# Tolerance Analysis

*Murphy's Law :*

*"Anything that can go wrong, will go wrong*


Cheng-Fang Ho
ark@phys.ncku.edu.tw

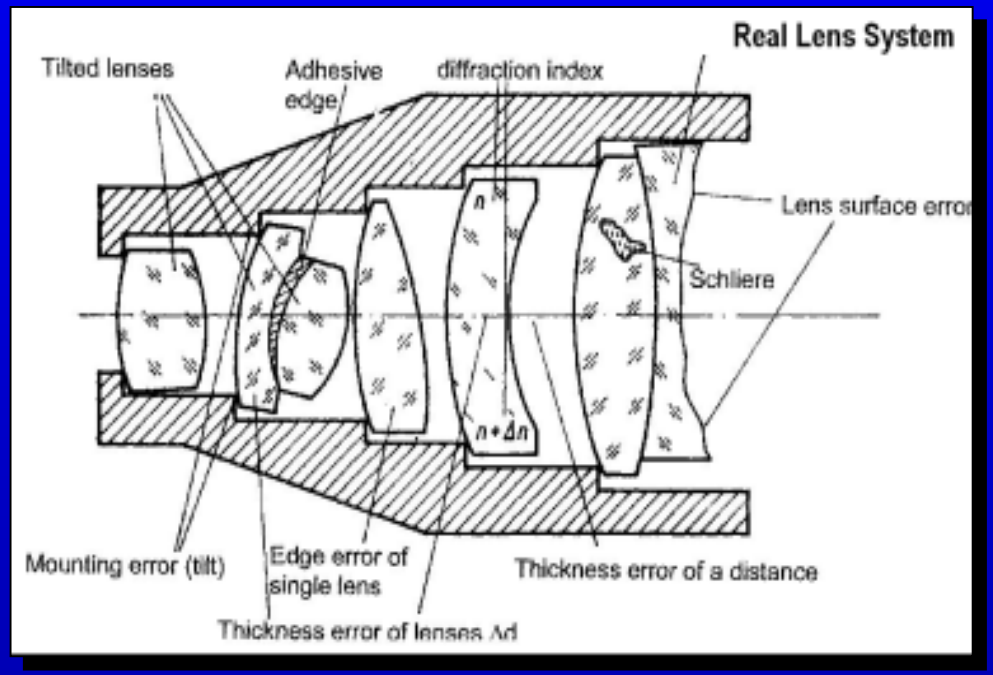
# About Tolerance

- What can go Wrong ?
  - Construction parameter errors
  - Mounting errors
- Tolerance Types
  - MTF or RMS wavefront….
  - Sensitive analysis
  - Inverse sensitivity analysis
  - Monte Carlo sample
- Compensators


Cheng-Fang Ho
ark@phys.ncku.edu.tw

# What Can Go Wrong ?

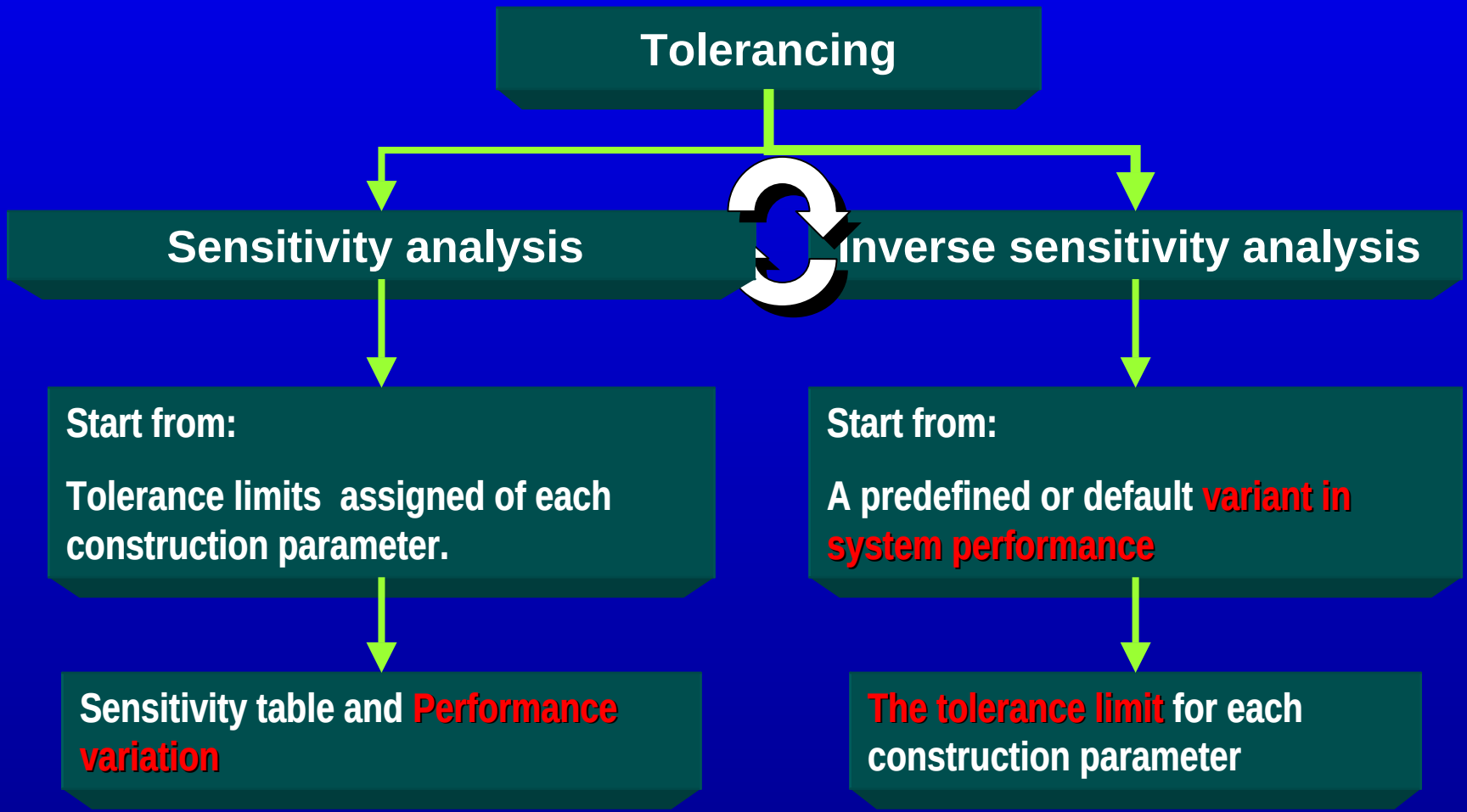
- Construction parameter errors
  - Lens surface error
  - Radius, thickness error
  - Index, V-number error….
- Mounting errors
  - Air space
  - Element tilting
  - Element decenterion





