Update on Adaptive Optics Scanning Laser Ophthalmoscope (AOSLO) for retinal imaging

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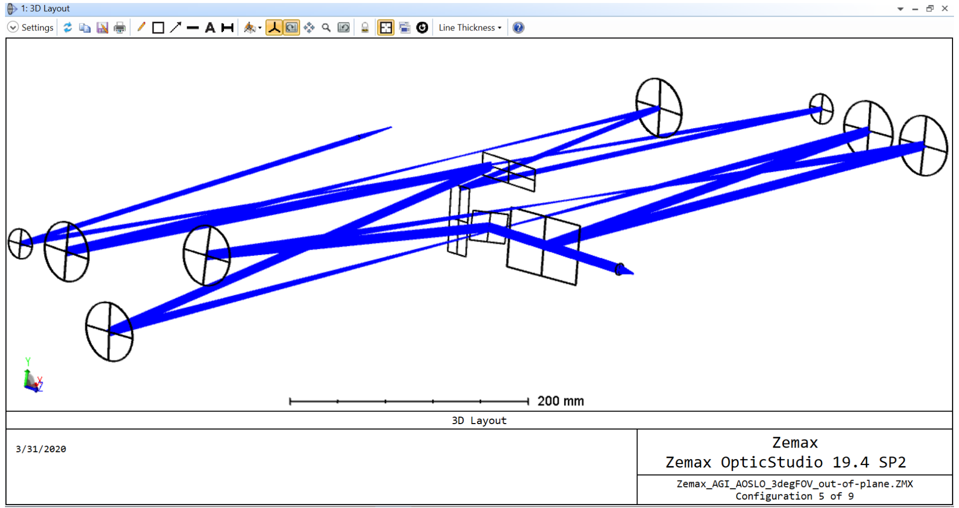
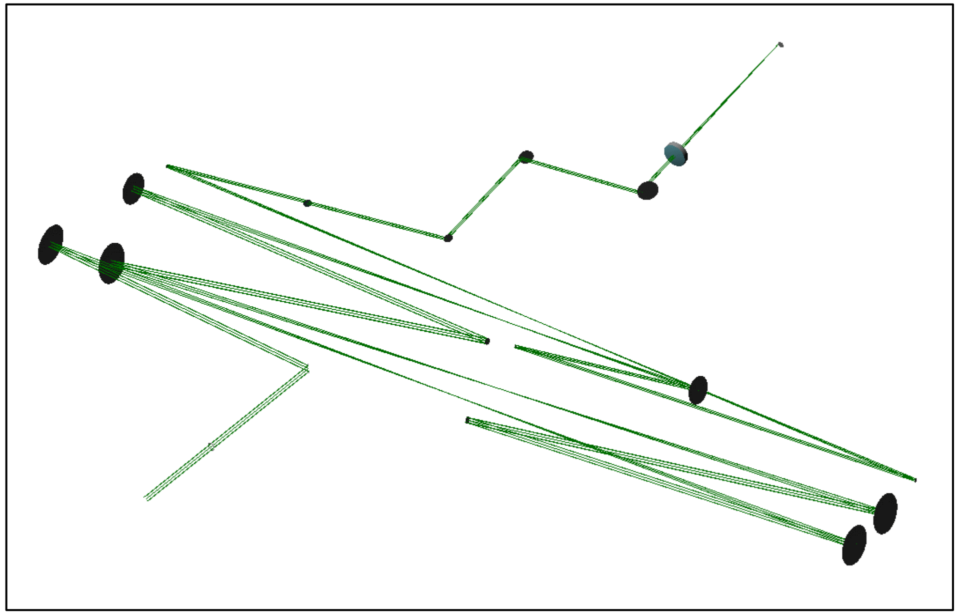
Tuesday, August 4, 2020

Active Perception Lab Meeting

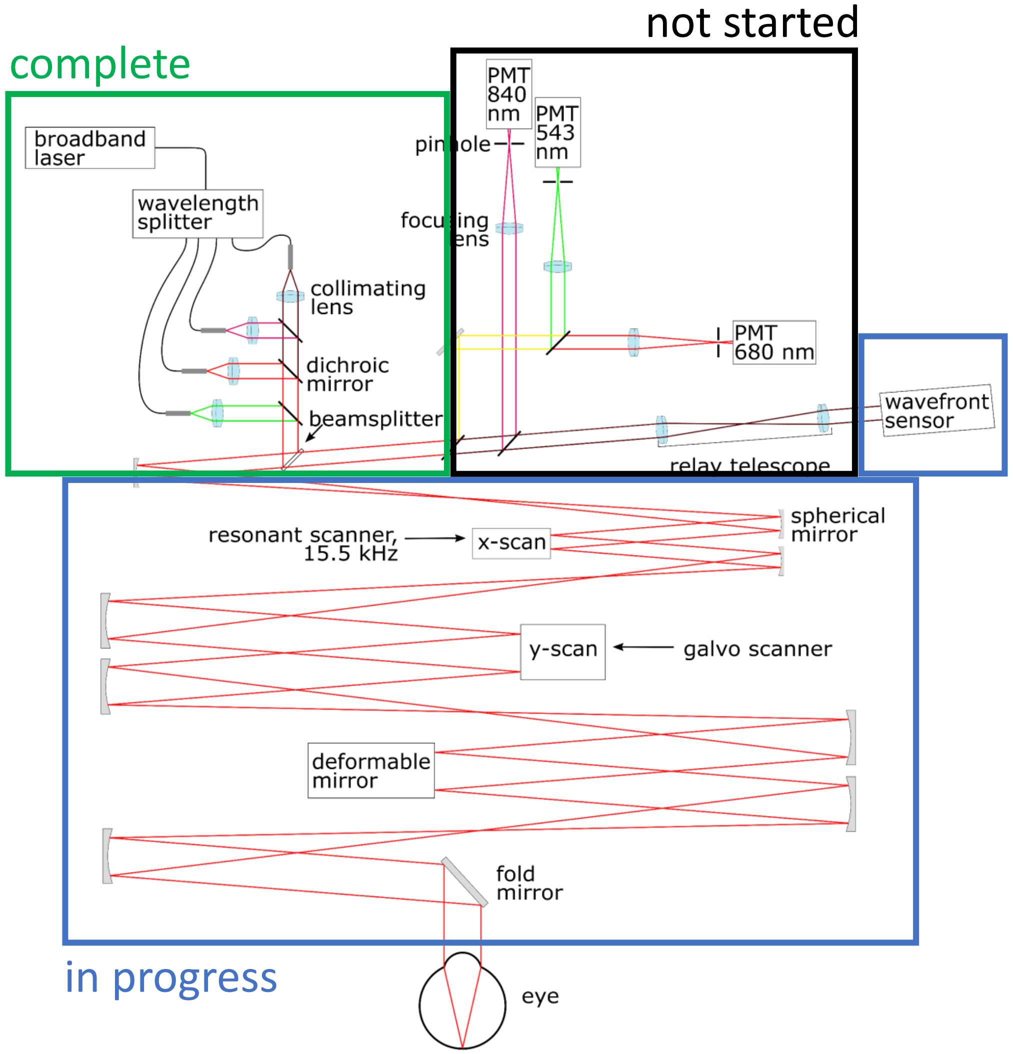
Since my last lab meeting presentation at the end of March, I've finished the optical modeling and some of the alignment



