Design Process Example

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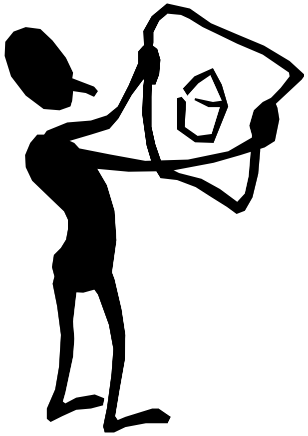


Opti 517

Goal of Optimization

- Å The goal of optimization is to achieve a design which meets the system performance requirements <u>and</u> all the optical and mechanical constraints
  - ï Constraints include things like focal length, overall lengths, clearances, distortion, etc.

- Å Optimization requires:
  - ï An error function (sometimes called a merit function)
    - Å This is a measure of the "non-goodness" of the lens
  - ï A process for reducing the error function
    - Å The way to get from the current state to better performance
  - ï A method for controlling the boundary conditions (constraints)
    - Å Acceptable performance which violates the constraints is not useful

What is an Error Function?

- A single positive number that represents the current state of the optical system

The Mona Lisa

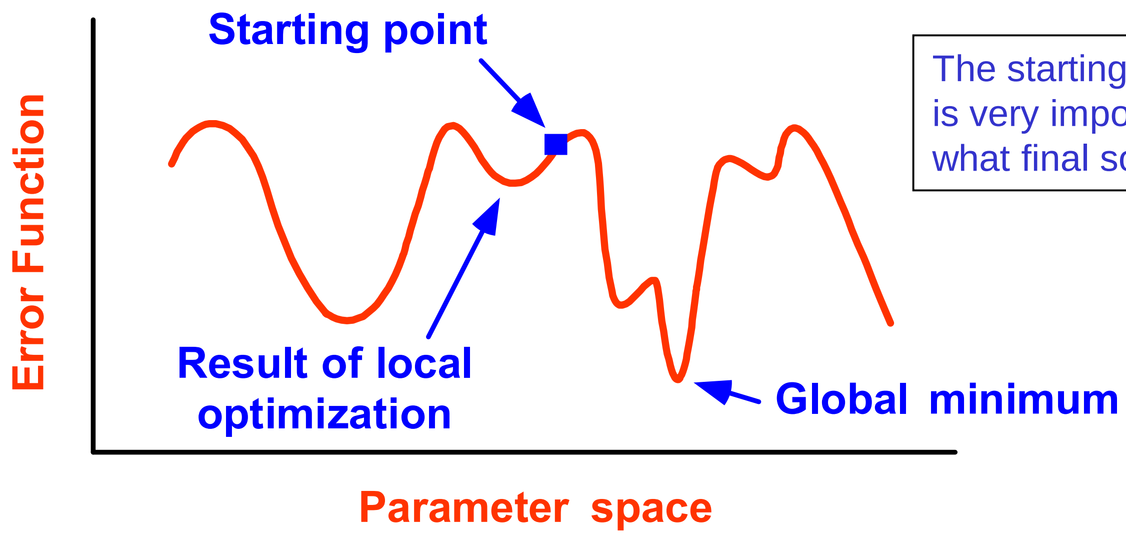
The "Single Number" representation of the Mona Lisa

- The error function is usually related to aberrations or image errors but can include other components as well
- Error functions are always structured such that smaller values are better than larger values
  - 0 is the best error function (zero errors)

- In CODE V, the default error function represents the mean square spot radius, suitably averaged over wavelengths and over the field of view, times 10^6
  - An error function of 16 means the RMS spot radius averaged over the FOV is 0.004 inches (dimensions in inches) or 4 microns (dimensions in mm)
  - Thus, it is possible to relate the default error function value to the size of the geometrical blur needed to achieve the desired performance
- It is also possible in CODE V to optimize on other error functions, such as RMS wavefront error, MTF, or a user-defined error function

Reducing the Error Function

- Å Most optical design programs use a method called Damped Least Squares
  - ï This is very effective at finding the local minimum
  - ï The approach to the solution proceeds in a damped manner so as to not overshoot the minimum
- Å Most optical design programs proceed to a local minimum, although most also have an option to search for a global minimum (takes longer and is not guaranteed to find the true global minimum)



The starting point of an optimization is very important in determining what final solution is obtained

Finding a Suitable Starting Point

- The choice of starting point is crucial in getting to a good optimization solution
  - A poor starting point usually has little or no hope of getting to a useful solution
- The considerations made by a designer in selecting a starting point include:
  - The application of the lens (how it will be used)
  - Lens form (Double Gauss, triplet, Petzval, wide-angle, etc.)
  - Number of lenses overall and number of lenses in each group
  - Glass choice
  - Whether and where to use special surfaces (aspherics, diffractives, etc.)
  - Constraints (optical and mechanical)
- How is this initial choice made?
  - Similar designs
  - Patents, literature, technical papers
  - Books (Smith, Laikin, Kingslake, etc.)
  - Experience
  - Lucky guess?

Variables

- The variables the optical designer has at his control include
  - Radii
  - Lens thicknesses and spacings
  - Glass choice (index and dispersion)
  - Special surface parameters (e.g., aspheric coefficients)
  - In unusual systems, tilt and decenter of one or more elements

- Depending on the complexity of the lens system, an optimization problem may have only a few variables or to up to 100 or more variables
  - With more variables, it takes longer to design the lens, but the design will usually turn out better

Constraints

- Constraints, or boundary conditions, must be imposed for many reasons
  - To meet optical system specifications (e.g., focal length, pupil locations)
  - To meet packaging requirements (e.g., overall length, diameters)
  - To aid manufacturability (e.g., lens edge thicknesses, clearances)
- Meeting both the performance requirements and the constraints is what makes optical design a challenging task
- Many constraints are specifically imposed by the designer
  - Focal length, distortion, overall length, etc.
- Some constraints are imposed automatically by the program (at least in CODE V) unless specifically released
  - Minimum and maximum lens thicknesses, minimum edge thicknesses of lenses, positive air spacings axially and at lens edges, etc.
- Every active constraint uses up one free variable available to achieve image quality
  - You cannot have more constraints than variables!
  - You should have more variables than constraints to have some free variables left over to improve the image quality

Controlling Constraints

- In CODE V, constraints are specified separately from the error function
  - They can be included, if desired
- The constraints can be equality constraints (e.g., EFL = 10) or can be one- or two-sided (e.g., OAL S1..10 < 10, or DIY FL > -0.02 < 0.02)
- They are controlled by a mathematical algorithm called Lagrange multipliers
- As a result, constraints in CODE V always meet their specified values
  - If holding a constraint to its target impacts the error function, this is something that must be accepted

- In Zemax, constraints are included as part of the merit function
- Their contributions to the merit function are their differences between their current values and their targets times a weighting factor
- How closely a given constraint is held is often a function of how large a weighting factor is used for that constraint
- As a result, in my experience, it is harder to get exact constraint control in Zemax than it is in CODE V

The Optimization Process

- Designers usually start with (hopefully) a reasonable starting point and a reasonable set of variables
- They make preliminary optimization runs
- They modify the optimization as needed to achieve better performance
  - Change the starting point
  - Add or delete elements and/or variables
  - Change the error function (change the weightings or other modifications)
  - Add or delete constraints
- They monitor the constraints and modify the optimization as needed to ensure the constraints are met
- When they have a possible solution, they perform detailed optical analyses to see if the performance specifications are met and make preliminary tolerance runs to see if the design is producible
  - If the performance is not met or the tolerances are not reasonable, they repeat the process
- They stop only when the money runs out or when the time runs out

Design of a Security Camera

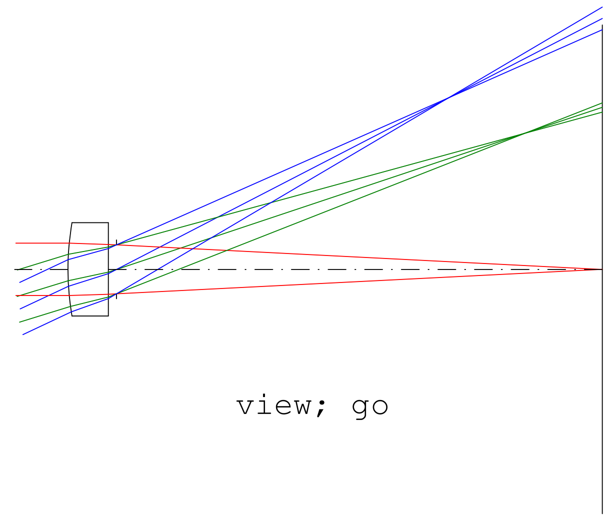
- Mounted on the ceiling, so objects of interest are located far enough away from the lens that we may assume the object is at infinity
- Optical system comprises an imaging lens and a CCD sensor
- A standard 1/3 inch CCD (one of the smallest formats) will be used
  - 4:3 aspect ratio, 6 mm diagonal dimension (4.8 mm x 3.6 mm)
- First, estimate the size of the scene you want to capture and the approximate distance the scene is from the camera
  - To image the full height of a 5'10" person 6 feet from the camera, a FOV of 50° (diagonal) is needed
- EFL = (6/2)/tan(50°/2) = 6.43 mm
- To keep the system small, the f/# is set to f/10
- Wavelengths are standard d, F, C (visible spectrum)
- Performance specification:
  - VGA format (640 x 480 pixels), pixel size is 7.5 μm
  - Nyquist frequency is 66.67 lp/mm
  - Set the MTF specification to be > 50% at 50 lp/mm

