Application-Specific Optical Design

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Introduction

Optical design software capabilities have advanced considerably from the late 1950s and early 1960s when computer tools first became available. Initially, the main purpose of the software was to geometrically trace rays and perform limited analyses. However, the introduction of automated optimization, generally using a damped least squares algorithm, is what has made software an indispensable tool for the optical engineer.

Today, optics are used in a variety of applications, and unique features and capabilities are often required to model, optimize, and analyze systems designed for a specific application. In this paper, we will look at several different application areas and discuss some of the software modeling, design, and analysis features important for those applications. The applications include:

- Commercial imaging systems
- Visual systems (i.e., optical systems that use the human eye as the detector)
- Off-axis tilted and decentered systems
- Telecommunications systems
- Astronomical applications
- Non-visible systems (e.g., UV, IR, etc.)
- Microlithographic (optical stepper) systems

Figure 1 shows a montage of several CODE V models used in different application areas.

Figure 1: CODE V models for different applications

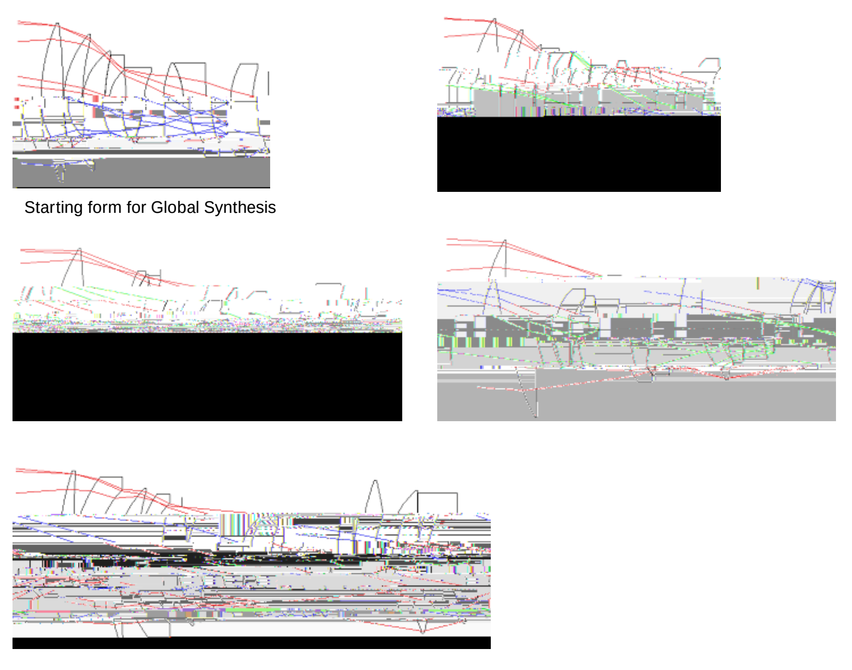
9. Modify the finished design for fabrication and cost considerations. Once a final design form is determined, there are additional steps that will facilitate the fabrication of the design and potentially lower lifecycle costs. These steps may include:
   - Verify the availability of optical materials in the finished design. In recent years, glass manufacturers have been trying to keep costs low by maintaining only small inventories of infrequently ordered glasses. When this happens, a glass that is offered in the manufacturer’s catalog is sometimes out of stock. This can often require a complete redesign to use different optical materials for time-critical designs. The designer should verify material availability as soon as they have a reasonable idea of which materials are required.
   - If possible, make bi-convex and bi-concave lenses with similar radii equi-convex or equi-concave to prevent them from being assembled backwards. This happens more often than fabrication shops would like to admit.
   - If possible, make spherical surfaces with long radii planar.
   - If possible, round lens thickness values to a limited number of significant digits (this will make the fabrication shop happy).
   - Adjust the radii in the design to match the test plates available to the fabrication shop. This step will save fabrication cost if test plates are being used to verify the manufactured radii. CODE V optimization supports automatic test plating to an input test plate list.
   - After all these changes have been implemented, perform final optimization and performance evaluations (both nominal and as-built).
   - Create and check lens and component drawings for the fabrication facility.
10. Post-fabrication analyses. After the design has been fabricated, there may be some additional steps necessary for precision applications:
   - The glass model for the design may need to be altered to match measured index data from samples of the real material to be used, and the airspaces adjusted slightly to compensate for performance changes due to the refractive index differences. This process is called melt fitting, and CODE V includes some special features to aid in the modeling of measured glass data.
   - Apply surface deformation data, measured with an interferometer directly to the surfaces in the model. Most commercial interferometer manufacturers can export the measurement data directly into CODE V’s interferogram file format.
   - Apply measured lens thicknesses to the model.
   - After these changes have been implemented, analyze the system’s as-built performance based on the information.
   - If needed, you can perform automated alignment on the design. CODE V contains an Alignment Optimization feature that can be used to determine the correct alignment adjustments based on optical system measurements using an interferometer.

