看了觉得可以，就留着作者的名字吧，这是对别人劳动的尊重

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Chapter13

13 章

Coma and astigmatism

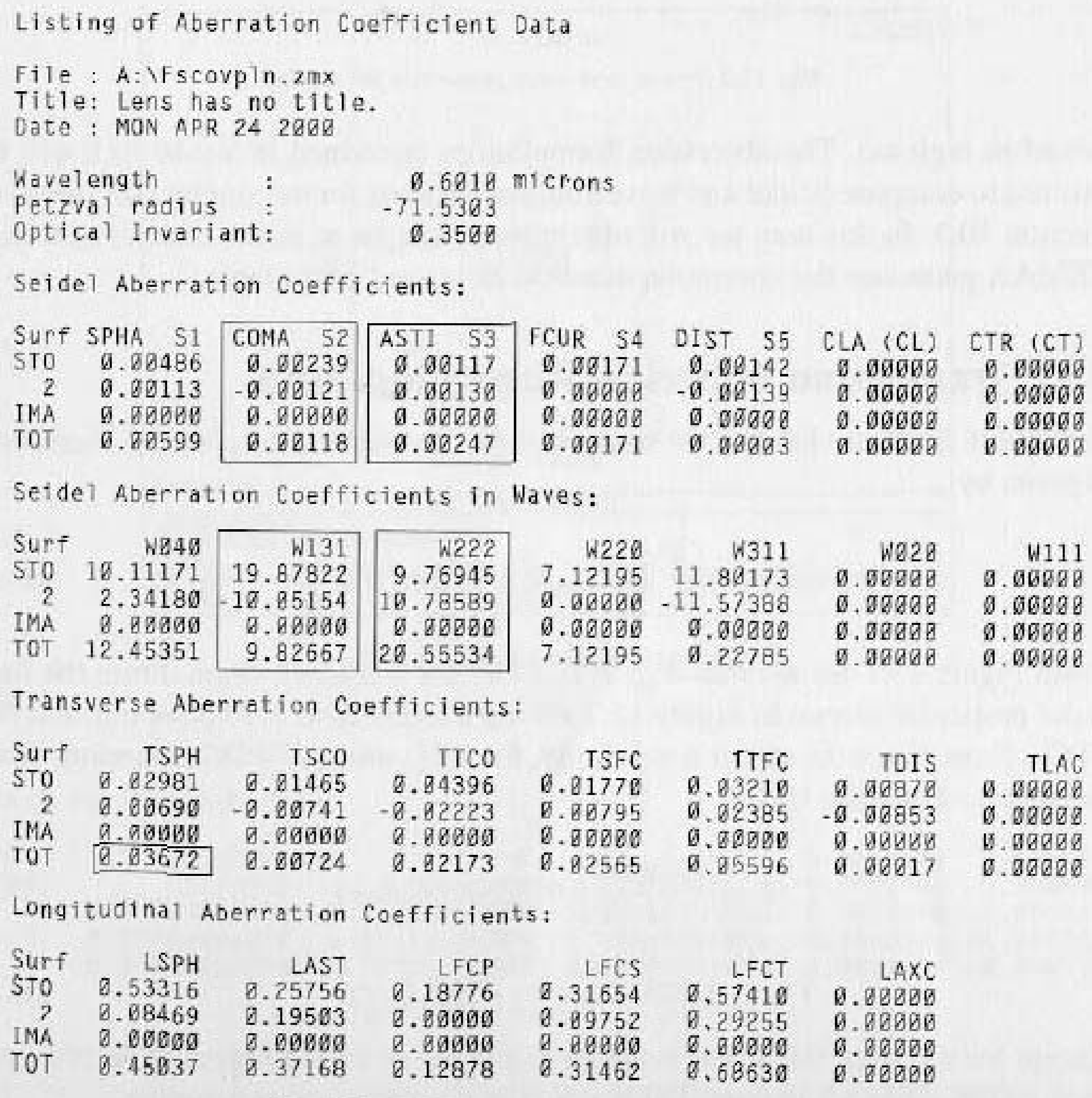
慧差与散光

13.1 introduction

介绍

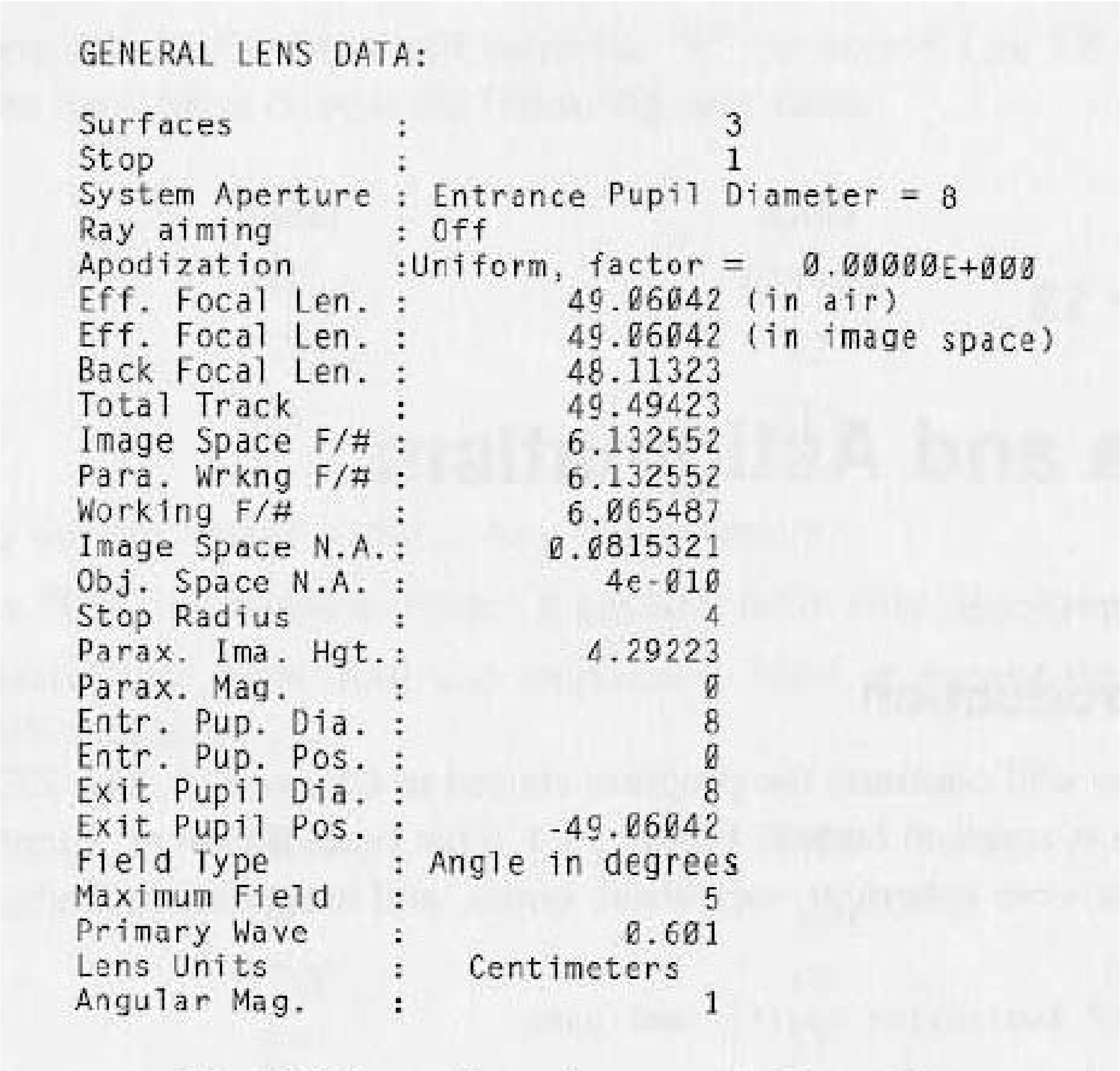
This chapter will continue the program started in chapter 10. the ZEMAX aberration table is reprised as here as figure 13.1. this time, however, attention focuses on the transverse spherical aberration, coma, and astigmatism (indicated the boxed-in regions). The aberration formulation contained in table 10.1 will be utilized to compute Seidel and wavefront coefficients for the singlet introduced in section 10.3. in this way we will obtain some insight as to the manner in which ZEMAX generates the aberration numbers displayed in the table.

这个章节将继续第 10 章的内容。 ZEMAX 像差表格如图 13.1 。 这时,注意焦点上横向球差,慧差, 并且散光(表明是 boxed-in 区域) 。像差表达式包含在表 10.1 将被用来计算 Seidel 和波前系数的单镜片在 10.3 部分有介绍. 这样我们将获得一些见解显示在 ZEMAX 引起像差值的表格里。



```
Listing of Aberration Coefficient Data

File : A:\Fscovpln.zmx
Title: Lens has no title.
Date : MON APR 24 2000

Wavelength          :          0.6010 microns
Petzval radius      :        -71.5303
Optical Invariant:             0.3500

Seidel Aberration Coefficients:

Surf SPHA   S1  COMA    S2  ASTI    S3  FCUR    S4  DIST    S5  CLA (CL)  CTR (CT)
STO   0.00486    0.00239     0.00117     0.00171     0.00142   0.00000   0.00000
  2   0.00113   -0.00121     0.00130     0.00000    -0.00139   0.00000   0.00000
IMA   0.00000    0.00000     0.00000     0.00000     0.00000   0.00000   0.00000
TOT   0.00599    0.00118     0.00247     0.00171     0.00003   0.00000   0.00000

Seidel Aberration Coefficients in Waves:

Surf       W040        W131        W222        W220        W311      W020      W111
STO    10.11171    19.87822     9.76945     7.12195    11.80173   0.00000   0.00000
  2     2.34180   -10.85154    10.78589     0.00000   -11.57388   0.00000   0.00000
IMA     0.00000     0.00000     0.00000     0.00000     0.00000   0.00000   0.00000
TOT    12.45351     9.82667    20.55534     7.12195     0.22785   0.00000   0.00000