Ceiling mounted security camera

Step 1 – Enter a Starting Lens

- Start with a plano-convex N-BK7 lens (n_d = 1.5168)
  - Thickness is 0.5 mm, radius is 3.33 mm (6.43*0.5168)
  - Stop is 0.1 mm behind the lens

```
lens
rdm
tit "Security Camera"
dim m
fno 10
wl 656.3 587.6 486.1
yan 0 17 25
s 3.33 0.5 nbk7
s 0 .1
s 0 0
sto
pim
go
set vig
```



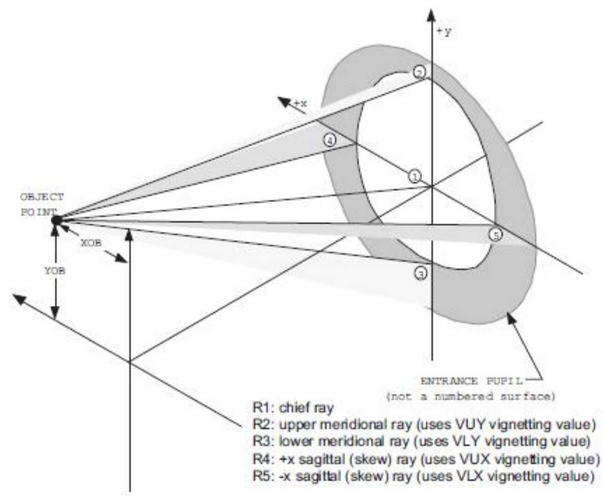

```
tho
```

Position 1, Wavelength = 587.6 NM

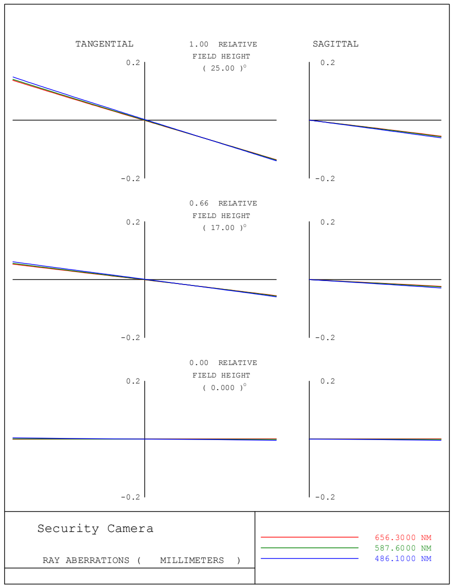
	SA	TCO	TAS	SAS	PTB	DST
1	-0.000655	-0.008167	-0.057012	-0.034399	-0.023093	-0.142877
2	-0.000216	0.006476	-0.064710	-0.021570	0.000000	0.215538
STO	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
SUM	-0.000871	-0.001691	-0.121723	-0.055970	-0.023093	0.072661

What Does SET VIG Do?

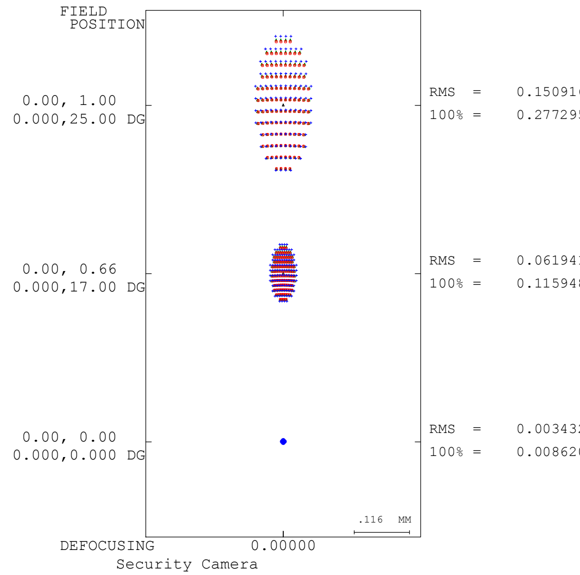
- Å CODE V traces rays initially to the entrance pupil
- Å It uses 5 reference rays to define the shape of the used entrance pupil for a given field point
  - ï R1 ï Chief ray
  - ï R2 and R3 ï Upper and lower meridional rays (YZ plane)
  - ï R4 and R5 ï Upper and lower sagittal rays (XZ plane)
- Å If the lens has pupil aberration and/or limiting apertures, the off-axis reference rays may not hit the entrance pupil at its full diameter or may not fully fill the stop surface
- Å Vignetting factors are used to adjust the reference ray positions in the entrance pupil
- Å In the lens here, the stop is internal to the lens, and vignetting factors are used to ensure the reference rays R2 to R5 hit the edge of the stop surface aperture, fully filling the stop



Starting Performance

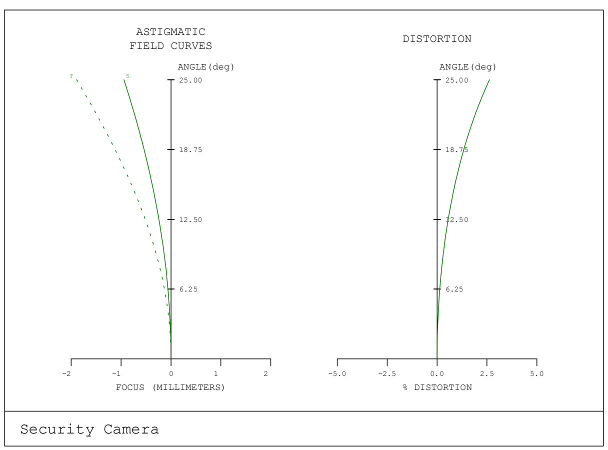


rim; ssi 0.2; go

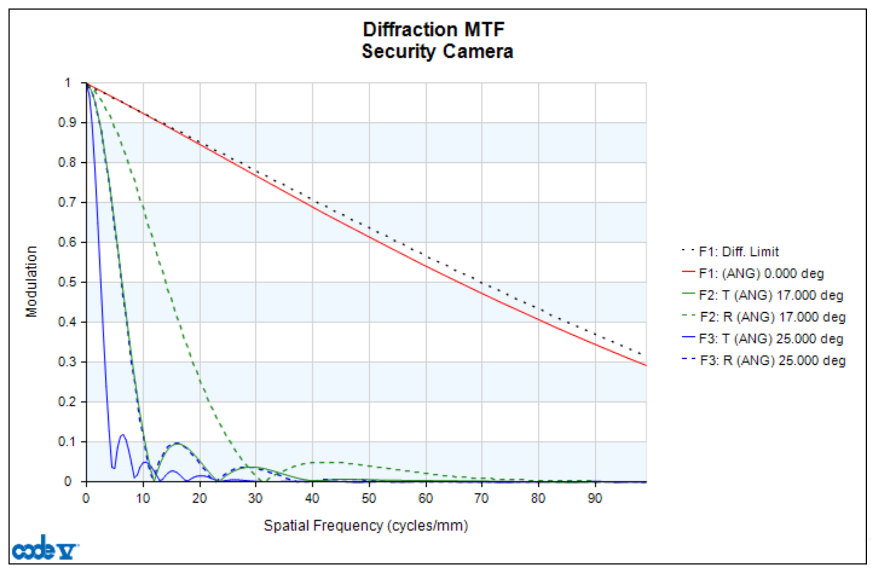


spo; go

fie; go

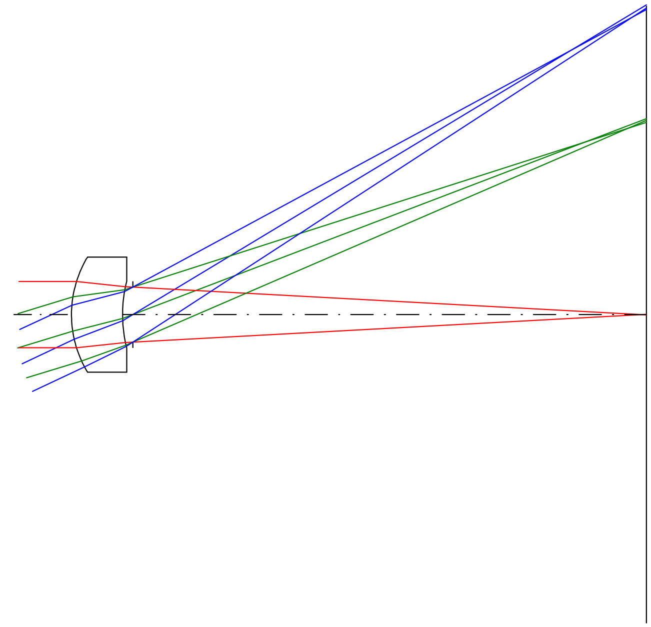


mtf; mfr 100; go



Step 2 – Bend the Lens

Å Vary the radii of the lens and the defocusing
  - ï The defocus is varied as the paraxial image plane is often not the best compromise image location across the field
  - ï Stop location is kept fixed

