光學系統設計
(Optical System Designs - 5)

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課程總目錄

幾何光學集要: 完美成像與高斯光學、像差理論估算與案例分析	第一週
物理光學集要: 繞射、點分散函數、MTF、偏振、高斯光束、部份同調與散射	第二週
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課程總目錄（續）

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照明光源與典型照明工法（schemes）	第十三週
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照明光學設計法II: Condenser and lenslet arrays	第十五週
照明光學設計法III:光管（lightpipe）	第十六週
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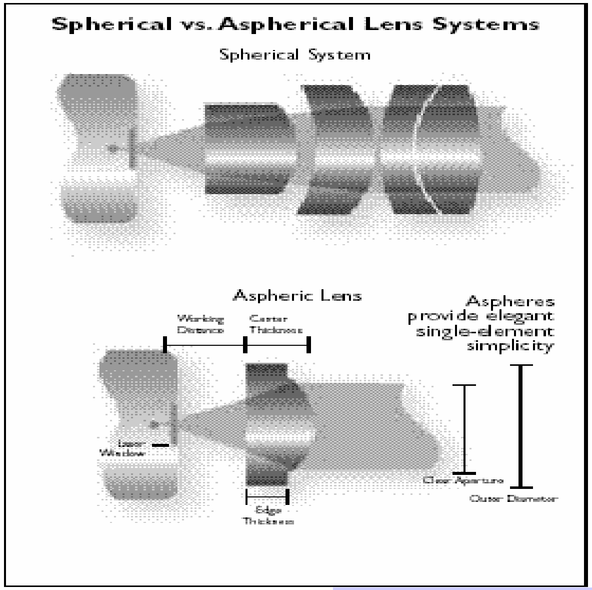
Outline

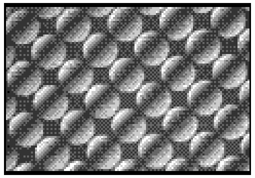
- Why aspheric/trends
- What is aspheric
  - Working principle and its limitation
  - OSLO interface to aspheric surface
- When to use aspheric and guidelines
- How to design (illustrated by examples)
  - Intuitive approach (starting from conic contestant)
  - Fermat principle
  - Wasserman-Wolf theory
  - Common approach with optimization
- How to make aspheric and how to test
- Conclusions and references
- Homework

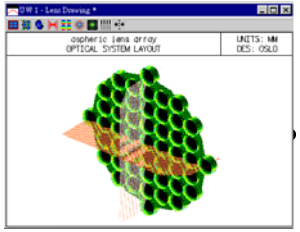
Why aspheric and trends?

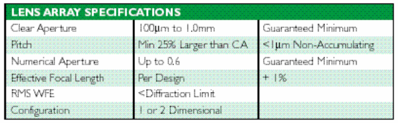
- Improving imaging quality
  - Small volume
  - Lighter
  - IP protection
  - …



From lightpath







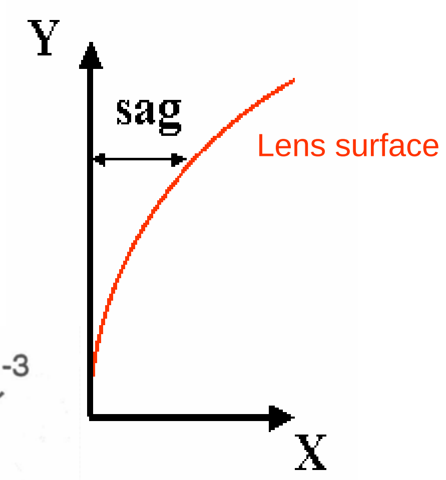
LENS ARRAY SPECIFICATIONS		
Clear Aperture	100µm to 1.0mm	Guaranteed Minimum
Pitch	Min 25% Larger than CA	<1µm Non-Accumulating
Numerical Aperture	Up to 0.6	Guaranteed Minimum
Effective Focal Length	Per Design	+ 1%
RMS WFE	<Diffraction Limit	
Configuration	1 or 2 Dimensional	

- In **Astronomical optics**, reflective aspheric components are widely used
- Refractive aspheric lenses are widely used in many kind of **Illumination systems**, from the condensers in projection systems and microscopes, to street lamps and searchlights.
  - Injection-molded component, if the component is not close to light source
  - Common glass material, B270
- **Consumer Optics**
  - CD players and data storage system
    - Collimating with LD or fiber coupling
  - Camera lens
  - Projection lens

What is aspheric?

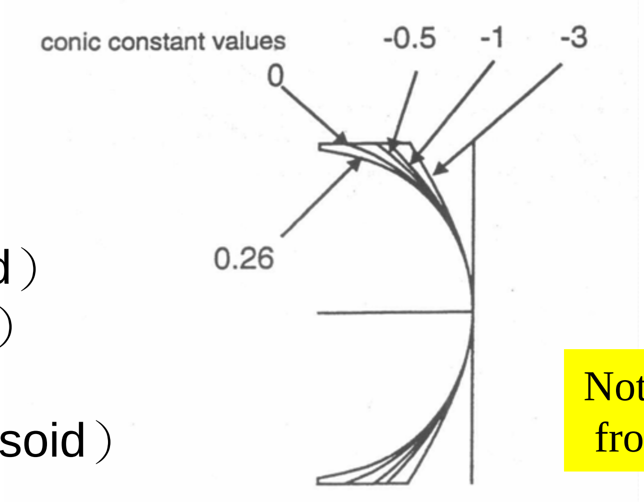
- In a rotationally symmetric surface with the sag defined

$$X=\frac{R_1Y^2}{1+\sqrt{1-Y^2R_1^2(1+K)}}+AY^4+BY^6+CY^8+DY^{10}$$



對於不同的K值所對應的曲線：

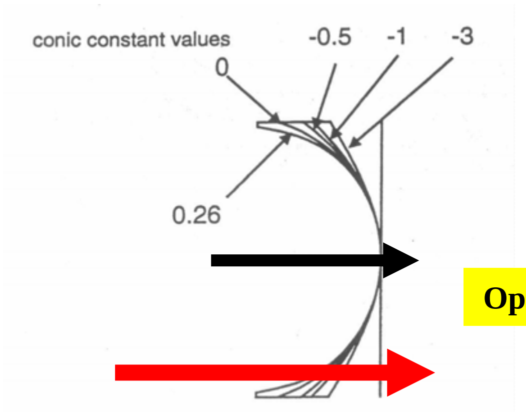
K = 0	圓（sphere）
K < -1	雙曲面（hyperboloid）
K = -1	拋物面（paraboloid）
-1 < K <0	橢圓面（ellipsoid）
K > 0	橫橢圓面（oblate ellipsoid）



Notions are different from textbook

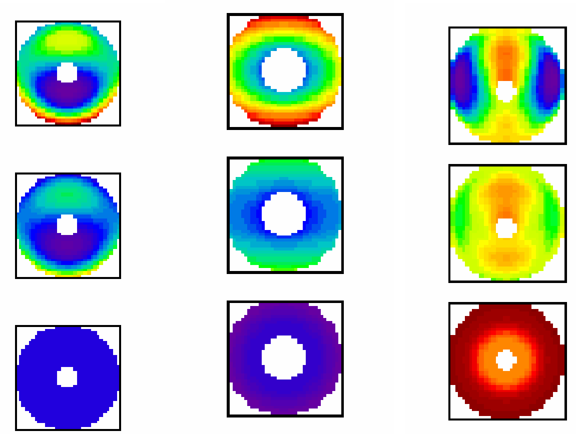
The working principle and limitation

- To cover the optical path difference by adjusting surface
  - Useful in improving the quality
  - But failed to change the power
    - This set the basic limitation
      - Not recommended in tuning system parameter

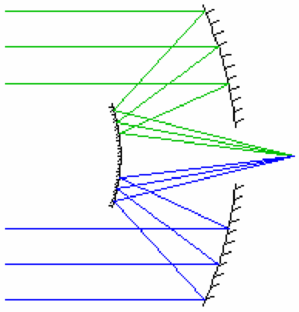


Optical path difference

Wavefront error representation

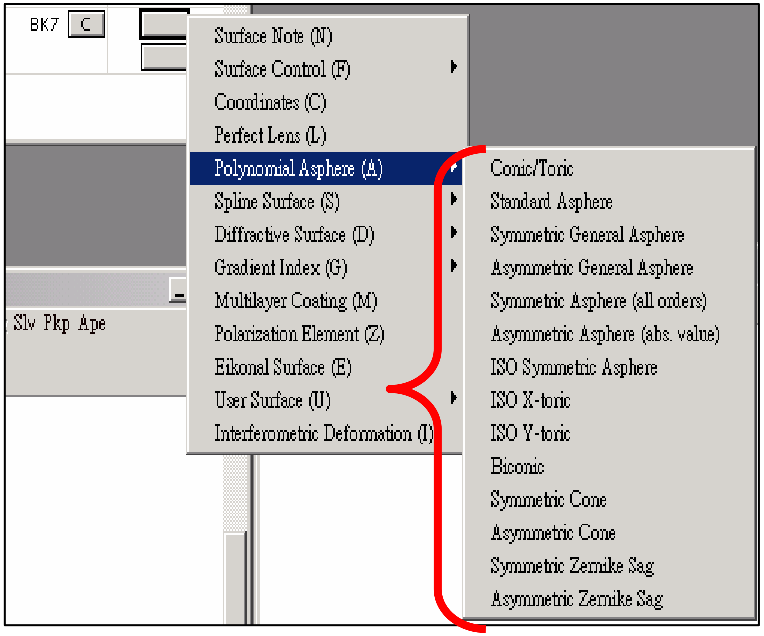


Cassegrain **Ritchey-Chretien** **Schmidt**



OSLO interface for aspheric

Because Aspheric can be very helpful, design interface is available



- Your designs somehow have to fit the machine of manufacturers
  - Polynomial setting is commonly used
    - Try to use fitting algorithm (e.g., in Mathematica) to fit the best form of polynomial, i.e., tune the coefficients of fitting polynomial to have closet approximation to your numerically evaluated best solution.
  - Spline/complicated surface may use “sagt” to evaluate the sag surface

When should we use aspheric

- Several factors could be crucial
  - – Mainly, “cost impact”

1. Which surfaces to make aspheric?
2. Where to use a conic section or, alternatively, a higher-order aspheric?
   - Conic section: paraboloids, hyperbolids, and ellipsoids

Once the basic system is set up on your computer, varying the appropriate conic constants is all it takes to reach a viable solution!!

Based on Fischer / Tadic-Galeb

How to decide which form of aspheric surface should be used?

- Think more about what we want
  - We hope to have a focus point such that its wavefront is a sphere
    - So, we can used a best-focus sphere to simulate this kind of perfect wavefront
    - The OPD is better to cover by varying the aspheric form
- You need to consider
  - The aspheric surface departures from the base spherical surface
  - The departures from what we call the "nearest sphere" or "best-fit sphere" to the aspheric surface

$$X = \underline{\frac{R_1 Y^2}{1+\sqrt{1-Y^2 R_1^2 (1+K)}}} \underbrace{+ AY^4 + BY^6 + CY^8 + DY^{10}}$$

- So, use these terms to correct the influence of OPD after a polynomial expansion for the first term
- You can use "Wavefront analysis" to assist your design!!!

Guidelines

1. Conic surfaces can be used for correcting third order spherical aberration and other low-order aberration.
2. If you have a nearly flat surface, then use an r^4 and higher order terms rather than a conic
   - negative or positive?
3. If you have at least a somewhat curved surface, then you can use the conic along with higher-order terms if required
4. It is generally best not to use both a conic and an r^4 surface, as they are mathematically quite similar.
5. Using aspherics beginning with the lower-order terms and working upward as required. If you can stay with conics, this make testing more manageable.
   - you should be able to asses the need for adding terms based on the character of the OPD plot.
6. It is very dangerous to use a large number of aspheric surfaces, especially with higher-order terms.
   - They will beat against each other.
7. If possible, optimize your design first using spherical surfaces, and then use the conic and/or aspheric coefficients in the final stage of optimization.

