Optics & Instruments

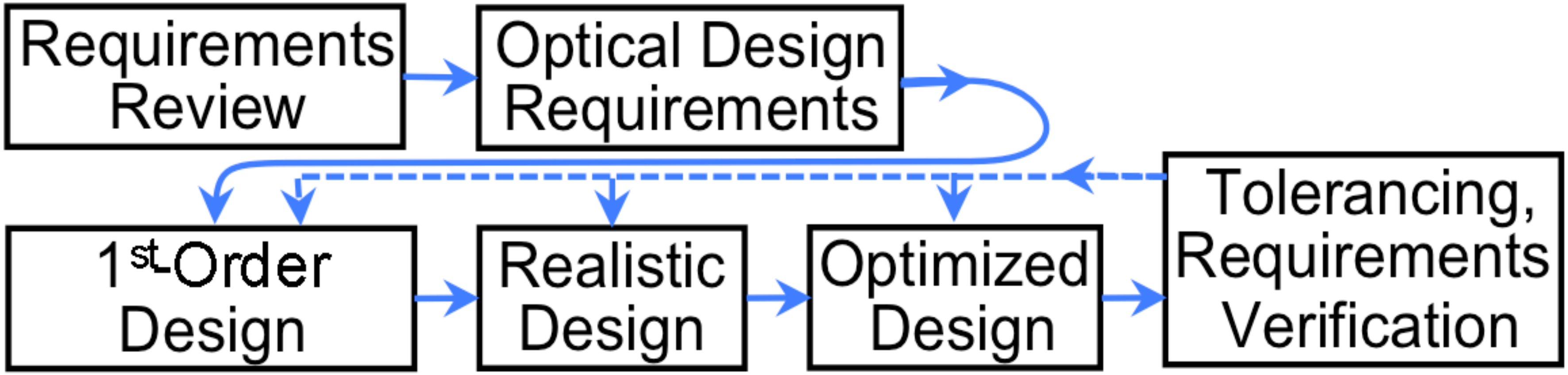
Lecture 8: Optical Design

Christoph U. Keller

Overview

- Introduction
- Requirements
- Optical Design Principles
- Ray-Tracing and Design Analysis
- Optimization and Merit Function
- Tolerance Analysis and Optomechanical Design
- Wavefront Error Budget
- Transmission Budget

Introduction



- optical design is not linear, but iterative process
- close coupling between optical, mechanical, electrical, controls, software design and science
- optical design is first design effort, provides first idea of how final instrument will look

Typical Requirements

- spatial range: field-of-view (FoV)
- spatial resolution, spatial sampling
- spectral range & resolution, sampling
- transmission
- detector pixel size
- stability and repeatability
- polarimetric sensitivity and accuracy

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Example Optical Design Requirements

Parameter	Specification	Comment
Spectral		
spectral lines	**630.1515, 630.2507 nm, 854.2089 nm, 1083.0 nm**	**selected suitable spectral lines**
spectral resolution	200,000	
wavelength range	**630.1515-0.05 nm to 630.2507+0.05 nm** **854.2 +/- 0.1 nm** **1083.0 +/- 0.5 nm**	**were unable to design efficient instrument over full range of 600 to 1600 nm**
spectral lines	at least two simultaneously	
Polarimetry		
type	630.2 nm: I,Q,U,V **854.2 nm: I,V** **1083.0 nm: I**	**Analysis of vector polarimetry in 854.2 nm not clear, traded wider spectral range in 1083.0 nm for polarimetry**
sensitivity	0.0002 per pixel in 0.5 s	
relative accuracy	0.001	
Miscellaneous		
image motion stabilization	at about 100 Hz	to improve spatial resolution
cloud	**detection at user-specified level**	
real time seeing monitoring		**for information only**
interruption of scanning during continuation after clouds		

excerpt from SOLIS VSM Optical Design Requirements

Boundary Conditions

- site characteristics (seeing, temperatures)
- telescope properties
- telescope interfaces
- instrument location (fixed or variable gravity vector, space and weight limits)
- detector availability
- available €, $, ...

Requirements Review

- requirements review
  - identifies unnecessary, incompatible and omitted requirements
  - ensures that all requirements can be verified and traced back to scientific needs
- optical design requirements
  - derive from science requirements
  - set boundary conditions for optical design in terms of optical quantities

Optical Design Principles 1 - 3

1. Minimize the number of optical components
   - additional elements add cost, ghosts, scattered light
   - but: additional elements increase performance
2. Minimize the radii of curvature
   - reduces aberrations
   - eases manufacturing and alignment
   - but: might require more elements and long designs
3. Maximize the allowed tolerances
   - simplifies manufacturing, mechanical design and operational requirements

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Optical Design Principles 3 - 6

3. Place components close to focus if they introduce wavefront aberrations
4. Place components close to pupil if all field points must pass same part of component
5. Place components in collimated beam if all rays from one field point should pass the component under the same inclination angle
6. Place components in a telecentric beam if the component is sensitive to the inclination angle