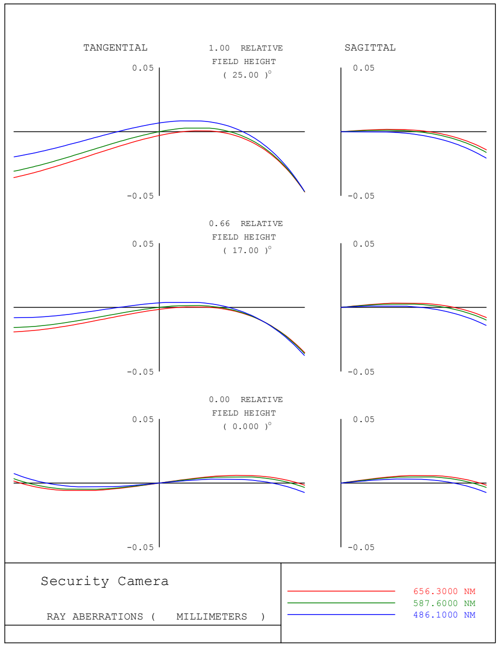


```
ccy s1..2 0
thc si 0
auto; int; efl = 6.43; go  ! 6 cycles
set vig
```

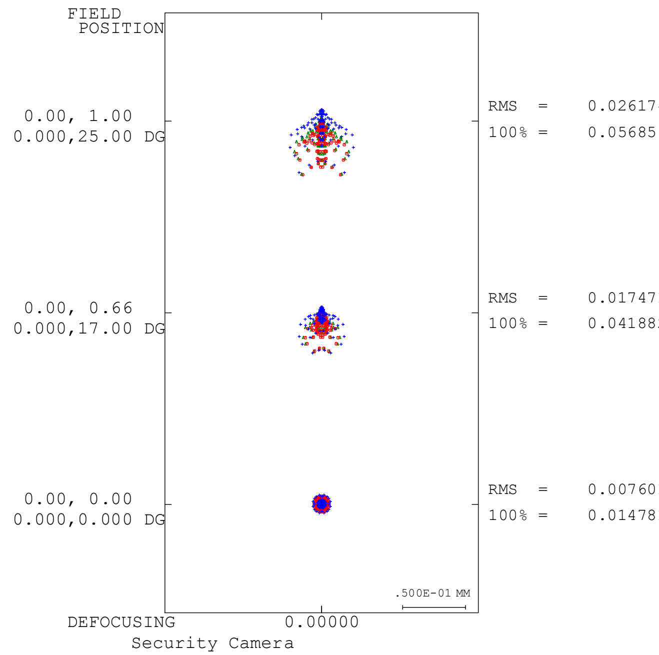
Position 1, Wavelength = 587.6 NM

	SA	TCO	TAS	SAS	PTB	DST
1	-0.019081	-0.045197	-0.106628	-0.082837	-0.070942	-0.065406
2	0.001045	0.010833	0.094316	0.069354	0.056873	0.239709
STO	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
SUM	-0.018036	-0.034364	-0.012312	-0.013483	-0.014069	0.174302

Step 2 – Performance

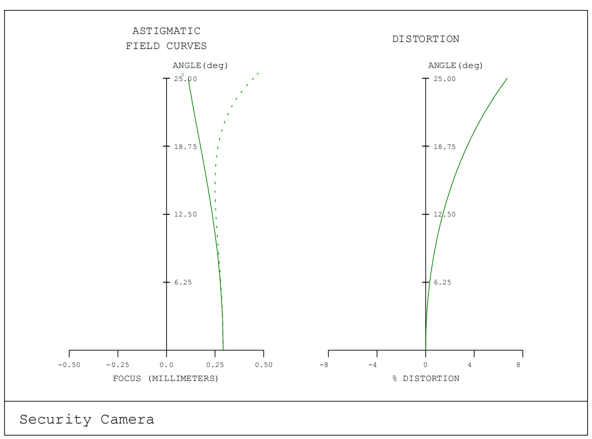


rim; ssi 0.05; go

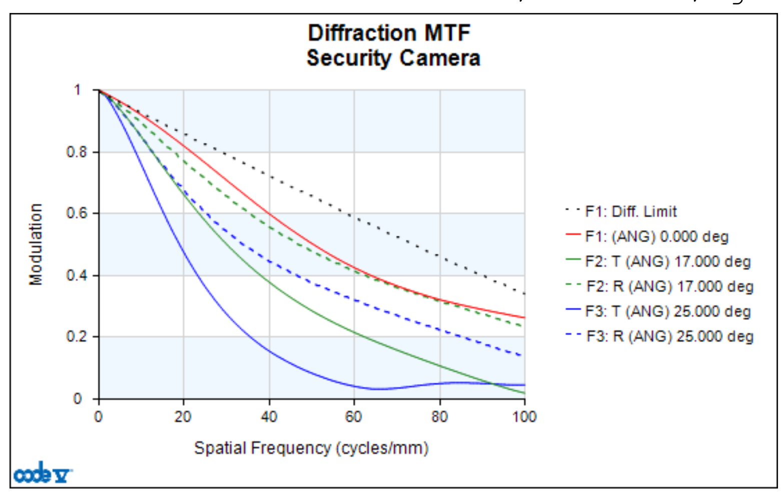


spo; ssi .05; go

fie; go



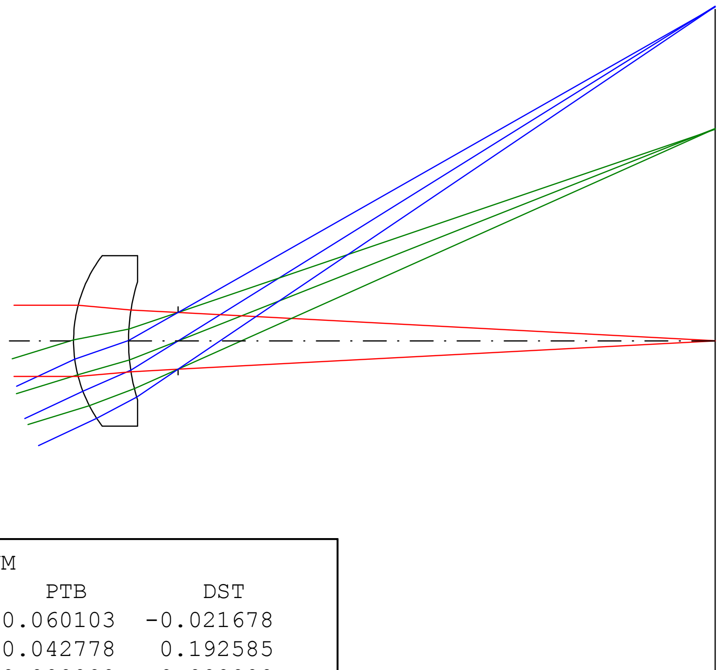
mtf; mfr 100; go



Step 3 – Shift the Stop

Å Coma can be reduced by varying the stop position

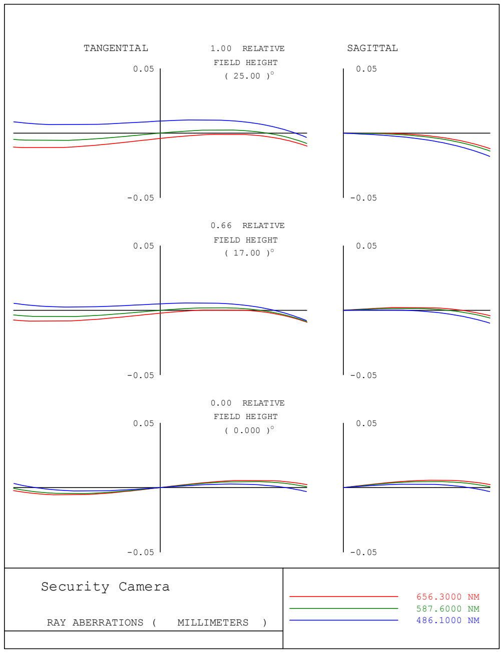
```
thc s2 0
auto; int; efl = 6.43; go  ! 4 cycles
set vig
```



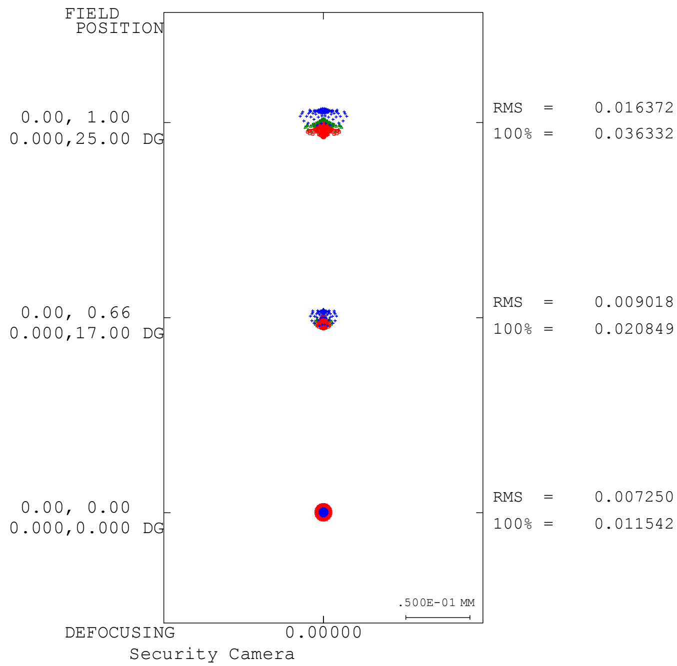
Position 1, Wavelength = 587.6 NM

	SA	TCO	TAS	SAS	PTB	DST
1	-0.011603	-0.012262	-0.064422	-0.061543	-0.060103	-0.021678
2	0.000207	0.002586	0.053519	0.046359	0.042778	0.192585
STO	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
SUM	-0.011396	-0.009676	-0.010903	-0.015184	-0.017325	0.170907