Transverse Aberration Coefficients:

Surf       TSPH        TSCO        TTCO        TSFC        TTFC      TDIS      TLAC
STO     0.02981     0.01465     0.04396     0.01770     0.03210   0.00870   0.00000
  2     0.00690    -0.00741    -0.02223     0.00795     0.02385  -0.00853   0.00000
IMA     0.00000     0.00000     0.00000     0.00000     0.00000   0.00000   0.00000
TOT     0.03672     0.00724     0.02173     0.02565     0.05596   0.00017   0.00000

Longitudinal Aberration Coefficients:

Surf       LSPH        LAST        LFCP        LFCS        LFCT      LAXC
STO     0.53316     0.25756     0.18776     0.31654     0.57410   0.00000
  2     0.08469     0.19503     0.00000     0.09752     0.29255   0.00000
IMA     0.00000     0.00000     0.00000     0.00000     0.00000   0.00000
TOT     0.45037     0.37168     0.12878     0.31462     0.60630   0.00000
```

Fig. 13.1 *ZEMAX aberration coefficient data list.*



```
GENERAL LENS DATA:

Surfaces            :                  3
Stop                :                  1
System Aperture     : Entrance Pupil Diameter = 8
Ray aiming          : Off
Apodization         :Uniform, factor =   0.00000E+000
Eff. Focal Len.     :         49.06042 (in air)
Eff. Focal Len.     :         49.06042 (in image space)
Back Focal Len.     :         48.11323
Total Track         :         49.49423
Image Space F/#     :         6.132552
Para. Wrkng F/#     :         6.132552
Working F/#         :         6.065487
Image Space N.A.    :        0.0815321
Obj. Space N.A.     :           4e-010
Stop Radius         :                4
Parax. Ima. Hgt.    :          4.29223
Parax. Mag.         :                0
Entr. Pup. Dia.     :                8
Entr. Pup. Pos.     :                0
Exit Pupil Dia.     :                8
Exit Pupil Pos.     :        -49.06042
Field Type          : Angle in degrees
Maximum Field       :                5
Primary Wave        :            0.601
Lens Units          :   Centimeters
Angular Mag.        :                1
```

