

Control of packaging constraints in the optimization of unobscured reflective systems

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Abstract

A method of maintaining precise control of packaging constraints in the optimization of unobscured reflective systems is described. The method is illustrated by reference to an example of a four-mirror telescope objective. A command sequence for the optimization of this system is presented.

Introduction

Unobscured all-reflective optical systems have potential applications in conditions requiring wide or multi-spectral band, hostile radiation environment, low stray radiation, and low weight. Because these systems usually contain tilted and decentered mirrors, special attention is needed in their design to prevent the optical surfaces from vignetting the beam or mechanically interfering with other optical components. Controlling clearances and other packaging constraints can be done easily if the designer uses a program with global user-defined constraints or global operands. This paper describes an efficient method of controlling packaging requirements with global constraints during optimization, which allows the designer to let all tilts and decenters to vary freely for optimizing image quality.

A method of controlling clearances

The general requirement that underlies all clearance control described in this paper is to keep a point on one side of a line. Algebraically, this condition is expressed as a linear inequality. The correspondence to optics is that the extreme ray in a bundle defines a line; the edge of a mirror (or its mount) or stop defines a point. The components of the linear inequality, i.e. slope and intercept, must be defined globally with respect to a common coordinate system.

A designer who uses an optical design optimization program having the capability of defining global user-defined constraints or global operands can implement and actively control the linear inequality during optimization. By keeping the point (edge of mirror or stop) a minimum distance from one side of the line (edge of ray bundle), the designer ensures that problems such as vignetting or inadequate mechanical clearances will not arise.

It should be noted that clearance control can be achieved by other methods which do not explicitly use linear inequalities in the way described in this paper. For example, the designer could simply set ray targets on dummy surfaces, optimize for a few passes, then check whether the clearances associated with the ray targets are still maintained, and revise the target if necessary. However, methods requiring iterative refinement of packaging constraints can be more demanding on a designer's time, are sometimes indirect, and are more computer-intensive to the extent that they require dummy surfaces. The method described in this paper may require more initial work than other methods, but it achieves precise control and requires little or no iterative refinement.

Four-mirror telescope example

The method of controlling clearances will be illustrated by referring to an example. An unobscured all-reflective system that has critical clearance constraints is a four-mirror telescope objective shown in Figure 1. It is a contrived example, and is not a configuration that one would choose to solve a real problem, but it contains the same kinds of clearance issues to be found in the common types of unobscured reflective systems, such as the multi-mirror anastigmat configurations.

Two constraints will be considered in detail: clearance of a Lyot stop, and clearance of the secondary mirror. Other constraints in the optical system are similar to one of these two types, and are included in a sample command sequence to be shown later. Both of these examples require constraints only in two dimensions (the plane of the drawing in Figure 1); however, the method can be extended to three dimensions for more complex clearance requirements.

i. Clearance between diverging bundle of rays and secondary mirror. The fourth mirror is free to tilt and decenter, so the diverging bundle of rays between mirrors 3 and 4 can be vignettted by the secondary if not constrained. (See Figure 1 for an indication of this clearance). The goal is to keep the edge of the secondary mirror a minimum distance TM above the bundle of rays between mirrors 3 and 4. Referring to Figure 2, one may define the constraint for mirror clearance by the following equations.

Line A is the upper boundary of the bundle between mirrors 3 and 4, and is the edge of the bundle closest to the lower edge of the secondary mirror. Its slope and intercept are

$$m_1 = \frac{\text{(y direction cosine of ray)}}{\text{(z direction cosine of ray)}} \quad (1)$$

$$b_1 = y_1 - m_1 * z_1 \quad (2)$$

The lower edge of the secondary mirror is defined by the point (z_0, y_0) , which is the point where the lowermost ray in the bundle between mirrors 1 and 2 intersects mirror 2. The mirror clearance is defined by the inequality

$$y_0 - (m_1 * z_0 + b_1) > TM \quad (3)$$

The designer uses global user-defined constraints or operands to implement Inequality (3) and as many of the intermediate equations as needed.

Clearance between the tertiary mirror and the converging bundle between the primary mirror and field stop requires the same type of analysis as in example i.

ii. Clearance of Lyot stop. The Lyot stop, whose location is shown in Figure 1, must be kept clear of the bundle between mirrors 3 and 4. The Lyot stop will tend to drift into the bundle if not constrained. We wish to keep the edge of the Lyot stop a minimum distance TL from the bundle of rays between mirrors 3 and 4. Referring to Figure 3, one may define the constraint for Lyot stop clearance as follows.