Step 3 – Performance

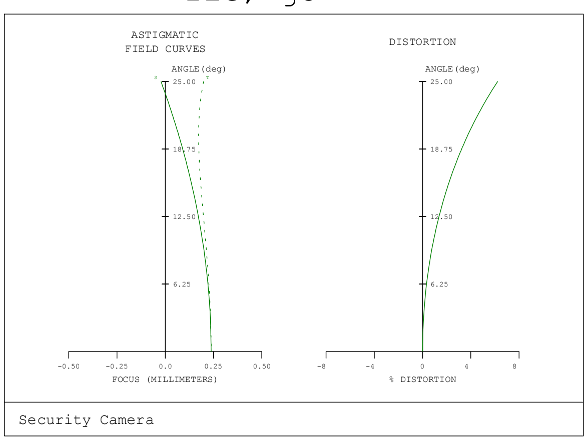


rim; ssi .05; go

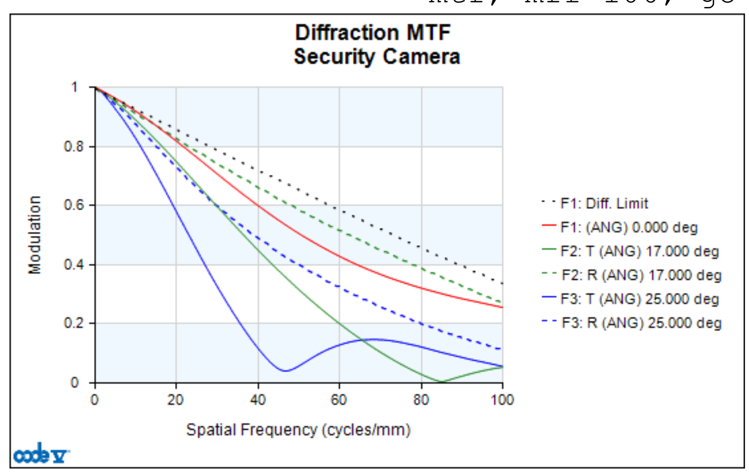


spo; ssi .05; go

fie; go



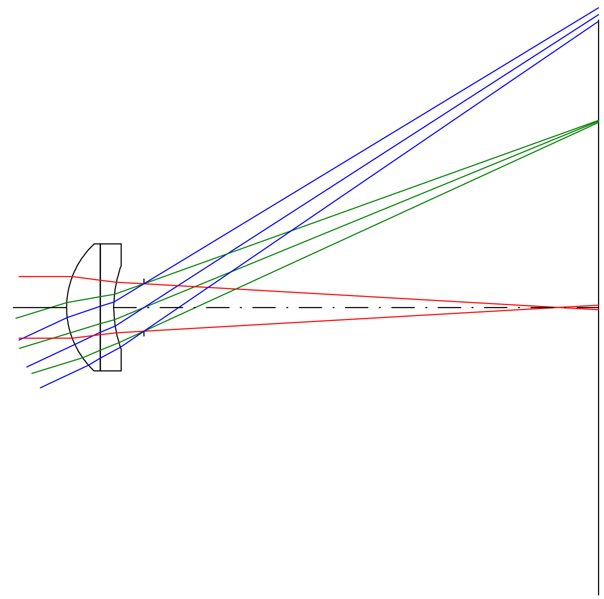
mtf; mfr 100; go



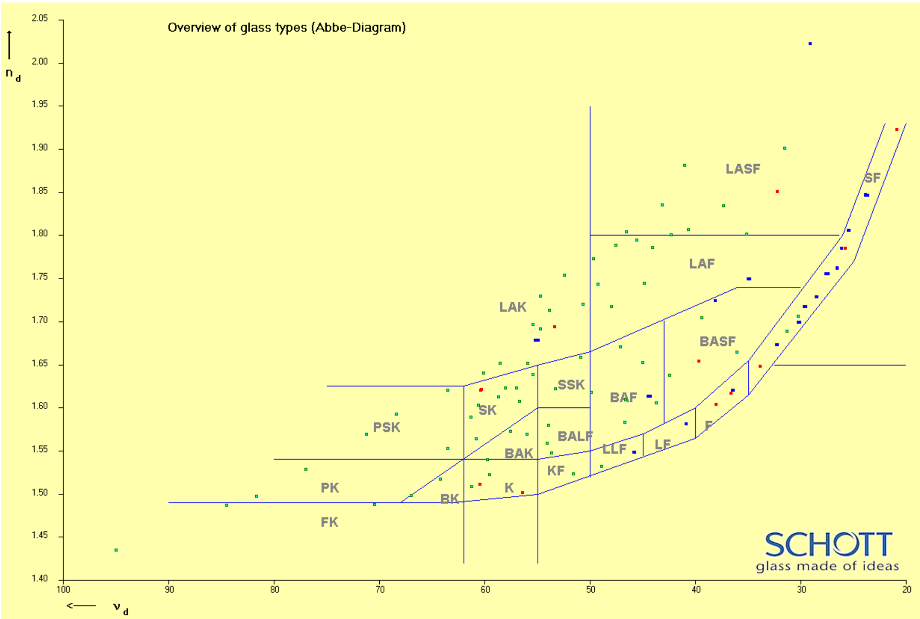
Step 4 – Add a Lens

- The primary way to reduce axial or lateral chromatic aberration is to add another lens to balance the dispersion across the wavelength band
- Convert the singlet to a cemented doublet by inserting a surface inside the lens with a thickness of 0.2 mm and making the glass N-SF2 (a flint glass to balance the front crown glass)
  - Make the radius of the cemented surface a variable
- Make both glasses fictitious so they can vary

```
ins s2 0 0.2 nsf2
ccy s2 0
glc s1..2 0
set vig
```

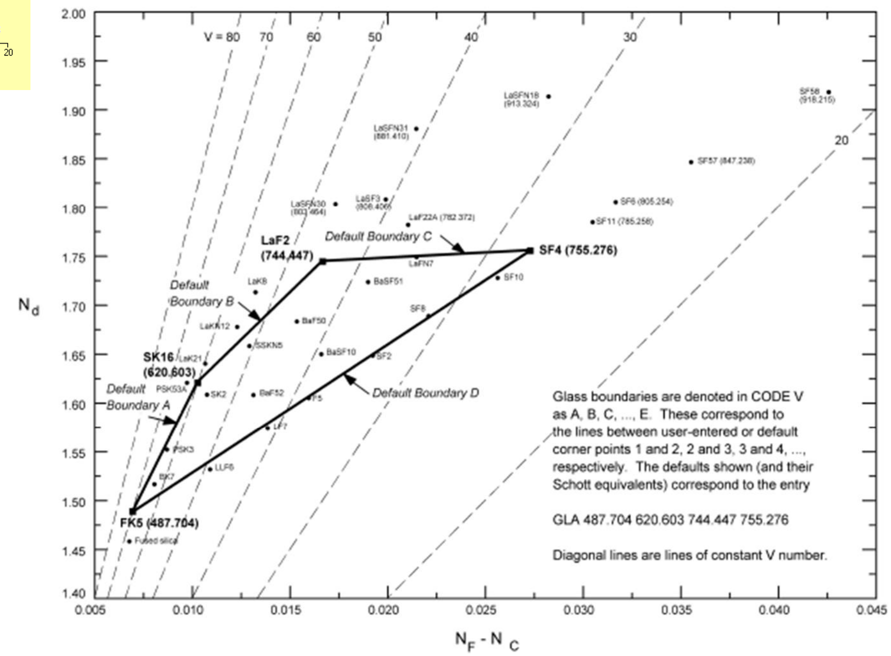


Step 4 – Optimizing Glasses



- CODE V cannot vary catalog glasses
- To vary a glass, it must be converted to a "fictitious" glass form
- Fictitious glasses are defined by n_d and v_d in the form nnn.vvv where nnn is n_d-1 and .vvv is v_d/100
  - For example, N-BK7 (n_d = 1.6148, v_d = 64.2) is represented as 6148.642

- CODE V varies the index (n_d) and the dispersion (n_F-n_C)
- By default, these values are constrained to stay within a region of the n_d vs. n_F-n_C map bounded by real glasses
- Note: fictitious glasses use the partial dispersion of the "normal" glass line

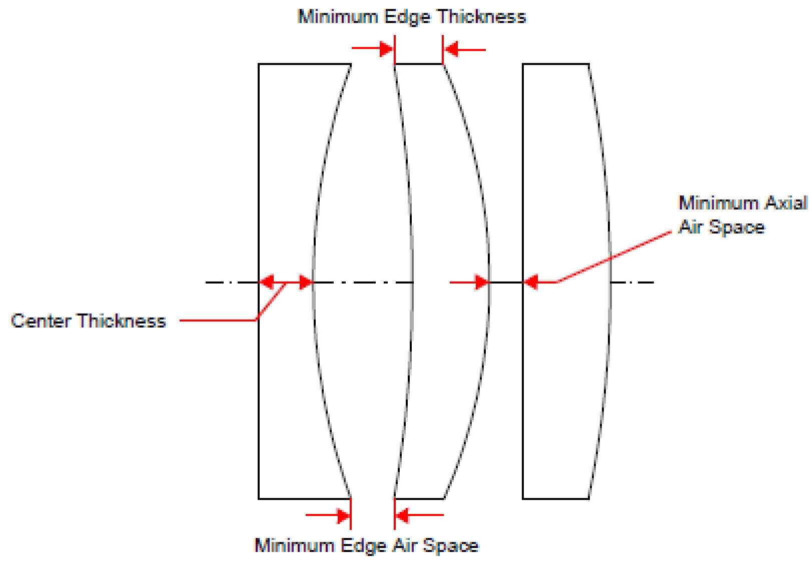


Step 4 – Controlling the Lens Form

Å By default AUTO keeps lenses from getting too thick or too thin, and keeps air spaces positive at the axis and edge of clear apertures so lenses do not physically overlap

