optical design

a very rough overview…

Astronomical Instrumentation course

lecture 7a

Dec 15, 2010

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requirements definition

- FOV
- (effective) focal length
- spatial resolution (+ sampling)
- spectral range & resolution (+ sampling)
- polarimetric performance
- transmission
- stability
- etc.

boundary conditions

- telescope
- telescope interfaces (see next lecture)
- focal station dimensions
- focal station gravity vector
- detector availability
- available € or $

optical design

global set-up

- 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
- etc.

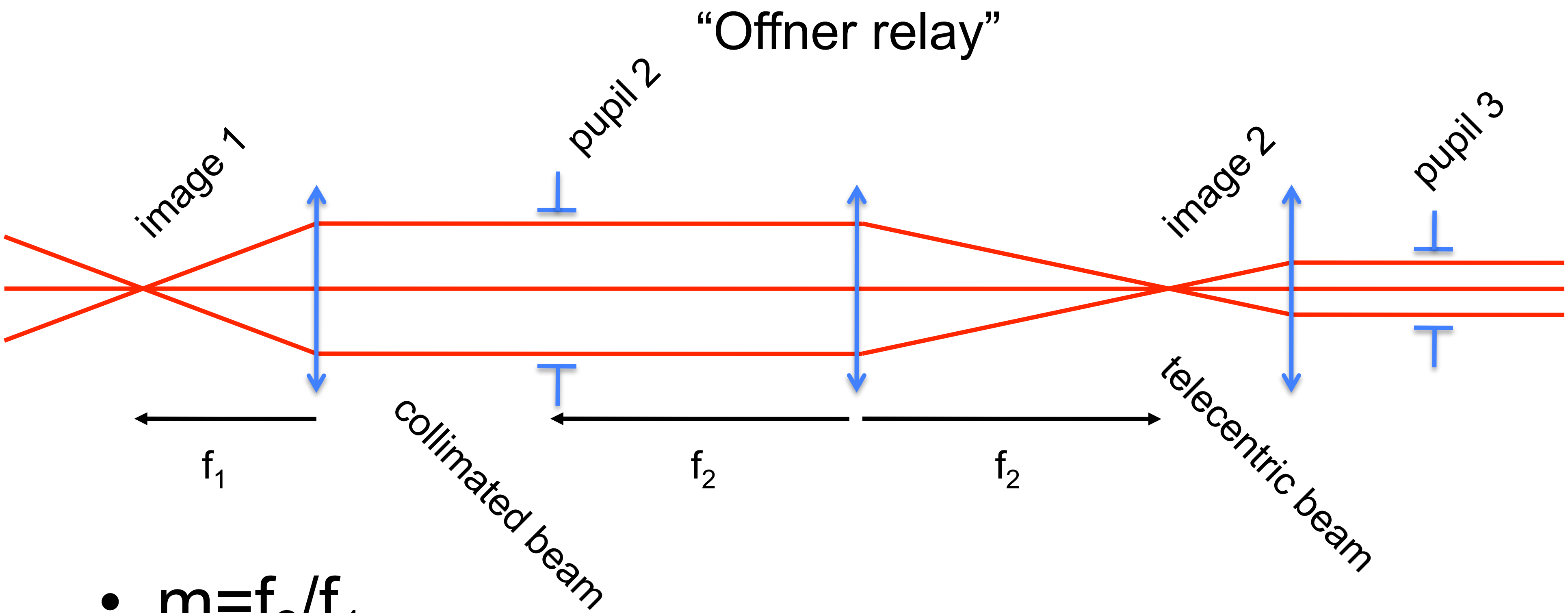
optical design

global set-up

- (de-)magnification
- F-numbers
  - the amount of problems with aberrations increases with smaller F-number…
- collimated beam?
- telecentric beam?

