if any are given by:

\[ H_{g,t} \approx \frac{-\Delta Z_{g,n}}{\sqrt{8(f / \#_{w,g})^2 \left[ W_{220,g} + W_{222,g} \right]}} \]

Similarly, the points of intersection between the sagittal ghost image surface and the Gaussian (if any) are given by:

\[ H_{g,s} \approx \frac{-\Delta Z_{g,n}}{\sqrt{8(f / \#_{w,g})^2 W_{220,g}}} \]

If the ghost image surface intersects the Gaussian nominal image plane, a focused ghost image is formed and these ghosts are problematic ghosts.

**Figure 5-6** Ghost tangential image surface intersects the ghost Gaussian image nominal image plane.
Figure 5-7 Ghost tangential image surface does not intersect the ghost Gaussian image nominal image plane.
6 DEPTH OF FIELD

6.1 Introduction

Depth of field is defined as the range of object distances over which an object is imaged with an acceptable blurring/contrast. Ghosts can reduce the image contrast and therefore, decrease the depth of field. In this chapter, a simulation model and an algorithm to estimate the depth of field for diffraction limited systems are introduced. This approach gives more complete understanding of the relation between object and the image. As a result, better understanding for the influence of the optical system parameters on the diffraction depth of field.

In addition, an experimental measurement technique that can be used to measure the depth of field for an imaging system is presented. The optical setup, experimental procedures, and results will be discussed. ZEMAX is used to simulate the depth of field for a nominal paraxial lens and the simulation results are compared to the experimental results.

6.2 Diffraction image

In high \( f \)-number systems, such as endoscopes, diffraction has a significant impact on imaging performance. The images of two point objects lying within the isoplanatic patch are identical except that they are centered at their respective Gaussian image points. Such an imaging is referred to as “shift-invariant imaging”. The diffraction
image of an isoplanatic incoherent object is equal to the convolution of its Gaussian image $i_g(x', y')$ and the point spread function of the imaging system $PSF(x', y')$ [15]:

$$i(x', y') = i_g(x', y') \otimes PSF(x', y')$$

6-1

The Gaussian image is simply a magnified (or demagnified) replication of the object $O$ and therefore, is represented by:

$$i_g(x', y') = \frac{1}{|m|} O\left(\frac{x'}{m}, \frac{y'}{m}\right)$$

6-2

Where, $m$ is the magnification of the system ($x' = mx$, $y' = my$), and $O(x, y)$ is the object distribution function.

### 6.3 Depth of field simulation model

The goal of this section is to develop a theoretical model to simulate the diffraction depth of field. The model is applicable only for fourth and higher order aberration corrected systems that might be subjected to defocus aberration coefficient $W_{020} \leq \lambda / 2$. In this model, the diffraction image is obtained by the convolution of the diffraction incoherent point spread function with the geometric image distribution. Image contrast at different object positions is calculated and thereby, the depth of field is simulated.
Figure 6-1 Object, exit pupil and image planes. $Z$ is the object distance from the front principle plane, $Z'$ is the image distance from the rear principle plane, $t_{xp}$ is the distance from the rear vertex to the exit pupil, $L'$ is the distance from the exit pupil to the Gaussian image plane.

Consider an imaging system as shown in Figure 6-1. The object function $O(x, y)$ is shown in Figure 6-2 and is represented by:

$$O(x, y) = \text{rect}\left(\frac{x + k}{b}\right)\text{rect}\left(\frac{y + k}{b}\right) + \text{rect}\left(\frac{x}{b}\right)\text{rect}\left(\frac{y}{b}\right) + \text{rect}\left(\frac{x - k}{b}\right)\text{rect}\left(\frac{y - k}{b}\right)$$

Figure 6-2 Object distribution function along the x axis.
The nominal Gaussian image \( i(x', y') \) is represented by:

\[
  i(x', y') = \frac{1}{|m|} \left[ \text{rect}\left(\frac{x' - m + k}{b}\right)\text{rect}\left(\frac{y' - m + k}{b}\right) + \text{rect}\left(\frac{x' - m}{b}\right)\text{rect}\left(\frac{y' - m}{b}\right) \right.
  
  \left. + \text{rect}\left(\frac{x' - m - k}{b}\right)\text{rect}\left(\frac{y' - m - k}{b}\right) \right]
\]

For aberration free system, the incoherent irradiance point spread function is given by [14]:

\[
  \text{IPSF}(r') = \frac{(2\pi)^2 E_o}{\lambda^2 L^2_n} \left| \int_0^{\Phi_o} J_o\left(\frac{2\pi r_p}{\lambda L'_d \Phi_o}\right) r_p dr_p \right|^2
\]

If the object is not at the nominal position, defocus is introduced in the system. The aberrated incoherent point spread function is given by [16]:

\[
  \text{IPSF}(r') = \frac{(2\pi)^2 E_o}{\lambda^2 L^2_d} \left| \int_0^{\Phi_o} \exp\left(i\Phi_d(r_p)\right) J_o\left(\frac{2\pi r_p}{\lambda L'_d \Phi_o}\right) r_p dr_p \right|^2
\]

Where: \( E_o \) is the irradiance on the exit pupil, \( \lambda \) is the wavelength, \( r \) is object position along at the object plane, \( r' \) is the image position along the image plane, and \( L'_d \) is the distance from the nominal exit pupil to the defocused image plane, and \( \Phi_d(r_p) \) is the phase defocus aberration term across the exit pupil and is given by [16]:

\[
  \Phi_d(r_p) = \frac{\pi}{\lambda} \left( \frac{1}{L'_d} - \frac{1}{L'_n} \right) r_p^2
\]

The diffraction image irradiance \( E(x', y') \) for an incoherent shift invariant imaging system is obtained by \( E(x', y') \) is given by:
\[ E(x', y) = i(x', y) \otimes IPSF(x', y) \]

Where, \( i(x', y) \) is the Gaussian image, and \( IPSF_s(x', y') \) is the irradiance point spread function for the lens system. The image contrast is calculated across the \( x' \) axis as shown in Figure 6-3. Therefore, the contrast \( C \) is calculated by the following equation:

\[
C = \frac{E(x' = 0; y' = 0) - E(x' = b'; y' = 0)}{E(x' = 0; y' = 0) + E(x' = b'; y' = 0)}
\]

![Image irradiance across the x' axis.](image)

Image contrast is simulated for several object positions. According to the system application, the minimum acceptable contrast is defined and thereby, the depth of field is estimated.

### 6.4 Diffraction depth of field simulation algorithm

A flow chart for the simulation of the depth of field is shown in Figure 6-4 and is discussed as follows: Given the distance from the rear vertex to the rear principle
plane $d'$, the exit pupil radius $a_{xp}$, the distance from the rear vertex to the exit pupil $t_{xp}$, the effective focal length $f_e$ for the lens system, detector location with respect to the rear principle plane $Z_n'$, and the resolution $\eta = 1/k$.