Based on Fischer / Tadic-Galeb

Working with aspheric surface

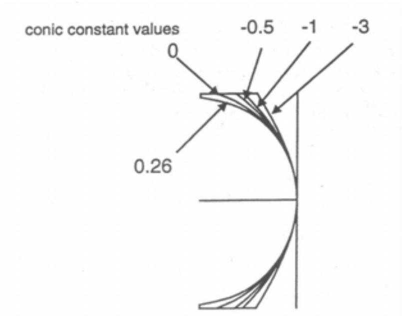
Approaches

- (1) Simplest form
  - With only conic constant
    - Try this one first
- (2) Fermat principle
  - Optical path difference
- (3) Wasermann-Wolf theory
- (4) Forced method with operand

To get useful initial design

Approach (1): conic surface

- In this case, higher-order aspheric terms are zero.



$$X = \frac{R_1 Y^2}{1+\sqrt{1-Y^2 R_1^2 (1+K)}} \cancel{+AY^4+BY^6+CY^8+DY^{10}}$$

R$_1$: Base curvature at the vertex

K: Conic coefficient

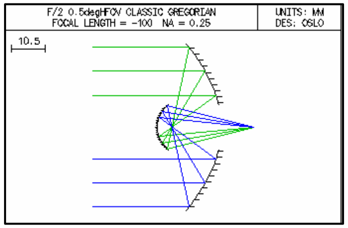
對於不同的K值所對應的曲線：

K = 0	圓（sphere）
K < -1	雙曲面（hyperboloid）
K = -1	拋物面（paraboloid）
-1 < K <0	橢圓面（ellipsoid）
K > 0	橫橢圓面（oblate ellipsoid）

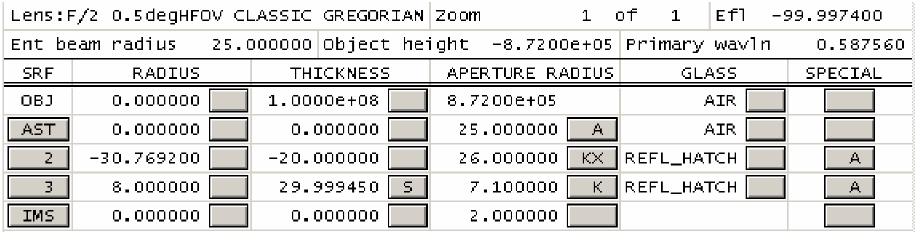
Based on Fischer / Tadic-Galeb

Reflector with conic constant

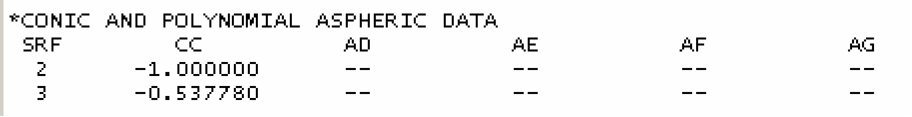
- Aspheric surfaces are widely used and often essential in reflective systems due to the small number of surfaces and typical large apertures.
  - A simple spherical reflecting telescope suffers from spherical aberration and coma
  - Using aspheric to correct
  - Classical solution: “parabolic” reflecting
    - (conic coefficient k=-1)
    - But, away from axis, coma appears (limits to a small field of view)



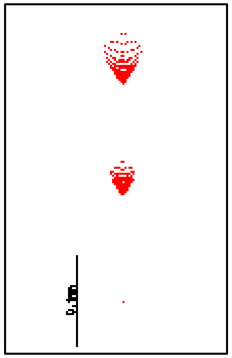
- **Two mirror Cassegrain telescope**
  - Paraboloidal primary mirror (K=-1)
  - Hyperboloidal secondary mirror (K<-1)
    - f1 is the location of image which formed by the primary mirror
    - f2 is the location of the image of the entire system
    - Limited by off-axis coma

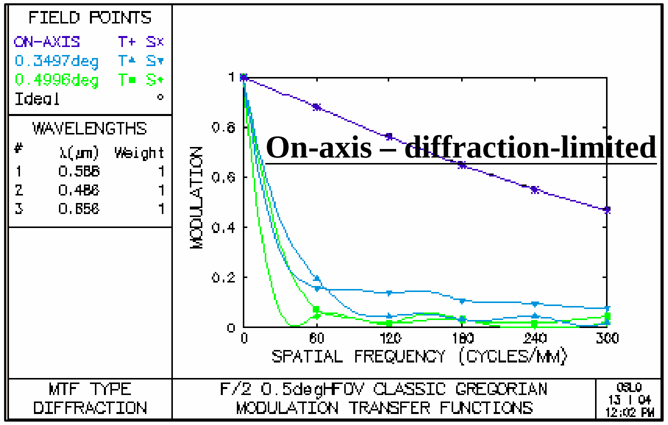


Lens:F/2 0.5degHFOV CLASSIC GREGORIAN		Zoom 1 of 1		Efl -99.997400	
Ent beam radius 25.000000		Object height -8.7200e+05		Primary wavln 0.587560	
SRF	RADIUS	THICKNESS	APERTURE RADIUS	GLASS	SPECIAL
OBJ	0.000000	1.0000e+08	8.7200e+05	AIR	
AST	0.000000	0.000000	25.000000 A	AIR	
2	-30.769200	-20.000000	26.000000 KX	REFL_HATCH	A
3	8.000000	29.999450 S	7.100000 K	REFL_HATCH	A
IMS	0.000000	0.000000	2.000000		



```
*CONIC AND POLYNOMIAL ASPHERIC DATA
 SRF        CC            AD          AE          AF          AG
  2     -1.000000         --          --          --          --
  3     -0.537780         --          --          --          --
```



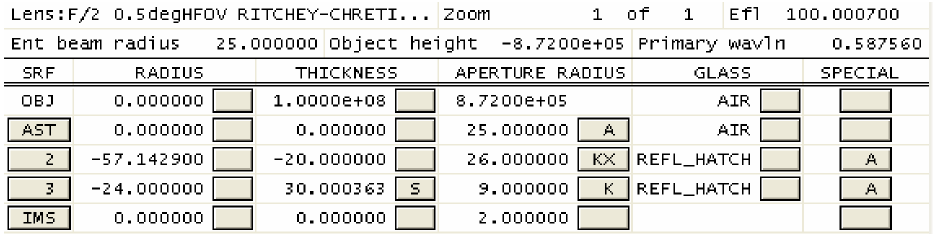


On-axis – diffraction-limited

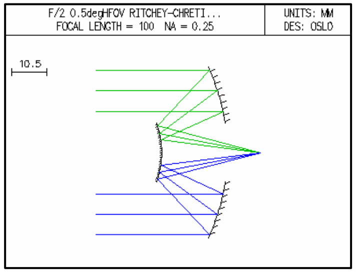
Telescope examples

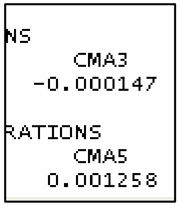
Ritchey-Chretien Cassegrain telescope

- Hyperboloidal primary mirror (K<-1)
- Hyperboloidal secondary mirror (K<-1)
  - Coma-free
  - Limited by astigmatism



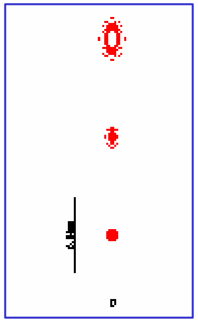
Lens:F/2 0.5degHFOV RITCHEY-CHRETI...		Zoom		1 of 1		Efl 100.000700			
Ent beam radius 25.000000		Object height -8.7200e+05				Primary wavln 0.587560			
SRF	RADIUS		THICKNESS		APERTURE RADIUS		GLASS		SPECIAL
OBJ	0.000000		1.0000e+08		8.7200e+05		AIR		
AST	0.000000		0.000000		25.000000	A	AIR		
2	-57.142900		-20.000000		26.000000	KX	REFL_HATCH		A
3	-24.000000		30.000363	S	9.000000	K	REFL_HATCH		A
IMS	0.000000		0.000000		2.000000				





```
NS
      CMA3
  -0.000147

RATIONS
      CMA5
   0.001258
```



```
*CONIC AND POLYNOMIAL ASPHERIC DATA
 SRF         CC            AD          AE          AF          AG
  2      -1.070710         --          --          --          --
  3      -3.886840         --          --          --          --
```

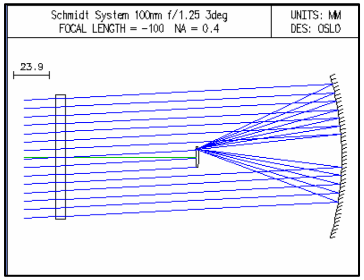
Schmidt telescope

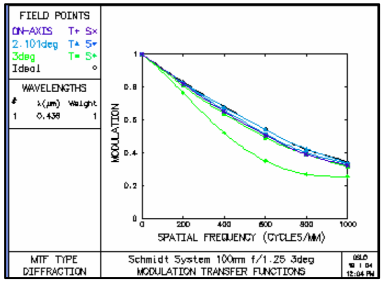
Spherical mirror

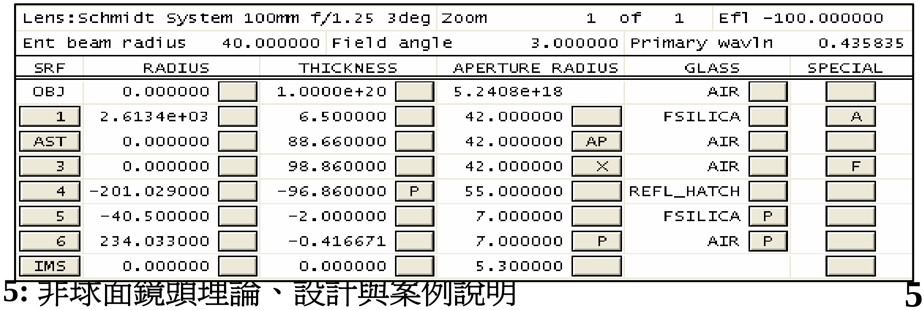
Aspheric corrector plate at the center of curvature of the mirror

Using weak positive power to further correct the chromatic aberration

-- Can be optimized to diffraction-limited performance by using GENII optimization





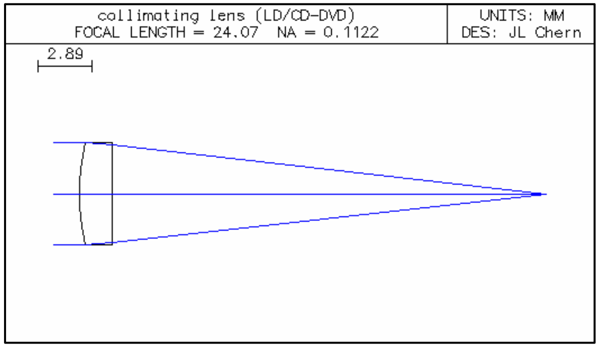


Lens:Schmidt System 100mm f/1.25 3deg		Zoom		1 of 1		Efl -100.000000			
Ent beam radius 40.000000		Field angle 3.000000				Primary wavln 0.435835			
SRF	RADIUS		THICKNESS		APERTURE RADIUS		GLASS		SPECIAL
OBJ	0.000000		1.0000e+20		5.2408e+18		AIR		
1	2.6134e+03		6.500000		42.000000		FSILICA		A
AST	0.000000		88.660000		42.000000	AP	AIR		
3	0.000000		98.860000		42.000000	X	AIR		F
4	-201.029000		-96.860000	P	55.000000		REFL_HATCH		
5	-40.500000		-2.000000		7.000000		FSILICA	P	
6	234.033000		-0.416671		7.000000	P	AIR	P	
IMS	0.000000		0.000000		5.300000				