optical design

global set-up



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

optical design

global set-up

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

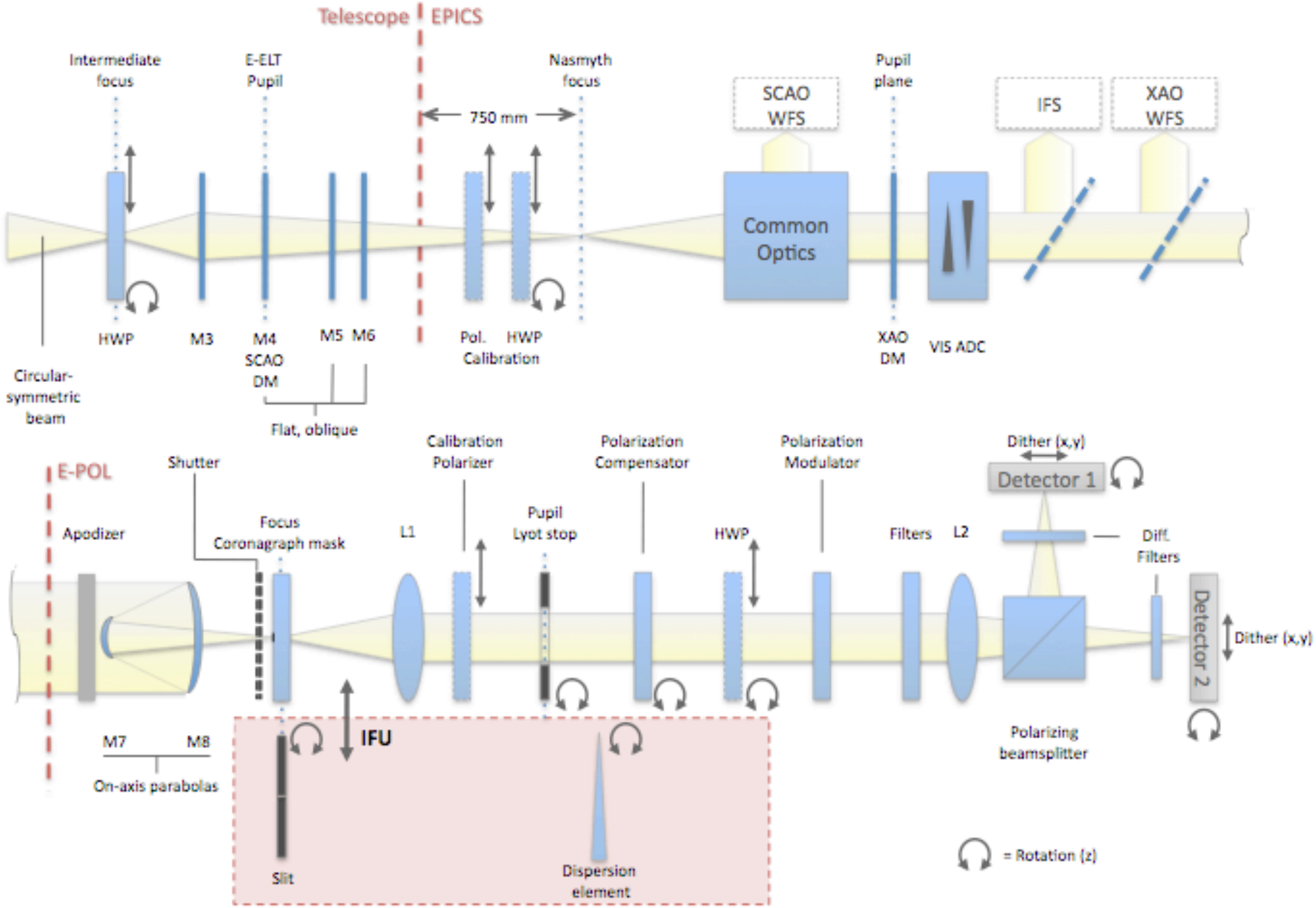
étendue

- or “throughput” or “grasp”, connected with “Lagrange invariant” or “optical invariant”
- derived from conservation of energy
- considered in every pupil plane:
  - 3D: aperture*FOV = A*Ω = constant
  - 2D: d*θ = constant
- unless focal ratio degradation in fibers…

optical design

block diagram

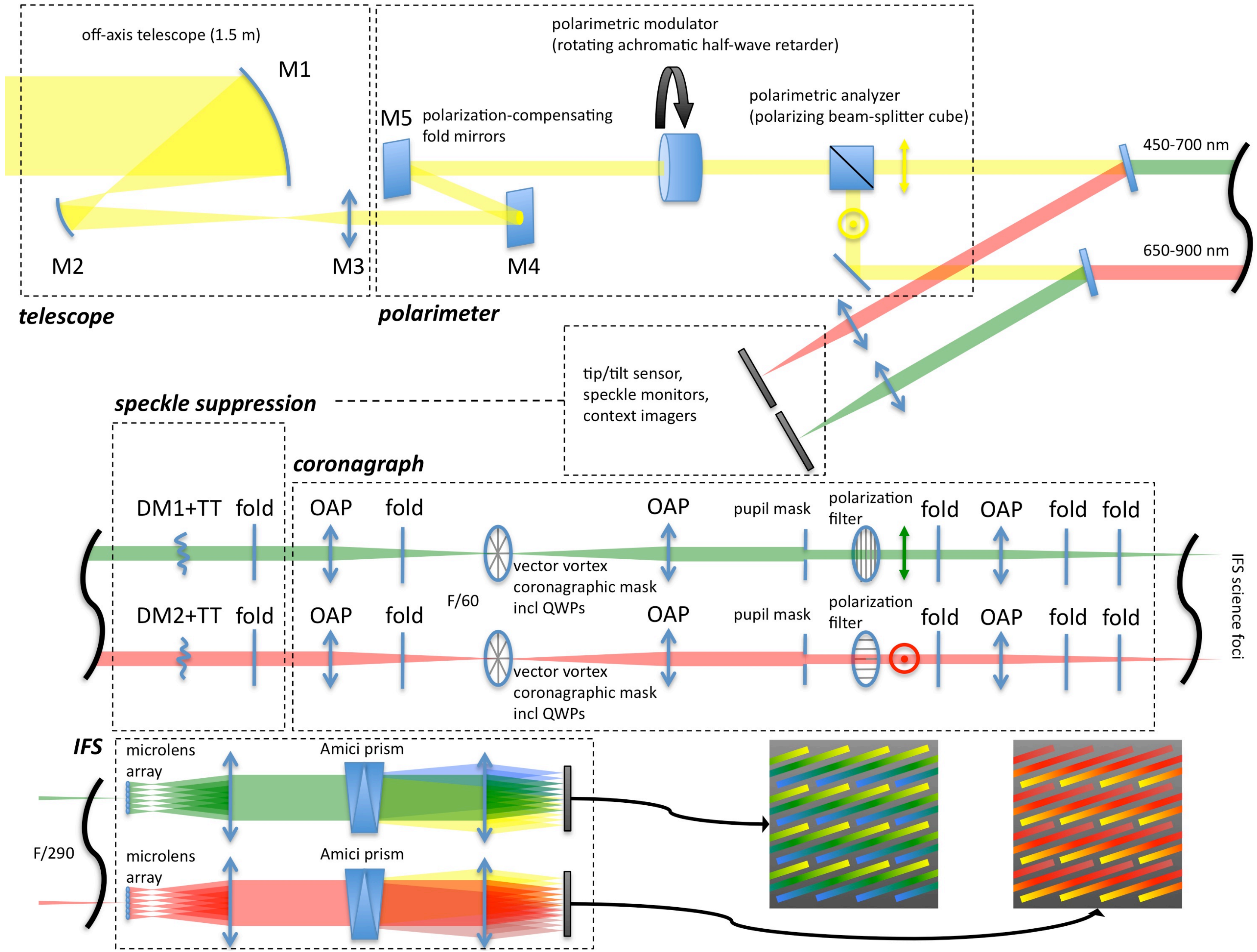
EPICS-EPOL



optical design

block diagram

SPICES



ray tracing

- used in optical design programs:
  - WinLens
  - ZEMAX
  - OSLO
  - CodeV
  - etc.
- Such programs are only useful when major design decisions have already been made!

ray tracing

- direction cosines $\mathbf{v}=(\gamma,\delta,\varepsilon)$
  - $\gamma = \cos\theta$
  - $\delta = \cos\varphi$
  - $\varepsilon = \cos\psi$
- propagation along distance s measured in z direction:
  - $x_2 = \gamma s/\varepsilon + x_1$
  - $y_2 = \delta s/\varepsilon + y_1$
  - $z_2 = s + z_1$

ray tracing

- surface P with normal $\mathbf{v'}=(\gamma',\delta',\varepsilon')$
- incidence angle $i = \arccos(\gamma\gamma' + \delta\delta' + \varepsilon\varepsilon')$
- reflection: $\gamma\gamma'' + \delta\delta'' + \varepsilon\varepsilon'' = \cos 2r$
- refraction: $\gamma\gamma'' + \delta\delta'' + \varepsilon\varepsilon'' = \cos (i-r)$

  use Snell's law
- relation with the surface normal:

  $\gamma'\gamma'' + \delta'\delta'' + \varepsilon'\varepsilon'' = \cos r$
- plus **v**, **v**' and **v**" should be in one plane:

  $(\mathbf{v} \mathrm{x} \mathbf{v}')\bullet\mathbf{v}'' = 0$

  $(\varepsilon\delta'-\varepsilon'\delta)\gamma'' + (\gamma\varepsilon'-\gamma'\varepsilon)\delta'' + (\delta\gamma'-\delta'\gamma)\varepsilon'' = 0$

optical design

ray tracing

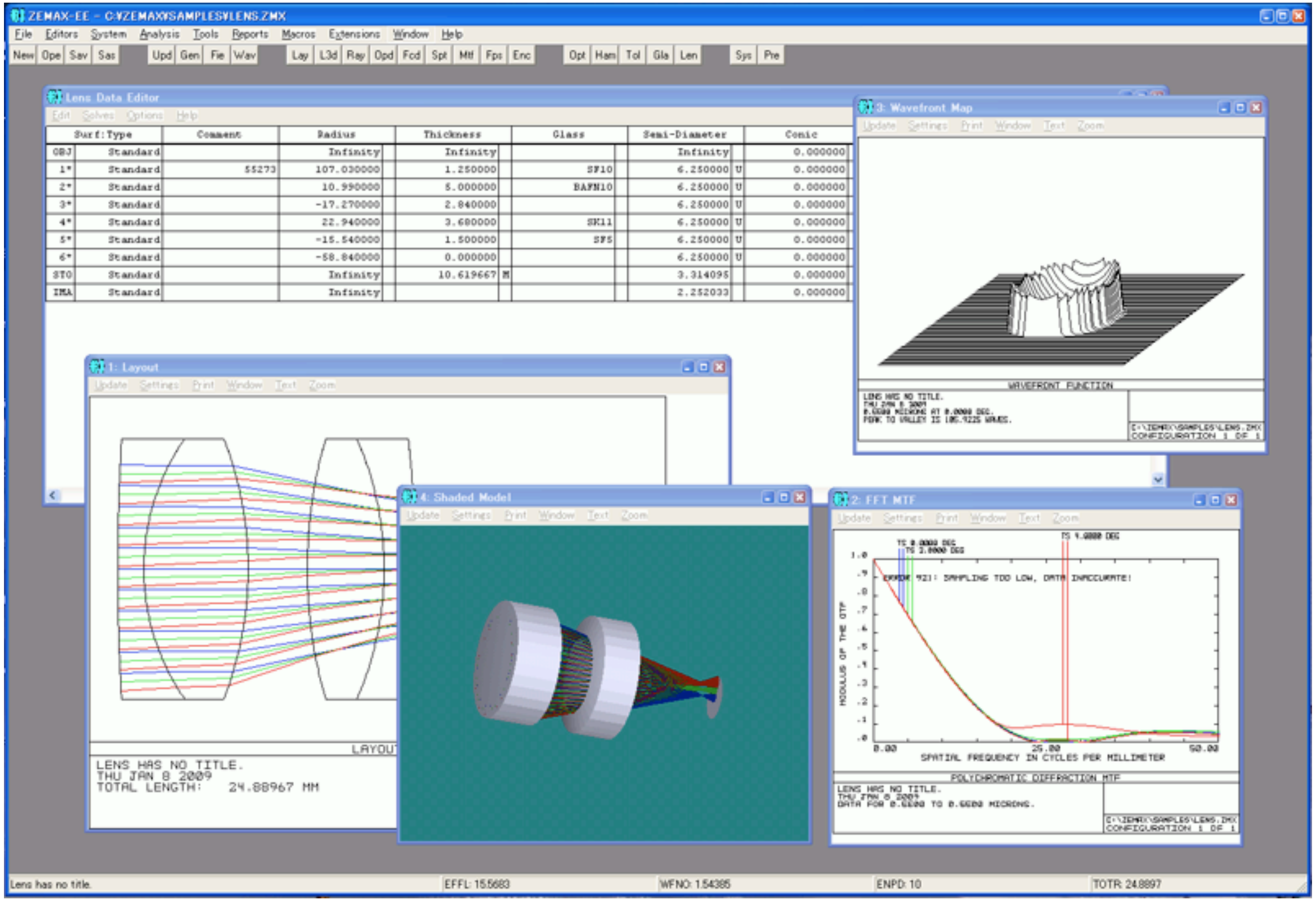
- sequential
  - from one surface to the next along the z axis
  - populate the pupil with rays
  - wavelength λ, field [x,y] as global parameters

