ME 297
L4-2 Optical design flow Analysis

Nayer Eradat

Fall 2011

SJSU

Are we meeting the specs?

- First order requirements (after scaling the lens)
- Distortion

- Sharpness (diffraction MTF-will establish depth of focus by analyzing MTF with a different object distance
- Vignetting / illumination (Transmission analysis
- Spot diagrams
- Ray aberration curves

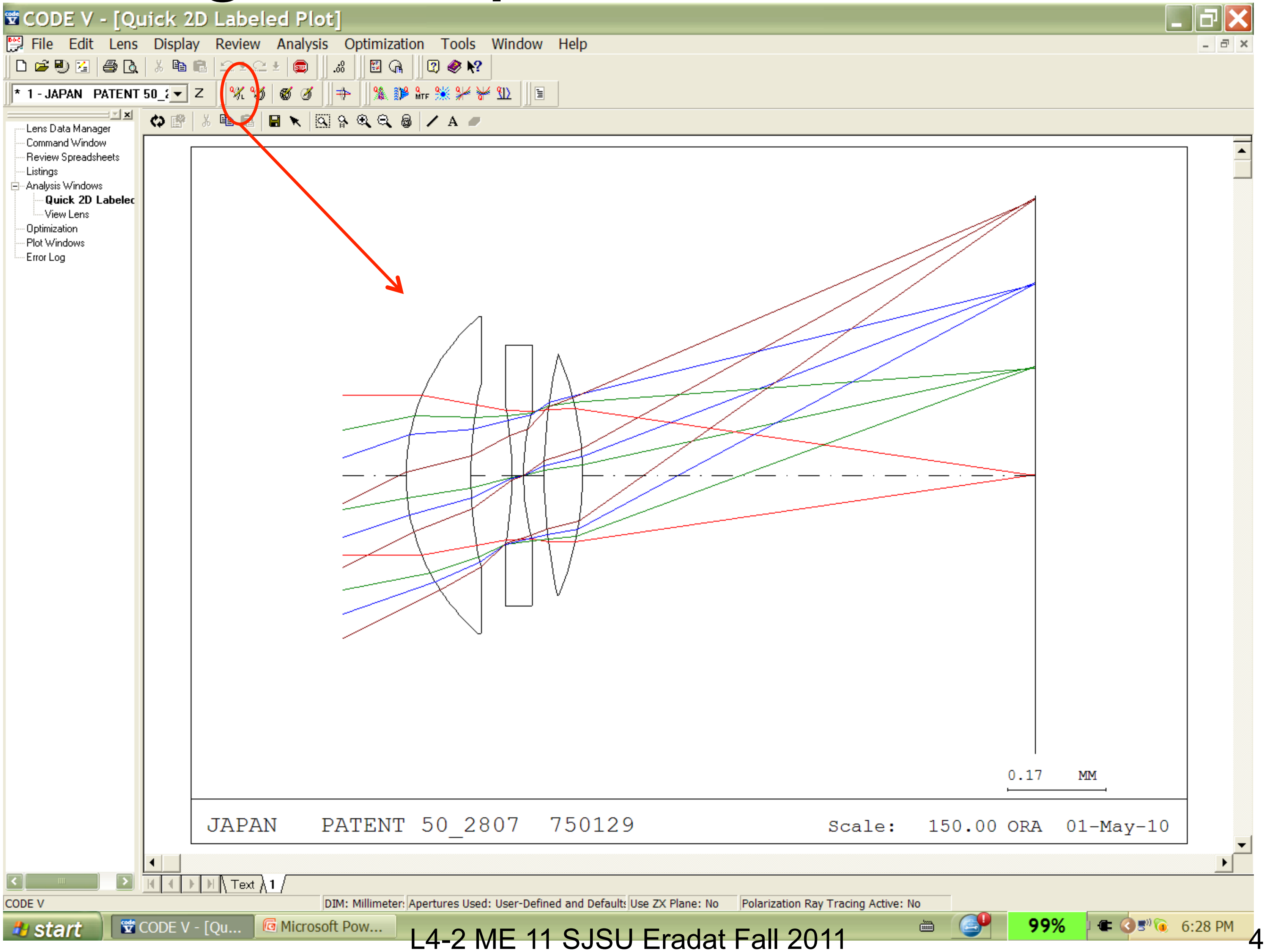
Fixed-focus VGA digital camera objective specs (Ref: CODE V user guide)

- Number of elements: 1-3
- Material: common glasses or plastics
- Image sensor: Agilent FDCS-2020
  - Resolution: 640x480
  - Pixel size: 7.4x7.4 microns
  - Sensitive area: 3.55x4.74 mm (full diagonal 6 mm)
- Objective lens:
  - Focus: fixed, depth of field 750 mm (2.5 ft) to infinity
  - Focal length: fixed, 6.0 mm
  - Geometric Distortion: <4%
  - f/number: Fixed aperture, f/3.5
  - Sharpness: MTF through focus range (central area is inner 3 mm of CCD)

Low frequency 17 lp/mm	>90% (central)	>85% (outer)
High frequency, 51 lp/mm	>30% (central)	>25% (outer)

  - Vignetting: Corner relative illumination > 60%
  - Transmission: Lens alone >80% 400-700 nm
  - IR filter: 1 mm thick Schott IR638 or Hoya CM500

Viewing a 2D picture of the lenses

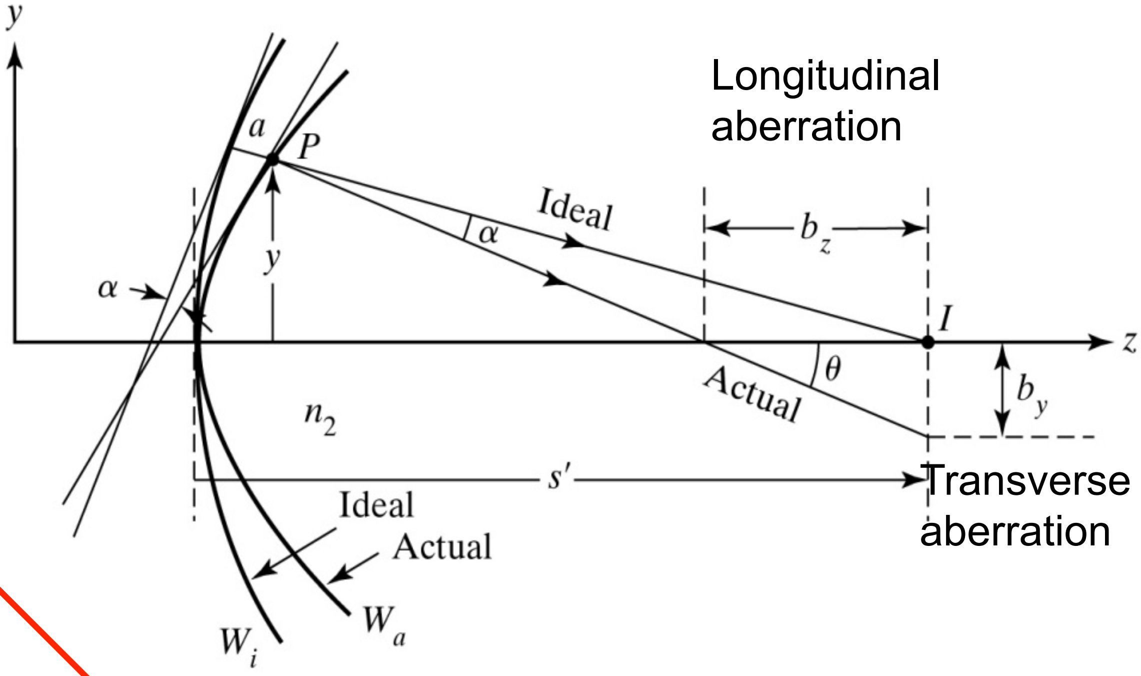


JAPAN PATENT 50_2807 750129 Scale: 150.00 ORA 01-May-10

DIM: Millimeter: Apertures Used: User-Defined and Default: Use ZX Plane: No Polarization Ray Tracing Active: No