1. Calculate the nominal object position $Z_n$ [11]:

$$Z_n = \frac{Z_n' \cdot f_e}{f_e - Z_n'}$$  \hspace{1cm} 6-10

2. Calculate image location with respect to the exit pupil $L_{n}'$ by:

$$L_{n}' = Z_n' + d' - t_{xp}$$  \hspace{1cm} 6-11

3. Calculate the magnification and use it to determine the Gaussian image given by Eq. (6-4).

4. Use Eq. (6-5) to calculate nominal the incoherent point spread function.

5. Convolve the irradiance point spread function with the Gaussian image.

6. Measure the image contrast across the axis $x'$. 

7. If the contrast is greater than the required accepted value $C_{\text{acceptable}}$, go to step 8. If the contrast is almost equal to required accepted value $C_{\text{acceptable}}$, go to step 15.

8. Increment/decrement the object position by a small value.

9. Calculate the new Gaussian image location by:

$$Z' = \frac{Zf_e}{Z + f_e}$$  \hspace{1cm} 6-12

10. Calculate the image location with respect to the exit pupil $L_{d}'$ by:

$$L_{d}' = Z' + d' - t_{xp}$$  \hspace{1cm} 6-13
11. Calculate the magnification and use it to determine the Gaussian image given by Eq. (6-4).

12. Calculate the phase defocus term given by Eq. (6-7).

13. Use Eq. (6-6) to simulate the defocused irradiance point spread function.

14. Go to step (5).

15. Determine the range of object distances (depth of field) that correspond to an acceptable contrast range.

Figure 6-4 Depth of field simulation flow chart. \( \eta_i \) is the initial value of resolution, \( \Delta \eta \) is the desired resolution range.
In general the scene has different spatial frequencies, so it might be desirable to simulate the depth of field as a function of the possible spatial frequencies. This can be done straightforward by incrementing/decrementing the target resolution and repeating steps 1 through 15. In addition, the depth of field as a function of wavelength can be simulated easily with this approach.

6.5 Depth of field experimental measurement technique

In this section the optical setup, the experimental procedures, and the experimental results are provided and discussed.

6.5.1 Depth of field optical set up

The optical setup for measuring the depth of field of Canon camera (EOS Rebel XSi) consists of a USAF Glass Slide resolution target that is mounted in a micrometer translation stage and a PC computer. The Canon camera consists of a 12.2 MP CMOS sensor and Canon lens with focal length of 60 mm and f/8. The camera is connected to a PC computer as shown in Figure 6-5.

Figure 6-5: Optical set up for measuring the depth of field.
The USAF target is translated in small steps around its nominal position and its image is recorded. For each resolution, the grey value across the three bars is displayed by using ImageJ software. The contrast is measured and plotted as a function in object position.

### 6.5.2 Experimental procedures

The image of a sub-target with resolution of 2 cycles/mm at the nominal position is shown in Figure 6-6a. The grey value profile across the sub-target is shown in Figure 6-6b.

![Figure 6-6](image.png)

(a) Image of a sub-target that has a resolution of 1/250um at its nominal position.

(b) Grey value profile across a sub-target.

Figure 6-6 Image of a sub-target that has a resolution of 1/250um at its nominal position.(b) Grey value profile across a sub-target.
Moving the USAF target from the nominal position will introduce defocus causing the blurriness of the object and contrast drop, this is illustrated in Figure 6-7.

6.5.3 Experimental Results

Contrast as a function in object position along the optical axis (Z) for resolution of 2, 4, 6.35, 8 and 10.1 cycles/mm are shown in Figure 6-8a, Figure 6-8.b, Figure 6-8.c, Figure 6-8.d, Figure 6-8.e, respectively.
Contrast vs displacement along z axis
f/8 bar separation 250 um
(0 corresponds to initial location of the object)

(6-8.a)

Contrast vs displacement along z axis
f/8 bar separation 125 um
(Resolution of 4 cycles/mm)

(6-8.b)
Contrast vs object displacement
f/8 bar separation 78.74 um
Resolution is 6.35 cycles/mm

Contrast vs. displacement along z axis
f/8 bar separation 62.5 um
(Resolution is 8 cycles/mm)

(6-8.c)

(6-8.d)
Figure 6-8 Contrast vs. object position for several resolutions: 2, 4, 6.35, 8, and 10.1 cycles/mm are shown in Figure 6-8.a, Figure 6-8.b, Figure 6-8.c, Figure 6-8.d, and Figure 6-8.e, respectively.

For each resolution, and for minimum acceptable contrast of $0.3C_{\text{max}}$, the depth of field is determined as shown in Table 6-1. The depth of field as a function in resolution for $0.3C_{\text{max}}$, $0.5C_{\text{max}}$, $0.7C_{\text{max}}$, and $0.7C_{\text{max}}$ are plotted in Figure 6-9.

Table 6-1 Depth of field values vs. resolution. The minimum acceptable contrast is $0.3C_{\text{max}}$

<table>
<thead>
<tr>
<th>Target label (group#,element#)</th>
<th>Resolution (cycles/mm)</th>
<th>DOF(mm)</th>
<th>Maximum contrast $C_{\text{max}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1,1)</td>
<td>2</td>
<td>14.5</td>
<td>0.95</td>
</tr>
<tr>
<td>(2,1)</td>
<td>4</td>
<td>7.3</td>
<td>0.93</td>
</tr>
<tr>
<td>(2,5)</td>
<td>6.35</td>
<td>4.75</td>
<td>0.89</td>
</tr>
<tr>
<td>(3,1)</td>
<td>8</td>
<td>3.35</td>
<td>0.76</td>
</tr>
<tr>
<td>(3,3)</td>
<td>10.1</td>
<td>2.7</td>
<td>0.74</td>
</tr>
</tbody>
</table>
6.6 Measuring the depth of field with ZEMAX

The depth of field can be estimated with ZEMAX by imaging a point object that is placed at a distance $-2f_e$ from a thin lens. The effective focal length of the lens is 60mm. The FFT through focus MTF for two resolutions: 2cycles/mm and 10cycles/mm are shown in Figure 6-10 and Figure 6-11, respectively. For several acceptable contrast ranges, the depth of field simulation values as a function in resolution is shown in Figure 6-12.
Figure 6-10 FFT through focus for spatial frequency 2 cycles per mm

Figure 6-11 FFT through focus for the spatial frequency 10.00 cycles per mm
6.7  Comparison between ZEMAX and experimental technique results

In this section, we compare the depth of field experimental values with the simulation values that are obtained with ZEMAX. The experimental and simulation results show good agreement for the two contrast criteria: $0.3 \, C_{\text{max}}$ and $0.5 \, C_{\text{max}}$ as shown in Figure 6-13 and Figure 6-14, respectively. As the acceptable contrast range increase, the depth of field increases and the experimental and simulation depth of field start to deviate from each other. This becomes more obvious for small resolution values as shown in Figure 6-15 and Figure 6-16.
Figure 6-13 Experimental and ZEMAX simulation depth of field results as a function of resolution.
The acceptable contrast range is $0.3 \ C_{\text{max}}$.

Figure 6-14 Experimental and ZEMAX simulation depth of field results as a function of resolution.
The acceptable contrast range is $0.5 \ C_{\text{max}}$. 
Figure 6-15 Experimental and ZEMAX simulation depth of field results as a function of resolution. The acceptable contrast range is $0.7 \ C_{max}$

Figure 6-16 Experimental and ZEMAX simulation depth of field results as a function of resolution. The acceptable contrast range is $0.9 \ C_{max}$
7 SIMULATION OF GHOST IMAGES

7.1 Introduction

In this chapter, we apply the geometrical and radiometric models that we have developed in the previous chapters to simulate ghost effects by three lens systems: paraxial biconvex lens, paraxial lens with a parallel plane plate, and the wide angle mapping camera lens.