Fig. 13.2 *System first order properties for singlet.*

13.2 Transverse spherical aberration: SA3

横向球面像差: SA3

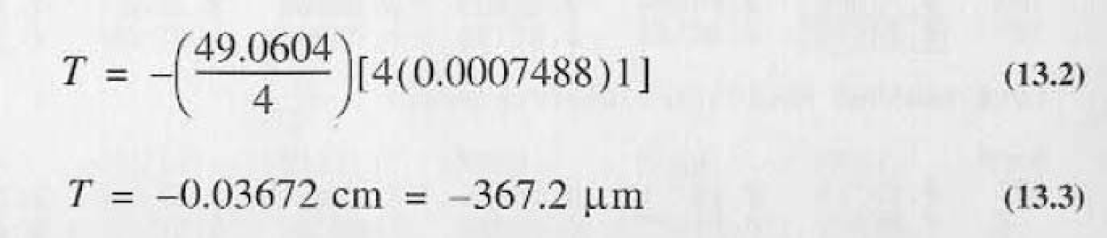
We saw in section 11.8 that the transverse ray aberration for spherical aberration is given by:

我们看见在 11.8 部分, 横向光线像差是球差引起的:

$$T = -\left(\frac{R}{r}\right)[4W_{040}\rho^3] = \mathrm{SA3}\rho^3 \qquad \mathbf{(13.1)}$$

From figure 13.1 we see that W_{040}=12.4535λ=0.00074846cm. from the first order properties shown in figure 13.2 we see that the EFL=49.0604cm, and the EPD=8cm. since the object is at infinity, R=EFL, and r=EPD/2. inserting these values into equation 13.1:

从图 13.1 我们看出 W040=12.4535λ=0.00074846cm 。 从第一阶性质被显示在上图 13.2 我们看见 EFL=49.0604cm, 并且 EPD=8cm 。 因为物体在无限远处, R=EFL, 并且 r=EPD/2 。 插入估价等式 13.1:



$$T = -\left(\frac{49.0604}{4}\right)[4(0.0007488)1] \qquad (13.2)$$

$$T = -0.03672\ \text{cm} = -367.2\ \mu\text{m} \qquad (13.3)$$

Except for the sign, this is the value shown in the boxed-in region under the column TSPH. ZEMAX defines TSPH = s1/ (2n′ u′), where u′ is negative.

除了符号以外, 这个评估被显示在 boxed-in 区域在专栏之下 TSPH s1/ (2n′ u′)处 。ZEMAX 定义 TSPH = s1/ (2n’u’), 那里 u ’ 是负的。

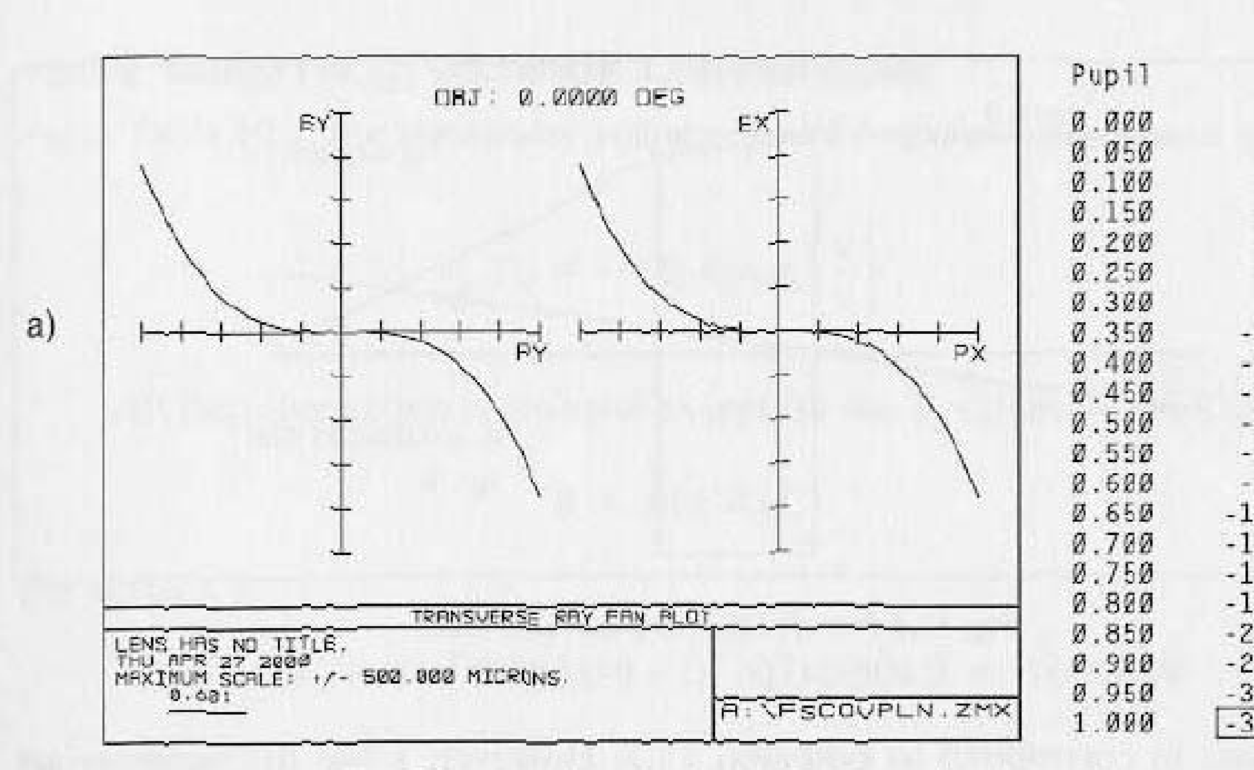
The ray fan plot is shown in figure 13.3a, and the magnitude at the pupil edge appears to correspond to equation 13.3. however, when the numbers are called up (via “text”), a discrepancy is seen (as indicated in figure 13.3b). the value at the pupil edge in shown to be 375.7μm. this value is also seen as the geometric radius in the spot diagram in figure 13.4. finally, when the ray trace is called up (figure 13.6), the same number appears once as the y-height in the image plane for the real ray.