Zemax model



CODE V model

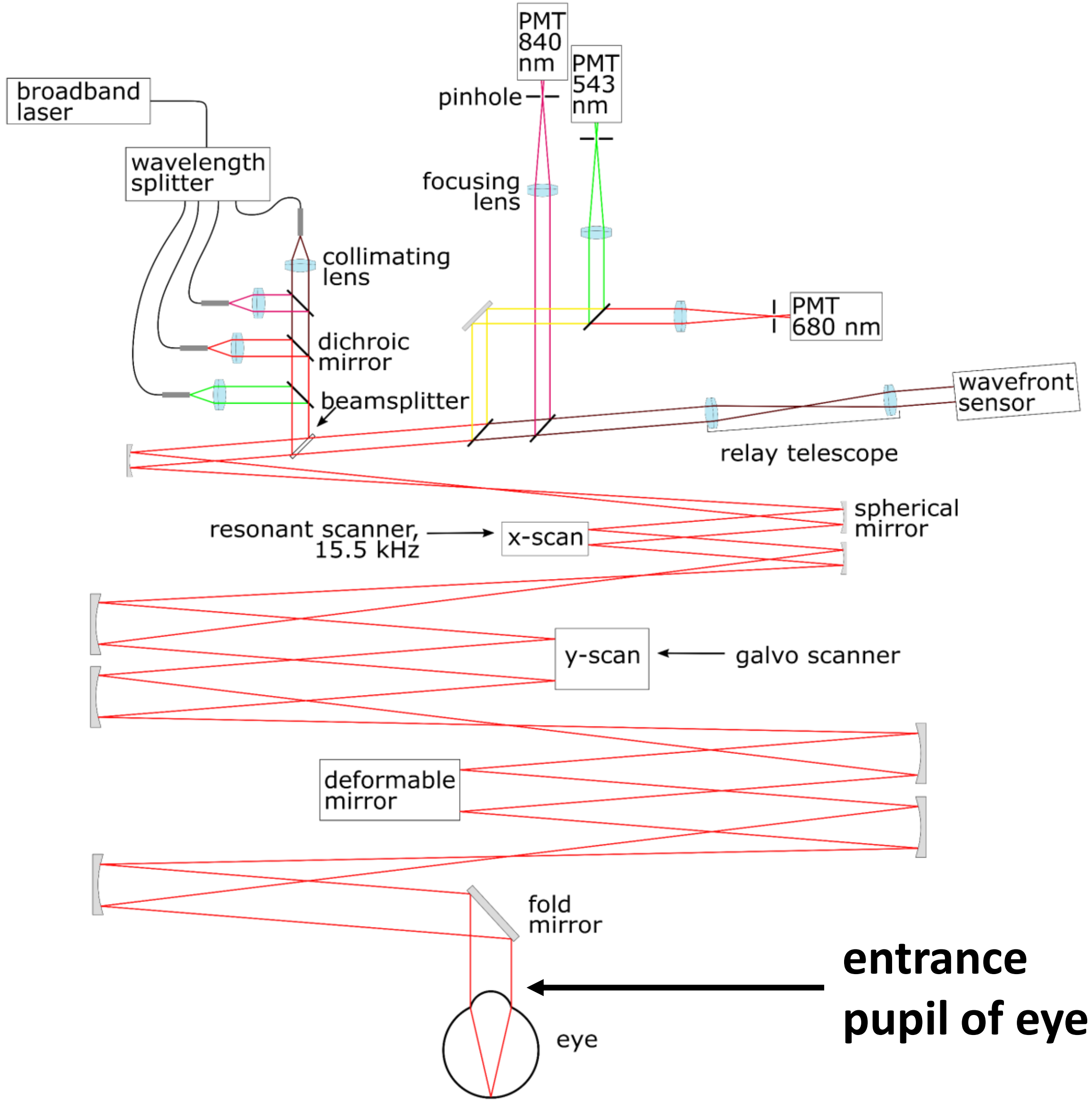


system layout showing alignment progress

Outline

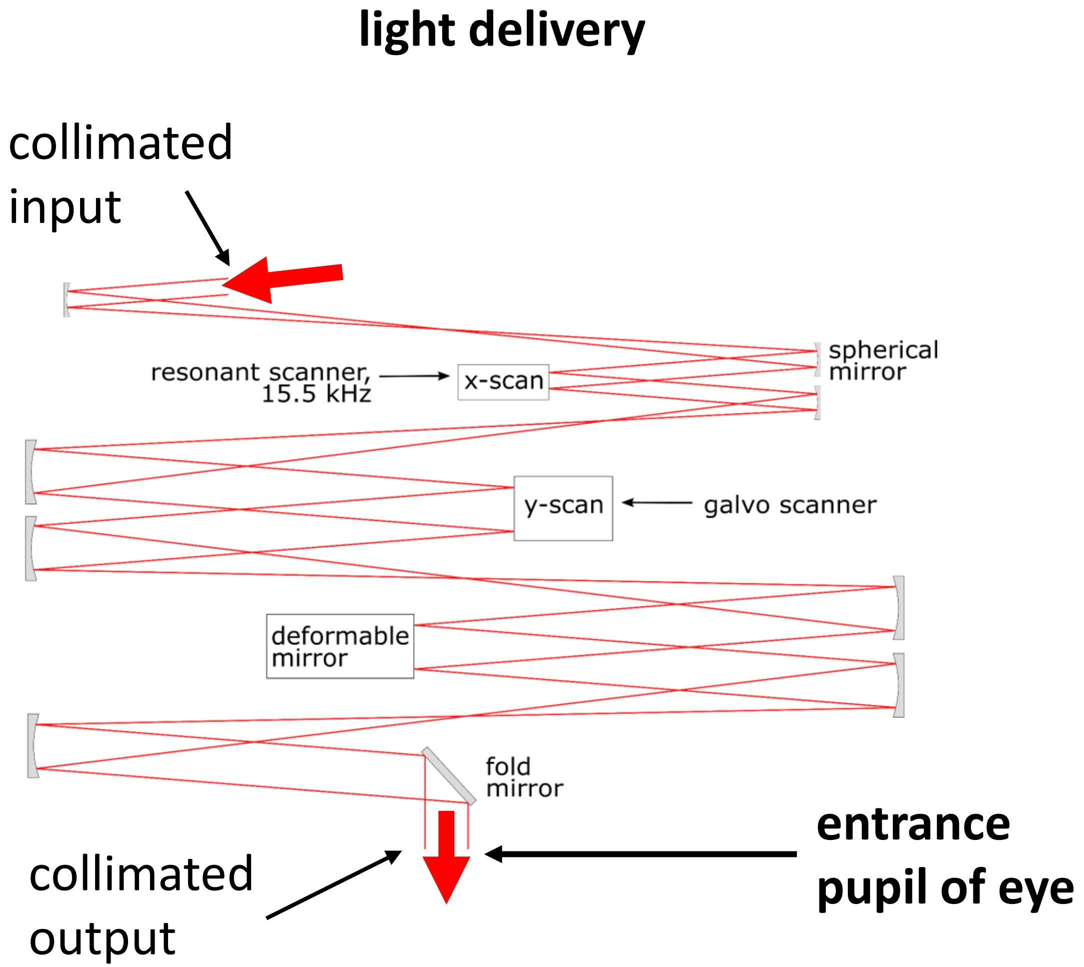
- Modeling the optical system in CODE V
- Tolerancing and sensitivity analysis in CODE V
- Optical alignment requirements
- Alignment techniques
- Alignment progress
- Project status updates

The system can be modeled as a light-delivery system and multiple collection channels