Aberrations: ray intercept curve

Ray intercept curve:
Plotted as a function of position on the stop (pupil) for a line of evenly spaced rays.
In other words distribution of light over the aperture stop



Longitudinal aberration

Transverse aberration

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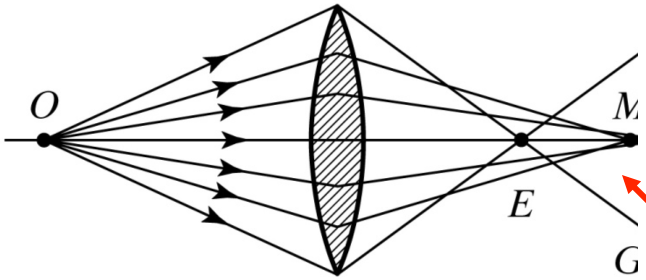
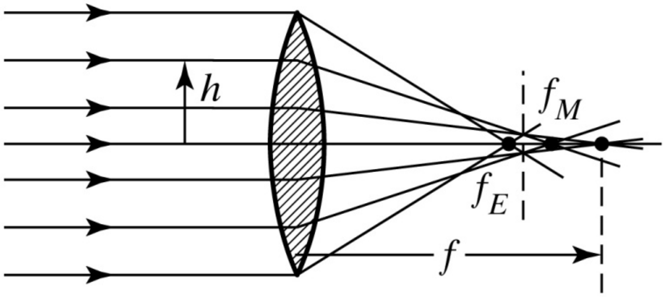


(a)



(b)

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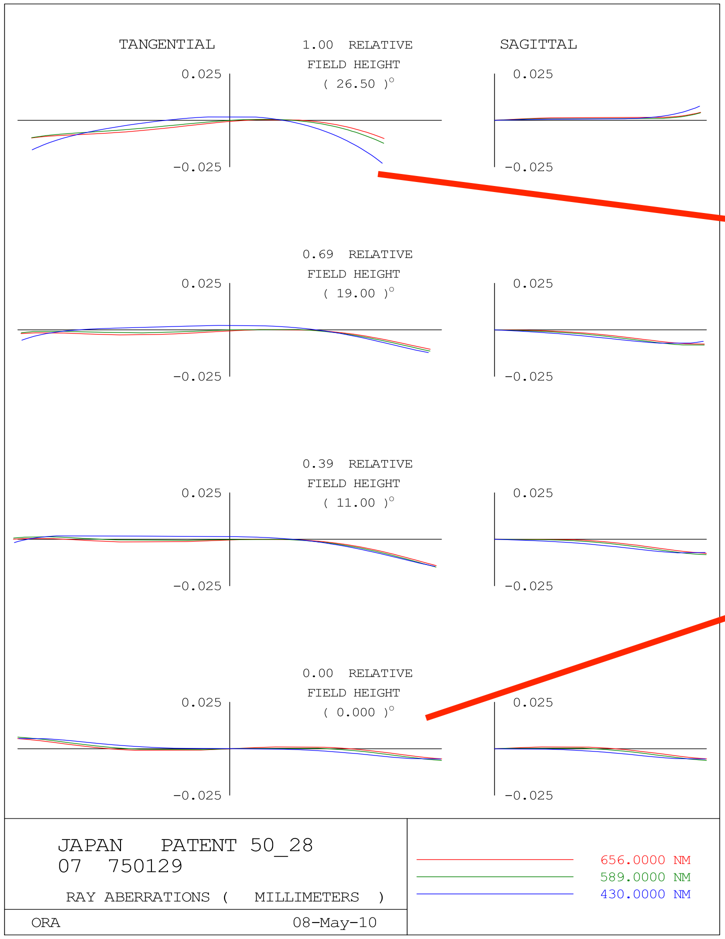
distance from a particular ray to the chief ray for the same field point on the image surface

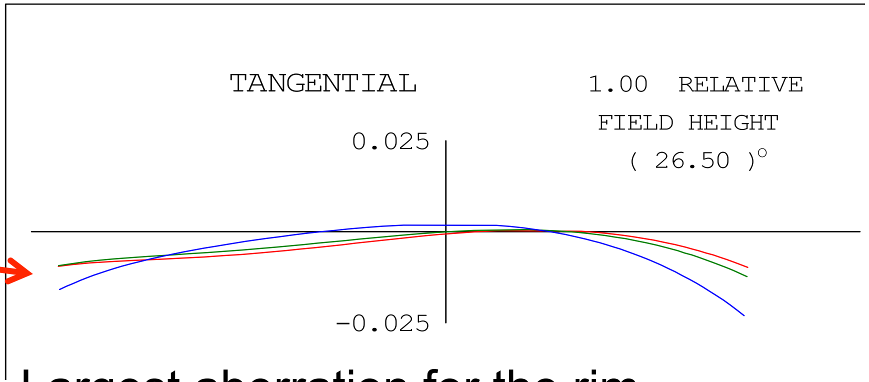
Ray Intercept Diagrams In Code V

- A geometrical optics calculation
- Selected rays are traced

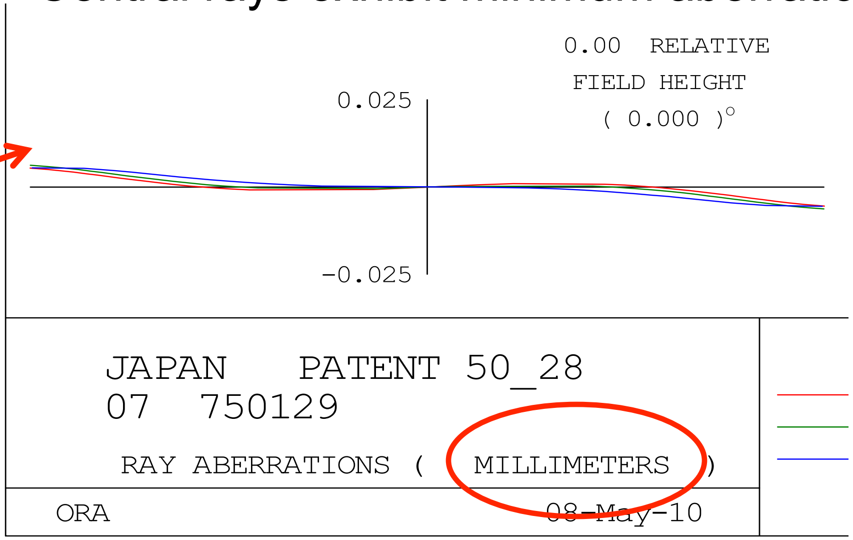
Ray aberration curve

- For quick ray aberration plot choose RIM option in: Analysis>Diagnosis>Ray Aberration Curves for “rim rays” only