光线 RAY fan 在图 13.3.a 显示，并且在瞳孔边缘大小对应于等式 13.3 。但是，当这个值给出时(通过"文本")，出现一个误差(在图 13.3b 中表明）。评估瞳孔边缘显示是 375.7μm 。这评估也看作为几何半径在斑点图如表 13.4 。最后，当给出光线追迹时(图 13.6)，同样的值一旦出现作为 y 轴的高度在像面为真实的光线。

The reason for the discrepancy is that the calculation for SA3 considers only Seidel aberration (fourth order in the exit pupil, third order in the image plane). The real ray is affected by all orders of aberration, and it is the real ray behavior that is reflected in both the ray fan spot plots. In our case, sixth order spherical aberration is the main culprit.

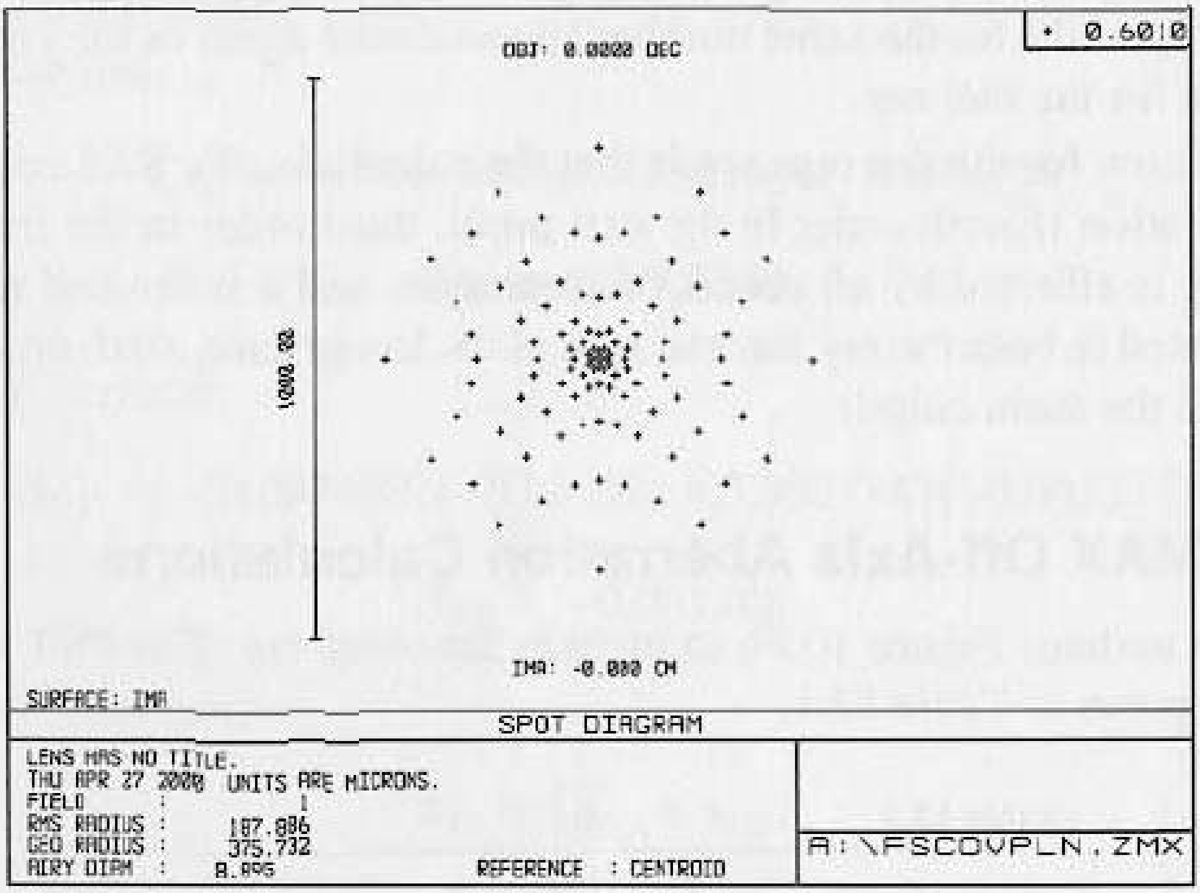
误差的原因是计算SA3 是仅仅只考虑了Seidel像差(第四阶在出瞳，第三阶在像面)，经过全阶像差的真实光线受影响，并且这是真实光线的行为更确切的说反射的在两个

光线扇型斑点图。 在我们的案例中，第六阶球差是主要错误。



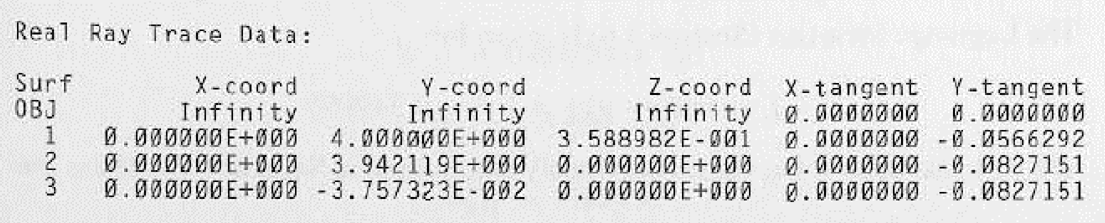
Pupil	
0.000	
0.050	
0.100	
0.150	
0.200	
0.250	
0.300	
0.350	-
0.400	-
0.450	-
0.500	-
0.550	-
0.600	-
0.650	-1
0.700	-1
0.750	-1
0.800	-1
0.850	-2
0.900	-2
0.950	-3
1.000	-3