7.2 Ghost simulation results for a biconvex lens

In this section we simulate ghost effects by a biconvex lens. For each possible second order ghost, the ghost geometrical parameters are calculated and the paraxial irradiance ghost point spread function is estimated. Ghost simulations by Fred are provided and compared to the results obtained by the ghost paraxial model. A comparison between the results of the simulation model and Fred is done.

7.2.1 Paraxial ghost image analysis

The nominal lens prescription and layouts are shown in Table 7-1 and Figure 7-1, respectively.

<table>
<thead>
<tr>
<th>Type</th>
<th>Comment</th>
<th>Radius</th>
<th>Thickness</th>
<th>Glass</th>
<th>Semi-Diameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>CT1</td>
<td>Standard</td>
<td>Infinity</td>
<td>Infinity</td>
<td></td>
<td>0.200000</td>
</tr>
<tr>
<td>CTD1</td>
<td>Standard</td>
<td>100.000000</td>
<td>5.000000</td>
<td>BK7</td>
<td>5.000000</td>
</tr>
<tr>
<td>CTZ</td>
<td>Standard</td>
<td>-100.000000</td>
<td>9.613447</td>
<td></td>
<td>4.510000</td>
</tr>
<tr>
<td>CTM1</td>
<td>Standard</td>
<td>Infinity</td>
<td>-</td>
<td></td>
<td>0.020061</td>
</tr>
</tbody>
</table>

Table 7-1 The prescription of a biconvex lens.
Figure 7-1 Biconvex lens layout

The ghost layout prescription is generated by the macro and is given in Table 7-2. Paraxial ray tracing is performed and the heights $y_g$ and optical angles $\omega_g$ of the marginal ghost ray are shown in Table 7-3. A sketch of the ghost lens with the geometrical parameters is shown in Figure 7-2. The ghost lens system has an effective focal length $f_{r.g}$, rear focal length $f_{R.g}$, back focal distance $BFD_g$, and the location of the rear ghost principle plane with respect to the rear vertex $d'_g$ are given in Table 7-4. The locations of the entrance and exit pupils $(Vep_g,V'xp_g)$ along with their diameters $(D_{ep.g},D_{xp.g})$ are given in Table 7-5. The values for $L'_g, L'_{g,n}, \Delta Z_{g,n}$ and $f/#_g$ are given in Table 7-5. Ghost reflectance/transmittance at each surface is given in Table 7-6.
Figure 7-2 Sketch of the biconvex lens with geometrical ghost parameters $BFD_g$, $d'_g$, $L'_g$, $\Delta Z_{g,n}$, $L'_{g,n}$, and $y'_{g,n}$.

Table 7-2 Ghost layout prescription. $S_n$ is the surface number in the nominal layout. $S_g$ is the surface number in the ghost layout.

<table>
<thead>
<tr>
<th>$S_n$</th>
<th>$S_g$</th>
<th>$n_g$</th>
<th>$t_g$ (mm)</th>
<th>$C_g$ (mm)</th>
<th>$\omega_g$ (mm)</th>
<th>$a_g$ (mm)</th>
<th>$T_g$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>1</td>
<td>infinity</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>-1.5168</td>
<td>5</td>
<td>0.01</td>
<td>5</td>
<td>0.0422</td>
<td>0.9578</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>1.5168</td>
<td>-5</td>
<td>-0.01</td>
<td>5</td>
<td>0.0422</td>
<td>0.9578</td>
</tr>
<tr>
<td>1</td>
<td>3</td>
<td>1</td>
<td>95</td>
<td>-0.01</td>
<td>5</td>
<td>0.0422</td>
<td>0.9578</td>
</tr>
<tr>
<td>2</td>
<td>4</td>
<td>1</td>
<td>95</td>
<td>-0.01</td>
<td>5</td>
<td>0.0422</td>
<td>0.9578</td>
</tr>
<tr>
<td>3</td>
<td>5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 7-3 Ghost marginal and chief rays (heights and angles at each surface in the ghost lens)

<table>
<thead>
<tr>
<th>$S_n$</th>
<th>$S_g$</th>
<th>$y_g$ (mm)</th>
<th>$\omega_g$ (radians)</th>
<th>$\bar{y}_g$ (mm)</th>
<th>$\bar{\omega}_g$ (radians)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>5.0000</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>5.0000</td>
<td>-0.0258</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>4.9148</td>
<td>-0.1749</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>3</td>
<td>4.3382</td>
<td>-0.3065</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>4</td>
<td>3.3277</td>
<td>-0.3237</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>5</td>
<td>-27.7251</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
Table 7-4 Ghost effective focal length $f_{e,g}$, rear focal length $f_{R,g}$, the back focal distance $BFD_g$ and the distance from rear vertex to ghost rear principle plane $d'_g$.

<table>
<thead>
<tr>
<th>$f_{e,g}$ (mm)</th>
<th>$f_{R,g}$ (mm)</th>
<th>$BFD_g$ (mm)</th>
<th>$d'_g$ (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>15.44</td>
<td>15.44</td>
<td>10.28</td>
<td>-5.16</td>
</tr>
</tbody>
</table>

Table 7-5 Ghost entrance $Vep_g$ and exit pupils locations $V'xp_g$, ghost entrance $D_{ep,g}$ and exit pupils $D_{xp,g}$ diameters, ghost exit pupil location with respect to the ghost Gaussian image plane $L'_g$, ghost exit pupil location with respect to the nominal Gaussian image plane $L'_{g,n}$.

<table>
<thead>
<tr>
<th>$Vep_g$ (mm)</th>
<th>$D_{ep,g}$ (mm)</th>
<th>$V'xp_g$ (mm)</th>
<th>$L'_g$ (mm)</th>
<th>$\Delta Z_{g,n}$ (mm)</th>
<th>$L'_{g,n}$ (mm)</th>
<th>$D_{xp,g}$ (mm)</th>
<th>$f$/#$_g$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>10</td>
<td>-12.93</td>
<td>23.21</td>
<td>85.92</td>
<td>108.6</td>
<td>15.03</td>
<td>1.54</td>
</tr>
</tbody>
</table>

Table 7-6 Ghost transmittance $T_g$ /reflectance $R_g$ at each surface of the ghost layout and the net ghost transmittance. $S_g$ is the surface number in the ghost layout and $S_n$ is the corresponding surface number in the nominal layout.

<table>
<thead>
<tr>
<th>$S_n$</th>
<th>$S_g$</th>
<th>$T_g$</th>
<th>$R_g$</th>
<th>Net ghost transmittance</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>0.9578</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td></td>
<td>0.0422</td>
<td></td>
</tr>
<tr>
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<td>0.0422</td>
<td></td>
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<td>4</td>
<td>0.9578</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>5</td>
<td></td>
<td></td>
<td>0.0016</td>
</tr>
</tbody>
</table>
7.2.2 Comparing ghost irradiance by the simulation model and FRED software

The paraxial ghost irradiance profile obtained by the paraxial simulation model is compared to the exact ghost irradiance profile obtained by FRED. The two profiles are shown in Figure 7-3. The processing time to trace $10^6$ rays by FRED is about 26 seconds.