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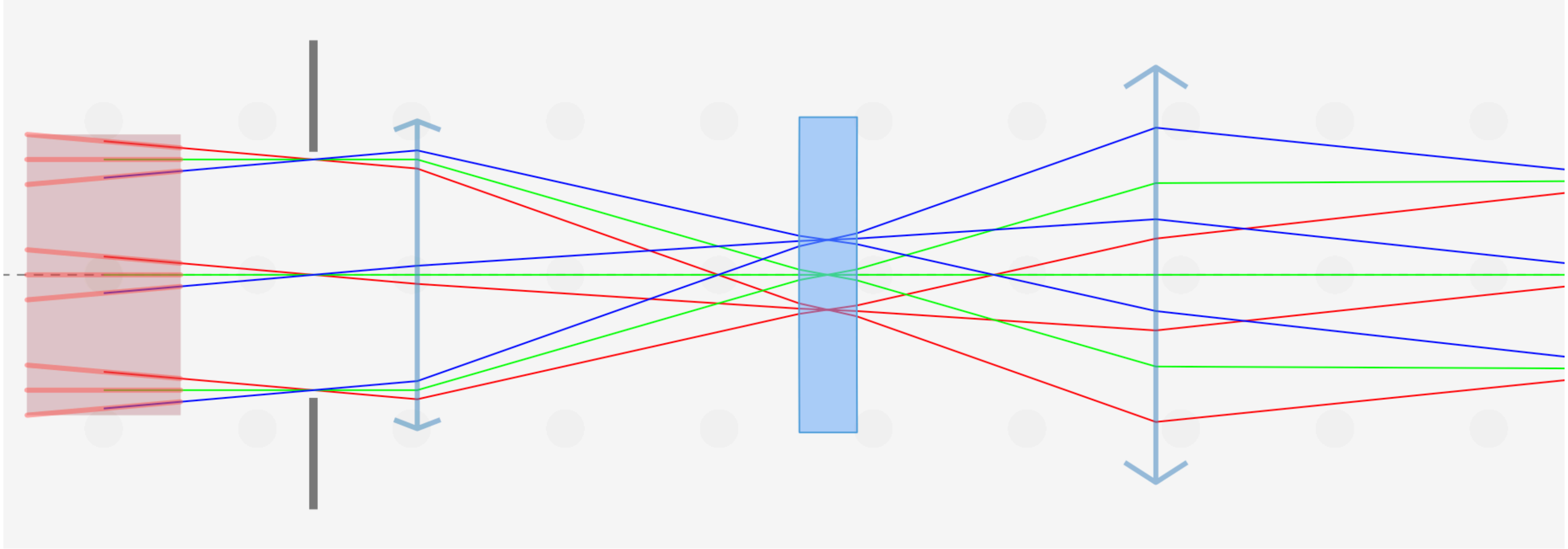
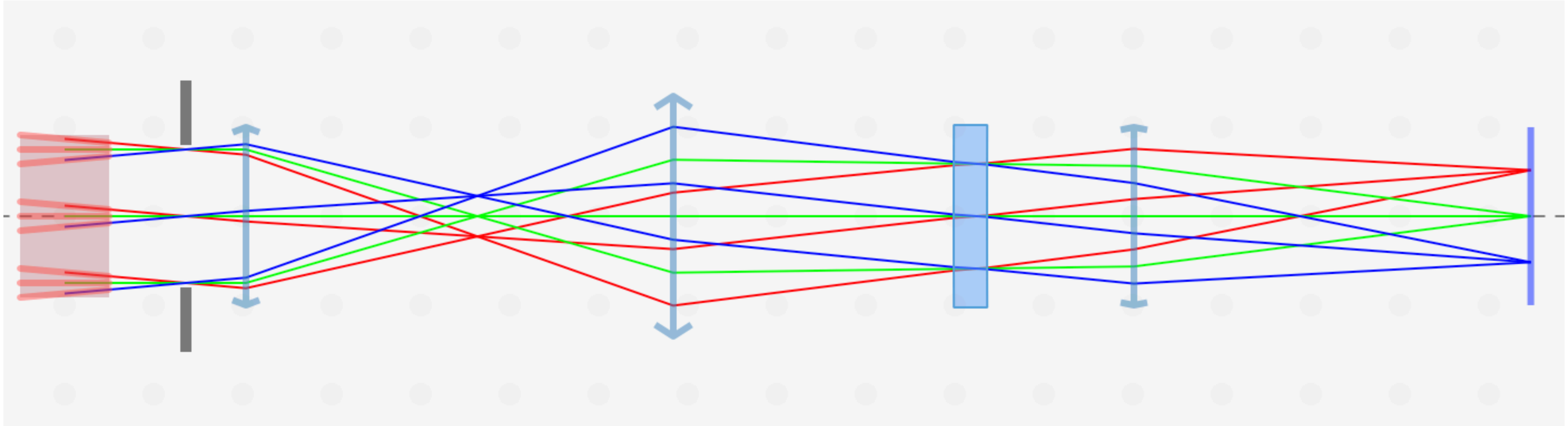
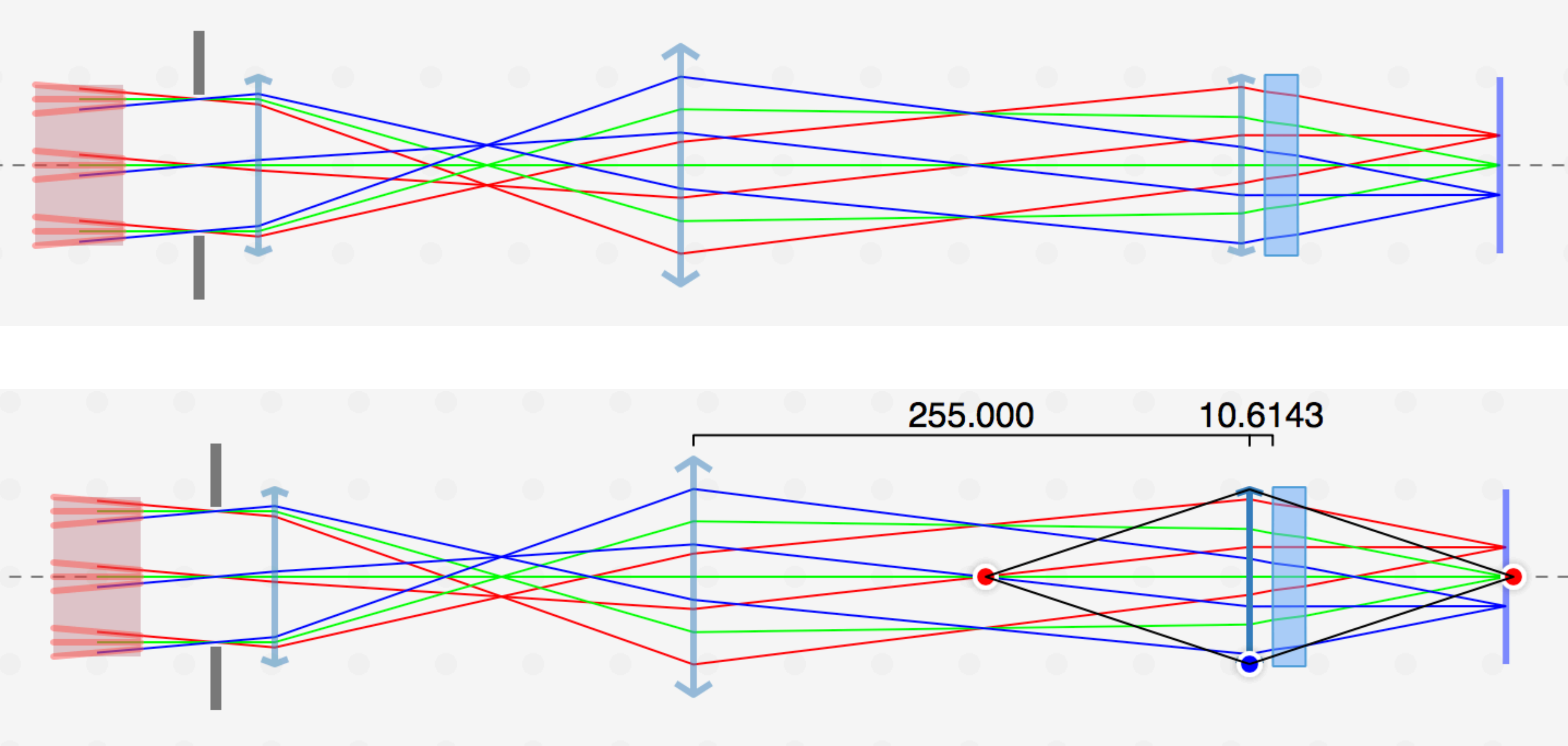
Example: Filter in Image



Example: Filter in Pupil



Example: Filter in Telecentric Beam



Optical Design Principle 7

7. Oversize optical elements
    - optical manufacturing quality always worse at edge

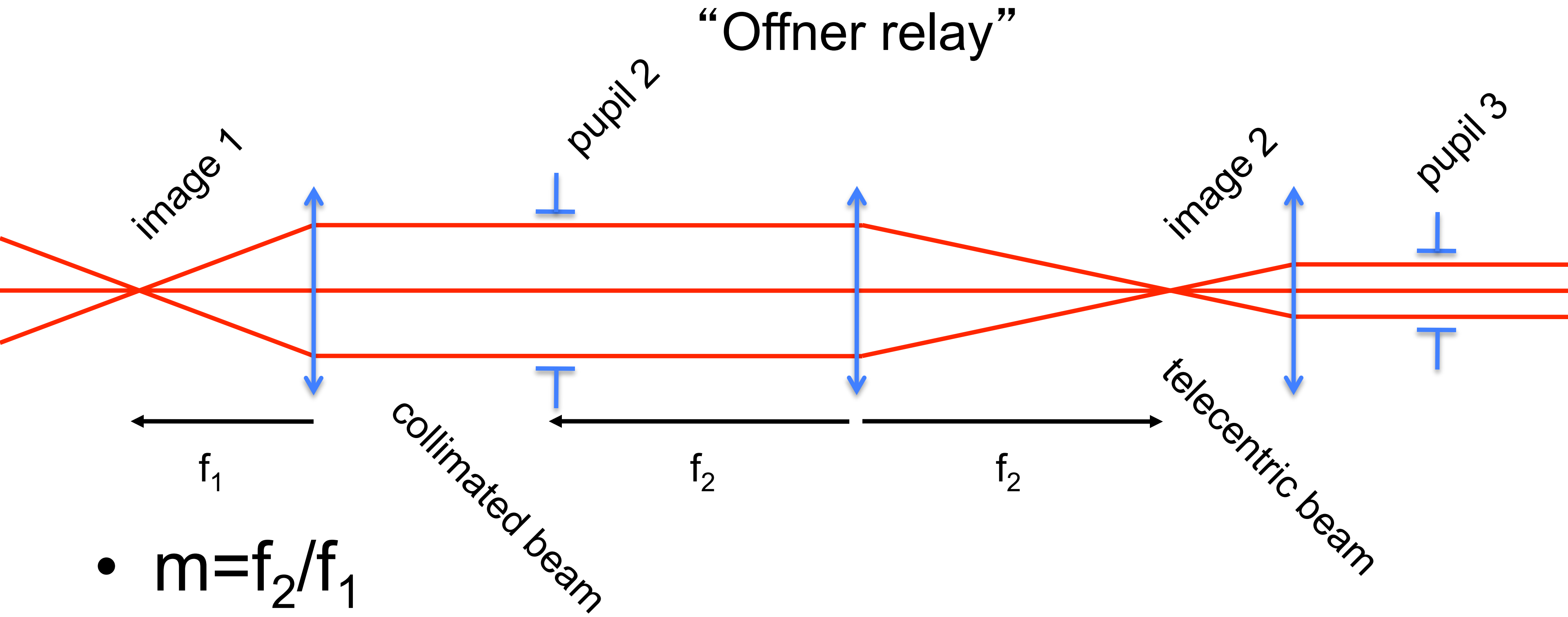
Global Design Choices

- lenses or mirrors (depends on wavelength range)
- choice of dispersing elements (prism, grating)
- location of aperture stop
- locations of image and pupil planes
- sampling (Nyquist: >2 pixels per resolution element)
- (dichroic) beam-splitting
- (de-)magnification
- F-numbers (problems ~1/F-number)
- collimated beam?
- telecentric beam?