Fig. 13.3 a. *Ray fan plot for singlet;* **b.** *ray fan data table.*



```
LENS HAS NO TITLE.
THU APR 27 2000  UNITS ARE MICRONS.
FIELD        :          1
RMS RADIUS   :      187.886
GEO RADIUS   :      375.732
AIRY DIAM    :      8.895                    REFERENCE   : CENTROID
```

Fig. 13.4 *Spot diagram for singlet.*



```
Real Ray Trace Data:

Surf         X-coord          Y-coord          Z-coord    X-tangent   Y-tangent
OBJ         Infinity         Infinity         Infinity    0.0000000   0.0000000
  1   0.000000E+000    4.000000E+000    3.588982E-001    0.0000000  -0.0566292
  2   0.000000E+000    3.942119E+000    0.000000E+000    0.0000000  -0.0827151
  3   0.000000E+000   -3.757323E-002    0.000000E+000    0.0000000  -0.0827151
```

Fig. 13.5 *Ray trace data for real ray.*

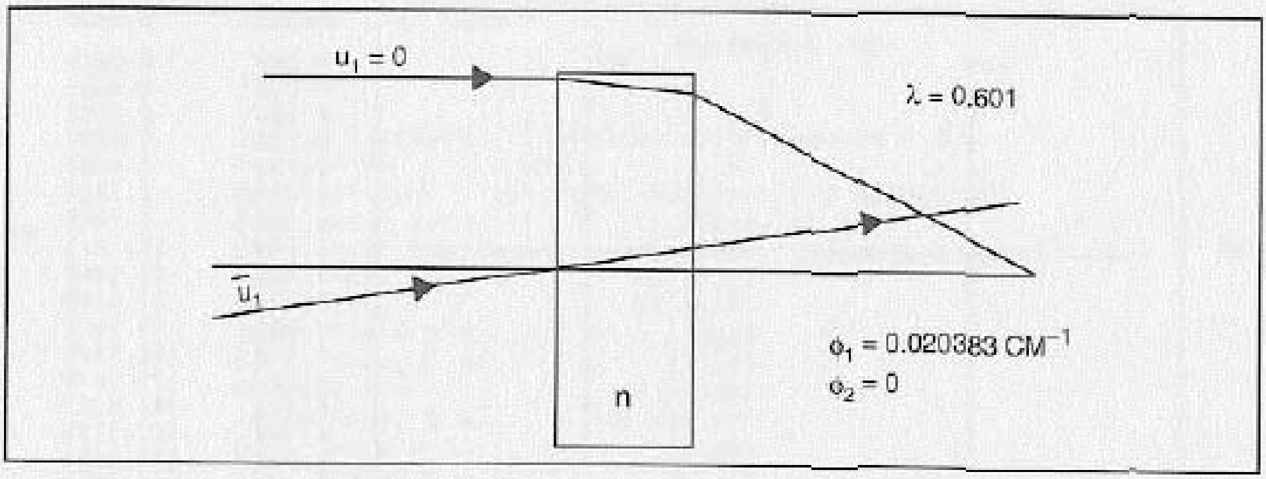


Fig. 13.6 *Paraxial convex-plano thin lens.*

13.3 ZEMAX off-axis aberration calculations

13.3 ZEMAX 离轴像差计算

Figure 13.6 updates figure 10.4b to include the chief ray. The PRT data for the chief ray is given in table 13.1.

图 13.6 是 10.4b 的补充资料包括主光轴。PRT 数据为主光轴在表 13.1 给出

。

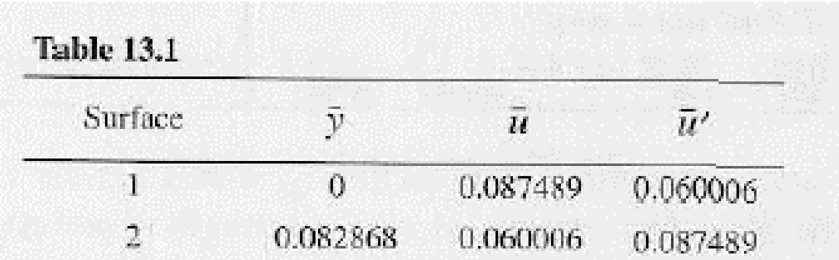


Table 13.1

Surface	$\bar{y}$	$\bar{u}$	$\bar{u}'$
1	0	0.087489	0.060006
2	0.082868	0.060006	0.087489

The Lagrange invariant (section 5.6) is given by:

拉格朗日不变式(5.6 部分)给出：

$$L = n[\bar{u}y - u\bar{y}] = \bar{u}y = 0.349955$$

We will also need some values previously determined in Section 10.3. these are:

在10.3部分早先被确定的我们将需要一些估价。 这些是:

$$\begin{aligned} A_1 &= 0.178016 \\ A_2 &= -0.081531 \\ \Delta_1\{u/n\} &= -0.038354 \\ \Delta_2\{u/n\} &= -0.043177 \end{aligned}$$

13.3.1 Coma (W_{131}) via Seidel contributions

慧差(W131)通过Seidel得到的

From table 10.1, the surface-by-surface Seidel formulation for coma is given by:

从表10.1, 表面通过表面Seidel 公式为慧差给出:

$$S_{II} = -\Sigma B_i A_i y_i \Delta_i \left\{\frac{u}{n}\right\} \qquad (13.4)$$

