DESIGN OPTIMIZATION OF
A SCHMIDT-CASSEGRAIN TELESCOPE

by

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ME 555-07-09

Winter 2007 Final Report

ABSTRACT

The goal of the project is to find an optimal design of a Schmidt-Cassegrain telescope which is popular for amateur astronomers. The telescope model includes two disciplines viz. Optics and Thermal design. Firstly, the optics is designed through a ray-tracing program which takes the system components and predicts the first-order and third-order optics. The objective function of the optical design is to reduce the aberrations to provide clear image. Next, a thermal subsystem considers the deformation of the telescope mirrors, caused because of the change in clamping force (preload) as they are exposed to different thermal environments. The objective function of this subsystem is to maximize the robustness of the mirrors with change in temperature, to maintain the quality of image. The optimization is done in MATLAB and iSIGHT which are interfaced with Ansys for the structural analysis of mirror system. Finally, the subsystems are integrated using 'All-in-one' approach, with the objective function being minimization of aberrations in the optical image, caused because of thermal gradients.

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1. INTRODUCTION

The Schmidt-Cassegrain Telescope (SCT) is a very popular telescope for amateur astronomers. It consists of two mirrors and a refractive medium, a Schmidt corrector.
The Schmidt corrector is an aspheric refraction lens inserted to help reduce monochromatic aberrations with spherical mirrors. The profile of a Schmidt corrector dictates how the rays are refracted through the profile. However, since the corrector is a refracting element, it creates chromatic aberrations which can be measured through spot diagrams. The corrector lens is usually an addition to a telescope with a reflective surface.

Advantages of SCT are its compactness, transportability and excellent reduction of chromatic aberrations. The SCT combines the Cassegrain telescope with a Schmidt corrector for a total of three optical components. The locations of these components are free which gives a large design space for the designer. The SCT system consists of two strongly curved mirrors for our model.

In addition, the Schmidt corrector helps reduce the amount of loss of light with respect to the traditional Cassegrain telescope. This system will give us a very interesting optimization model as many different objects and disciplines rely on the same design variables of the system.

In addition to Optical design, the design for changes in thermal environment also is considered. Temperature changes cause quite a lot of corresponding changes to occur in optical surface radii, air spaces and lens thicknesses, the refractive indices of optical materials and of the surrounding air, as well as the physical dimensions of structural members. Any of these effects will tend to defocus and misalign the system.

The subsystem design break-up is made in the following way:
1) Optical design – Kwang Jae Lee
2) Thermal design – Anupam Garge

2. OPTICAL DESIGN

2.1. Problem Statement

Aberrations within the system lead to reduced optical quality. An ideal optical system would produce a point image for the astronomer's eyes if the source was a star. However, in most cases a blurred circle is obtained where it is a combination of different kinds of aberrations. There are two types of aberrations: chromatic and monochromatic. Chromatic aberrations are a function of the color of light or wavelength of the light entering in the system. While monochromatic aberrations will be the same for all types of wavelengths entering in the system.

The SCT consists of two mirrors and a refractive medium, a Schmidt corrector. The Schmidt corrector is an aspheric refraction lens inserted to help reduce monochromatic aberrations with spherical mirrors. However, since the corrector is a refracting element, it creates chromatic aberrations.

In addition, a baffle system was designed in our system to help reduce stray light entering the telescope.

2.2. Nomenclature

Variable	Description	Unit
D_{sch}	Diameter of Schmidt corrector and primary stop	mm
D_1	Inner Diameter of tube and primary mirror	mm
D_3	Diameter of secondary mirror	mm
D_{eye}	Diameter of eyepiece	mm
Z_{sch}	Length of outside edge of schmidt corrector to primary mirror	mm
$Z_{mirrors}$	Location of secondary mirror	mm
v	Vertex of Back Focus	mm
ε_1	Eccentricity of primary mirror	
ε_2	Eccentricity of secondary mirror	
R_1	Radius of curvature of the vertex of primary mirror	mm
R_2	Radius of curvature of the vertex of secondary mirror	mm
$Airy$	Airy disk radius	mm
$\frac{F}{\#}$	$\frac{focal}{\#}$ of Schmidt-Cassegrain	
$\frac{F}{\#}_{\max}$	Maximum $\frac{focal}{\#}$ range for Schmidt-Cassegrain	
$\frac{F}{\#}_{\min}$	Minimum $\frac{focal}{\#}$ range for Schmidt-Cassegrain	
2w	Angular Field of View	degree
δS_I^*	Contribution of an aspheric plate to third order aberrations	
$\hat{m}_2$	Integer in definition of characteristic function of SCT	
numrays	Minimum Number of rays for ray-tracing	
$\max_{deadraysratio}$	Maximum ratio of dead rays/total rays	
d_{pl}	Thickness of Schmidt Corrector	mm
k_{pl}	Dimensionless Profile Constant for Schmidgt Corrector	
h	Baffle optimization free parameter	mm
X_1, Z_1	Baffle Position of primary mirror	
X_3, Z_3	Baffle Position of secondary mirror	
g	Relative power of Schmidt corrector	

2.3. Mathematical Model (I)

In this study, we will find better design based on the model introduced in Mark [2]. Figure 1 shows the base profile and design variables of the SCT.

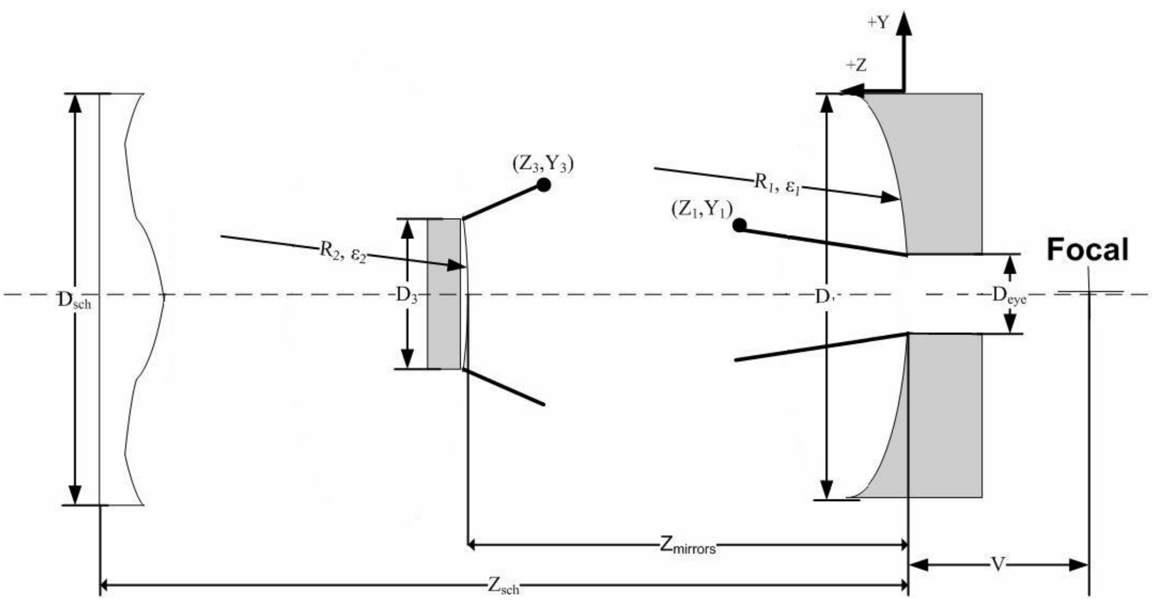


Figure 1 Dimensioned Draiwing of Schmidt-Cassegrain Telescope

Schmidt corrector:

$$d_{pl} = \frac{1}{512}\left(\frac{1}{n_0' - 1}\right)\frac{D_{sch}}{N^3}\left(\rho_{pl}{}^4 - k_{pl}\rho_{pl}{}^2\right) + (d_{pl})_0$$

where

$$N = \frac{-f_1'}{D_{sch}}$$

$$\rho_{pl} = \frac{y}{D_{sch}/2}$$

$$k_{pl} = \Delta Z \frac{16 f'}{y_m{}^2}$$

2.3.1. Objective Function

The main purpose of this sub problem is to minimize the aberrations. The aberrations are viewed by the astronomer as a blurred image and can be caused by a variety of reasons. A visual method to view these aberrations is through a series of spot diagrams. The circle in which the light must encompass can be measured through an Airy disk which includes 84% of the energy in the image [6].

$$\min_X \sum_{\lambda=1}^{3} \sum_{rays=1}^{numrays} \Phi(X)$$

where

$$Airy = 2.44 * \lambda * F/\#$$

$$\Phi(x,y,z,\lambda) = \frac{2000}{1+e^{100000(\frac{Airy}{2} - spot(x,y,z,\lambda))}}$$

2.3.2. Constraints

Physical constraints

Focal Ratio:

An important system performance parameter considered with all telescope is the focal ratio. The focal ratio is a ratio of the focal length of a mirror and the diameter of the aperture. Most telescopes are designed with a focal ratio specified, however for our model the focal ratio will be calculated from the radius of curvatures of the mirrors and the separation in-between mirrors.

$$\frac{1}{f'} = \frac{-f'_2 + f'_1 - Z_{mirrors}}{f'_1 \, f'_2}$$

$$\frac{F}{\#} = \frac{f'}{D_{sch}}$$

$$\frac{F}{\#}_{\max} \geq \frac{F}{\#}$$

$$\frac{F}{\#}_{\min} \leq \frac{F}{\#}$$

Baffle Design:

A baffle system was designed in our system to help reduce stray light entering the telescope. The baffle system goal is to eliminate all the direct stray light entering the system without limiting the contrast and resolution of the object you are trying to view. Terebizh [5] has a optimal baffle algorithm which was used for this project.

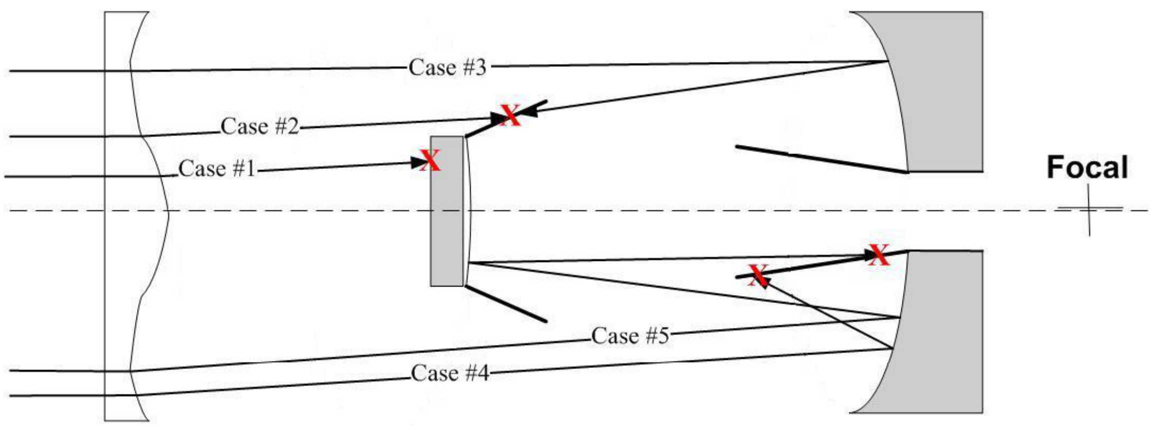


Figure 2 Scenarios of Rays Blocked be Baffles

$$\rho_{baf}(h_*) = [(Z_3 - Z_2)^2 + (Y_3 - Y_2)^2]^{1/2} = 0$$

$$\frac{deadrays}{rays_{total}} \leq \max_{deadraysratio}$$

Dead rays

Case #1: $-\mu \cdot Z_{mirrors} + \mu \cdot z_0 + y_0 \leq \frac{D_3}{2}$

Case #2: $Z_3 \leq \frac{b - b_1}{m_1 + \mu} \leq Z_{mirrors}$

Case #3: $Z_3 \leq \frac{a - b_1}{m_1 - k} \leq Z_{mirrors}, y = kz + a : reflectedray$

Case #4: $0 \le \dfrac{a - b_2}{m_2 - k} \le Z_1$

Case #5: $-v \le \dfrac{b_3 - b_2}{m_2 - m_3} \le Z_1$

where

(z_0, y_0) : Ray Position, α : angle of ray

$$\mu = \tan\alpha$$

$$b = \mu \cdot z_0 + y_0$$

$$b_1 = -m_1 Z_3 + Y_3$$

$$b_2 = \frac{D_{eye}}{2}$$

$$b_3 = -S_s m_3 + y_2$$

$$m_1 = \frac{Y_3 - \frac{D_3}{2}}{Z_3 - Z_{mirrors}}$$

$$m_2 = \frac{Y_1 - \frac{D_{eye}}{2}}{Z_1}$$

$$m_3 = \frac{Y + l}{S_2 + v}$$

Monochromatic Aberrations:

$-f'\zeta + L\zeta + \delta S_I^* = 0$ spherical aberration

$-d_1\xi - \dfrac{-f'}{2} + \dfrac{s_{pl}}{f'}\delta S_I^* = 0$ coma

$\dfrac{f'}{L}(f' + d_1) + \dfrac{d_1^2}{L}\xi + \left(\dfrac{s_{pl}}{f'}\right)^2 \delta S_I^* = 0$ astigmatism

Where

$$\hat{m}_2 = \frac{f'}{f_1'}$$

$$\xi = \frac{(\hat{m}_2 + 1)^3}{4}\left[\left(\frac{\hat{m}_2 - 1}{\hat{m}_2 + 1}\right)^2 - \varepsilon_2^2\right]$$

$$\zeta = \frac{\hat{m}_2{}^2}{4}(1 - \varepsilon_1^2)$$

$$d_1 = Z_{mirrors}$$

$$L = v - Z_{mirrors}$$

$$s_{pl} = -Z_{sch} f'$$

$$\delta S_I^* \le \frac{-f_1'}{4}$$

Geometric relations:

$Z_{sch} \ge -Z_{mirrors}$

Practical constraints

From the practical point of view, the range of design variables is restricted as:
(Sign convention follows the classical optics)

$10mm \le Z_{sch} \le 4000mm$

$-4000mm \le Z_{mirrors} \le 10mm$

$-20000 \le R_1 \le 0mm$

$-20000 \le R_2 \le 0mm$

$0mm \le v \le 2000mm$

Geometric relations

Following dimensions are determined from the result of ray tracing with 0 and given angular field of view

D_1	Inner Diameter of tube and primary mirror
D_3	Diameter of secondary mirror
D_{eye}	Diameter of eyepiece

2.3.3. Design Variables and Parameters

Variables:

R_1	Radius of curvature of the vertex of primary mirror
R_2	Radius of curvature of the vertex of secondary mirror
ε_1	Eccentricity of primary mirror
ε_2	Eccentricity of secondary mirror
Z_{sch}	Length of outside edge of Schmidt corrector to primary mirror
$Z_{mirrors}$	Location of secondary mirror
δS_I^*	Contribution of an aspheric plate to third order aberrations
h	Baffle optimization free parameter

Parameters:

$D_{sch} = 8inch$	Diameter of Schmidt corrector and primary stop
$\frac{F}{\#}_{\max} = 5$	Maximum $\frac{focal}{\#}$ range for Schmidt-Cassegrain
$\frac{F}{\#}_{\min} = 2.5$	Minimum $\frac{focal}{\#}$ range for Schmidt-Cassegrain
$\max_{deadraysratio} = 0.35$	Maximum ratio of dead rays/total rays
$\lambda_1 = 656.27nm$	Wavelength of red light
$\lambda_2 = 546.07nm$	Wavelength of green light
$\lambda_3 = 486.13nm$	Wavelength of blue light

$n_1 = 1.51432$	Red light refractive index of BK7 glass
$n_2 = 1.51872$	Green light refractive index of BK7 glass
$n_3 = 1.52238$	Blue light refractive index of BK7 glass
$2w = 1°$	Angular Field of View

2.3.4. Summary Model

$$\min_X \sum_{\lambda=1}^{3} \sum_{rays=1}^{numrays} \Phi(X)$$

where

$$Airy = 2.44 * \lambda * F/\#$$

$$\Phi(x, y, z, \lambda) = \frac{2000}{1 + e^{100000\left(\frac{Airy}{2} - spot(x,y,z,\lambda)\right)}}$$

subject to

g1: $\dfrac{F}{\#} - \dfrac{F}{\#}_{\max} \le 0$

g2: $\dfrac{F}{\#}_{\min} - \dfrac{F}{\#} \le 0$

g3: $\dfrac{deadrays(case\#1 \sim \#5)}{rays_{total}} - \max_{deadraysratio} \le 0$

g4: $\delta S_I^* + \dfrac{f_1'}{4} \le 0$

g5: $-Z_{mirrors} - Z_{sch} \le 0$

h1: $-f'\zeta + L\zeta + \delta S_I^* = 0$

h2: $-d_1\xi - \dfrac{-f'}{2} + \dfrac{s_{pl}}{f'}\delta S_I^* = 0$

h3: $\dfrac{f'}{L}(f' + d_1) + \dfrac{d_1^2}{L}\xi + \left(\dfrac{s_{pl}}{f'}\right)^2 \delta S_I^* = 0$

h4: $\rho_{baf}(h) = [(Z_3 - Z_2)^2 + (Y_3 - Y_2)^2]^{1/2} = 0$

2.4. Mathematical Model (II)

After first mathematical model is defined, a lot of changes and corrections are made. Objective function is changed to minimize RMS (root mean square) of spot size based on geometric optics, and baffle equality constraint is removed to simplify the model.