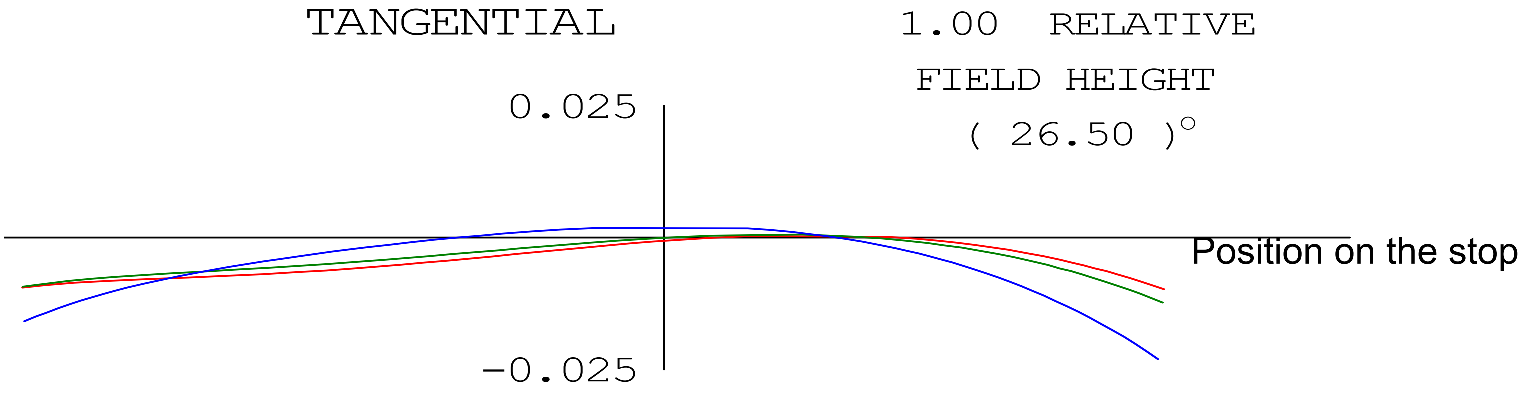


Largest aberration for the rim.
Central rays exhibit minimum aberration



Ray aberration curve

- Based on ray trace data we look for patterns that may cause problem
  - Transverse ray aberration (zero for perfect lens). Plotted as a function of position on the stop (pupil) for a line of evenly spaced rays.
  - For quick ray aberration plot choose RIM option in: Analysis>Diagnosis>Ray Aberration Curves for “rim rays” only
  - The rim ray is usually the most problematic one so if this is ok we don’t expect any problem.



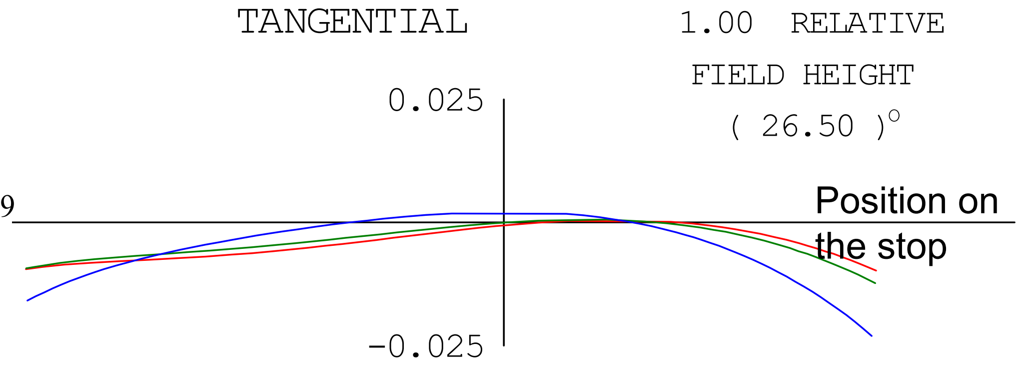
Ray aberration curve

- What is big and what is small on this graph (scale is in mm).
- We compare the aberrations to the size of the airy disc on the diffraction pattern.

$$D_{Airy} = \frac{(2)1.22\lambda}{D_L / f} = 2.44\lambda f\#$$

$$D_{Airy} = 2.44 \times 3.5 \times 500nm = 4270 \times 10^{-9}$$

$$D_{Airy} \simeq 4\mu$$



The largest aberration for this lens

is 23μ, about $6 \times D_{Airy}$.

If the aberrations were less or equal to the D_{Airy} then our lens was

a diffraction-limited lens but it is not.

Note: for positive-dispersion glasses $(dn / df > 0)$ the largest chromatic

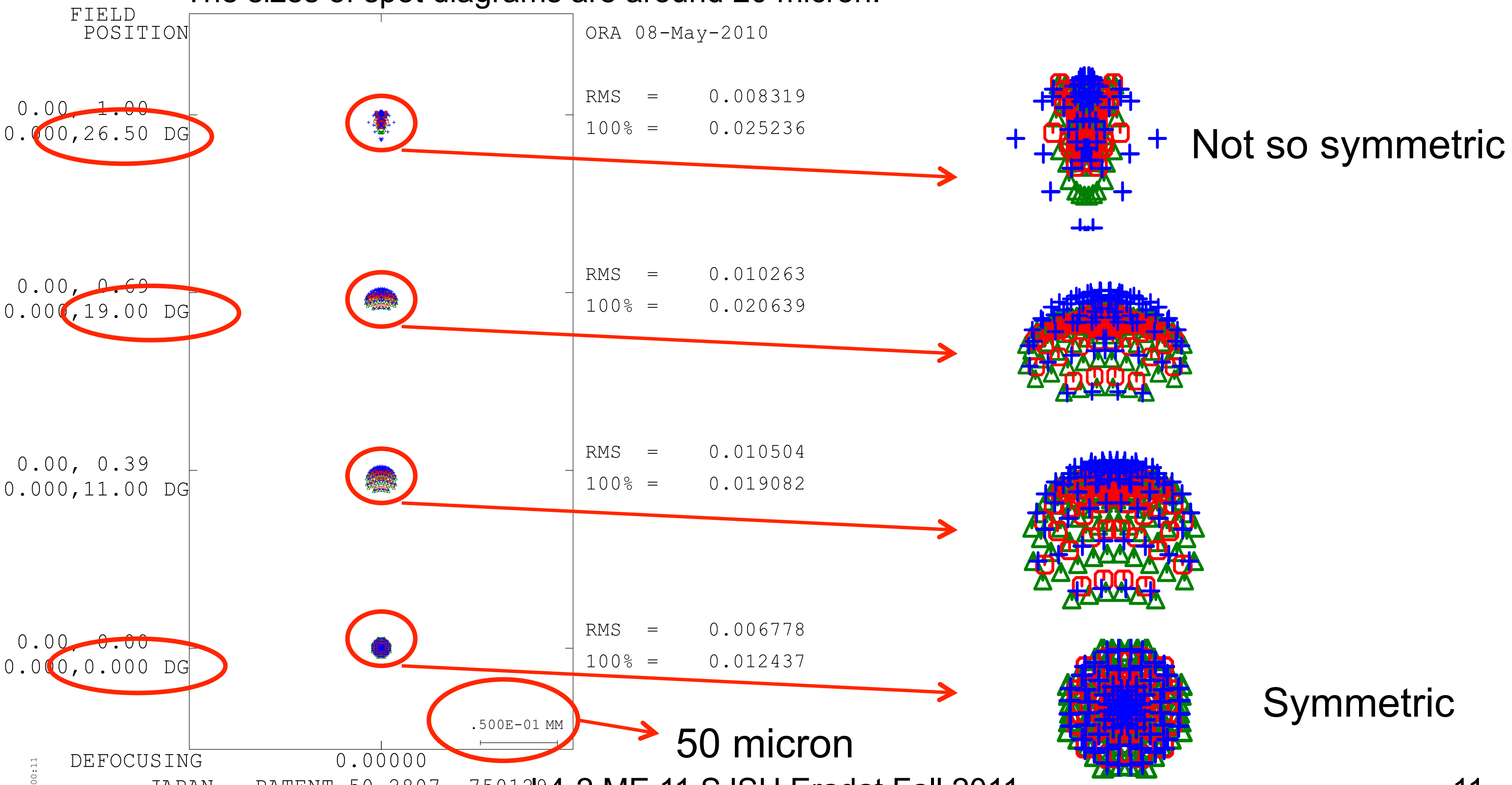
aberration belongs to the highest frequency (shortest λ) in the spectrum.