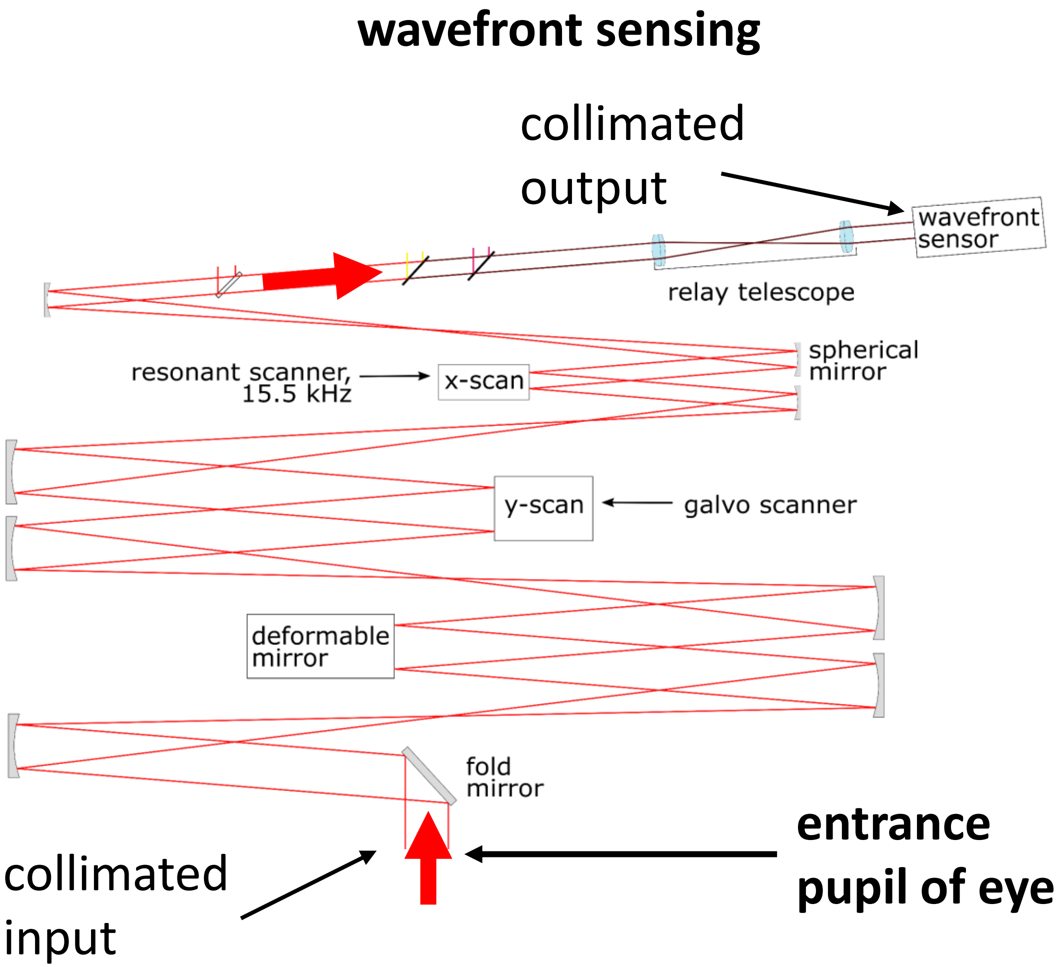
entrance pupil of eye

The system can be modeled as a light-delivery system and multiple collection channels



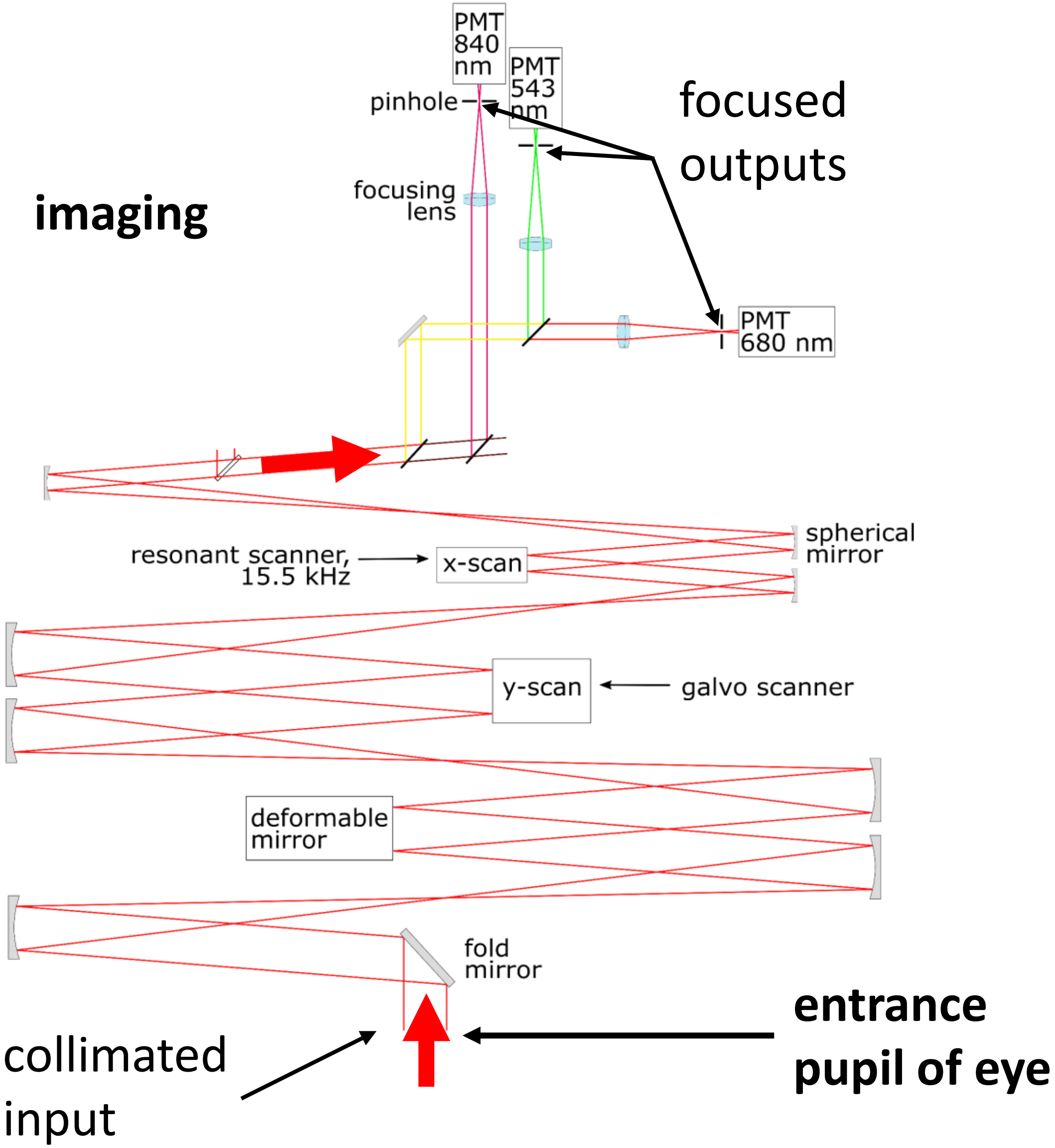
- Light delivery system
  - All wavelengths combined
  - Collimated input and collimated output

The system can be modeled as a light-delivery system and multiple collection channels