![Figure 7-3 Incoherent point spread function by FRED (solid line) and the simulation model (dotted line).](image)

7.2.3 Simulation results for the ghost aberration coefficients

For an on axis object point, only spherical aberration exists and the ghost spherical aberration coefficients at each ghost surface are given in Table 7-7. Ghost total spherical aberration coefficient $W_{020,g} = 20.9815$ waves for light with wavelength of 0.587 microns. The ghost defocus aberration coefficient is -1630 waves and this ghost is highly aberrated.
Table 7-7 Ghost spherical aberration coefficient $W_{040,g}$ at each surface in the ghost layout.

<table>
<thead>
<tr>
<th>Ghost surface number</th>
<th>$W_{040,g}$ (waves)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>0.0299</td>
</tr>
<tr>
<td>2</td>
<td>0.6835</td>
</tr>
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<td>3.0625</td>
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<td>4</td>
<td>17.2056</td>
</tr>
<tr>
<td>5</td>
<td></td>
</tr>
</tbody>
</table>

7.3 Biconvex lens with plane parallel plate

In this section we emphasize that the nominal aperture stop is not the ghost stop in some systems. The system consists of a biconvex lens and a plane parallel plate and the nominal prescription is given in Table 7-8. The nominal layout is shown in Figure 7-4.

Figure 7-4 Nominal layout for a biconvex lens and plane parallel plate.

Table 7-8 The prescription for the nominal system prescription

<table>
<thead>
<tr>
<th>Part</th>
<th>Type</th>
<th>Comment</th>
<th>Radius</th>
<th>Thickness</th>
<th>Glass</th>
<th>Semi-Diameter</th>
<th>Comic</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Standard</td>
<td>Infinity</td>
<td>Infinity</td>
<td></td>
<td></td>
<td>9.000000</td>
<td>0.900000</td>
</tr>
<tr>
<td>0</td>
<td>Standard</td>
<td>140.0000</td>
<td>0.00000</td>
<td>B27</td>
<td></td>
<td>5.000000</td>
<td>0.900000</td>
</tr>
<tr>
<td>1</td>
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<td>-140.0000</td>
<td>0.090000</td>
<td></td>
<td></td>
<td>4.919533</td>
<td>0.900000</td>
</tr>
<tr>
<td>2</td>
<td>Standard</td>
<td>Infinity</td>
<td>1.000000</td>
<td></td>
<td></td>
<td>2.399922</td>
<td>0.900000</td>
</tr>
<tr>
<td>3</td>
<td>Standard</td>
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<td>41.254700</td>
<td></td>
<td></td>
<td>2.330740</td>
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<tr>
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<td></td>
<td></td>
<td>9.000000</td>
<td>0.900000</td>
</tr>
</tbody>
</table>
This system has six ghosts which are formed by reflection between the lens’ surfaces, namely $G_{2,1}$, $G_{3,1}$, $G_{3,2}$, $G_{4,1}$, $G_{4,2}$, and $G_{4,3}$. For each ghost, the ratio between an on axis ghost ray height and the corresponding surface semidiameter is shown in Table 7-9. The surface that serves as the ghost aperture stop corresponds to the maximum ratio as shown in Table 7-10.

### Table 7-9 The ratio between the preliminary ghost marginal ray and the corresponding semi-diameter surface in the ghost layout.

<table>
<thead>
<tr>
<th>Ghost surface #</th>
<th>$G_{2,1}$</th>
<th>$G_{3,1}$</th>
<th>$G_{3,2}$</th>
<th>$G_{4,1}$</th>
<th>$G_{4,2}$</th>
<th>$G_{4,3}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>2</td>
<td>0.1966</td>
<td>0.1966</td>
<td>0.1966</td>
<td>0.1966</td>
<td>0.1966</td>
<td>0.1966</td>
</tr>
<tr>
<td>3</td>
<td>0.1735</td>
<td>0.2011</td>
<td>0.2011</td>
<td>0.2011</td>
<td>0.2011</td>
<td>0.2011</td>
</tr>
<tr>
<td>4</td>
<td>0.1331</td>
<td>0.0084</td>
<td>0.0084</td>
<td>0.2010</td>
<td>0.2010</td>
<td>0.2010</td>
</tr>
<tr>
<td>5</td>
<td>1.0991</td>
<td>0.0150</td>
<td>0.02547</td>
<td>0.1953</td>
<td>0.1953</td>
<td>0.1953</td>
</tr>
<tr>
<td>6</td>
<td>1.1331</td>
<td>0.0201</td>
<td>0.2615</td>
<td>0.0111</td>
<td>0.0111</td>
<td>0.1953</td>
</tr>
<tr>
<td>7</td>
<td>_____</td>
<td>0.1976</td>
<td>_____</td>
<td>0.0176</td>
<td>0.2663</td>
<td>0.1952</td>
</tr>
<tr>
<td>8</td>
<td>_____</td>
<td>0.2025</td>
<td>_____</td>
<td>0.0224</td>
<td>0.2733</td>
<td>_____</td>
</tr>
<tr>
<td>9</td>
<td></td>
<td></td>
<td></td>
<td>0.1913</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.1959</td>
<td></td>
</tr>
</tbody>
</table>

### Table 7-10 Surface that serves as the ghost aperture stop in the ghost layout.

<table>
<thead>
<tr>
<th>Surface that serves as the ghost stop in the ghost layout</th>
<th>$G_{2,1}$</th>
<th>$G_{3,1}$</th>
<th>$G_{3,2}$</th>
<th>$G_{4,1}$</th>
<th>$G_{4,2}$</th>
<th>$G_{4,3}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface that serves as the ghost stop in the ghost layout</td>
<td>6</td>
<td>8</td>
<td>6</td>
<td>3</td>
<td>8</td>
<td>3</td>
</tr>
</tbody>
</table>
7.4 **Biconvex lens and an extended parallel plane plate**

In this section, the plate semi-diameter is increased so that the nominal aperture stop AS is the AS for all ghosts. The system prescription is given in Table 7-11. For an on axis object point at infinity, paraxial ray tracing is performed for each ghost layout prescription and the geometrical paraxial results are shown in Table 7-12 and Table 7-13.