Spot Diagrams / Ray Scatter Diagrams

- A geometrical optics calculation
- They show symmetry of aberration

Quick spot diagram

- A quick and easy graphical measure of the image quality
  - Many rays from each field point (forming a rectangular grid on the entrance pupil) are traced.
  - A scatter plot of the rays position on the image plane is generated.
  - This is done for each field angle and color coded for wavelength.
  - Analysis>Geometrical>Spot Diagram (note the scale bar is 50 micron).
  - The sizes of spot diagrams are around 20 micron.



FIELD
POSITION

ORA 08-May-2010

0.00, 1.00
0.000,26.50 DG

RMS = 0.008319
100% = 0.025236

0.00, 0.69
0.000,19.00 DG

RMS = 0.010263
100% = 0.020639

0.00, 0.39
0.000,11.00 DG

RMS = 0.010504
100% = 0.019082

0.00, 0.00
0.000,0.000 DG

RMS = 0.006778
100% = 0.012437

.500E-01 MM

DEFOCUSING 0.00000

JAPAN PATENT 50_2807 750129

Not so symmetric

Symmetric

50 micron

Aberration of an off-axis object point

$$\boxed{a(Q) = {}_0C_{40}r^4 + {}_1C_{31}h'r^3\cos\theta + {}_2C_{22}h'^2r^2\cos^2\theta + {}_2C_{20}h'^2r^2 + {}_3C_{11}h'^3r\cos\theta}$$

The ${}_iC_{jk}$ aberration coenfficients have indecies that are powers of the terms:

h': departure from axial image

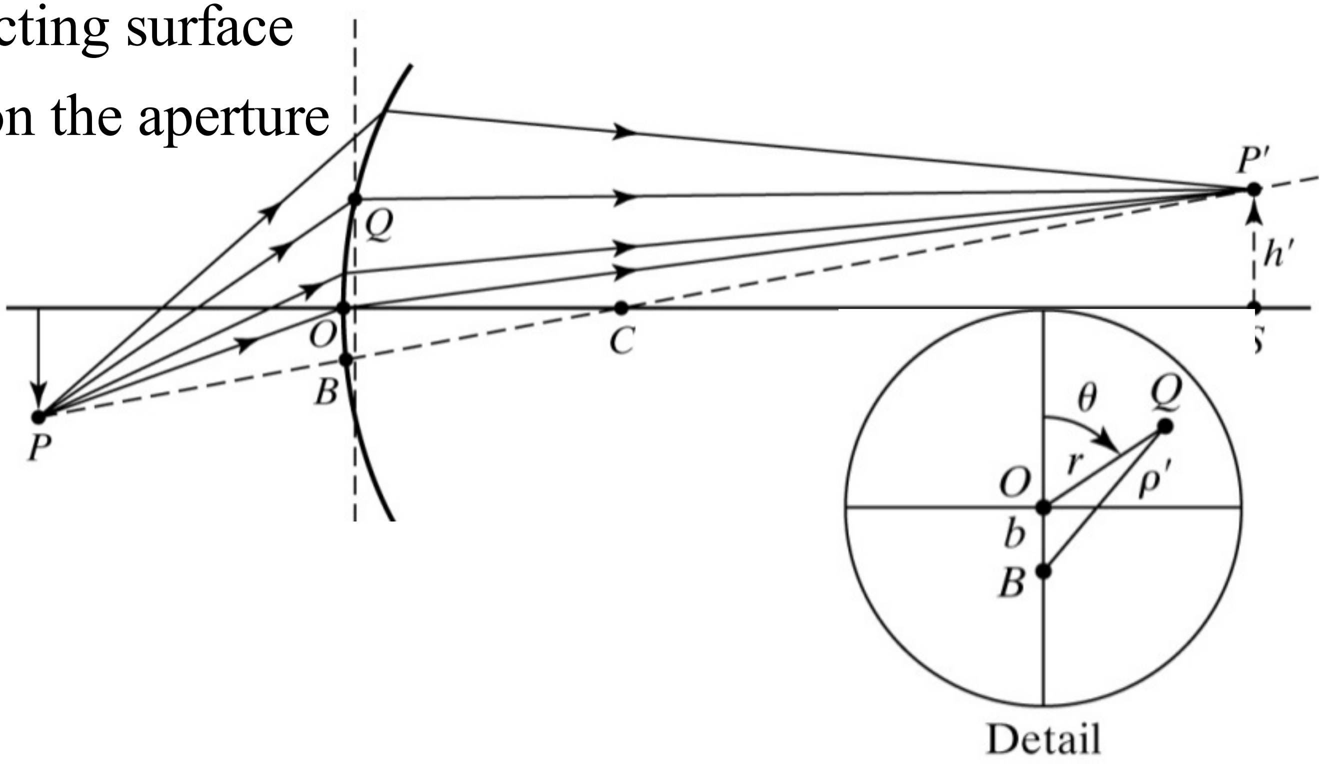
r: aperture of the refracting surface

$\cos\theta$: azimutal angle on the aperture

i is power of h'

j is power of r

k is power of $\cos\theta$



Distortion

$$a(Q) = \underbrace{{}_0C_{40}r^4 + {}_1C_{31}h'r^3\cos\theta}_{\textit{Aplanatic}\text{ optics corrects spherical and coma}} + h'^2 r^2\left(\underbrace{{}_2C_{22}\cos^2\theta}_{\text{Astigmatism}} + \underbrace{{}_2C_{20}}_{\text{Curvature of field}}\right) + \underbrace{{}_3C_{11}h'^3 r\cos\theta}_{\textit{Distortion}}$$

Distortion exists even if all the other chromatic & Seidel aberations (third order) have been eleiminated.

It is caused by variations of the lateral magnifications for the object points at different distance from the optical axis.

Pincushion distortion :

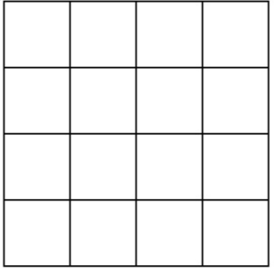
if magnification increases with distance from the axis.

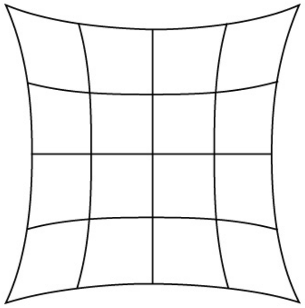
Barrel distortion :

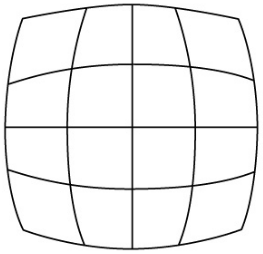
if magnification decreases with distance from the axis.

The image is sharp but distorted.

Can be treated by using stops and apertures at approprite locations between the lens and object or lens and image.


(a)


(b)


(c)

Distortion

Distortion is the difference between the real image height and the paraxial image height.