- non-sequential
  - specific 3D volume and fire off rays in all directions

optical design

ray tracing

sequential



spot diagrams

- traced rays + Airy disk
- FFT PSF

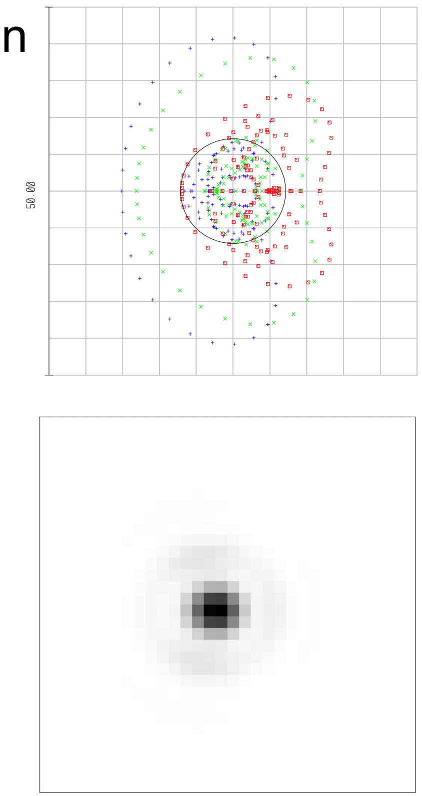
optical design

spot diagrams

S5T

custom spherical doublets

Jan



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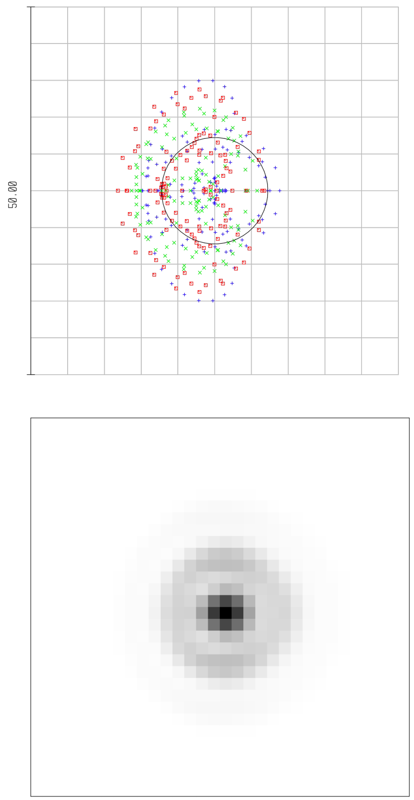

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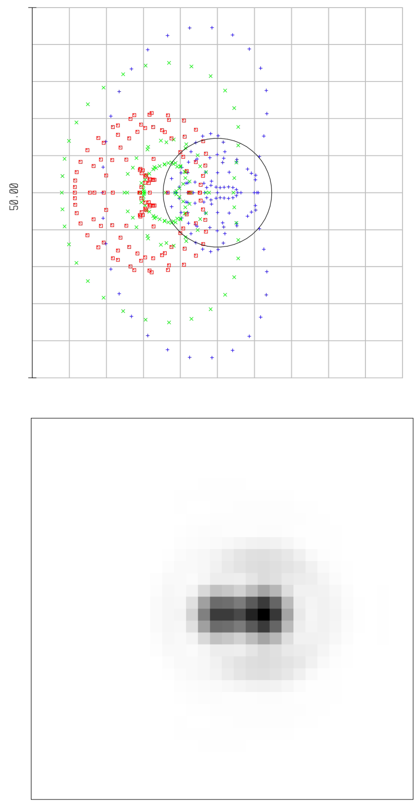
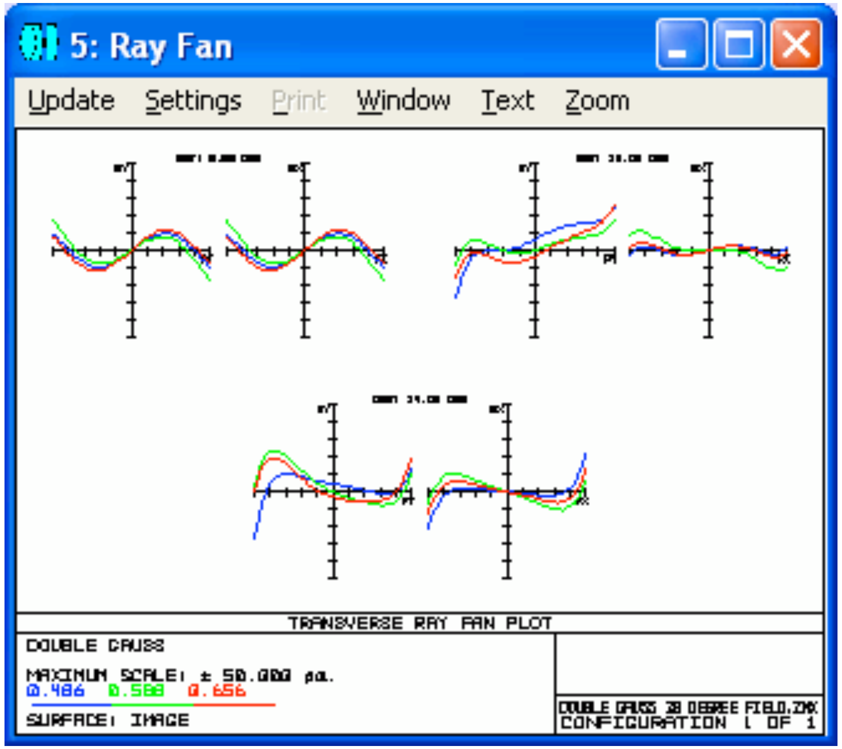
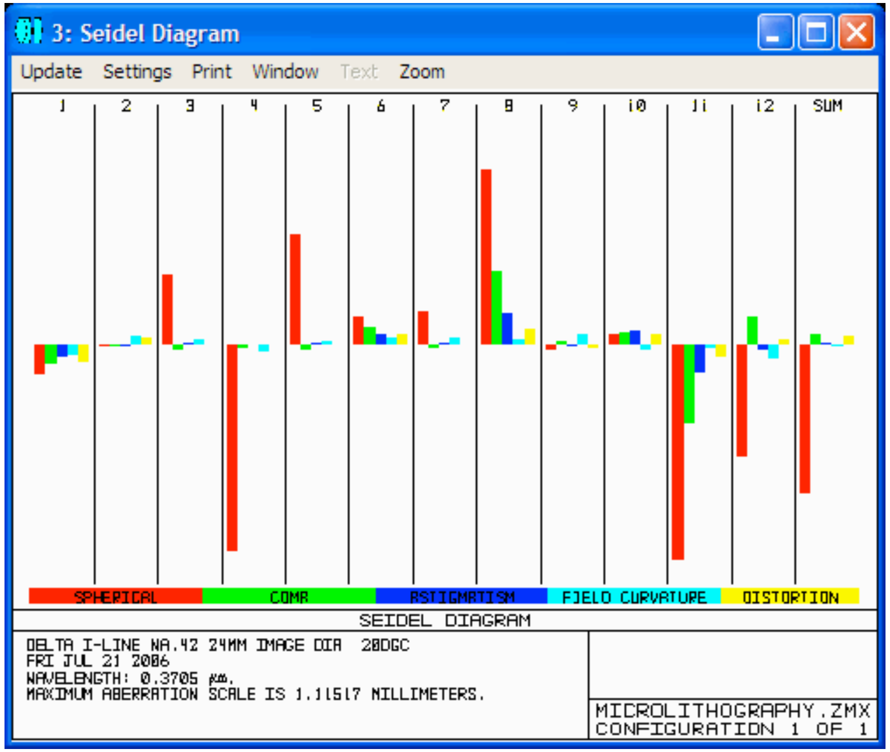


optical design

aberration plots

- transverse / longitudinal aberration
- Seidel diagram





optimization

- variables:
  - positions
  - angles
  - radii of curvature
  - conic constants
  - glass type
  - coating layers and material
  - etc.