<table>
<thead>
<tr>
<th>Surface #</th>
<th>Radius</th>
<th>thickness</th>
<th>Material</th>
<th>Semidiameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>100</td>
<td>5</td>
<td>BK7</td>
<td>5</td>
</tr>
<tr>
<td>2</td>
<td>-100</td>
<td>50</td>
<td></td>
<td>5</td>
</tr>
<tr>
<td>3</td>
<td>Infinity</td>
<td>1</td>
<td>BK7</td>
<td>20</td>
</tr>
<tr>
<td>4</td>
<td>Infinity</td>
<td>45.25</td>
<td></td>
<td>20</td>
</tr>
<tr>
<td>Image</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Ghost</th>
<th>$f_{e,g}$ (mm)</th>
<th>$BFD_g$ (mm)</th>
<th>$d'_g$ (mm)</th>
<th>$y'_{g,n}$ (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$G_{2,1}$</td>
<td>15.447</td>
<td>-40.38</td>
<td>-55.825</td>
<td>-27.7216</td>
</tr>
<tr>
<td>$G_{3,1}$</td>
<td>138.1156</td>
<td>-64.5371</td>
<td>-202.6527</td>
<td>-3.9745</td>
</tr>
<tr>
<td>$G_{3,2}$</td>
<td>90.2153</td>
<td>-54.4331</td>
<td>-144.6485</td>
<td>-5.5247</td>
</tr>
<tr>
<td>$G_{4,1}$</td>
<td>149.099</td>
<td>-67.3887</td>
<td>-216.4877</td>
<td>-3.1169</td>
</tr>
<tr>
<td>$G_{4,2}$</td>
<td>88.0681</td>
<td>-55.5335</td>
<td>-143.6015</td>
<td>-5.7219</td>
</tr>
<tr>
<td>$G_{4,3}$</td>
<td>97.5804</td>
<td>43.9402</td>
<td>-53.6402</td>
<td>-0.0671</td>
</tr>
</tbody>
</table>
Table 7-13 Ghost entrance and exit pupil diameters ($D_{xp,g}$ and $D_{ep,g}$), the ghost exit pupil location with respect to the ghost image plane $L'_g$, the ghost exit pupil location with respect to the nominal image plane $L'_{g,n}$, the ghost f numbers $f/\#_g$, and the ghost-nominal planes separation $\Delta Z_{g,n}$.

<table>
<thead>
<tr>
<th>Ghost</th>
<th>$D_{ep,g}$ (mm)</th>
<th>$L'_g$ (mm)</th>
<th>$\Delta Z_{g,n}$ (mm)</th>
<th>$L'_{g,n}$ (mm)</th>
<th>$D_{xp,g}$ (mm)</th>
<th>$f/#_g$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$G_{2,1}$</td>
<td>10</td>
<td>23.204</td>
<td>85.63</td>
<td>108.837</td>
<td>15.0255</td>
<td>1.5445</td>
</tr>
<tr>
<td>$G_{3,1}$</td>
<td>10</td>
<td>-43.7472</td>
<td>109.7871</td>
<td>66.0399</td>
<td>3.1674</td>
<td>13.8116</td>
</tr>
<tr>
<td>$G_{3,2}$</td>
<td>10</td>
<td>29.9239</td>
<td>99.6831</td>
<td>129.6071</td>
<td>3.3169</td>
<td>9.0215</td>
</tr>
<tr>
<td>$G_{4,1}$</td>
<td>10</td>
<td>-46.4730</td>
<td>112.6387</td>
<td>66.1657</td>
<td>3.1169</td>
<td>14.9099</td>
</tr>
<tr>
<td>$G_{4,2}$</td>
<td>10</td>
<td>28.9627</td>
<td>100.7834</td>
<td>129.7461</td>
<td>3.2887</td>
<td>8.8068</td>
</tr>
<tr>
<td>$G_{4,3}$</td>
<td>10</td>
<td>99.2716</td>
<td>1.3098</td>
<td>100.5814</td>
<td>10.1733</td>
<td>9.1733</td>
</tr>
</tbody>
</table>

The most serious ghost for this system is the $G_{4,3}$ ghost because, the separation between the nominal and ghost image planes $\Delta Z_{g,n}$ is 1.3098mm. The locations of the rear focal and rear principles points relative to the nominal system elements are shown in Figure 7-5 and Figure 7-6, respectively.

![Diagram](image-url)  
Figure 7-5 Locations of the ghost images (rear focal points) with respect to the nominal system elements. Figure is not to scale.
Figure 7-6 Locations of the rear principle points with respect to the nominal system elements. Figure is not to scale.

7.4.1 Ghost aberrations

The ghost defocus aberration coefficient $W_{020g}$ and ghost spherical aberration coefficient $W_{040g}$ for second order possible ghosts are shown in Table 7-14.

Table 7-14 Ghost spherical and defocus aberration coefficients

<table>
<thead>
<tr>
<th>Ghost</th>
<th>$W_{040g}$ (waves)</th>
<th>$W_{020g}$ (waves)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$G_{2,1}$</td>
<td>20.1097</td>
<td>-1630</td>
</tr>
<tr>
<td>$G_{3,1}$</td>
<td>0.4542</td>
<td>81.1860</td>
</tr>
<tr>
<td>$G_{3,2}$</td>
<td>0.4506</td>
<td>-60.2176</td>
</tr>
<tr>
<td>$G_{4,1}$</td>
<td>0.4551</td>
<td>75.7842</td>
</tr>
<tr>
<td>$G_{4,2}$</td>
<td>0.4490</td>
<td>-61.7686</td>
</tr>
<tr>
<td>$G_{4,3}$</td>
<td>0.4502</td>
<td>-2.8911</td>
</tr>
</tbody>
</table>
7.4.2 Comparing the simulated ghost irradiances with FRED

The individual paraxial ghost irradiances obtained by the simulation model are given in Table 7-15. The individual simulated paraxial ghost irradiance for each ghost is compared to FRED results as shown in Figure 7-7 and through Figure 7-12.

<table>
<thead>
<tr>
<th>Ghost</th>
<th>( T_g )</th>
<th>( E_{g,n} ) (watts/mm(^2))</th>
</tr>
</thead>
<tbody>
<tr>
<td>( G_{2,1} )</td>
<td>00016</td>
<td>( 6.4648 \times 10^{-7} )</td>
</tr>
<tr>
<td>( G_{3,1} )</td>
<td>0.0014</td>
<td>( 2.7705 \times 10^{-5} )</td>
</tr>
<tr>
<td>( G_{3,2} )</td>
<td>0.0015</td>
<td>( 1.56 \times 10^{-5} )</td>
</tr>
<tr>
<td>( G_{4,1} )</td>
<td>0.0013</td>
<td>( 4.1347 \times 10^{-5} )</td>
</tr>
<tr>
<td>( G_{4,2} )</td>
<td>0.0014</td>
<td>( 1.3956 \times 10^{-5} )</td>
</tr>
<tr>
<td>( G_{4,3} )</td>
<td>0.0016</td>
<td>0.1104</td>
</tr>
</tbody>
</table>

Figure 7-7 Ghost irradiance by the simulation model (dotted line) and FRED (solid line) for ghost \( G_{32} \)
Figure 7-8 Ghost irradiance by the simulation model (dotted line) and FRED (solid line) for ghost $G_{21}$.

Figure 7-9 Ghost irradiance by the simulation model (dotted line) and FRED (solid line) for ghost $G_{41}$. 
Figure 7-10 Ghost irradiance by the simulation model (dotted line) and FRED (solid line) for ghost $G_{31}$

Figure 7-11 Ghost irradiance by the simulation model (dotted line) and Fred (solid line) for ghost $G_{42}$
Figure 7-12 Irradiance point spread function by the simulation model (dotted line) and FRED (solid line) for ghost $G_{43}$.