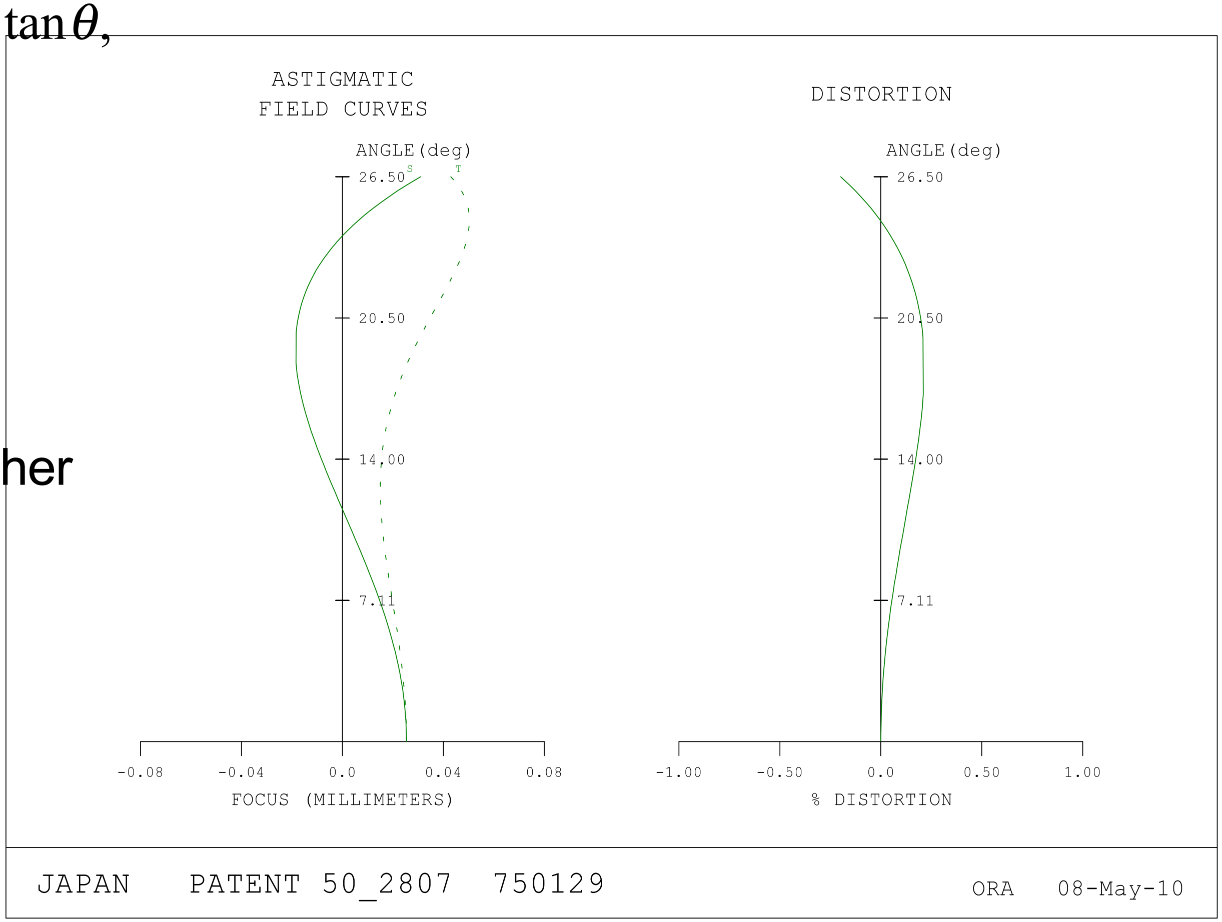
Paraxial image height: $h = f\tan\theta$,

Real image height: h',

$$distortion = \frac{h' - h}{h} \times 100$$

Distortion is a **field - related aberration.**

It is usually plotted with another field-aberration astigmatism.



Use: Analysis>Diagnostics>Field curves or "Quick field plot"

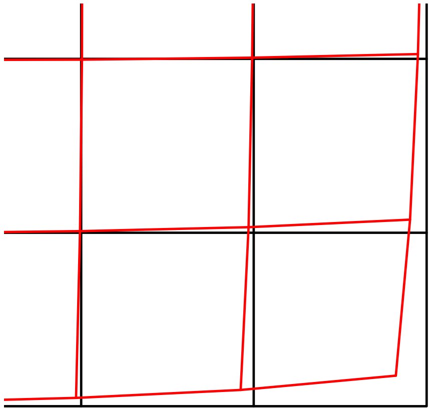
Distortion grid

Distortion grid displays the distortion on a grid that displays the ideal paraxial image superimposed on a distorted grid. We need to convert the CCD horizontal (X) and vertical (Y) dimensions to the angles. $h = f\tan\theta$

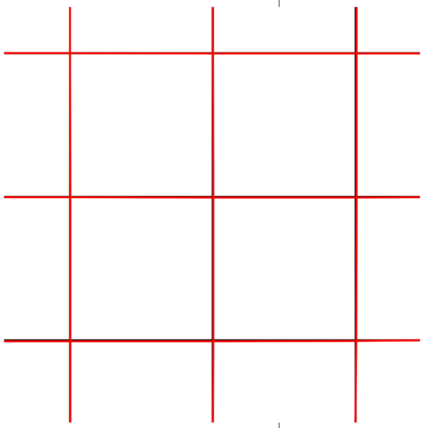
$$\theta_{horizontal} = \theta_x = \tan^{-1}\left(\frac{4.74}{2}\frac{1}{6}\right) = 21.55^0 \quad \& \quad \theta_{vertical} = \theta_y = \tan^{-1}\left(\frac{3.55}{2}\frac{1}{6}\right) = 16.48^0$$

Choose: Analysis>Diagnostics>Distortion Grid:

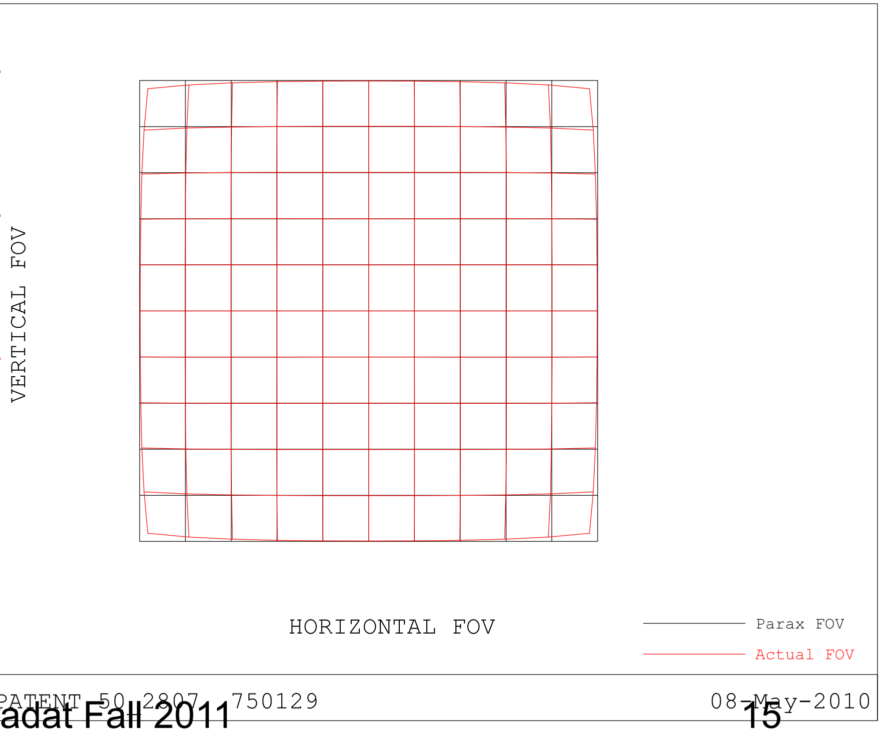
$X\text{-}FOV\ \ semi\text{-}field = 21.55$ & $y\text{-}FOV\ \ semi\text{-}field = 16.48$



Larger outer distortion



Very small central distortion



Point Spread Function (PSF)

- A physical optics calculation
- Light intensity distribution in the diffraction image if the lens were made perfectly (diffraction-limited).
- It is simply image of a point object.

