Optical Design

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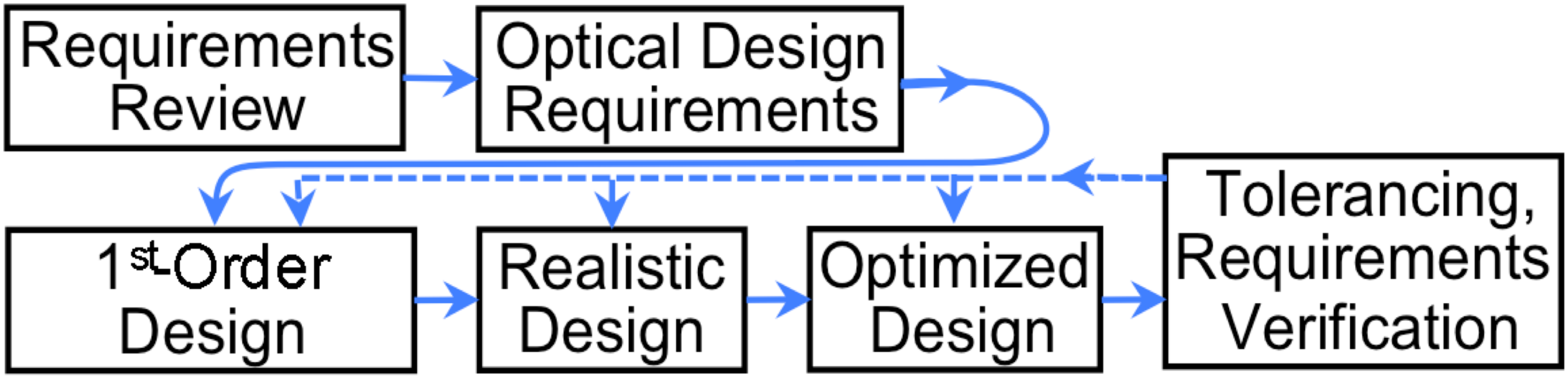
Optical Design Life Cycle



- 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

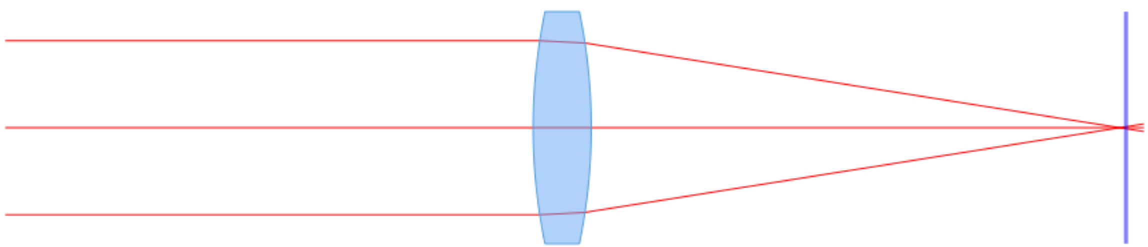
Requirements

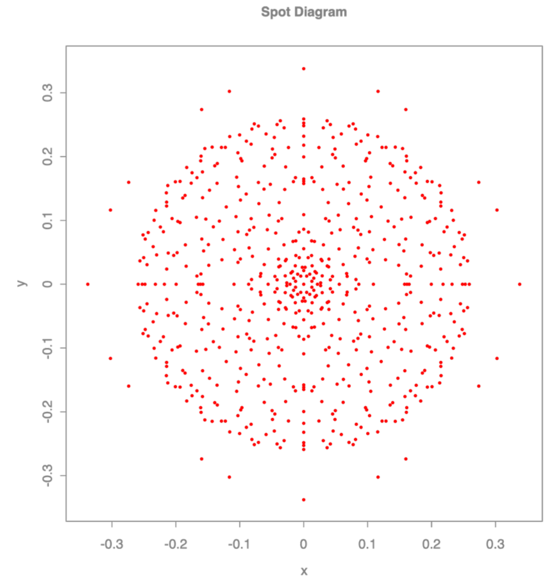
- Common optical requirements
  - field-of-view & angular resolution
  - spectral range & resolution, transmission
- Common boundary conditions
  - telescope interfaces & instrument location
  - cooling, weight limit, size limit, cost, schedule, …
  - detector pixel size
- Review requirements
  - completeness, consistency