Cheng-Fang Ho
ark@phys.ncku.edu.tw

# Tolerance Types

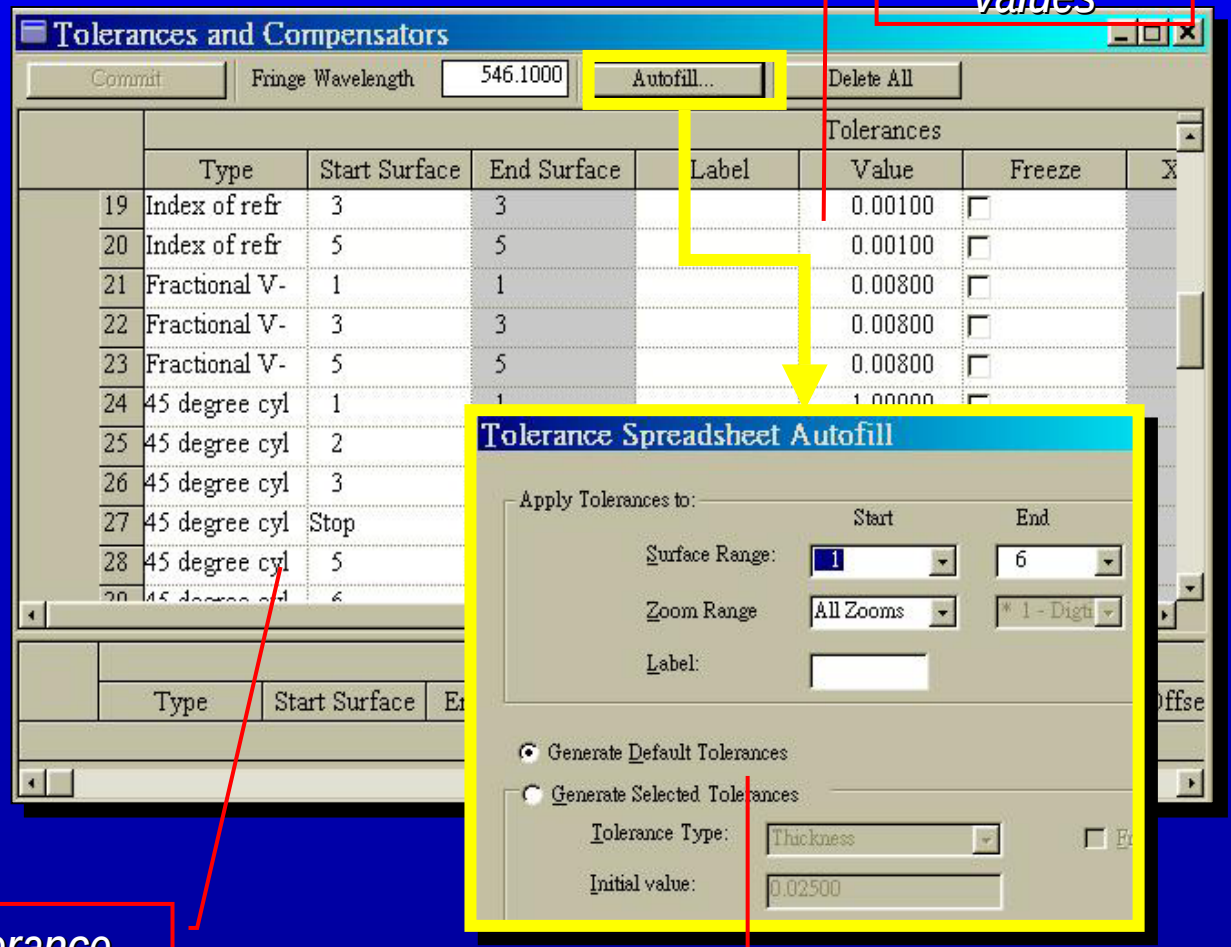




Cheng-Fang Ho
ark@phys.ncku.edu.tw

# Tolerance with Code V LDM

- Review > Tolerance
  - Creating and Checking the tolerance terms
- Analysis > Tolerance
  - Selecting the tolerance type




•Tolerance type

MTF
RMS wavefront error
Fiber Coupling Efficiency
Distortion
User - Finite Differences
User - Monte Carlo
Interactive Tolerancing

Tolerance terms

Tolerance terms selecting

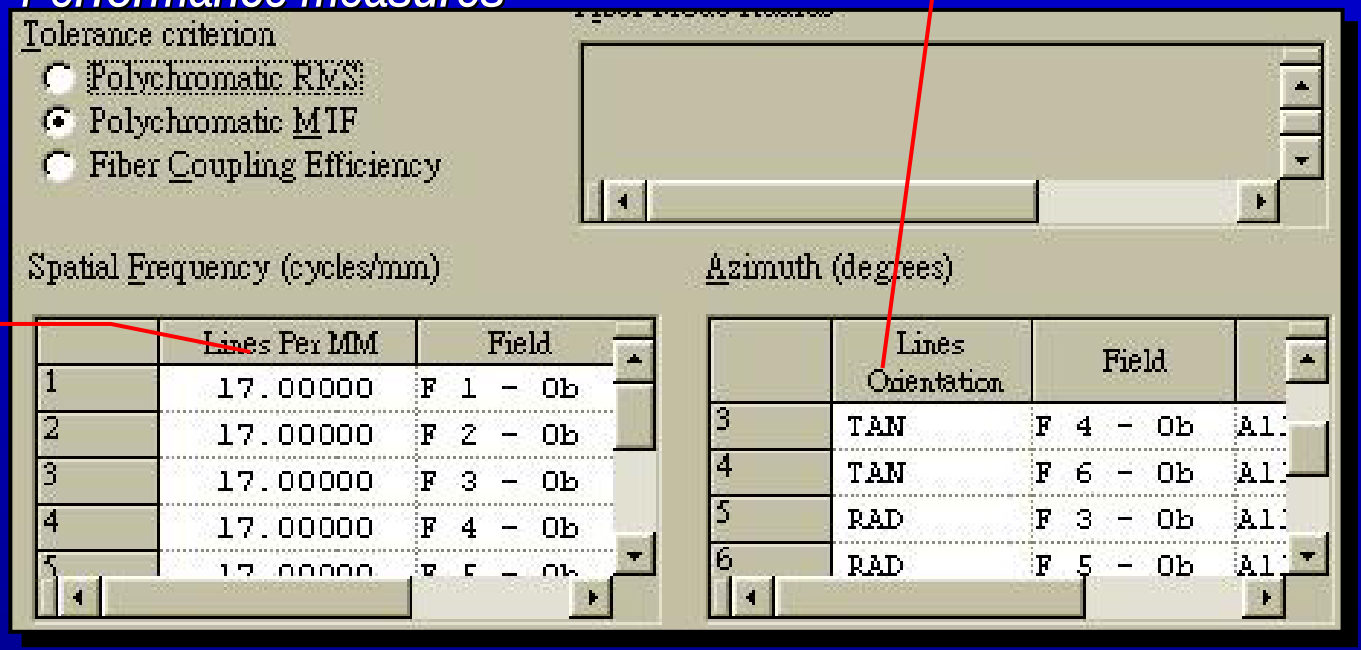

Cheng-Fang Ho
ark@phys.ncku.edu.tw

# MTF Tolerance ( 1 )

- *Tolerance terms*
  - *Code V default*
- *Analysis > Tolerance > MTF*
  - *The MTF degeneracy due to the error*

*Line Orientation*

*Performance measures*




*Spatial Frequency*


Cheng-Fang Ho
ark@phys.ncku.edu.tw

# MTF Tolerance ( 2 )

- Tolerance limits
  - Min. ,Max., and Increment value

| Type | Minimum | Maximum | Increment |
|---|---|---|---|
| DLF - DLF - Test plate fit | 2.00000 | 12.00000 | 2.00000 |
| DLT - Thickness | 0.00200 | 0.05000 | 0.00200 |
| DLN - Index of refraction | 0.00010 | 0.00200 | 0.00010 |
| DLV - Fractional V-number | 0.00200 | 0.00800 | 0.00100 |
| DLR - Radius | 0.00200 | 1.00000e+010 | 0.00200 |
| DLS - Surface sag at CA - | 0.00020 | 0.00500 | 0.00020 |
| DLC - Curvature - Alt to D | 1.00000e-010 | 1.00000e+010 | 1.00000e-006 |
| DAK - Conic constant | 1.00000e-010 | 1.00000e+010 | 1.00000e-006 |
| DAA - Aspheric A term | 1.00000e-010 | 1.00000e+010 | 1.00000e-006 |
| DAB - Aspheric B term | 1.00000e-010 | 1.00000e+010 | 1.00000e-006 |
| DAC - Aspheric C term | 1.00000e-010 | 1.00000e+010 | 1.00000e-006 |
| DAD - Aspheric D term | 1.00000e-010 | 1.00000e+010 | 1.00000e-006 |
| DAE - Aspheric E term | 1.00000e-010 | 1.00000e+010 | 1.00000e-006 |
| DAF - Aspheric F term | 1.00000e-010 | 1.00000e+010 | 1.00000e-006 |
| DAG - Aspheric G term | 1.00000e-010 | 1.00000e+010 | 1.00000e-006 |
| DAH - Aspheric H term | 1.00000e-010 | 1.00000e+010 | 1.00000e-006 |
| DAJ - Aspheric J term | 1.00000e-010 | 1.00000e+010 | 1.00000e-006 |