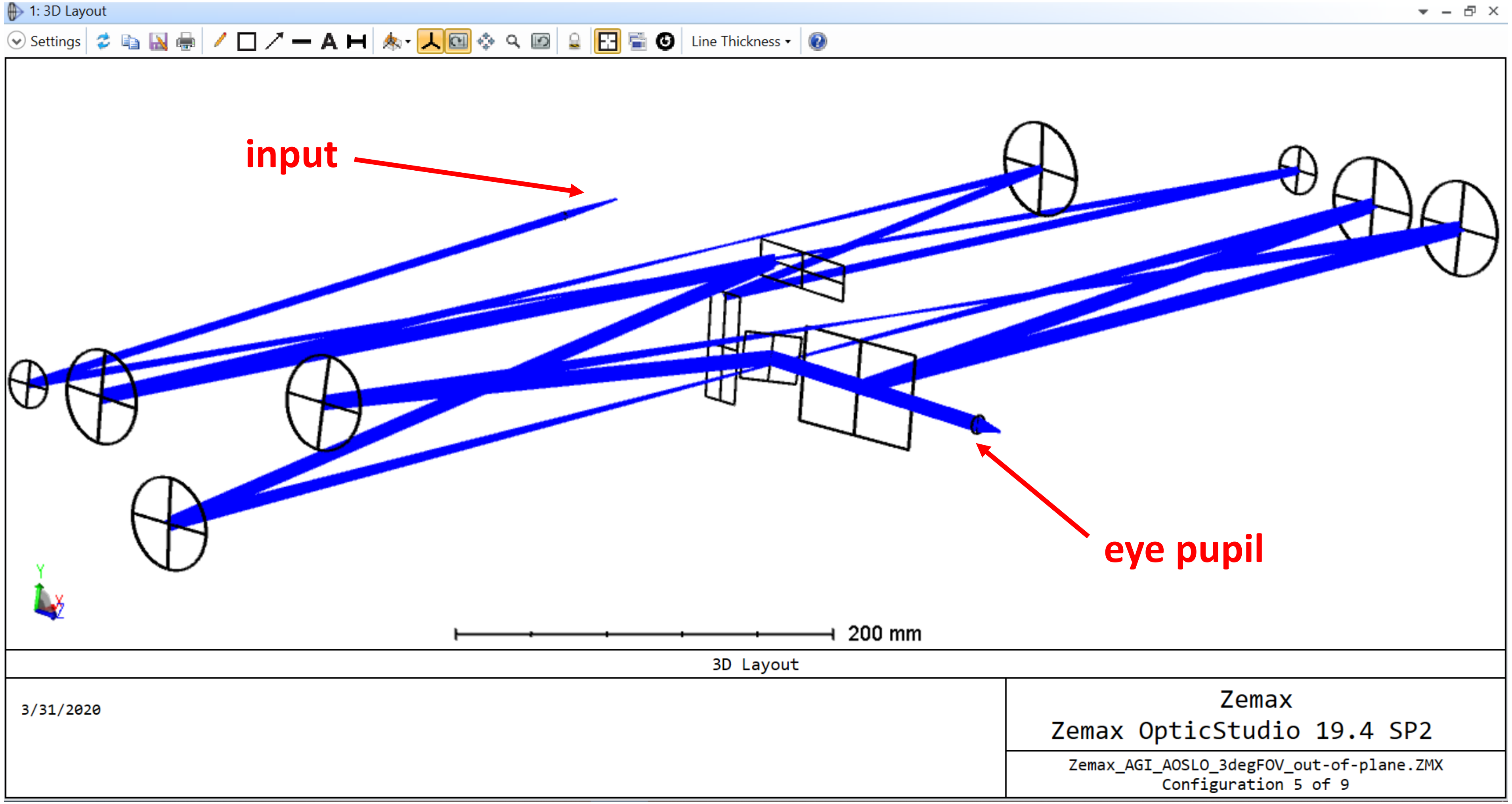
- Light delivery system
  - All wavelengths combined
  - Collimated input and collimated output
- Wavefront sensing channel
  - Single wavelength (940 nm)
  - Includes additional relay telescope
  - Collimated input and output

The system can be modeled as a light-delivery system and multiple collection channels



- Light delivery system
  - All wavelengths combined
  - Collimated input and collimated output
- Wavefront sensing channel
  - Single wavelength (940 nm)
  - Includes additional relay telescope
  - Collimated input and output
- Imaging channels
  - Each color channel modeled independently
  - Most of the optics are the same
  - Collimated input and focused output