2.4.1. Objective function

$$\min_X (f_1(X) + f_2(X)) * 10^3$$

where

$$f_1 = \sqrt{\frac{1}{numRays} \sum_{i=1}^{numRays} \left(\sqrt{x_i^2 + y_i^2} \right)^2} \quad \text{with w = 0°}$$

$$f_2 = \sqrt{\frac{1}{numRays} \sum_{i=1}^{numRays} \left(\sqrt{x_i^2 + y_i^2} \right)^2} \quad \text{with w = 0.5°}$$

(Xi, Yi) : Position of i-th spot

2.4.2. Design Variables and Parameters

Variables:

R_1	Radius of curvature of the vertex of primary mirror
R_2	Radius of curvature of the vertex of secondary mirror
ε_1	Eccentricity of primary mirror
ε_2	Eccentricity of secondary mirror
$Z_{mirrors}$	Location of secondary mirror
v	Vertex of back focus
g	Relative power of Schmidt corrector

Parameters:

$D_{sch} = 200mm$	Diameter of Schmidt corrector and primary stop
$Z_{sch} = 600mm$	Length of outside edge of Schmidt corrector to primary mirror
$\frac{F}{\#} = 10$	$\frac{focal}{\#}$ for Schmidt-Cassegrain
$\lambda_1 = 656.27nm$	Wavelength of red light
$\lambda_2 = 546.07nm$	Wavelength of green light
$\lambda_3 = 486.13nm$	Wavelength of blue light
$n_1 = 1.51432$	Red light refractive index of BK7 glass
$n_2 = 1.51872$	Green light refractive index of BK7 glass
$n_3 = 1.52238$	Blue light refractive index of BK7 glass
$2w = 1°$	Angular Field of View

2.4.3. Summary Model

$$\min_X (f_1(X) + f_2(X)) * 10^3$$

where

$$f_1 = \sqrt{\frac{1}{numRays} \sum_{i=1}^{numRays} \left(\sqrt{x_i^2 + y_i^2}\right)^2} \quad \text{with w} = 0°$$

$$f_2 = \sqrt{\frac{1}{numRays} \sum_{i=1}^{numRays} \left(\sqrt{x_i^2 + y_i^2}\right)^2} \quad \text{with w} = 0.5°$$

(Xi, Yi) : Position of spot

$$Airy = 1.22 * \lambda * F/\#$$

$$\frac{1}{f'} = \frac{-f'_2 + f'_1 - Z_{mirrors}}{f'_1 \, f'_2}, \quad f'_1 = R_1/2, \; f'_2 = R_2/2$$

subject to

g1: max distance of spot$(w = 0^\circ)$ - Airy ≤ 0

g2: max distance of spot$(w = 0.5^\circ)$ - Airy ≤ 0

g3: $-Z_{mirrors} - Z_{sch} \leq 0$

g4: $-20000 \leq R_1 \leq 0$

g5: $-20000 \leq R_2 \leq 0$

g6: $0 \leq {\varepsilon_1}^2 \leq 1$

g7: $0 \leq {\varepsilon_2}^2 \leq 1$

g8: $0.5 \leq g \leq 1.0$

g9: $-1000 \leq Z_{mirrors} \leq -10$

g10: $20 \leq v \leq 500$

h1: $\frac{F}{\#} * D_{sch} - f' = 0$

2.5. Ray Tracing

In the following sections, the results of ray-trace will be presented. Negative values for r, d(distance between mirrors), and n(refractive index) mean that rays go to the left. The following examples are used to show the ray-trace results. Last surfaces are the focal planes in the tables.

System 1: Newtonian. D=150, Primary mirror is spherical

Surface	r	e^2	d	n
1	-500	0	300	1
2	0	0	-250	-1

System 2: Cassegrain. D=150

Surface	r	e^2	d	n
1	-1000	1	500	1
2	-373.33	2.778	-360	-1
3	0	0	560	1

System 3: Spherical mirror with Schmidt corrector. D=150 (same as 1 except corrector)

Surface	r	e^2	d	n
1(Sch)	0	0	5	1.51872
2	-500	0	295	1
3	0	0	-250	-1

System 4: Schmidt-Cassegrain. D=150

Surface	r	e^2	d	n
1(Sch)	0	0	5	1.51872
2	-1000	1	495	1
3	-373.33	2.778	-360	-1
4	0	0	560	1

2.5.1. Initial rays

Initial rays are constructed in concentric pattern using given minimum number of rays. These rays are used in spot diagram.

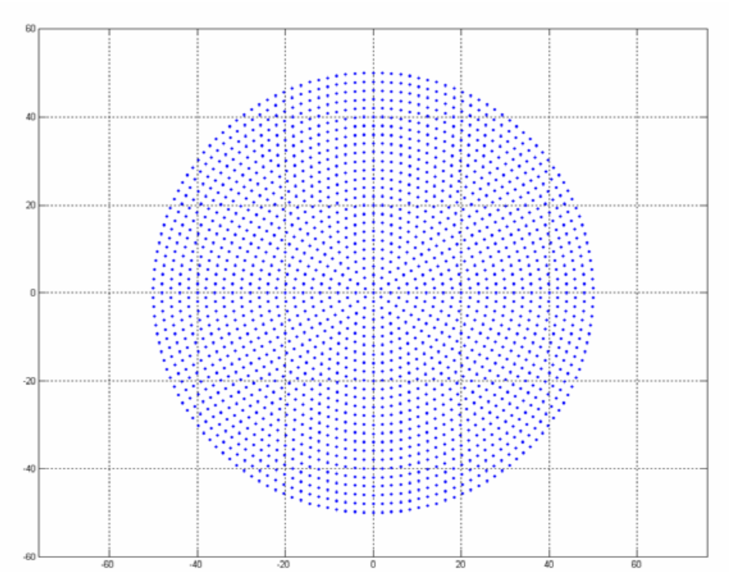


Figure 3 Example of initial rays. (D=100mm)

2.5.2. Examples of ray-trace

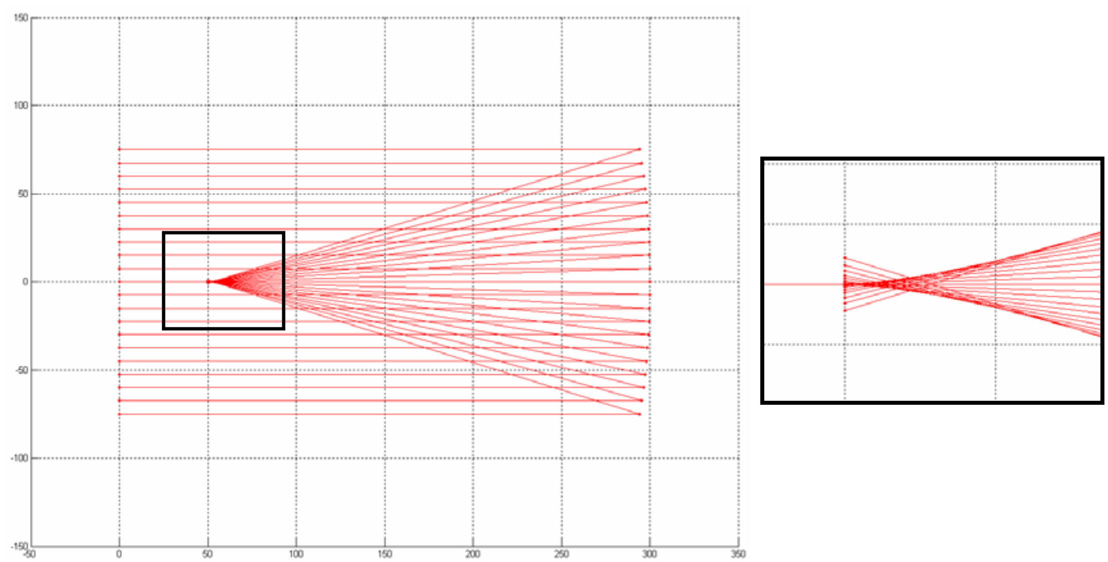


Figure 4 Result of ray-trace of System 1 and its spherical aberration. (w=0°)

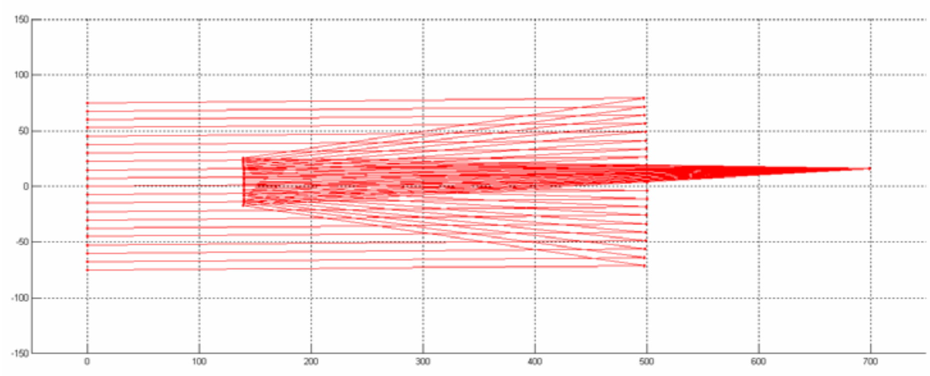


Figure 5 Result of ray-trace of System 2. (w=0.45°)

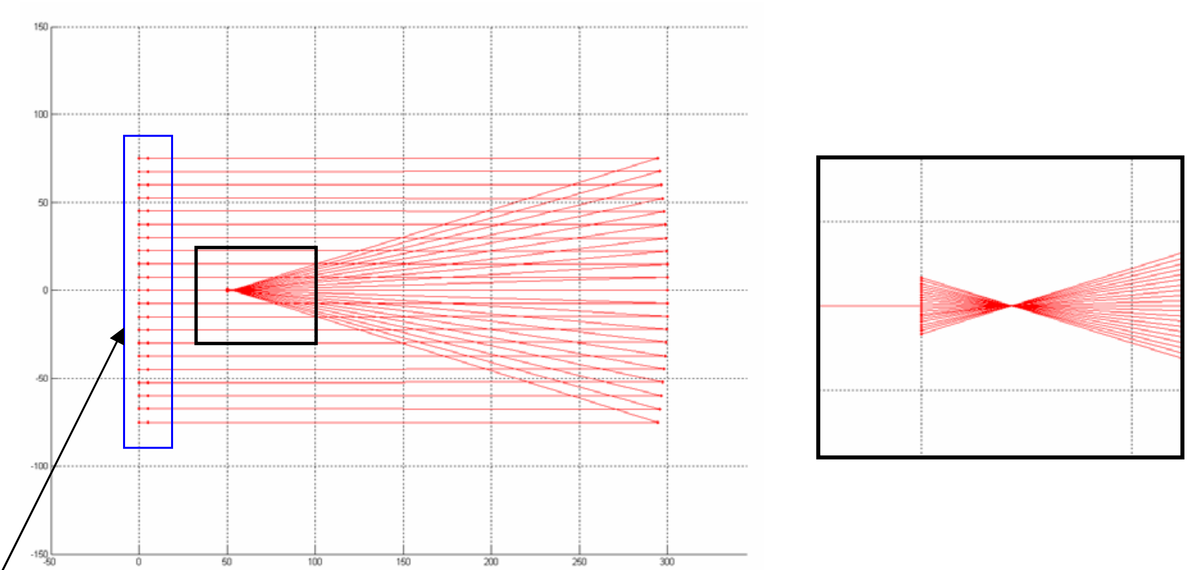


Figure 6 Result of ray-trace of System 3 and its corrected spherical aberration. (w=0°)

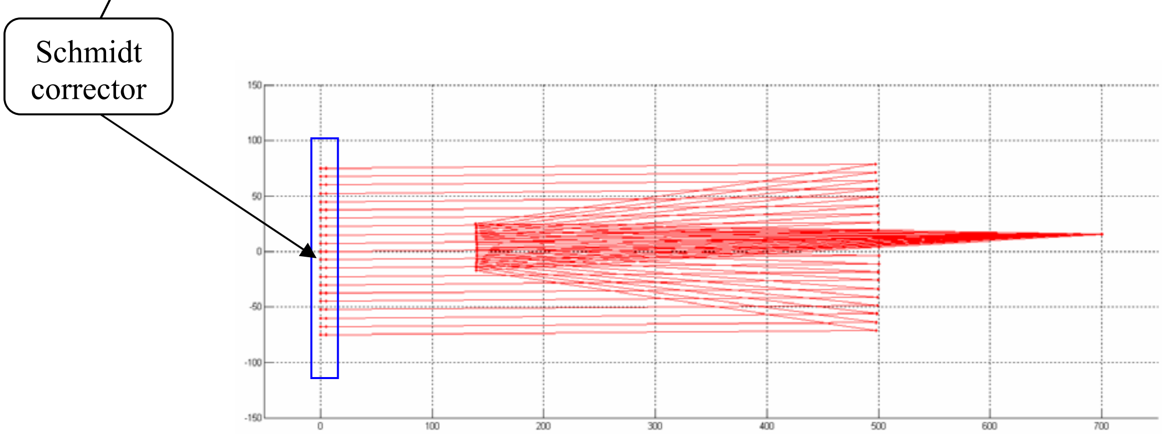
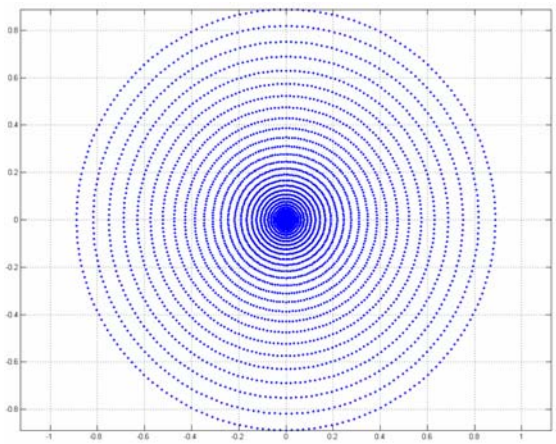


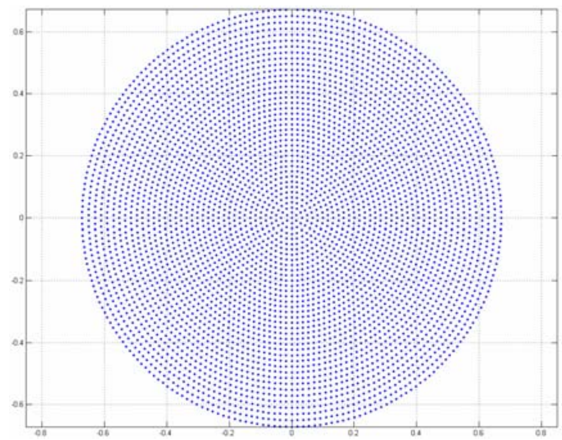
Figure 7 Result of ray-trace of System 4. (w=0.45°)

2.5.3. Spot diagram

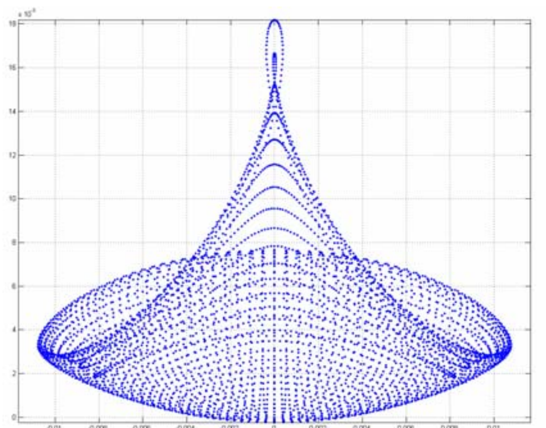
Spot diagram is the set of points which is formed on the focal plane after passing several lenses and mirrors. Examples of spot diagram are given in Figure 8.