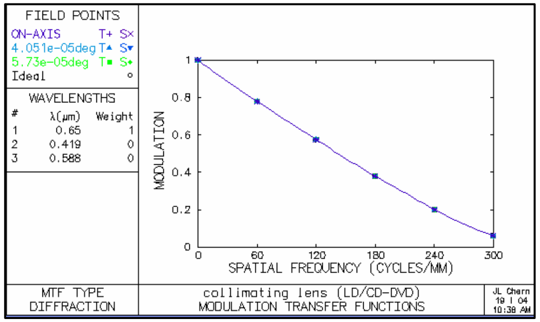
```
*CONIC AND POLYNOMIAL ASPHERIC DATA
 SRF        CC           AD           AE           AF           AG
  1     -1.000000 -5.8678e-08 -4.2209e-12  1.2779e-15 -3.0697e-19
```

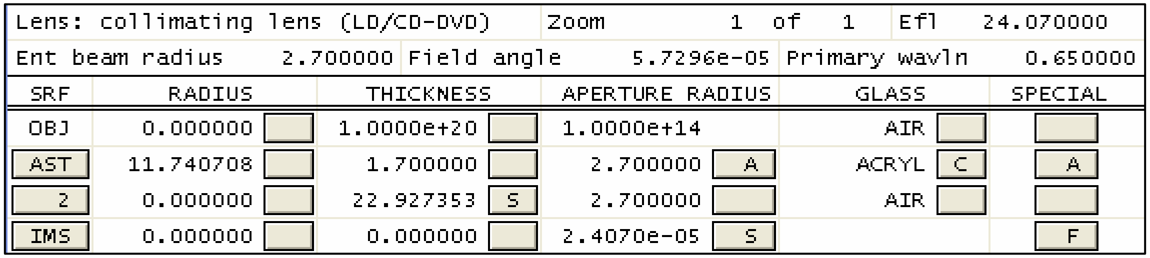
Example 2: LD’s collimating lens

- Application to CD/DVD
  - Used for LD collimating
    - Plastic (acryl)
  - Only one conic constant is enough



Diffraction-limited performance





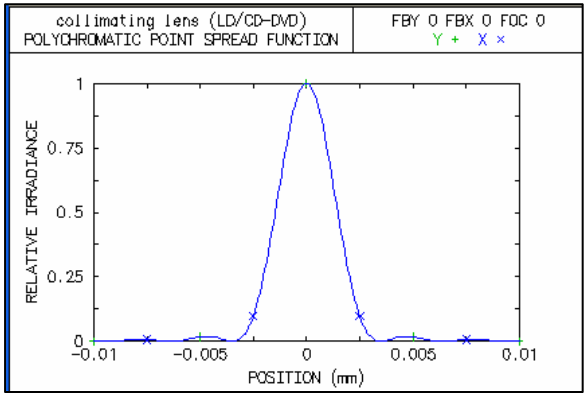
Lens: collimating lens (LD/CD-DVD) Zoom 1 of 1 Efl 24.070000

Ent beam radius 2.700000 Field angle 5.7296e-05 Primary wavln 0.650000

SRF	RADIUS		THICKNESS		APERTURE RADIUS		GLASS		SPECIAL
OBJ	0.000000		1.0000e+20		1.0000e+14		AIR		
AST	11.740708		1.700000		2.700000	A	ACRYL	C	A
2	0.000000		22.927353	S	2.700000		AIR		
IMS	0.000000		0.000000		2.4070e-05	S			F

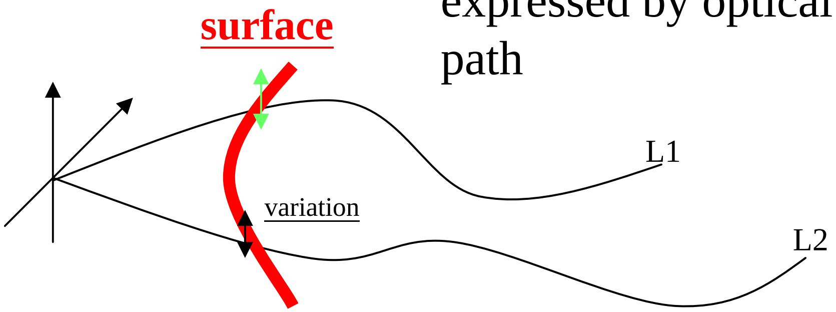
*CONIC AND POLYNOMIAL ASPHERIC DATA

SRF	CC	AD	AE	AF	AG
1	-0.577354	--	--	--	--



Approach (2): Design with Fermat Principle

- A good starting
  - Highly recommended
    - Physical picture is clear
    - Can be extended to multiple configuration design
    - How to apply?
      - Start a drawing with your desired property which can be expressed by optical path



- What is Fermat principle?
  - Light travels from one point to another along a path for which the travel time is stationary with respect to small variations in the shapes of the path

$$t(P_1,P_2)=\int_{P_1}^{P_2}\frac{ds}{c/n}=\frac{1}{c}\int_{P_1}^{P_2}\frac{ds}{n}$$

Optical path: L

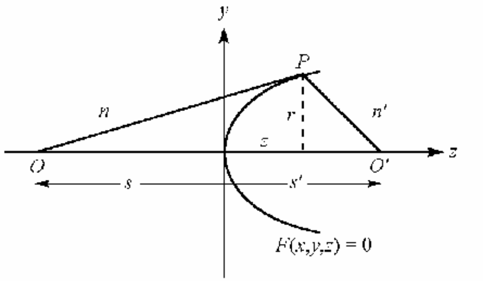
$$L=\int_{P_1}^{P_2}\frac{ds}{n}$$

$$\frac{\delta L}{\delta s}=\delta\left(\int_{P_1}^{P_2}\frac{ds}{n}\right)/\,\delta s=0$$

Example 1: Cartesian oval

- Consider the refracting surface that forms a perfect, on-axis image of a single on-axis object point. This surface is known as a *Cartesian oval*. The geometry is illustrated in the figure above.
- The surface defined by $F(x, y, z) = 0$ separates media of refractive indices n and n' The object point O is located at $z = s$ and the image point O' is formed at $z = s'$

Optical path:



$$OPL_{axis} = -ns + n's'$$

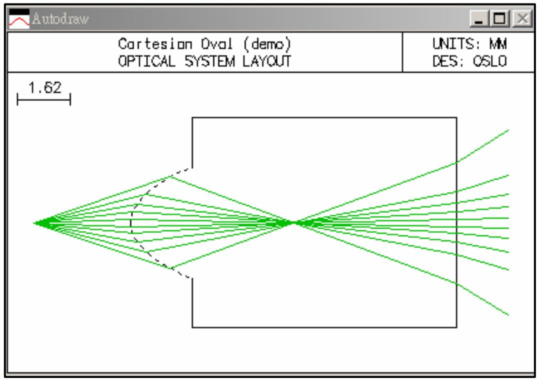
(along z axis)

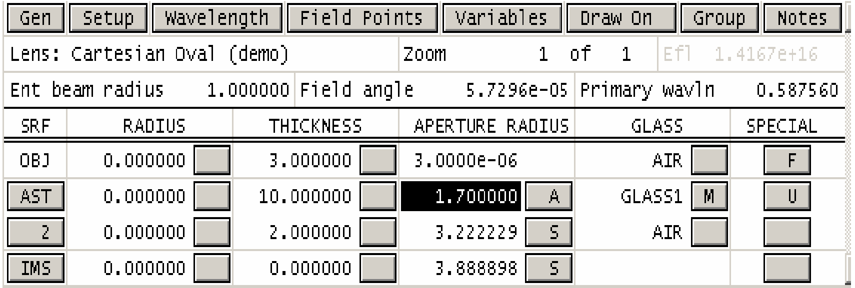
$$\begin{aligned} OPL_p &= nOP + n'PO' \\ &= n\sqrt{(s-z)^2 + r^2} + n'\sqrt{(s'-z)^2 + r^2} \end{aligned}$$

(along p point)

Perfect imaging:

$$OPL_{axis} - OPL_p = 0$$

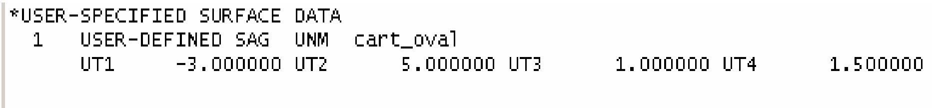




Lens: Cartesian Oval (demo)	Zoom 1 of 1	Efl 1.4167e+16

Ent beam radius 1.000000	Field angle 5.7296e-05	Primary wavln 0.587560

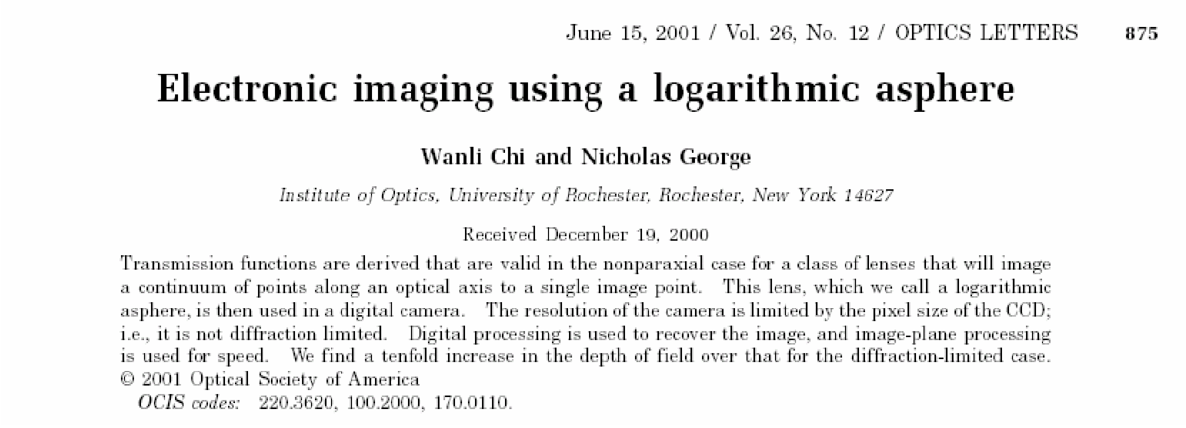
SRF	RADIUS	THICKNESS	APERTURE RADIUS	GLASS	SPECIAL
OBJ	0.000000	3.000000	3.0000e-06	AIR	F
AST	0.000000	10.000000	1.700000 A	GLASS1 M	U
2	0.000000	2.000000	3.222229 S	AIR	
IMS	0.000000	0.000000	3.888898 S		



```
*USER-SPECIFIED SURFACE DATA
  1    USER-DEFINED SAG   UNM   cart_oval
       UT1      -3.000000 UT2        5.000000 UT3        1.000000 UT4        1.500000
```

Example 2: logarithmic aspheric lens

- A lens with wide depth of field
  - You can reverse this one to have wide field of focus



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Electronic imaging using a logarithmic asphere

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Transmission functions are derived that are valid in the nonparaxial case for a class of lenses that will image a continuum of points along an optical axis to a single image point. This lens, which we call a logarithmic asphere, is then used in a digital camera. The resolution of the camera is limited by the pixel size of the CCD; i.e., it is not diffraction limited. Digital processing is used to recover the image, and image-plane processing is used for speed. We find a tenfold increase in the depth of field over that for the diffraction-limited case.