Tolerance terms and it's limits

- Code V default tolerance limits

Table 4. Tolerance Limits

**LIM** tolerance_code min max increment - For INV.
Defaults (where 3 numbers appear, they correspond to inches, centimeters, millimeters):

| tolerance_code | min | max | increment |
|---|---|---|---|
| Centered Tolerances | | | |
| **LIM DLF** | 2.0 | 12.0 | 2.0 |
| **LIM DLT** | .001/.002/.02 | .025/.05/.5 | .001/.002/.02 |
| **LIM DLN** | .0001 | .002 | .0001 |
| **LIM DLV** | .002 | .008 | .001 |
| **LIM DLR** | .001/.002/.02 | 1.E10 | .001/.002/.02 |
| **LIM DLS** | .0001/.0002/.002 | .002/.005/.05 | .0001/.0002/.002 |
| **LIM DLC\|DAK\|DAA\|DAB\| DAC\|DAD\|DAE\|DAF\| DAG\|DAH\|DAJ** | 1.E-10 | 1.E10 | 1.E-6 |
| **LIM HOM** | 5.E-6 | .001 | 5.E-6 |
| **LIM AXG\|RAG** | .0001 | .002 | .0001 |
| Irregularity Tolerances | | | |
| **LIM IRR\|CYD\|CYN** | .5 | 3.0 | .5 |
| Single Surface Decenters & Displacements | | | |
| **LIM DEC\|DLX\|DLY\|DLZ** | .001/.002/.02 | .025/.05/.5 | .001/.002/.02 |
| **LIM TIL\|DLA\|DLB\|DLG** | .0003 | .005 | .0005 |
| **LIM TIR\|TRX\|TRY** | .0001/.0002/.002 | .005/.01/.1 | .0001/.0002/.002 |
| Group Decentering Tolerances | | | |
| **LIM STI\|STX\|STY** | .0003 | .005 | .0005 |
| **LIM BTI\|BTX\|BTY** | .0003 | .005 | .0005 |
| **LIM BRL** | .0003 | .005 | .0005 |
| **LIM DIS\|DSX\|DSY\|DSZ** | .001/.002/.02 | .025/.05/.5 | .001/.002/.02 |
| **LIM ROL\|RLX\|RLY** | .001/.002/.02 | .025/.05/.5 | .001/.002/.02 |
| **LIM DOL** | .001/.002/.02 | .025/.05/.5 | .001/.002/.02 |

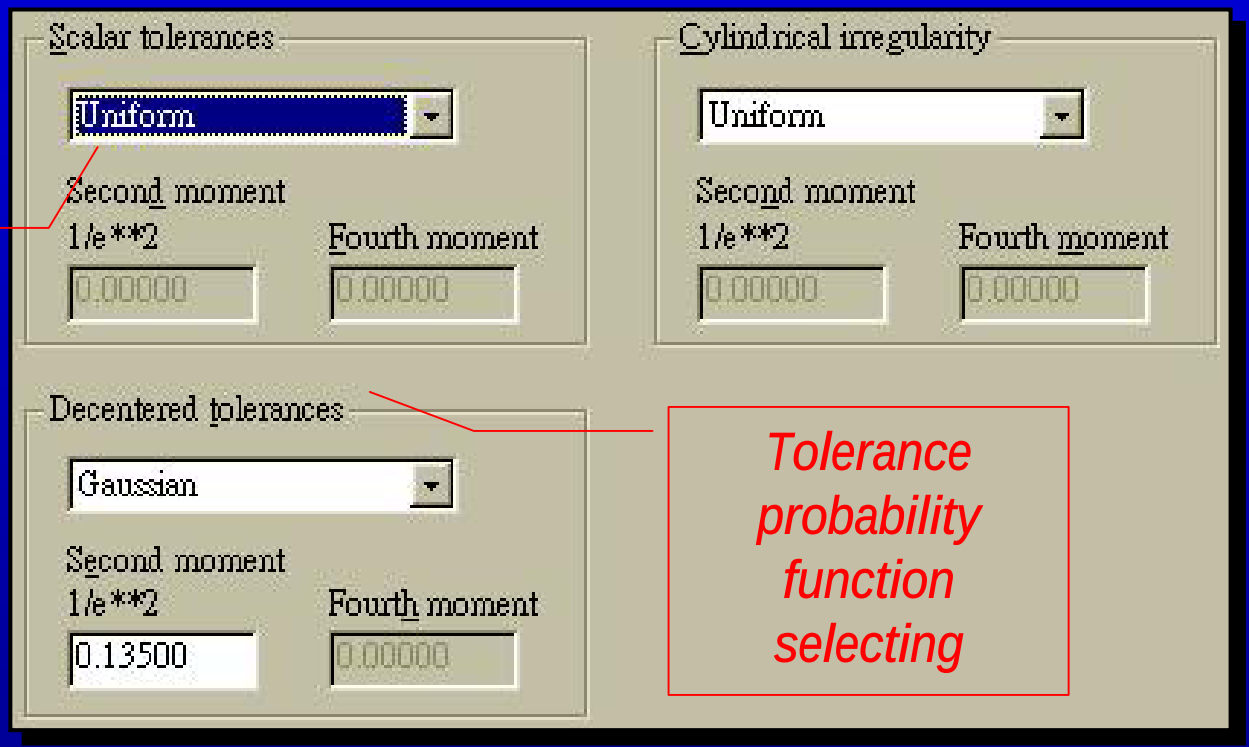
**Note that if limits have been specified for both test plate fit tolerances (DLF) and irregularity tolerances (IRR, CYD, or CYN), TOR will use the limits on irregularity tolerances for both test plate fit tolerances and irregularity tolerances. If limits have been specified for both radius tolerances (DLR) and sag (DLS) or curvature (DLC) tolerances, TOR will use the limits on radius tolerances for both radius tolerances and sag or curvature tolerances.**


Cheng-Fang Ho
ark@phys.ncku.edu.tw

# MTF Tolerance ( 3 )

- *Probability Functions*
  - *Uniform*
  - *2nd and 4th moments*
  - *Gaussian*
  - *End point*

*Tolerance probability function selecting*




*Tolerance probability function selecting*


Cheng-Fang Ho
ark@phys.ncku.edu.tw

# Understanding the Tolerance Output

- *Checking the changes in MTF*
  - *It's useful to budget for the reasonable tolerance terms*

| MANUFACTURING ERROR | | CHANGES IN MTF FOR PLUS AND MINUS MANUFACTURING ERRORS | |
|---|---|---|---|
| TYPE | CHANGE | | |
| DLR S1 | 0.0200000v | -0.117 | -0.058 |
| DLR S2 | 0.0200000v | 0.001 | -0.001 |
| DLR S3 | 0.0200000v | -0.004 | 0.002 |
| DLR S4 | 0.0200000v | -0.007 | -0.038 |
| DLR S5 | 0.0200000v | -0.005 | 0.002 |
| DLR S6 | 0.0200000v | 0.001 | -0.002 |
| DLT S1 | 0.0200000v | -0.002 | -0.024 |
| DLT S2 | 0.0200000v | -0.041 | -0.088 |
| DLT S3 | 0.0200000v | 0.001 | -0.016 |
| DLT S4 | 0.0200000v | 0.001 | -0.001 |
| DLT S5 | 0.0200000v | 0.002 | -0.004 |
| DLN S1 | 0.0001000v | 0.001 | -0.001 |
| DLN S3 | 0.0002000v | -0.001 | 0.001 |
| DLN S5 | 0.0005000v | 0.001 | -0.001 |
| DLV S1 | 0.0080000v | 0.001 | -0.001 |