Figure 7-13 Irradiance distribution for ghosts $G_{42}$, $G_{41}$, $G_{32}$, $G_{31}$, $G_{32}$ at the nominal image plane.
The ghost irradiance point spread function for this lens system, is shown in Figure 7-14. The plane parallel plate has the main contribution to the ghost irradiance at the nominal Gaussian image plane.

![Figure 7-14 Ghost irradiance point spread function for a biconvex lens and a glass plate after it.](image)

7.4.3 Small aperture stop lens system

The purpose of this section is to simulate ghost effects system that consists of a biconvex lens and a parallel plane plate. The curvatures, refractive indices, and thickness are the same as for the lens system that is prescribed in section 7.3. The semi-diameter of the aperture stop in this example is much smaller than the semi-diameter of the aperture stop in the previous example. The system prescription is given in Table 7-16.
Table 7-16 Lens prescription.

<table>
<thead>
<tr>
<th>Surface</th>
<th>Radius</th>
<th>Thickness (mm)</th>
<th>Glass</th>
<th>Semi-diameter (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Object</td>
<td>Infinity</td>
<td>Infinity</td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>Stop</td>
<td>100</td>
<td>5</td>
<td>BK7</td>
<td>0.5</td>
</tr>
<tr>
<td>2</td>
<td>-100</td>
<td>50</td>
<td></td>
<td>5</td>
</tr>
<tr>
<td>3</td>
<td>Infinity</td>
<td>1</td>
<td>BK7</td>
<td>20</td>
</tr>
<tr>
<td>4</td>
<td>Infinity</td>
<td>45</td>
<td></td>
<td>20</td>
</tr>
<tr>
<td>Image</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

For this lens system, paraxial ghost image analysis is performed to calculate the paraxial ghost parameters. For each ghost, the values of $D_{ep,g}$, $L'_{g,n}$, and $D_{sp,g}$ are given in Table 7-17. The ghost aberrations are calculated and are given in Table 7-18. The ghost $G_{2,1}$ has the largest amount of aberrations, while the ghost $G_{4,3}$ has the lowest amount of aberrations.

Table 7-17 Ghost entrance and exit pupil diameter ($D_{ep,g}$ and $D_{sp,g}$), ghost exit pupil location with respect to the nominal image plane $L'_{g,n}$.

<table>
<thead>
<tr>
<th>Ghost</th>
<th>$D_{ep,g}$ (mm)</th>
<th>$L'_{g,n}$ (mm)</th>
<th>$D_{sp,g}$ (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$G_{2,1}$</td>
<td>0.5</td>
<td>108.837</td>
<td>1.502</td>
</tr>
<tr>
<td>$G_{3,1}$</td>
<td>0.5</td>
<td>66.0399</td>
<td>0.316</td>
</tr>
<tr>
<td>$G_{3,2}$</td>
<td>0.5</td>
<td>129.6071</td>
<td>0.332</td>
</tr>
<tr>
<td>$G_{4,1}$</td>
<td>0.5</td>
<td>66.1657</td>
<td>0.312</td>
</tr>
<tr>
<td>$G_{4,2}$</td>
<td>0.5</td>
<td>129.7461</td>
<td>0.329</td>
</tr>
<tr>
<td>$G_{4,3}$</td>
<td>0.5</td>
<td>100.5814</td>
<td>1.017</td>
</tr>
</tbody>
</table>
Table 7-18 Ghost aberration spherical $W_{040g}$ and defocus $W_{020g}$ aberration coefficients.

<table>
<thead>
<tr>
<th>Ghost</th>
<th>$W_{040g}$ (waves)</th>
<th>$W_{020g}$ (waves)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$G_{2,1}$</td>
<td>-16.2995</td>
<td>0.0020</td>
</tr>
<tr>
<td>$G_{3,1}$</td>
<td>0.8119</td>
<td>4.54*10^{-5}</td>
</tr>
<tr>
<td>$G_{3,2}$</td>
<td>-0.6022</td>
<td>4.5*10^{-5}</td>
</tr>
<tr>
<td>$G_{4,1}$</td>
<td>0.7578</td>
<td>4.55*10^{-5}</td>
</tr>
<tr>
<td>$G_{4,2}$</td>
<td>-0.6177</td>
<td>4.49*10^{-5}</td>
</tr>
<tr>
<td>$G_{4,3}$</td>
<td>-0.0289</td>
<td>4.50*10^{-5}</td>
</tr>
</tbody>
</table>

7.5 Wide angle mapping camera lens

The wide mapping camera lens consists of three groups: a positive central group to provide the convergent power and negative groups at the front and rear to both expand the field and increase the off-axis illumination by the introduction of coma of the entrance pupil. The nine element lens which consists of two negatively meniscus lenses, followed by two positive lenses cemented triplets, grouped symmetrically around the aperture stop, followed by a single negative meniscus lens [17]. The mapping lens prescription data and the layout are shown in Table 7-19 and Figure 7-15, respectively. The performance of the nominal lens as described by the spot diagrams and the modulation transfer function at wavelength of 0.588 microns are given in Figure 7-17 and Figure 7-18, respectively.
Table 7-19 Prescription for the nominal wide angle mapping camera lens.

<table>
<thead>
<tr>
<th>Part Type</th>
<th>Comment</th>
<th>Surface</th>
<th>Radius</th>
<th>Thickness</th>
<th>Class</th>
<th>Semi-Diameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>00</td>
<td>Standard</td>
<td>Infinity</td>
<td>Infinity</td>
<td>Infinity</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>Standard</td>
<td>Infinity</td>
<td>1.00000</td>
<td></td>
<td></td>
<td>5.828751</td>
</tr>
<tr>
<td>2*</td>
<td>Standard</td>
<td>5.59000</td>
<td>0.54160</td>
<td>0.85550</td>
<td>R47</td>
<td>5.506000 U</td>
</tr>
<tr>
<td>3*</td>
<td>Standard</td>
<td>2.82000</td>
<td>2.42400</td>
<td>2.62450</td>
<td>U</td>
<td>2.62450 U</td>
</tr>
<tr>
<td>4*</td>
<td>Standard</td>
<td>2.69300</td>
<td>0.12200</td>
<td>0.37750</td>
<td>R47</td>
<td>1.750000 U</td>
</tr>
<tr>
<td>5*</td>
<td>Standard</td>
<td>1.75800</td>
<td>0.72400</td>
<td>0.92500</td>
<td>U</td>
<td>1.506500 U</td>
</tr>
<tr>
<td>6*</td>
<td>Standard</td>
<td>1.78800</td>
<td>1.30100</td>
<td>1.76250</td>
<td>1.1</td>
<td>1.305500 U</td>
</tr>
<tr>
<td>7*</td>
<td>Standard</td>
<td>6.82300</td>
<td>0.71700</td>
<td>R46</td>
<td>0.668500 U</td>
<td></td>
</tr>
<tr>
<td>8*</td>
<td>Standard</td>
<td>-1.49400</td>
<td>0.06700</td>
<td>R66</td>
<td>0.499000 U</td>
<td></td>
</tr>
<tr>
<td>90*</td>
<td>Standard</td>
<td>Infinity</td>
<td>0.31100</td>
<td>0.39600</td>
<td>U</td>
<td>0.39600 U</td>
</tr>
<tr>
<td>10*</td>
<td>Standard</td>
<td>-4.44600</td>
<td>0.30300</td>
<td>R62</td>
<td>0.588500 U</td>
<td></td>
</tr>
<tr>
<td>11*</td>
<td>Standard</td>
<td>2.63700</td>
<td>0.92100</td>
<td>RACK5</td>
<td>0.703000 U</td>
<td></td>
</tr>
<tr>
<td>12*</td>
<td>Standard</td>
<td>-2.28200</td>
<td>0.39500</td>
<td>1.54811</td>
<td>0.526000 U</td>
<td></td>
</tr>
<tr>
<td>13*</td>
<td>Standard</td>
<td>-4.54400</td>
<td>1.64300</td>
<td>1.22600</td>
<td>U</td>
<td>1.22600 U</td>
</tr>
<tr>
<td>14*</td>
<td>Standard</td>
<td>-1.67100</td>
<td>0.17200</td>
<td>RACK7</td>
<td>1.615000 U</td>
<td></td>
</tr>
<tr>
<td>15*</td>
<td>Standard</td>
<td>-3.67900</td>
<td>1.26300</td>
<td>2.34600</td>
<td>U</td>
<td>2.34600 U</td>
</tr>
<tr>
<td>16*</td>
<td>Standard</td>
<td>Infinity</td>
<td></td>
<td></td>
<td></td>
<td>4.671000 U</td>
</tr>
</tbody>
</table>