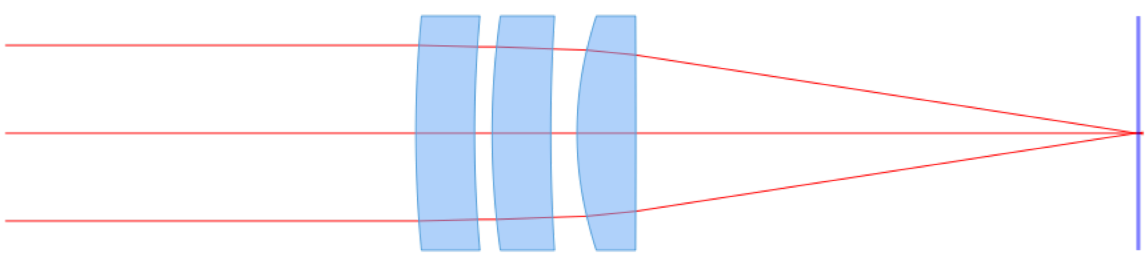
Optical Design Principles 1 - 3

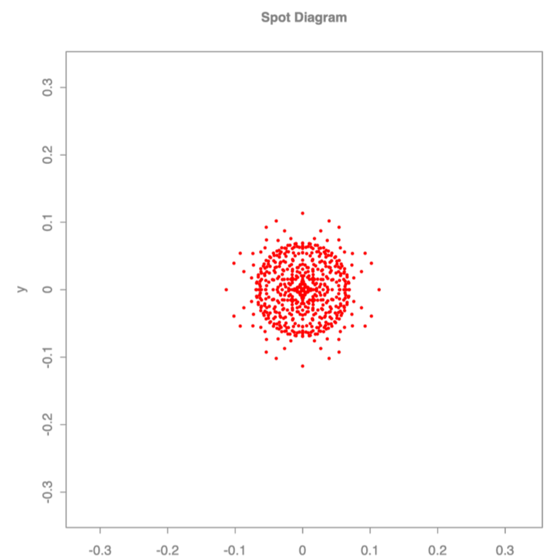
1. Minimize the number of optical components
   - additional elements add cost, ghosts, scattered light
   - but: additional elements increase performance
2. Maximize the radii of curvature
   - reduces aberrations
   - eases manufacturing and alignment
   - but: might require more elements and long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

Better Performance with More Optics









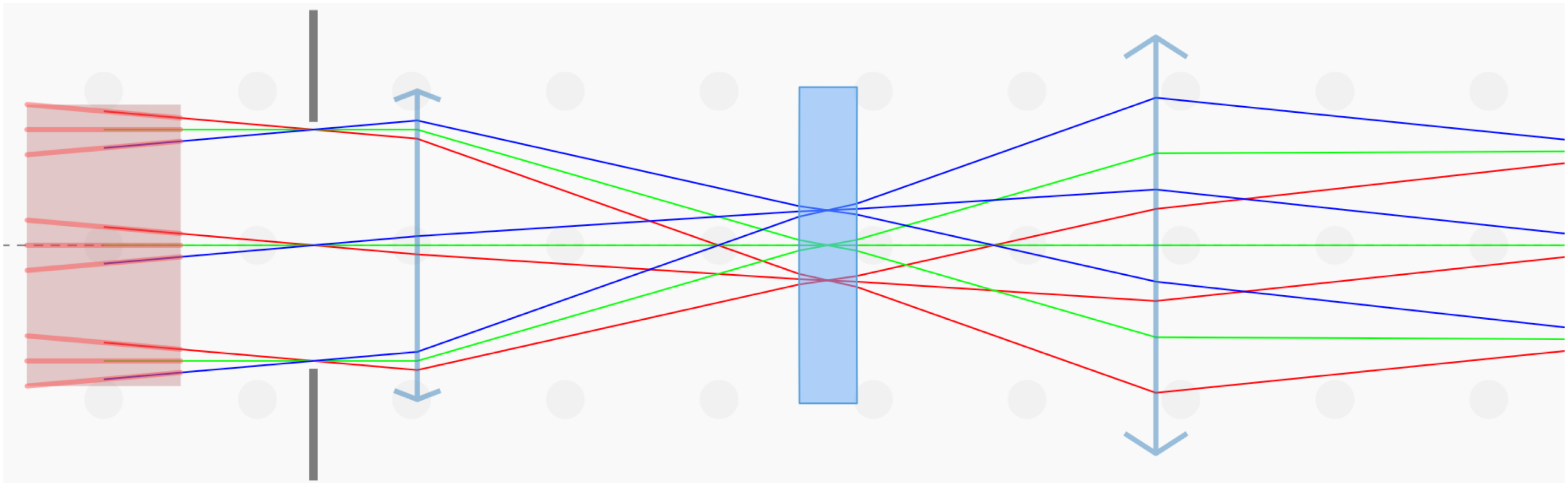
Optical Design Principles 4 - 7

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

Collimated vs. Converging Beam

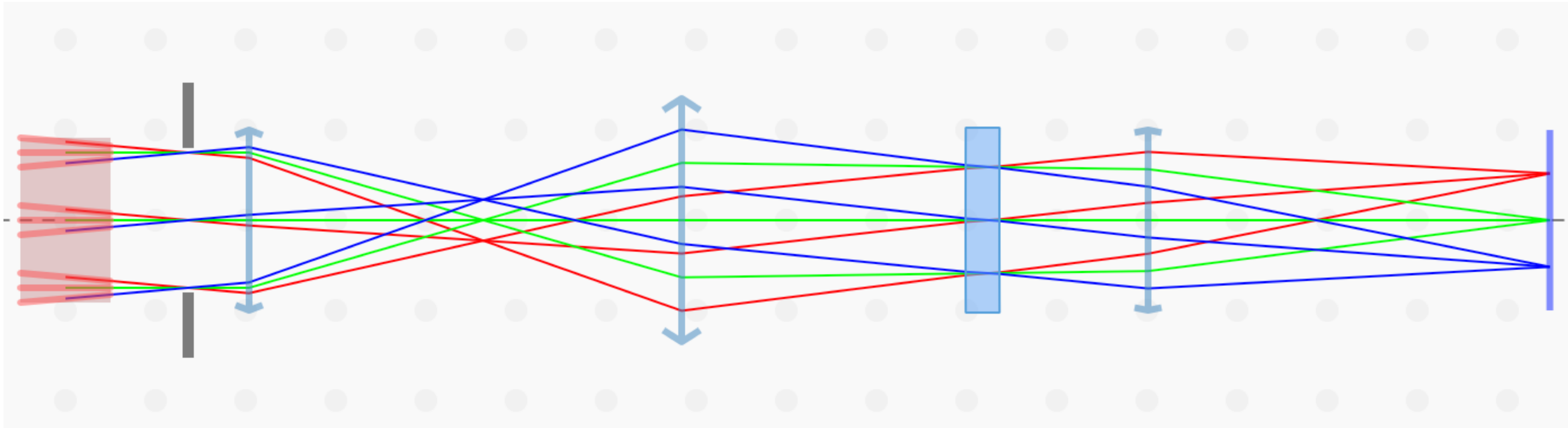
- Components in collimated beam
  - grating, prism
  - cold stop
  - Lyot stop
  - filter?
  - polarization modulator?
- Components in converging beam
  - slit
  - coronagraphic mask
  - detector
  - filter?