optical design

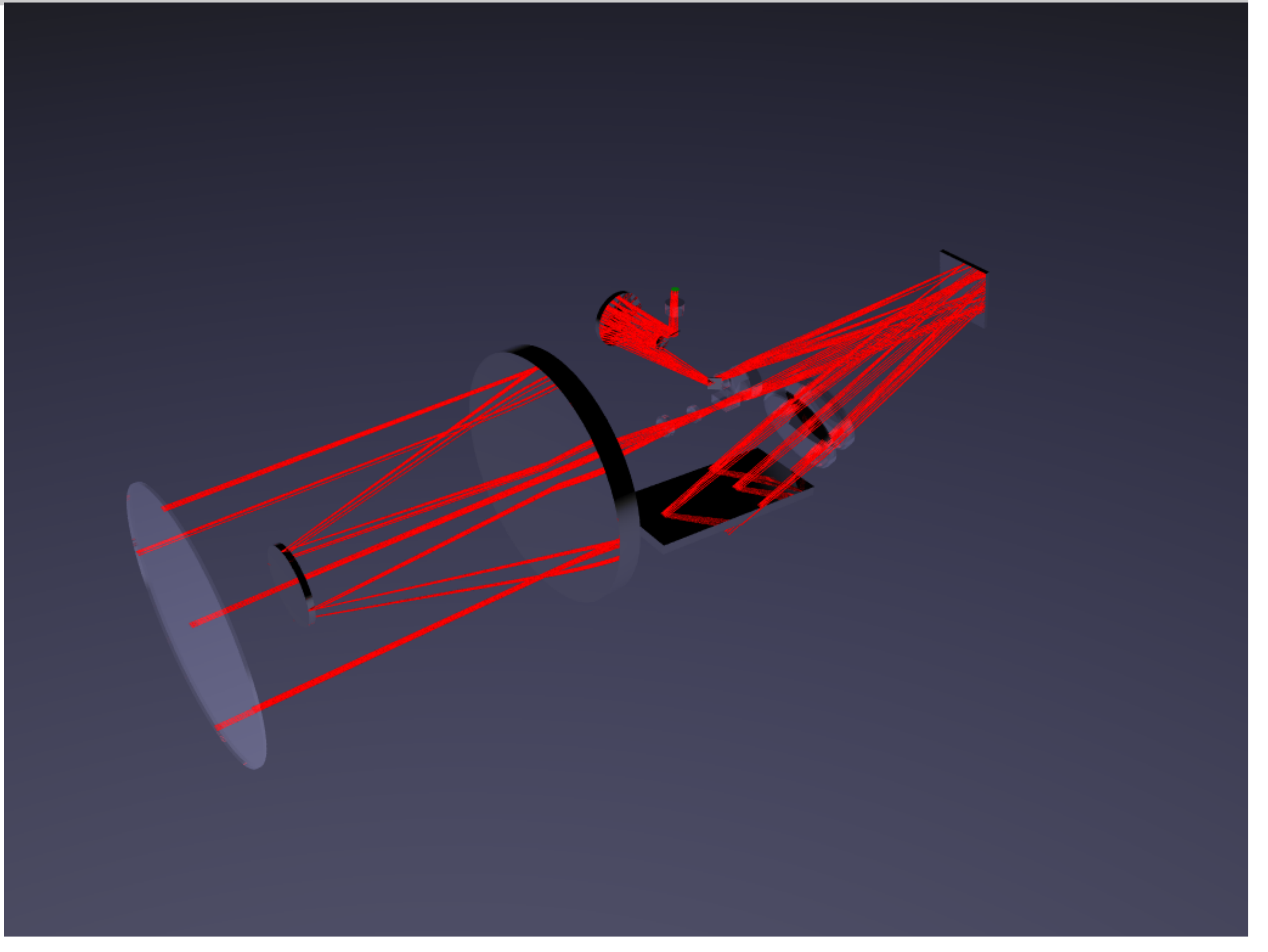
optimization

- merit function
- weighted linear combination of:
  - system:
    - effective focal length
  - spot:
    - centroid position
    - RMS radius
    - MTF
    - Strehl ratio (observed peak intensity / maximum peak intensity)
    - encircled energy
  - coating polarization properties
  - etc