Figure 7-15 Wide angle mapping camera lens layout at half fields of views: 0°, 26.25° and 60°
Figure 7-16 Field curvature/distortion curves for the wide angle mapping camera lens at half field of view of 60° degrees and wavelength 0.5876 microns.

Figure 7-17 Nominal spot diagrams at half fields of views of: 0°, 26.25°, 52.5°, and 60° and wavelength 0.5876 microns.
7.5.1 Paraxial ghost image analysis for the wide mapping camera lens

The wide angle mapping camera lens consists of 14 surfaces, thus there are 91 second order ghosts. For each possible ghost \((k_1, k_2)\): the ghost-nominal image plane separations \(\Delta Z_{g,n}\), the ghost marginal and chief ray heights at the nominal image plane \(y_{g,n}, -y_{g,n}\), the paraxial half field of view \(HFOV_g\), the ghost \(f/\#_g\), and the ghost depth of field \(DOF_g\) are given in Table 7-20. The circle of confusion diameter is assumed to be 20.8µm.
Table 7-20 The ghost-nominal image plane separations $\Delta Z_{g,n}$, the ghost marginal and chief ray heights at the nominal image plane $y_{g,n}$, $\bar{y}_{g,n}$, the ghost $f$/#$_g$, and the ghost depth of focus $DOF_g$.

<table>
<thead>
<tr>
<th>$k_1$</th>
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On-axis ghosts that are formed within one inch from the nominal image plane are listed in Table 7-21. The ghost $G_{11,1}$ is the nearest ghost to the nominal Gaussian image plane.

Table 7-21 Ghosts that are formed within one inch from the nominal image plane.

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7.5.2 Exact ghost analysis for the wide angle mapping camera lens

The ghosts $G_{9,8}$, $G_{12,13}$, $G_{12,13}$, $G_{12,13}$ are analyzed in the following sections:

7.5.2.1 Exact ray analysis for the ghost $G_{9,8}$

The ghost layout, the ghost OPD, and the ghost spot diagrams are shown in Figure 7-19, Figure 7-20, and Figure 7-21, respectively.
Figure 7-19 Ghost $G_{9,8}$ layout.

Figure 7-20 Ghost $G_{9,8}$ OPD at half fields of view $0^\circ$, and $2^\circ$. 
7.5.2.2 Exact ray tracing for the ghost $G_{11,10}$

The ghost layout, the ghost OPD, and the ghost spot diagrams are shown in Figure 7-22, Figure 7-23, and Figure 7-24, respectively.

Figure 7-21 Ghost spot diagram for $G_{9,8}$ at half fields of view $0^\circ$, and $2^\circ$. 
Figure 7-22 Ghost $G_{11,10}$ layout

Figure 7-23 Ghost $G_{11,10}$ OPD.
Figure 7-24 Ghost $G_{11,10}$ spot diagram.
7.5.2.3 Exact ray analysis for the ghost $G_{12,11}$

The ghost layout, ghost formation, the ghost OPD, and the ghost spot diagrams are shown in Figure 7-25, Figure 7-26, Figure 7-27, and Figure 7-28, respectively.

Figure 7-25 Ghost $G_{12,11}$ layout at half field of views of 0°, 6.5°, and 13°.

Figure 7-26 Ghost $G_{12,11}$ formation.
Figure 7-27 Ghost $G_{12,11}$ OPD at half field of views of 0°, 6.5°, and 13°.
Figure 7-28 Ghost $G_{12,11}$ spot diagrams at half field of views of $0^\circ$, $6.5^\circ$, and $13^\circ$. 
7.5.2.4 Exact ray analysis for the ghost \( G_{13,12} \)

The ghost layout, the ghost OPD, and the ghost spot diagrams are shown in Figure 7-29, Figure 7-30, and Figure 7-31.

Figure 7-29 Ghost \( G_{13,12} \) layout at half field of views of 0°, 11°, and 22°.
Figure 7-30 Ghost $G_{13,12}$ OPD at half field of views of $0^\circ$, $11^\circ$, and $22^\circ$.

Figure 7-31 Ghost $G_{13,12}$ spot diagrams at half field of views of $0^\circ$, $11^\circ$, and $22^\circ$. 
7.5.2.5 Exact ray tracing for the ghost $G_{14,13}$

The ghost $G_{14,13}$ layout, the ghost OPD, and the ghost spot diagram are shown in Figure 7-32, Figure 7-33 and Figure 7-34, respectively. The maximum ghost half field of view (object space is $21^\circ$).

Figure 7-32 Ghost ($G_{14,13}$) layout at half field of views of $0^\circ$, $12^\circ$, and $21^\circ$. 
Figure 7-33 The OPD for the ghost $G_{14,13}$ at half field of views of 0°, 12°, and 21°.
Figure 7-34 The ghost \( G_{14,13} \) spot diagram at half field of views of 0°, 12°, and 21°.

7.6 Discussion

In this chapter we have simulated ghost effects for three systems to illustrate certain concepts that were developed in previous chapters. For a system that consists of a biconvex lens and a plane parallel plate placed to the right of the lens, the ghost that is formed by the plate is the most serious ghost. The on-axis ghost irradiances due to the other ghosts can be ignored compared to this ghost. To exaggerate the effect of this ghost, the aperture stop size is decreased. Thus, spherical aberration and defocus coefficients decrease dramatically. Exact ray tracing for the wide angle mapping camera lens shows
an interesting feature for one of the ghosts. The ghost $G_{14,13}$ becomes more focused at the edge of the nominal Gaussian image plane.
8 CONCLUSION AND FUTURE WORK

8.1 Conclusion

In this work, we have developed several methodologies to simulate ghost images in multi-element lens systems. These methodologies are faster than stray light software codes.