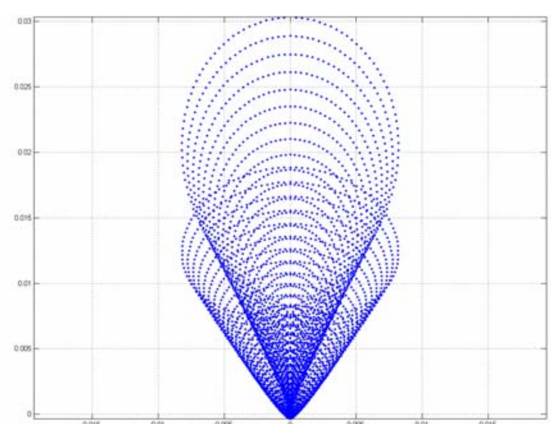
(a) System 1 (w=0°)



(b) System 2 (w=0°)



(c) System 3 (w=0.45°, defocus -1)



(d) System 1 (w=0.45°, R1=-300, d=-1500)

Figure 8 Examples of spot diagrams

2.6. Result

2.6.1. iSIGHT Model

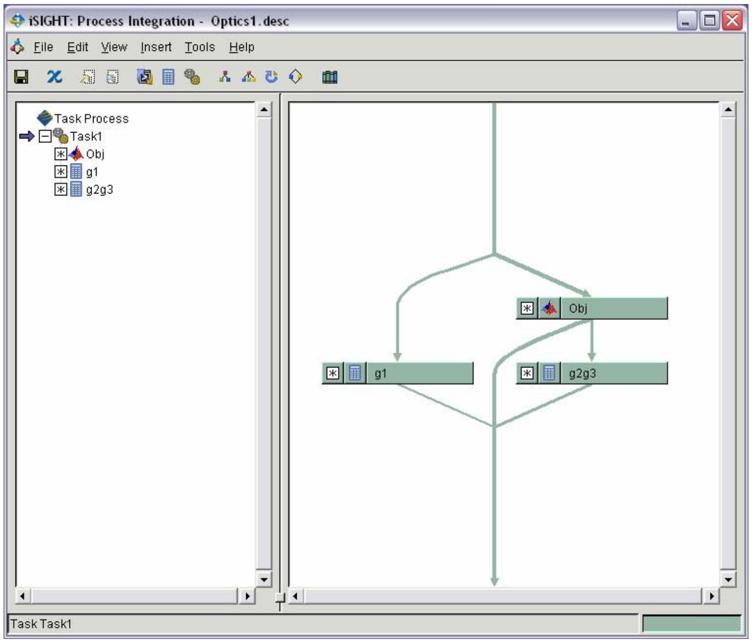
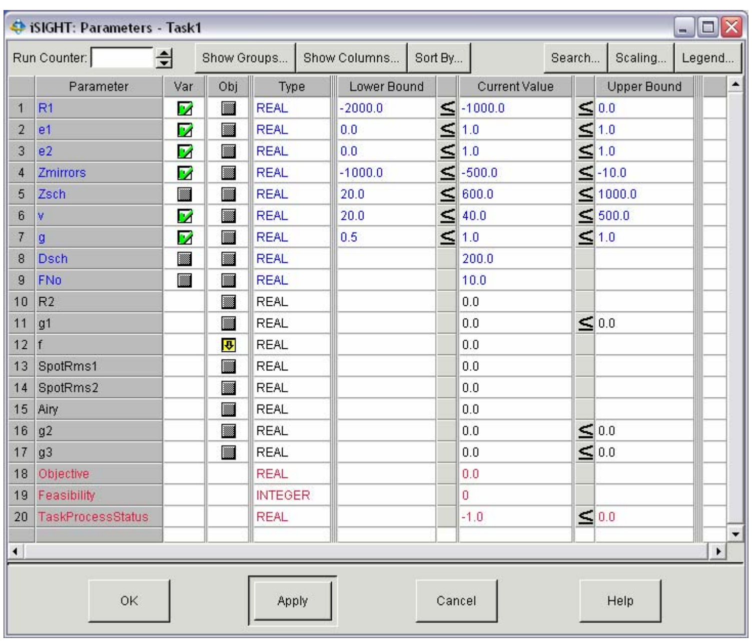


Figure 9 iSIGHT process integration



	Parameter	Var	Obj	Type	Lower Bound		Current Value		Upper Bound
1	R1			REAL	-2000.0	≤	-1000.0	≤	0.0
2	e1			REAL	0.0	≤	1.0	≤	1.0
3	e2			REAL	0.0	≤	1.0	≤	1.0
4	Zmirrors			REAL	-1000.0	≤	-500.0	≤	-10.0
5	Zsch			REAL	20.0	≤	600.0	≤	1000.0
6	v			REAL	20.0	≤	40.0	≤	500.0
7	g			REAL	0.5	≤	1.0	≤	1.0
8	Dsch			REAL			200.0		
9	FNo			REAL			10.0		
10	R2			REAL			0.0		
11	g1			REAL			0.0	≤	0.0
12	f			REAL			0.0		
13	SpotRms1			REAL			0.0		
14	SpotRms2			REAL			0.0		
15	Airy			REAL			0.0		
16	g2			REAL			0.0	≤	0.0
17	g3			REAL			0.0	≤	0.0
18	Objective			REAL			0.0		
19	Feasibility			INTEGER			0		
20	TaskProcessStatus			REAL			-1.0	≤	0.0

Figure 10 Parameters and initial values in iSIGHT

2.6.2. iSIGHT Result

Parameter Information

Inputs	Type	Current Value
R1	REAL	-1599.42925616822
e1	REAL	0.0666500298321939
e2	REAL	1.0
Zmirrors	REAL	-552.446054174238
Zsch	REAL	600.0
v	REAL	61.2673611322561
g	REAL	0.644926034485024
Dsch	REAL	200.0
FNo	REAL	10.0

Outputs	Type	Current Value
R2	REAL	-824.032616560787
g1	REAL	-47.553945825762
f	REAL	288.974630307584
SpotRms1	REAL	0.000585767967671273
SpotRms2	REAL	0.0682401995228084
Airy	REAL	0.006662054
g2	REAL	-0.00607628603232873
g3	REAL	0.0615781455228084
Objective	REAL	288.974630307584
Feasibility	INTEGER	3
TaskProcessStatus	REAL	-1.0

* Current Value = value when report was generated

Optimization Techniques

Step 1	Sequential Quadratic Programming - NLPQL
Step 2	Mixed Integer Optimization - MOST

Design Variables	Type	Lower Bound	Current Value	Upper Bound
e1	REAL	0.0	0.0666500298321939	1.0
e2	REAL	0.0	1.0	1.0
Zmirrors	REAL	-1000.0	-552.446054174238	-10.0
v	REAL	20.0	61.2673611322561	500.0
g	REAL	0.5	0.644926034485024	1.0
R1	REAL	-2000.0	-1599.42925616822	0.0

Output Constraints	Type	Lower Bound	Current Value	Upper Bound
g1	REAL		-47.553945825762	0.0
g2	REAL		-0.00607628603232873	0.0
g3	REAL		0.0615781455228084	0.0

Objectives	Type	Direction	Current Value
f	REAL	minimize	288.974630307584

Execution Results (After first iteration 222)

Task	Task1
Total runs	146
Feasible runs	0
Infeasible runs	146
Failed runs	0
Database file	Task1.db

Best design:	currently	previously
RunCounter	369	222
ObjectiveAndPenalty	302.766498313612	302.824676106791
Objective	288.974630307584	289.036636836608
Penalty	13.791868006028	13.788039270183

Best design parameter values

R1	-1599.42925616822	previously
e1	0.0666500298321939	
e2	1.0	
Zmirrors	-552.446054174238	
Zsch	600.0	
v	61.2673611322561	
g	0.644926034485024	
Dsch	200.0	
FNo	10.0	
R2	-824.032616560787	
g1	-47.553945825762	
f	288.974630307584	
SpotRms1	0.000585767967671273	
SpotRms2	0.0682401995228084	
Airy	0.006662054	
g2	-0.00607628603232873	
g3	0.0615781455228084 (violates UpperBound 0.0)	

2.6.3. Spot diagram of optimal design

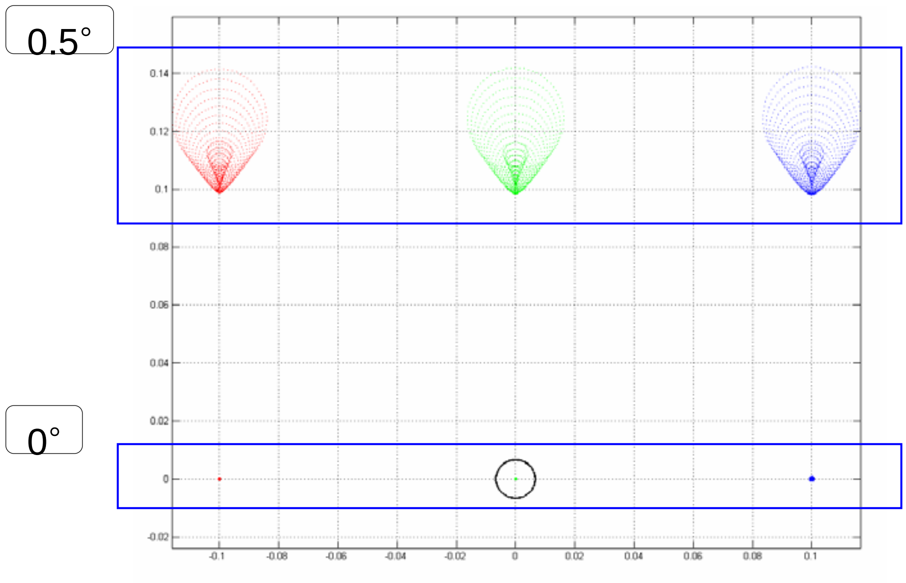


Figure 11 Spot diagram

2.7. Discussion

First, optimization problems from the one mirror system to Cassegrain telescope were solved with MATLAB fmincon to check the availability of the mathematical model. After verifying the feasibility of the model, SCT optimization model was constructed by iSIGHT because of easy manipulation of design variables and constraints, and the preparation of system integration.

Figure 11 shows the spot diagram of optimal design by iSIGHT. A black circle in Figure 11 is the airy disc which is a diameter of the first PSF minima, given by 2.44λF linearly and 2.44λ/D angularly (in radians) - λ being the wavelength of light, F the ratio of focal length vs. aperture D of the optical system, and it encircles 83.8% of the total energy contained by the diffraction pattern. As can be seen, this optimal solution has the good optical performance with the incident angle 0 degree.

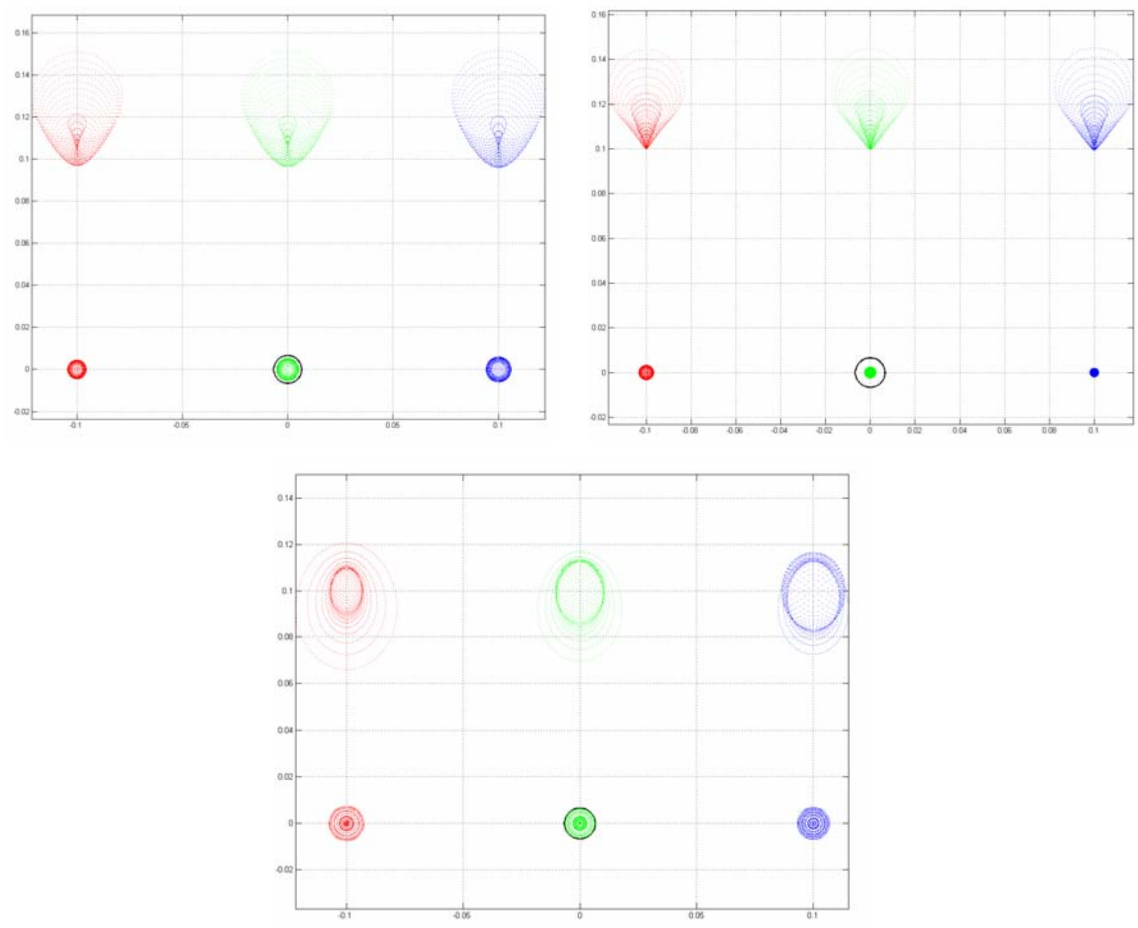


Figure 12 Various results of optimization

However, coma aberration of which spot diagram is the comet shape still exists. Although 10 combinations of different objective functions and constraints are used to try to remove coma aberration, there is no feasible solution to get rid of the coma. Various results are given in Figure 12, but every spot diagram has coma or spherical aberration.

Different starting points or scaling the problem might be needed to get better result. Also, surrogate model may result in better design because the objective function could have the noise, so it could have many local optima. Although these were not covered in this study, these could be done as the future work.

3. THERMAL DESIGN

3.1. Problem Statement

The telescope can be used in different temperature environments which will affect the performance of the system. Thermal expansion or compression will result in misalignments of the parts and aberrations within the system. The system is designed for room temperature; however the telescope could be brought outside during a cold night or used in very hot conditions. Thermal displacements shall be taken into account for the outside tube. This will affect the positioning of the Schmidt corrector and secondary mirror.

When temperature changes, corresponding changes occur in optical surface radii, air spaces and lens thicknesses, the refractive indices of optical materials and of the surrounding air, as well as the physical dimensions of structural members. Any of these effects will tend to defocus and misalign the system.

Temperature gradients, axial and radial, can also exist in the system. These may cause effects similar to decentrations or tilts of optics (affecting imagery) and develop line-of-sight pointing errors. But in our model, we shall neglect these temperature gradients and assume that temperature is uniform throughout the lens and that; there is no tilting of the lens. Dimensional changes of optical and mechanical parts forming assemblies usually cause changes in clamping forces (preloads); these changes affect contact stresses at opto-mechanical interfaces. Although these problems may be serious if they are not attended to, most can be eliminated or drastically reduced in magnitude by careful opto-mechanical design.

3.2. Nomenclature

Variable	Description	Units
α_M	Coefficient of thermal expansion of optical materials	1/ºC
α_G	Coefficient of thermal expansion of mount	1/ºC
ΔT	Temperature change	ºC
D_G	Optic outer diameter	mm
D_1	Diameter of primary mirror	mm
D_2	Diameter of secondary mirror	mm
Dsch	Diameter of Schmidt corrector	mm
tc	Mount wall thickness	mm
Δr	Radial clearance	mm
σ_R	Radial Stress	N/mm^2
σ_M	Tangential Stress	N/mm^2
R_1	Radius of back-surface of primary mirror	mm
R_2	Radius of back-surface of secondary mirror	mm
R	Radius of front-surface of primary mirror	mm
r	Radius of front-surface of secondary mirror	mm
m_1	Mass of primary mirror	Kg
m_2	Mass of secondary mirror	Kg
P	Total axial Preload	N
ΔP	Change in preload	N
T_A	Assembly temperature	ºC
Δa	Axial gap	mm
t_1	Edge thickness of primary mirror	mm
t_2	Edge thickness of secondary mirror	mm
Zmirrors	Distance between primary and secondary mirrors	mm
Zsch	Distance between primary mirror and Schmidt corrector	mm
Z_{tube}	Length of the tube	mm
D_{tube}	Nominal diameter of tube	mm
f_1	Focal length of primary mirror	mm
f_2	Focal length of secondary mirror	mm
f	Focal length of telescope	mm
fno	Focal number of the telescope	-
fno_new	Focal number of telescope after deformation	-

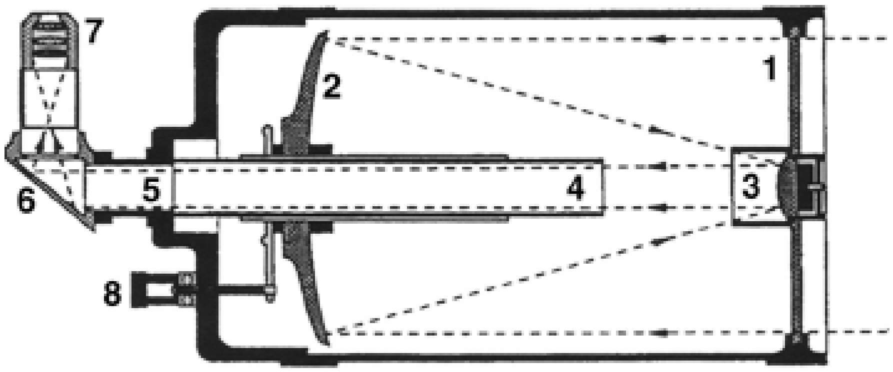


Figure 13 Schematic Layout

Changes in temperature cause differential expansion or contraction of circular-aperture optics (lenses, windows, filters and mirrors) with respect to mounting materials in both axial and radial directions. In the discussion of effects of changes in radial dimensions, we assume rotational symmetry of optics and pertinent portions of mount. That is, clearance between optical outer diameter and inner diameter of mount is small; that all components are at uniform temperature before and after each temperature change; that the co-efficients of thermal expansion (CTEs) of optical materials and of the mount are α_G and α_M respectively; and that the temperature changes are ΔT.