  ï These are controlled by the general constraints MXT, MNT, MNE, MNA, and MAE (note that MNE overrides MXT, if necessary)

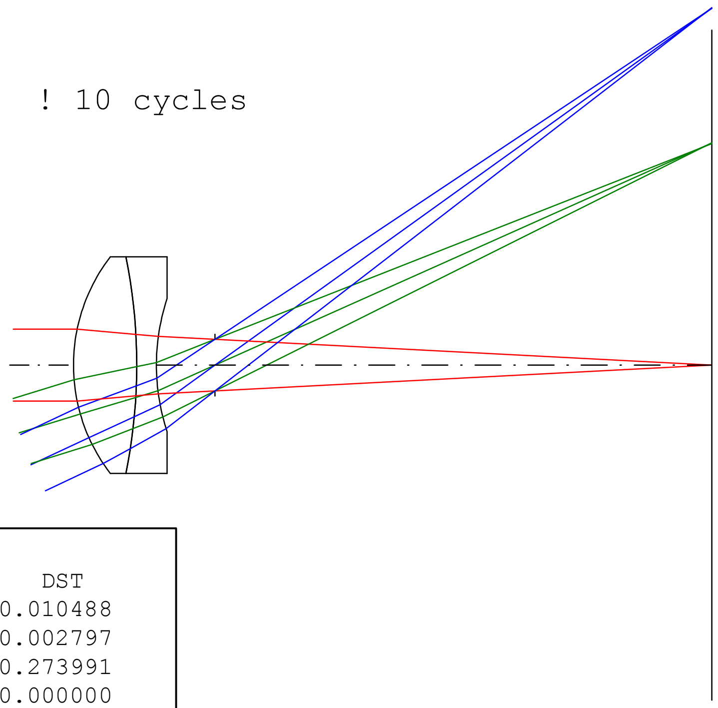
  ï The defaults for these can be changed in AUTO



Step 4 – Optimization

- We will constrain the minimum thickness of a lens to 0.1 mm with MNT 0.1 and control the minimum edge thickness to 0.25 mm with MNE 0.25
- We will let the thicknesses of the two lenses vary, subject to the general constraints we impose

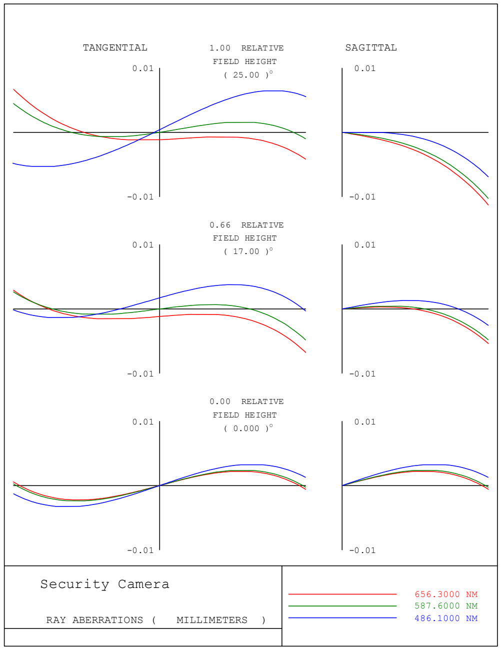
```
thc s1..2 0
auto; efl = 6.43; mnt .1; mne .25; int; go  ! 10 cycles
set vig
```



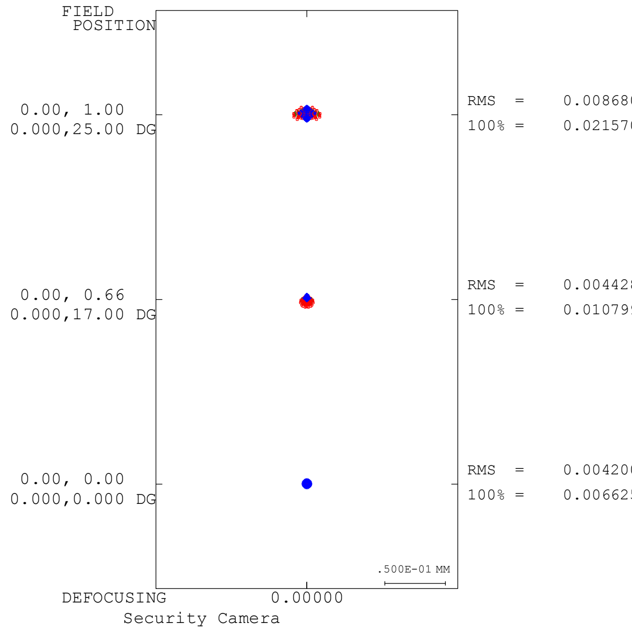
Position 1, Wavelength = 587.6 NM

	SA	TCO	TAS	SAS	PTB	DST
1	-0.006603	-0.003416	-0.061201	-0.060809	-0.060612	-0.010488
2	-0.000048	0.000543	-0.002107	-0.000741	-0.000057	0.002797
3	0.000000	0.000000	0.051031	0.051031	0.051031	0.273991
STO	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
SUM	-0.006650	-0.002873	-0.012277	-0.010518	-0.009639	0.266300

Step 4 – Performance

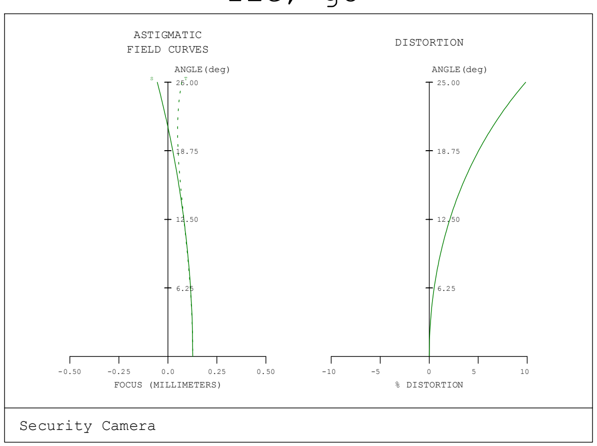


rim; ssi .01; go

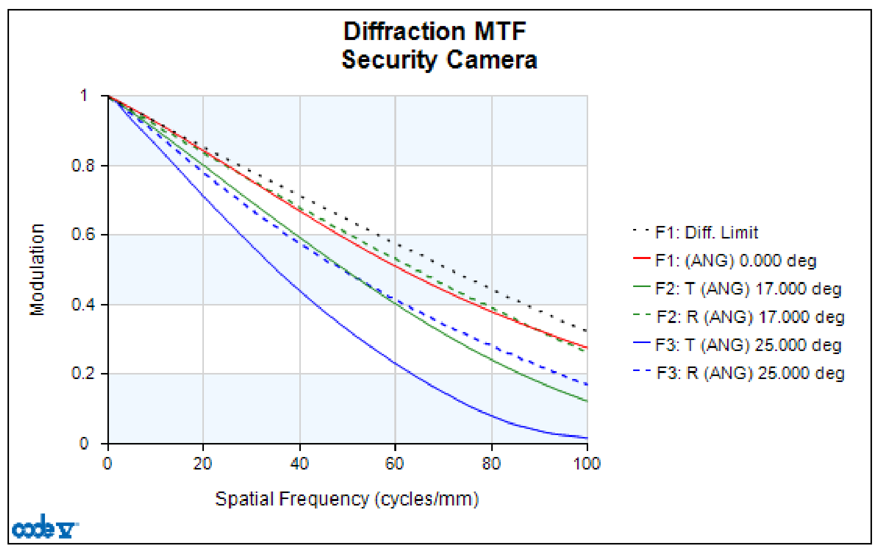


spo; ssi .05; go

fie; go



mtf; mfr 100; go



Step 5 – Add a Field Flattener

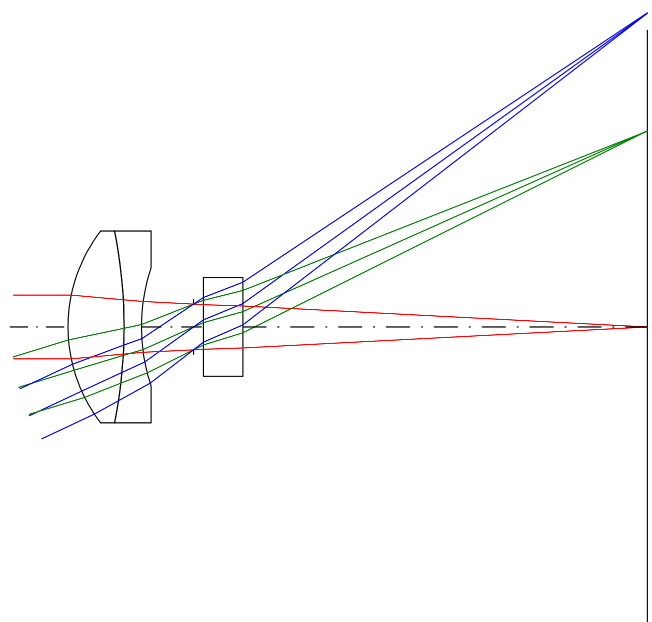
Å The MTF curves indicate residual astigmatism and the third-order coefficients indicate there is residual Petzval in the lens