With the optical design process outlined, we can examine how the specifics of the process can vary for different applications.

Commercial Imaging Systems

Imaging systems for commercial applications (such as camera objectives and projector lenses) were one of the earliest application areas that benefited from optical design and analysis software. These systems cover a large range of f-numbers (F/#) and fields of view (FOV).

Commercial imaging systems commonly use centered, rotationally symmetric refractive systems. A starting point could be chosen from one of the 2,400 patents in CODE V’s built-in patent database, or by using global optimization. The applicability of global optimization for starting point generation can be seen in Figure 2. The application is a 200 mm EFL, F/1.25, all-spherical, 8-element, camera lens for photographing a CRT display. The starting configuration is indicated.



Starting form for Global Synthesis

Figure 2: Several distinct solutions for a CRT camera lens, generated by Global Synthesis

Early imaging system performance metrics were based on geometrical ray tracing and included ray aberrations, geometrical Modulation Transfer Function (MTF), and 3rd and higher-order aberrations. Later, as diffraction computations were added to

Since diffraction-based MTF is a leading performance metric for commercial imaging systems, optimization and tolerance metrics that compute diffraction-based MTF can be very beneficial. CODE V’s fast and accurate wavefront differential algorithm is used for both MTF optimization (i.e., an optimization merit function that directly optimizes diffraction-based MTF at specified frequencies) and MTF tolerancing.

Visual Systems

The effective design and analysis of visual systems can benefit from specialized handling of the light emerging from the system. In

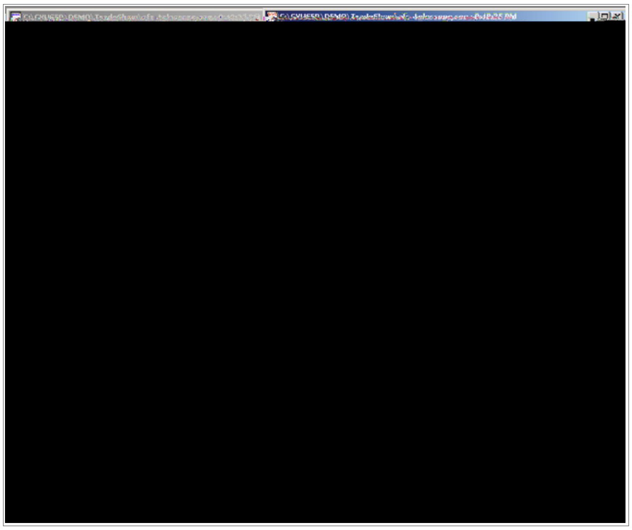


Figure 5: Analysis curves with units of diopters, arc minutes, or cycles/arc minute

Off-Axis, Tilted, and Decentered Systems

Rotational symmetry has a number of benefits in an optical design, including symmetry of the aberration field and generally easier fabrication and alignment. However, many applications require the symmetry to be violated, especially to meet packaging constraints. Space-borne reflective optics and heads up displays (HUDs) can often be fit into a much smaller space if the components are tilted and decentered relative to a common axis.

For these types of systems, flexibility in how the tilts and decenters can be defined is an important software modeling feature. For

Another important aspect for the design of systems utilizing off-axis tilted and decentered components is that traditional diagnostic analyses, such as transverse ray aberration curves or field curves, can be deceiving. These traditional tools were developed for systems with rotational symmetry, and rely on the symmetry to be meaningful across the entire field of view. To address this limitation, CODE V includes a field map diagnostic option that can plot various performance metrics across the full field of view. The information in these plots can provide great insight on what steps to take to improve the system performance (see Thompson 1996:2 and Rogers 1999:286). Figure 7 shows two field map outputs for the system above, one showing astigmatic focal lines and the other a plot of the magnitude and orientation of wavefront Zernike coefficients for 3rd order coma.