The CTE of mount usually exceeds that of optic mounted in it. In usual case, a drop in temperature will cause the mount to contract radially toward the optic's rim. Any radial clearance between these components will decrease in size and, if temperature falls far enough, the inner diameter of mount will contact outer diameter of optic. Any further decrease in temperature will cause radial force to be exerted upon the rim of optic. The force compresses the optic radially and creates radial stresses. To the degree of approximation applied here, the strain and stress are symmetrical about the axis. If stress is large enough, the performance of optic will be adversely affected. Extremely large stresses will cause failure of optic and plastic deformation of the mount.

If $\alpha G > \alpha M$, increase in temperature will cause the mount to expand away from the optic, thereby increasing radial clearance or creating such a clearance. Significant increase in radial clearance may allow the optic to shift under external forces such as shock or vibration, and then the alignment may be affected.

(1) Radial Stress in optic

The magnitude of radial stress, σ_R in a rim contact mounted optic for a given temperature drop ΔT can be estimated as,

$$\sigma_R = -K_1 K_2 \, \Delta T$$

$$\text{where,} \quad K_1 = \frac{\alpha_M - \alpha_G}{\dfrac{1}{E_G} + \dfrac{D_G}{2E_M t_C}}$$

$$K_2 = 1 + \frac{2\Delta r}{D_G \Delta T(\alpha_M - \alpha_G)}$$

Where, D_G is optic OD, t_c the mount wall thickness directly outside the rim of optic, and Δr the radial clearance.

Note that ΔT is negative for temperature decrease. Also $0 < K_2 < 1$.

If Δr exceeds $[D_G.\Delta T(\alpha_M - \alpha_G)/2]$, the optic will not be constrained by the mount ID and radial stress will not develop within the temperature range ΔT as a result of rim contact.

(2) Tangential (Hoop) Stress in the mount wall

Another consequence of differential contraction of the mount relative to rim contact optic is that the stress built up within the mount in accordance with the following equation,

$$\sigma_M = \sigma_R . D_G / (2t_c)$$

Where, σ_M is the tangential stress.

With this expression, we can determine if the mount is strong enough to withstand the force exerted upon the optic without causing plastic deformation or failure. If yield strength of mount material exceeds σ_M, a safety factor exists. Note that if K_2 is negative, there can be no stress in the cell wall.

Radial Effects at increased temperature

The increase ΔGAP_R, in nominal radial clearance GAP_R, between the optic and its mount that is due to temperature increase of ΔT can be estimated by,

$$\Delta GAP_R = (\alpha_M - \alpha_G)\,(D_{G/2})\,\Delta T$$

Changes in Axial Preload caused by temperature variations

Optical and mounting materials usually have dissimilar CTEs, generally $\alpha_M > \alpha_G$. So temperature changes of ΔT cause changes in total axial preload P. This change in preload is given by the equation,

$$\Delta P = K_3\,\Delta T$$

Where, K_3 is the 'temperature sensitivity factor' which is the rate of change of preload with temperature for the design.

Knowledge of K_3 would be advantageous because it would allow the estimation of actual preload at any temperature by adding ΔP to actual preload. In absence of friction, the preload will be same at all surfaces of all lenses clamped by single retaining ring.

If $\alpha_M > \alpha_G$, the metal in the mount expands more than the optic for given temperature increase ΔT. Any axial preload existing at assembly temperature T_A, will then decrease. If temperature rises sufficiently, preload will disappear. If the lens is not otherwise constrained axially, it will be free to move within the mount in response to externally applied forces. We define the temperature at which preload goes to zero as T_C. It is given by the equation,

$$T_C = T_A - (P_A / K_3)$$

The mount maintains contact with the lens until temperature rises to T_C. A further temperature increase introduces an axial gap between mount and the lens. This gap should not exceed the design tolerance for despace of this lens.

The increase in axial gap ΔGAP_A created in single element lens subassembly, a cemented doublet lens subassembly, air-spaced doublet subassembly, and general multilens subassembly as the temperature rises by ΔT above T_C can be approximated, respectively as,

$$\Delta GAP_A = (\alpha_M - \alpha_G)\,(t_E)\,(T - T_c)$$

$$\Delta GAP_A = [(\alpha_M - \alpha_{G1})\,(t_{E1}) + (\alpha_M - \alpha_{G2})\,(t_{E2})]\,(T - T_c)$$

$$\Delta GAP_A = [(\alpha_M - \alpha_{G1})\,(t_{E1}) + (\alpha_M - \alpha_S)\,(t_S) + (\alpha_M - \alpha_{G2})\,(t_{E2})]\,(T - T_c)$$

$$\Delta GAP_A = \Sigma_1^{\,n}\,(\alpha_M - \alpha_1)\,(t_i)\,(T - T_c)$$

In all the cases, if the preload applied at assembly is large, the calculated value for T_C may exceed T_{MAX}. In this case, ΔGAP_A will be negative, indicating that glass-to-metal contact is never lost within the range $T_A \leq T \leq T_{MAX}$.

Small changes in position and orientation of the lens are tolerable. However, high accelerations applied to lens assembly when clearance exists between lens and its mounting surfaces may cause damage to the lens from glass-to-metal impacts. Also, various optical errors like change of focus, astigmatism, and coma result from shifts in the position of optical surfaces. All these considerations translate into our objective function for design optimization of the thermal subsystem.

Clamping mechanism of the mirrors

A threaded retainer mechanism is used for mounting the mirrors in the outer tube. The retainer can be moved on the threaded tube wall, which then holds the lens within opposite retaining pads. The retainer applies the required clamping force (preload) at assembly temperature. This retainer then, moves along the threads due to expansion/contraction of mirrors and the tube during temperature changes, which causes the preload to vary.

The mechanism is shown below:

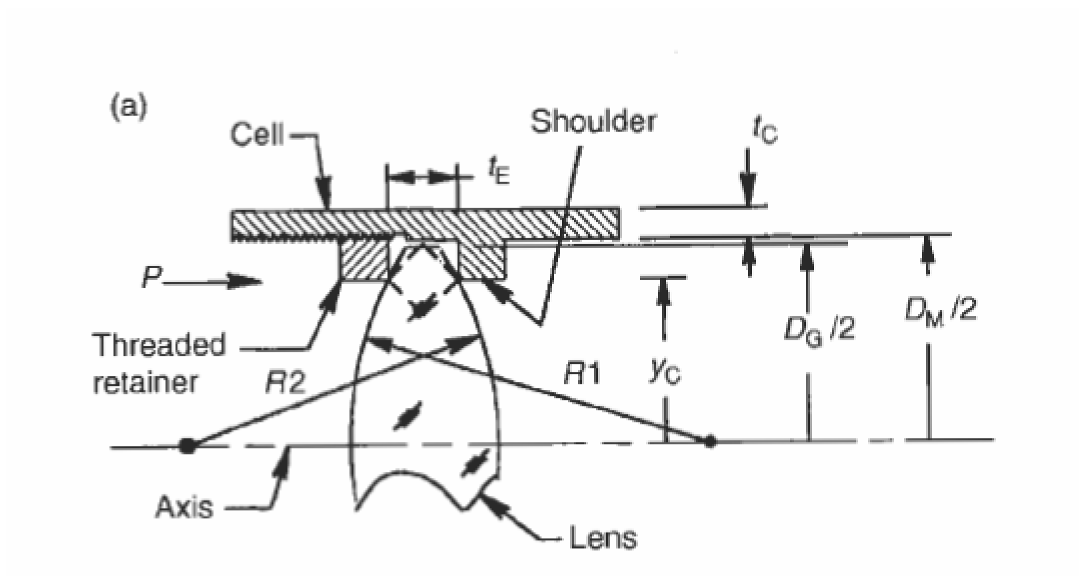


Figure 14 Lens mounting configuration for a single lens

3.3. Mathematical Model

3.3.1. Objective Function

The objective function of thermal subsystem is to maximize the **robustness** of the lens system. Now, the change in temperature causes equivalent expansion/contraction of the mirrors, which effectively deforms the mirrors and causes change in the focal length of the system.

So, we define our objective function as,

'To minimize the change in focal number of the system, because of the change in temperature.'

Minimize

$$f = \left| \left(\frac{f}{no.} \right)_{new} - \left(\frac{f}{no.} \right) \right|$$

3.3.2. Design Variables

The dimensions of the two mirrors will be considered while optimizing the design.

The radius of back-surface of the mirrors and the thickness of the mirrors will be the design variables, which will affect the objective function.

Variables:

R_1-back	Radius of back-surface of primary mirror
R_2-back	Radius of back-surface of secondary mirror
t_1	Thickness of primary mirror
t_2	Thickness of secondary mirror

3.3.3. Design Parameters

Hard Parameters

A careful selection of materials for the optical mirrors and the mounting tube will be executed.

Corning Pyrex® 7740 Borosilicate glass is used for the primary and secondary mirrors. Pyrex® provides unique chemical, thermal, mechanical and optical properties. The material selected for the mounting tube is a wrought aluminum alloy called Aluminum 7050-T7451.

The mechanical and thermal properties for these materials can be considered as hard parameters.

α_M	Coefficient of thermal expansion of the mounting tube	2.353×10^{-5} m/m°C
α_G	Coefficient of thermal expansion of the mirrors	3.25×10^{-6} m/m°C
ρ_M	Density of mounting tube	2823 kg/cu.m
ρ_G	Density of mirrors	2230 kg/cu.m

Performance Parameters

Certain values are considered as parameters during formulation of the design optimization model.

ΔT	Change in temperature	90°C
T_{max}	Maximum temperature	60°C
T_{min}	Minimum temperature	-30°C
T_A	Assembly temperature	20°C
D_1	Diameter of primary mirror	203 mm
D_2	Diameter of primary mirror	60 mm
R_1	Radius of front surface of primary mirror	810 mm
R_2	Radius of front surface of secondary mirror	250 mm
D_{sch}	Diameter of Schmidt corrector	203 mm
$Z_{mirrors}$	Distance between the mirrors	255 mm
f	Focal length of telescope at assembly temperature	2030 mm

3.3.4. Constraints

Dimensional constraints for primary mirror

g1: $-t1 + S + S1 \le 0.003$

g2: $-S1 \le 0$

Dimensional constraints for primary mirror

g3: $-S2 + s \le 0.004$

g4: $S2 - s \le 0$

g5: $-S2 \le 0$

Mass constraint for primary mirror

g6: $\Pi \times \rho G \times [t1\times (D1^2/4) - S1^2\times (R1back - S1/3) - S^2(R1 - S/3)] \le 1$

Mass constraint for secondary mirror

g7: $\Pi \times \rho G \times [t2\times (D2^2/4) - S2^2\times (R2back - S2/3) - s^2(R2 - s/3)] \le 0.7$

Definitions

Mirror geometry

1) $$S = R_1 - \sqrt{R_1 - (D_1/4)^2}$$

2) $$S_1 = R_1 back - \sqrt{R_1 back - (D_1/4)^2}$$

3) $$s = R_2 - \sqrt{R_2 - (D_2/4)^2}$$

4) $$S_2 = R_2 back - \sqrt{R_2 back - (D_2/4)^2}$$

Focal length

5) $f_1 = R_1/2$

6) $f_2 = R_2/2$

7) $$\frac{1}{f} = \frac{-f_2 + f_1 - Z_{mirrors}}{f_1 \times f_2}$$

8) $\dfrac{1}{f_{new}} = \dfrac{-f_{2new} + f_{1new} - Z_{mirrors}}{f_{1new} \times f_{2new}}$

9) $\left(\dfrac{f}{no.}\right) = \dfrac{f}{D_{sch}}$

10) $\left(\dfrac{f}{no.}\right)_{new} = \dfrac{f_{new}}{D_{sch}}$

3.3.5. Summary of the model

Minimize

$$f = \left| \left(\frac{f}{no.}\right)_{new} - \left(\frac{f}{no.}\right) \right|$$

Subject to

g1: $-t1 + S + S1 \leq 0.003$

g2: $-S1 \leq 0$

g3: $-S2 + s \leq 0.004$

g4: $S2 - s \leq 0$

g5: $-S2 \leq 0$

g6: $\Pi \times \rho G \times [t1 \times (D1^2/4) - S1^2 \times (R1back - S1/3) - S^2(R1 - S/3)] \leq 1$

g7: $\Pi \times \rho G \times [t2 \times (D2^2/4) - S2^2 \times (R2back - S2/3) - s^2(R2 - s/3)] \leq 0.7$

3.4. Model Analysis

The model involves thermal analysis of the mirrors. The behavior of the lens with change in temperature will be analyzed. This means, various important design considerations like deformations, change in focal number, and stresses developed will be observed.

3.4.1. Determination of preload at temperature limits

As stated earlier, the change in preload due to change in temperature is given as,

$$\Delta P = K_3 . \Delta T$$

where, K_3 is the temperature sensitivity factor. $K_3 = \dfrac{-(\alpha_M - \alpha_G)}{\dfrac{2t_E}{E_G A_G} + \dfrac{t_E}{E_M A_M}}$

For mirror 1

On careful study, K_3 is taken equal to -10 N/°C

Also, acceleration due to vibrations, in axial direction is taken to be 15 times gravity and mass to be 0.6 kg.

Then preload needed to overcome acceleration = 0.6 × 15 × 9.81 = 90 N

The preload dissipated from T_A to T_{MAX} = (-10) × 40 = - 400 N

So total preload needed at assembly = 90 + 400 = 490 N

And,

Preload dissipated from T_A to T_{MIN} = (-10) × 50 = - 500 N

So total preload at T_{MIN} = 490 + 500 = 990 N = approx. 1000 N

For mirror 2

On careful study, K_3 is taken equal to -6 N/°C

Also, acceleration due to vibrations, in axial direction is taken to be 15 times gravity and mass to be 0.4 kg.

Then preload needed to overcome acceleration = 0.4 × 15 × 9.81 = 60 N

The preload dissipated from T_A to T_{MAX} = (-6) × 40 = - 240 N

So total preload needed at assembly = 60 + 240 = 300 N

And,

Preload dissipated from T_A to T_{MIN} = (-6) × 50 = - 300 N

So total preload at T_{MIN} = 300 + 300 = 600 N

The next step in problem solving is structural analysis in Ansys. We have accounted for the thermal changes by calculating the preloads at temperature limits. For simplification purposes, we shall use only the maximum preload. This preload occurs at minimum temperature, as can be seen above.

3.4.2. FEM Analysis

FEM analysis holds a crucial role in the model optimization. Ansys is used for getting the finite element results.

Since the dimensions of the mirrors are unknown, we will use the parametric batch mode programming in Ansys. Ansys will perform its regular run and will give the deformation of the mirror, and will generate output file giving the deformations at the nodes.

The values of back-radius of the mirrors and the thickness will affect the deformation for the given preload, and our aim is to find the optimum value of these minimizers to get the minimum objective function, which is change in focal number.

Since, focal length depends on front-radius, we will get the deflections of only the nodes on front face of the mirrors. Also, we know the initial co-ordinates of these nodes, from which we can calculate the new co-ordinates after deformation. Once these co-ordinates are known, a quadratic curve is fitted to this data, from which the new focal length can be calculated.

The output from the analysis is shown below.