We received a Zemax model for the light delivery system

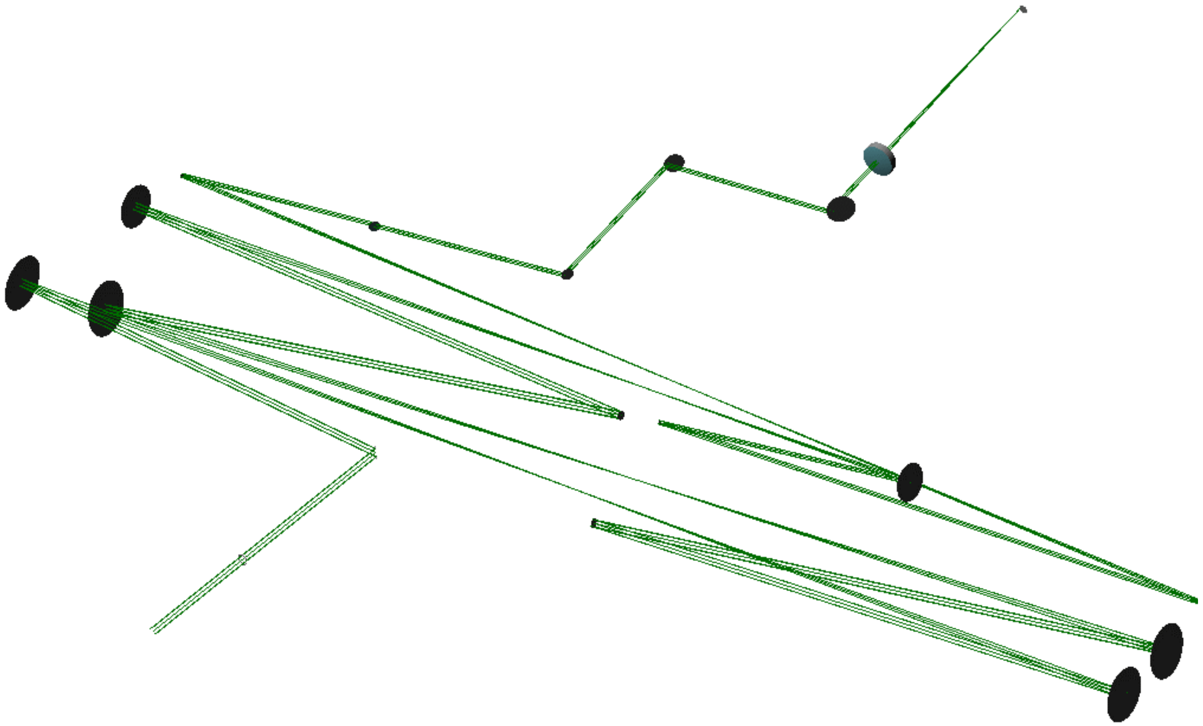


Zemax model of the light delivery system

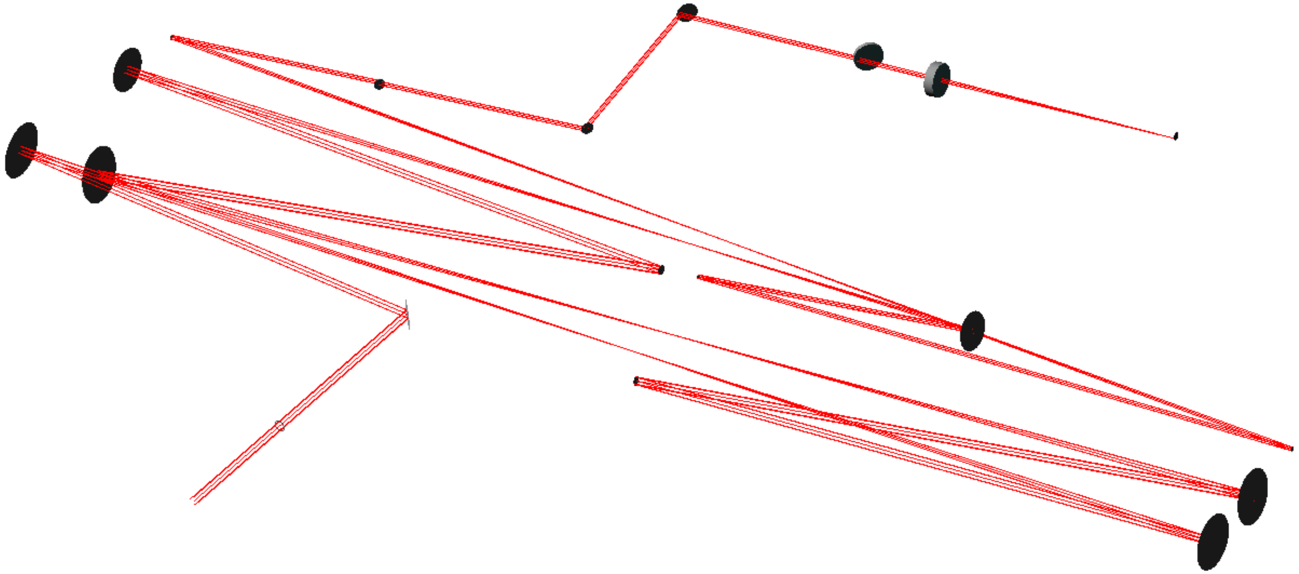
- System parameters were manually copied into CODE V
- I used CODE V because I'm more familiar with it
- Testing of the CODE V model showed that it was equivalent to the Zemax model

Using the light delivery optical model and the CAD file, collection channels were developed

543 nm collection channel

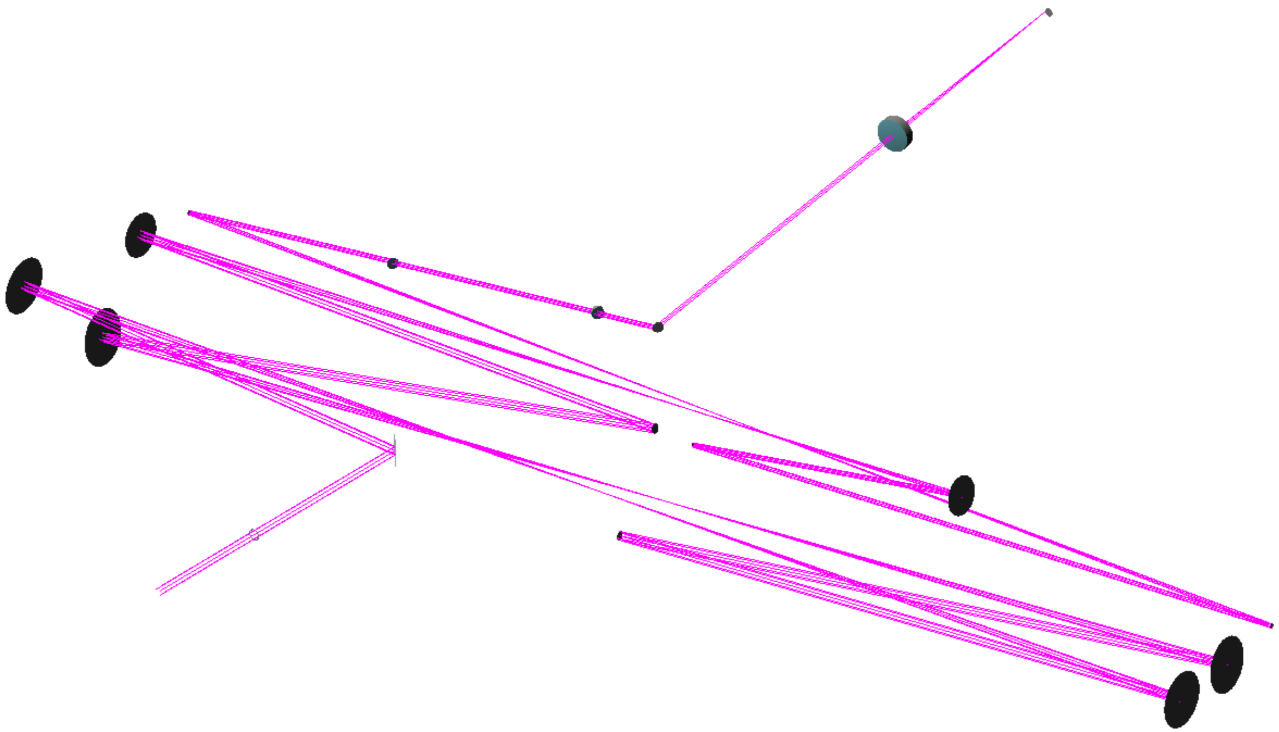


680 nm collection channel

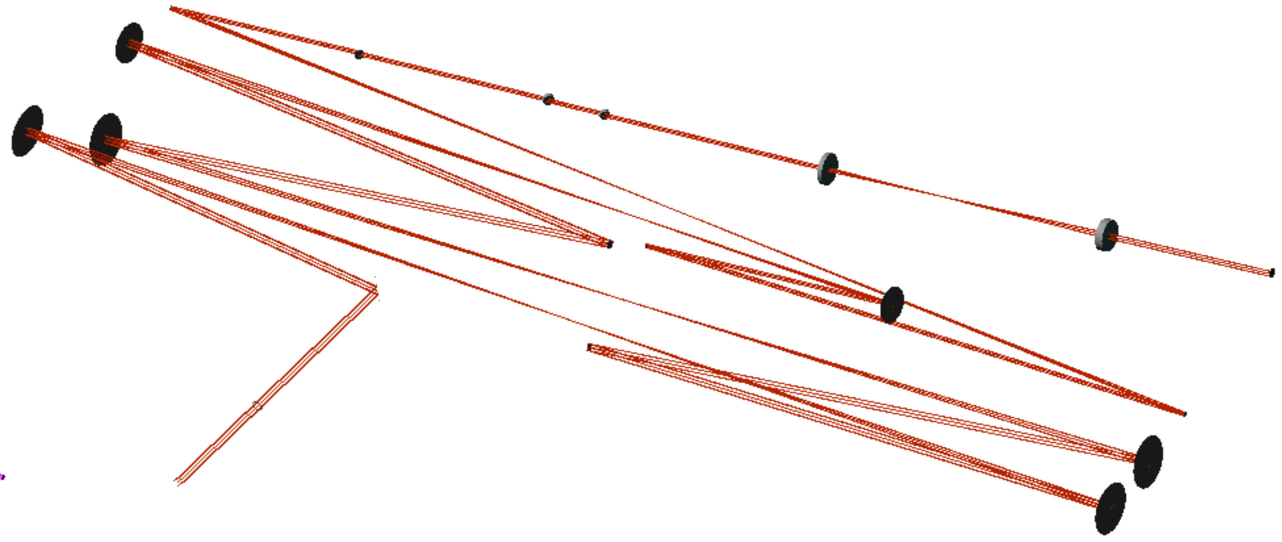


Using the light delivery optical model and the CAD file, collection channels were developed