Å Adding a field flattener could reduce the field curvature (astigmatism + Petzval)

Å We will insert a lens (two surfaces) with thickness 0.4 mm and glass N-BK7

- ï The field flattener will initially be set 0.1 mm after the stop
- ï We will vary both radii and the thickness of the field flattener, its glass, and the thickness between the stop and the field flattener

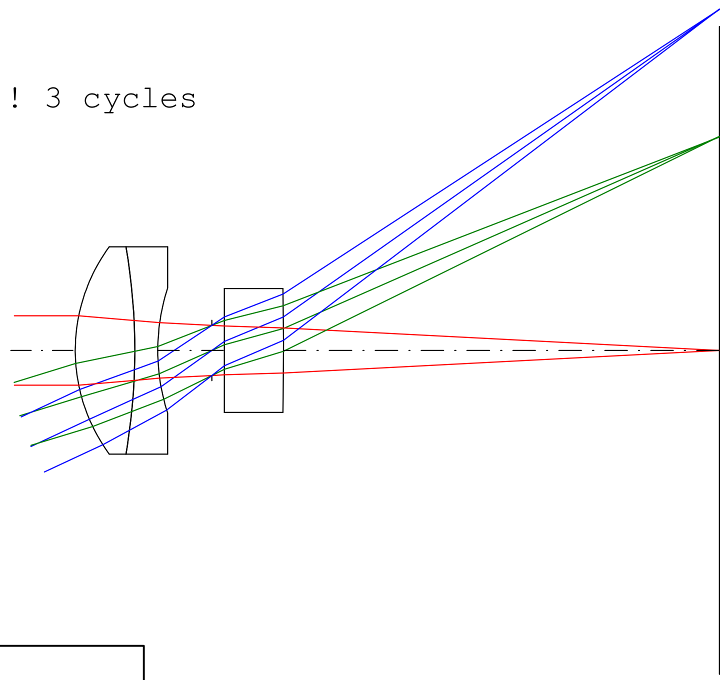
```
ins s5..6
thi s4 .1
thi s5 0.4
gla s5 nbk7
ccy s5..6 0
thc s4..5 0
glc s5 0
set vig
```



Step 5 – Initial Optimization

Å Use the same AUTO commands as before

```
auto; efl = 6.43; mnt .1; mne .25; int; go  ! 3 cycles
set vig
```



Position 1, Wavelength = 587.6 NM

	SA	TCO	TAS	SAS	PTB	DST
1	-0.006259	-0.004889	-0.060814	-0.059965	-0.059541	-0.015614
2	-0.000063	0.000726	-0.002881	-0.001011	-0.000076	0.003903
3	0.000024	0.000385	0.052971	0.051596	0.050908	0.276169
STO	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
5	0.000152	-0.005962	0.078530	0.026472	0.000443	-0.346735
6	-0.000187	0.006471	-0.076593	-0.026769	-0.001857	0.309150
SUM	-0.006332	-0.003267	-0.008786	-0.009678	-0.010124	0.226873

Step 5 – Stuck in a Local Minimum

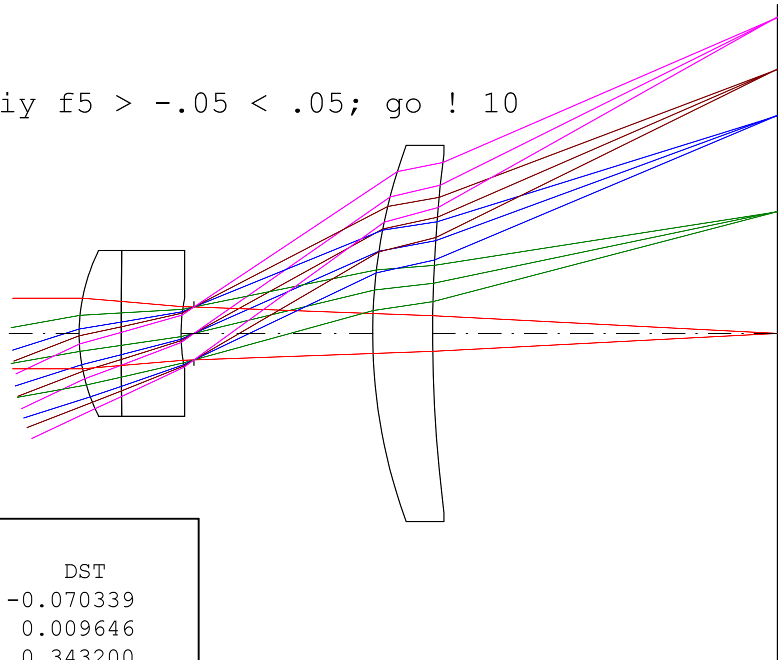
- The lens did not significantly improve, because it is stuck in a local minimum
- Getting it unstuck is part of the design process and every experienced designer has his or her own set of techniques for getting out of a local minimum
    - For example, small changes in a radius or an air space can often send the optimizer into a new design space
- In this case, we will add some fields and weight the higher off-axis fields heavier and see if this helps
- Also, there is about +8% distortion in the lens
- By default, the optimizer does not control distortion, so we will add a distortion constraint to the optimization to keep the distortion within ±5%

Step 6 – Add Fields and Control Distortion

Å Specify 5 fields (0°, 10°, 17.5°, 21°, and 25°) and weight fields 4 and 5 heavier than fields 1 to 3

Å Add a distortion constraint to the AUTO commands

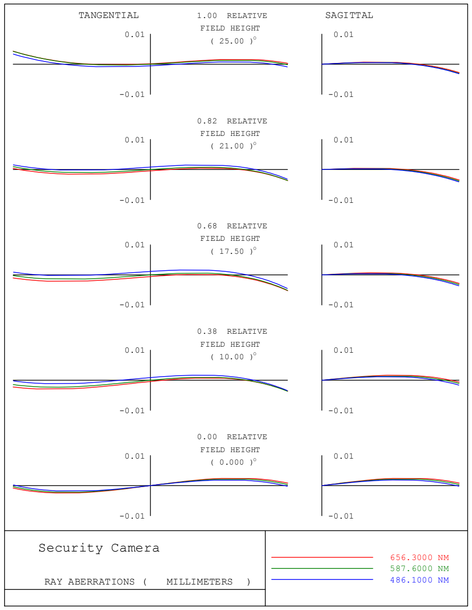
```
yan 0 10 17.5 21 25
wtf 1 1 1 2 3
set vig
auto; efl = 6.43; mnt .1; mne .25; int; diy f5 > -.05 < .05; go ! 10
set vig
```



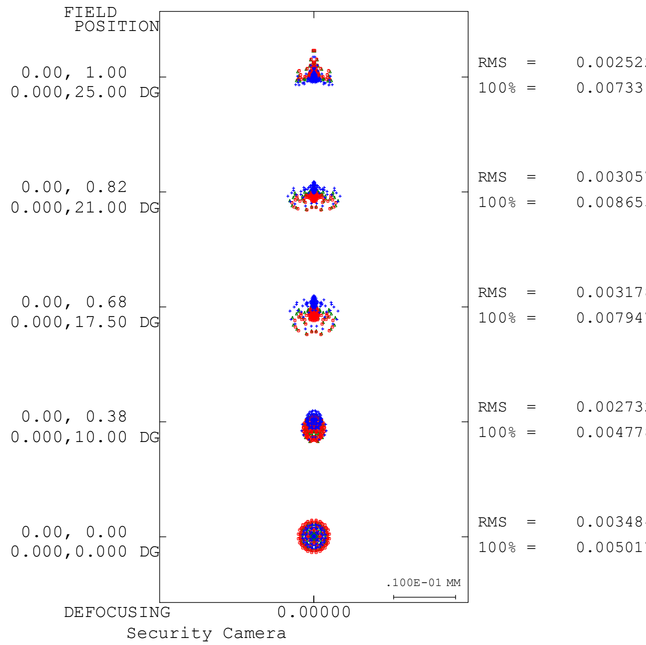
Position 1, Wavelength = 587.6 NM

	SA	TCO	TAS	SAS	PTB	DST
1	-0.005476	-0.018158	-0.077019	-0.063639	-0.056949	-0.070339
2	-0.000085	0.001242	-0.006018	-0.001977	0.000044	0.009646
3	0.000446	0.006694	0.090970	0.068665	0.057513	0.343200
STO	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
5	0.000000	0.000149	0.030799	-0.001396	-0.017494	-0.452822
6	-0.000064	0.003302	-0.050305	-0.012330	0.006658	0.212674
SUM	-0.005178	-0.006771	-0.011573	-0.010676	-0.010227	0.042359