*Tolerance term*

*Tolerance term changed value*

*Changes in MTF*


Cheng-Fang Ho
ark@phys.ncku.edu.tw

# Understanding the Tolerance Output

- It's easy to read out the MTF degeneracy

Change in MTF

Cumulative probability

The worst change in MTF

Specific spatial frequency

Design MTF and MTF degeneracy

• Probability of MTF in Change

```
Units - linear dimensions in mm.     angles in radians,
        fringes in wavelengths at 546.1 nm.

The probable change in MTF assumes a uniform distribution of manufacturing
errors over the range for all parameters except tilt and decenter
which have a truncated Gaussian distribution in X and Y

     CUMULATIVE          CHANGE
    PROBABILITY          IN MTF
      50.0 PCT.          -0.064          * If it is assumed that the errors can
      84.1 PCT.          -0.179            only take on the extreme values
      97.7 PCT.          -0.293 *          of the tolerances, the 97.7 percent
      99.9 PCT.          -0.407            probable change in MTF is  -0.716
```

• MTF degeneracy of specific spatial frequency

| RELATIVE FIELD | FREQ L/MM | AZIM DEG | WEIGHT | DESIGN | DESIGN + TOL * |
|---|---|---|---|---|---|
| 0.00, 0.00 | 17.00 | TAN | 1.00 | 0.909 | 0.664 |
| 0.00, 0.39 | 17.00 | TAN | 1.00 | 0.920 | 0.644 |
| 0.00, 0.39 | 17.00 | RAD | 1.00 | 0.895 | 0.602 |
| 0.00, 0.69 | 17.00 | TAN | 1.00 | 0.885 | 0.461 |
| 0.00, 0.69 | 17.00 | RAD | 1.00 | 0.743 | 0.305 |
| 0.00, 1.00 | 17.00 | TAN | 1.00 | 0.784 | 0.000 |
| 0.00, 1.00 | 17.00 | RAD | 1.00 | 0.767 | 0.257 |

# Re-budget Tolerance and Analysis

- Based on the tolerance terms contribution in MTF error
  - Re-budgeting the tolerance range
  - Limiting the tolerance terms which make a larger error

- MTF degeneracy before re-budget

| RELATIVE FIELD | FREQ L/MM | AZIM DEG | WEIGHT | DESIGN | DESIGN + TOL * |
|---|---|---|---|---|---|
| 0.00, 0.00 | 17.00 | TAN | 1.00 | 0.909 | 0.664 |
| 0.00, 0.39 | 17.00 | TAN | 1.00 | 0.920 | 0.644 |
| 0.00, 0.39 | 17.00 | RAD | 1.00 | 0.895 | 0.602 |
| 0.00, 0.69 | 17.00 | TAN | 1.00 | 0.885 | 0.461 |
| 0.00, 0.69 | 17.00 | RAD | 1.00 | 0.743 | 0.305 |
| 0.00, 1.00 | 17.00 | TAN | 1.00 | 0.784 | 0.000 |
| 0.00, 1.00 | 17.00 | RAD | 1.00 | 0.767 | 0.257 |

- MTF degeneracy after re-budget

| RELATIVE FIELD | FREQ L/MM | AZIM DEG | WEIGHT | DESIGN | DESIGN + TOL * |
|---|---|---|---|---|---|
| 0.00, 0.00 | 17.00 | TAN | 1.00 | 0.909 | 0.857 |
| 0.00, 0.39 | 17.00 | TAN | 1.00 | 0.920 | 0.873 |
| 0.00, 0.39 | 17.00 | RAD | 1.00 | 0.895 | 0.810 |
| 0.00, 0.69 | 17.00 | TAN | 1.00 | 0.885 | 0.775 |
| 0.00, 0.69 | 17.00 | RAD | 1.00 | 0.743 | 0.574 |
| 0.00, 1.00 | 17.00 | TAN | 1.00 | 0.784 | 0.532 |
| 0.00, 1.00 | 17.00 | RAD | 1.00 | 0.767 | 0.589 |

The MTF raised after re-budget


Cheng-Fang Ho
ark@phys.ncku.edu.tw

# Design Example (2) : 10X Microscope Objective

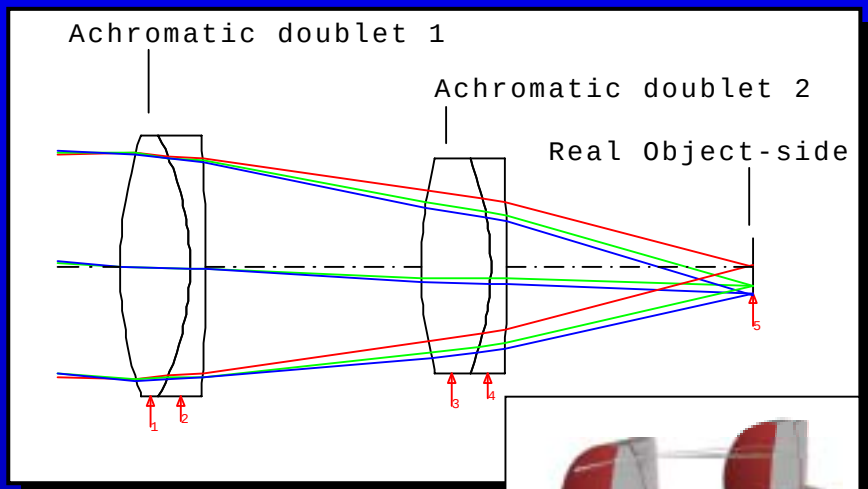

Cheng-Fang Ho
ark@phys.ncku.edu.tw

# Outline

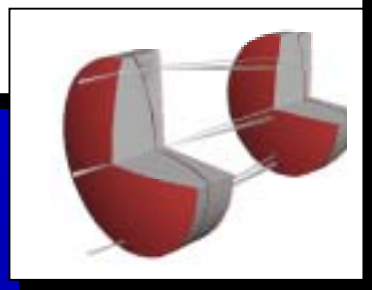
- Specification of 10X microscope objective
- Selecting a starting point
- Building the Lens system
- Performance evaluation
- Optimization and Re-evaluation
- Tolerance analysis


Cheng-Fang Ho
ark@phys.ncku.edu.tw

# 10X Lister-type Microscope Objective




• *Lens layout*



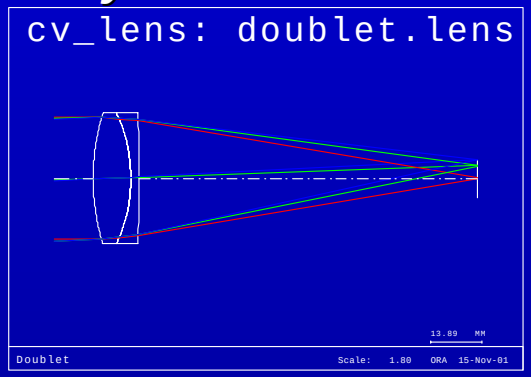
| Typical medium power objective specification: | |
|---|---|
| * Lister-type : Two achromatic Doublet | |
| * Magnification (M) : | 10X |
| * The image-side N.A : | 0.025* |
| * The object-side N.A : | 0.025M |
| * Image field diameter : | 20 mm |
| * The object-to-image distance: | 180 mm |
| * The image distance : | 160 mm |


Cheng-Fang Ho
ark@phys.ncku.edu.tw

# Selecting A starting Point

- Starting a new lens
  - Selecting a suitable stating point
  - Use New Lens Wizard
    - CODE V sample lenses

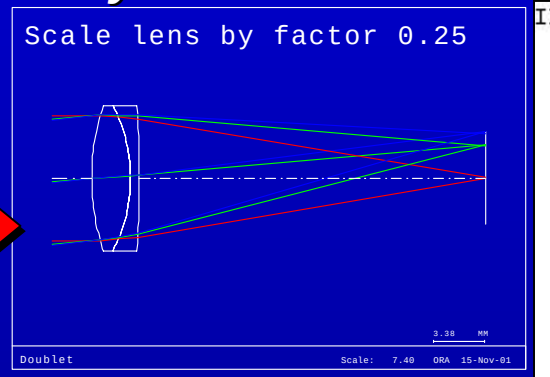
**• Layout & First order output**




| INFINITE CONJUGATES | |
|---|---|
| EFL | 100.0014 |
| BFL | 92.4514 |
| FFL | -99.7469 |
| FNO | 3.0000 |
| IMG DIS | 92.4514 |
| OAL | 12.6969 |
| PARAXIAL IMAGE | |
| HT | 5.2409 |
| ANG | 3.0000 |
| ENTRANCE PUPIL | |
| DIA | 33.3333 |
| THI | 0.0000 |
| EXIT PUPIL | |
| DIA | 33.4184 |
| THI | -7.8052 |