First-Order Design

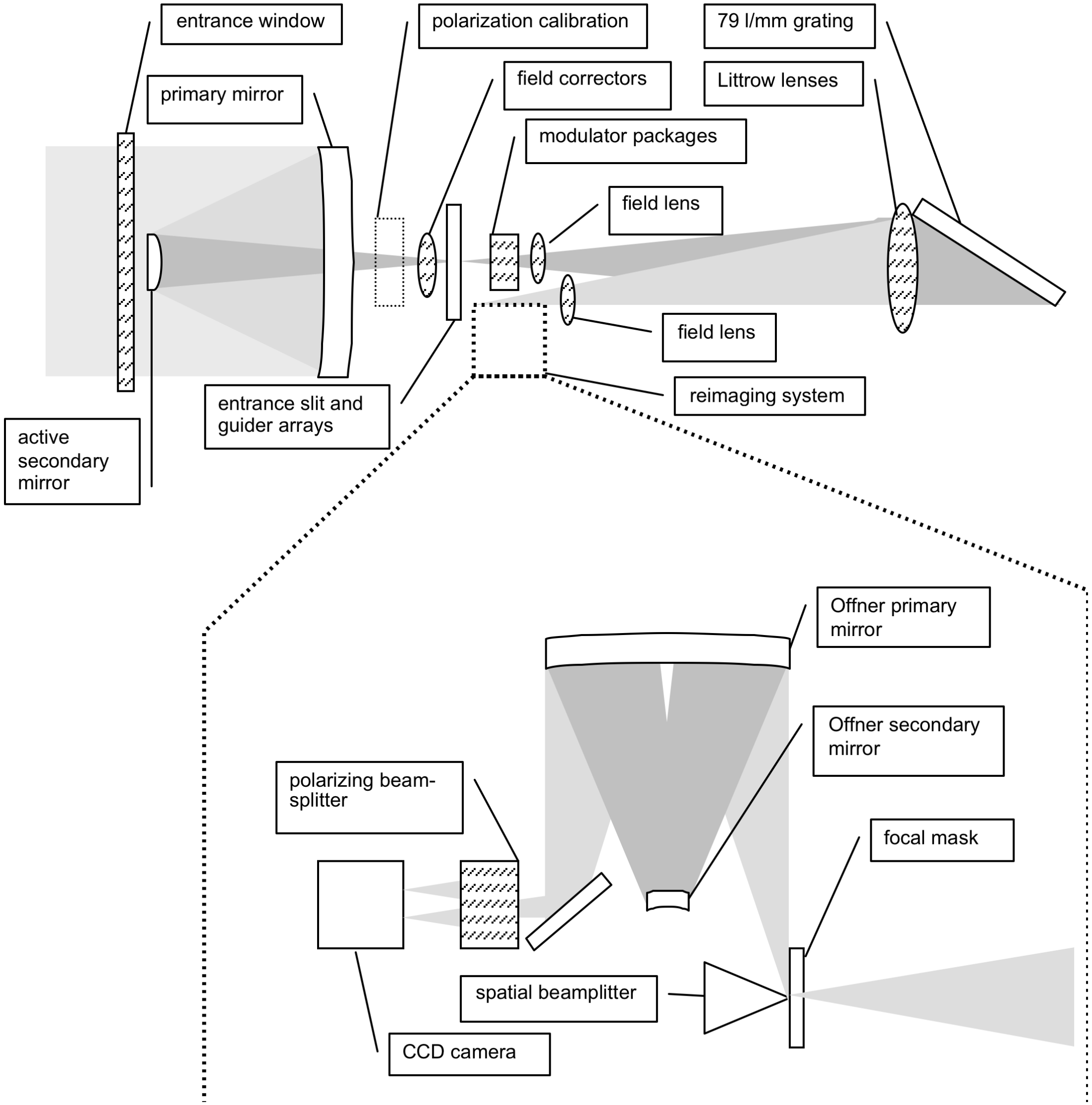
- first-order optical designs use
  - ideal optical elements (e.g. paraxial surfaces)
  - central and extreme field points and rays
  - image and pupil locations
- establishes general configuration
- often based on existing designs
- can be sketched on paper or in a spreadsheet
- provide first idea of size of different designs

Example First-Order Design 1



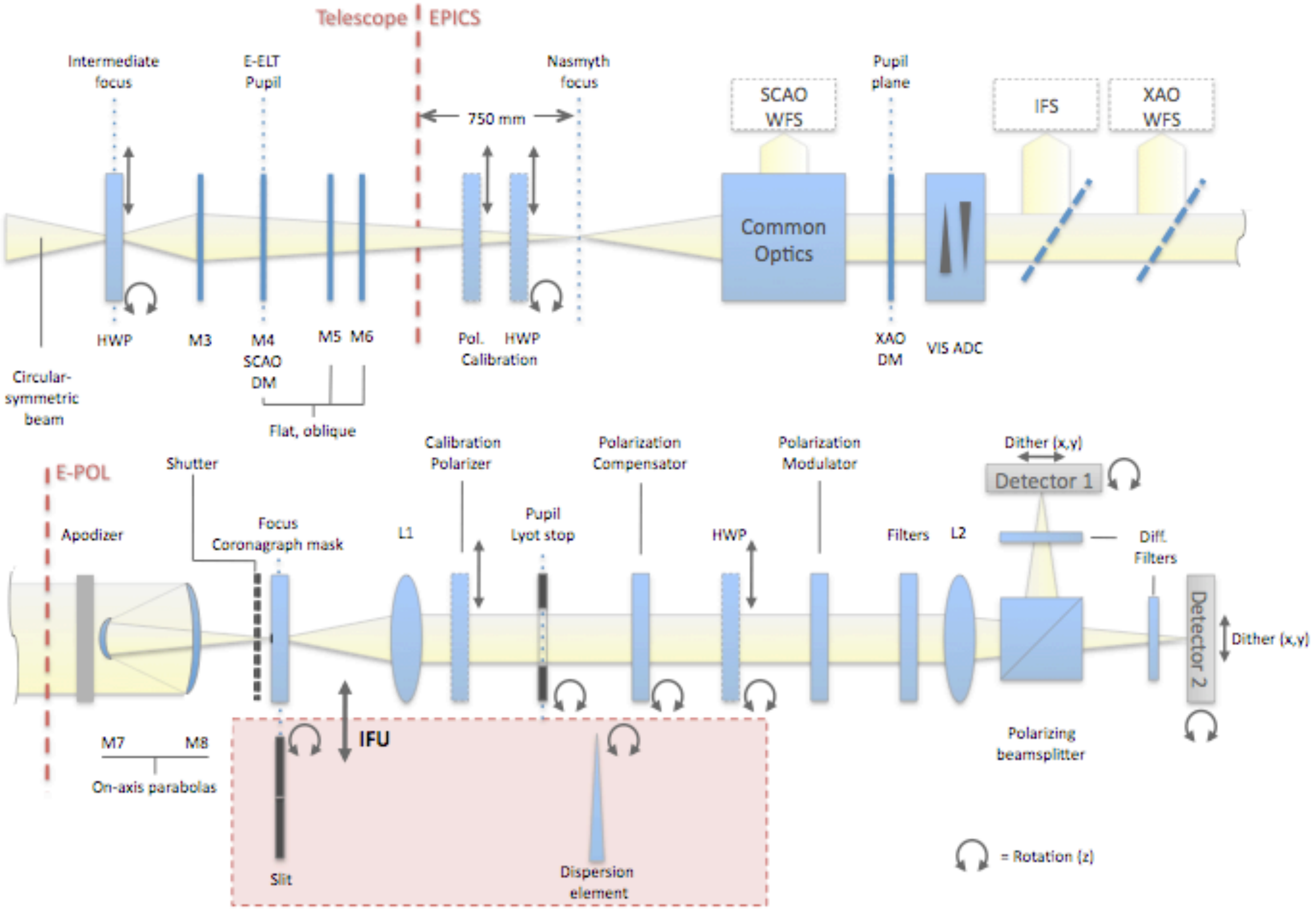
- $m=f_2/f_1$
- minimum geometrical aberrations for symmetric system ($m=1$)