Example: Interference Filter in Image



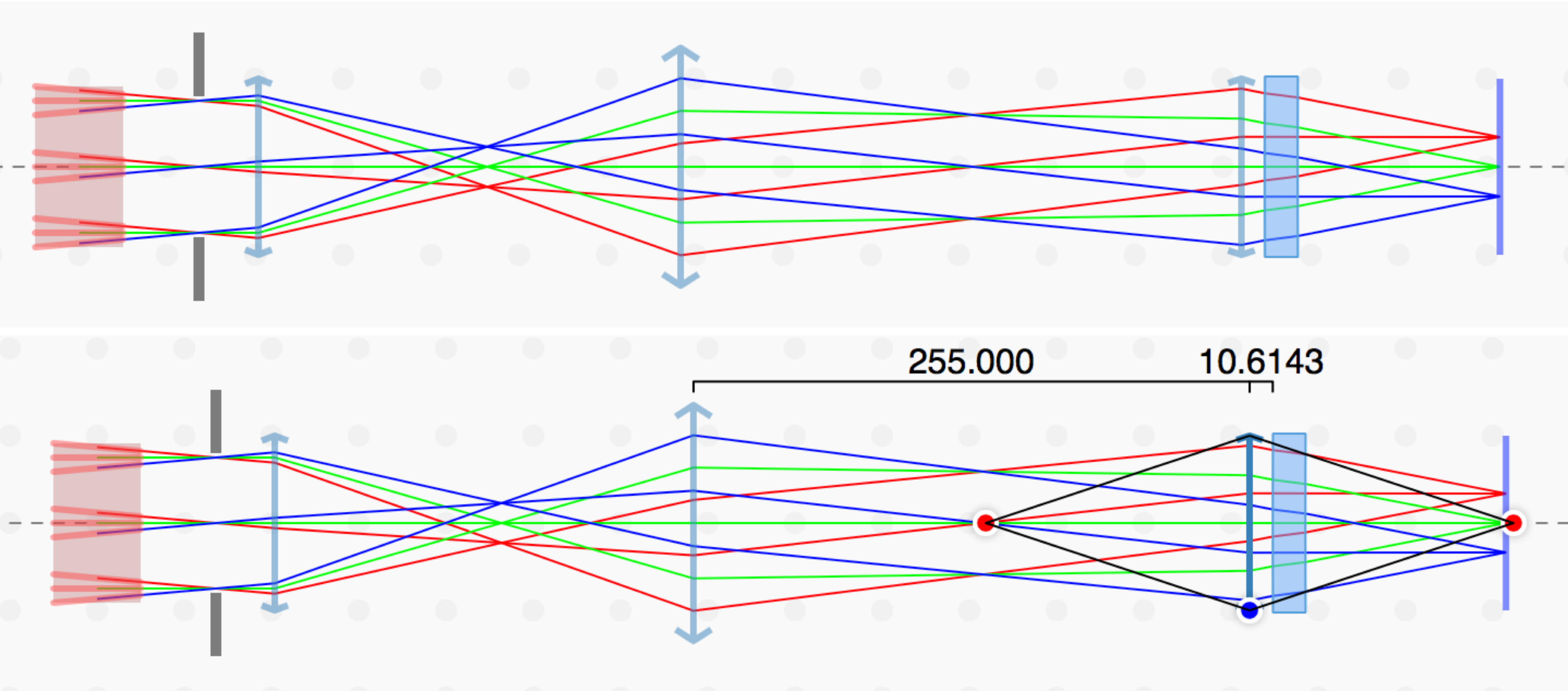
- Filter in image plane, optical quality unimportant
- Rays from different fields pass filter at different angles
- Filter profile will depend on field position
- Cone of rays for each field position broadens filter profile

Example: Interference Filter in Pupil



- Filter in pupil plane, optical quality crucial
- Rays from different fields pass filter at different angles
- Filter profile will depend on field position
- Same incidence angles of all rays from one field position, narrowest possible filter profile