Scale by 0.25

**• Layout & First order output**




EFL=25mm

| INFINITE CONJUGATES | |
|---|---|
| EFL | 25.0004 |
| BFL | 23.1129 |
| FFL | -24.9367 |
| FNO | 3.0000 |
| IMG DIS | 23.1129 |
| OAL | 3.1742 |
| PARAXIAL IMAGE | |
| HT | 1.3102 |
| ANG | 3.0000 |
| ENTRANCE PUPIL | |
| DIA | 8.3333 |
| THI | 0.0000 |
| EXIT PUPIL | |
| DIA | 8.3546 |
| THI | -1.9513 |


Cheng-Fang Ho
ark@phys.ncku.edu.tw

# Building the Lens System

- Combination of two achromatic doublet
  - determine the separation distance between two element d
  - Objection distance S
  - Image distance S'
- Base on the first order approximation
  - $f_A$ and $f_B$ are EFL of each doublet (25 mm )
  - $\phi_A$ is the power of doublet A ( $\phi_A = 1/f_A$ )
  - T is total track length (the object-to-image distance = 180 mm )
  - m is magnification ( 10X )
- The solution is
  - d = 8 mm
  - S = -11 mm
  - S'= 160 mm

$$O = d^2 - dT + T(f_A + f_B) + \frac{(m-1)^2 f_A f_B}{m}$$

$$s = \frac{(m-1)d + T}{(m-1) - md\phi_A}$$

$$s' = T + s - d$$

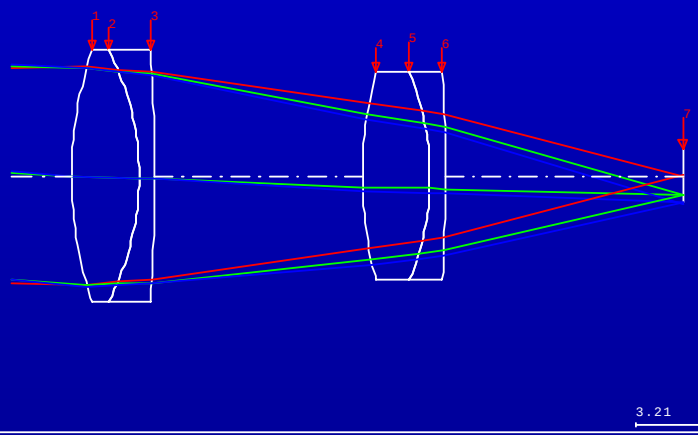


Cheng-Fang Ho
ark@phys.ncku.edu.tw

## • Surface date

| | RDY | THI | RMD | GLA | CCY | THC | GLC |
|---|---|---|---|---|---|---|---|
| ▷ OBJ: | INFINITY | 160.000000 | | | 100 | 100 | |
| STO: | 15.26805 | 2.586408 | | BSM24_OHARA | 0 | 100 | |
| 2: | -10.54386 | 0.587820 | | SF1_SCHOTT | 100 | 100 | |
| 3: | -79.03463 | 8.000000 | | | 0 | 0 | |
| 4: | 15.26805 | 2.586408 | | BSM24_OHARA | 0 | 0 | |
| 5: | -10.54386 | 0.587820 | | SF1_SCHOTT | 100 | 0 | |
| 6: | -79.03463 | 9.123212 | | | 100 | PIM | |
| IMG: | INFINITY | 0.000000 | | | 100 | 100 | |

## • System layout




FNO=1/2NA, NA~0.25

Reduction Ratio = 0.1

Objective distance = 160 mm

Total track length =183.4717 mm

## • First order output

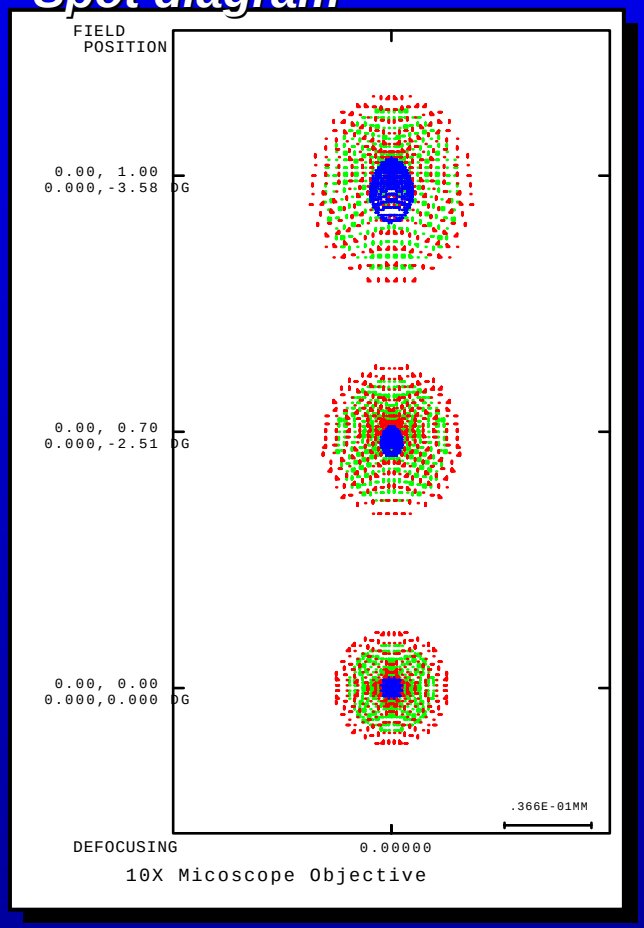
```
INFINITE CONJUGATES
    EFL          15.6061
    BFL           7.5068
    FFL          -9.3306
    FNO           1.8727
AT USED CONJUGATES
    RED           0.1036
    FNO           1.9894
    OBJ DIS     160.0000
    TT          183.4717
    IMG DIS       9.1232
    OAL          14.3485
    PARAXIAL IMAGE
     HT           1.0358
     THI          9.1232
    ANG           3.5763
    ENTRANCE PUPIL
     DIA          8.3333
     THI          0.0000
    EXIT PUPIL
     DIA         13.9381
     THI        -18.5955
```