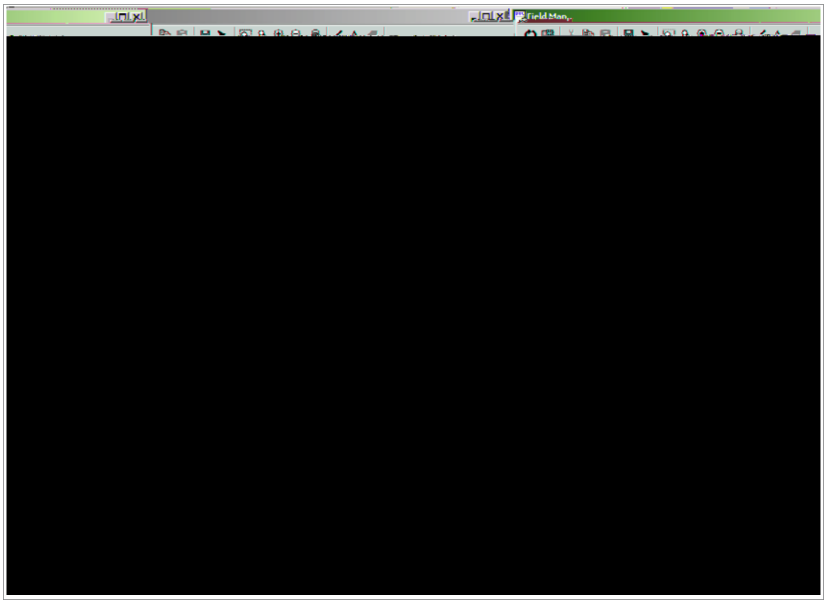


Figure 7: Full field maps of aberration fields

Telecommunication Systems

CODE V can also be used to design and analyze free-space telecom devices (i.e., light propagation outside of the waveguide or optical fiber). These components are generally very small. The governing performance metric is how much energy is gathered from an input

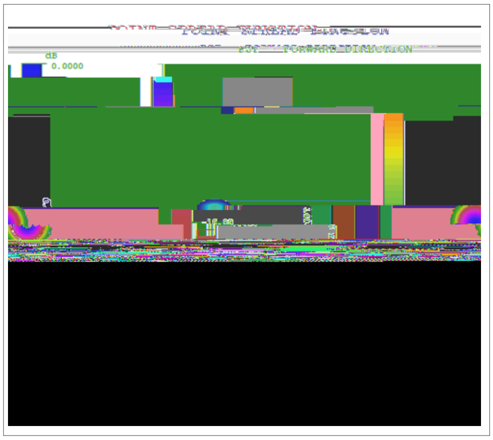


Figure 8b: Field intensity at output fiber

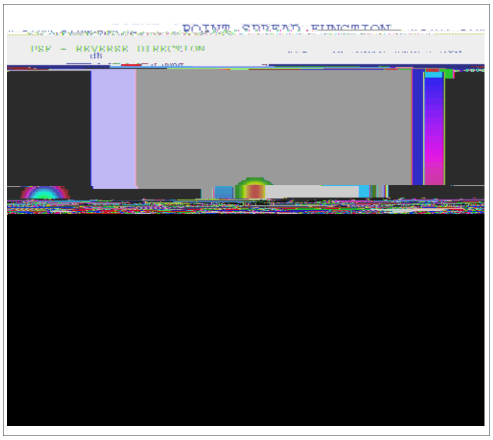
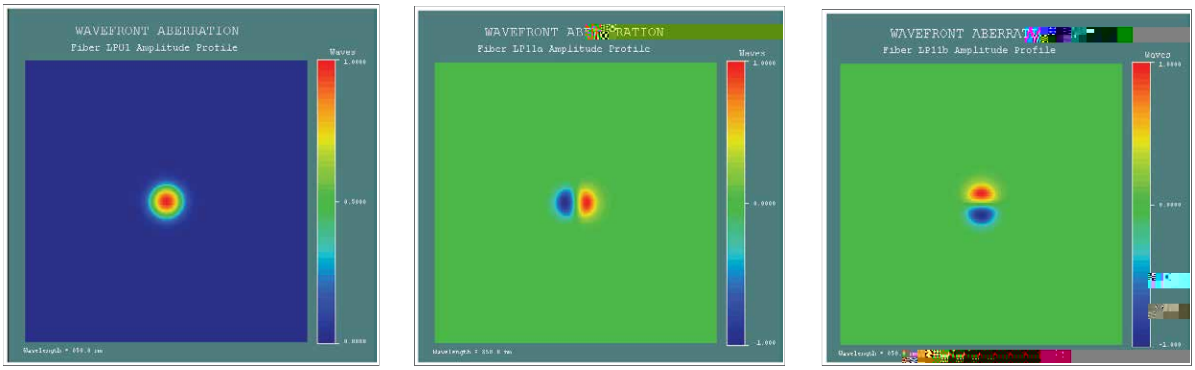