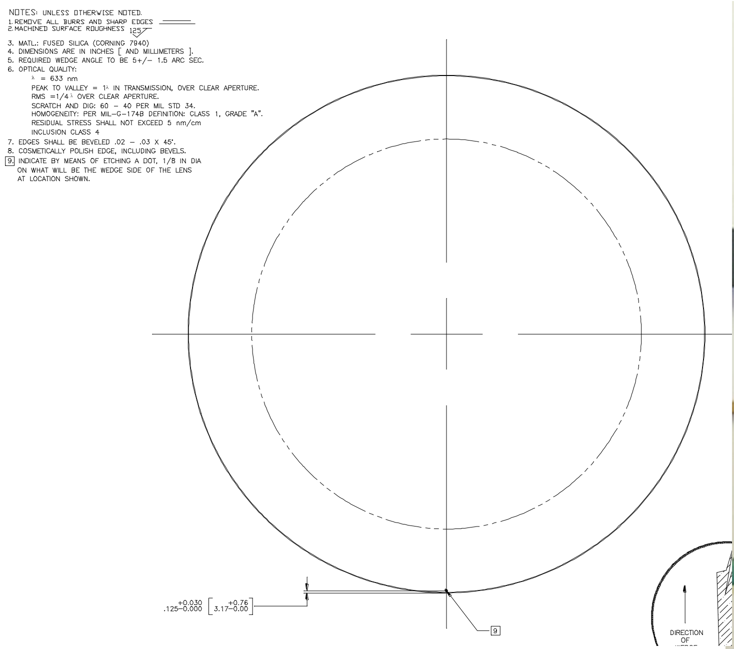
Interference Filter in Telecentric Beam

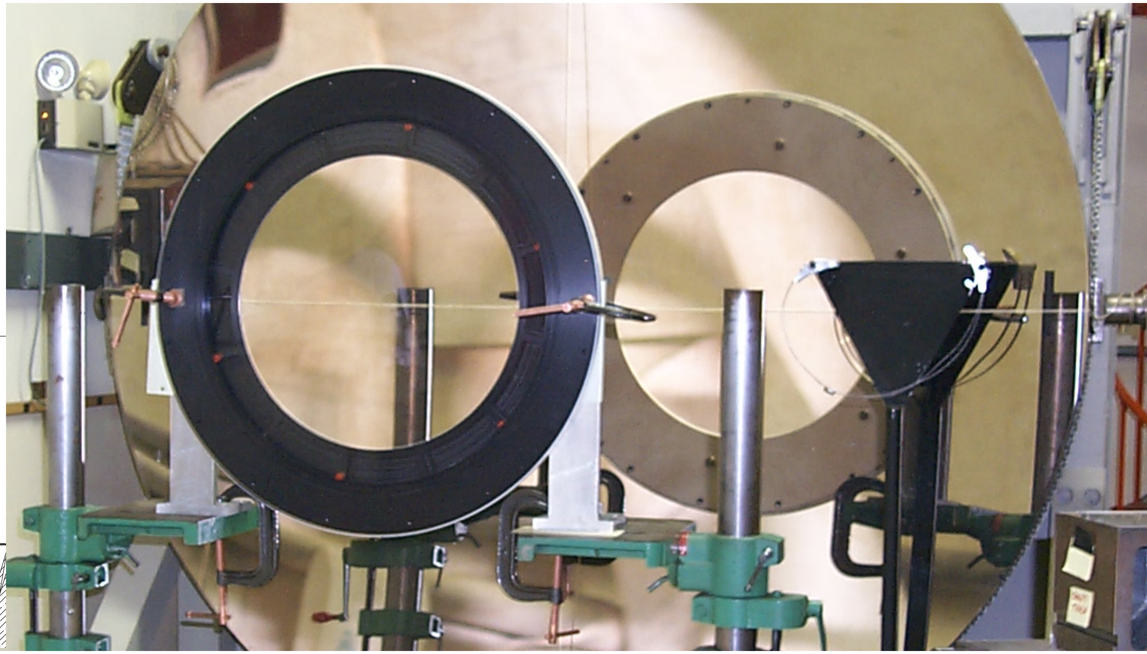


- Last lens is one focal length away from pupil
- Seen from image, pupil is at infinity
- Broadened filter profile, constant across field

Optical Design Principle 8

8. Oversize optical elements
   - optical manufacturing quality always worse at edge
   - need to hold/mount optical elements
   - thermal, stress effects most pronounced at edges





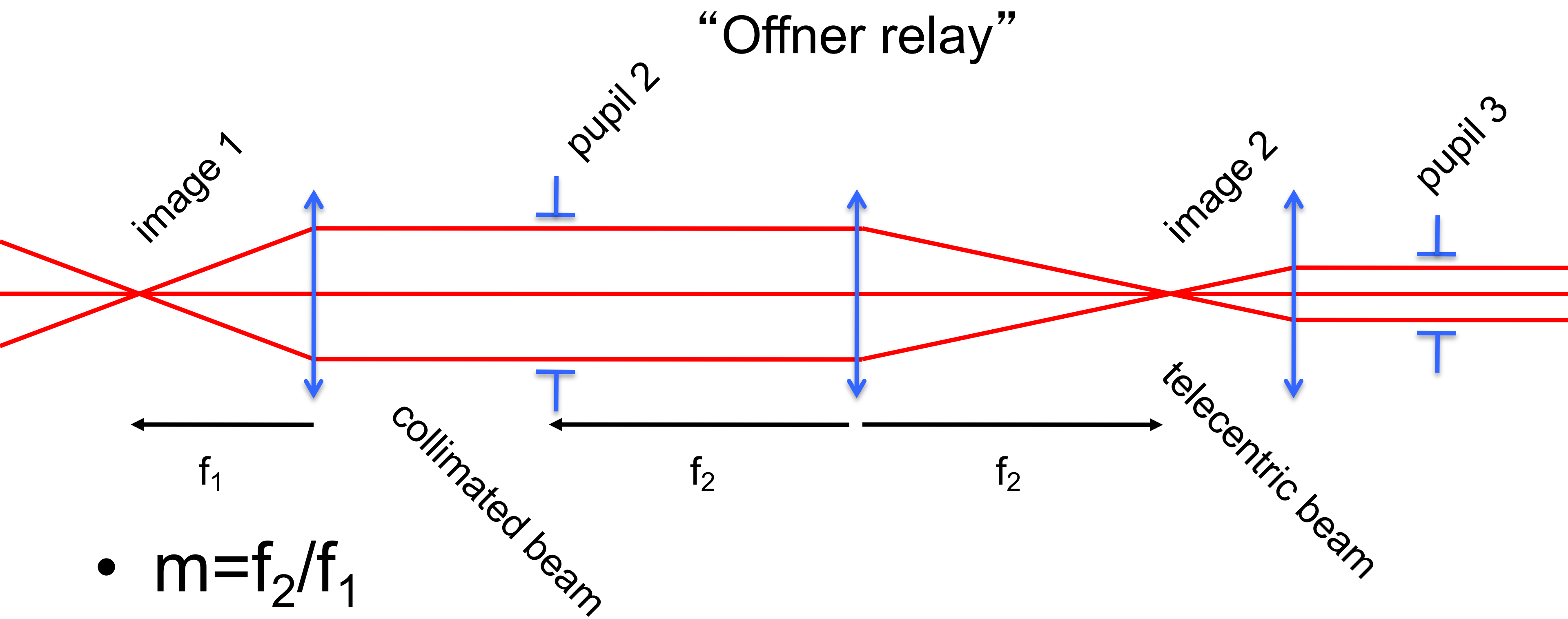
Global Design Choices

- 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)$^{x>1}$
- Operating temperature range, pressure