Example First-Order Design 2



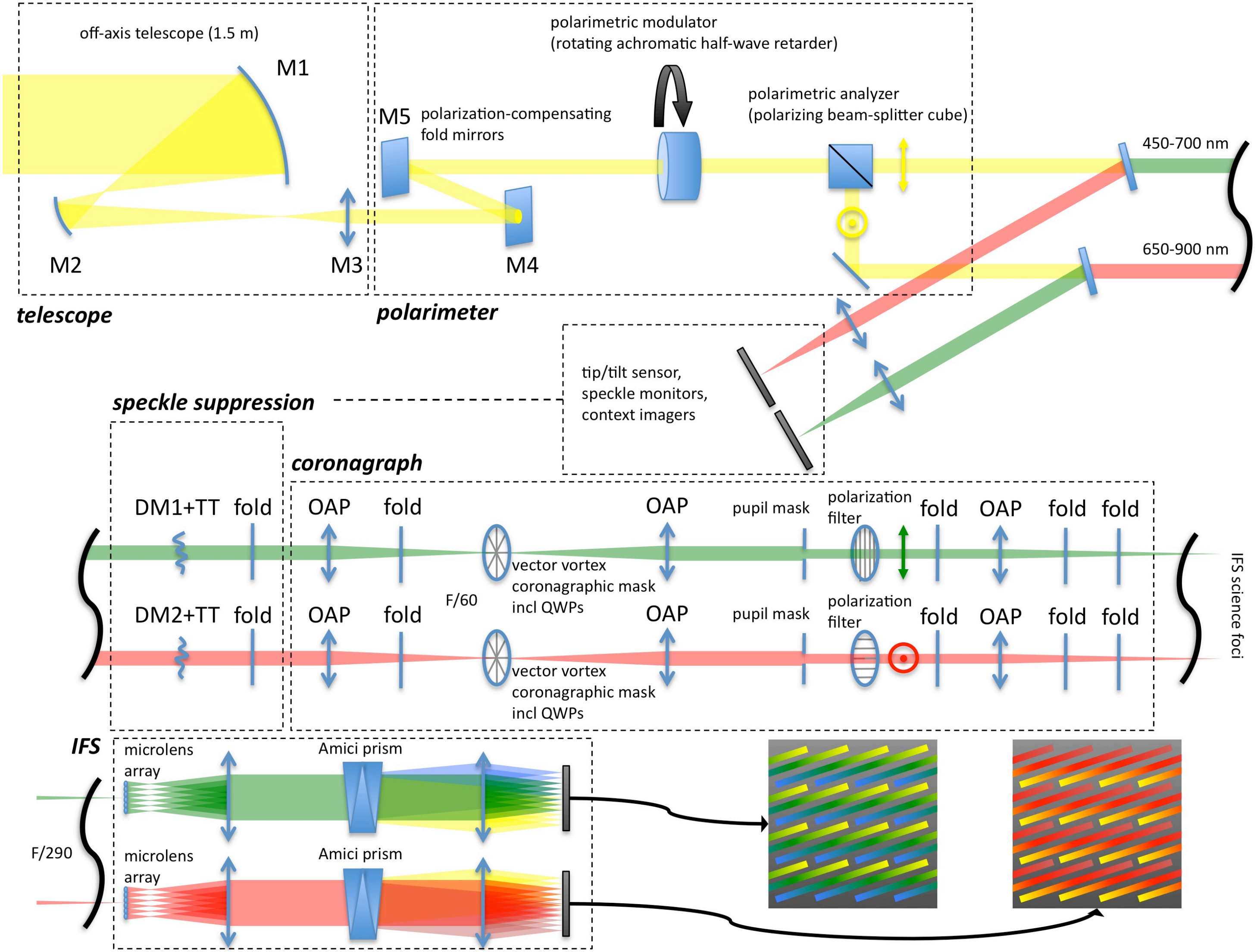
First-Order Design Example 3

EPICS-EPOL



First-Order Design Example 4

SPICES



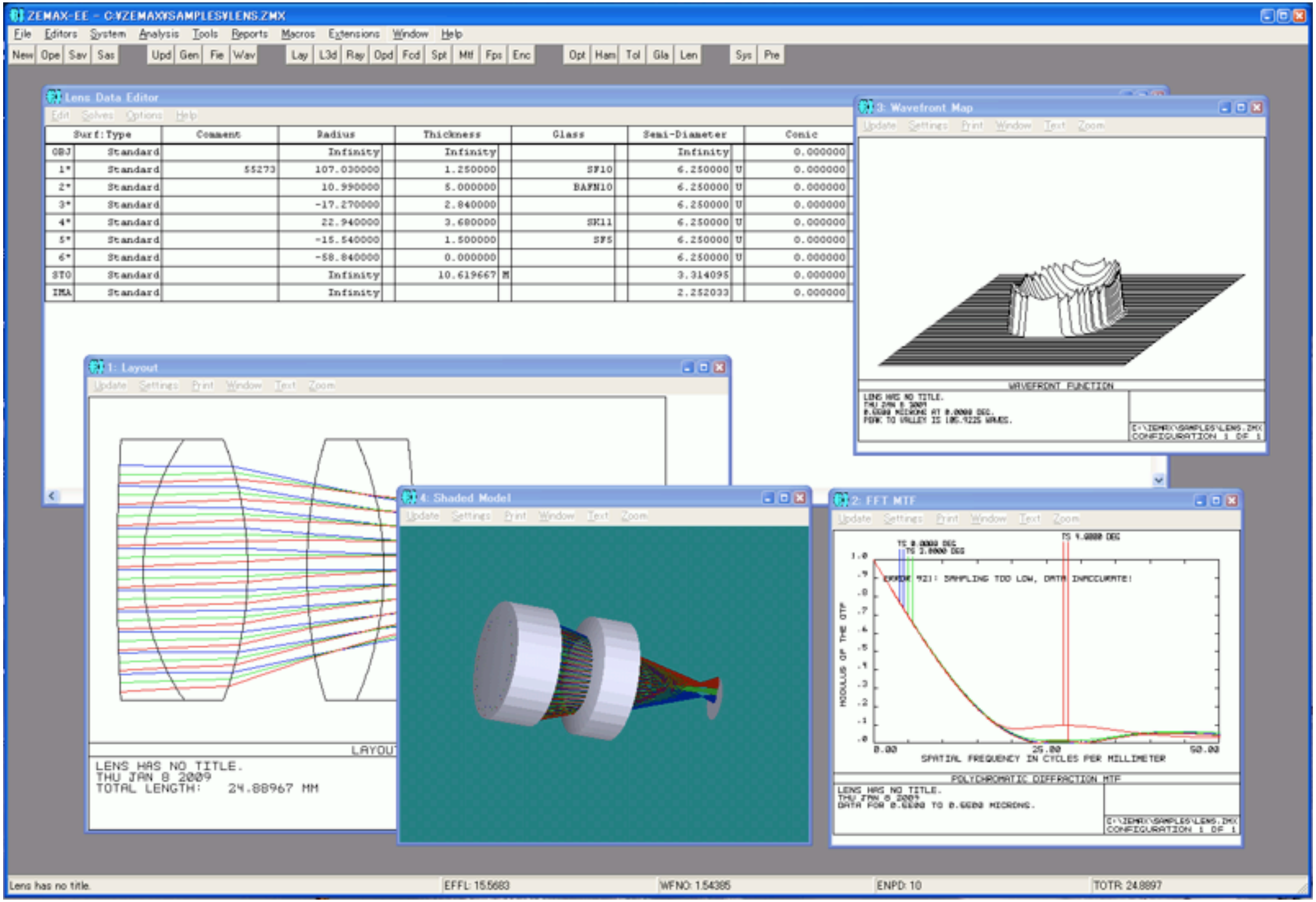
Collimated vs. Converging Beam

- components in collimated beam?
  - dispersion element
  - cold stop
  - Lyot stop
  - filter?
  - polarization modulator?
- components in converging beam?
  - slit
  - coronagraphic mask
  - detector
  - filter?

Ray Tracing

- Ray-tracing based on geometrical optics approximation (wavefronts are locally flat)
- Rays are traced from source to image
- Sequential ray-tracing traces rays according to predetermined sequence of optical elements
- Non-sequential ray-tracing determines at each step next surface a given ray will reach (much slower)
- Optical design programs: WinLens, ZEMAX, OSLO
- Programs only useful once major design decisions have already been made!

Ray Tracing Software (sequential)



Surf:Type		Comment	Radius		Thickness		Glass		Semi-Diameter		Conic
OBJ	Standard		Infinity		Infinity				Infinity		0.000000
1*	Standard	55273	107.030000		1.250000		SF10		6.250000	U	0.000000
2*	Standard		10.990000		5.000000		BAFN10		6.250000	U	0.000000
3*	Standard		-17.270000		2.840000				6.250000	U	0.000000
4*	Standard		22.940000		3.680000		SK11		6.250000	U	0.000000
5*	Standard		-15.540000		1.500000		SF5		6.250000	U	0.000000
6*	Standard		-58.840000		0.000000				6.250000	U	0.000000
STO	Standard		Infinity		10.619667	M			3.314095		0.000000
IMA	Standard		Infinity						2.252033		0.000000

WAVEFRONT FUNCTION

LENS HAS NO TITLE.
THU JAN 8 2009
0.5880 MICRONS AT 0.0000 DEG.
PEAK TO VALLEY IS 106.9225 WAVES.