Figure 8c: Field intensity at input fiber

Typical analysis models for traditional imaging systems treat all diffraction as occurring at the optical system exit pupil. This may be inadequate for telecommunication systems, since the beams are typically only a few hundred wavelengths in diameter and often propagate several thousand wavelengths in distance between components. The physics of this arrangement cause the beam diameter to grow due to diffraction spreading, and cannot be accurately modeled with geometric ray tracing techniques. In this case, general beam propagation algorithms must be used throughout the entire optical system to adequately account for diffraction.

CODE V's general beam propagation feature can be used to determine the complex field throughout the system, and most importantly, at the output fiber face. CODE V's fiber coupling efficiency feature calculates the overlap integral between the complex field and the mode profile of the single mode fiber. Multimode fiber analysis is also supported, by computing the coupling efficiency into each supported mode of the fiber. Figure 9 illustrates the amplitude profile for three modes supported by a Corning SMF28 fiber operating at 850 nm. Typically, this fiber is used at 1310 nm or 1550 nm, and only the fundamental mode (LP01) will propagate. However, when used at 850 nm, the modes shown in Figure 9 are supported. The data used to create these plots is used to define the mode structure for the multi-mode fiber coupling efficiency calculation.



LP01 M

LP11a M

LP11b M

Figure 9: Supported modes for Corning SMF-28 fiber used at 850 nm

CODE V supports both a fiber coupling efficiency merit function for optimization and a coupling efficiency (and polarization dependent loss)tolerancing performance metrics. These allow the optical design process outlined at the beginning of this paper to be directly applied to these types of systems.

Astronomical Applications

Astronomical applications generally require small fields of view, fast (small F-number) optics, and point image performance metrics, since the objects of interest are small and faint. In addition, many large telescopes and planned space-borne optics are using segmented apertures. Traditional optical system modeling defines systems sequentially for ray tracing. That is, rays must go from surface 1, to surface 2, to surface 3, and so forth. When segmented apertures are used, different rays will intersect different