Mirror 1 Analysis

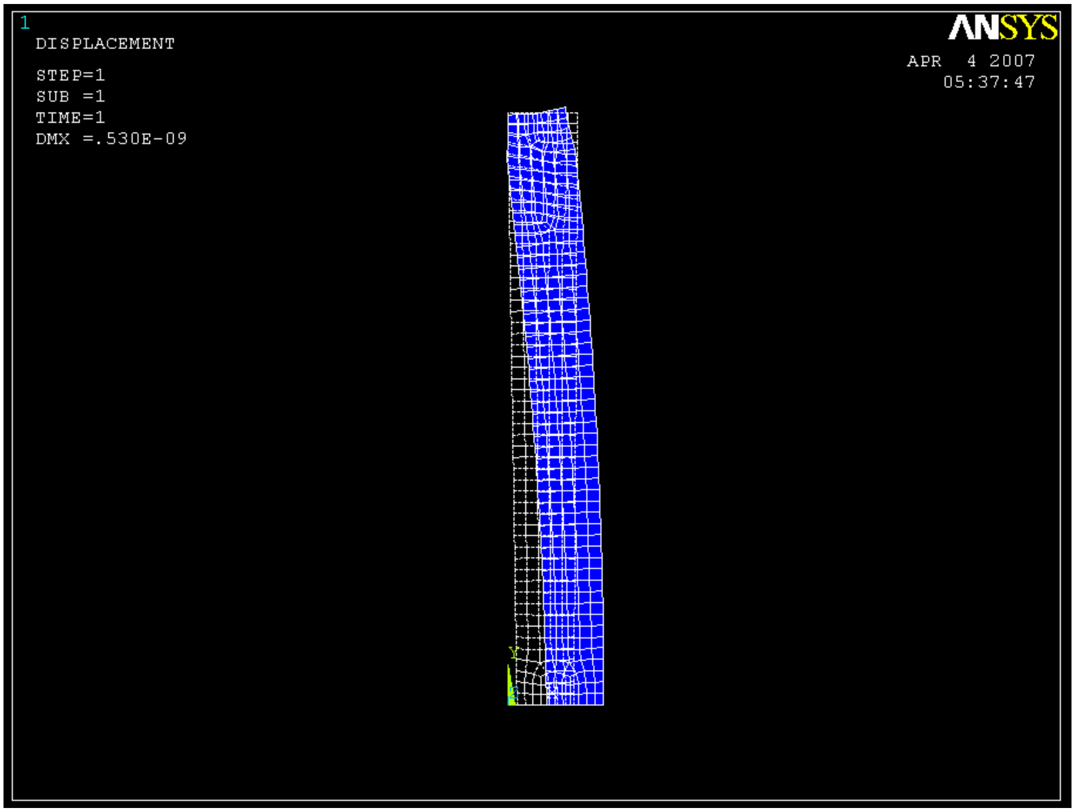


Figure 15 Deformed Structure

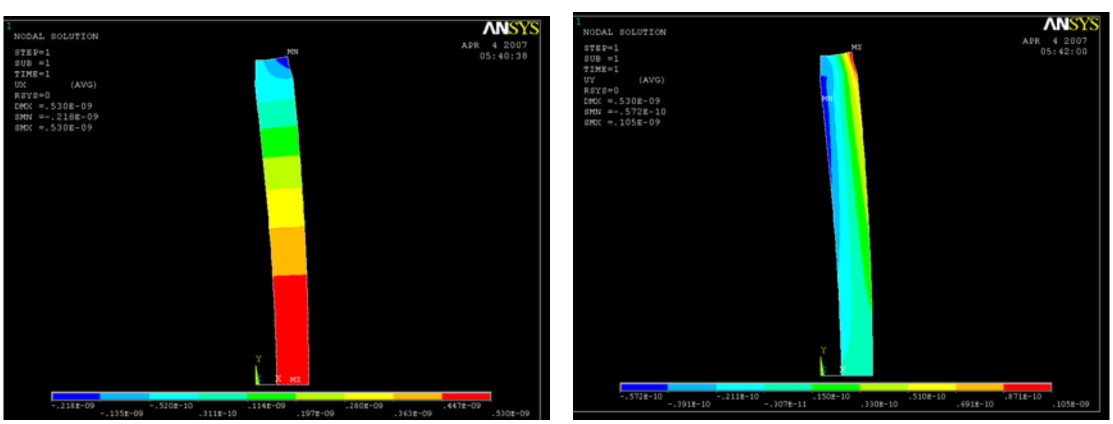


Figure 16 X and Y deformations

Mirror 2 Analysis

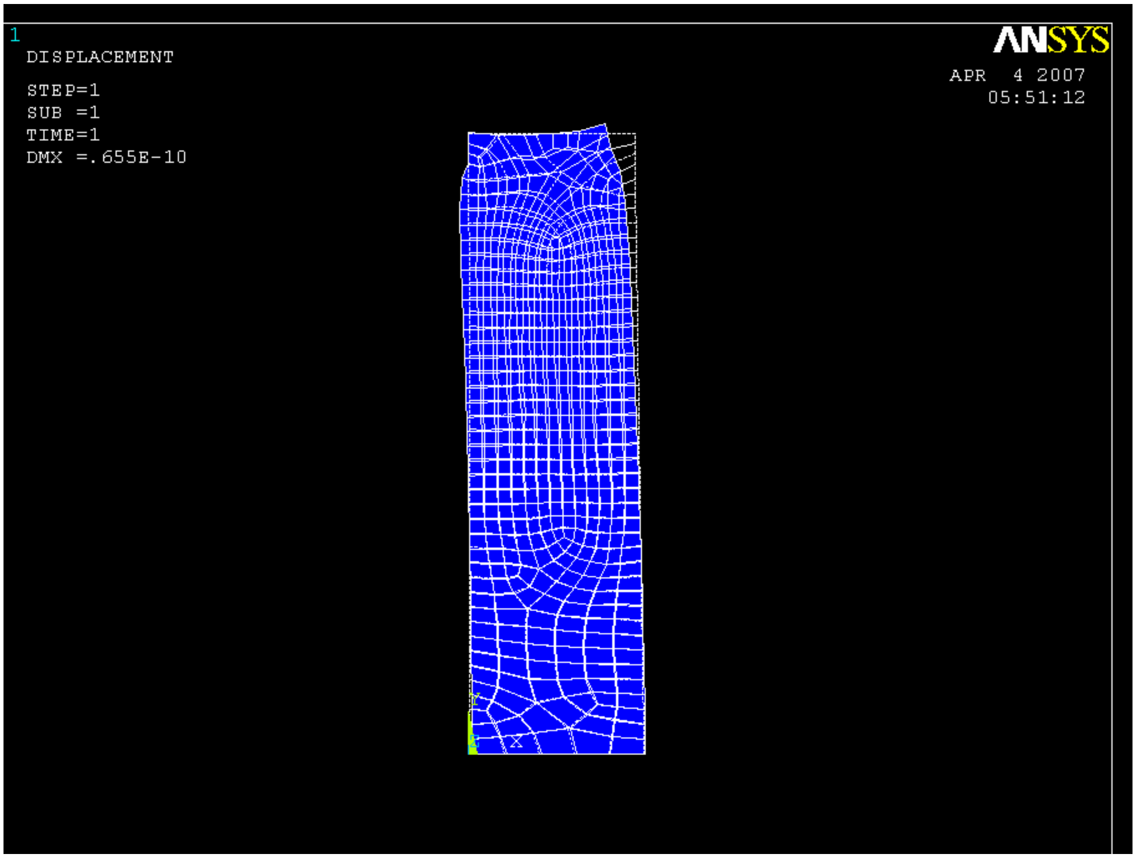


Figure 17 Deformed structure

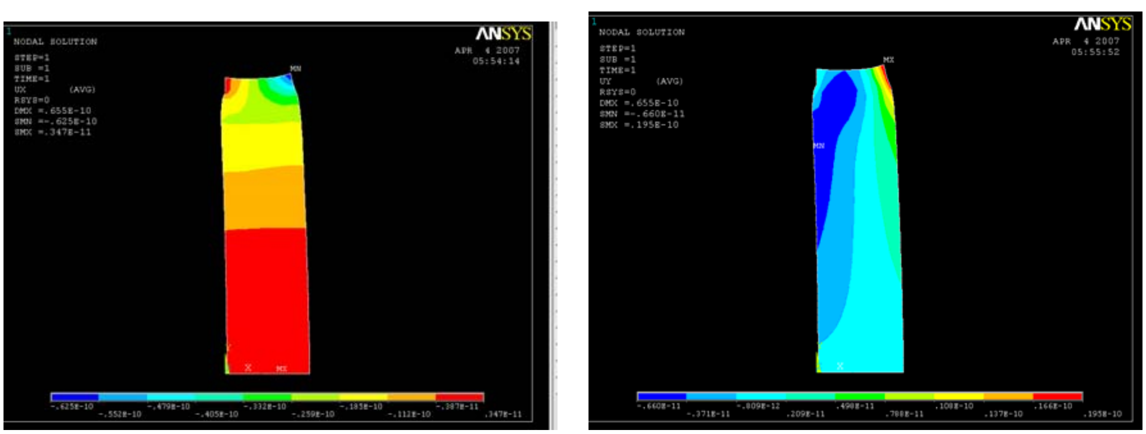


Figure 18 X and Y deformations

3.5. Optimization Study

The Optimization study will give the optimum values of design variables, namely R_1back, R_2back, $t_1$and t_2, for which the telescope will have the minimum change in focal number, when exposed to temperature gradient.

3.5.1. MATLAB Analysis

The MATLAB code for optimization, **fmincon**, will be interfaced with Ansys using the batch mode. Ansys will then perform the iterative analysis for optimization, which will give the optimized value for the variables and minimum change in focal number, for changes in temperature.

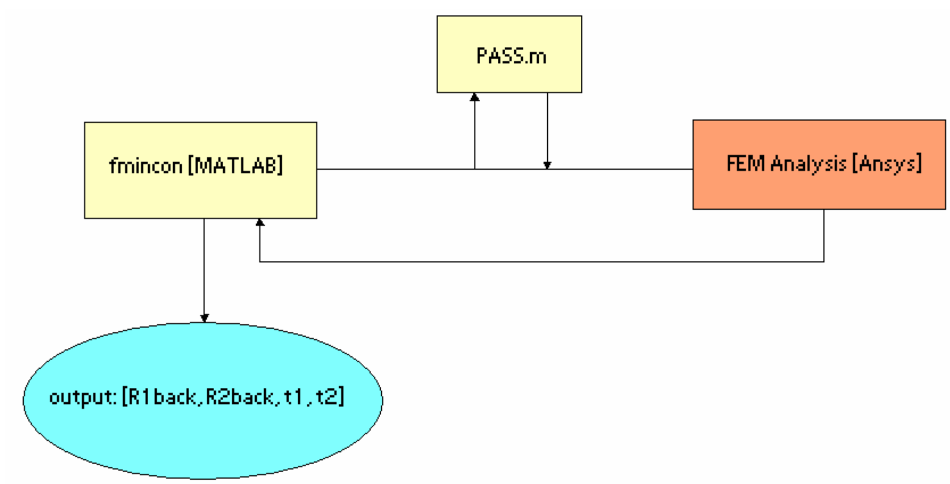


Figure 19 Process flow

The functions and the constraints were carefully scaled as the variables were of different orders, with the radii of back-surfaces being of the order of meters, and the thicknesses of mirrors of the order of millimeters. After scaling was performed, fmincon gave a feasible optimum solution and the results are quoted below. The following results were obtained.

Numerical Results:

Warning: Large-scale (trust region) method does not currently solve this type of problem,
using medium-scale (line search) instead.
> In fmincon at 303
In mainfile at 29

%%%
Diagnostic Information
Number of variables: 4

Functions
Objective: myfun
Gradient: finite-differencing
Hessian: finite-differencing (or Quasi-Newton)
Nonlinear constraints: nonlcon
Gradient of nonlinear constraints: finite-differencing

Constraints
Number of nonlinear inequality constraints: 7
Number of nonlinear equality constraints: 0

Number of linear inequality constraints: 0
Number of linear equality constraints: 0
Number of lower bound constraints: 4
Number of upper bound constraints: 4

Algorithm selected
medium-scale
%%%
End diagnostic information

y =

1.0e+003 *

2.800 0.0079 2.020 0.00704

f =

1.0152

Iter	F-count	f(x)	Max constraint	Line search steplength	Directional derivative	First order optimality	Procedure
4	45	1.0152	-0.1125	1	-0.166	25	Hessian modified

As seen, the objective is minimized and all the constraints are satisfied. The minimum change in the focal number of the system comes out to be 1.0152, which is practically a good value.

3.5.2. iSIGHT Analysis

The model was also tested and run in iSIGHT to see whether the same optimum solution is obtained. The iSIGHT results are shown below.

Parameter Information

Inputs	Type	Current Value
R1Back	REAL	2799.99999999988
R1	REAL	810.0
t1	REAL	7.99999994722238
R2Back	REAL	1999.99799999976
R2	REAL	250.0
t2	REAL	7.00421985643328
rho	REAL	2.23e-006
D1	REAL	203.0
D2	REAL	60.0
pi	REAL	3.141592
Dsch	REAL	203.0
Zmirrors	REAL	255.0

Auxiliaries	Type	Current Value
S	REAL	1.59141673285035
s	REAL	0.450405730644405
S1	REAL	0.459959654086106
S2	REAL	0.0563070997220621

Outputs	Type	Current Value
g1	REAL	-0.441112165449894
g2	REAL	-0.656236593761532
g3	REAL	-2.94862356028593
g4	REAL	-3.60584511664595
g5	REAL	-0.394154883354048
g6	REAL	-0.459959654086106
g7	REAL	-0.0562508472903573
f	REAL	1.0142764223645
Objective	**REAL**	**1.0142764223645**
Feasibility	INTEGER	9
TaskProcessStatus	REAL	-1.0

*** Current Value = value when report was generated**

Task Setup

---Optimize: PriorityRankedPlan

Optimization Techniques:

Step 1	Sequential Quadratic Programming - NLPQL
Step 2	Mixed Integer Optimization - MOST

Design Variables	Type	Lower Bound	Current Value	Upper Bound
R1Back	REAL	1000.0	2799.99999999988	3200.0
t1	REAL	3.0	7.99999994722238	10.0
R2Back	REAL	600.0	1999.99799999976	2000.0
t2	REAL	3.0	7.00421985643328	8.0

Output Constraints	Type	Lower Bound	Current Value	Upper Bound
g1	REAL		-0.441112165449894	0.0
g2	REAL		-0.656236593761532	0.0
g3	REAL		-2.94862356028593	0.0
g4	REAL		-3.60584511664595	0.0
g5	REAL		-0.394154883354048	0.0
g6	REAL		-0.459959654086106	0.0
g7	REAL		-0.0562508472903573	0.0

Objectives	Type	Direction	Current Value
f	**REAL**	**minimize**	**1.0142764223645**

Execution Results

Task	Task1
Total runs	100
Feasible runs	95
Infeasible runs	5
Failed runs	0
Database file	Task1.db

Optimization Plan: PriorityRankedPlan

Executed between RunCounter 723 and 822 (100 runs)

Techniques used:

Step1	Sequential Quadratic Programming - NLPQL
Step2	Mixed Integer Optimization - MOST

Best design:	currently	previously
RunCounter	776	722
ObjectiveAndPenalty	1.0142764223645	1.01709992437423
Objective	1.0142764223645	1.01709992437423
Penalty	0.0	0.0

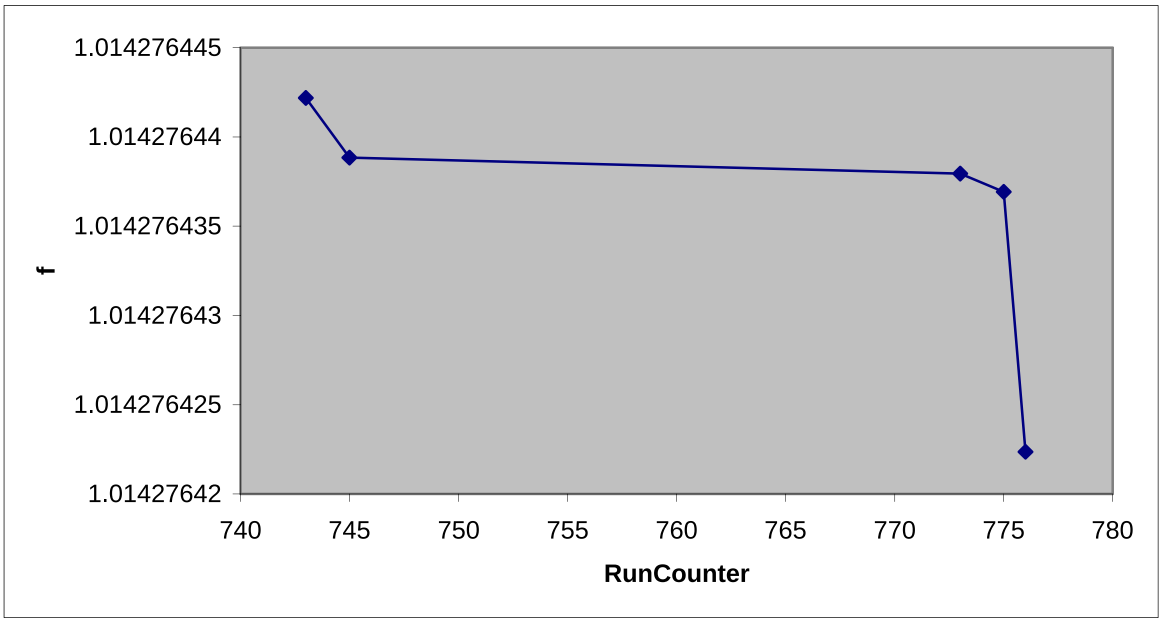
Best design ObjectiveAndPenalty value improved by 0.00282350201 (0.28%) after executing this Optimization Plan

Best design parameter values:

R1Back	**2799.99999999988**
R1	810.0
t1	**7.99999994722238**
R2Back	**1999.99799999976**
R2	250.0
t2	**7.00421985643328**
rho	2.23e-006
D1	203.0
D2	60.0
pi	3.141592
Dsch	203.0
Zmirrors	255.0
g1	-0.441112165449894
g2	-0.656236593761532

g3	-2.94862356028593
g4	-3.60584511664595
g5	-0.394154883354048
g6	-0.459959654086106
g7	-0.0562508472903573
f	**1.0142764223645**

History Plots (improvements only)



The above figure shows the progress of objective function against the number of runs. The figure is a plot of 8^{th} run at which the minimum result was obtained with very small change than the previous.