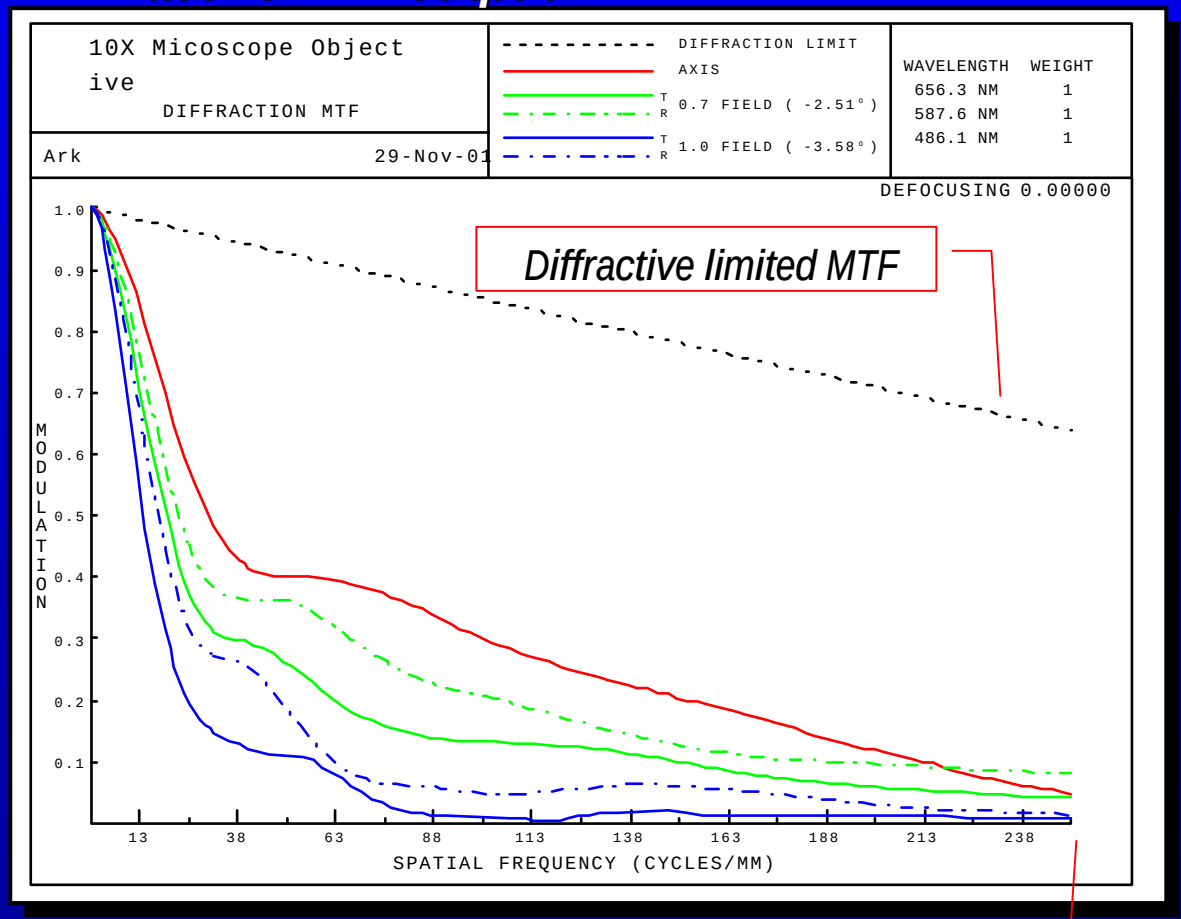
Cheng-Fang Ho
ark@phys.ncku.edu.tw

# Performance Evaluation

- **Spot diagram**




- **Diffractive MTF output**




- The MTF is far away from the diffractive limited MTF

Max. spatial frequency for analysis = 250 lp/mm



Cheng-Fang Ho
ark@phys.ncku.edu.tw

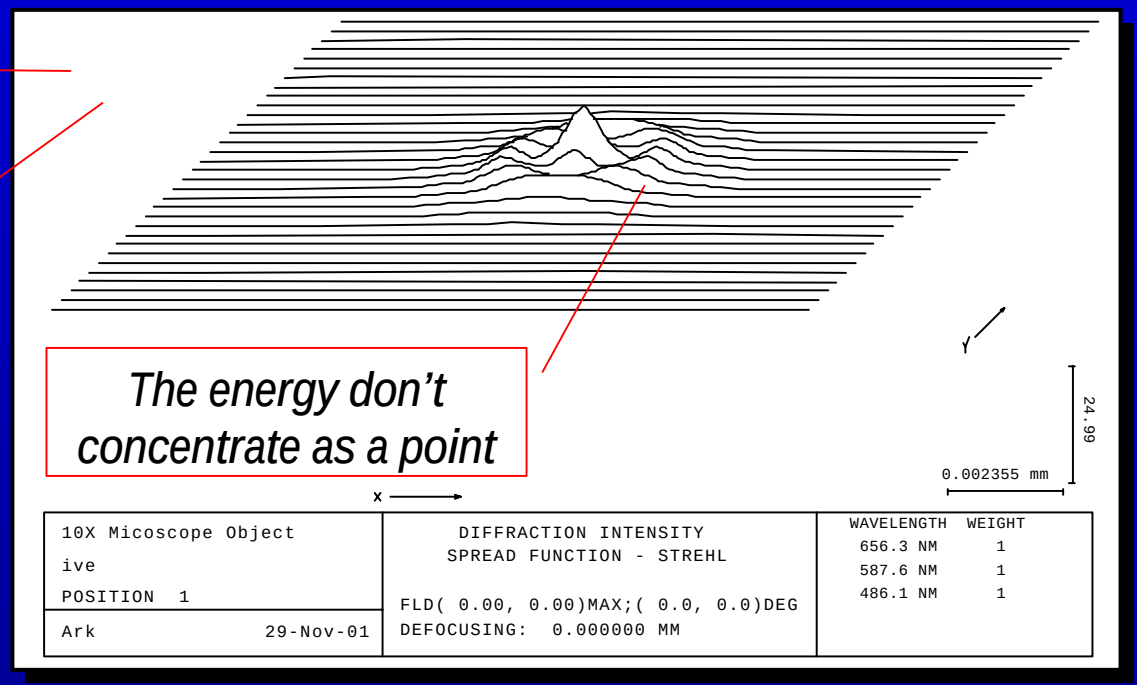
# Performance Evaluation – PSF

- *PSF – Point Spread Function*
  - *It can be performed as the “ Strehl Ratio ”*
  - *It is useful to check the resolution or focusing ability of a system*

- ***Strehl PSF output***

*This kind of PSF output mean poor resolution*

*NOTE :The shape of PSF is sharper, the resolution is better.*



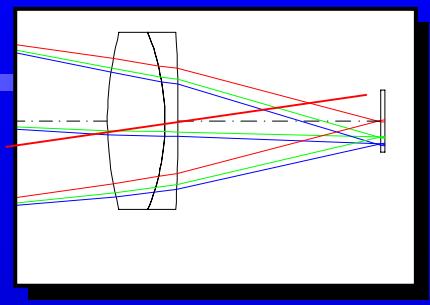


Cheng-Fang Ho
ark@phys.ncku.edu.tw

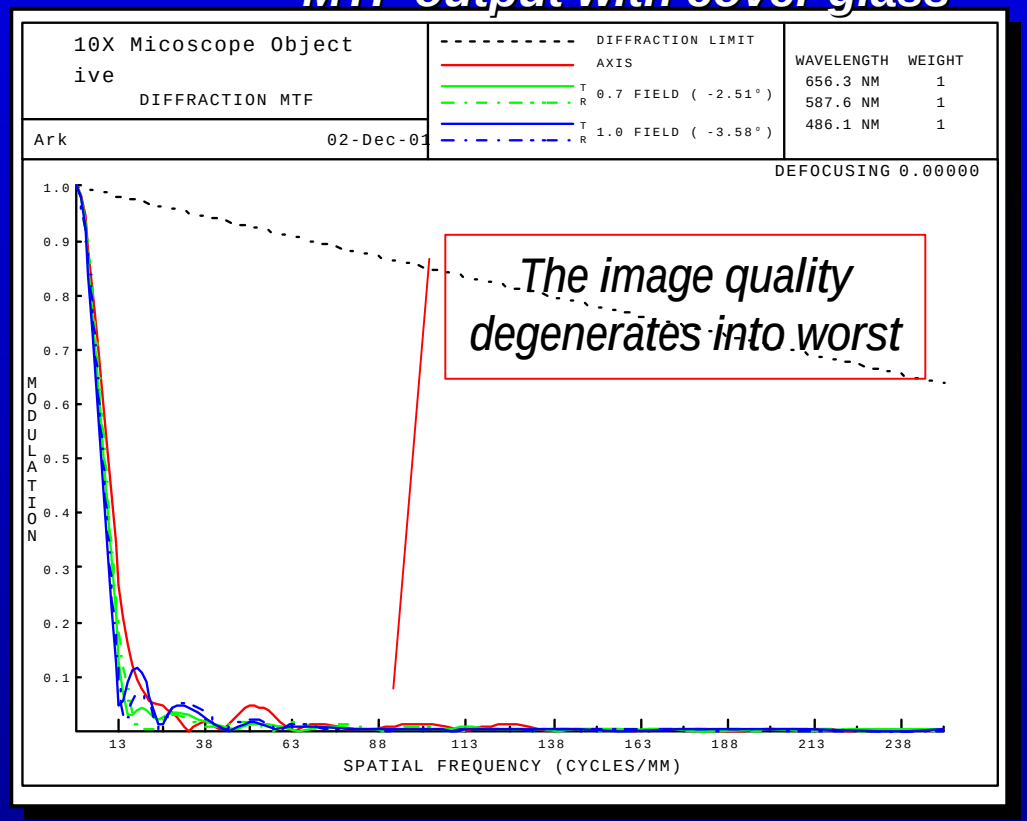
# Performance Evaluation

- Consider the “ Cover Glass”
  - 0.17~0.18 mm, this type of glass is close to K5_SCHTOO