C:\ZEMAX\SAMPLES\LENS.ZMX
CONFIGURATION 1 OF 1

LAYOUT

LENS HAS NO TITLE.
THU JAN 8 2009
TOTAL LENGTH: 24.88967 MM

ERROR 921: SAMPLING TOO LOW, DATA INACCURATE!

POLYCHROMATIC DIFFRACTION MTF

LENS HAS NO TITLE.
THU JAN 8 2009
DATA FOR 0.4800 TO 0.6600 MICRONS.

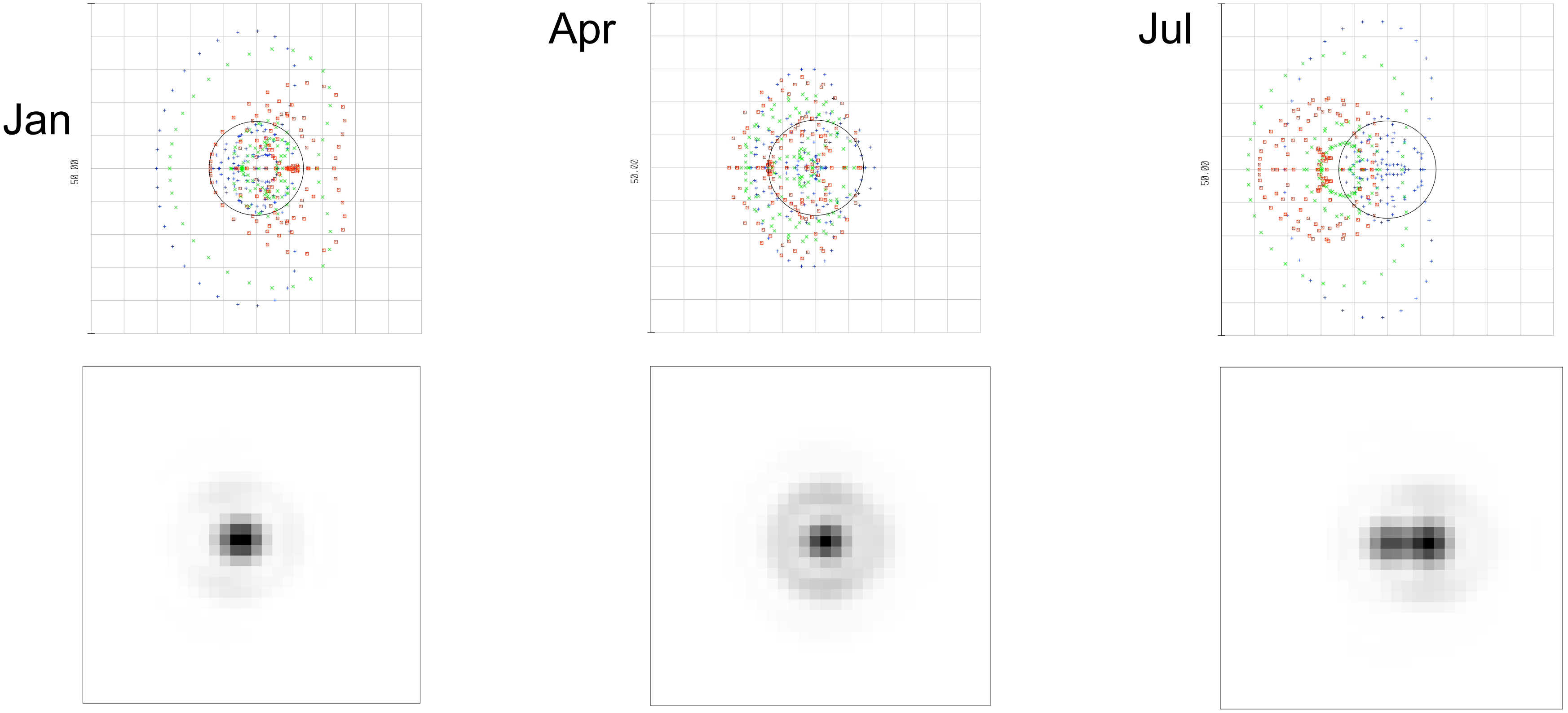
C:\ZEMAX\SAMPLES\LENS.ZMX
CONFIGURATION 1 OF 1

Lens has no title. EFFL: 15.5683 WFNO: 1.54385 ENPD: 10 TOTR: 24.8897

Spot Diagrams

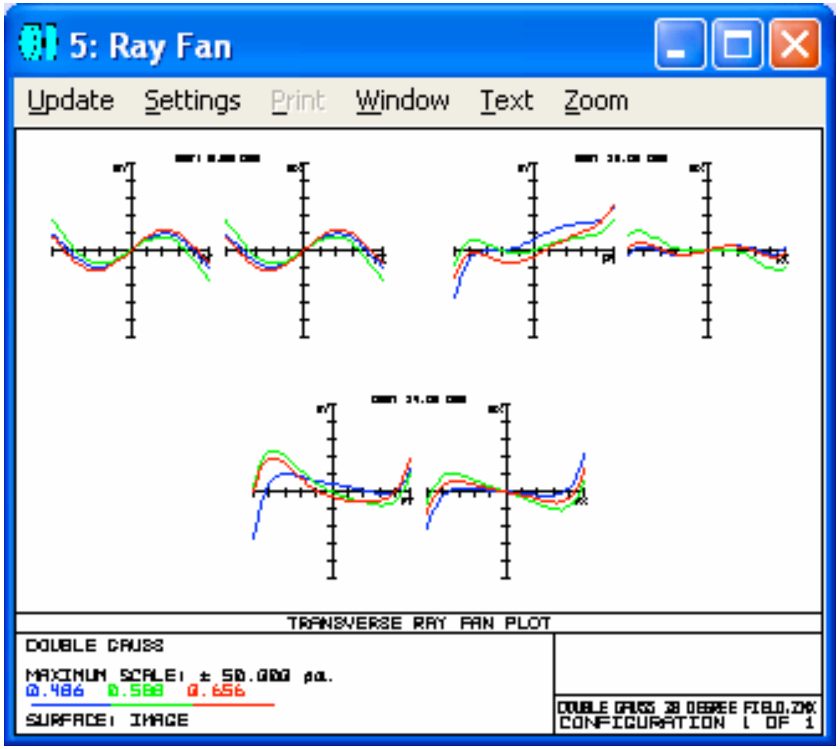
S5T

custom spherical doublets

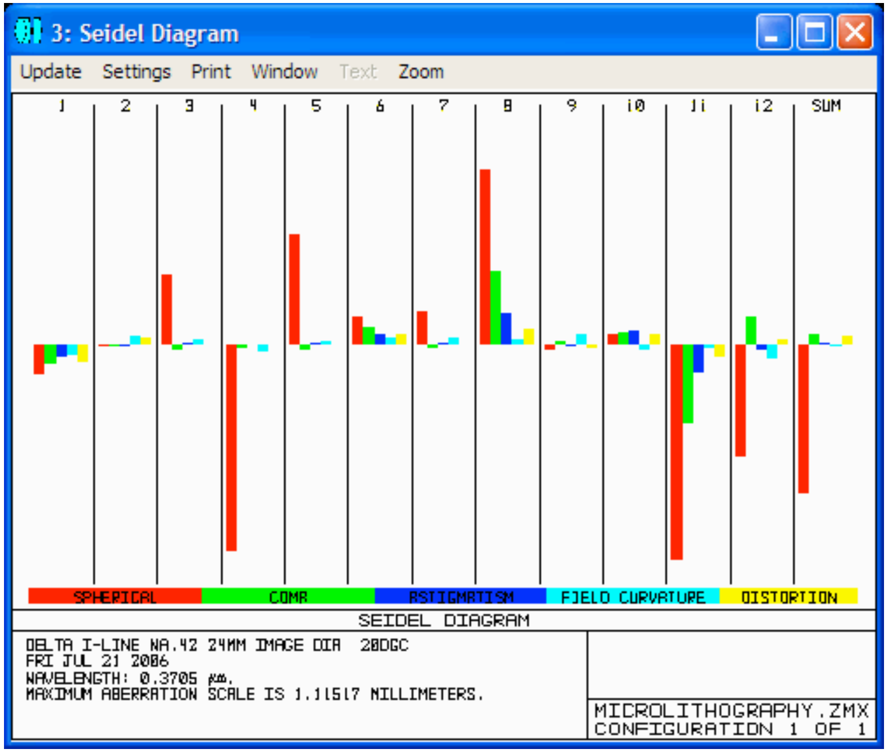


Aberration Plots

- optical path differences
- Seidel diagram



```
TRANSVERSE RAY FAN PLOT
DOUBLE GAUSS
MAXIMUM SCALE: ± 50.000 µm.
0.486  0.588  0.656
SURFACE: IMAGE
DOUBLE GAUSS 28 DEGREE FIELD.ZMX
CONFIGURATION 1 OF 1
```



```
SEIDEL DIAGRAM
DELTA I-LINE NA.42 24MM IMAGE DIA  20DGC
FRI JUL 21 2006
WAVELENGTH: 0.3705 µm.
MAXIMUM ABERRATION SCALE IS 1.11517 MILLIMETERS.
MICROLITHOGRAPHY.ZMX
CONFIGURATION 1 OF 1
```