All the information is on-hand except for the Bi values. From table 10.1:

所有信息是现有的 除了Bi 估价。 从表10.1:

$$B = n(\bar{u} + \bar{y}C) \qquad (13.5)$$

For surface 1:

面一:

$$B_1 = 1 \cdot [0.087489 + 0 \cdot (0.044504)] = 0.087489$$

For surface2:

面二：

$$B_2 = 1.458[0.060006 + (0.082868) \cdot 0] = 0.087489$$

Now employing equation 13.4:

现在使用等式 13.4:

First surface:

第一面

$$S_{II1} = -(0.087489)(0.178016)4(-0.038354)$$

$$S_{II1} = +0.002389$$

Second surface:

第二面

$$S_{II2} = -(0.087489)(-0.081531)(3.922774)(-0.043177)$$

$$S_{II2} = -0.001208$$

Surface summation:

表面总和

$$S_{II} = [S_{II1} + S_{II2}]$$

$$S_{II} = 0.001181 \text{ cm}$$

This is the value seen in table 13.1 under the heading COMA S2.

这是估价在表 13.1 慧差标题 S2 下看。

Recalling that $W_{131}=S_{II}/2$ we have:

取消 W131=SII/2 我们有:

$$W_{131} = 0.0005904 \text{ cm}$$

$$W_{131} = 5.904 \ \mu\text{m}$$

$$W_{131} = 9.824\lambda$$

This is essentially the value seen in table 13.1 under the heading W_{131}. this is the magnitude of the aberration at the edge of the pupil.

这本来是在表 13.1 标题 W131 之下看它的估价 。这个是像差在瞳孔边缘的大小。

13.3.2 Coma(W_{131}) via Thin Lens Formulation

13.3.2 慧差(W_{131})通过薄透镜的表达公式

From Table 10.1 we see that the thin lens formula for coma is given by:

从表 10.1 我们看见薄透镜公式为慧差给出:

$$W_{131} = \frac{1}{2}S_{II} = \frac{1}{2}\left[\frac{1}{2}Ly^{2}\phi^{2}\sigma_{II}\right] \qquad (13.6)$$

Also from Table 10.1 we see that the structural aberration coefficient for coma is given by:

并且从表 10.1 我们看见像差结构系数为慧差给出:

$$\sigma_{II} = eX - fY \qquad (13.7)$$

Since the object is at infinity, the magnification factor Y=1. Since the lens is convex-plano, the shape factor X=1 as well. Inserting the values for e and f from Table 10.1, Equation 13.7 reduces to:

因为物是无限大，放大因素 Y=1 。 因为透镜是平凸的，形状因素 X=1 。 插入估价为 e 和 f 来自表 10.1，等式 13.7 归纳为:

$$\sigma_{II} = e - f = \left[\frac{n+1}{n(n-1)}\right] - \left(\frac{2n+1}{n}\right) \qquad \textbf{(13.8)}$$

Since the index is 1.458, δ_{II} becomes: $\delta_{II}=0.99507$.

因为折射率是 1.458， δ_{II} 变成: $\delta_{II}=0.99507$

We now have all the numbers needed to insert into S as found in Equation 13.6.

我们现有的所有值必须插入 S 建立等式 13.6 。

$$S_{II} = \frac{1}{2}(0.349955)4^2(0.020383)^3(0.99507)$$

$$S_{II} = 0.001157\ \text{cm}$$

The wavefront aberration coefficient W_{131} is given by:

波前像差系数 W_{131} 给出:

$$W_{131} = \frac{1}{2}S_{II} = 0.000579\ \text{cm}$$

Therefore: $W_{131}=9.63\lambda$.

因此：$W_{131}=9.63\lambda$

This is close to the value found via the Seidel summation method. The difference is due to the fact that lens thickness was not taken into account.

这是接近估价建立通过 Seidel 总和的方法。 区别是由于真实透镜厚度未被考虑到。

13.3.3 Astigmatism(W_{222}) via Seidel contributions

13.3.3 散光(W222) 通过 Seidel 获得

From Table 10.1, the surface-by-surface Buchdahl formulation for astigmatism is given by:

表 10.1, 表面通过表面 Buchdahl 用散光公式给出为:

$$S_{III} = -\Sigma B_i^2 y_i \Delta_i \left\{\frac{u}{n}\right\} \tag{13.9}$$

All the information is on hand.

现有的所有信息。

First Surface:

第一面

$$S_{III1} = -(0.087489)^2(4)(-0.038354)$$

$$S_{III1} = +0.001174$$

Second Surface:

第二面

$$S_{III2} = -(0.087489)^2(3.922774)(-0.043177)$$

$$S_{III2} = +0.001296$$

Surface Summation:

总面数

$$S_{III} = [S_{III1} + S_{III2}]$$

$$S_{III} = 0.002470\ \mathrm{cm}$$

This is the value seen in Table 13.1 under the heading ASTI S3.

这是估价在表 13.1 标题 ASTI S3 之下看。

Recalling that:

取消那个：

$$W_{222} = \frac{1}{2}S_{III},$$

We have:

我们有：

$$W_{222} = 0.001235\ \mathrm{cm}$$

$$W_{222} = 12.35\ \mu\mathrm{m}$$

$$W_{222} = 20.55\ \lambda$$

This is the value seen in Table 13.1 under the heading W_{222}. This is the magnitude of the aberration at the edge of the pupil.