optical design

design examples

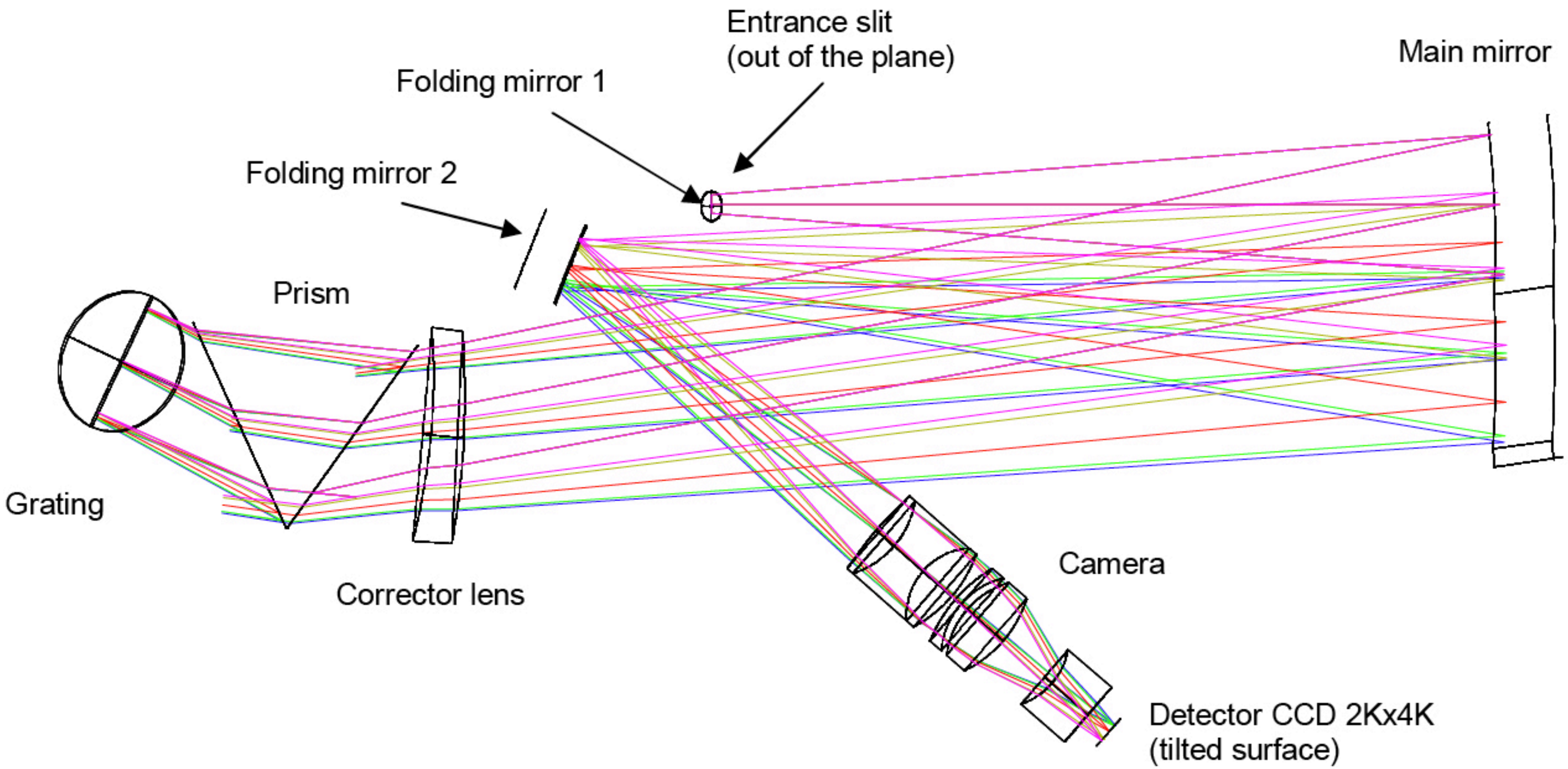
SOLIS-VSM



optical design

design examples

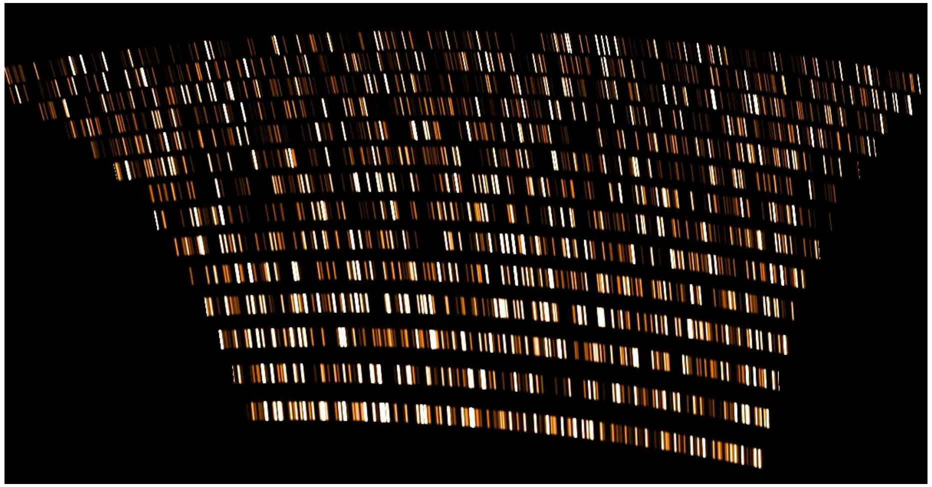
X-shooter



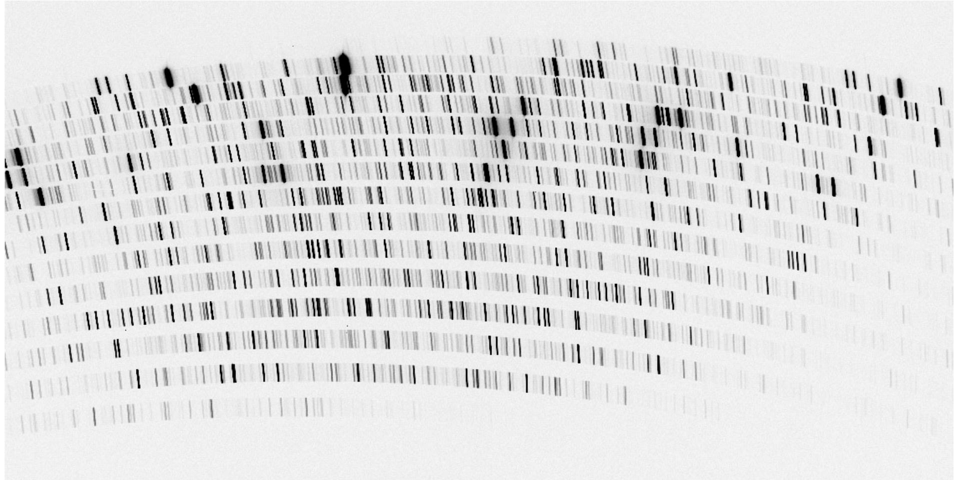
optical design

design examples

X-shooter



simulated from optical design



measured

tolerancing

- spot diagram diffraction limited with margin?
- sensitivity analysis for individual elements
- in the end: Monte Carlo

tolerancing

Decentre			Tilt		
$\frac{\partial X}{\partial x_i}$	$\frac{\partial Y}{\partial x_i}$	$\frac{\partial Z}{\partial x_i}$	$\frac{\partial X}{\partial \alpha_i}$	$\frac{\partial Y}{\partial \alpha_i}$	$\frac{\partial Z}{\partial \alpha_i}$
$\frac{\partial X}{\partial y_i}$	$\frac{\partial Y}{\partial y_i}$	$\frac{\partial Z}{\partial y_i}$	$\frac{\partial X}{\partial \beta_i}$	$\frac{\partial Y}{\partial \beta_i}$	$\frac{\partial Z}{\partial \beta_i}$
$\frac{\partial X}{\partial z_i}$	$\frac{\partial Y}{\partial z_i}$	$\frac{\partial Z}{\partial z_i}$	$\frac{\partial X}{\partial \gamma_i}$	$\frac{\partial Y}{\partial \gamma_i}$	$\frac{\partial Z}{\partial \gamma_i}$