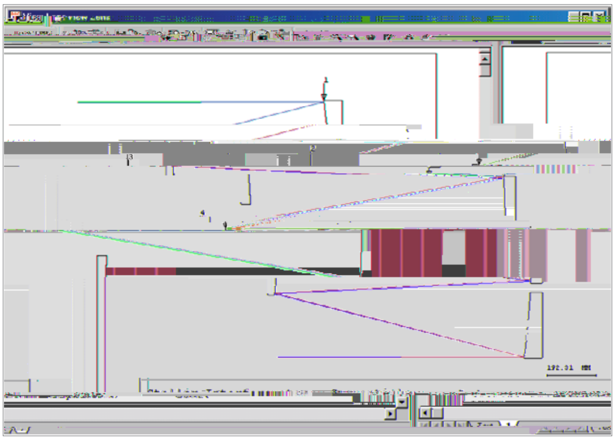


Figure 10a: Stellar interferometer systems

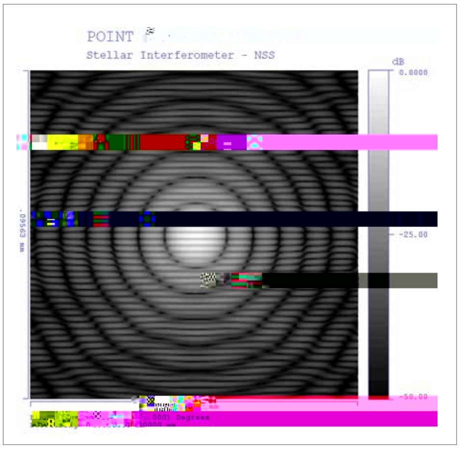


Figure 10b: PSF for Aligned System

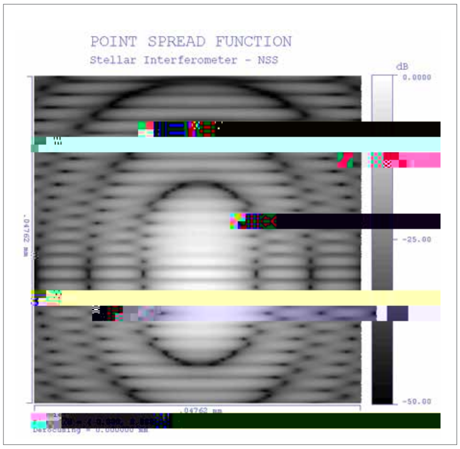


Figure 10c: PSF for Misaligned System

Figure 10a shows a stellar interferometer system used for ultra-high resolution studies. The path for the light from the two separated apertures is carefully maintained to be approximately equal so that the beam remains coherent and interference results. The angular size of the object under observation can be inferred by adjusting the separation between the two apertures until the fringe

In general, material considerations have the most significant impact when working outside the visible spectral region. Optical glasses eventually become opaque in the ultraviolet and infrared. Often other crystalline materials must be used. Reflective optics have the benefit of working across a larger spectral band, but sometimes their use is restricted due to packaging considerations or fabrication limitations.

In the near ultraviolet and infrared, optical glasses will transmit, but their optical properties will be different than when they are used in the visible. For example, in the visible spectral region, the 2nd derivative of the index vs. wavelength curve, represented by the partial dispersion (P), varies nearly linearly with Abbe number for most commonly available optical glasses. This representation is sometimes called “the normal dispersion line” and is useful for understanding glass selection to correct the aberration of secondary color. Figure 11 is a plot of the partial dispersion (P) versus Abbe number (V) for the Schott glass catalog, in the visible region.

Figure 11: Plot of P vs. V for optical glasses in the visible spectral band

Fictitious glasses, i.e., glass models that can be variable for optimization, are typically based on this normal dispersion model. However, outside the visible spectral region, the concept of a “normal line” may not exist. Consider the P vs. V plot for the same glasses operating in a typical telecommunications wavelength band of 1550 to 1610 nm. The result is shown in Figure 12.

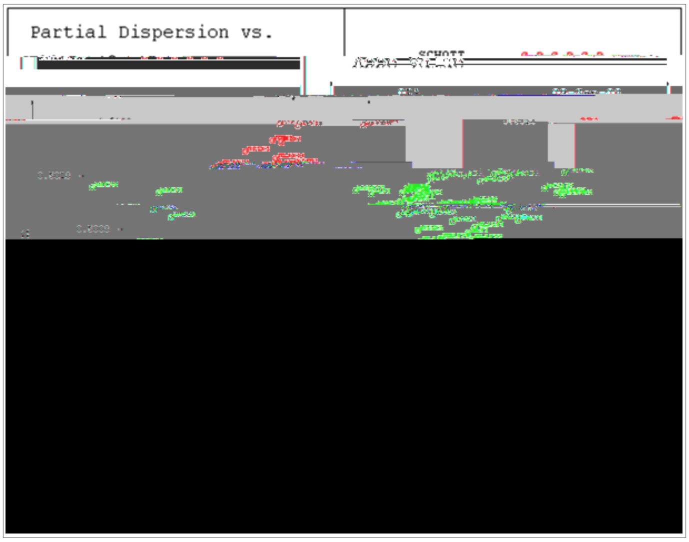


Figure 12: Plot of P vs. V for optical glasses in the 1550 nm—1610 nm spectral band

A fictitious glass dispersion model based on the “normal line” in the visible would not do a very good job of modeling real glass dispersion behavior in the infrared. In CODE V, users can redefine the fictitious glass model wavelengths and dispersion characteristics to match those of real glasses used in that wavelength region. This makes it much easier to substitute real optical materials for variable optical materials.