Line A, which is the lower boundary of the bundle between mirrors 3 and 4, and which is the part of the bundle closest to the Lyot stop, has slope and intercept

$$m_1 = \frac{\text{(y direction cosine of ray)}}{\text{(z direction cosine of ray)}} \quad (4)$$

$$b_1 = y_1 - m_1 * z_1 \quad (5)$$

Lines B and C are the upper marginal rays from the extreme positive and negative field points. The slopes and intercepts of lines B and C (m_2 , b_2 , m_3 , and b_3 respectively) are defined by equations analogous to (4) and (5).

The upper edge of the Lyot stop is defined by the intersection point between lines B and C:

$$z_0 = \frac{(b_3 - b_2)}{(m_2 - m_3)} \quad (6)$$

$$y_0 = m_2 * z_0 + b_2 \quad (7)$$

The Lyot stop clearance is held by the inequality

$$m_1 * z_0 + b_1 - y_0 > TL \quad (8)$$

The designer writes a command sequence with the design program to implement Inequality (8) and as many of the intermediate equations as needed.

The clearance between the field stop and the converging bundle between mirrors 2 and 3 can be controlled by the same type of analysis as in example ii.

Command sequence

Any optical design computer program having the capability to define and control global constraints in optimization can be used to design the reflective system discussed above and pictured in Figure 1. There are several such programs generally available. One program is CODE V™, which was used by the author in this example. Figure 4 lists a sequence of CODE V commands that will allow the system to be optimized subject to the packaging constraints. In this system, mirrors 2-4 were allowed to freely translate, tilt, and decenter. The clearances that were constrained are indicated in Figure 1.

Considerations in defining constraints

It is quite possible that the edge of a particular bundle or surface will be defined by different rays as the optimization progresses. This is especially true if the part of the surface or bundle of interest is near an intermediate image or an image of the stop. Therefore it is a good idea for the designer to periodically plot the lens to make sure that the constraint-defining rays have not changed, and that the constraints are being held. In the few cases where several rays can alternately define the boundary during the optimization process, all of these rays can be controlled by single-sided constraints.

Conclusion

By using a design program that can control global user-defined constraints or operands in optimization, a designer can use the methods described in this paper to design unobscured reflective systems with adequate mirror and stop clearances. All mirror locations, tilts, and decenters can vary freely to achieve best image quality while clearance and packaging requirements remain under control. An example of a complex reflective system was used to show how the equations to control these constraints could be defined. A command sequence for one commercially available optical design program was listed, and this approach can be applied to other programs as well.