optical design

tolerancing

- example: EPICS-EPOL

DECENTERS			TILTS		
Apodiser					
0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0
Entire telescope					
1000.0	0.0	-0.1	0.0	2016.8	10.8
0.0	1000.0	-0.1	-2016.8	0.0	34.8
0.0	0.0	-1000.0	0.0	0.0	0.0
EPOL M1					
14997.8	0.0	520.6	0.0	-4654.0	88.5
0.0	14997.8	539.5	4654.0	0.0	85.8
-0.4	0.0	-256224.9	0.0	0.0	0.0
EPOL M2					
-13997.7	0.0	967.1	0.0	872.5	0.1
0.0	-13997.7	948.2	-872.5	0.0	0.6
0.4	0.0	195390.7	0.0	0.0	0.0
Folding 1					
0.0	0.0	0.0	0.0	-345.3	0.1
0.0	0.0	0.0	348.9	0.0	0.1
287.0	0.0	-1979.3	0.0	0.0	0.0
folding 2					
0.0	0.0	0.0	0.0	194.4	0.1
0.0	0.0	0.0	-196.5	0.0	0.1
287.0	0.0	1979.3	0.0	0.0	0.0

optical design

stray light analysis

- look at where “second order” light ends up in non-sequential ray tracing
- or light outside FOV (in sequential ray tracing)

- solutions:
  - baffling
  - “ghosts”: defocus or tilt surfaces to move outside FOV

systems engineering

Astronomical Instrumentation course

lecture 7b

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systems engineering

why?

- Consider instrument as being more than just sum of its parts (subsystems).
- Crucial for complex instruments.
- Implement from beginning of the project.
- Interaction with optical, mechanical, electronic, software design.
- Interaction between different international teams (interfaces).

budgets

- wavefront error
- transmission
- thermal background
- radial velocity
- polarimetric accuracy
- etc.

- financial!

budgets

- top-down or bottom-up?
- first: distribution of best guess
- add quadratically or linearly?
- continuously update during design process and evaluate
- identify (critical) issues that contribute substantially to overall degradation of performance, and take action to mitigate

budgets

- system
  - subsystem A
    - component 1
    - component 2
  - subsystem B
    - component 3
    - component 4
    - component 5
- total

systems engineering

budgets

	static	dynamic
• observing system imaging performance		
– seeing		
– telescope		
• M1		
– manufacturing & testing		
– alignment		
– active optics performance		
– wind buffeting		
• pointing & guiding		
– AO		
• optics wavefront error		
• wavefront sensor noise influence		
• DM correction		
• non-common path errors		
– spectrograph		
• flexure		
• detector focusing		

WFE budget

- magnitude of error in [nm]
- decomposition in spatial frequencies or Zernike polynomials
- location: close to pupil plane or image plane?
- sensitivity analysis in optical design to assess whether or not a certain error is critical

systems engineering

WFE 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

interaction w/ mechanical design

- mounting precision [x,y,x], [φ,χ,ψ] from optical design
- optics deformation from mechanical design and finite element modeling
- several iterations of loop between optical and mechanical design

cryogenic instruments

- alignment at room temperature
- contraction and deformation due to cool-down
- cryogenic alignment mechanisms

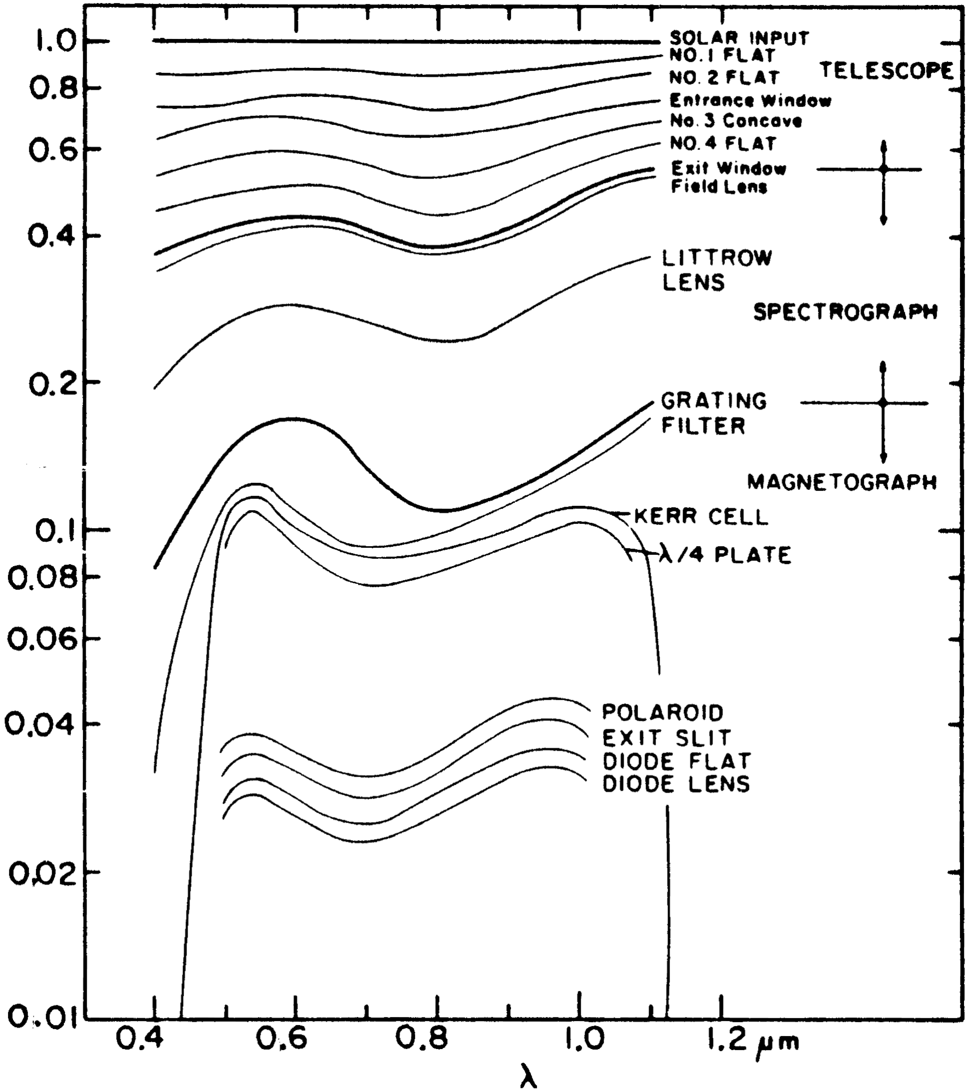
- ZEMAX allows for lengths to be determined by metal at certain temperature
- mirrors, mounts and bench out of aluminum: focus invariant
- invar material

transmission budget

- reduce number of surfaces (>1% loss per surface)
- optimize coatings

- main ingredient for photon budget, plus photon noise and readout noise
- exposure time calculator: S/N for science goal feasible within a night?