OCIS codes: 220.3620, 100.2000, 170.0110.

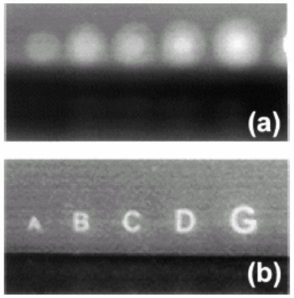


Fig. 4. Segments of images obtained with (a) a Nikon conventional camera and (b) a logarithmic asphere camera.

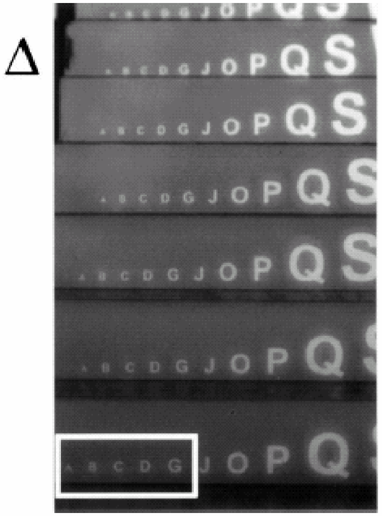


Fig. 3. Recovered image of a step chart from a 3-D object.

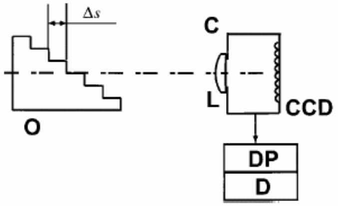


Fig. 1. Imaging setup: O, object; C, digital camera; DP, digital processor; D, display. See text for other definitions.

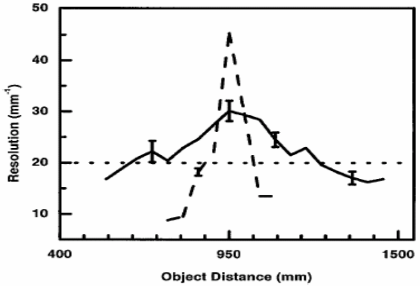


Fig. 5. Resolution versus object distance: dashed curve, Nikon camera; solid curve, logarithmic asphere; dotted line at 20 mm^{-1}.

Underlying approach: Fermat principle

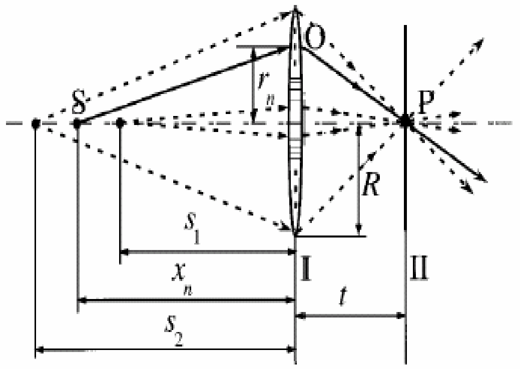


Fig. 2. Notation for lens theory. See text for definitions.

- Optical length
- Transmission function
  - T(r)=exp[-iϕ(r)]
- Fermat's principle

$$\phi(r) = -\left\{\frac{2\pi}{\lambda_0}\left[(r^2+t^2)^{1/2}-t\right]+\frac{\pi}{\lambda_0}\frac{R^2}{s_2-s_1}\right.$$
$$\times\left[\ln\left(2\frac{s_2-s_1}{R^2}\left\{\left[r^2+\left(s_1+\frac{s_2-s_1}{R^2}r^2\right)^2\right]^{1/2}\right.\right.\right.$$
$$\left.\left.\left.+\left(s_1+\frac{s_2-s_1}{R^2}r^2\right)\right\}+1\right)-\ln\left(4\frac{s_2-s_1}{R^2}s_1+1\right)\right]\right\}. \tag{7}$$

$$L = \sqrt{r^2+x^2} + \phi(r)\lambda_0/(2\pi) + \sqrt{r^2+t^2}\,,$$

Total optical length for ray through SOP

Fermat principle

$$\boxed{\frac{\partial L}{\partial r} = 0}$$

$$\boxed{\begin{aligned}\phi(r) = -\frac{2\pi}{\lambda_0}\{&[0.02r^2 - 8\times10^{-6}r^4\\ &+6.4\times10^{-9}r^6 - 6.4\times10^{-12}r^8\\ &+7\times10^{-15}r^{10}] + [7.435\times10^{-4}r^2 +\\ &-7.563\times10^{-5}r^4 + 5.1431\times10^{-6}r^6 +\\ &-1.803\times10^{-7}r^8 + 2.4614\times10^{-9}r^{10}]\}.\end{aligned}}$$

Approach (3): Wassermann-Wolf theory

- **The Wassermann-Wolf solve (WW) is a technique for designing two adjacent aspheric surfaces such that the optical system containing these two surfaces is aplanatic**
  - i.e., all orders of spherical aberration are corrected and the Abbe sine condition is satisfied for all points in the aperture.

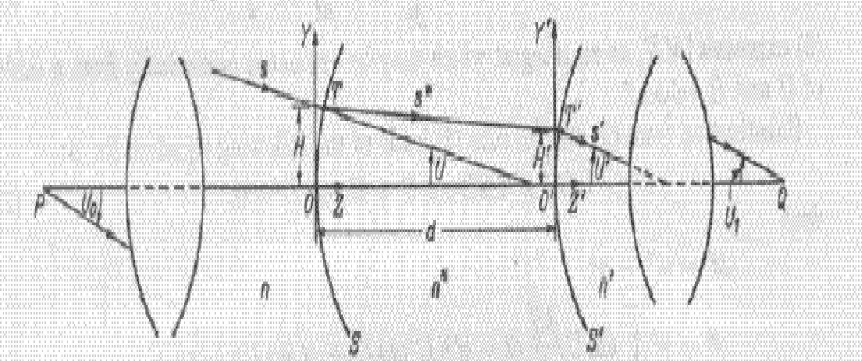


Fig. 4.42. Design of two aspheric surfaces to attain aplanatism.

- Wassermann-Wolf theory reduced the problem of aplanatism to solve a coupled differential equations

$$\frac{dZ}{dt} = \left(\frac{nD\cos U - n^*D_x}{nD\sin U - n^*D_y} + \tan U\right)^{-1}\left(\frac{dH}{dt} - Z\frac{d}{dt}(\tan U)\right).$$

$$\frac{dZ'}{dt'} = \left(\frac{n'D\cos U' - n^*D_x}{n'D\sin U' - n^*D_y} + \tan U'\right)^{-1}\left(\frac{dH'}{dt'} - Z'\frac{d}{dt'}(\tan U')\right).$$

dZ/dt=f(Z,Z’,t)
dZ/dt=g(Z,Z’,t)
Boundary conditions: Z=Z’=0 when t=t’=0

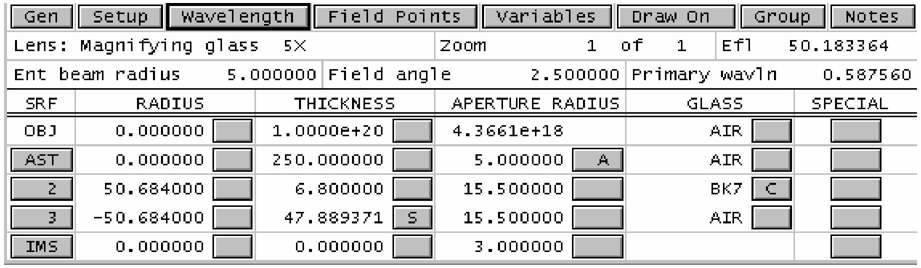
- **G. D. Wassermann and E. Wolf, Proc. Phys. Soc. B, 62 (1949), 2.**
- **M. Born and E. Wolf, “Principles of Optics,” 7th. ed. pp. 214-217.**

Assumptions

- The system is rotationally symmetric.
- The two WW surfaces are adjacent, i.e., there are no intervening optical surfaces between the two WW aspheric surfaces.
- Obviously, there can be only a single pair of WW solve surfaces in an optical system.
- The media before the first WW surface, between the two WW surfaces, and after the second WW surface are all homogeneous.
- The construction parameters of the optics before and after the WW surfaces are known. The practical implication of this is that no curvature or thickness solves are allowed after the WW surfaces.
- The nature of the WW differential equations is such that if a physical solution exists for the equation, it is unique.
- If the solve fails, it is usually because too few solution points have been specified.
  - Because the equations are solved numerically, the solution is found at a discrete number of points. Between the points, the surfaces are found by interpolation (a cubic spline). This interpolant will not, in general, match the desired exact surface profile (except at the spline zone heights), so the ray-intercept curves (for example) will typically exhibit a zigzag pattern around the "true" value.
  - Increasing the number of solution points will, in general, both decrease the magnitude and increase the frequency of the zigzag pattern.

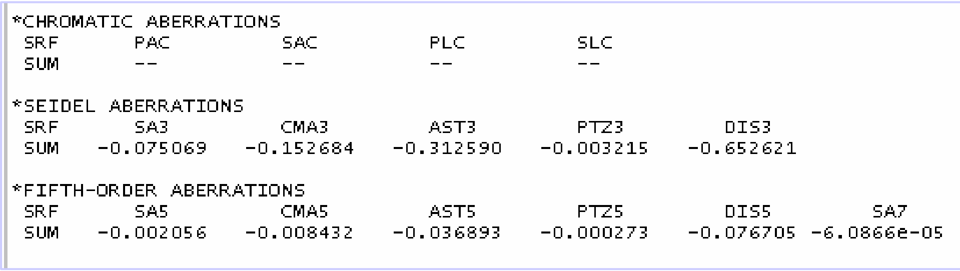
Example: 5X magnifier

Common 5X magnifier



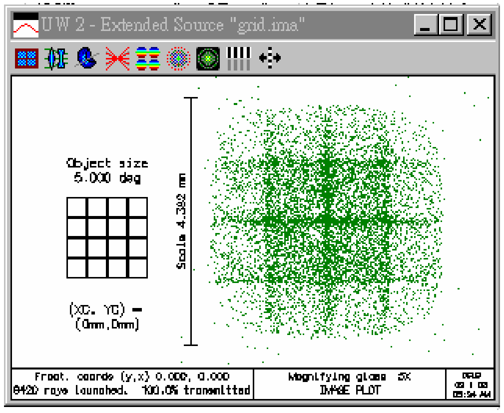
Lens: Magnifying glass 5X | Zoom 1 of 1 | Efl 50.183364
Ent beam radius 5.000000 | Field angle 2.500000 | Primary wavln 0.587560

SRF	RADIUS	THICKNESS	APERTURE RADIUS	GLASS	SPECIAL
OBJ	0.000000	1.0000e+20	4.3661e+18	AIR	
AST	0.000000	250.000000	5.000000 A	AIR	
2	50.684000	6.800000	15.500000	BK7 C	
3	-50.684000	47.889371 S	15.500000	AIR	
IMS	0.000000	0.000000	3.000000		