Step 6 – Performance

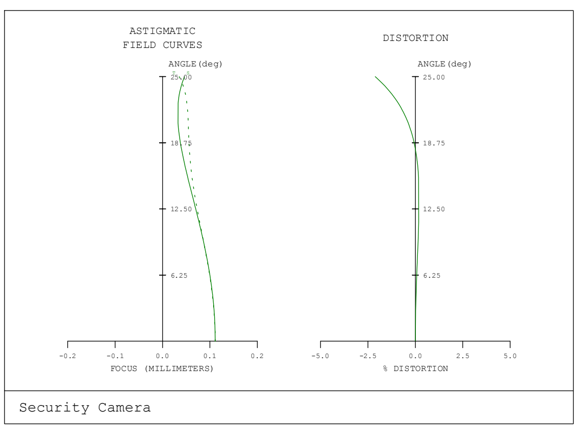


rim; ssi .02; go

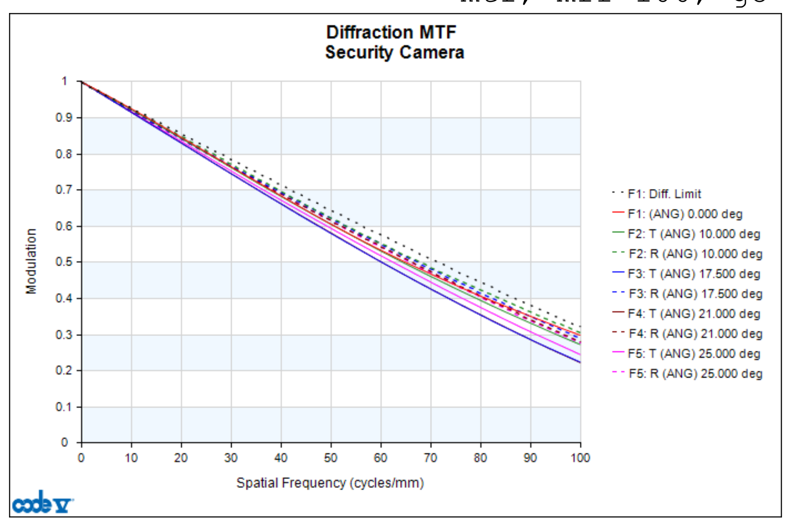


spo; ssi .01; go

fie; go



mtf; mfr 100; go



Step 7 – Return to Real Glasses – GLASSFIT

- The design is not yet finished because it is a solution based on fictitious glasses
  - The fictitious glasses must be replaced with catalog glasses
- We will do this with a CODE V supplied macro called GLASSFIT
  - GLASSFIT can be run from the GUI (Lens -> Glass Fitting...) or by executing the macro from the command line (in cv_macro:glassfit)
- Use of GLASSFIT
  - Allows you to select which catalog(s) you wish to use (e.g., Schott, Ohara, Hoya, etc.)
    - You can also create a custom glass catalog with selected glasses your optical shop prefers to use
  - Allows you to automatically fit one or more fictitious glasses
  - Allows you to review the closest glasses to a fictitious glass and select which one to use based on various glass properties
- After using GLASSFIT, a final AUTO run should be made to account for the glass differences

Using GLASSFIT (1)

```
CODE V> in cv_macro:glassfit

Manufacturer's catalogs to choose from
 (multiple catalogs may be selected,
  use spaces between choices):

        ALL
        CDGM
        HIKARI
        HOYA
        NHG
        NIKON
        OHARA
        SCHOTT
        SUMITA

schott

Using catalog(s): SCHOTT

Select task:

  1  Evaluate 5 closest glasses for all fictitious glasses in a range
  2  Fit one surface (allows user selection of glass)
  3  Automatically fit all fictitious glasses for a surface range
  Q  Quit this macro

3

Fitting closest glasses for surfaces   1 to   6

y
```

Using GLASSFIT (2)

Header	Description
Fit	Ranking number of fit
Delta Nd	Deviation in Nd between this glass and the fictitious glass
Delta Vd	Deviation in Vd between this glass and the fictitious glass
Avail	Availability code
Price	Price per pound for gob glass
DPF	Deviation in partial dispersion * 1000
Bubl	Bubble quality (refer to glass catalog for description)
Stain	Stain group (refer to glass catalog for description)

Availability Codes:

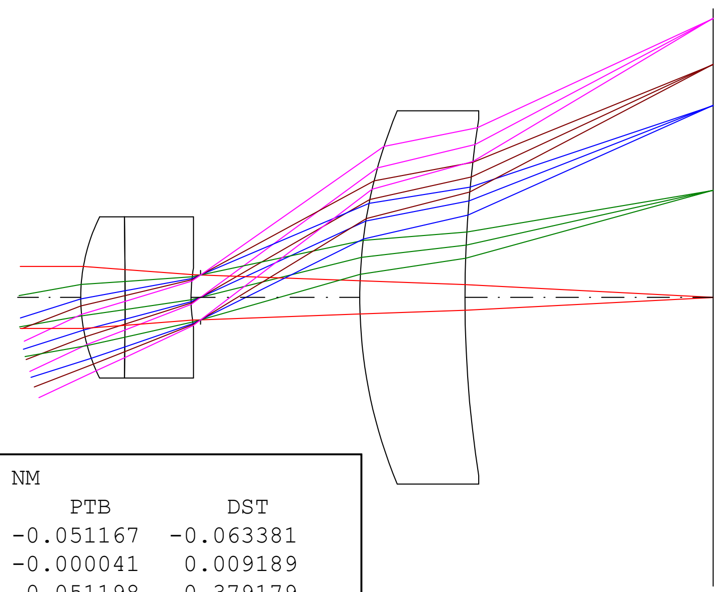
Catalog	Code	Definition
All	3	Discontinued
	4	Discontinued with recommended replacement glass
	5	Preliminary
	8	Check with vendor
Schott	0	Preferred glass
	1	Standard Glass
	2	Inquiry Glass

Surf	Catalog	Glass	Delta Nd	Delta Vd	Avail	Price	DPF	Bubl	Stain
1	SCHOTT	NLAF2	0.00000	-0.0004	0	23.87	-21	0	3
2	SCHOTT	NSF1	-0.00469	-0.0892	0	16.40	56	0	0
5	SCHOTT	NSK16	0.00000	-0.0007	0	13.50	0	0	4

Re-Optimize After GLASSFIT

Å After running GLASSFIT, a SET VIG should be run again, and the lens should have a final optimization run to correct for the (hopefully slight) changes in the glasses

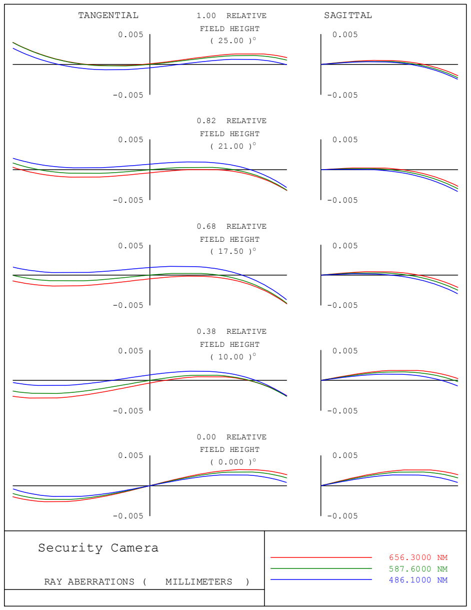
```
set vig
auto; efl = 6.43; mnt .1; mne .25; int; diy f5 > -.05 < .05; go ! 10 cycles
set vig
```



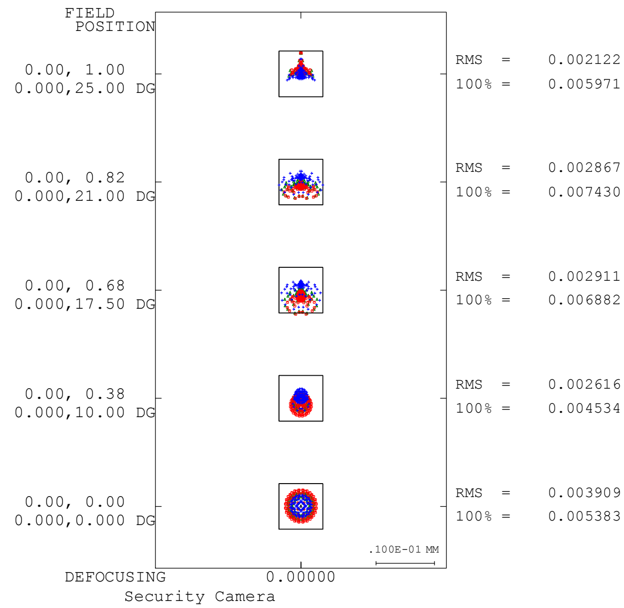
Position 1, Wavelength = 587.6 NM

	SA	TCO	TAS	SAS	PTB	DST
1	-0.003972	-0.013435	-0.066314	-0.056216	-0.051167	-0.063381
2	-0.000074	0.001104	-0.005497	-0.001860	-0.000041	0.009189
3	0.000164	0.003205	0.072089	0.058162	0.051198	0.379179
STO	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
5	0.000000	-0.000035	0.035434	0.000316	-0.017243	-0.470939
6	-0.000057	0.003121	-0.049434	-0.011695	0.007174	0.212128
SUM	-0.003940	-0.006040	-0.013721	-0.011293	-0.010079	0.066176