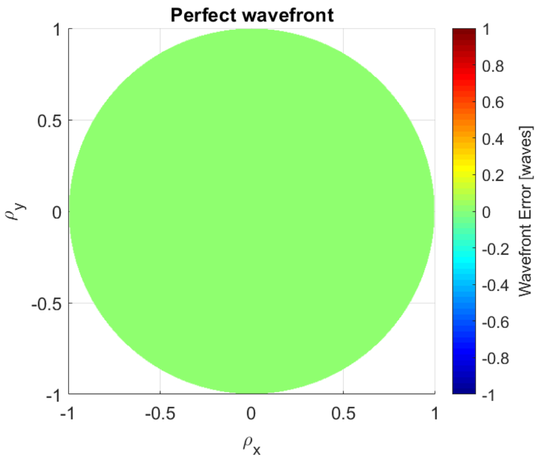
840 nm collection channel



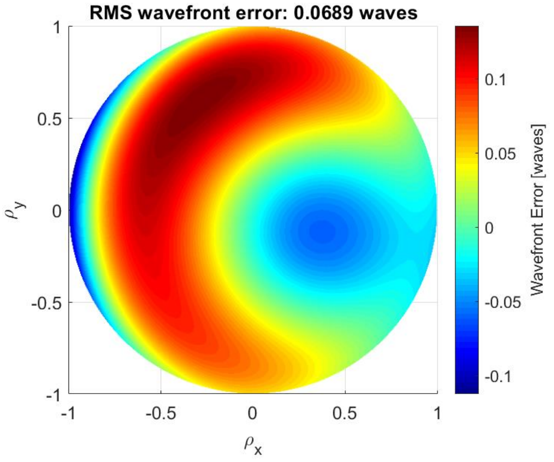
940 nm collection channel (WFS)



Assessing the RMS wavefront error in CODE V tells us about the expected performance



perfect, flat wavefront: this is the ideal case



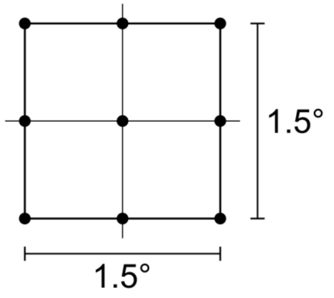
example wavefront with some aberrations

- In CODE V, we can measure both the **nominal** and the **as-built** performance
  - **nominal:** all optics perfectly match the specifications and alignment is perfect
  - **as-built:** imperfections in the optics and alignment are accounted for using the relevant tolerances

- RMS (root-mean-squared) wavefront error is a good measure of the system's performance
  - RMS wavefront errors less than < $\lambda/14$ (0.0714 λ) are considered diffraction-limited
  - The example wavefront shown above has an RMS wavefront error of 0.0689 λ
- Diffraction-limited performance is required to resolve cones at the foveal center: inter-cone spacing is 2-3 µm and the Rayleigh resolution limit of the eye at 840 nm is 2-2.5 µm

Nominal performance is diffraction-limited for all illumination and collection channels*

scanning field of view as seen by the subject



nominal performance for illumination (543 nm)

Scan position	RMS wavefront error (λ)
center	0.0152
left	0.0250
right	0.0299
top	0.0175
bottom	0.0311
top left	0.0319
bottom left	0.0333
top right	0.0405
bottom right	0.0341

< 0.041 for all scan positions

nominal performance for collection (543 nm)

Scan position	RMS wavefront error (λ)
center	0.0160
left	0.0256
right	0.0294
top	0.0171
bottom	0.0316
top left	0.0314
bottom left	0.0344
top right	0.0392
bottom right	0.0343

< 0.040 for all scan positions

*results for the 543 nm channel are shown because the diffraction limit is hardest to achieve for this wavelength

Some of the initial alignment tolerances were too loose, resulting in poor performance

spherical mirrors

Power (radius of curvature)	≤ 3 λ
Irregularity	≤ λ/2

scan mirrors

Power (radius of curvature)	≤ λ/10
Irregularity	≤ λ/10

fold mirrors and dichroics

Power (radius of curvature)	≤ 1 λ
Irregularity	≤ λ/5

lenses

Power (radius of curvature)	≤ 1.5 λ
Irregularity	≤ λ/4
Tilt	+/- 3 arcmin
Thickness	+/- 0.2 mm

tolerances for optics
(set by manufacturer)