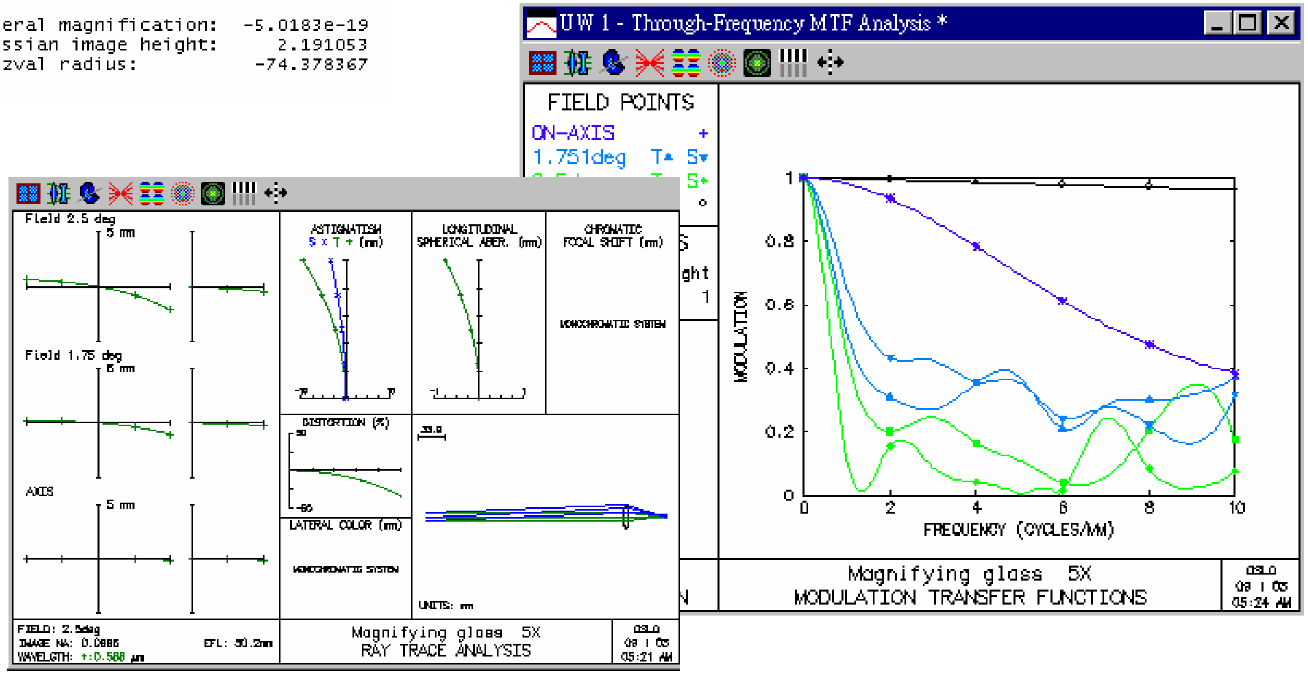


```
*CHROMATIC ABERRATIONS
 SRF       PAC          SAC          PLC          SLC
 SUM       --           --           --           --

*SEIDEL ABERRATIONS
 SRF       SA3          CMA3         AST3         PTZ3         DIS3
 SUM    -0.075069    -0.152684    -0.312590    -0.003215    -0.652621

*FIFTH-ORDER ABERRATIONS
 SRF       SA5          CMA5         AST5         PTZ5         DIS5         SA7
 SUM    -0.002056    -0.008432    -0.036893    -0.000273    -0.076705  -6.0866e-05
```

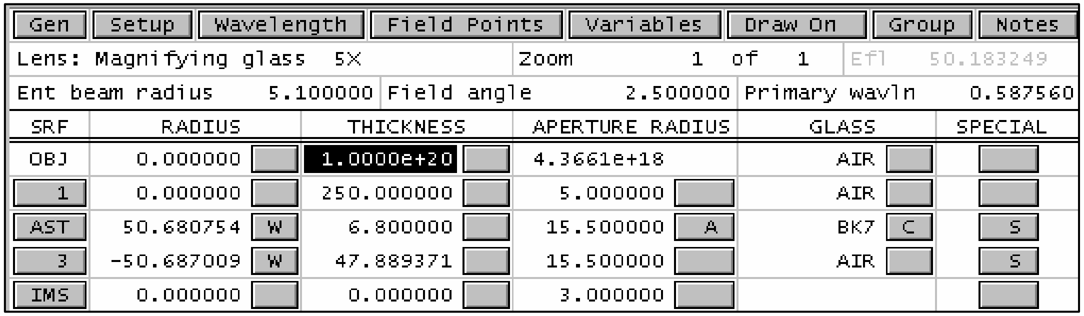
```
*PARAXIAL CONSTANTS
   Effective focal length:     50.183364    Lateral magnification:  -5.0183e-19
   Numerical aperture:          0.099635    Gaussian image height:     2.191053
   Working F-number:            5.018336    Petzval radius:          -74.378367
   Lagrange invariant:         -0.218305
```



Fract. coords (y,x) 0.000, 0.000
8420 rays launched. 100.0% transmitted



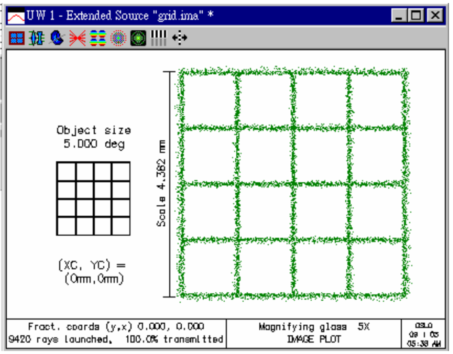
Improved with WW solver



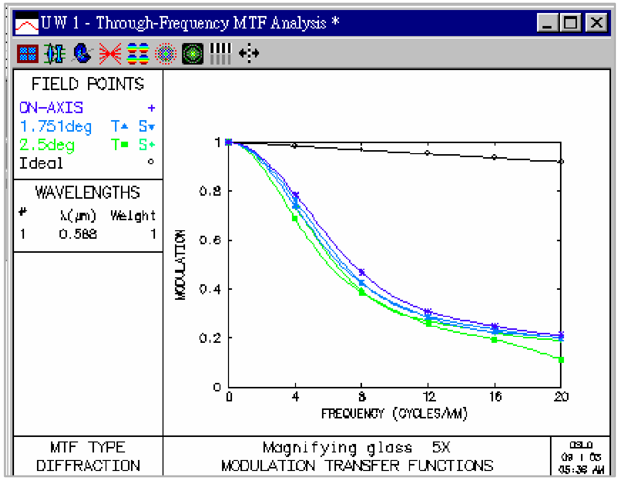
Lens: Magnifying glass 5X | Zoom 1 of 1 | Efl 50.183249

Ent beam radius 5.100000 | Field angle 2.500000 | Primary wavln 0.587560

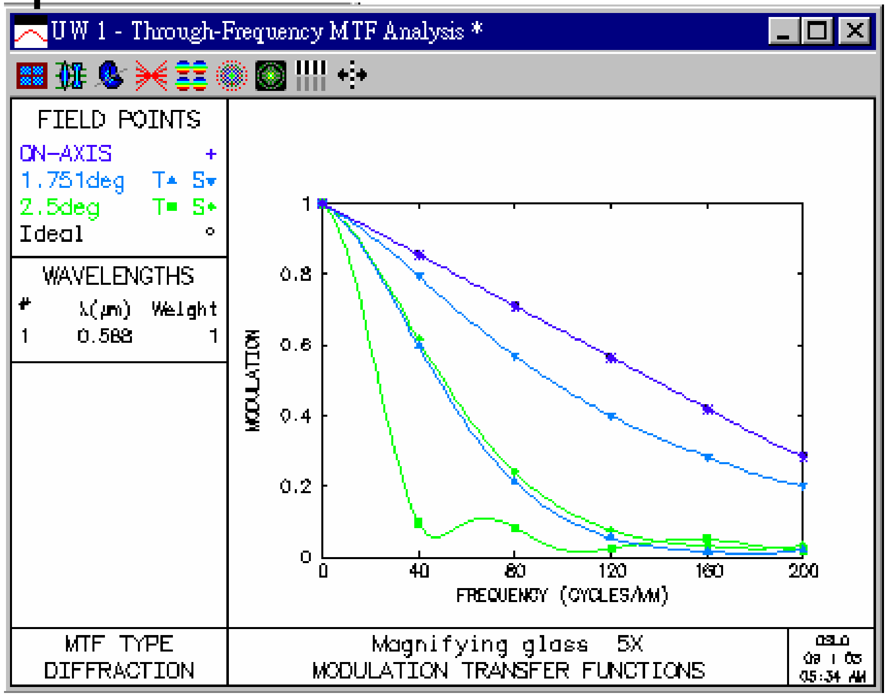
SRF	RADIUS		THICKNESS		APERTURE RADIUS		GLASS		SPECIAL
OBJ	0.000000		1.0000e+20		4.3661e+18		AIR		
1	0.000000		250.000000		5.000000		AIR		
AST	50.680754	W	6.800000		15.500000	A	BK7	C	S
3	-50.687009	W	47.889371		15.500000		AIR		S
IMS	0.000000		0.000000		3.000000				



8 spline



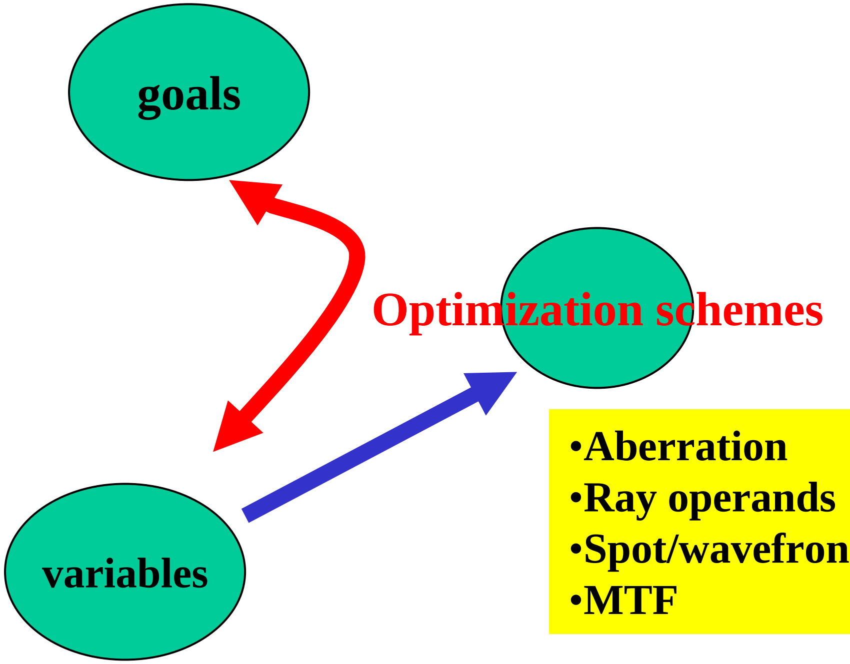
32 spline



- **With better spline surface approximation, here from 8 to 32, MTF performance is approaching to diffraction limit**
  - **This shows the power of WW theory**

Approach (4) Design with operands

- A most common approach (widely used)
  - But may fail because
    - the initial design is not good
      - Wrong range of aspheric coefficient
    - Mis-used Aspheric coefficients
- It sill depends on the schemes of optimization



goals

Optimization schemes

variables

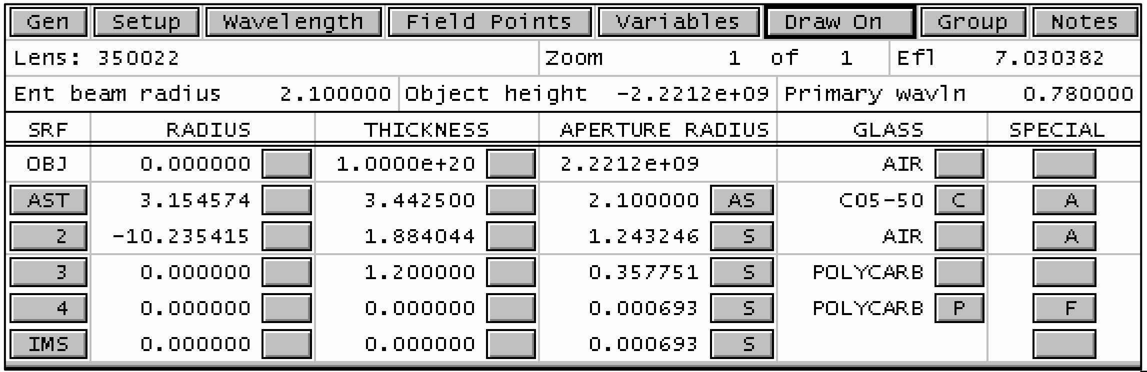
- **Aberration**
- **Ray operands**
- **Spot/wavefront**
- **MTF**

What kinds of variables?
What are the corresponding ranges?