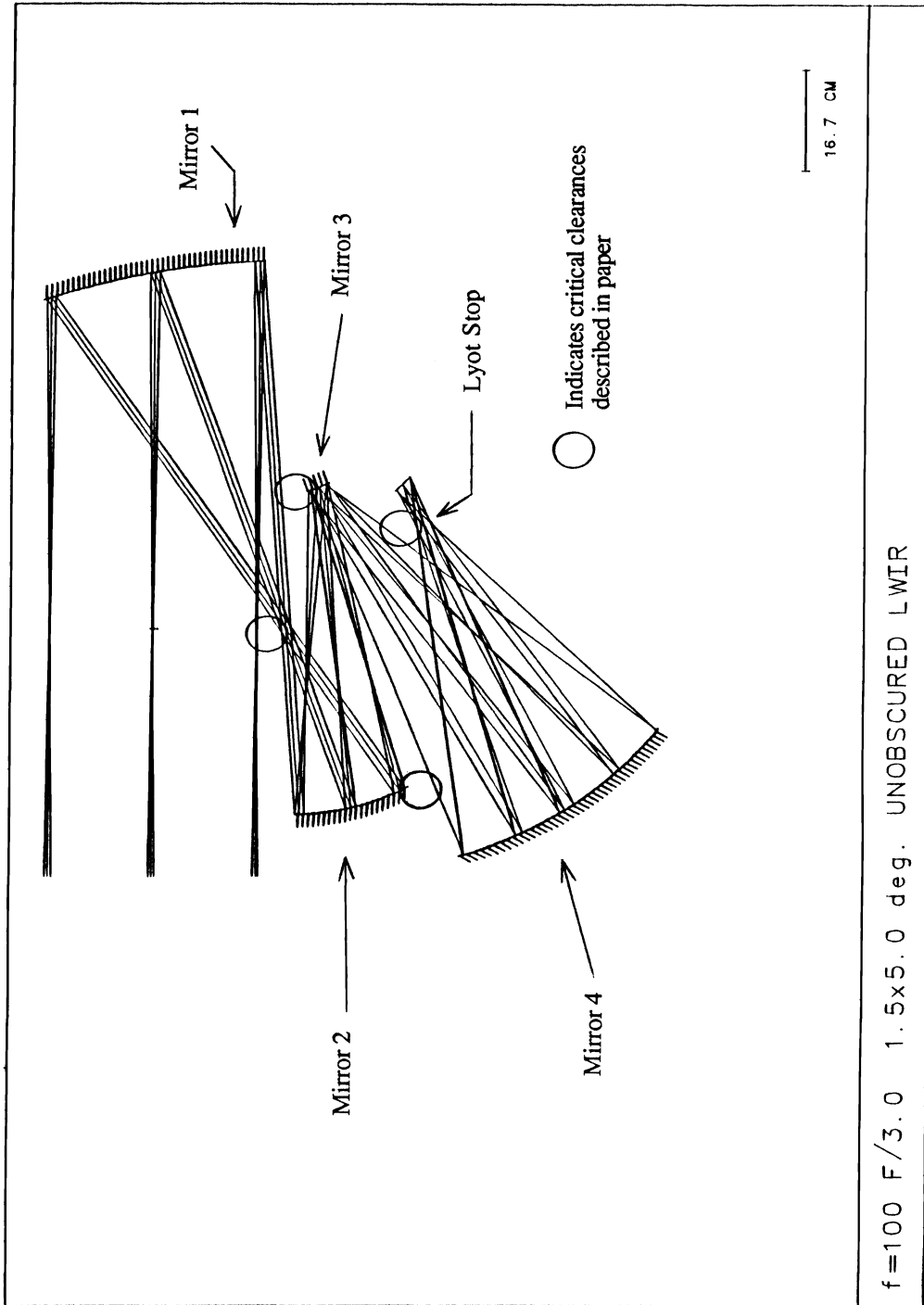


Figure 1. Four-mirror telescope example

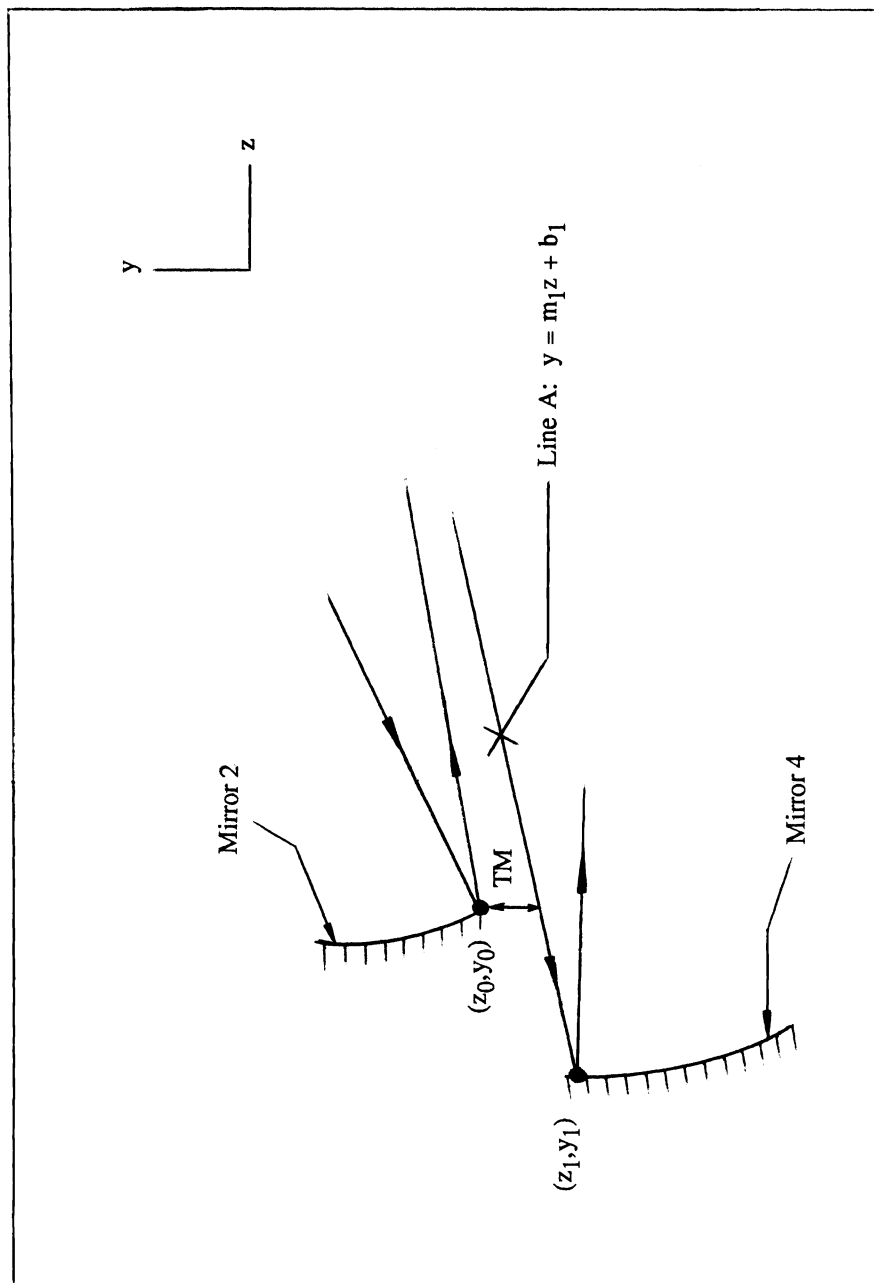


Figure 2. Secondary mirror clearance

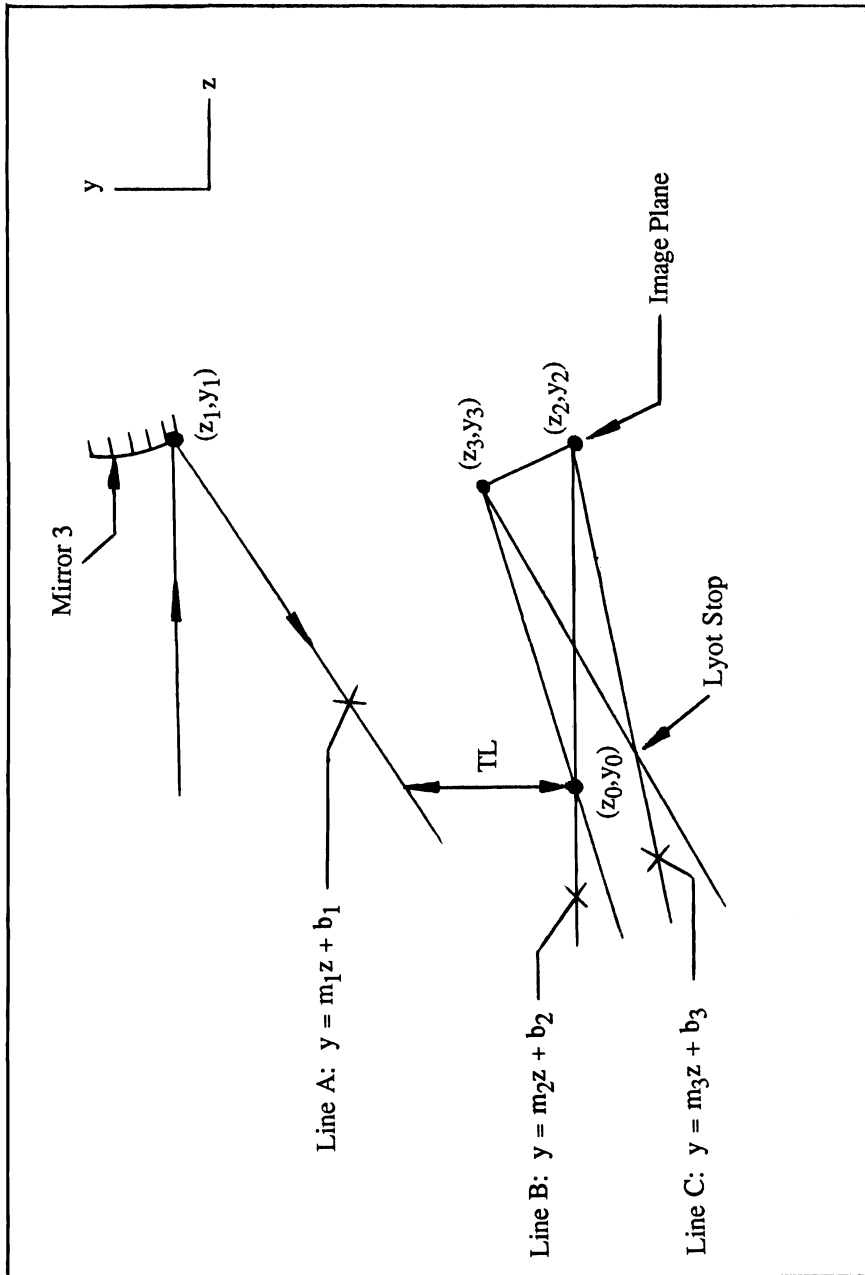


Figure 3. Lyot stop clearance

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!! AUTO of unobscured 4-mirror system.
!! Field angles defined as
!!      YAN  -0.75  0  0.75  -0.75  0.75
!!      XAN   0    0    0    2.5    2.5
!! (e.g. field 3, or F3, is YAN = 0.75 and XAN = 0).
!!
!! Surface definitions:
!!      Surface      Element
!!      1            Aperture stop
!!      2            Mirror 1
!!      3            Mirror 2
!!      4            Mirror 3
!!      5            Mirror 4
!!      6            Focal surface
!! =====
auto
int
wtf fa 1      ! equal weights on all fields
!
!! ----- Real focal length -----
x r1 f5 si = 4.366      ! f = 100, 2.5 deg. semifield.
!
!! ----- Clearance between 2nd mirror and rays between mirrors 3 and 4 ---
@s12 := (m r2 f1 s5 g2)/(n r2 f1 s5 g2)      ! slope of extreme ray.