First-Order Design

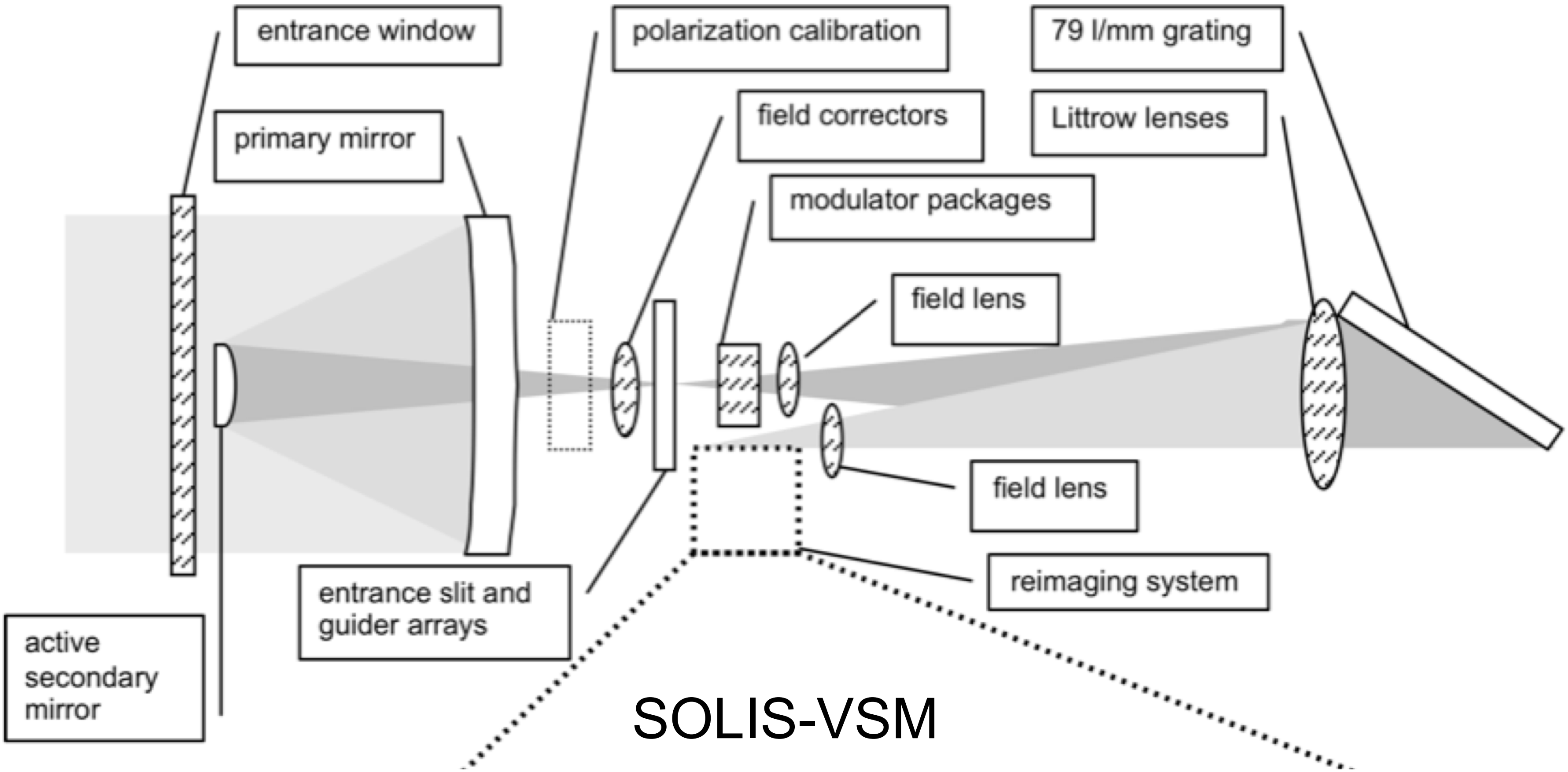
- First-order optical designs use
  - ideal optical elements (e.g. paraxial surfaces)
  - central and extreme field points and rays
  - image and pupil locations
- Establishes general configuration
- Often based on existing designs
- Can be sketched on paper or in a spreadsheet
- Provides first idea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