Optical Transfer Function (OTF)
A physical optics calculation

- A functional representation of the spatial frequency response of the lens.
- OTF is a <u>Fourier transform</u> of the PSF
- Spatial frequency or wavenumber: number of wavelengths in a unit length (not time)
- OTF describes the contrast between images of different sinusoidal elements with specified spatial frequency
- Image analysis with OTF is equivalent to Frequency band analysis in communication

Modulation Transfer Function (MTF) A physical optics calculation

- MTF which is modulus of the OTF is a more interesting function to the lens users.
- Shows the contrast between the different frequency components.

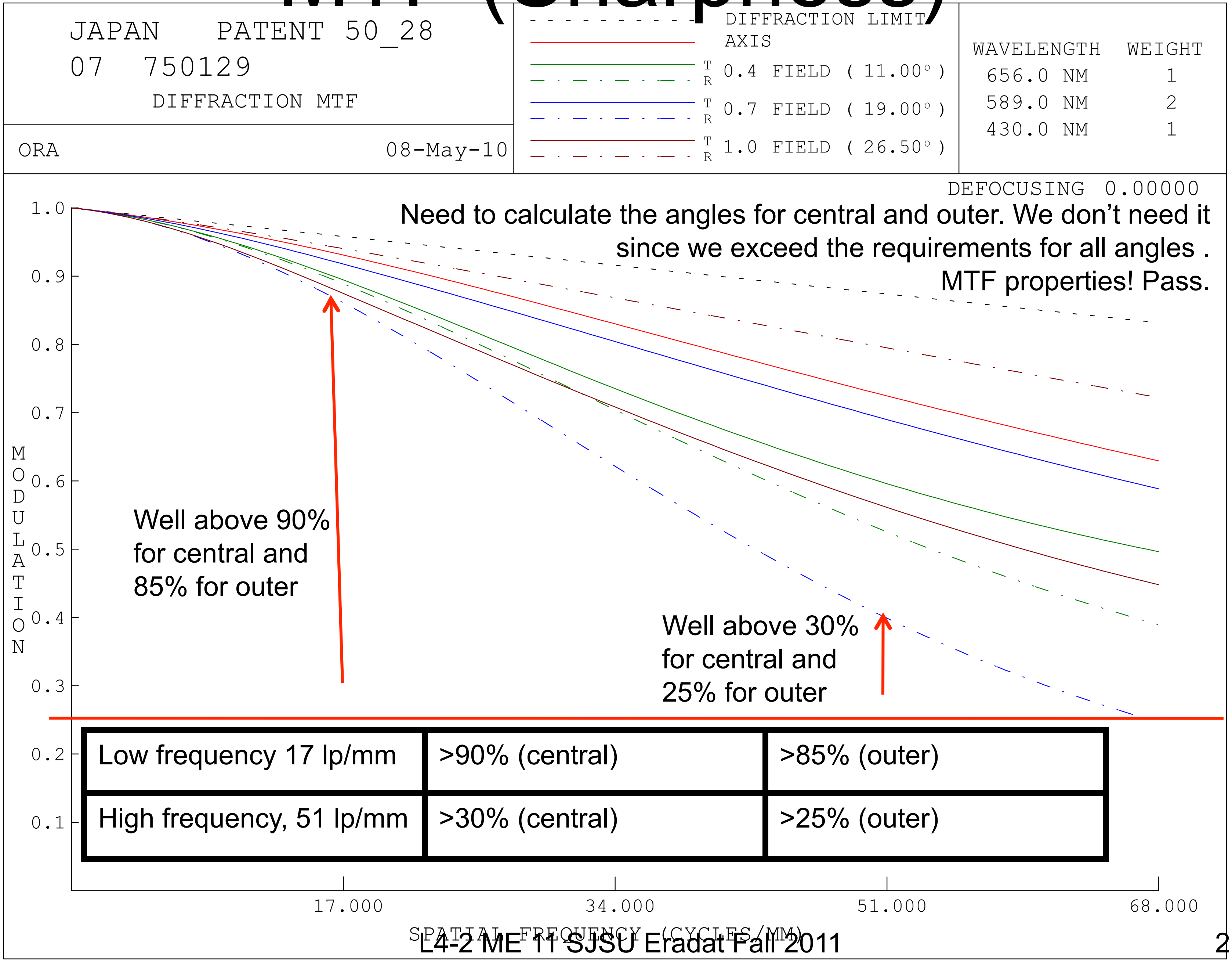
MTF (Sharpness)

- User wants sharpness of resolution, designer has to relate these to Modulation Transfer Function (MTF).
- MTF is the relative contrast.
  - 1 for ideal and
  - 0 for no contrast at all.
- For low frequencies (large features) any lens will have good contrast
- For high frequencies (small features we need good lenses)
- Use Analysis>Diffraction>MTF
  - Maximum frequency 68 (max spatial frequency of our CCD array is 67,
  - Increment frequency 17 (low frequency of the specs is 17 lines/ mm 4*17=68 will cover all the information we need)
  - Number of rays across diameter 60
- Usually the MTF is used in its one-dimensional form, calculated for one azimuthal section through the image plane.

Sagittal and tangential azimuth

- The azimuth (section plane) of the object pattern is called **radial (sagittal) azimuth** when the **prolongation of the slit or object passes through the reference axis**.
- When the prolongation of the slit pattern is perpendicular to the reference axis, the azimuth is called tangential azimuth.

MTF (Sharpness)



Need to calculate the angles for central and outer. We don't need it since we exceed the requirements for all angles . MTF properties! Pass.

Well above 90% for central and 85% for outer

Well above 30% for central and 25% for outer

Low frequency 17 lp/mm	>90% (central)	>85% (outer)
High frequency, 51 lp/mm	>30% (central)	>25% (outer)