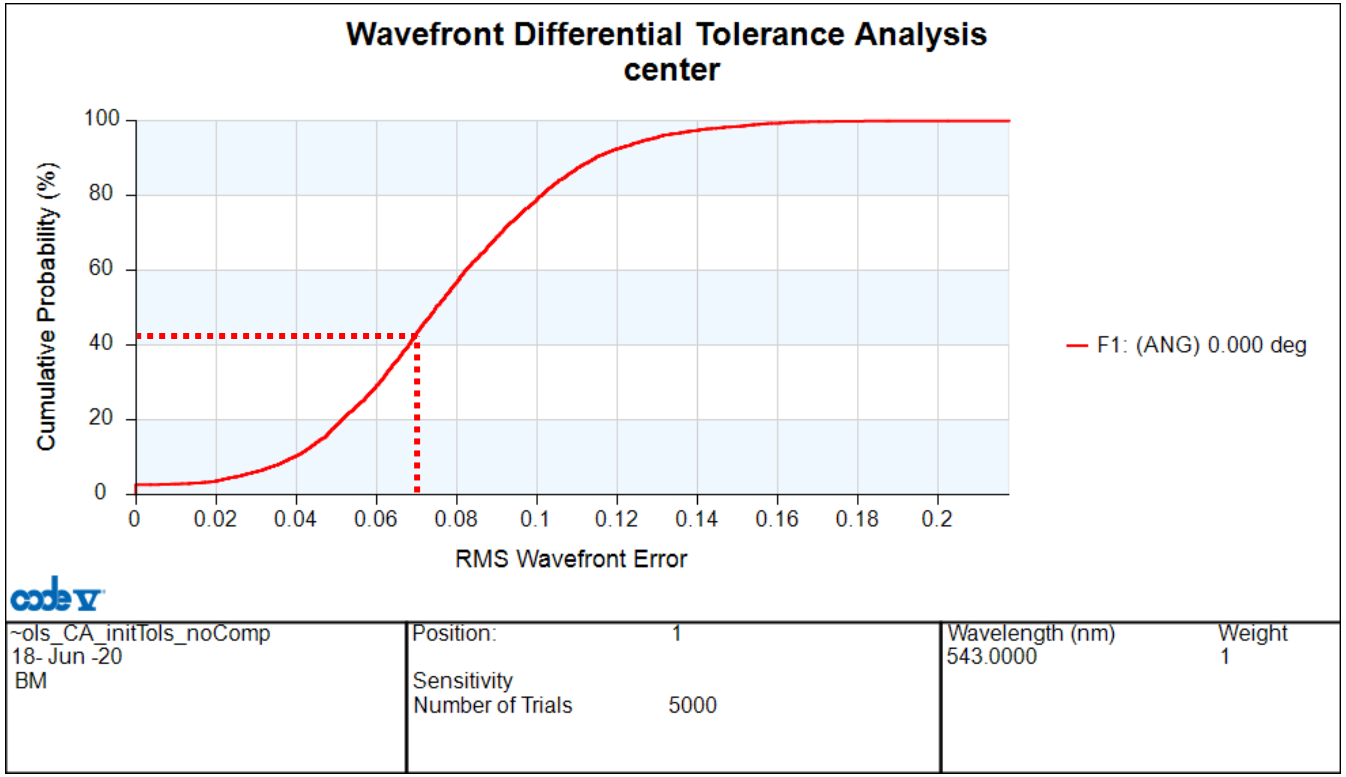
alignment

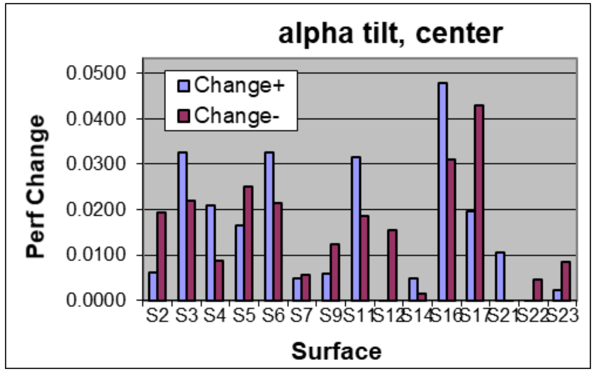
x position	+/- 1 mm
y position	+/- 1 mm
z position	+/- 1 mm
alpha tilt (about x)	+/- 1°
beta tilt (about y)	+/- 1°

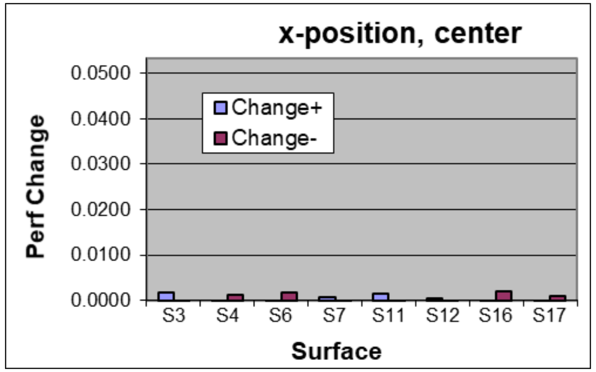
λ = 633 nm for all tolerances listed

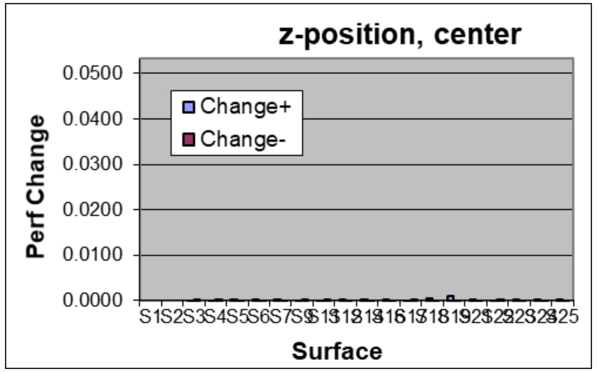
Tilt is the main cause of the poor performance

- Only 40% yield for the center scan position (worse for other positions)
- We want at least 97.7% confidence that the as-built system will be diffraction-limited
- We need to tighten tolerances and possibly add additional compensators









Sensitivity plots showing that tilt is the main driver of the performance decrease (all plots on the same scale)

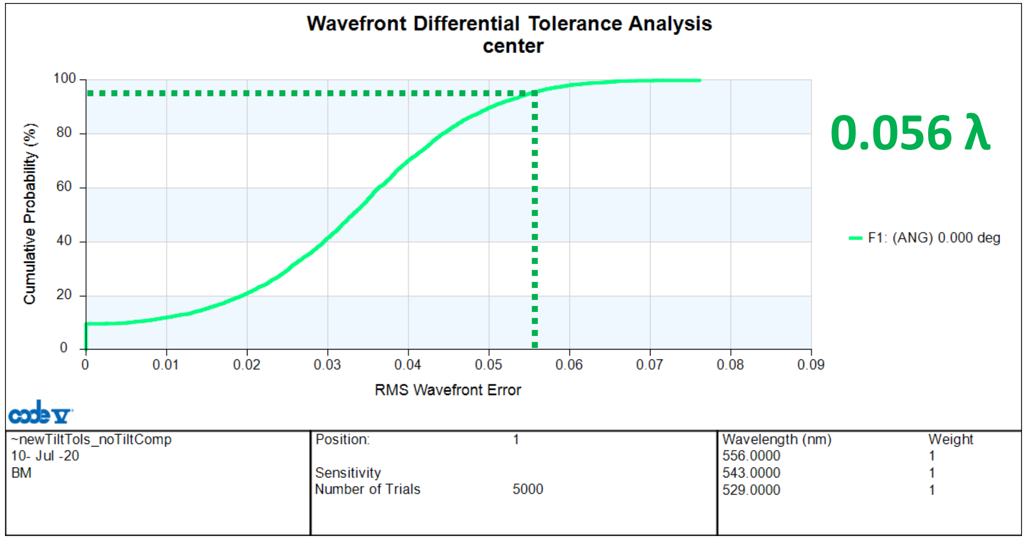
Tilt tolerances can be significantly tightened due to alignment guides and long baselines

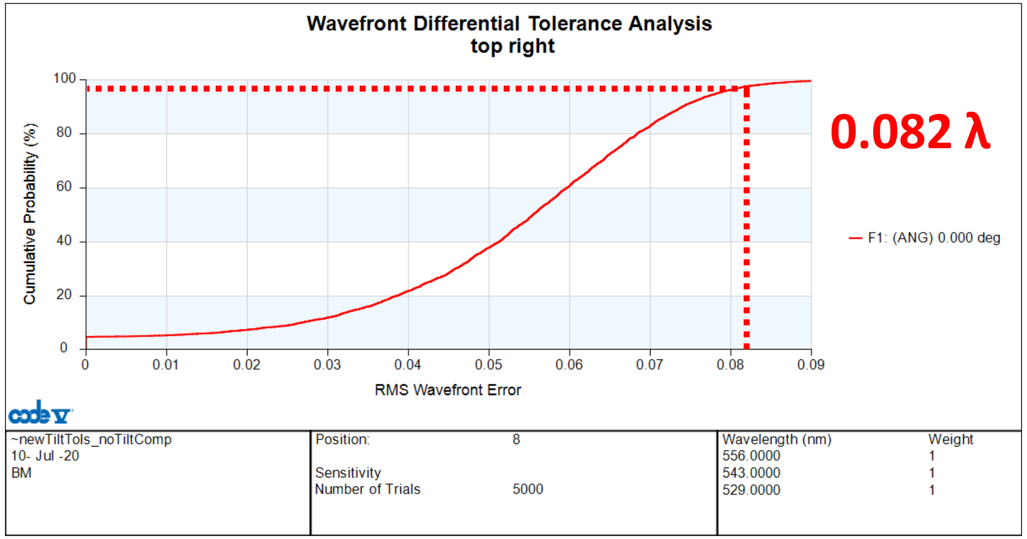
- Using alignment guides from Thorlabs, we should be able to achieve +/- 2 mm centration of the beam on each optic (this accounts for +/- 1 mm in position)
  - The shortest baseline in the system is 250 mm (between the fast scanner and the third spherical mirror)
  - All other mirrors are separated by at least 500 mm (1000 mm between some spherical mirror pairs)
  - +/- 2 mm on 250 mm corresponds to +/- 0.46° (27.6 arcmin)
  - +/- 2 mm on 500 mm corresponds to +/- 0.23° (13.8 arcmin)
  - +/- 2 mm on 1000 mm corresponds to +/- 0.11° (6.6 arcmin)
- New tilt tolerances to use:

fast scanner, dichroics, and lenses	+/- 30 arcmin
most spherical mirrors and flat mirrors	+/- 15 arcmin
spherical mirrors 1, 5, and 7	+/- 7.5 arcmin