这个估价在表 13.1 标题 W222 之下看 。这个是像差在瞳

孔边缘的大小。

13.3.4 Astigmatism (W_{222}) via Thin Lens Formulation

13.3.4 散光 (W_{222})通过薄透镜的表达式

From Table 10.1 we see that the thin lens formula for astigmatism is given by:

从 10.1 我们看出那个薄透镜公式给出：

$$W_{222} = \frac{1}{2}S_{III} = \frac{1}{2}[L^2\phi\,\sigma_{III}] \qquad \textbf{(13.10)}$$

Also from table 10.1 we see that the value of δ $_{III}$=1. Therefore, S_{III} becomes:

并且从表 10.1 我们看见 δ $_{III}$=1 的估价。 所以, SIII 成为:

$$S_{III} = (0.349955)^2(0.020383)\cdot 1$$

$$S_{III} = 0.002496 \text{ cm}$$

The wavefront aberration coefficient is given by:

波前像差系数给出:

$$W_{222} = 0.001248 \text{ cm}$$

$$W_{222} = 20.76\,\lambda$$

Once again the difference between this and the summation result is due to lens thickness.

再次区别在这个和总和结果导致的应归于透镜厚度。

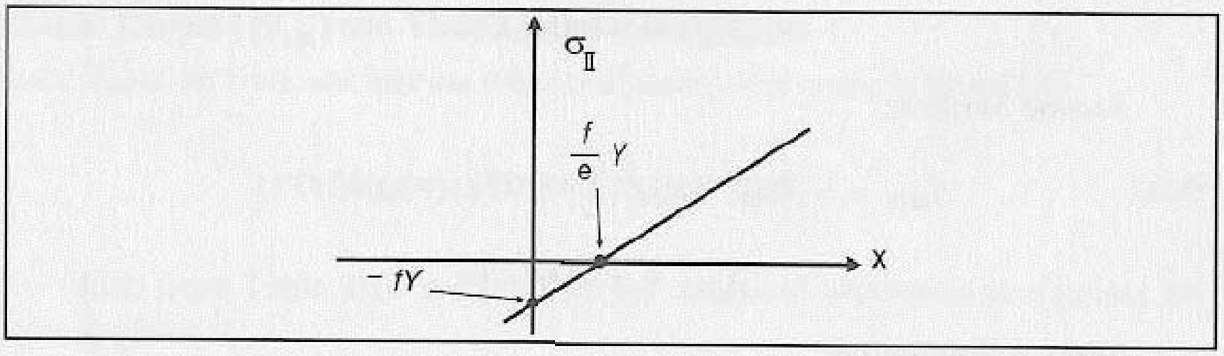


Fig. 13.7 Generic plot of σ_{II}.

13.4 Coma and Lens Bending

慧差和透镜曲率

In Chapter 11, we saw how the structural aberration coefficient δ_1 lent itself to exploring the effects of lens bending to find the shape that minimized spherical aberration. A similar procedure can be used with the structural aberration coefficient for coma, δ_{II}. Figure 13.7 shows a generic plot for δ_{II}. It is a linear function described by:

在 11 章里，我们看见了多少像差结构系数 δ1 自己对探测透镜曲率的作用发现使球差减到最小。 一个相似的做法可能被习惯用在像差结构系数，δII 。图 13.7 显示 δ_{II}是一个普通结构图。 它是一个线性函数被描述为:

$$\sigma_{II} = eX - fY \tag{13.11}$$

At the point where this plot crosses the abscissa, δ_{II} =0. Therefore:

表明交叉横坐标结构的点，δII = 0 。 所以:

$$X = \left(\frac{f}{e}\right) Y \qquad (13.12)$$

For an object at infinity, X=(f/e). For an object at unit magnification, X=0.

一个物无限大, X=(f/e) 。放大一个物体, X=0 。

Consider a Bk7 singlet with an object at infinity. Operating in d light, n=1.5168. Consequently, e=3.2107 and f=2.6593. Inserting these values into Equation 13.12:

考虑 Bk7 单透镜以一个物体在无限大。运行 d 光, n=1.5168 。 结果, e=3.2107 和 f=2.6593 。 插入这些估价到等式 13.12:

$$X=0.8283$$

Recall from Section 11.3 that the shape factor for minimum spherical was X=0.7397, which is not far from that for coma.

取消 11.3 部分形状因素为极小球状是 X=0.7397, 那个不是离的很远的地方为慧差

13.5 Coma and Astigmatism vs. F-Number and Field

13.5 慧差和散光对应的焦距值和视场

Both coma and astigmatism increase as field angle increases and as aperture size grows. But now do coma and astigmatism compete with each other in the same arena? Under what conditions does one dominate the other? Consider the thin lens forms for coma and astigmatism as given by Equations 13.6 and 13.10 respectively. For an object at infinity and stop at the lens, the Lagrange invariant is L=uy. We will also use the relation f-number=f/2y. Equations 13.6 and 13.10 become:

慧差和散光增大视场角增大并且孔径尺寸也增大。 但此时慧差和散光彼此会出现在同样的地方吗? 在什么情况下一个压制另外一个? 依照由公式 13.6 和 13.10 各自地考虑薄透镜的慧差和散光。 为一个物体在无限大并且中止在透镜, 拉格朗日不变式是 L=uy 。 我们将同样使用这个关系 f-number=f/2y 。 等式 13.6 和 13.10 成为:

$$W_{131} = \frac{1}{4}(\bar{u}y)\left(\frac{y}{f}\right)^2 \sigma_{II} = \frac{1}{4}\bar{u}y\left(\frac{2y}{f}\right)^2\left(\frac{\sigma_{II}}{4}\right) = \left[\frac{\bar{u}y}{4(f/\#)}\right] \cdot \left[\frac{\sigma_{II}}{4f/\#}\right] \qquad \textbf{(13.13)}$$

$$W_{222} = \frac{1}{2}(\bar{u}y)^2 \frac{\sigma_{III}}{f} = \frac{1}{2}(\bar{u}y)\left(\frac{2y}{f}\right)\left(\frac{\bar{u}\sigma_{III}}{2}\right) = \left[\frac{\bar{u}y}{4(f/\#)}\right] \cdot \left[\bar{u}\sigma_{III}\right] \qquad \textbf{(13.14)}$$