Optimization

- built into most optical design software
- automatically improves performance
- degrees of freedom = variables of optical design
  - radii of curvature of optical surfaces
  - spacing between elements
  - conic constants
  - glass thicknesses
- can change glass type
- generally does not add or remove optics

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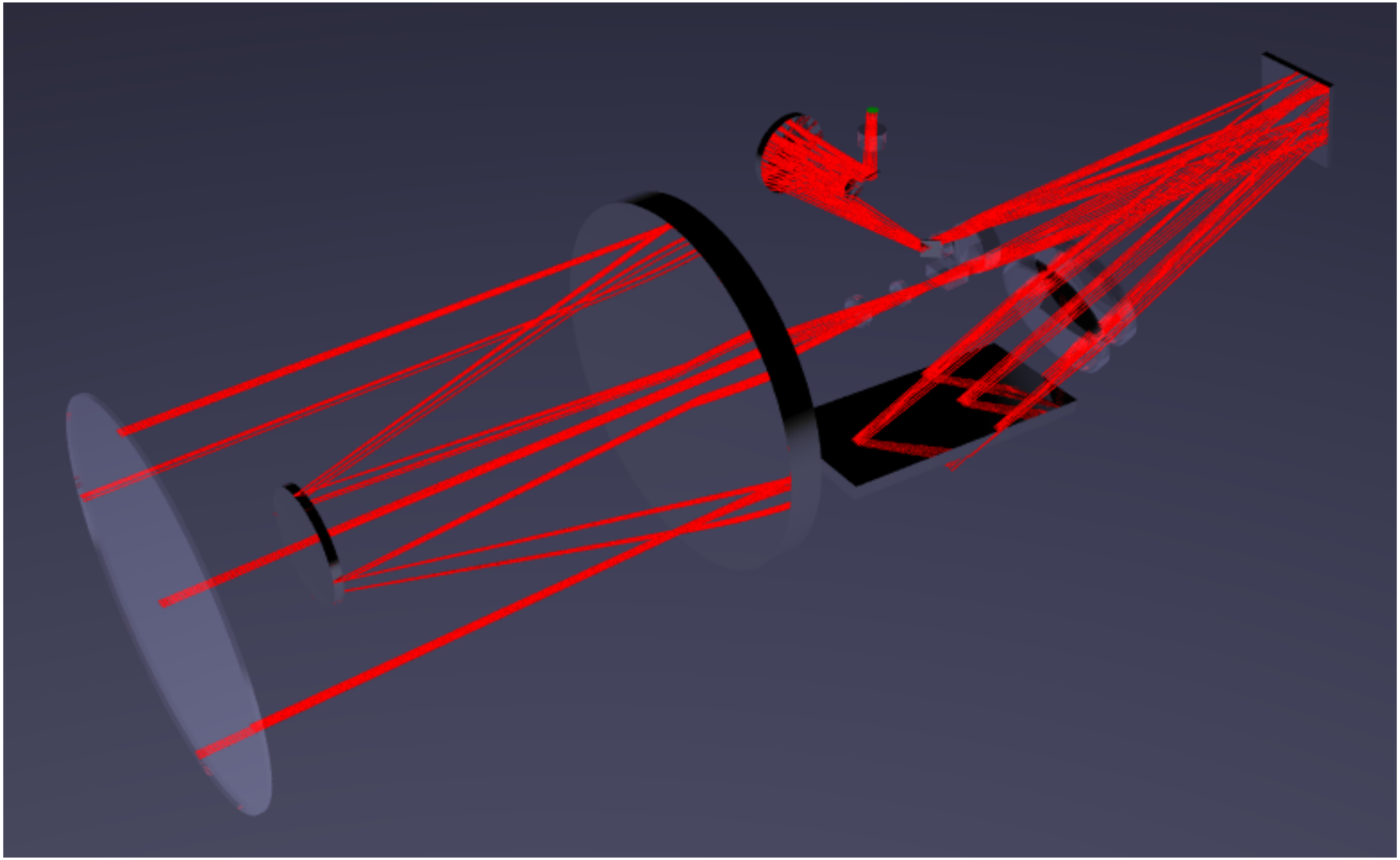
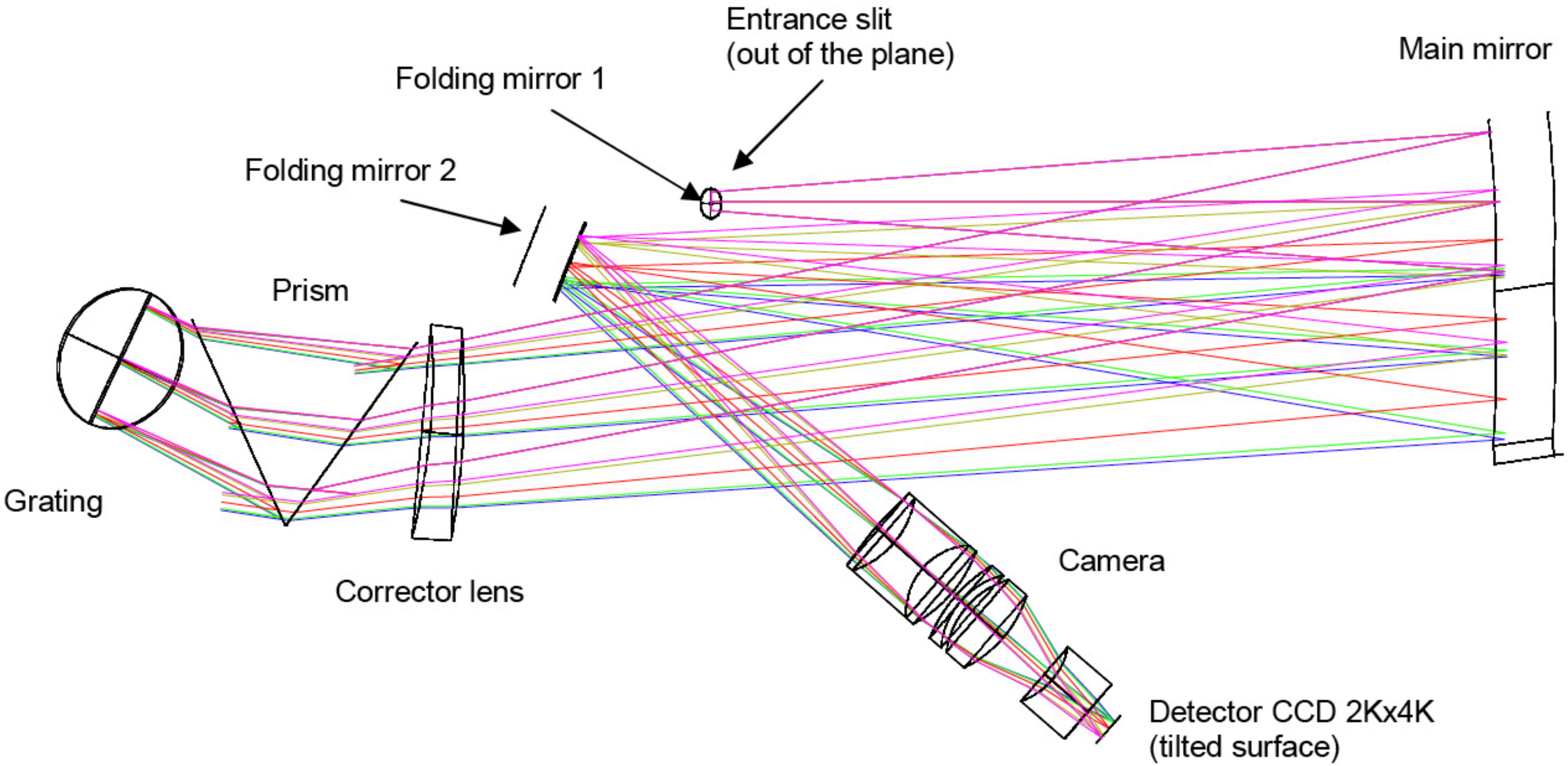
Optimization: Merit Function