You may need to create your macro

Example 2: pickup lens

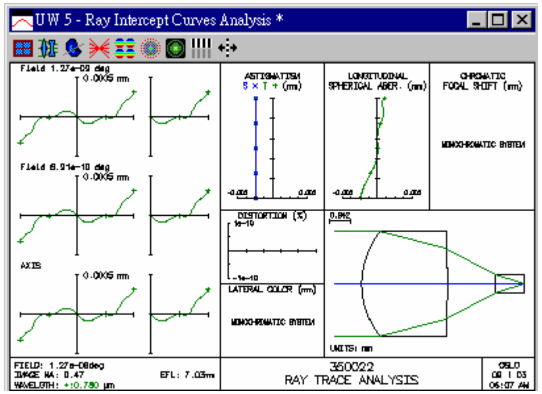
Optimization tool:
Using OSLO's optimization of spot size and wavefront error



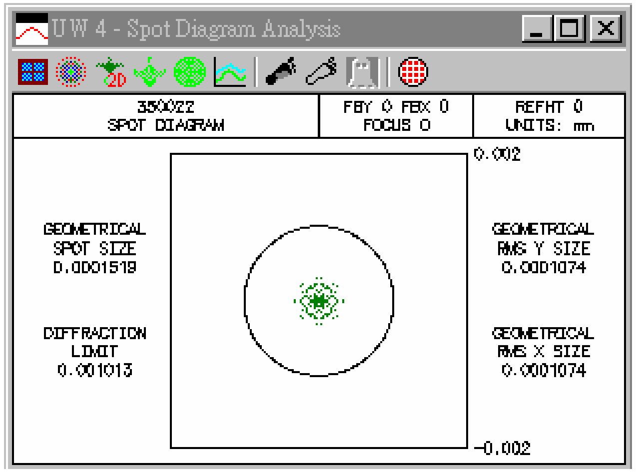
Lens: 350022 | Zoom 1 of 1 | Efl 7.030382

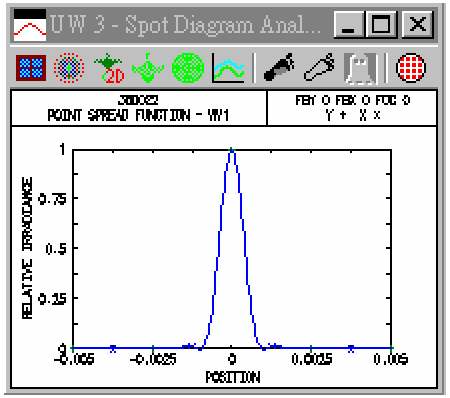
Ent beam radius 2.100000 | Object height -2.2212e+09 | Primary wavln 0.780000

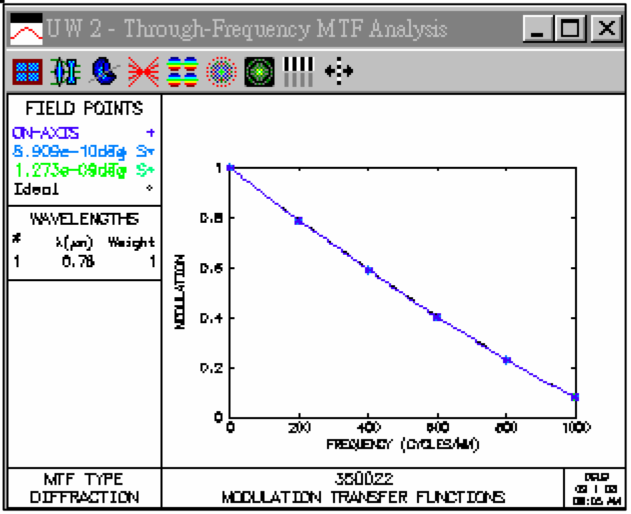
SRF	RADIUS	THICKNESS	APERTURE RADIUS		GLASS		SPECIAL
OBJ	0.000000	1.0000e+20	2.2212e+09		AIR		
AST	3.154574	3.442500	2.100000	AS	C05-50	C	A
2	-10.235415	1.884044	1.243246	S	AIR		A
3	0.000000	1.200000	0.357751	S	POLYCARB		
4	0.000000	0.000000	0.000693	S	POLYCARB	P	F
IMS	0.000000	0.000000	0.000693	S			



Aspheric surface



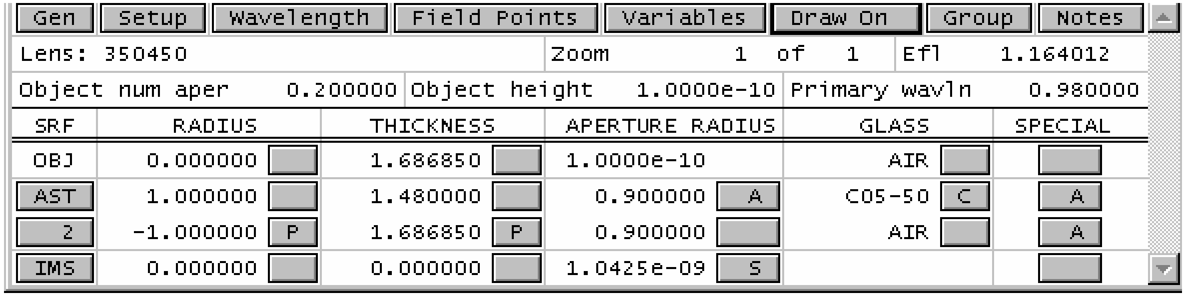




Commercial product

Example 3: focusing lens

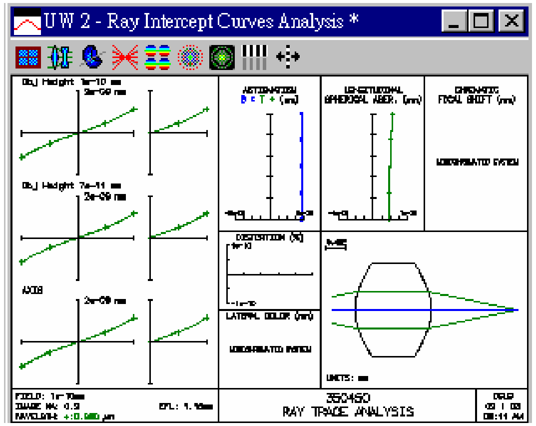
Optimization tool:
Using OSLO's optimization of spot size and wavefront error

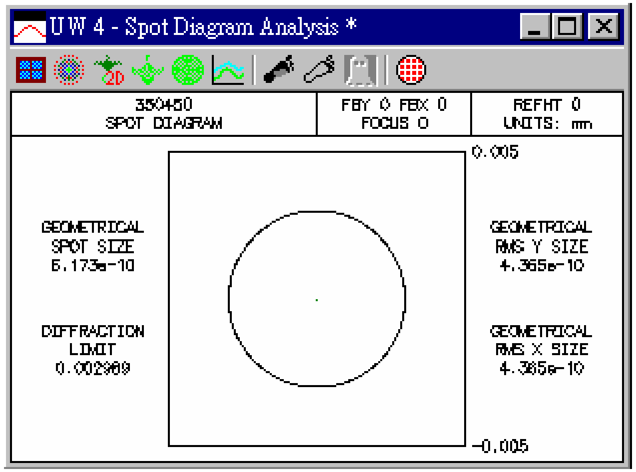


Lens: 350450 Zoom 1 of 1 Efl 1.164012

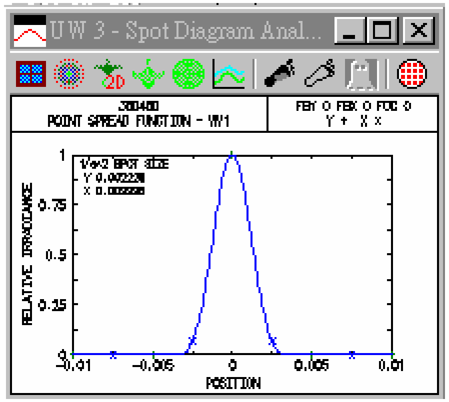
Object num aper 0.200000 Object height 1.0000e-10 Primary wavln 0.980000

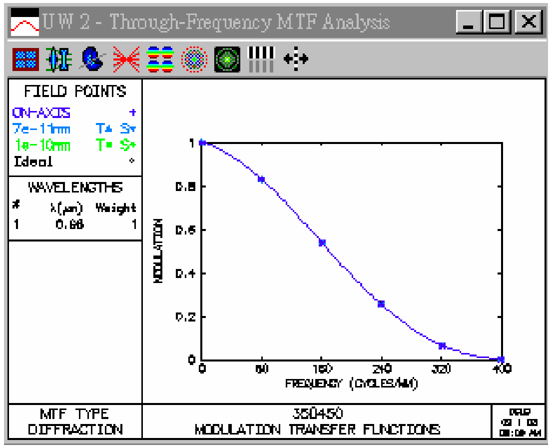
SRF	RADIUS		THICKNESS		APERTURE RADIUS		GLASS		SPECIAL
OBJ	0.000000		1.686850		1.0000e-10		AIR		
AST	1.000000		1.480000		0.900000	A	C05-50	C	A
2	-1.000000	P	1.686850	P	0.900000		AIR		A
IMS	0.000000		0.000000		1.0425e-09	S			