3.5.3. Discussion

(1) When compared with the results generated by fmincon, it is seen that the values of minimizers obtained in iSIGHT match well.

(2) The value of radius of back-surface of secondary mirror hits the upper bound, which implies that the function is oppositely monotonic with respect to this variable.

(3) The thermal analysis has been done by considering only the extreme temperature at which the preload is maximum. A better curve for the function variation can be obtained if all the temperatures over the temperature range and the respective preloads are considered.

(4) The algorithm has good global convergence, as the values obtained for optimal variables are same even if the initial point is changed.

(5) A parametric study will prove helpful to understand the sensitivity of the objective function with respect to various parameters.

(6) Some other techniques for optimization other than Sequential Quadratic Programming (SQP) and Mixed Integer Optimization (MOST) may be used if they can give a better design.

4. SYSTEM INTEGRATION

4.1. Interaction between subsystems

Both the subsystems have an objective function which ultimately gives a better image quality.

The optical subsystem aims at minimizing the aberrations in the telescope, so that maximum number of light rays hit the eyepiece and a clear image is obtained. The thermal subsystem considers the effects of temperature changes on performance of lens system. It aims at maximizing the robustness of the telescope with respect to temperature.

Thus, both the systems will give geometry of the structure after analysis. So a trade-off will have to be done between the geometries obtained from the two optimization processes for aberrations and robustness. This trade-off will have to be done, keeping in mind, the final objective of 'high quality image' of the telescope, as it is mainly used by amateur astronomers. We shall be following the 'All-in-one' approach for the system Integration and Optimization using iSIGHT.

4.2. Mathematical model

4.2.1. Design Variables

R_2	Radius of curvature of the vertex of secondary mirror
ε_1	Eccentricity of primary mirror
ε_2	Eccentricity of secondary mirror
$Z_{mirrors}$	Location of secondary mirror
v	Vertex of back focus
g	Relative power of Schmidt corrector
R1-back	Radius of back-surface of primary mirror
R2-back	Radius of back-surface of secondary mirror
t1	Thickness of primary mirror
t2	Thickness of secondary mirror

4.2.2. Summary Model

$$\min_X (f_1(X) + f_2(X)) * 10^3$$

where

$$f_1 = \sqrt{\frac{1}{numRays} \sum_{i=1}^{numRays} \left(\sqrt{x_i^2 + y_i^2}\right)^2} \quad \text{with w = 0°}$$

$$f_2 = \sqrt{\frac{1}{numRays} \sum_{i=1}^{numRays} \left(\sqrt{x_i^2 + y_i^2}\right)^2} \quad \text{with w = 0.5°}$$

(Xi, Yi) : Position of i-th spot

$$Airy = 1.22 * \lambda * F/\#$$

$$\frac{1}{f'} = \frac{-f'_2 + f'_1 - Z_{mirrors}}{f'_1 \, f'_2}, \quad f'_1 = R_1/2, \; f'_2 = R_2/2$$

subject to

g1: maximum distance of spot$(w = 0^\circ)$ - Airy ≤ 0

g2: maximum distance of spot$(w = 0.5^\circ)$ - Airy ≤ 0

g3: $-Z_{mirrors} - Z_{sch} \leq 0$

g4: $-t1 + S + S1 \leq 0.003$

g5: $-S1 \leq 0$

g6: $-S2 + s \leq 0.004$

g7: $S2 - s \leq 0$

g8: $-S2 \leq 0$

g9: $\Pi \times \rho G \times [t1 \times (D1^2/4) - S1^2 \times (R1back - S1/3) - S^2(R1 - S/3)] \leq 1$

g10: $\Pi \times \rho G \times [t2 \times (D2^2/4) - S2^2 \times (R2back - S2/3) - s^2(R2 - s/3)] \leq 0.7$

g11: $f = \left| \left(\frac{f}{no.} \right)_{new} - \left(\frac{f}{no.} \right) \right| < 1.5$

g12: $-20000 \leq R_2 \leq 0$

g13: $0 \leq \varepsilon_1^{\ 2} \leq 1$

g14: $0 \leq \varepsilon_2^{\ 2} \leq 1$

g15: $0.5 \leq g \leq 1.0$

g16: $-1000 \leq Z_{mirrors} \leq -10$

g17: $20 \leq v \leq 500$

g18: $1000 \leq R1back \leq 3200$

g19: $600 \leq R2back \leq 2000$

g20: $3 \leq t_1 \leq 10$

g21: $3 \leq t_2 \leq 8$

h1: $\frac{F}{\#} * D_{sch} - f' = 0$

4.3. Result

4.3.1. iSIGHT Model

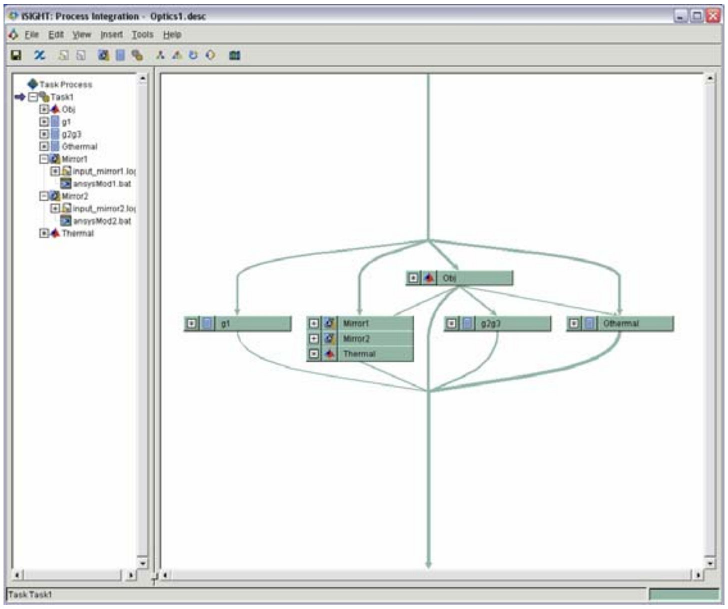
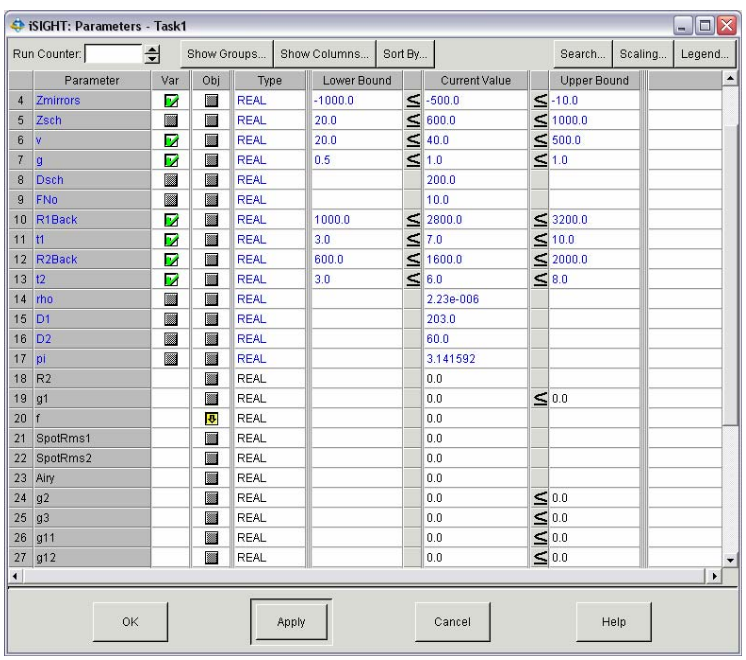


Figure 20 iSIGHT process integration



	Parameter	Var	Obj	Type	Lower Bound		Current Value		Upper Bound
4	Zmirrors	☑	■	REAL	-1000.0	≤	-500.0	≤	-10.0
5	Zsch	■	■	REAL	20.0	≤	600.0	≤	1000.0
6	v	☑	■	REAL	20.0	≤	40.0	≤	500.0
7	g	☑	■	REAL	0.5	≤	1.0	≤	1.0
8	Dsch	■	■	REAL			200.0		
9	FNo	■	■	REAL			10.0		
10	R1Back	☑	■	REAL	1000.0	≤	2800.0	≤	3200.0
11	t1	☑	■	REAL	3.0	≤	7.0	≤	10.0
12	R2Back	☑	■	REAL	600.0	≤	1600.0	≤	2000.0
13	t2	☑	■	REAL	3.0	≤	6.0	≤	8.0
14	rho	■	■	REAL			2.23e-006		
15	D1	■	■	REAL			203.0		
16	D2	■	■	REAL			60.0		
17	pi	■	■	REAL			3.141592		
18	R2		■	REAL			0.0		
19	g1		■	REAL			0.0	≤	0.0
20	f		⇩	REAL			0.0		
21	SpotRms1		■	REAL			0.0		
22	SpotRms2		■	REAL			0.0		
23	Airy		■	REAL			0.0		
24	g2		■	REAL			0.0	≤	0.0
25	g3		■	REAL			0.0	≤	0.0
26	g11		■	REAL			0.0	≤	0.0
27	g12		■	REAL			0.0	≤	0.0

Figure 21 Parameters and initial values in iSIGHT

4.3.2. iSIGHT Result

Parameter Information

Inputs	Type	Current Value
R1	REAL	-1000.0
e1	REAL	0.241268158665424
e2	REAL	0.813188920132218
Zmirrors	REAL	-364.24710736342
Zsch	REAL	600.0
v	REAL	162.87204520286
g	REAL	0.54313763628044
Dsch	REAL	200.0
FNo	REAL	10.0
R1Back	REAL	2800.00015952392
t1	REAL	7.06575666672614
R2Back	REAL	1800.18001534471
t2	REAL	6.00667234586645
rho	REAL	2.23e-006
D1	REAL	203.0
D2	REAL	60.0
pi	REAL	3.141592

Auxiliaries	Type	Current Value
S	REAL	1.28861150981163
s	REAL	0.310672531191358
S1	REAL	0.459959627876742
S2	REAL	0.0624948348738599

Outputs	Type	Current Value
R2	REAL	-362.007713697547
g1	REAL	-235.75289263658
f	REAL	12.2698322075955
SpotRms1	REAL	0.00214761407079987
SpotRms2	REAL	0.00214761407079987
Airy	REAL	0.006662054
g2	REAL	-0.00451443992920013
g3	REAL	-0.00451443992920013
g11	REAL	-0.50580708618426
g12	REAL	-0.662421204465261
g13	REAL	-2.31718552903777
g14	REAL	-3.7515944720937
g15	REAL	-0.2484055279063
g16	REAL	-0.459959627876742
g17	REAL	-0.0624948348738599
Fthermal	REAL	0.984277856815019
Objective	**REAL**	**12.2698322075955**
Feasibility	INTEGER	9
TaskProcessStatus	REAL	-1.0

* Current Value = value when report was generated

Optimization Techniques

Step 1	Sequential Quadratic Programming - NLPQL
Step 2	Mixed Integer Optimization - MOST

Design Variables	Type	Lower Bound	Current Value	Upper Bound
e1	REAL	0.0	0.241268158665424	1.0
e2	REAL	0.0	0.813188920132218	1.0
Zmirrors	REAL	-1000.0	-364.24710736342	-10.0
v	REAL	20.0	162.87204520286	500.0
g	REAL	0.5	0.54313763628044	1.0
R1Back	REAL	1000.0	2800.00015952392	3200.0
t1	REAL	3.0	7.06575666672614	10.0
R2Back	REAL	600.0	1800.18001534471	2000.0
t2	REAL	3.0	6.00667234586645	8.0

Output Constraints	Type	Lower Bound	Current Value	Upper Bound
g1	REAL		-235.75289263658	0.0
g2	REAL		-0.00451443992920013	0.0
g3	REAL		-0.00451443992920013	0.0
g11	REAL		-0.50580708618426	0.0
g12	REAL		-0.662421204465261	0.0
g13	REAL		-2.31718552903777	0.0
g14	REAL		-3.7515944720937	0.0
g15	REAL		-0.2484055279063	0.0
g16	REAL		-0.459959627876742	0.0
g17	REAL		-0.0624948348738599	0.0
Fthermal	REAL		0.984277856815019	1.5

Objectives	Type	Direction	Current Value
f	REAL	minimize	12.2698322075955

Execution Results

Task	Task1
Total runs	236
Feasible runs	0
Infeasible runs	236
Failed runs	0
Database file	Task1.db

Best design parameter values

R1	-1000.0
e1	0.241268158665424
e2	0.813188920132218
Zmirrors	-364.24710736342
Zsch	600.0
v	162.87204520286
g	0.54313763628044
Dsch	200.0
FNo	10.0
R1Back	2800.00015952392
t1	7.06575666672614
R2Back	1800.18001534471
t2	6.00667234586645
rho	2.23e-006
D1	203.0
D2	60.0
pi	3.141592
R2	-362.007713697547
g1	-235.75289263658
f	12.2698322075955
SpotRms1	0.00214761407079987
SpotRms2	0.00214761407079987
Airy	0.006662054
g2	-0.00451443992920013
g3	-0.00451443992920013
g11	-0.50580708618426
g12	-0.662421204465261
g13	-2.31718552903777
g14	-3.7515944720937
g15	-0.2484055279063
g16	-0.459959627876742
g17	-0.0624948348738599
Fthermal	0.984277856815019

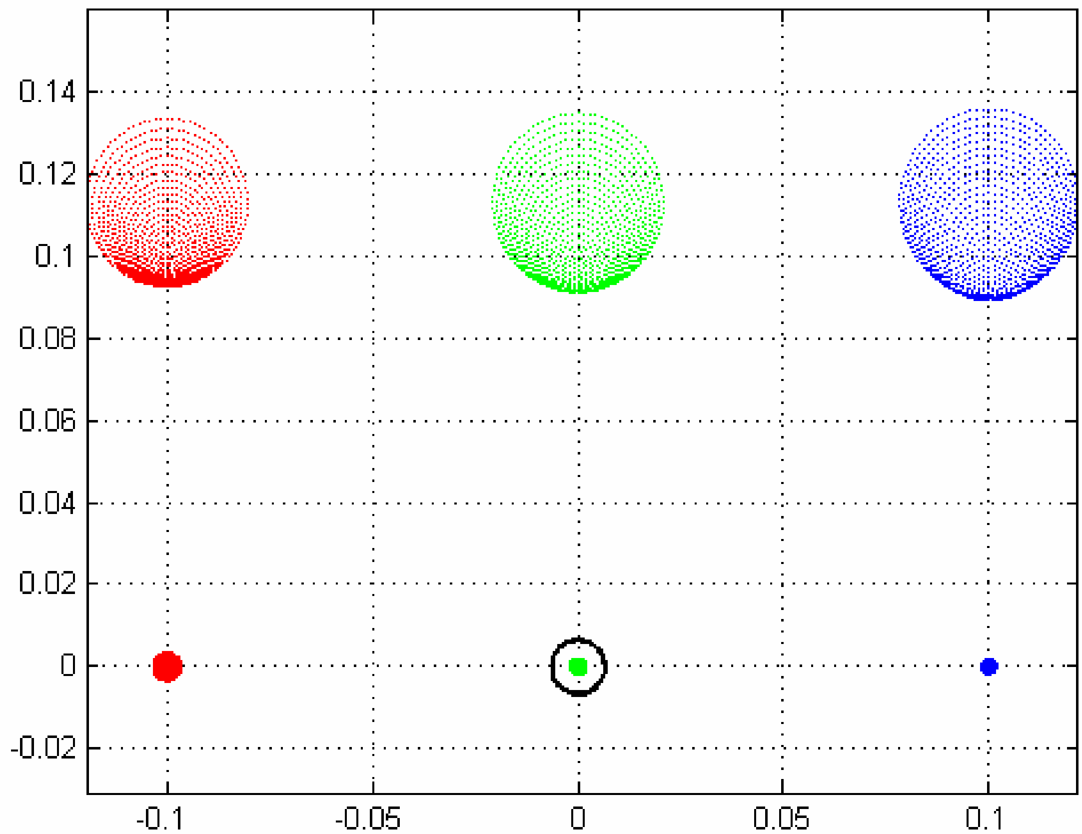


Figure 22 Spot diagram of optimal design

4.4. Discussion

(1) An ‘All-in-one’ approach has been used for integrating the two subsystems and developing an optimal design. An additional study regarding the method of approach (eg: Analytical Target Cascading) for subsystems integration will prove helpful in getting more accurate and better design.