Example First-Order Design 1



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

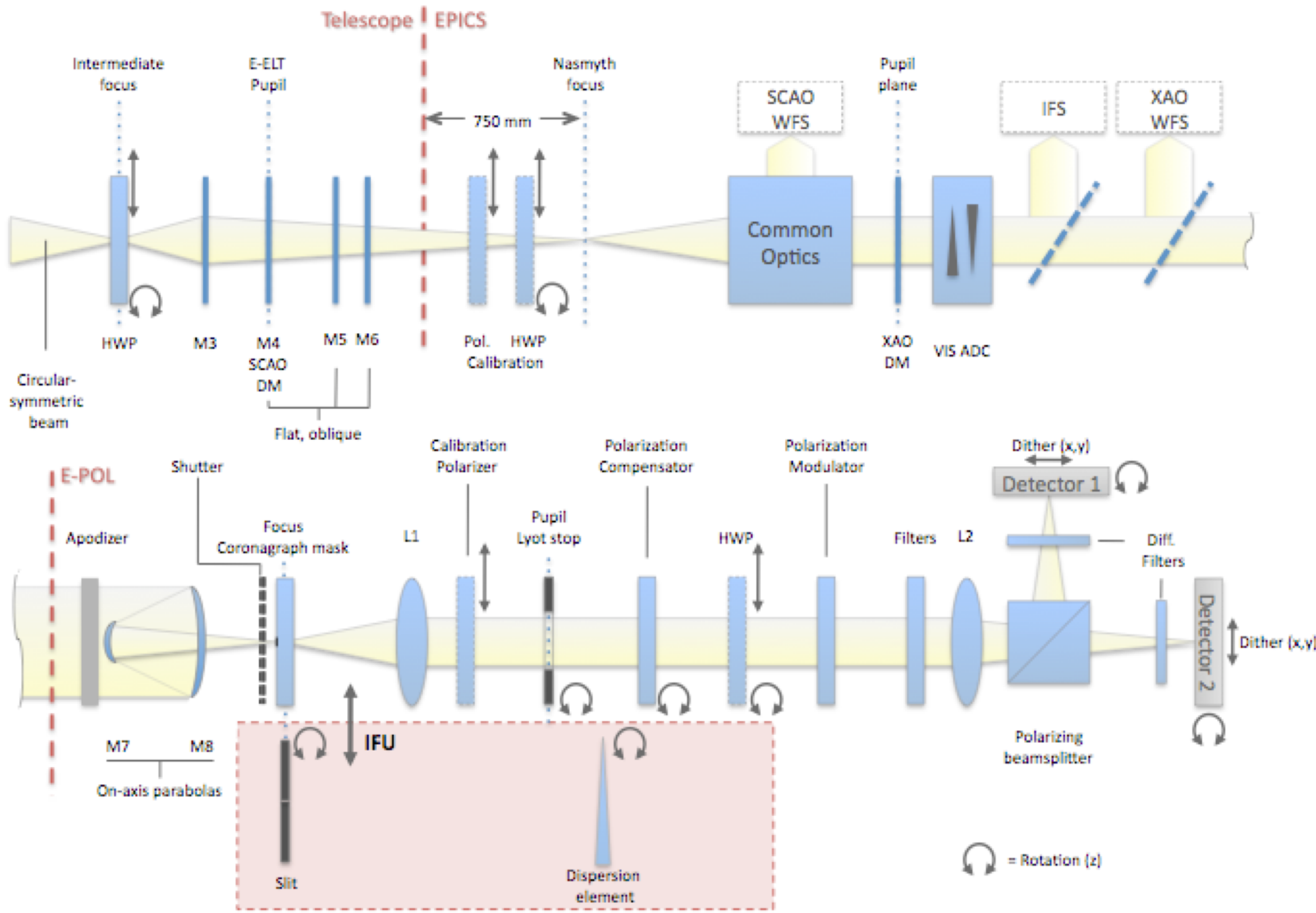
Example First-Order Design 2



SOLIS-VSM

First-Order Design Example 3

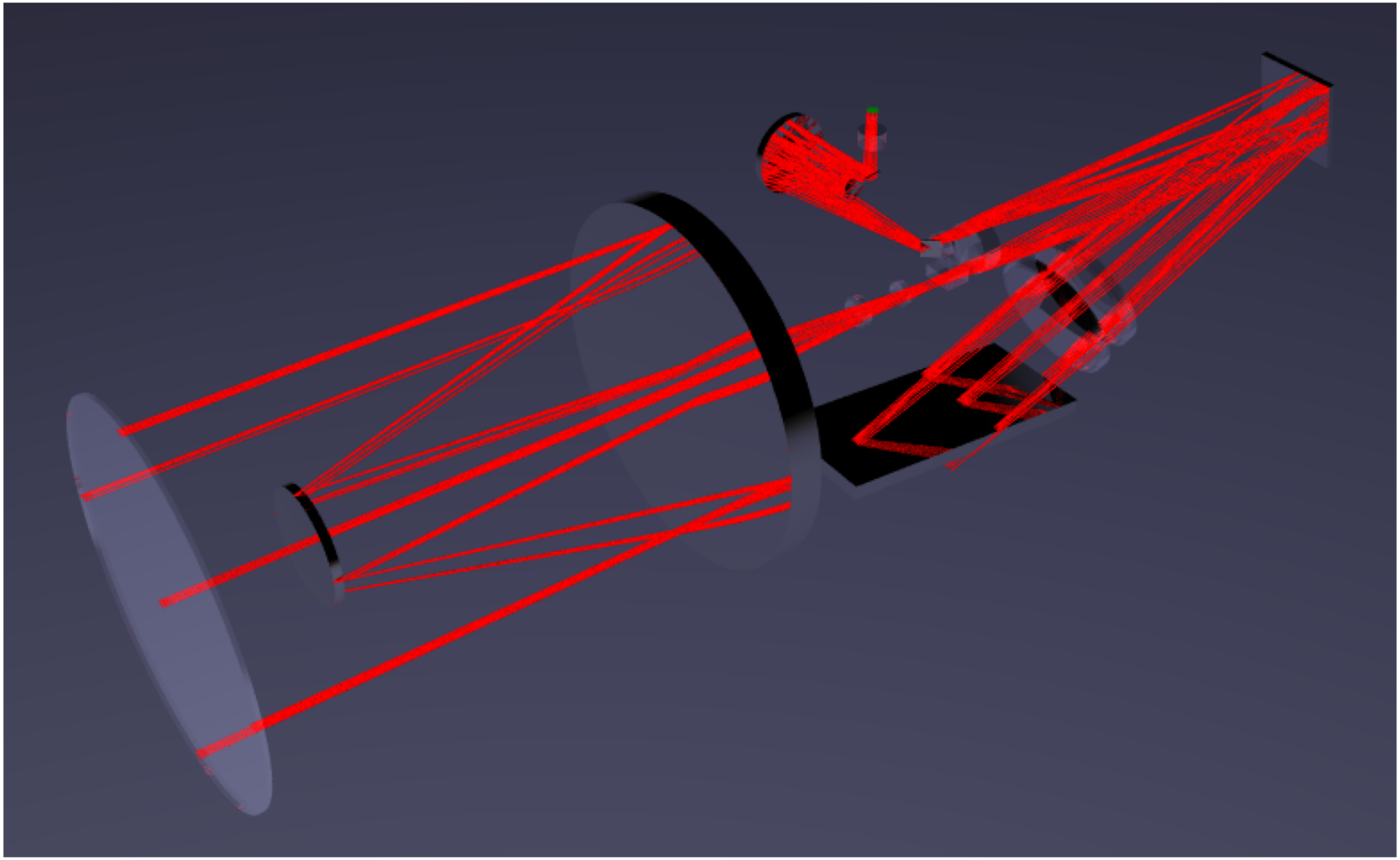
EPICS-EPOL



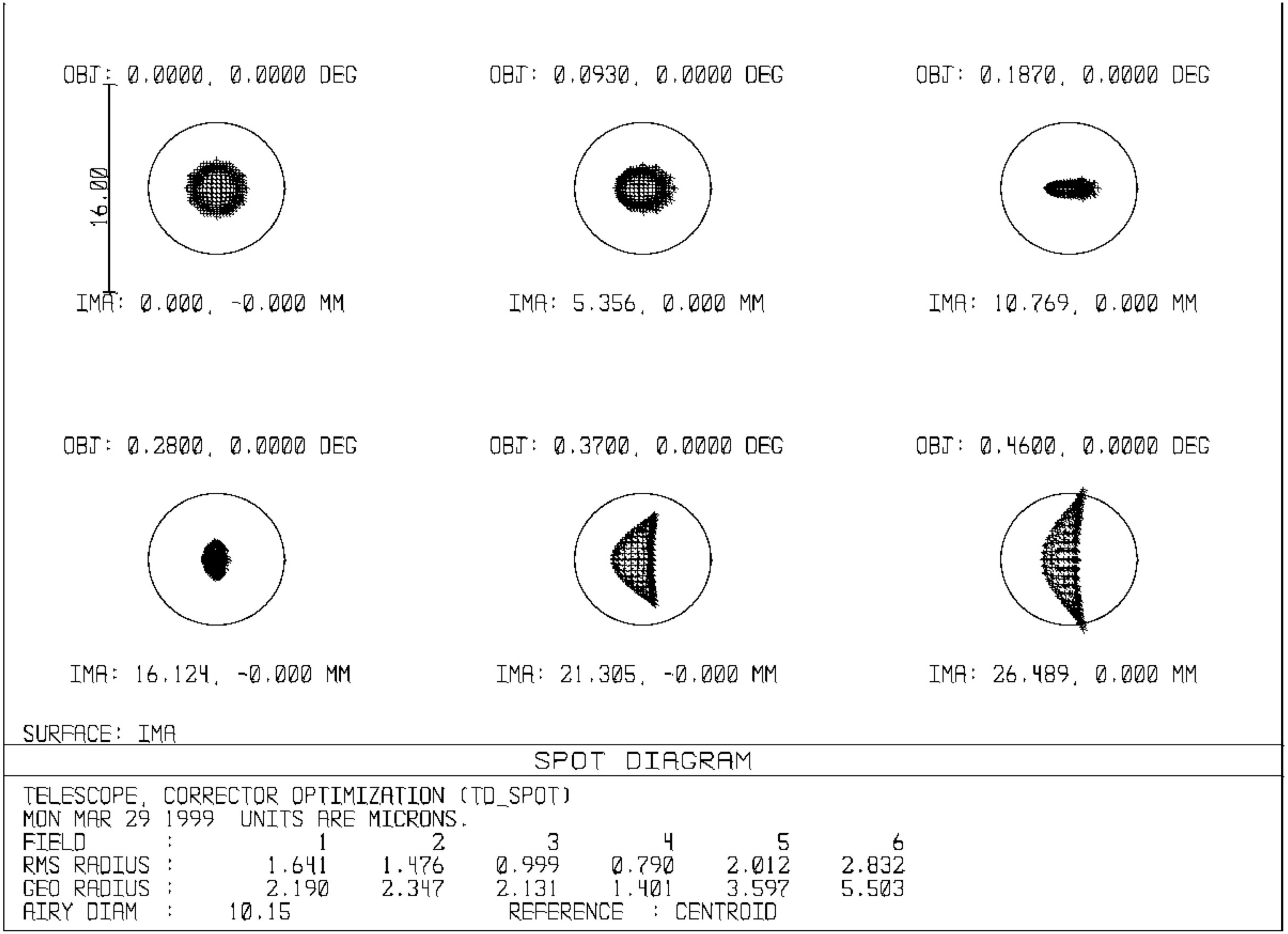
Ray Tracing

- Ray-tracing based on geometrical optics approximation (wavefronts are locally flat)
- Rays are traced from source to image
- Optical elements are decomposed into surfaces:
  - radius of curvature
  - distance to following surface
  - diameter
  - index of refraction following surface
- Optical design programs: WinLens, ZEMAX, OSLO
- Programs only useful once major design decisions have already been made!