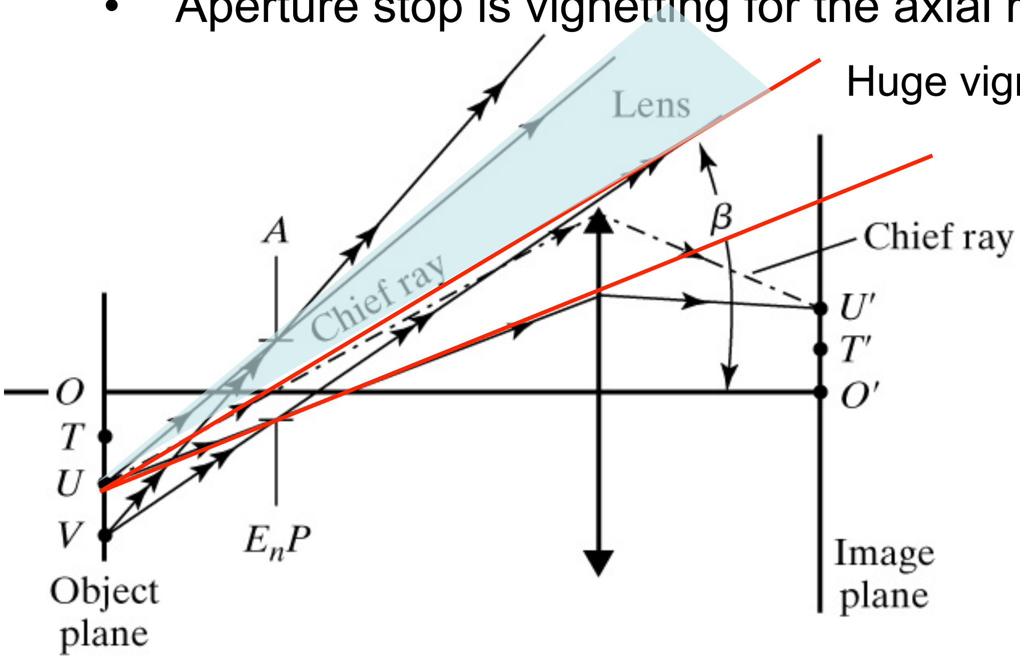
Reference rays

- Reference rays: a special set of rays traced from each field position (angle) of the lens with no symmetry. Usually five rays are traced from each field. The coordinates of the five rays are retained for every surface and recalculated any time a surface is changed.
  - Chief ray (one ray)
  - Outmost rays in x-z and y-z planes of the bundle from each field point (4 rays)

- The chief ray always goes through the center of the aperture stop and it is considered the representative of its field
- Other 4 rays pass through the edge of the paraxial entrance pupil

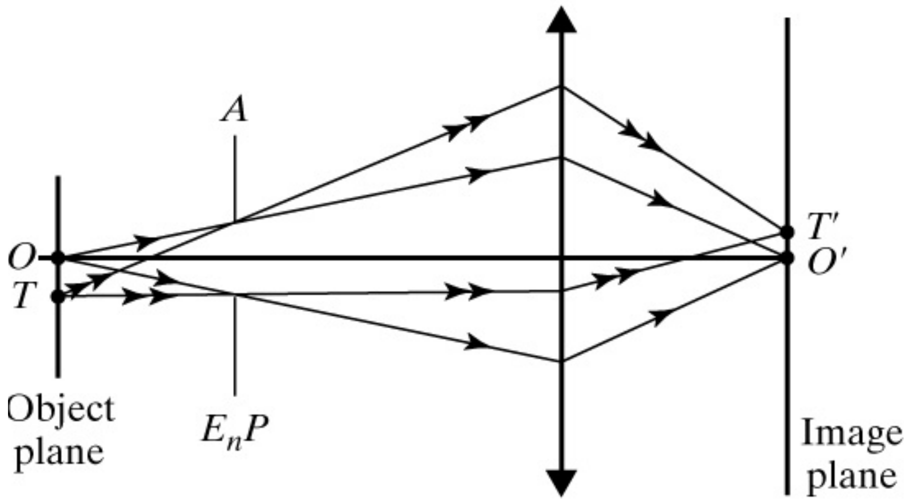
Vignetting

- For <u>non-axial field points</u>, the aperture stop may not be the limiting aperture and portions of off-axis bundles may be clipped by apertures on other surfaces.
- If vignetting is present then the reference rays can not reach the edges of the paraxial entrance pupil. Instead they are pushed inward (towards the optical axis) by a factor called “vignetting factor”.
- Aperture stop is vignetting for the axial rays.



Huge vignetting.

There is vignetting, and vignetting factor is less than one, the reference rays can not hit the edges of the entrance pupil. They have to come closer to the optical axis



There is no vignetting so vignetting factor is one, the reference rays hit the edges of the entrance pupil

Vignetting: problem and solution

- Solution: we may use vignetting to remove the bad rays (rays with severe aberration)
- Problem: vignetting reduces the illumination of the off-axis points (the rays do not reach the system).
- Vignetting as result of limitation in size of the lenses is also a problem.
- Vignetting limits the FOV

Vignetting/Illumination?

- Vignetting: clipping of off-axis rays due to apertures on surfaces other than the aperture stop surface.
- Angular effects:
  - relative illumination(angle)=$\cos^4$(field angle)/4
- Requirements: at least 60% relative illumination at the corner of the field (full field).
- Vignetting factors determine the reference rays
- Reference rays determine default apertures
- Default apertures determine the rays that are included in calculation of MTF
- Designer can change the vignetting factors to expand or contract the cone of light entering the system from off-axis fields.
- You can see the vignetting-related data from the MTF screen click on the text.

MTF (Sharpness)-text

```
GEO  NO
MFR  68
IFR  17
PLO FRE Y
GO
           APERTURE STOP
           SEMI-DIAMETER =     0.685366
            (Based on the maximum reference ray height at the stop.)
   X and Y focal lengths for each field angle
     X       0.595785E+01      0.607819E+01      0.632056E+01      0.665978E+01
     Y       0.595785E+01      0.632659E+01      0.708043E+01      0.798371E+01
   X and Y F-numbers for each field angle
     X          3.475412          3.545608          3.714552          3.975541
     Y          3.475412          3.690510          4.230523          5.524230
   Reference sphere radius for each field angle
             0.535692E+01      0.548322E+01      0.574632E+01      0.614527E+01
   Relative execution time  =    1.21 UNITS
  POSITION  1        DIFFRACTION MTF           ORA          09-May-10
        JAPAN   PATENT 50_2807  750129
                                        WAVELENGTH   WEIGHT  NO. OF RAYS
    FIELD (X,Y)=( 0.00, 0.00)MAX, (  0.00,  0.00)DEG      656.0 NM       1       524
    RELATIVE ILLUMINATION = 100.0 PER CENT                589.0 NM       2       648
    ILLUMINATION (UNIT BRIGHTNESS) = 0.064999             430.0 NM       1      1224
    DISTORTION =    0.00 PER CENT
   DIFFRACTION LIMIT    FOCUS POSITION
    Formula  Actual      0.00000
L/MM f/3.500 RAD  TAN    RAD  TAN
---- ----------------   ---------
  0 .999   .999      .999
 17 .957   .958      .931
 34 .914   .916      .830
 51 .872   .874      .725
 68 .829   .832      .629
POSITION  1        DIFFRACTION MTF           ORA          09-May-10
        JAPAN   PATENT 50_2807  750129
                                        WAVELENGTH   WEIGHT  NO. OF RAYS
    FIELD (X,Y)=( 0.00, 0.39)MAX, (  0.00, 11.00)DEG      656.0 NM       1       486
    RELATIVE ILLUMINATION =  93.0 PER CENT                589.0 NM       2       604
    ILLUMINATION (UNIT BRIGHTNESS) = 0.060457             430.0 NM       1      1134
    DISTORTION =    0.12 PER CENT
```

```
DIFFRACTION LIMIT    FOCUS POSITION
    Formula  Actual      0.00000
L/MM f/3.500 RAD  TAN    RAD  TAN
---- ----------------   ---------
  0 .999   .999 .999   .999 .999
 17 .957   .957 .955   .889 .894
 34 .914   .915 .910   .704 .735
 51 .872   .872 .865   .525 .596
 68 .829   .829 .821   .390 .496
      POSITION  1        DIFFRACTION MTF           ORA          09-May-10
        JAPAN   PATENT 50_2807  750129
                                        WAVELENGTH   WEIGHT  NO. OF RAYS
    FIELD (X,Y)=( 0.00, 0.69)MAX, (  0.00, 19.00)DEG      656.0 NM       1       406
    RELATIVE ILLUMINATION =  78.6 PER CENT                589.0 NM       2       510
    ILLUMINATION (UNIT BRIGHTNESS) = 0.051069             430.0 NM       1       964
    DISTORTION =    0.21 PER CENT
   DIFFRACTION LIMIT    FOCUS POSITION
    Formula  Actual      0.00000
L/MM f/3.500 RAD  TAN    RAD  TAN
---- ----------------   ---------
  0 .999   .999 .999   .999 .999
 17 .957   .955 .948   .861 .918
 34 .914   .911 .896   .621 .804
 51 .872   .866 .844   .399 .690
 68 .829   .821 .794   .247 .588
      POSITION  1        DIFFRACTION MTF           ORA          09-May-10
        JAPAN   PATENT 50_2807  750129
                                        WAVELENGTH   WEIGHT  NO. OF RAYS
    FIELD (X,Y)=( 0.00, 1.00)MAX, (  0.00, 26.50)DEG      656.0 NM       1       310
    RELATIVE ILLUMINATION =  58.8 PER CENT                589.0 NM       2       380
    ILLUMINATION (UNIT BRIGHTNESS) = 0.038205             430.0 NM       1       720
    DISTORTION =  -0.20 PER CENT
   DIFFRACTION LIMIT    FOCUS POSITION
    Formula  Actual      0.00000
L/MM f/3.500 RAD  TAN    RAD  TAN
---- ----------------   ---------
  0 .999   .999 .999   .999 .999
 17 .957   .954 .935   .940 .875
 34 .914   .908 .869   .868 .708
 51 .872   .863 .803   .795 .561
 68 .829   .818 .729   .722 .448
```