(2) One of the design variables, R1 (the radius of front-surface of primary mirror) is considered as a parameter during integration, for the purpose of simplification of model.

(3) 6 different combinations of objective function, constraints and parameter values of optical design are tried to get an optimal design. This has immensely helped in getting the best result.

(4) It is observed that there are no coma aberrations seen and the best result is obtained when the angle $w=0°$.

(5) One of the improvements in the design method is that proper scaling can be done in future. This will greatly help in minimizing the spherical aberrations, which still are visible in the present design.

5. ACKNOWLEDGMENTS

We thank Prof. Papalambros for assisting us and for his insightful suggestions. We also acknowledge all the help and support provided by James Allison and Marc Zawislak. Also, we thank Ivan Krastev who gave us valuable answers related to ray trace algorithm. We would like to extend our regards to Jarod Kelly for his valuable inputs and extended help in Ansys programming.

6. REFERENCES

[1] Harrie Rutten and Martin van Verooij. *Telescope Optics: Evaluation and Design.* Willmann-Bell, Inc., 1988.

[2] Marc R. Zawislak. *Design Optimization Mode for a Schmidt-Cassegrain Telescope.* ME590 Final Report, 2006.

[3] Paul R. Yoder, Jr. *Opto-Mechanical Systems Design*. Taylor & Francis Group, 2006.

[4] R.N. Wilson. *Reflecting Telescope Optics I*. Spring-Varlag Berlin Heidelberg, Inc., 1996.

[5] V. Yu. Terebizh. *Optimal baffle design in a cassegrain telescope*. Experimental Astronomy, 11:171–191, 2001.

[6] Warren J. Smith. *Practical Optical System Layout*. McGraw-Hill, Inc., 1997.

[7] Company Seven, *Consumer Lines- Celestron Celestar 8 Schmidt-Cassegrain Telescope*

[8] Celestron Celestar Instruction manual

[9] MatWeb- Material property data

[10] Dietrich Korsch, Reflective Optics. Academic Press, Inc., 1991.

[11] Max Herzberger, Modern Geometrical Optics. Interscience Publichers, Inc., 1958.

[12] Ivan Krastev, *Back to Theory - Ray Tracing by Donald Feder through Aspherical Surfaces – Conic Sections*., ATM Letters, Vol. 2, 02 2004.

[13] Ivan Krastev, *Back to Theory - Ray Tracing by Donald Feder through Aspherical Surfaces – High Order*., ATM Letters, Vol. 2, 03 2004.

7. APPENDICES

7.1. Subsystem I : Optical design MATLAB code

7.1.1. MakeInputRay.m

```
function [RayIn nRays] = MakeInputRay(dDia, nMinRays, bYOnly,
nCircleInput)

% Initialize
nRays       = 1;      % Intializes ray counters
RayIn(1,1)  = 0;      % X-Coordinate
RayIn(1,2)  = 0;      % Y-Coordinate
RayIn(1,3)  = 0;      % Z-Coordinate at outside of Schmidt Corrector

% Calc Minimum circles
nMinCircles = 0;  % Intializes number of circles around center
i           = 1;  % Intializes ray counter
while i < nMinRays
    nMinCircles = nMinCircles + 1;
    i = i + 6*nMinCircles;
end

% Number of circles
dRefGap  = 2;
nCircles = ( dDia/2 - mod(dDia/2, dRefGap) ) / dRefGap + 1;     %
Intializes number of circles around center

if( mod(dDia/2, dRefGap) == 0 )
    nCircles = nCircles - 1;
end

if( nCircles <= nMinCircles )
     nCircles = nMinCircles;
end

if( nCircleInput ~= 0 )
    nCircles = nCircleInput;
end

% dH in R-direction
dH = (dDia/2) / nCircles;

if( bYOnly==1 )
    for i = 1:nCircles
        nRays = nRays + 1;
        RayIn(nRays, 1) = 0;
        RayIn(nRays, 2) = dH*i;
```

```
        RayIn(nRays, 3) = 0;

        nRays = nRays + 1;
        RayIn(nRays, 1) = 0;
        RayIn(nRays, 2) = -dH*i;
        RayIn(nRays, 3) = 0;
    end
else
    for i = 1:nCircles
        dTheta =  2. * pi / (6*i);

        for j=1:6*i
            dAng = dTheta*(j-1) + pi/2;

            nRays = nRays + 1;
            RayIn(nRays, 1) = (dH*i) * cos( dAng );     % Using the
angles in-between: calcualtes the x-coordinate
            RayIn(nRays, 2) = (dH*i) * sin( dAng );     % Using the
angles in-between: calcualtes the y-coordinate
            RayIn(nRays, 3) = 0;                        % Assigns a z-
coordinate

        end
    end
end
```

7.1.2. RayTraceSch.m

```
function [ptXX ptYY ptZZ] = RayTraceSch(Dsch, g, x0, y0, z0, Xi0, Eta0, 
Zeta0, Sk, r, e, d, n)

% Init.
Crefl = 0;

ptX(1) = x0;
ptY(1) = y0;
ptZ(1) = z0;

Xi(1)   = Xi0;
Eta(1)  = Eta0;
Zeta(1) = Zeta0;

p(1) = ptX(1)*Zeta(1);
q(1) = ptY(1)*Zeta(1);

% Schmidt Corrector is the second surface in our model
nSchIdx = 2;
NN      = 1.51872;  % G    Refractive Indexes for BK7 Glass
k       = 1.5;
UC      = 1/(NN-1) * ( -1/r(nSchIdx+1)^3);
UB      = 1/(NN-1) * k * Dsch^2 / (8*r(nSchIdx+1)^3);
UC      = UC * g;
UB      = UB * g;

for k= 1: Sk-1
    if( k ~= nSchIdx )
        if( r(k) == 0 ) % Plane
            B = 0;
        else
            B = 1/r(k);
        end

        A       = B * (p(k)^2 + q(k)^2);
        C       = Zeta(k)^2;
        DD      = -C + B*(p(k)*Xi(k) + q(k)*Eta(k));
        Qt      = sqrt(DD^2 - A*B*(n(k)^2 - e(k) * C^2));
        ptZ(k)  = A / (-DD + Qt);
        tt      = 1 + B * ptZ(k) * e(k);
        RR      = tt^2 - B * ptZ(k) * (tt-1);

        if ( n(k)/n(k+1) < 0 )
            Qtp = -Qt;
            Psi = -2*Qt/(RR*C);
            Crefl = Crefl+1;
        else
            Qtp = sqrt(Qt^2 + RR * C * (n(k+1)^2 - n(k)^2));
            Psi = (Qtp-Qt)/(RR*C);
        end
```

```
    Alpha       = Psi * ( p(k) + ptZ(k)*Xi(k) );
    Beta        = Psi * ( q(k) + ptZ(k)*Eta(k) );
    Xi(k+1)     = Xi(k) - ( B * Alpha );
    Eta(k+1)    = Eta(k) - ( B * Beta );
    Zeta(k+1)   = sqrt( n(k+1)^2 - Xi(k+1)^2 - Eta(k+1)^2 );

    if ( mod(Crefl,2)==1 )
        Zeta(k+1) = -Zeta(k+1);
    end

    % P2 = P' + d*S' (p36)
    p(k+1) = p(k) + (tt*Alpha) + ( d(k+1) * Xi(k+1) );
    q(k+1) = q(k) + (tt*Beta)  + ( d(k+1) * Eta(k+1) );

else % Schmidt-Corrector
    PP = p(k)^2 + q(k)^2;
    PS = p(k)*Xi(k) + q(k)*Eta(k);
    SS = Xi(k)^2 + Eta(k)^2;

    u = (ptX(k)^2 + ptY(k)^2 )/2;
    v = PS/Zeta(k)^2;
    w = ( SS / Zeta(k)^2 ) / 2;
    A = [w v u];
    B = conv(A,A);
    COEF = UC * B + UB *[0 0 w v u] + [0 0 0 -1 0];
    ptZ(k) = min( roots(COEF) );

    Fz  = 1;
    Fu  = -UB - 2 * UC * u;
    t   = ptZ(k) - Fz/Fu;
    C   = n(k)^2 - SS;
    R   = PP + 2*PS*ptZ(k) + SS*(ptZ(k))^2 + (Fz/Fu)^2*C;
    Q   = -PS - ptZ(k) * SS + (t-ptZ(k))*C;
    Qp  = sqrt( (n(k+1)^2 - n(k)^2 ) * R + Q^2 );

    if( Fz/Fu > 0 )
        Qp = - Qp;
    end

    Psi     = (Qp-Q)/R;
    Alpha   = Psi * ( p(k) + ptZ(k)*Xi(k) );
    Beta    = Psi * ( q(k) + ptZ(k)*Eta(k) );

    Xi(k+1)     = Xi(k) - Alpha;
    Eta(k+1)    = Eta(k) - Beta;
    Zeta(k+1)   = sqrt( n(k+1)^2 - Xi(k+1)^2 - Eta(k+1)^2 );

    p(k+1) = p(k) + (t*Alpha) + ( d(k+1) * Xi(k+1) );
    q(k+1) = q(k) + (t*Beta)  + ( d(k+1) * Eta(k+1) );
end

ptX(k+1) = p(k+1) / Zeta(k+1);
ptY(k+1) = q(k+1) / Zeta(k+1);
ptZ(k+1) = 0.;
```

```
    % actual intersection : A*
    ptXX(k) = ptX(k) + ptZ(k) * Xi(k) / Zeta(k);
    ptYY(k) = ptY(k) + ptZ(k) * Eta(k) / Zeta(k);
    ptZZ(k) = ptZ(k) + sum(d(1:k));
end

% at focal plane
ptXX(Sk) = ptX(Sk);
ptYY(Sk) = ptY(Sk);
ptZZ(Sk) = ptZ(Sk) + sum(d);
```

7.1.3. RayTraceBaffle.m

```
function [s1,y1,s2,y2,l] = ray_trace_baffle(R1, epsilon1, R2, epsilon2,
delta, v, xo, yo, alpha1)

% make values be positive
R1       = abs(R1);
R2       = abs(R2);
delta    = abs(delta);
v        = abs(v);
alpha1   = alpha1*pi()/180;

% Equation #'s in reference to "Optimal Baffle Design"
mu       = tan(alpha1);
b        = xo*mu + yo;                                   % Eq. 4
Calculates Initial Ray location
P1       = epsilon1-1-mu^2;                              % Eq. 8
Coefficient of primary mirror profile
P2       = 2*(R1+mu*b);                                  % Eq. 8
Coefficient of primary mirror profile
P3       = -(b^2);                                       % Eq. 8
Coefficient of primary mirror profile
s1       = -(2*P3)/(P2+sign(P2)*sqrt(P2^2-4*P1*P3));     % Eq. 9
Quadratic formula of mirror profile
y1       = b - mu*s1;                                    % Eq. 10 Height
of the ray at the primary mirror
theta1   = atan(y1/(R1+(epsilon1-1)*s1));                % Eq. 12 Slope
of ray after  hitting primary mirror
beta     = 2*theta1-alpha1                               % Eq. 13 Angle
of Ray after hitting primary mirror
k        = tan(beta);                                    % Eq. 15
Coeficients of ray refected off primary mirror
a        = y1 - k*(delta-s1);                            % Eq. 15
Coefficients of ray refected off primary mirror
q1       = epsilon2 -1 - k^2;                            % Eq. 17
Coefficients of surface of secondary mirror
q2       = 2*(R2+k*a);                                   % Eq. 17
Coefficients of surface of secondary mirror
q3       = -a^2;                                         % Eq. 17
Coefficients of surface of secondary mirror
s2       = -2*q3/(q2+sign(q2)*(sqrt(q2^2-4*q1*q3)));     % Eq. 19
Sagitta of the ray at the secondary mirror
y2       = a - k*s2;                                     % Eq. 20 Height
of the ray at the secondary
theta2   = atan(y2/(R2+(epsilon2-1)*s2));                % Eq. 21 Angle
between optical axis and normal surface to secondary mirror
u        = beta - 2*theta2;                              % Eq. 22 Angle
of ray of after the secondary mirror
l        = y2 - ((delta+v+s2)*tan(u));                   % Eq. 23 the
height of the image at the eyepiece
```

7.1.4. TestRay.m

```
clear;
nSystemNo = 0;    % System # used in the project report
switch(nSystemNo)
    case 1
        Sk       = 2;
        Diam     = 150;
        w        = 10;
        r        = [-500  0];
        e        = [0  0];
        d        = [300 -250];
        n        = [1 -1];
        bSch     = 0; % Just conic section
    case 2
        Sk       = 3;
        Diam     = 150;
        w        = 0.45;
        r        = [-1000 -373.33 0];
        e        = [1 2.778 0];
        d        = [500 -360 560];
        n        = [1 -1 1];
        bSch     = 0; % Just conic section
    case 3
        Sk       = 4;
        Diam     = 150;
        w        = 0;
        r        = [0 0 -500 0];
        e        = [0 0 0 0];
        d        = [0 5 295 -250];
        n        = [1 1.51872 1 -1];
        g        = 1;
        bSch     = 1; % With Schmidt corrector
    case 4
        Sk       = 5;
        Diam     = 150;
        w        = 0.45;
        r        = [0 0 -1000 -373.33 0];
        e        = [0 0 1 2.778 0];
        d        = [0 5 495 -360 560];
        n        = [1 1.51872 1 -1 1];
        g        = 1;
        bSch     = 1; % With Schmidt corrector
    otherwise
        Sk       = 2;
        Diam     = 150;
        w        = 0.5;
        r        = [-3000  0];
        e        = [1  0];
        d        = [0 -1500];
        n        = [1 -1];
        bSch     = 0; % Just conic section
end
nTestMode = 3;    % 1: Ray Trace Only 2 : SpotOnly 3 : Both
TestRaySub;
```

7.1.5. TestRaySub.m

```
Xi0   =  0;
Eta0  =  sin(w*pi/180);
Zeta0 =  cos(w*pi/180);

%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%% Ray Trace
%%%%%%%%%%%%%%%%%%%%%%%%%
if( nTestMode==1 || nTestMode==3 )
    figure(1);

    % Make InputRay : D, MinRay, bYOnly, nInputCircle(0:Auto)
    [RayIn nRays] = MakeInputRay(Diam, 200, 1, 10);

    for i=1:nRays
        Ray(i,1) = RayIn(i,1) + d(1) * Xi0 / Zeta0;
        Ray(i,2) = RayIn(i,2) + d(1) * Eta0 / Zeta0;
        Ray(i,3) = d(1);

      if( bSch==1 )
            [ptX ptY ptZ] = RayTraceSch(Diam, g, Ray(i,1), Ray(i,2),
Ray(i,3), Xi0, Eta0, Zeta0, Sk, r, e, d, n);
        else
            [ptX ptY ptZ] = RayTraceConic(Ray(i,1), Ray(i,2), Ray(i,3),
Xi0, Eta0, Zeta0, Sk, r, e, d, n);
        end

        ptX = [ RayIn(i,1) ptX ];
        ptY = [ RayIn(i,2) ptY ];
        ptZ = [ RayIn(i,3) ptZ ];
        %plot3(ptX, ptY, ptZ,  'Marker','.','Color','r');
        plot3(ptZ, ptY, -ptX,  'Marker','.','Color','r');

        if( i==1 )
            axis equal;
            axis([-50 max( [max(d) ptZ(Sk+1)] )+50 -Diam Diam -
(Diam+20)/2 (Diam+20)/2]);
            grid on;
            view(0,90);
            hold;
       end
    end
end

%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%% Spot Diagram
%%%%%%%%%%%%%%%%%%%%%%%%%
if( nTestMode==2 || nTestMode==3 )
    figure(2);

    % Make InputRay : D, MinRay, bYOnly, nInputCircle(0:Auto)
    [RayIn nRays] = MakeInputRay(Diam, 200, 0, 0);
```

```
    for i=1:nRays
        Ray(i,1) = RayIn(i,1) + d(1) * Xi0 / Zeta0;
        Ray(i,2) = RayIn(i,2) + d(1) * Eta0 / Zeta0;
        Ray(i,3) = d(1);

        if( i== 1 )
              if( bSch==1 )
                  [ptX0 ptY0 ptZ0] = RayTraceSch(Diam, g, Ray(i,1), 
Ray(i,2), Ray(i,3), Xi0, Eta0, Zeta0, Sk, r, e, d, n);
              else
                  [ptX0 ptY0 ptZ0] = RayTraceConic(Ray(i,1), Ray(i,2), 
Ray(i,3), Xi0, Eta0, Zeta0, Sk, r, e, d, n);
              end
        end

        if( bSch==1 )
            [ptX ptY ptZ] = RayTraceSch(Diam, g ,Ray(i,1), Ray(i,2), 
Ray(i,3), Xi0, Eta0, Zeta0, Sk, r, e, d, n);
        else
            [ptX ptY ptZ] = RayTraceConic(Ray(i,1), Ray(i,2), Ray(i,3), 
Xi0, Eta0, Zeta0, Sk, r, e, d, n);
        end

        plot(ptX(Sk)-ptX0(Sk) , ptY(Sk)-ptY0(Sk), 'LineStyle', 'none', 
'Marker','.','Color','bl');
        %  plot(ptX(Sk), ptY(Sk), 'LineStyle', 'none', 
'Marker','.','Color','g');

        if( i==1 )
            axis equal;
            grid on;
            hold;
        end
    end
end
```