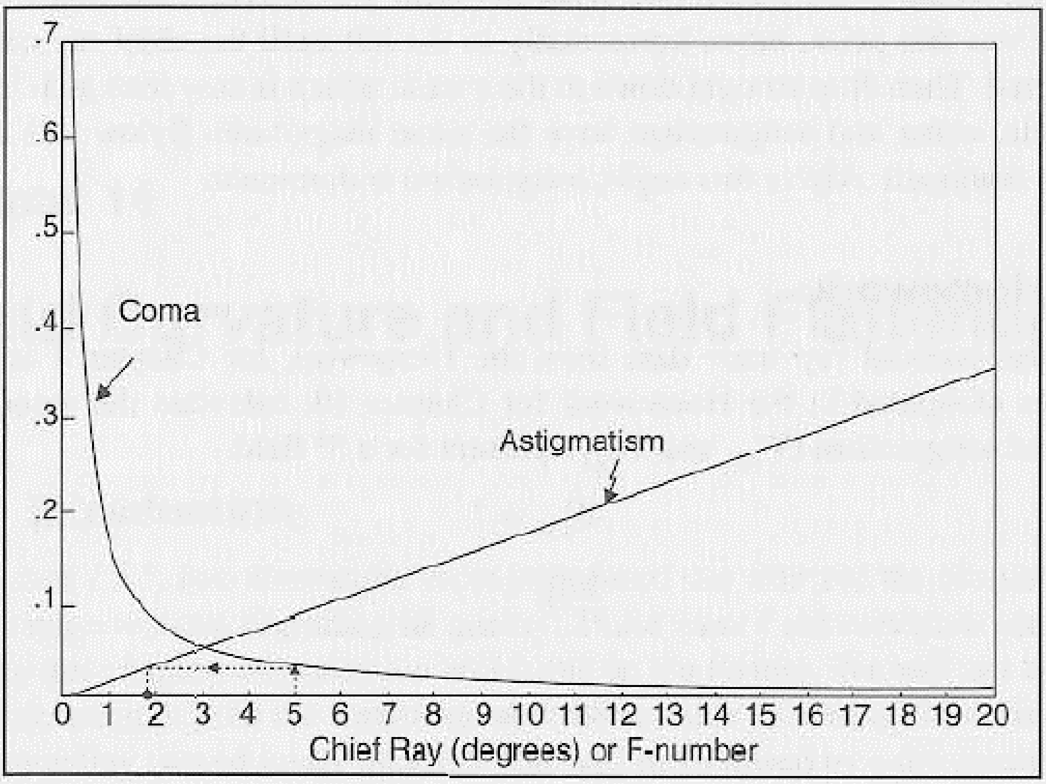


Fig. 13.8 *Difference factor plot of coma and astigmatism for a plano-convex thin lens.*

From Equations 13.13 and 13.14 we see that coma and astigmatism have been reformatted into two factors: one factor is common to both (unshaded); the other, the source of difference (shaded). Assuming that δ_{II} and δ_{III} are constant, then, relatively speaking, coma varies inversely with f-number and astigmatism varies directly with u.

从等式 13.13 和 13.14 我们看见慧差和散光有二个因素被重新定义：一个因素是两个有共同的(unshaded)；其他，区别来源于 (shaded) 。假设δII and δIII 是恒定的，然后，相对地讲，慧差随 f 值相反地变化并且散光直接地随 u 变化。

As an example, let us plot the difference part for a thin plane-convex lens. The structural aberration coefficients become: δ_{II}=(e-f) and δ_{III}=1. as indicated in table 10.1, both e and f are functions of the refractive index. Letting n=1.5, δ II=0.667. the resulting plot is shown in figure 13.8.

例如，假如我们这个图的区别部分为一个薄的平凸面透镜。 像差结构系数成为：δ II=(e- f) and δ III=1 。 依照被表明在表 10.1, e 和 f 是折射率的作用。 让 n=1.5, δ II=0.667 。 结果部分被显示在表 13.8 。

The numbers along the x-axis represent either the chief ray angle, u, in degrees or f-number (depending upon which difference factor is being considered). Recall that:

这个值沿 X 轴描绘任一主光束角度，u，在角度和 f 值中(取决于考虑那个区别因素) 。 给出：

$$\bar{u} = \tan \bar{U} .$$

As an example, suppose we have an f/5 system. Considering the x-axis as f-number, locate 5 and then move vertically until you intercept the 0.667/(4f/#) curve. From this point, move horizontally to the left until the chief ray curve is intercepted. Then drop straight down to the x-axis, which is now read as 1.75 ° .at this angle, coma and astigmatism have the same magnitude. Below this angle, come is dominant. Above this angle, astigmatism is dominant.

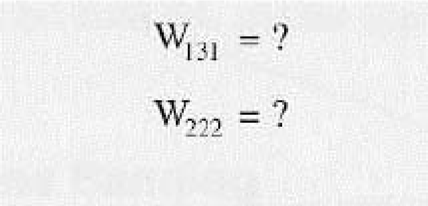
例如，假设我们有一个 f/5 的系统。就X轴而论作为f值，设置 5 并且然后垂直移动直到您获取 0.667/(4f/#)的曲率。从这点，水平地移动到左边直到主光束曲线被获取。然后顺着平直的下来到X轴,那个现在错误的读作为 1.75°。在这个角度,慧差和散光有同样数量。在这个角度之下，慧差来统治的。在这个角度之上，散光是统治的

13.6 Homework

家庭作业

Using the paraxial ray trace data from the homework for chapter 4 and the A-values computed in the homework for chapter 10, calculate the amount of coma and astigmatism (W_{131} and W_{222}) present for a 5° field.

用旁轴光束追迹数据来自家庭作业的第 4 章并且计算 A 估价的第十章的家庭作业，计算慧差和散光出现(W131 和 W222) 为 5°的视场。



$W_{131} = ?$

$W_{222} = ?$