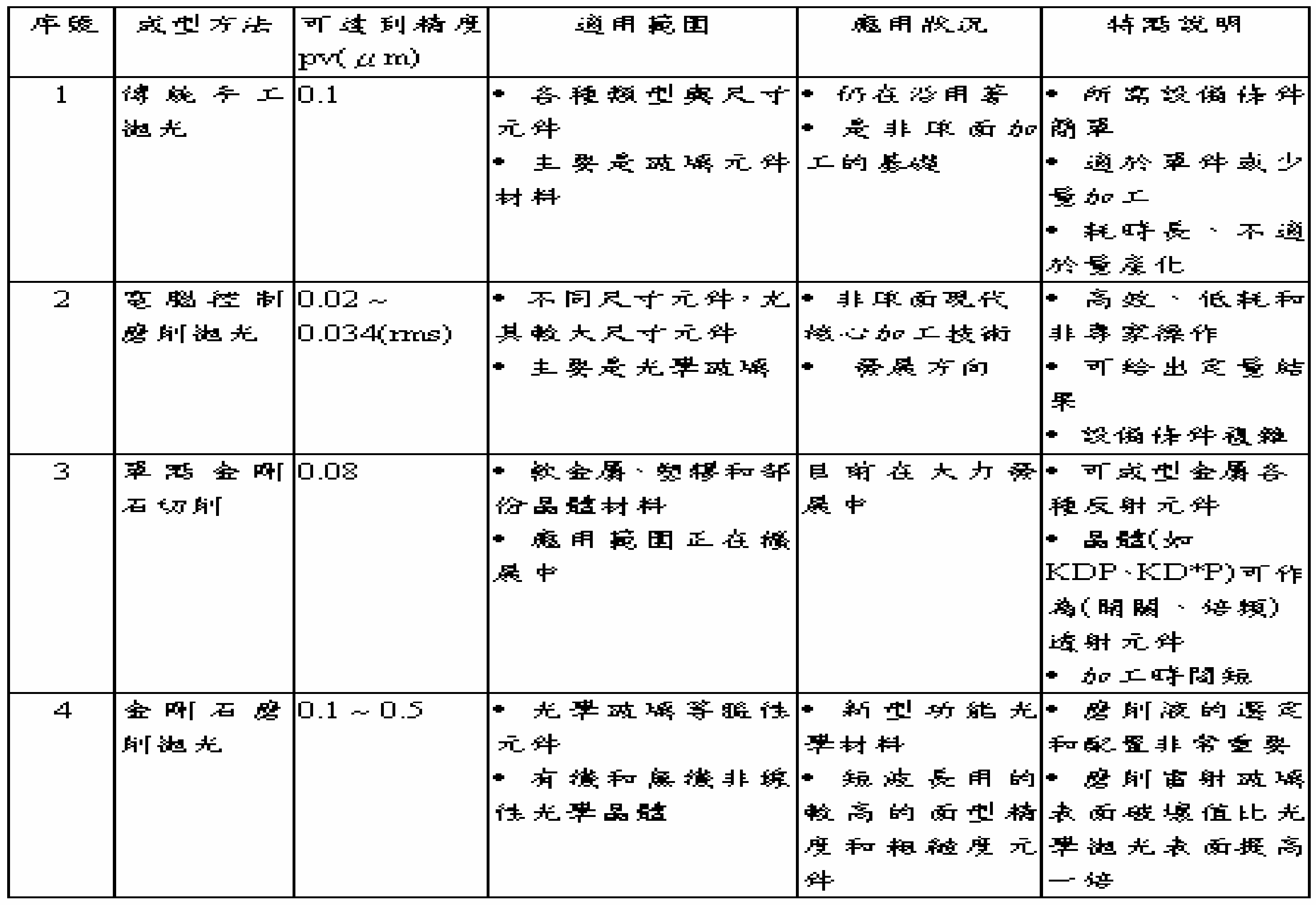
Aspheric surface





Commercial product

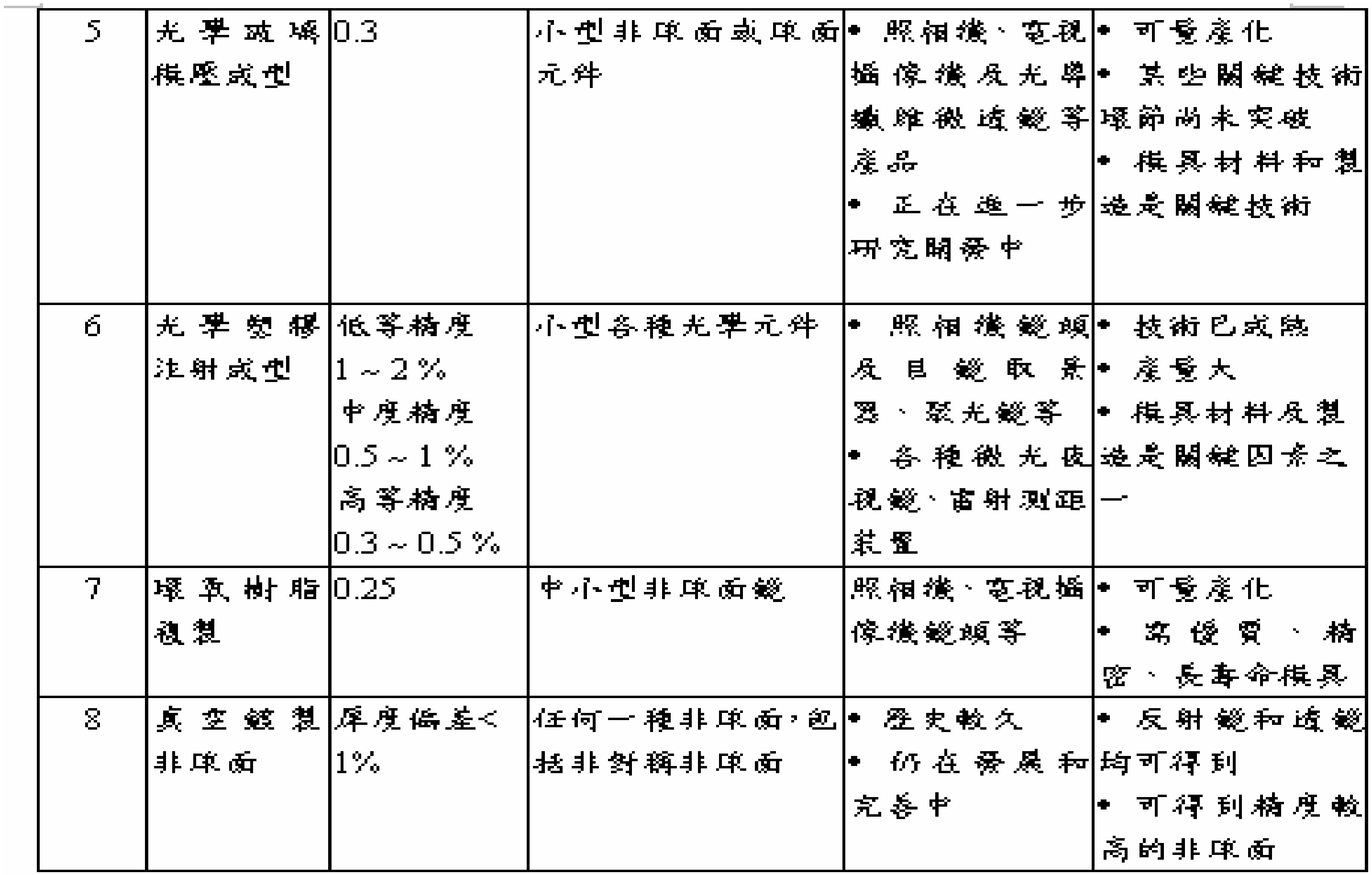
How to make aspheric



序號	成型方法	可達到精度 pv(μm)	適用範圍	應用狀況	特點說明
1	傳統手工拋光	0.1	• 各種類型與尺寸元件 • 主要是玻璃元件材料	• 仍在沿用著 • 是非球面加工的基礎	• 所需設備條件簡單 • 適於單件或少量加工 • 耗時長、不適於量產化
2	電腦控制磨削拋光	0.02～0.034(rms)	• 不同尺寸元件，尤其較大尺寸元件 • 主要是光學玻璃	• 非球面現代核心加工技術 • 發展方向	• 高效、低耗和非專家操作 • 可給出定量結果 • 設備條件複雜
3	單點金剛石切削	0.08	• 軟金屬、塑膠和部份晶體材料 • 應用範圍正在擴展中	目前在大力發展中	• 可成型金屬各種反射元件 • 晶體(如KDP、KD*P)可作為(開關、倍頻)透射元件 • 加工時間短
4	金剛石磨削拋光	0.1～0.5	• 光學玻璃等脆性元件 • 有機和無機非線性光學晶體	• 新型功能光學材料 • 短波長用的較高的面型精度和粗糙度元件	• 磨削液的選定和配置非常重要 • 磨削雷射玻璃表面破壞值比光學拋光表面提高一倍

From “徐德衍，光學非球面檢測技術，科儀新知，22(117)，p.31(2000)”
網站 http://home.kimo.com.tw/shpao5824/optic_test.htm

Cont’d



5	光學玻璃模壓成型	0.3	小型非球面或球面元件	• 照相機、電視攝像機及光學纖維微透鏡等產品 • 正在進一步研究開發中	• 可量產化 • 某些關鍵技術環節尚未突破 • 模具材料和製造是關鍵技術
6	光學塑膠注射成型	低等精度 1～2％ 中度精度 0.5～1％ 高等精度 0.3～0.5％	小型各種光學元件	• 照相機鏡頭及目鏡取景器、聚光鏡等 • 各種微光夜視鏡、雷射測距裝置	• 技術已成熟 • 產量大 • 模具材料及製造是關鍵因素之一
7	環氧樹脂複製	0.25	中小型非球面鏡	照相機、電視攝像機鏡頭等	• 可量產化 • 高優質、精密、長壽命模具
8	真空鍍製非球面	厚度偏差<1%	任何一種非球面，包括非對稱非球面	• 歷史較久 • 仍在發展和完善中	• 反射鏡和透鏡均可得到 • 可得到精度較高的非球面

Specification on aspherics

1. The surface to be aspheric is labeled aspheric on the component drawing
2. You should include an equation of the surface shape along with the aspheric coefficients
   - A small sketch indicating the nomenclature and sign convention is recommended
3. A table listing the sag as a function of the radial distance from the surface vertex normal to the optical axis, r, is imperative
4. You should list how close the actual surface must come to the ideal design prescription.
   - the form of this can be “surface to match nominal surface to within four visible fringe (or 0.001 mm~1 um) over clear aperture
5. You may need to call out higher-frequency surface irregularity and/or surface finish.
   - the higher-frequency irregularities can be called out by indicating the maximum slope departure from nominal over the surface.
   - Surface finish is normally called by indicating the rms surface finish, in nanometer.
6. You should, if possible, indicate the form of testing to be used.

Based on Fischer / Tadic-Galeb

How to test: - Fizeau interfence

- 菲索干涉(Fizeau Interference)
- 補償法(null test)
- 圓形擋板(circular stop)

(There are many different methods; only three of them are outlined here.)

- 目前用來檢測鏡面曲度的最方便、可靠的方法就是光學干涉。首先我們將介紹菲索型干涉儀 (Fizeau Interferometer)，它一般可用於二次曲面的檢測。此種儀器由於採用平行光路，所以設備的精密度與價格十分昂貴。可靠的整套設備目前約需NT100 ~ 200萬。目前在國內比較高級的非球面鏡片研製大都採取這種檢驗方式。
  - 徐德衍，光學儀器，8(3)，p.15(1986)
- 這種檢驗方法有幾點值得注意的：
  - (1)檢驗波長為He-Ne雷射，若為其他波長，則有一個波長轉換問題。
  - (2)較適用於旋轉對稱非球面系統。
  - (3)由於干涉儀的氣浮工作台尺寸的限制，被檢測的非球面焦距有一定的限制。例如ZYGO MARK III干涉儀可測得非球面透鏡的焦距約700 mm左右。