- merit function
  - based on design requirements
  - design optimal = merit function at global minimum
- merit function depends on
  - optical design parameters (restrictions on diameters, thicknesses, etc.)
  - system parameters (f-number to be achieved, overall system length, etc.)
  - aberration parameters (such as rms wavefront aberration, field curvature etc., often as a function of field angle and wavelength)

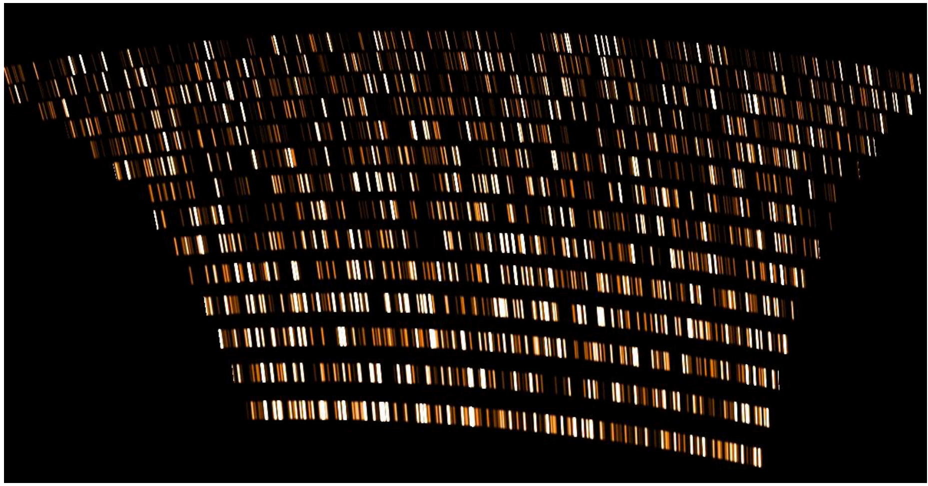
Design Example 1: SOLIS VSM



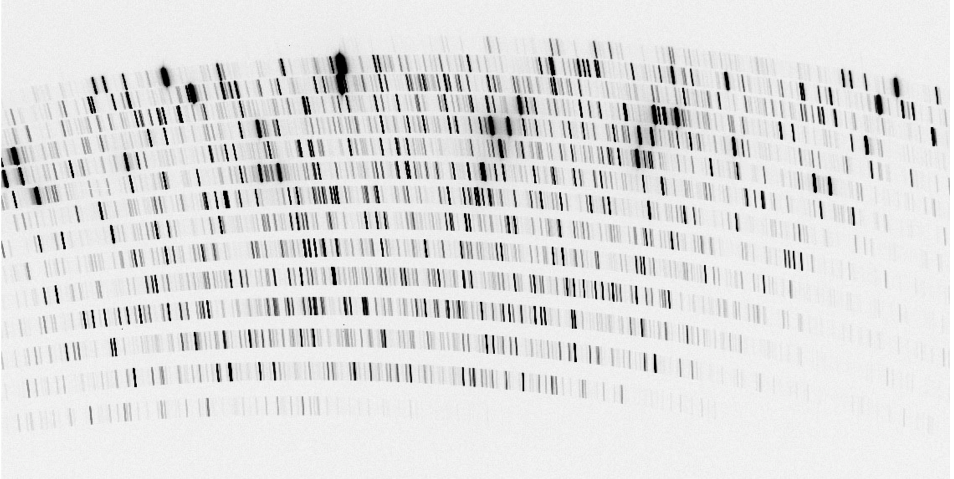
Design Example 2: X-shooter



Design Example 2: X-shooter



simulated from optical design



measured

Tolerance Analysis

- determines tolerances to which
  - optical elements have to be manufactured
  - optical elements have to be positioned
  - environmental parameters have to be controlled
- needs to consider all design parameters that are subject to errors
- different optical designs may have same performance but one may be much more demanding on the manufacturing and/or alignment than another design

Sensitivity Analysis

- tolerance analysis based on merit function
  - maybe the same as used for optimization
- sensitivity analysis
  - simplest form of tolerance analysis
  - reveals sensitivity of merit function with respect to an assumed error in each design parameter (e.g. known manufacturing tolerances)

Inverse Sensitivity Analysis

- inverse sensitivity analysis
  - determines maximum allowed error in design parameter for given maximum allowed change in merit function
  - provides first approximation to tolerances to be specified
  - does not consider coupled effect of simultaneous errors in all design parameters
- Monte Carlo tolerance analysis provides realistic estimate of expected performance by using statistical distributions

Tolerancing Example

Toerance sensitive analysis table

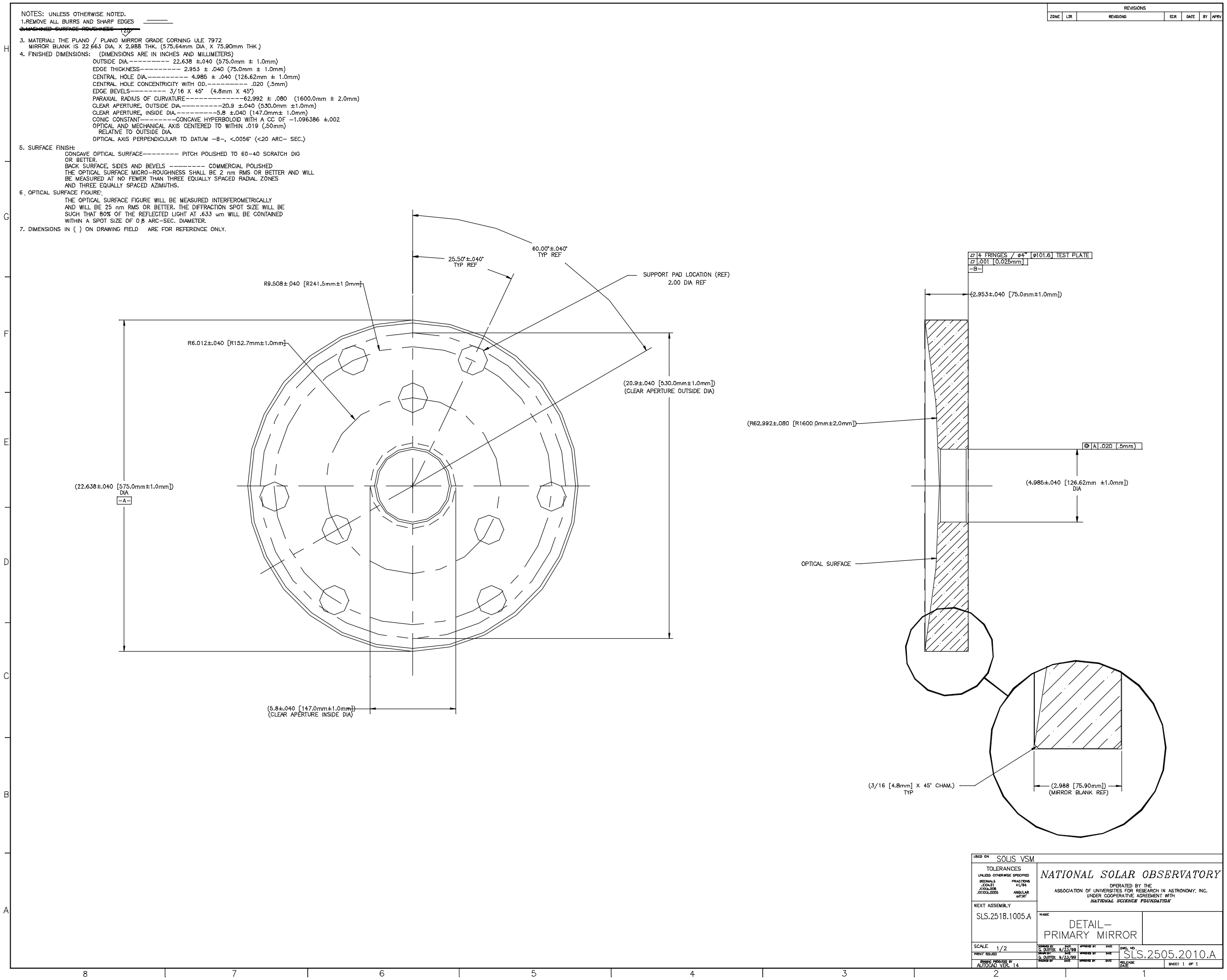
		errors	CC	Δ CC	R	Δ R	budget error	CC errors
r1	69.5879	0.02	-1.09576	.00062	1599.9329	-0.0671	0.02	0.000624
		-0.02	-1.09701	-.00063	1600.0673	0.06732		
r2	92.6792	0.02	-1.09657	-.00018	1599.9967	-0.003262	0.02	-0.000183
		-0.02	-1.09620	.00018	1600.0033	0.00326		
d1	280	0.02	-1.09576	.00062	1600.0804	0.08041	0.04	0.0012482
		-0.02	-1.09701	-.00063	1599.9195	-0.0805		
d2	12	0.03	-1.09738	-.00099	1599.9283	-0.0717	0.01	-0.000331
		-0.03	-1.09665	-.00026	1599.9106	-0.0894		
d3	169.082	0.05	-1.09732	-.00094	1600.0224	0.02238	0.03	-0.000561
		-0.05	-1.09545	.00093	1599.9776	-0.0224		
d4	5	0.02	-1.09637	.00001	1600.0132	0.0132	0.02	1.309E-05
		-0.02	-1.09640	-.00001	1599.9868	-0.0132		
d5*	53.994	1	-1.09572	.00067	1600.9999	0.9999	2	0.0013325
		-1	-1.09705	-.00067	1599.0001	-0.9999		

Total conic constant error 0.0020447

***The error of d5 including the radius measurement error of the primary mirror.**

excerpt from SOLIS VSM conic constant tolerance analysis

Drawing Example



NOTES: UNLESS OTHERWISE NOTED.