@b2 := (y r2 f1 s5 g2) - @s12*(z r2 f1 s5 g2) ! y-int of extreme ray.
@c12 := -@s12*(z r2 f1 s3 g2) - @b2 + (y r2 f1 s3 g2)
@c12 = 5      ! clearance of 5 units.
!
!!-----Lyot stop clearance.-----
!
@s13 := (m r2 f1 si g2)/(n r2 f1 si g2)      ! Upper marginal ray, -field,
@b3 := (y r2 f1 si g2) - @s13 * (z r2 f1 si g2) ! edge of Lyot stop.
!
@s14 := (m r2 f3 si g2)/(n r2 f3 si g2)      ! Upper marginal ray, +field,
@b4 := (y r2 f3 si g2) - @s14 * (z r2 f3 si g2) ! edge of Lyot stop.
!
@zc := (@b4 - @b3)/(@s13 - @s14)      ! coordinates of
@yc := @s13*@zc + @b3      ! edge of Lyot stop
!
@s15 := (m r3 f3 s5 g2)/(n r3 f3 s5 g2)      ! Lower edge of bundle
@b5 := (y r3 f3 s5 g2) - @s15*(z r3 f3 s5 g2) ! above Lyot stop.
!
@lcl := @s15*@zc + @b5 - @yc      ! Clearance between
@lcl = 5      ! bundle and Lyot stop.
!
!! ----- Clearance between incoming bundle and field stop -----
!
@s1a := (m r2 f3 s3 g2)/(n r2 f3 s3 g2)      ! upper marginal ray,
@ba := (y r2 f3 s3 g2) - @s1a * (z r2 f3 s3 g2) ! top of field stop.