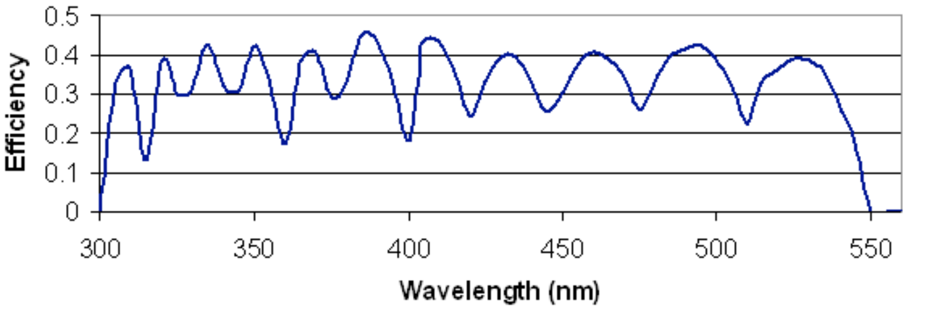
systems engineering
transmission budget

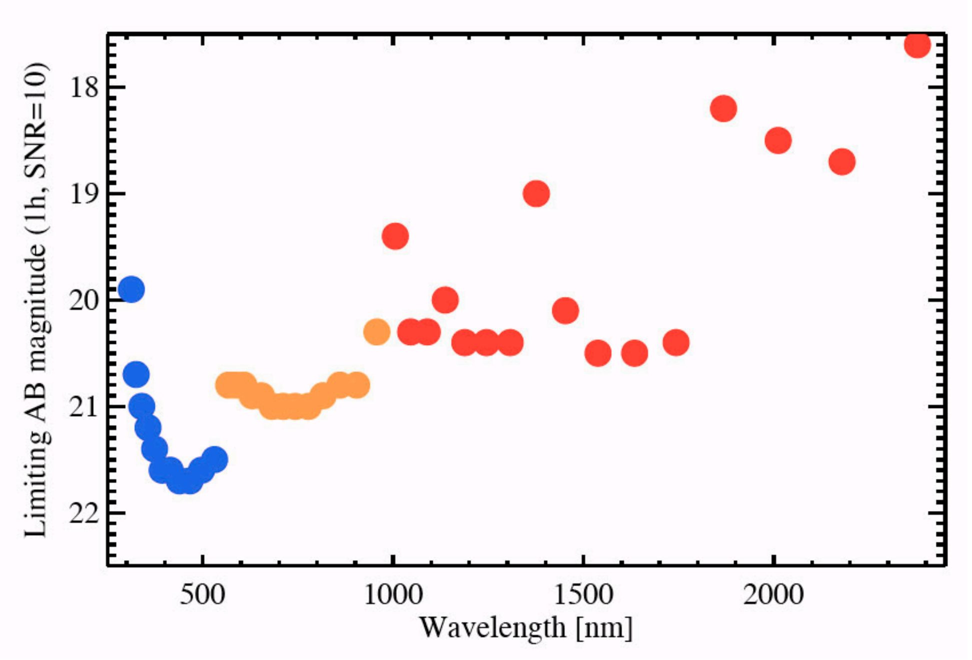


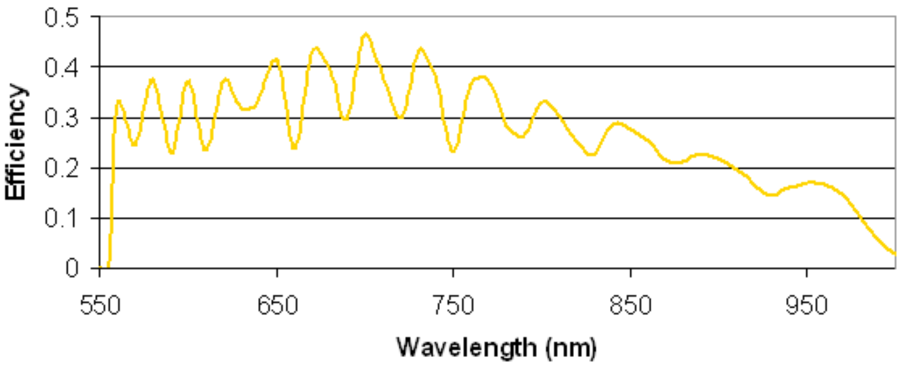
systems engineering

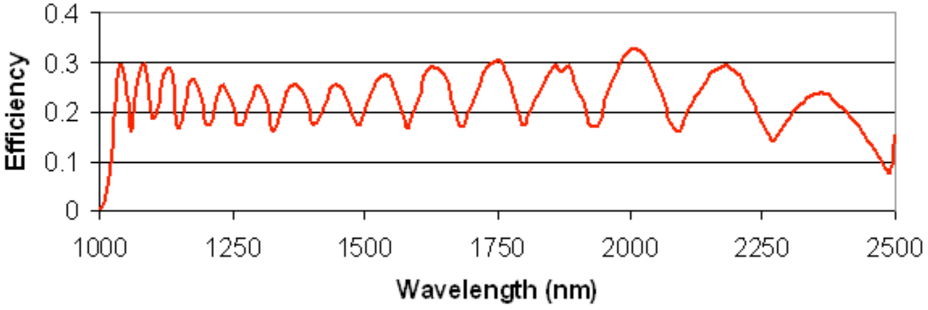
transmission budget

X-shooter









controlling complexity

- number of moving parts
- thermal control
- vacuum systems
- number of observing modes

- deal with single-point failures
  - redundancy

requirements verification

- verification matrix for lab tests
- traceability to science requirements
  - What is the science impact if a certain spec cannot be achieved?