Raytracing Example: SOLIS VSM



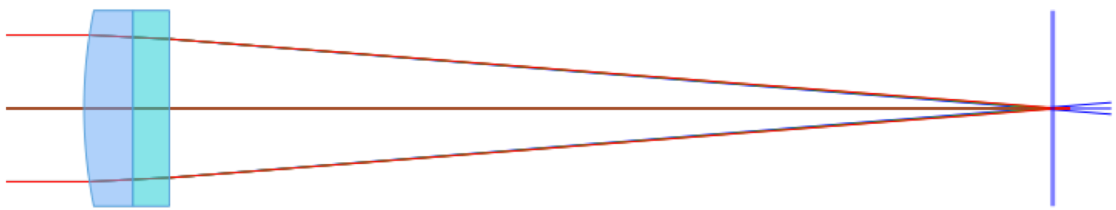
Spot Diagrams for Perfect Optics

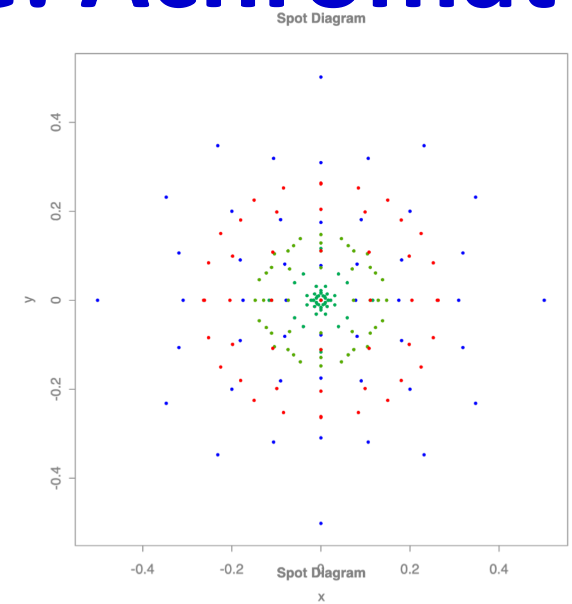


Optimization

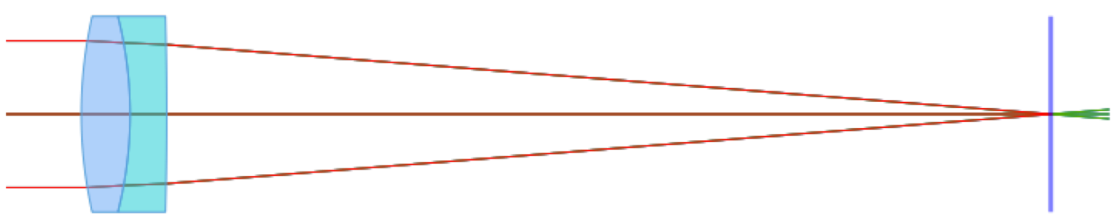
- Built into most optical design software
- Automatically improves performance
- Degrees of freedom = variables of optical design
  - radii of curvature of optical surfaces
  - spacing between elements
  - conic constants
  - glass thicknesses
- Can change glass type
- Generally does not add or remove optics
- Must define scalar performance (merit) function

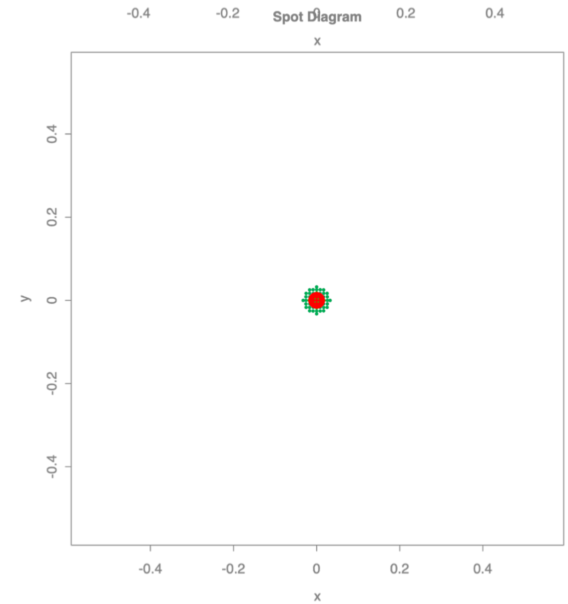
Optimization Example: Achromat





made with Touch Optical Design version 0.40.0 pro





Tolerance Analysis

- Determines tolerances to which
  - optical elements have to be manufactured
  - optical elements have to be positioned
  - environmental parameters have to be controlled
- Often uses optimization merit function to quantify performance change
- Most design parameters are subject to errors
- Compensator parameters are optimized
- Can trade off tolerances between optical elements to optimize manufacturability

Example Monte Carlo Analysis

```
Monte Carlo Analysis:
Number of trials: 500
Statistics: Normal Distribution
Nominal     0.001782
Best        0.001325
Worst       0.002580
Mean        0.001846
Std Dev     0.000263
```

```
Compensator Statistics:
Thickness Surf 57:
Nominal            :       12.000000
Minimum            :       11.619700
Maximum            :       12.364922
Mean               :       12.017660
Standard Deviation :        0.126113
```

```
98% of Monte Carlo lenses have a merit function below 0.002418.
90% of Monte Carlo lenses have a merit function below 0.002218.
50% of Monte Carlo lenses have a merit function below 0.001829.
10% of Monte Carlo lenses have a merit function below 0.001511.
 2% of Monte Carlo lenses have a merit function below 0.001384.
```

Assuming that we know the manufacturing statistics, Monte Carlo analysis provides likelihood of achieving required performance