Overall System Considerations

There are many factors which should be considered when constructing an optical system. The Books section has a list of relevant texts that deal with these aspects in more detail than can possibly be covered in the following short discussion. It is likely that you may need to consult more than one of these to cover all the areas relevant to your application if it is particularly complex.

A possible list of main criteria which may apply to simple systems that are likely to be constructable from standard components is as follows

- System Packaging Requirements and Field of View
- Spectral Bandwidth and Transmission
- System Resolution and Aberrations
- Environmental

Even if you are not designing the system yourself, you are very likely to be asked questions about these.

System Packaging Requirements and Field of View

The packaging requirements basically involve squeezing your system into an available volume, with any necessary clearances. This and the Field of View requirements are the predominant, but not the sole, driving factors to selecting the focal lengths and diameters of components.

One way of starting a system design is to examine all the positions at which any images are required to be formed and their magnification, and then to determine the thin lens focal lengths necessary to meet these conditions. This can be achieved by repeated applications of the conjugate equations on Page 1 of the Theory section.
The paraxial raytrace equations on Page 5 are probably the best equations to use for the second stage analysis once a rough idea of the focal lengths of the individual modules in your system has been obtained. By tracing two paraxial rays through a chosen system of thin lenses you can determine fairly good approximations of the diameters you are likely to require for each lens, and the field angle and magnification that each is likely to operate at.

If the paraxial raytrace shows up any lens where the diameter is a substantial fraction of its focal length, or where the field angle is more than 5 degrees, then it is likely that more than one component is going to be needed at that point to achieve good resolution. If the field angle approaches 45 degrees, or the diameter equals or exceeds the focal length, then even a complex lens assembly may not offer a solution. Eliminating problem areas like these, where you can, is the way to improve performance and reduce system cost. A paraxial layout is all important here.

If possible try to lay out the optics first and provide enough space afterwards. If size is an a priori requirement then be prepared to consider the possibility of folding your system using mirrors and prisms. As the use of weaker components can have a beneficial effect on performance, the extra length of a folded system may allow them to be used.

Spectral Bandwidth and Transmission

The choice of materials for the components is usually defined by the spectral bandwidths over which transmission is required. Windows, lenses and beamsplitters (used in transmission) should all be transparent at the required wavelengths. In addition, if you are working with high power lasers, it is often advisable to use substrates which are transparent as well.

Where high power lasers are concerned you should look for materials with the lowest absorption or a high thermal conductivity. Zinc Selenide for the Infrared and Fused Silica for the Visible and Ultraviolet are the preferred materials. Specially prepared grades of BK7, such as platinum–free, are also used for this purpose.

Lenses and windows made from high refractive index materials should be coated in order to reduce surface reflections. Even where the directly transmitted radiation gives an adequate signal, the surface reflections may produce ghost images or glare which reduces image contrast. The signal to noise ratio can be the more important consideration.

For the most critical applications you may need to include extra filters or stops and baffles, which serve no other purpose than to reduce the unwanted signals which can arise in a system. These can occur from surface or bulk material scatter of the components, or the side walls of the housings. The scatter characteristics of a mock–up on a lens bench can be very different from the prototype lens in a proper housing. If the results from your assembly have changed between these two stages in a project, scatter could be your problem.

System Resolution and Aberrations

Aberration levels

One of the most complex areas to examine is the aberrations of a system. It is not possible to present all the techniques which are employed in their calculation. Certain equations have been given earlier (Page 12), to allow initial assessments to be made. You may find them useful, at an early stage, in identifying areas in a system which need something better than a single lens.

There is a discussion of the general forms of the more common aberrations earlier in this Theory section. The equations are based on third order thin lens theory only. Therefore they can only give an approximate indication of the

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aberrations. However, for many systems they are good enough to determine the overall behavior. For the important cases of Spherical Aberration and Axial Color - the ones most likely to concern typical users of standard catalog components - the stop shift equations are not likely to be required.

Before we go any farther in this discussion it must be pointed out that not all aberrations can be conveniently corrected with systems constructed exclusively of simple stock components. Because this is especially true of systems requiring extended field coverage, we will discuss this first and the reasons why this is so.

Astigmatism and Field curvature

The most serious aberrations which will limit the off–axis performance of any system using standard components are likely to be Primary Astigmatism and Field Curvature. If any of the components in the system is used at a field angle in excess of a few degrees then it is very likely that these aberrations will occur. Depending on how good the system has to be, they may need attention. They vary as the square of the field angle and can quickly swamp the spherical aberration at off–axis field points. This is particularly noticeable for lenses such as achromatic doublets in which the axial aberrations and Coma have been reduced.

A len which is required to cover a large angular field of view will require the astigmatism and field curvature to be small if it is to be worth fully correcting the Spherical Aberration, Coma and Axial Color.

If the system consists of a thin lens at the stop then the third order astigmatism and field curvature can be estimated using the equations on Page 12. These terms involve three parameters – the refractive index n, the lens power K and the Lagrange Invariant H. For a thin lens there are no terms involving the lens shape. Therefore we have no hope of eliminating these aberrations with a single lens at the stop.
However if you examine the stop shift equations you will see that the expression for astigmatism (Page 13) contains terms involving the Spherical Aberration and Coma. Clearly a way of compensating for astigmatism is to have lenses with specific non–zero amounts of Spherical Aberration and Coma at locations away from the stop. However as standard singlet lenses are only available in certain shapes, and doublets are designed to have very small amounts of Spherical Aberration and Coma, the task of reducing Astigmatism in a system of stock components is not really a practical option.