We need 60%
This is close enough that we leave it to see if it will be fixed during the optimization
$\text{Cos}^4(26.5)=0.64$

Vignetting/Illumination

- Analysis>system>Transmission data   provides more detailed illumination data including coatings. Default is a quarter wavelength anti-reflection coating for each glass surface.

```
FIELD (X,Y)=(  0.00, 26.50) DEG

      ------------------------------------------------------------------------
     PRODUCT  REF   0.9412     0.9696     0.8985     0.9447
              ABS   1.0000     1.0000     1.0000     1.0000
Ave Transmittance:   0.9412     0.9696     0.8985     0.9447
ILLUMINATION:        0.03571    0.03682    0.03430   0.03591
RELATIVE ILLUM:        56.5       57.2       61.1       57.9
PROJECTED SOLID
ANGLE (IMAGE SPACE): 0.03794    0.03798    0.03818   0.03802
USED AREA OF
ENTRANCE PUPIL:      2.02455    2.02488    2.02510   2.02485
```

Analysis>Fabrication support>Cost Analysis

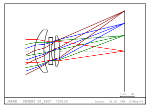
```
15-May-10                    C O D E  V                    POSITION 1
                  BLOCKING COST FACTORS FOR LENS PRODUCTION
     JAPAN   PATENT 50_2807  750129
SURFACE    RADIUS OF   THICKNESS   OUTSIDE    GLASS    BLOCKING   APPROXIMATE   SPINDLE LOADS
 NUMBER    CURVATURE               DIAMETER    NAME     FACTOR        NUMBER    PER 1000 ELTS
-----------------------------------------------------------------------------------------
  1        2.2451           0.693  3.126      LAKN17    1.000        1          1000
  2        4.4211                  3.126                0.467        4           250
  3       -4.1545           0.126  2.011       SF1      0.362        6           167
  4        2.6249                  2.011                0.574        2           500
  5        5.7998           0.409  2.245      NLASF41   0.327        7           143
  6       -3.4062                  2.245                0.543        2           500
                                                                                ------
                               Spindle loads for 1000 assemblies =   2560
```

NOTE:

1. Linear dimensions are in millimeters unless otherwise noted.
2. The "OUTSIDE DIAMETER" is larger than the clear aperture for beveling/mounting purposes
3. "APPROXIMATE NUMBER" is an estimate of the number of elements on a block, based on the following assumptions:
   A. Maximum blocker diameter is 300.0 MM.
   B. Maximum blocker "STEEPNESS" is 160.0 degrees.

Establish feasibility: Issues

- Size of the elements:
  - At 6 mm EFL this lens system is tiny. 126 micorn thickness of the central part of the middle lens.
  - Reasonable values for the thickness at the center is about 0.8 mm and at the edges about 0.9 mm
  - We need optimization to fix this.



- Index of the glases:
  - They are too high (1.786, 1.717, 1.835)
  - High (n>1.65) and low index (n<1.45) glasses are less common and more expensive
- Tools>Macro Manager>glassfit.seg
  - Use the dialog box and answer the questions

```
Catalog   Code   Definition
-------   ----   ----------
All        3     Discontinued
           4     Discontinued with recommended replacement glass
           5     Preliminary
Schott     0     Preferred glass
           1     Standard Glass
           2     Inquiry Glass
Surf Catalog     Glass       Delta Nd  Delta Vd  Avail  Price  DPF  Bubl  Stain
  1  SCHOTT      LAKN17     -0.00103    0.1666    3      0.00  -73   0     0
  3  SCHOTT      SF1         0.00000   -0.0129    0     25.00    0   1     1
  5  SCHOTT      NLASF41    -0.00020   -0.2291    0      0.00  -79   1     1
```

Conclusion

- Interpret the specs for the design
- Locate the suitable starting design using patent search
- Select the lens
- Analyze the starting points
- Determine the guidelines for optimization
  - Constrain the glass choices
  - Constrain the size of the lenses

Optimization

- Generate “best” possible system that can be achieved within a given set of constraints
- “best” is measured by an error function.
- The error function for a software is usually predetermined but it might be possible to change the weighting factors. Code V uses accelerated Damped Least Square (DLS) method.
  - Local optimization finds the closest valley to the starting point.
  - Global optimization finds the deepest valley or global minimum
- We need to
  - Set up variables
  - Determine and define the constraints
  - Analyze the results

Optimization: the game plan

- **Define** as variables all the following
  - Radii of curvatures
  - Thickness values
  - Fictitious glasses
- Save the starting point
- **Place general constraints** on
  - glass thicknesses
  - indexes of refraction
- **Place specific constraints** on effective focal length (EFL=6mm here)
- Use output control **to draw the lens on each optimization cycle**
- Use the error function definition and control tab for **defining the (transverse ray aberration) error function** but trace more rays in the grid.
- **Rerun the evaluations** to see the results of optimization (VIEW, MTF, FIELD)
- Modify the error function weights to **refine the solution**.

Defining Variables in LDM

- In centered systems it is common to vary all the
  - surface curvatures but the image surface.
  - Thickness of the air gaps and glasses
  - Type of he glasses (index and dispersion) by using fictitious glass (right click to change it to variable, left click to select index, dispersion or both to e varied).
- The variables are defined in LDM by right clicking on the parameter and changing it to variable

Automatic design settings

- Optimization>Automatic design
  - General constraints to define the boundary conditions of the glass map boundaries and thicknesses

How it works

Tolerancing

Reflecting systems

Non spherical curfaces

Decentered System

Zoom Systems

Tech Talk

Example for minimizing coma

Abbe's sine condition: $\boxed{m = \frac{h'}{h} = -\frac{n\sin\theta}{n'\sin\theta'}}$

The proper Coddington shape factor for absence of coma:

$$\boxed{\sigma = \left(\frac{2\mathrm{n}^2 - n - 1}{n+1}\right)\left(\frac{s - s'}{s + s'}\right)}$$

Example: $n = 1.50$, object at infinity, we get σ=0.8 very close to the value of minimum spherical aberration 0.7.

Thus we can minimize both spherical and coma aberration simultaneously in one design called *aplanatic* optics.