Cover glass on image side



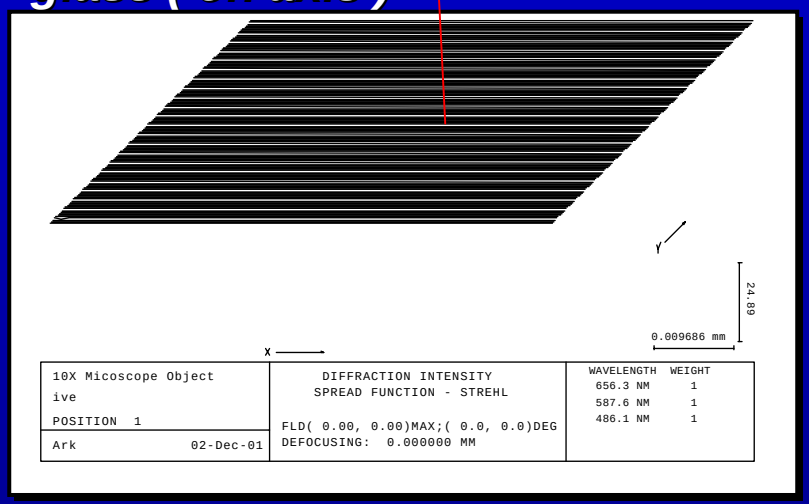
• **MTF output with cover glass**




Very very poor resolution

The image quality degenerates into worst

• **Strehl PSF output with cover glass ( on axis )**



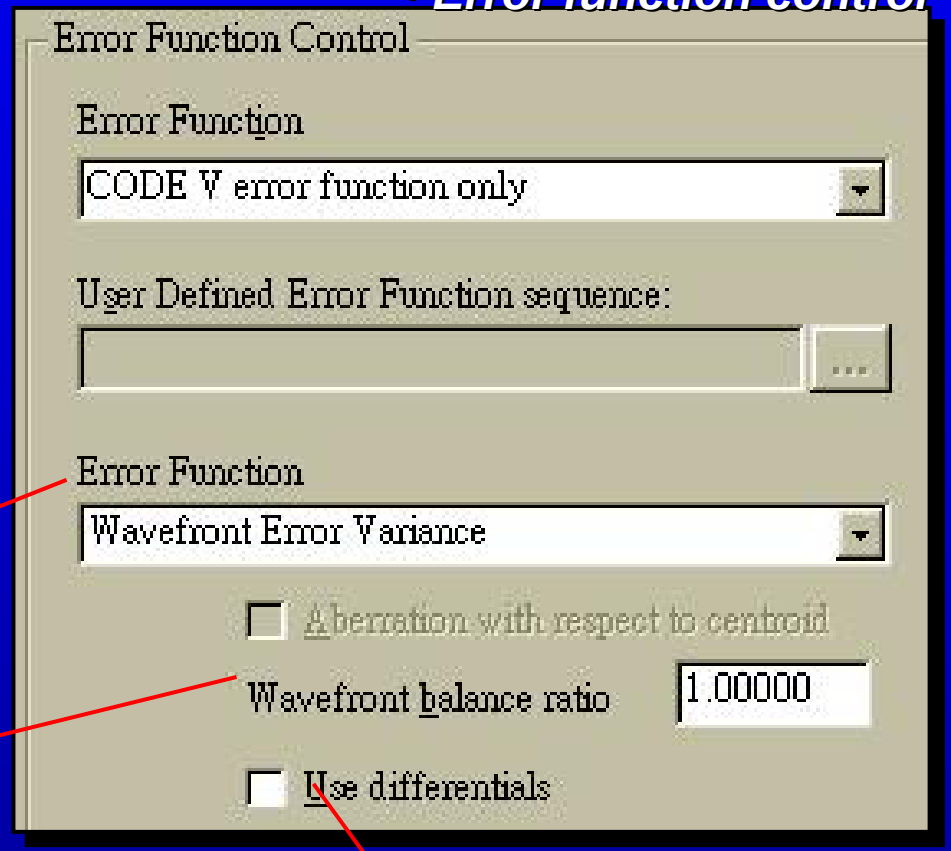


Cheng-Fang Ho
ark@phys.ncku.edu.tw

# Optimization

- Constraints
  - Reduction ration= 0.1
  - Object-image distance =180 mm
- Error function type
  - CODEV error function
  - Wavefront error variance

• Error function control




Wavefront error variance

Wavefront balance ratio (default)

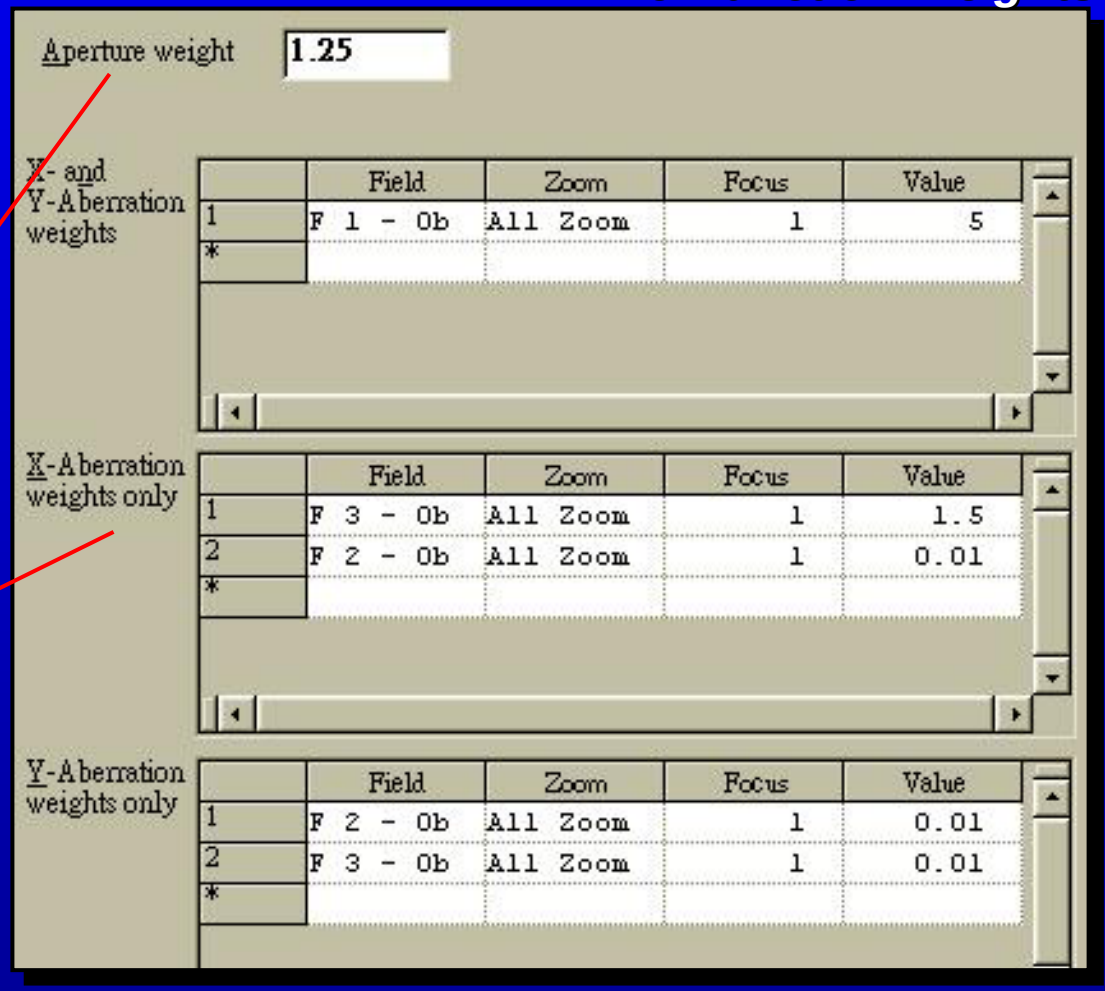
Differentials (no)