1.REMOVE ALL BURRS AND SHARP EDGES

~~2.MACHINED SURFACE ROUGHNESS~~

3. MATERIAL: THE PLANO / PLANO MIRROR GRADE CORNING ULE 7972
MIRROR BLANK IS 22.663 DIA. X 2.988 THK. (575.64mm DIA. X 75.90mm THK.)

4. FINISHED DIMENSIONS: (DIMENSIONS ARE IN INCHES AND MILLIMETERS)
OUTSIDE DIA.---------- 22.638 ±.040 (575.0mm ± 1.0mm)
EDGE THICKNESS---------- 2.953 ± .040 (75.0mm ± 1.0mm)
CENTRAL HOLE DIA.---------- 4.985 ± .040 (126.62mm ± 1.0mm)
CENTRAL HOLE CONCENTRICITY WITH OD.---------- .020 (.5mm)
EDGE BEVELS--------- 3/16 X 45° (4.8mm X 45°)
PARAXIAL RADIUS OF CURVATURE--------------62.992 ± .080 (1600.0mm ± 2.0mm)
CLEAR APERTURE, OUTSIDE DIA.----------20.9 ±.040 (530.0mm ±1.0mm)
CLEAR APERTURE, INSIDE DIA.----------5.8 ±.040 (147.0mm± 1.0mm)
CONIC CONSTANT---------CONCAVE HYPERBOLOID WITH A CC OF −1.096386 ±.002
OPTICAL AND MECHANICAL AXIS CENTERED TO WITHIN .019 (.50mm) RELATIVE TO OUTSIDE DIA.
OPTICAL AXIS PERPENDICULAR TO DATUM -B-, <.0056° (<20 ARC- SEC.)

5. SURFACE FINISH:
CONCAVE OPTICAL SURFACE--------- PITCH POLISHED TO 60-40 SCRATCH DIG OR BETTER.
BACK SURFACE, SIDES AND BEVELS --------- COMMERCIAL POLISHED
THE OPTICAL SURFACE MICRO-ROUGHNESS SHALL BE 2 nm RMS OR BETTER AND WILL BE MEASURED AT NO FEWER THAN THREE EQUALLY SPACED RADIAL ZONES AND THREE EQUALLY SPACED AZIMUTHS.

6. OPTICAL SURFACE FIGURE:
THE OPTICAL SURFACE FIGURE WILL BE MEASURED INTERFEROMETRICALLY AND WILL BE 25 nm RMS OR BETTER. THE DIFFRACTION SPOT SIZE WILL BE SUCH THAT 80% OF THE REFLECTED LIGHT AT .633 um WILL BE CONTAINED WITHIN A SPOT SIZE OF 0.8 ARC-SEC. DIAMETER.

7. DIMENSIONS IN ( ) ON DRAWING FIELD ARE FOR REFERENCE ONLY.

USED ON SOLIS VSM

TOLERANCES
UNLESS OTHERWISE SPECIFIED
DECIMALS
.XX±.01
.XXX±.005
.XXXX±.0005
FRACTIONS
±1/64
ANGULAR
±0°30'

NATIONAL SOLAR OBSERVATORY
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ASSOCIATION OF UNIVERSITIES FOR RESEARCH IN ASTRONOMY, INC.
UNDER COOPERATIVE AGREEMENT WITH
NATIONAL SCIENCE FOUNDATION

NEXT ASSEMBLY
SLS.2518.1005.A

NAME
DETAIL–
PRIMARY MIRROR

SCALE 1/2
PRINT ISSUED
DRAWING PRODUCED BY
AUTOCAD VER. 14

DESIGNED BY C. DUFFEK DATE 6/23/99
DRAWN BY C. DUFFEK DATE 6/23/99
CHECKED BY DATE
APPROVED BY DATE
APPROVED BY DATE
APPROVED BY DATE

DWG. NO. SLS.2505.2010.A
RELEASE DATE
SHEET 1 OF 1

System Budgets

- Look at the whole instrument at once
- Find the optimum balance
- The whole is the sum of its parts
- Examples:
  - wavefront error
  - transmission/photon budget
  - thermal background
  - polarimetric accuracy
  - weight, cost, ...

Wavefront Error Budget

overall:

		Δs in nm	Number of surface	Materials interface	index of refraction difference	Δw for each component in nm	PV spec nm in wave at 633 nm
Polarization compensator		13.9	2	Fused Silica-Air	0.455	9.0	20
HWP-Z		19.0				9.0	20
	Surface1	9.5	1	Air-Quartz	0.541		
	Surface2	9.5	1	Quartz-Air	0.541		
	Surface3	9.5	1	Air-MgF2	0.376		
	Surface4	9.5	1	MgF2-Air	0.376		
Window FLC		26.9	2			8.9	20
Housing	Surface1	19	1	Air-Fused Silica	0.455		
	Surface2	19	1	Fused Silica-Cement_NOA61	0.108		
Zero		24.0				9.3	20
order plate	Surface1	17	1	Cement_NOA61-Quarzt	0.022		
	Surface2	17	1	Quartz-Air	0.541		
FLC		9.2	2	Fused Silica-Air	0.455	6.0	30
Window FLC Housing		13.9	2	Fused Silica-Air	0.455	9.0	20
Beam Splitter	Surface1	**14.0**	1	Air-N-SF15	0.689	**9.7**	19
	Surface2	**14.0**	1	Air-N-SF15		**9.7**	19
Filter 1		28.0	2	Fused Silica-Air	0.455	18.1	10
Camera Lens		26.0				8.9	20
	Surface1	13	1	Air-S-NSL36	0.513		
	Surface2	13	1	S-NSL36-Cement_NOA61	0.050		
	Surface3	13	1	Cement_NOA61-CAF2	0.153		
	Surface4	13	1	CAF2-Air	0.410		
Filter 2		**28.0**	2	Fused Silica-Air	0.455	**18.1**	10
Field Lens		**14.0**	2	Caf2-Air	0.410	**8.1**	22
					Total WFE in nm	**37.9**	

sensitivities from ZEMAX:

	Δ Φ / Φ (%)	Pup ΔX/Φ (%)	WFE RMS (in nm)
Dx EPOL M1	0.6		52.9
Dy EPOL M1		0.3	52.8
Dz EPOL M1	0.1		909.6
Tx EPOL M1	1.2	0.6	49.3
Ty EPOL M1			49.3
TFRN EPOL M1			72.7
Dx EPOL M2	0.9		52.8
Dy EPOL M2		0.5	52.8
Dz EPOL M2	0.01		912.1
Tx EPOL M2	0.3	0.2	9.2
Ty EPOL M2			9.3
TFRN EPOL M2			59.8
Tx folding 1	1.4	0.7	0.1
Dz folding 1	0.01		8.2
TFRN folding 1			21.2
Tx folding 2	1.7	0.8	0.1
Dz folding 2			8.2
TFRN folding 2			9.2

Photon Budget

Quantity	**wavelength (nm)**			**units**	**comment**
	630.2	**854.2**	**1083**		
Total transmission	0.228804	0.227108	0.225067		unpolarized
Photoelectric flux	1.23E+08	1.12E+08	3.13E+06	e-/s	per pixel
CCD maximum detection	1.20E+08	1.20E+08	6.00E+07	e-/s	given by full-well depth
Detected flux	1.20E+08	1.12E+08	3.13E+06	e-/s	
Stokes Q modulation efficiency	0.58				
Stokes V modulation efficiency	0.50	1.00			
Stokes I noise in 0.5s	1.29E-04	1.34E-04	7.99E-04		
Stokes Q,U noise in 0.5s	**2.24E-04**				
Stokes V noise in 0.5s	**2.58E-04**	**1.34E-04**			

Transmission Budget

X-shooter