Step 7 – Performance

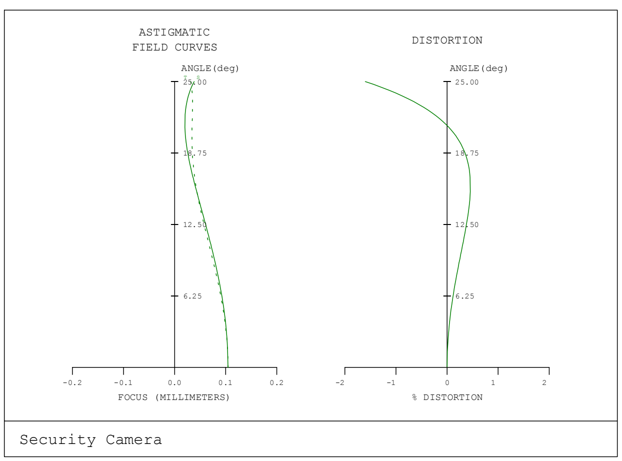


rim; ssi .01; go

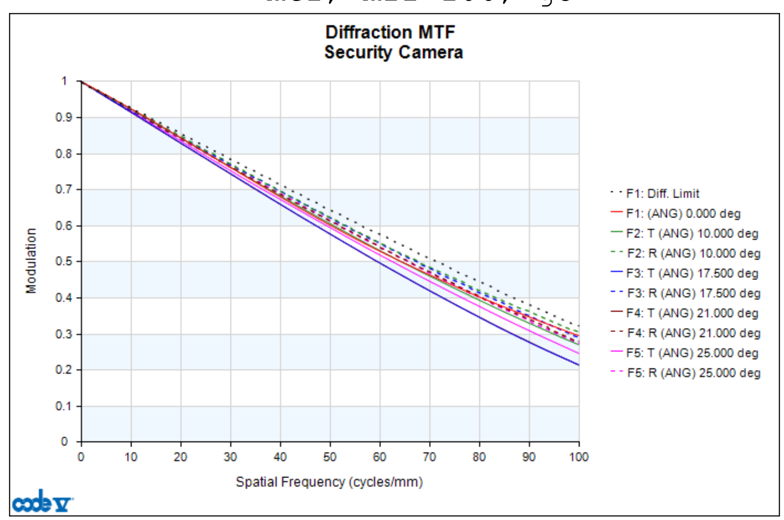


spo; ssi .01; det rec .0075; go

fie; go



mtf; mfr 100; go



Step 8 – Open Up the Lens

Å The aperture stop is so small that the limitation on performance is primarily diffraction rather than aberrations

Å To increase the MTF further, we need to open up the lens aperture to increase the diffraction limit and also to provide additional light to the sensor

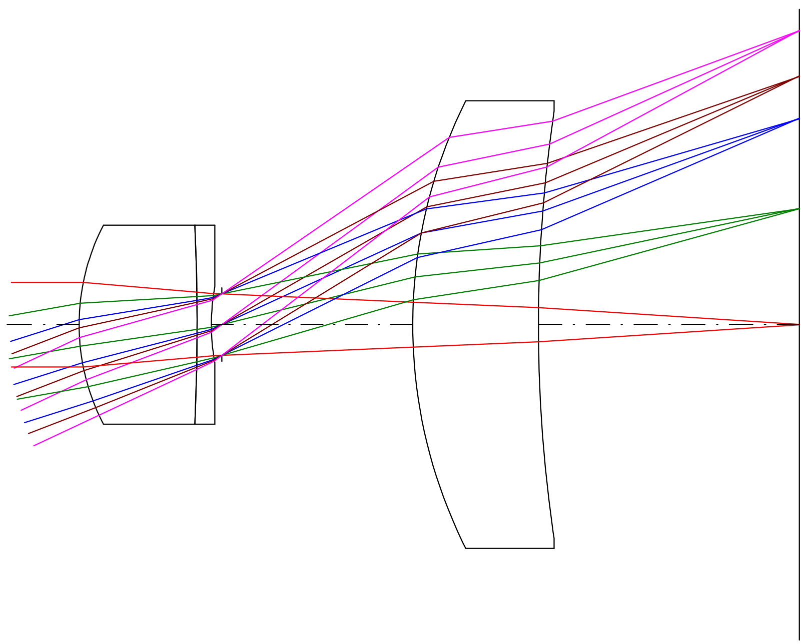
Å We will decrease the f/# from f/10 to f/8 (a $1.25^2 = 1.56$x increase in light)

Å After opening up the lens, the lens must be re-optimized to correct for the performance loss from the additional aberrations introduced by the larger aperture

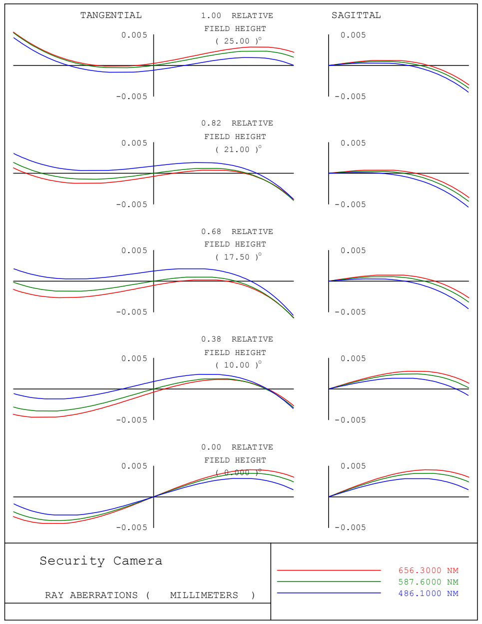
Step 8 Optimization

Å Use the same AUTO commands as before

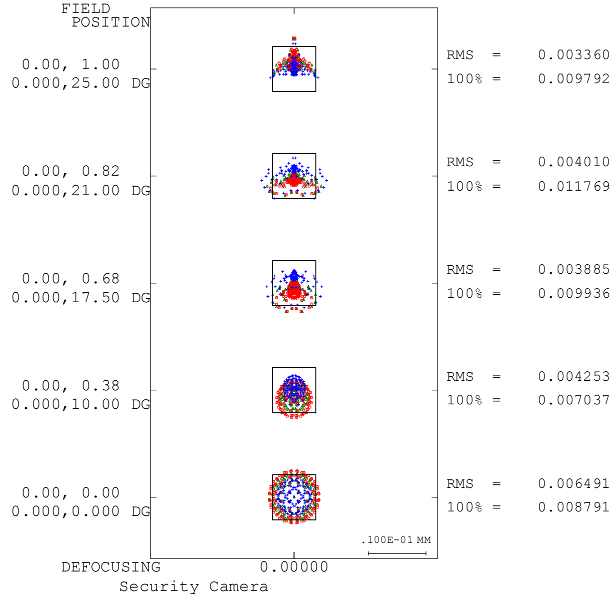
```
fno 8
set vig
auto; efl = 6.43; mnt .1; mne .25; int; diy f5  > -.05 < .05; go  ! 5 cycles
set vig
```



Step 8 Performance

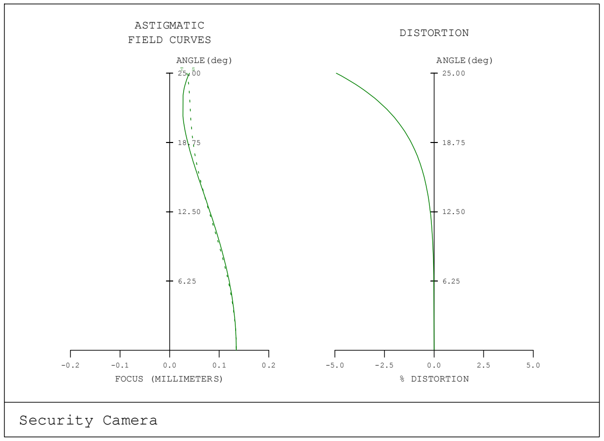


rim; ssi .01; go

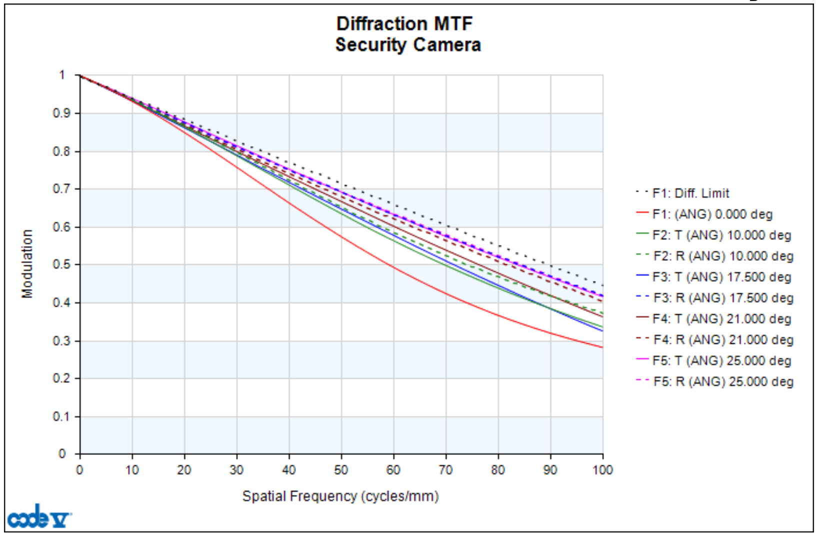


spo; ssi .01; det rec .0075; go

fie; go



mtf; mfr 100; go



Conclusions

- This lens was "built from scratch" to thoroughly describe the design process
- It is often easier to start from a classic design form with the right number of elements, a good negative/positive power balance for Petzval correction, and a good selection of glasses for color correction
- What has not been covered is "is it makeable?"
  - After designing a lens, the lens and opto-mechanical tolerances must be determined to ensure a manufacturable (and preferably cost-efficient) design while still maintaining the desired optical performance