7.2. Subsystem II: Thermal Design Code

7.2.1. mainfile.m

```
% D1 = 203;
% D2 = 60;
% R1 = 810;
% R2 = 250;
% Z_m = 255;
% f1 = R1/2;
% f2 = R2/2;
% f = 2030;
% D_sch = 203;
% rho = 2230e-9;
%x_i = [R1 t1 R2 t2];
% Initial value
x_0 = [18 7 10 5];
% Inequality constraints
A=[];
b=[];
% Equality Constraints
Aeq=[];
beq=[];
% Upper and Lower bounds for x_i's
lb=[8 4 6 2 ];
ub=[32 10 15 8 ];
%
options =
optimset('Display','iter','Diagnostics','on','DiffMinChange',0.1,'DiffM
axChange',0.2,'MaxIter',30);
%nonlcon=[];
[xopt,fval,exitflag,output]=
fmincon('myfun',x_0,A,b,Aeq,beq,lb,ub,'nonlcon',options);
```

7.2.2. myfun.m

```
function [f] = myfun(x)
% Define objective function

R1back = x(1)*100;
t1 = x(2);
R2back = x(3)*100;
t2 = x(4);

y=[R1 t1 R2 t2]

% ANSYS analysis
[f1_new f2_new] = PASS(y);
R1 = 810;
```

```
R2 = 250;
D_sch = 203;
Z_m = 255;
f1 = R1/2;
f2 = R2/2;
fno = (((f1*f2)/(-f2+f1-Z_m))/D_sch);
fno_new = (((f1_new*f2_new)/(-f2_new+f1_new-Z_m))/D_sch);

% Objective function
f = abs(fno_new - fno)

end
```

7.2.3. nonlcon.m

```
% Define the nonlinear constraint function
function [g,h] = nonlcon(x)

R1back = x(1)*100;
t1 = x(2);
R2back = x(3)*100;
t2 = x(4);

rho = 2230e-9;
pi = 3.14159;
D1 = 203;
D2 = 60;
R1 = 810;
R2 = 250;
S = R1-(R1^2-(D1/4)^2)^0.5;
s = R2-(R2^2-(D2/4)^2)^0.5;
S1 = R1back-(R1back^2-(D1/4)^2)^0.5;
S2 = R2back-(R2back^2-(D2/4)^2)^0.5;

% Ineqality constraints
g(1) = (pi*rho*(t1*(D1^2/4)-S1^2*(R1-S1/3)-S^2*(R-S/3)))-1;
g(2) = (pi*rho*(t2*(D2^2/4)-S2^2*(R2-S2/3)-s^2*(r-s/3)))-0.7;
g(3) = -(t1-S-S1-3);
g(4) = -S2+s-4;
g(5) = S2-s;
g(6) = -S1;
g(7) = -S2;

h = [];
```

7.2.4. ReadOutput.m

```
function FinalPnt = ReadOutput(File1Name,File2Name)
```

```
fid = fopen(File1Name,'r');
count = 0;
while ~feof(fid)
    line = fgetl(fid);

    [Pnt nReadCnt] = sscanf('line', '%d %f %f');
    if( nReadCnt ~= 0 )
        count = count + 1;
        X(count) = Pnt(2);
        Y(count) = Pnt(3);
    end
end
OrgPntCoord = [X' Y'];
fclose(fid);

fid = fopen(File2Name,'r');
count = 0;
while ~feof(fid)
    line = fgetl(fid);

    [Pnt nReadCnt] = sscanf('line', '%d %f');
    if( nReadCnt ~= 0 )
        count = count + 1;
        DX(count) = Pnt(2);
    end
end
DxDy = [DX(1:count/2)' DX(count/2+1:count)'];
fclose(fid);

% Final nodal position
FinalPnt = OrgPntCoord + DxDy;
```

7.2.5. PASS.m (The m-file which interfaces with Ansys)

```
function [f1_new f2_new] = PASS(x_inPASS)
%
% INPUT:
% x_inPASS(1) = R1back
% x_inPASS(2) = t1
% x_inPASS(3) = R2back
% x_inPASS(4) = t3
%
% OUTPUT:
% f1_new, f2_new
% See also testPASS

warning off

x_inPASS;
R1back = x_inPASS(1); % R1back
```

```
t1 = x_inPASS(2); % t1
R2back = x_inPASS(3); % R2back
t2 = x_inPASS(4); % t1


PASSfilename1 = 'input_mirror1.log';

% Generate input file (mirror1) for pass

writefile = {
    '/batch';
    '/filename,input_mirror1';
    '';
    '!Enter the preprocessor';
    '/prep7';
    '';
    '!Load inputs';
    'PRESLOAD = 1000';
    '';
    '!Specify element type';
    '!Plane stress element';
    'ET,1,PLANE42';
    '!Axis-symmetric element';
    '!ET,1,PLANE42,0,0,1';
    '';
    '! Specify material properties ';
    'uimp,1,EX,PRXY,DENS,62.75e9,.2,2230       ! Youngs modulus,
Poissons ratio and Density of Pyrex glass, from MatWeb';
    '';
    '! Mirror variables';
    ['R1back = ' num2str(R1back)];
    ['t1 = ' num2str(t1)];
    '';
    '! Define the mirror fixed points,diameter (D1), front radius (R)';
    '! and several (WIDTH), and (HEIGHT)';
    '';
    'PI = 3.14159265359';
    'D1 = 203';
    'R = 810';
    'SCALE = 0.001';
    'S = R-SQRT((R*R-(D1/4)*(D1/4)))';
    'S1 = R1-SQRT(R1*R1-(D1/4)*(D1/4))';
    '';
    'WIDTH1 = S';
    'WIDTH2 = t1-S1';
    'WIDTH3 = t1';
    'WIDTH4 = 0';
    'WIDTH5 = S-R1';
    'WIDTH6 = t1-S1+R1back';
    '';
    'HEIGHT1 = 0';
    'HEIGHT2 = (D1/2)';
    '';
    '! Define the keypoints for the mirror';
    'k,1,WIDTH1*SCALE,HEIGHT1*SCALE';
    'k,2,WIDTH2*SCALE,HEIGHT1*SCALE';
```

```
'k,3,WIDTH3*SCALE,HEIGHT2*SCALE';
'k,4,WIDTH4*SCALE,HEIGHT2*SCALE';
'k,5,WIDTH5*SCALE,HEIGHT1*SCALE';
'k,6,WIDTH6*SCALE,HEIGHT1*SCALE';
'';
'! Define the lines for the mirror surface';
'l,1,2 !1';
'l,3,4 !2';
'';
'! Define the arcs of the mirror surface';
'larc,1,4,5,R1 !3';
'larc,2,3,6,R1back !4';
'';
'';
'!Divide lines for the mounting rings';
'ldiv,3,0.95,,,,';
'ldiv,4,0.95,,,,';
'';
'! Define half the cross-sectional area of mirror';
'a,1,2,8,3,4,7';
'';
'! Segment the lines';
'lsel,none';
'lsel,s,,,1';
'lsel,a,,,2';
'lesize,all,,,7,1';
'';
'! Segment the lines';
'lsel,none';
'lsel,s,,,3';
'lsel,a,,,4';
'lesize,all,,,50,1';
'';
'! Segment the lines';
'lsel,none';
'lsel,s,,,5';
'lsel,a,,,6';
'lesize,all,,,3,1';
'';
'! Mesh the area';
'amesh,all';
'';
'';
'! Done with the preprocessor';
'finish';
'';
'';
'! Enter the solver';
'/solu';
'antype,static';
'';
'! Select ICCG solver';
'eqslv,iccg,,3';
'';
'! Apply boundary conditions ';
'DL,1,,Symm';
'DL,5,,UX,0';
```

```
    '';
    '! Apply pressure load';
    'SFL,6,PRES,PRESLOAD';
    '';
    '';
    '! Solve the model';
    'allsel';
    'solve';
    'finish';
    '';
    '';
    '! Go to the preprocessor';
    '/post1';
    '';
    'allsel';
    '';
    '! Get the displacement values';
    'nsort,u,x';
    '*GET,delta_xmax,sort,,max';
    'nsort,u,y';
    '*GET,delta_ymax,sort,,max';
    '';
    '! Get the stress values';
    'nsort,S,EQV';
    '*GET,stress_max,sort,,max';
    '';
    '';
    '! Display the deformed structure';
    '!PLDISP,1';
    '/output,output1.txt';
    '*VWRITE,delta_xmax,delta_ymax,stress_max';
    '%-16.8G %-16.8G %-16.8G';
    '/output';
    '';
    'nsel,s,node, ,1';
    'nsel,a,node, ,72, 120,';
    'nsel,a,node, ,69';
    '';
    '/output,outputStructInit1.txt';
    'nlist,,,coord,node';
    '/output';
    '';
    '/output,outputStructDef1.txt';
    'PRNSOL,U,X';
    'prnsol,u,y';
    '/output';
    '';
    'save';
    'finish'};
% fid = fopen(filename)
fid = fopen(PASSfilename1,'r');
if fid ~= -1
    %input file already exists
    delete(PASSfilename1);
end
fid = fopen(PASSfilename1,'w');
%write new input file
```

```
fprintf(fid,'%s',writefile{1});
for i = 2:length(writefile)
    fprintf(fid,'\n %s', writefile{i});
end
fclose(fid);
% Input file (mirror1) complete

PASSfilename2 = 'input_mirror2.log';

% Generate input file (mirror2) for pass

writefile = {
    '/batch';
    '/filename,input_mirror2';
    '';
    '!Enter the preprocessor';
    '/prep7';
    '';
    '!Load inputs';
    'PRESLOAD = 600';
    '';
    '!Specify element type';
    '!Plane stress element';
    'ET,1,PLANE42';
    '!Axis-symmetric element';
    '!ET,1,PLANE42,0,0,1';
    '';
    '! Specify material properties ';
    'uimp,1,EX,PRXY,DENS,62.75e9,.2,2230       ! Youngs modulus, 
Poissons ratio and Density of Pyrex glass, from MatWeb';
    '';
    '! Mirror variables';
    ['R2back = ' num2str(R2back)];
    ['t2 = ' num2str(t2)];
    '';
    '! Define the mirror fixed points,diameter (D1), front radius (R)';
    '! and several (WIDTH), and (HEIGHT)';
    '';
    'PI = 3.14159265359';
    'D2 = 60';
    'r = 250';
    'SCALE = 0.001';
    'S2 = R2back-SQRT(R2back^2-(D2/4)*(D2/4))';
    's = R2-SQRT((R2^2-(D2/4)*(D2/4)))';
    '';
    'WIDTH1 = S2';
    'WIDTH2 = t2+s';
    'WIDTH3 = t2';
    'WIDTH4 = 0';
    'WIDTH5 = S2-R2back';
    'WIDTH6 = t2+s-R2';
    '';
    'HEIGHT1 = 0';
    'HEIGHT2 = (D2/2)';
    '';
    '! Define the keypoints for the mirror';
```

```
'k,1,WIDTH1*SCALE,HEIGHT1*SCALE';
'k,2,WIDTH2*SCALE,HEIGHT1*SCALE';
'k,3,WIDTH3*SCALE,HEIGHT2*SCALE';
'k,4,WIDTH4*SCALE,HEIGHT2*SCALE';
'k,5,WIDTH5*SCALE,HEIGHT1*SCALE';
'k,6,WIDTH6*SCALE,HEIGHT1*SCALE';
'';
'! Define the lines for the mirror surface';
'l,1,2 !1';
'l,3,4 !2';
'';
'! Define the arcs of the mirror surface';
'larc,1,4,5,R2back !3';
'larc,2,3,6,R2 !4';
'';
'';
'!Divide lines for the mounting rings';
'ldiv,3,0.95,,,,';
'ldiv,4,0.95,,,,';
'';
'! Define half the cross-sectional area of mirror';
'a,1,2,8,3,4,7';
'';
'! Segment the lines';
'lsel,none';
'lsel,s,,,1';
'lsel,a,,,2';
'lesize,all,,,5,1';
'';
'! Segment the lines';
'lsel,none';
'lsel,s,,,3';
'lsel,a,,,4';
'lesize,all,,,40,1';
'';
'! Segment the lines';
'lsel,none';
'lsel,s,,,5';
'lsel,a,,,6';
'lesize,all,,,3,1';
'';
'! Mesh the area';
'amesh,all';
'';
'';
'! Done with the preprocessor';
'finish';
'';
'';
'! Enter the solver';
'/solu';
'antype,static';
'';
'! Select ICCG solver';
'eqslv,iccg,,3';
'';
'! Apply boundary conditions ';
```

```
    'DL,1,,UY,0';
    'DL,5,,UX,0';
    '';
    '! Apply pressure load';
    'SFL,6,PRES,PRESLOAD';
    '';
    '';
    '! Solve the model';
    'allsel';
    'solve';
    'finish';
    '';
    '';
    '! Go to the preprocessor';
    '/post1';
    '';
    'allsel';
    '';
    '! Get the displacement values';
    'nsort,u,x';
    '*GET,delta_xmax,sort,,max';
    'nsort,u,y';
    '*GET,delta_ymax,sort,,max';
    '';
    '! Get the stress values';
    'nsort,S,EQV';
    '*GET,stress_max,sort,,max';
    '';
        '! Display the deformed structure';
    '!PLDISP,1';
    '/output,output2.txt';
    '*VWRITE,delta_xmax,delta_ymax,stress_max';
    '%-16.8G %-16.8G %-16.8G';
    '/output';
    '';
    'nsel,s,node, ,2';
    'nsel,a,node, ,8, 46,';
    '';
    '/output,outputStructInit2.txt';
    'nlist,,,coord,node';
    '/output';
    '';
    '/output,outputStructDef2.txt';
    'PRNSOL,U,X';
    'prnsol,u,y';
    '/output';
    '';
    'save';
    'finish'};

fid = fopen(PASSfilename2,'r');
if fid ~= -1
    %input file already exists
    delete(PASSfilename2);
end
fid = fopen(PASSfilename2,'w');
%write new input file
```

```
fprintf(fid,'%s',writefile{1});
for i = 2:length(writefile)
    fprintf(fid,'\n %s', writefile{i});
end
fclose(fid);
% Input file (mirror2) complete

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% run PASS
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
command_line = ['h:\matlab\ansysMod1.bat'];
[status,result] = system(command_line);
pause on;
pause(10)
command_line = ['h:\matlab\ansysMod2.bat'];
[status,result] = system(command_line);
pause(10)
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

FinalPnt1 = ReadOutput('outputStructInit1.txt',
'outputStructDef1.txt');
FinalPnt2 = ReadOutput('outputStructInit2.txt',
'outputStructDef2.txt');

p1 = polyfit(FinalPnt1(:,1),FinalPnt1(:,2),2);

a_f1=p1(1);
b_f1=p1(2);
c_f1=p1(3);
% Calculate and save function value
f1_new = 1/4*a_f1;

p2 = polyfit(FinalPnt2(:,1),FinalPnt2(:,2),2);

a_f2=p2(1);
b_f2=p2(2);
c_f2=p2(3);
% Calculate and save function value
f2_new = 1/4*a_f2;
```

7.2.6. ansysMod1.bat

```
cd /d H:\Matlab
S:\CAEN\ANSYS10\SETENV.CMD
S:\CAEN\Ansys10\v100\ANSYS\bin\intel\ansys100.exe -p ansysrf -b -i
input_mirror1.log -o outputfrom1.txt

exit
```

7.2.7. ansysMod2.bat

```
cd /d H:\Matlab
S:\CAEN\ANSYS10\SETENV.CMD
S:\CAEN\Ansys10\v100\ANSYS\bin\intel\ansys100.exe -p ansysrf -b -i
input_mirror2.log -o outputfrom2.txt
exit
```