In chapter two, an algorithm has been developed to generate the ghost layouts that arises from two, four and generalized to N reflections between the surfaces of multi-element lens system. Flow charts and examples were provided.

In chapter three, by applying the paraxial ray tracing equations for each possible ghost layout, the ghost paraxial properties can be estimated. Second order ghost properties include: ghost cardinal points, entrance and exit pupils locations, entrance and exit pupils diameters, marginal and chief rays heights and angles. Anomalous ghost systems are identified and discussed.

In chapter four, radiometry equations for point and extended objects are reviewed. Ghost irradiance equations at the nominal image plane are derived for a point and an extended object. Paraxial irradiance ghost point spread function is constructed and illustration examples are provided.

In chapter five, the formulas for calculating the ghost fourth order optical aberrations are stated. Potential ghosts are focused at the nominal Gaussian image plane if there is an intersection between the ghost image surfaces and the nominal Gaussian image plane.
In chapter six, techniques are presented to simulate and measure the depth of field for a nominal system. The experimentally measured depth of field values as a function in object resolution for a Canon Camera is provided. Ghost effects on reducing the depth of field are discussed briefly.

In chapter seven, ghost simulation examples are provided. The ghost irradiance simulation results are compared with FRED results for: a biconvex lens, and biconvex lens and a plane parallel plate. Ghosts by the wide angle mapping camera lens is analyzed. The developed simulation model is used to estimate the first order properties for each ghost. ZEMAX sequential exact ray tracing is used to show the ghost layouts, ghost OPD’s, and ghost spot diagrams for ghosts that are formed by reflections within the surfaces after the nominal aperture stop.

We have developed a methodology to model ghost images at the nominal image plane. The geometrical model simulates ghost images locations and sizes by determining the ghost chief and marginal rays. Ghost fourth order aberration coefficients are estimated from the ghost chief and marginal rays (paraxial heights and angles at each surface). The radiometric model simulates the individual ghost irradiances at the nominal image plane. The ghost paraxial point spread function is obtained by adding up the irradiance contributions of all ghosts. Since tracing rays sequentially is much faster than non-sequential tracing, the developed analysis has a shorter time to simulate ghost effects.

We have presented a technique that can be used to measure the depth of field. The optical system, procedures, and results for measuring the depth of field for a Canon
camera are provided. Ghost images can decrease the nominal image contrast and therefore, can cause depth of field reduction.

In this dissertation, ghost simulations for a paraxial biconvex lens with a glass plate. The paraxial simulation results show that the ghost that is formed by the glass plate is the more problematic one. This ghost is focused very near to the nominal image plane. In addition, the on-axis aberration function for this ghost is much smaller than all other ghosts. Decreasing the system aperture stop size, decreases the on-axis ghost wavefront aberration function further more.

For a nominal system that has several ghosts, it is important to identify the most problematic ghosts. In general ghosts are highly aberrated and therefore, ghosts with smaller aberration function are considered to be the most bothersome.

8.2 Suggestions for future work

In this work we have developed methodologies to analyze the incoherent ghost effects on the nominal system performance. We need to apply the simulation model to different designs, to accumulate design experiences for systems with minimal ghost effects. Future work may also include developing methodologies to deal with coherent ghost effects. In addition, experiments can be conducted to determine the ghost irradiance point spread and system modulation transfer function after including ghost effects. Finally, future work may include developing ghost reduction techniques.
Appendix

Appendix A1

In this section we provide the macro that generates all possible second order ghost layouts. ZEMAX store the nominal lens prescription data that is entered in the lens editor window as INDX ( ), CURV ( ), THIC ( ), and SDIA ( ). The possible reflection surfaces are generated by two loops. The first loop assigns values for $k_2$ ($2 \leq k_1 \leq M$) while the second loop assign values for $k_2$ ($1 \leq k_2 \leq M - 1$). Three other loops are used to generate the ghost sub-layouts (TF1, TB1, and TF2).

\[ N = \text{nsur}() \]
\[ M = N - 1 \]
for $k_1 = 2, M, 1$
  for $k_2 = 1, k_1 - 1, 1$
    for $i = 0, k_1 - 1, 1$
      \[ \text{vec1}(i) = \text{CURV}(i) \]
      \[ \text{vec2}(i) = \text{THIC}(i) \]
      \[ \text{vec3}(i) = \text{INDX}(i) \]
      \[ \text{vec4}(i) = \text{SDIA}(i) \]
    next
  for $i = k_1, 2 * k_1 - k_2 - 1, 1$
    \[ \text{vec1}(i) = \text{CURV}(2 * k_1 - i) \]
    \[ \text{vec2}(i) = -\text{THIC}(2 * k_1 - i) \]
    \[ \text{vec3}(i) = -\text{INDX}(2 * k_1 - i) \]
    \[ \text{vec4}(i) = \text{SDIA}(2 * k_1 - i) \]
  next
for $i = 2 * k_1 - k_2, 2 * k_1 - 2 * k_2 + M, 1$
  \[ \text{vec1}(i) = \text{CURV}(2 * k_2 - 2 * k_1 + i) \]
  \[ \text{vec2}(i) = \text{THIC}(2 * k_2 - 2 * k_1 + i) \]
  \[ \text{vec3}(i) = \text{INDX}(2 * k_2 - 2 * k_1 + i) \]
  \[ \text{vec4}(i) = \text{SDIA}(2 * k_2 - 2 * k_1 + i) \]
next
next
next
Appendix A2

This macro generates the 4th order ghost layouts from the nominal layout. Four loops are used to generate all possible reflection surfaces pairs. For each possible ghost $G_{k1,k2,k3,k4}$, five sub-layouts are generated from the nominal lens prescription.

\[ N = \text{nsur}() \]
\[ M = N - 1 \]

for \( k1 = 2, M, 1 \)
  for \( k2 = 1, k1 - 1, 1 \)
    for \( k3 = k2 + 1, M, 1 \)
      for \( k4 = 1, k3 - 1, 1 \)
        for \( i = 0, k1 - 1, 1 \)
          vec1(i) = CURV(i)
          vec2(i) = THIC(i)
          vec3(i) = INDEX(i)
          vec4(i) = SDIA(i)
        next
        for \( i = k1, 2 * k1 - k2 - 1, 1 \)
          vec1(i) = CURV(2*k1-i)
          vec2(i) = THIC(2*k1-1-i)
          vec3(i) = INDEX(2*k1-1-i)
          vec4(i) = SDIA(2*k1-i)
        next
        for \( i = 2 * k1 - k2, 2 * k2 - k3 - 1, 1 \)
          vec1(i) = CURV(2*k2-2*k1+i)
          vec2(i) = THIC(2*k2-2*k1+i)
          vec3(i) = INDEX(2*k2-2*k1+i)
          vec4(i) = SDIA(2*k2-2*k1+i)
        next
        for \( i = 2 * k1 - 2 * k2 + 2 * k3 - k4 - 1, 1 \)
          vec1(i) = CURV(2*k1-2*k2+2*k3-i)
          vec2(i) = THIC(2*k1-2*k2+2*k3-i)
          vec3(i) = INDEX(2*k1-2*k2+2*k3-i)
          vec4(i) = SDIA(2*k1-2*k2+2*k3-i)
        next
      next
    next
  next
next
References