Third order Field Curvature is even more difficult to remove as it is completely unaffected by stop shift. A field flattening lens, usually plano–cave with the plane surface towards and very close to the image, can sometimes help. Bear in mind that due to its proximity to the image plane, any scratches or defects on a field flattening lens will almost be in focus.

If you have a system which is currently afflicted with Astigmatism or Field Curvature, or a theoretical analysis suggests it may be significant, then you could consider the following courses of action before resorting to a custom solution or a change in design concept.

1) See if the field angle can be reduced at critical areas by increasing the system length. For example, if you have to image a particular linear object at a set magnification, doubling the length of the system at fixed F/ratio has no effect on the Lagrange Invariant H, but halves the value of power K.

2) You could try replacing critical simple components in the system with complex anastigmatic lenses (e.g. camera or enlarger lenses). This is not a universal panacea, however, and really only one such lens should ever be contemplated. Information on the entrance and exit pupil positions and the locations of the principal planes is not always readily available, even from the manufacturer. Unless you can match the pupils into the rest of your system you may experience vignetting problems (with loss of off–axis illumination). Although it can seem particularly attractive, it is best to avoid using infinity corrected optics such as camera lenses back–to–back in an attempt to create wide field finite conjugate imaging. The light loss can be significant without using field lenses, which will introduce more of the Field Curvature you were trying to eliminate.

Axial and Lateral Color

Looking at the equations on Page 12, you will see that the Lateral Color of a thin lens at the stop is zero. The Axial Color is proportional to the lens power and inversely proportional to the Abbe number. If a single lens is to be used then it is advisable to select a material with a high Abbe number.

An estimate of the amount of Axial Color contributed by a single lens at the stop can be made using the equations on page 12. It is possible to sum these for a complete system, including those systems where lenses are located away from the stop. For lenses away from the stop the stop–shift equations will have to be applied to determine the Lateral Color.

Where the value of axial color is unacceptable then there are several courses of action.

1) Reduce the bandwidth, as this will effectively increase the value of the Abbe number. Provided there is sufficient signal available then this

could be an acceptable method.

2) Use a combination of lenses with opposing powers and different Abbe numbers. This technique is used in cemented achromatic doublets.

3) Consider a reflecting solution. For systems requiring the broadest bandwidths this is often the only option.

A drawback to reflecting systems is the need to either work off–axis or to accept obscuration of the aperture. The conic mirrors are all free of color and spherical aberration. They do, however, suffer from coma and other field aberrations.

In the Infrared region the Abbe numbers of most of the materials are quite high, so achromatization is often not necessary.

In the Ultraviolet region achromatization is possible using Calcium Fluoride and Fused Silica. However, if the wavelength range is too large the secondary spectrum can become dominant and there is no third material available to correct this. Also the components are not usually cemented, which limits the F/ratios available unless many components are used.

In the visible region, the achromatic cemented doublets offer axial color values around 30 times smaller than BK7 lenses of the same focal length and diameter. However, the cemented surface prevents their use in high power applications.

Spherical aberration and Coma

If you are using a simple component or a doublet make sure you have chosen the best standard form for your application, and that you are using it the correct way round for its conjugates of usage.

Look for any parts of the system where the axial clear aperture of a component given by the paraxial raytrace is a significant fraction of its focal length. Consider sharing the labor of that component amongst several components of weaker power (longer focal length).

If your system consists entirely of simple components then you may use the equations on Page 12 to make an estimate of the third order (Primary) Spherical Aberration of the system. To assess the Coma of a multi–lens system, you will need to include the "stop shift" terms for any components which are not at the stop.

The relevant coefficients are listed along with each lens material and type. They have been calculated for the design wavelength and assume the lenses are thin. However they are a sufficiently good approximation for estimates of performance to be made and will help you avoid totally unsuitable lens choices. A precise evaluation of lens performance requires real rays to be traced through the system.

If either of these aberrations is too large then you should first consider reducing the numerical aperture by means of a mechanical stop, as this can have a significant effect on both the Spherical Aberration and Coma. If the aperture cannot be reduced because of the need to maintain light throughput or to give adequate resolving power, then a change in construction will be necessary.

Environmental

The components nearest to high power lamps can often be exposed to considerable amounts of thermal radiation; Fused Quartz or Fused Silica is preferable to ordinary glass in these areas. If the thermal radiation is not required further down the system you should always try to remove it by using Hot/Cold mirrors, according to the geometry of your system or, if the power levels are lower, with a heat absorbing glass such as the Schott KG glasses.

Certain materials have a refractive index which varies strongly with temperature, e.g. Germanium. For critical applications you may need to consider passive compensation by designing the appropriate mounts, or active compensation by using microprocessor control movements (e.g Ealing DPS equipment).

For applications such as laser cutting, where hot debris can be thrown back onto the optical components, consider the use of sacrificial windows to limit the damage. If the wavelength permits, sapphire windows are both durable and able to withstand rigorous cleaning. Another approach is to make the light reach the workpiece by way of a fold mirror, keeping the more expensive lens components safely out of the line of fire of debris from the cutting area.