!
@s1b := (m r3 f3 s3 g2)/(n r3 f3 s3 g2)      ! lower marginal ray,
@bb := (y r3 f3 s3 g2) - @s1b * (z r3 f3 s3 g2) ! top of field stop.
!
@zf := (@bb - @ba)/(@s1a - @s1b)      ! coordinates of
@yf := @s1a*@zf + @ba      ! top edge of field stop.
!
@s1c := (m r3 f2 s2 g2)/(n r3 f2 s2 g2)      ! Lower edge of
@bc := (y r3 f2 s2 g2) - @s1c*(z r3 f2 s2 g2) ! incoming bundle.
@fcl := @s1c*@zf + @bc - @yf      ! Clearance between
@fcl > 4      ! bundle and field stop edge.
!
!! ----- Clearance between tertiary mirror
!! and rays between mirrors 1 and 2 -----
!
@s16 := (m r3 f1 s3 g2)/(n r3 f1 s3 g2)      ! Lower edge of bundle
@b6 := (y r3 f1 s3 g2) - @s16*(z r3 f1 s3 g2) ! between M1 and M2.
!
@c13 := @s16*(z r2 f1 s4 g2) + @b6 - (y r2 f1 s4 g2) ! Clearance between bundle
@c13 = 5      ! and mirror edge.
! ----- Central ray through center of image surface. -----
y si r1 f2 = 0
go

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Figure 4. Sample command sequence to control packaging constraints during optimization