Cheng-Fang Ho
ark@phys.ncku.edu.tw

# Optimization

- Control the aperture weight to get the balance between contrast and resolution
- Control the weights of fields and azimuths to raise the total performance

• **Error function Weights**




Aperture weight

Aberration weights for fields and azimuths


Cheng-Fang Ho
ark@phys.ncku.edu.tw

# Optimization- understanding output

```
Active Constraints -  7:      target          value          diff          cost
RED Z1                =   1.03578E-01   1.03578E-01  -3.543E-09   1.550E-07
TT Z1                 =   1.83472E+02   1.83472E+02   2.842E-14   1.525E-10
GL A S1                                                            8.360E-10
Mn ET S1                                                          -1.318E-11
Mx CT S2                                                           6.513E-11
Mn ET S4                                                          -1.451E-10
Mn CT S5                                                          -2.084E-10
Mn ET S7

CYCLE NUMBER 10:

ERR. F.  =          0.06077875        (change =        -0.00147056)

OPD      0.02607179      0.08604974      0.15741766
WAV      0.06010580      0.12105892      0.22794521


   Normal AUTO Completion - System improvement less than IMP
```

*Constraint : Reduction ratio*

*Constraint : Total track*

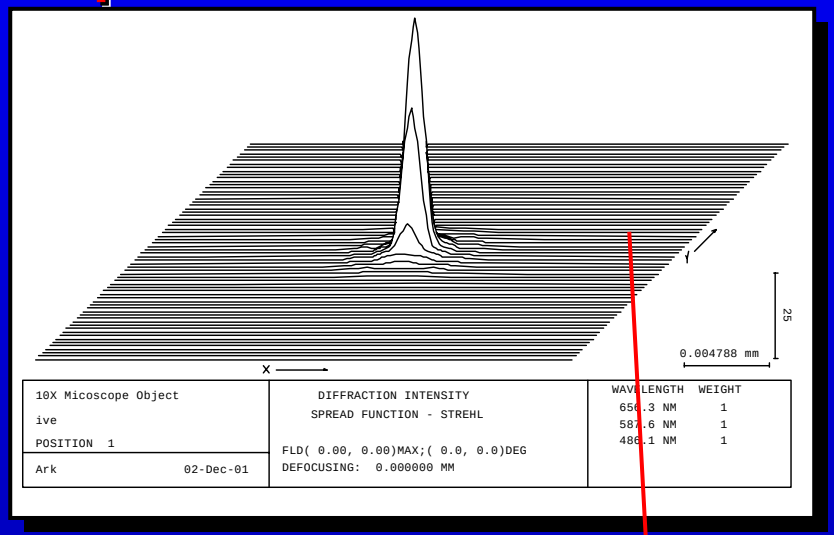
*Error function output*

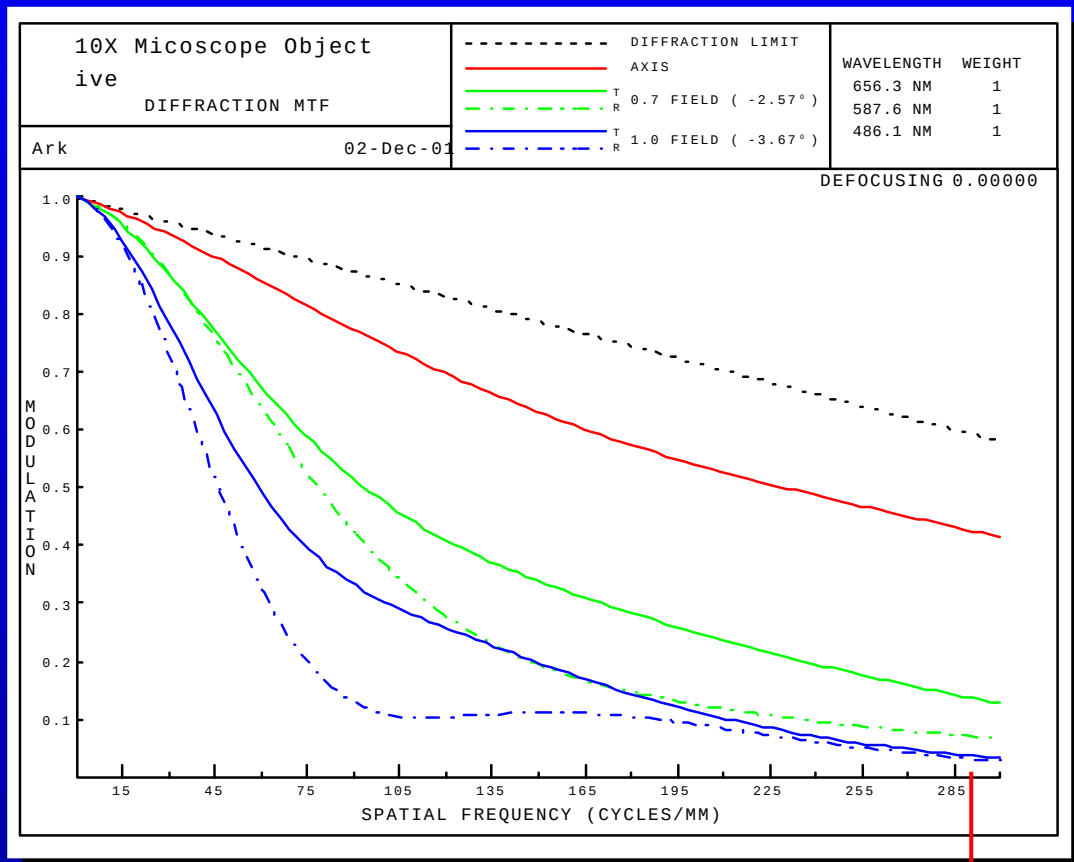
*The OPD and WAV*

- *The error function output is changed by the Difference error function type*
  - *Here , the ERR. F is based on the OPD*
- *The ERR. F of each fields are still a good guideline to determine the weights of error function*

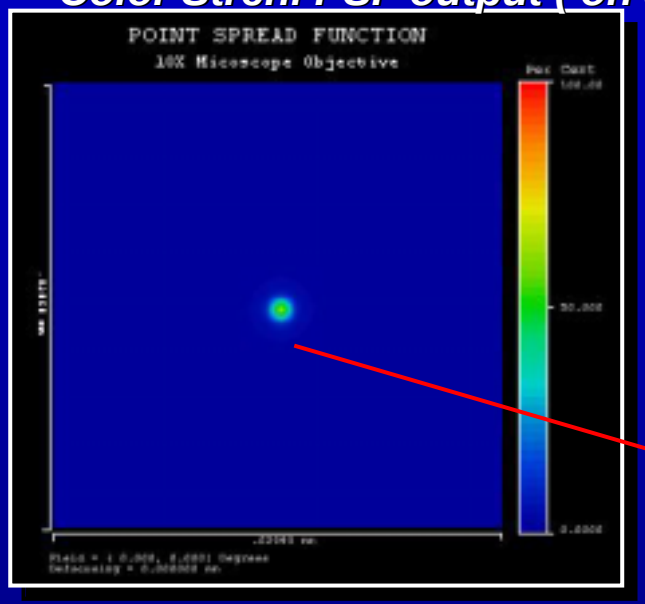

Cheng-Fang Ho
ark@phys.ncku.edu.tw

# Optimization and Revaluation




- *Color Strehl PSF output ( on axis )*




*The sharp PSF shape means a higher resolution*

*max. spatial frequency 300 lp/mm*

*The color shows the Strehl ratio directionally*

*Cheng-Fang Ho*
*ark@phys.ncku.edu.tw*

# Tolerance Analysis


Cheng-Fang Ho
ark@phys.ncku.edu.tw