Null test and circular stop

- 上述菲索干涉(Fizeau Interference)的方法，是利用無像差共軛點的二次曲面，大都需要一塊高質量滿足口徑要求的標準球面(或平面)反射鏡，夠成自準直光線。為簡化檢驗方式和所需的條件，常常不在無像差共軛點位置上的物點發出球面波，經被檢驗的非球面反射後波面就要發生變形。為此專門設計一種帶有像差的光學系統，稱其為補償鏡(null lens)。
- 將補償鏡放置在光路的確定位置上，使它所產生的像差和被測非球面產生的像差相補償，使得經過補償鏡和被測非球面後成為球面波光束，這樣一來我們就可以利用一般檢驗球面波的方法進行檢測。此種方法即所謂的補償法或稱零位法(null test)。因為補償鏡產生的波前是用來做為檢驗非球面的標準，所以應有嚴格的要求。
  - (1)應嚴格控制像差值，使其與被測非球面產生的特定值相補償。
  - (2)補償鏡的材料和製造應有嚴格要求。
  - (3)補償鏡儘量結構簡單，製造容易，裝配誤差盡可能小。
  - (4)補償鏡的通光口徑盡可能小些。
- 補償法有很多種，因此補償鏡的型式也不盡相同，例如在Rufino Diaz-Uribe和Manuel Campos-Garcia的論文「Null-screen testing of fast convex aspheric surfaces」中，所用的補償鏡則為圓柱面鏡，根據數值模擬分析精確度可達到5μm。(see Rufino Diaz-Uribe and Manuel Campos-Garcia, "Null-screen testing of fast convex aspheric surfaces," Appl. Opt. vol39, p.2670 (2000)).
- 許多非球面的檢測方法都十分的複雜，有一個利用圓形擋板(circular stop)來檢測圓形對稱非球面簡單的方法，此種方法的精確度可達到10 nm
  - 詳細內容請參見Andrianto Handojo and Hans J. Frankena, "Testing aspheric surfaces: simple method with a circular stop," Appl. Opt.vol37, p.5969 (1998).
- 他們考慮一個光源位置在凹球面的曲率中心，這時候由面所反射回來的光，將通過曲率中心。但是如果我們所考慮的是一個非球面，此時光就不會反射回到曲率中心，入射光與反射光間將形成一個角度。當他們將一個很小的不透明擋板放在曲率中心上，此時來自於中心軸的反射光線將被擋掉，而愈遠離軸的反射光線將愈不會被擋到，這是由於愈遠離中心軸線段，非球面與best-fitting球面的凹陷差距會愈大，則光的反射角也將愈大愈不容易被擋到，而光所遮到的多寡也與擋板的直徑有關。他們利用反射回來的光圖形與理論比對，用以檢測非球面。

Conclusions

- Aspheric lens design has been summarized and reviewed.
- It should be emphasized that an introduction of aspheric to design can improve the “imaging quality”
  - However, this should be done after you have settle your design with system requirement and even paraxial optics
  - It is always good to use Fermat principle for initial design
- Also as a part of conclusions, it is still worthwhile to remind you that in design:
  - Make a list of specification
  - Make notes in analysis (every phase!!)
    - Store your codes in every phase
  - Thinking before doing further
  - Review your simulation data carefully

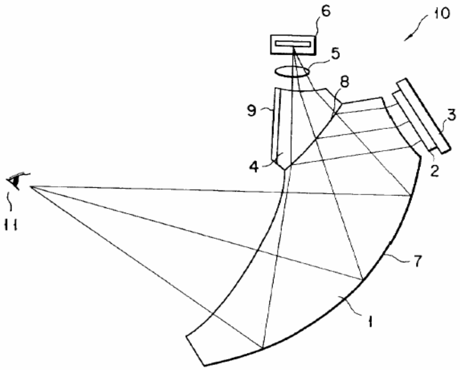
References

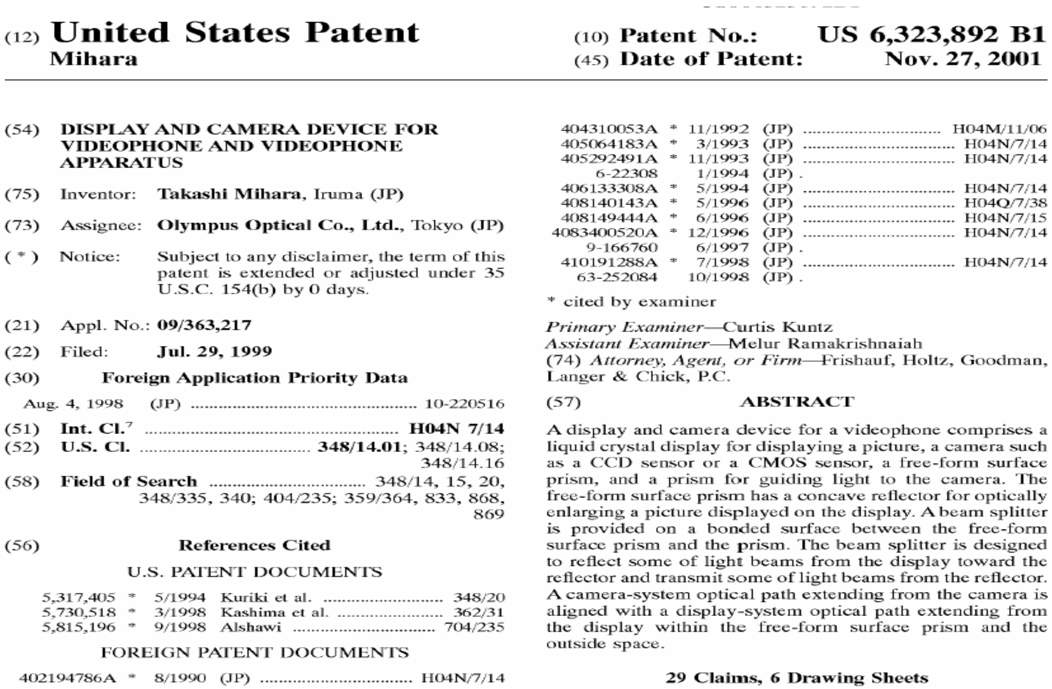
- General and useful reference on aspheric surface
  - R. E. Fischer and B. Tadic-Galeb
    - “Optical System Design” (McGraw-Hill) chapter 7
- On Fermat principle
  - A. Walther, “The ray and wave theory of lenses (Cambridge)

Homework

- 右圖是美國專利6323892的一個圖樣
  - 如果圖中2/3是display, 請問面7的樣子(aspheric form)是如何?

  *試著用ray-tracing與前後端的成像要求去定出面7的幾個點再擬合定出面7 .





(12) **United States Patent**
Mihara

(10) **Patent No.:** **US 6,323,892 B1**
(45) **Date of Patent:** **Nov. 27, 2001**

(54) **DISPLAY AND CAMERA DEVICE FOR VIDEOPHONE AND VIDEOPHONE APPARATUS**

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(73) Assignee: **Olympus Optical Co., Ltd.**, Tokyo (JP)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

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(22) Filed: **Jul. 29, 1999**

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(52) **U.S. Cl.** **348/14.01**; 348/14.08; 348/14.16
(58) **Field of Search** 348/14, 15, 20, 348/335, 340; 404/235; 359/364, 833, 868, 869

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(57) **ABSTRACT**

A display and camera device for a videophone comprises a liquid crystal display for displaying a picture, a camera such as a CCD sensor or a CMOS sensor, a free-form surface prism, and a prism for guiding light to the camera. The free-form surface prism has a concave reflector for optically enlarging a picture displayed on the display. A beam splitter is provided on a bonded surface between the free-form surface prism and the prism. The beam splitter is designed to reflect some of light beams from the display toward the reflector and transmit some of light beams from the reflector. A camera-system optical path extending from the camera is aligned with a display-system optical path extending from the display within the free-form surface prism and the outside space.

29 Claims, 6 Drawing Sheets

Revisit the aspheric surface in OSLO

$$z=\frac{\mathrm{cv}\,r^2}{1+\sqrt{1-\mathrm{cv}^2(\mathrm{cc}+1)r^2}}+\mathrm{ad}\,r^4+\mathrm{ae}\,r^6+\mathrm{af}\,r^8+\mathrm{ag}\,r^{10}$$

$$z=\frac{\mathrm{cv}\,r^2}{1+\sqrt{1\text{-}\mathrm{cv}^2(\mathrm{cc}+1)r^2}}+\mathrm{as0}+\mathrm{as1}\,r^2+\mathrm{as2}\,r^4$$
$$+\mathrm{as3}\,r^6+\mathrm{as4}\,r^8+\mathrm{as5}\,r^{10}+..$$

$$z=\mathrm{cns}\sqrt{x^2+y^2}+\mathrm{asa3}\,H^3+\mathrm{asa4}\,H^4+\mathrm{asa5}\,H^5+\cdots$$

$$z=\frac{\mathrm{cv}\,r^2}{1+\sqrt{1-\mathrm{cv}^2(\mathrm{cc}+1)r^2}}+\mathrm{as0}+\mathrm{as1}\,H+\mathrm{as2}\,H^2+\mathrm{as3}\,H^3+\mathrm{as4}\,H^4+\cdots$$

where

$$H=\left|\sqrt{x^2+y^2}\right|$$

$$z=\frac{\mathrm{cv}\,r^2}{1+\sqrt{1-\mathrm{cv}^2(\mathrm{cc}+1)r^2}}+\sum_{i=0}^{n}(\mathrm{as}i)Z_i$$

Zi: Zernike polynomial

$$z=\frac{\mathrm{cv}\,r^2}{1+\sqrt{1-\mathrm{cv}^2(\mathrm{cc}+1)r^2}}+\mathrm{asa3}\,H^3+\mathrm{asa4}\,H^4$$
$$+\mathrm{asa5}\,H^5+\mathrm{asa6}\,H^6+\cdots$$

where

$$H=\left|\sqrt{x^2+y^2}\right|$$

Asymmetrical aspheric (toward Free-form optics)

$$z = \sum_{i=0}^{n} z_i$$

where

$$z_i = (\mathbf{as}i)x^j y^k$$

$$z = \frac{\mathbf{cv}\left[y^2 - g^2(x)\right] + 2g(x)}{1 + \sqrt{1 - \mathbf{cv}\left\{\mathbf{cv}\left[y^2 - g^2(x)\right] + 2g(x)\right\}}}$$

where

$$g(x) = \frac{\mathbf{cvx}x^2}{1 + \sqrt{1 - \mathbf{cvx}^2(\mathbf{ccx} + 1)x^2}} + \mathbf{asc3}|x|^3 + \mathbf{asa4}x^4 + \mathbf{asc5}|x|^5 + \mathbf{asa6}x^6 + \cdots$$

$$z = \frac{\mathbf{cvx}\left[x^2 - g^2(y)\right] + 2g(y)}{1 + \sqrt{1 - \mathbf{cvx}\left\{\mathbf{cvx}\left[x^2 - g^2(y)\right] + 2g(y)\right\}}}$$

where

$$g(y) = \frac{\mathbf{cv}y^2}{1 + \sqrt{1 - \mathbf{cv}^2(\mathbf{cc} + 1)y^2}} + \mathbf{asd3}|y|^3 + \mathbf{asb4}y^4 + \mathbf{asd5}|y|^5 + \mathbf{asb6}y^6 + \cdots$$

$$z = \sum_{i=0}^{n} Z_i$$

where

$$Z_i = (\mathbf{as}i)|x|^j\,|y|^k \quad \text{and} \quad i = \frac{1}{2}\left[(j+k)^2 + j + 3k\right]$$

$$z = \frac{\mathbf{cvx}x^2 + \mathbf{cv}y^2}{1 + \sqrt{1 - \mathbf{cvx}^2(\mathbf{ccx} + 1)x^2 - \mathbf{cv}^2(\mathbf{cc} + 1)y^2}}$$
$$+ \mathbf{asa4}x^4 + \mathbf{asb4}y^4 + \mathbf{asa6}x^6 + \mathbf{asb6}y^6 + \cdots$$
$$+ \mathbf{asc3}|x|^3 + \cdots + \mathbf{asd3}|y|^3 + \cdots$$

$$z = \mathbf{cns}\sqrt{\frac{x^2}{\mathbf{cnx}^2} + \frac{y^2}{\mathbf{cny}^2}}$$
$$+ \mathbf{asa4}x^4 + \mathbf{asb4}y^4 + \mathbf{asa6}x^6 + \mathbf{asb6}y^6 + \cdots$$
$$+ \mathbf{asc3}|x|^3 + \cdots + \mathbf{asd3}|y|^3 + \cdots$$

$$z = \frac{\mathbf{cv}r^2}{1 + \sqrt{1 - \mathbf{cv}^2(\mathbf{cc} + 1)r^2}} + \sum_{i=0}^{n} (\mathbf{as}i)Z_i$$

Zi: Zernike polynomial