Alignment guide from Thorlabs with ⌀ 1 mm central hole and ⌀ 2 mm concentric circles

Tightened tolerances provide much better performance but corner scan positions still don't meet specs



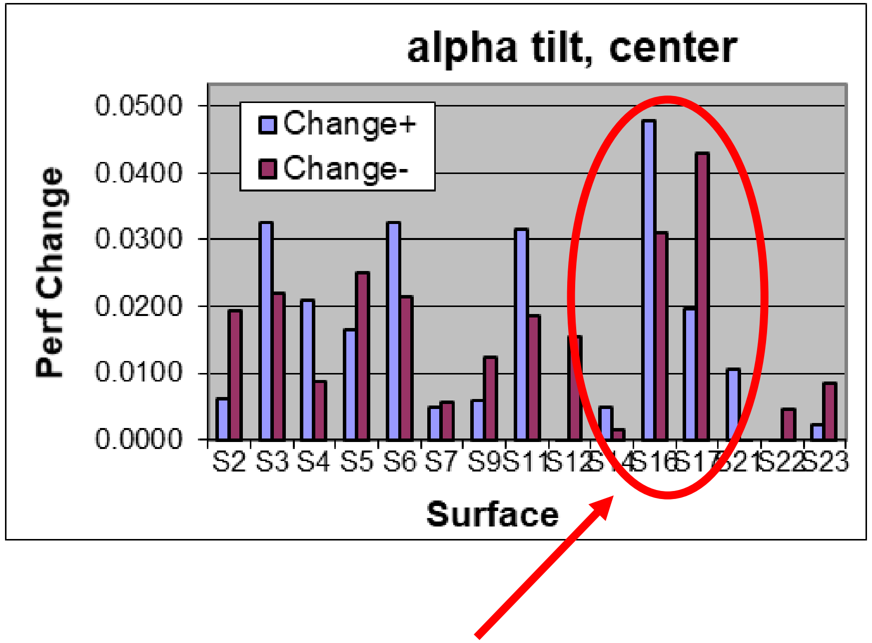


as-built performance for illumination (543 nm)

Scan position	RMS wavefront error (λ)
center	0.0559
left	0.0679
right	0.0708
top	0.0592
bottom	0.0647
top left	0.0727
bottom left	0.0725
top right	0.0819
bottom right	0.0716

- This suggests we need to add an additional compensator (focus is already used)

Using mirror 1 as a tilt compensator yields diffraction-limited as-built performance



Mirrors 1 and 2 are the most sensitive to tilt misalignment, so they will likely make good tilt compensators. Choose mirror 1 because it’s more accessible and has a longer baseline.

as-built performance for illumination (543 nm)*

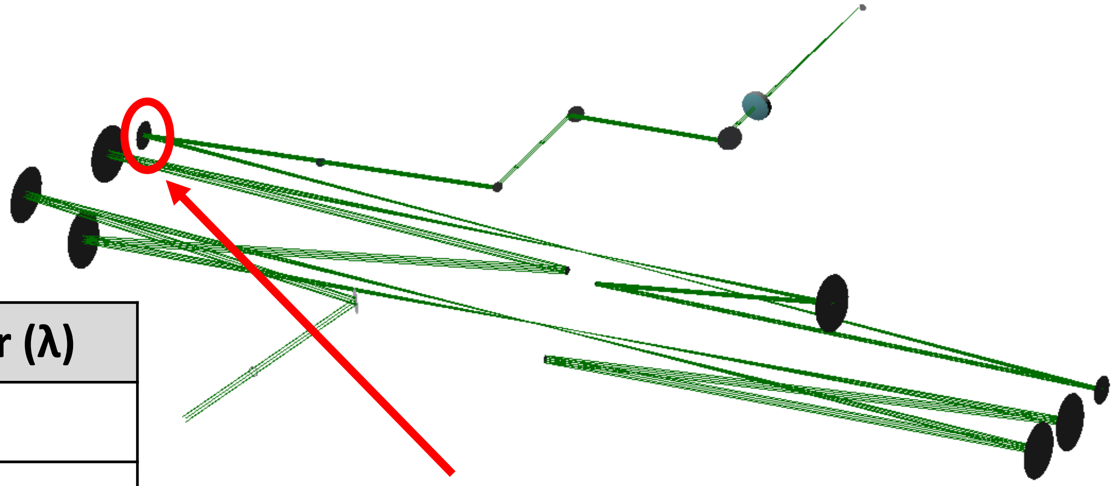
Scan position	RMS wavefront error (λ)
center	0.0269
left	0.0498
right	0.0517
top	0.0362
bottom	0.0514
top left	0.0626
bottom left	0.0616
top right	0.0657
bottom right	0.0620

< 0.066 for all scan positions

*other illumination channels perform even better than this: diffraction-limited criterion is most restrictive for the shortest wavelength channel

Summary of as-built performance

Channel	Maximum RMS wavefront error (λ)
illumination (all wavelengths)	0.0657
543 nm collection	0.0512
680 nm collection	0.0448
840 nm collection	0.0321
940 nm collection (WFS)	0.0349



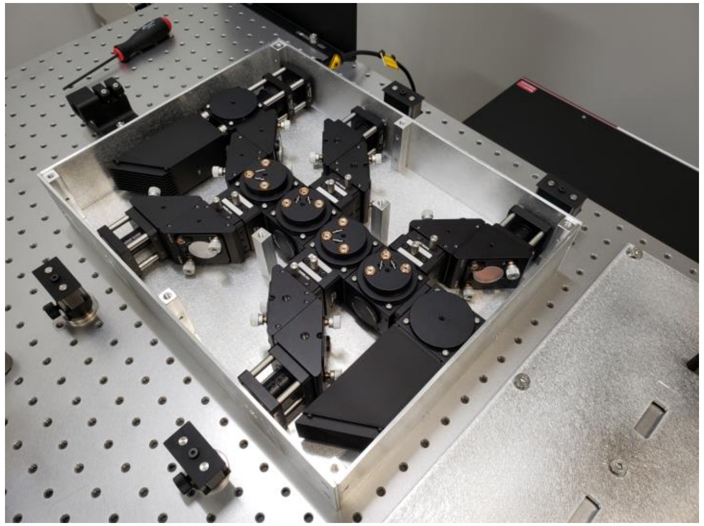
Mirror 1, the additional tilt compensator (pictured with the 543 nm collection channel)

- These values represent the worst performance across the different scanning angles
- In all cases, the worst performance occurs for the top right corner of the scan
- Three compensators used:
  - Focus (image plane position) – probable focus range of +/- 10 mm
  - Tilt about x-axis on mirror 1 – probable tilt range of +/- 1.5°
  - Tilt about y-axis on mirror 1 – probable tilt range of +/- 1.2°

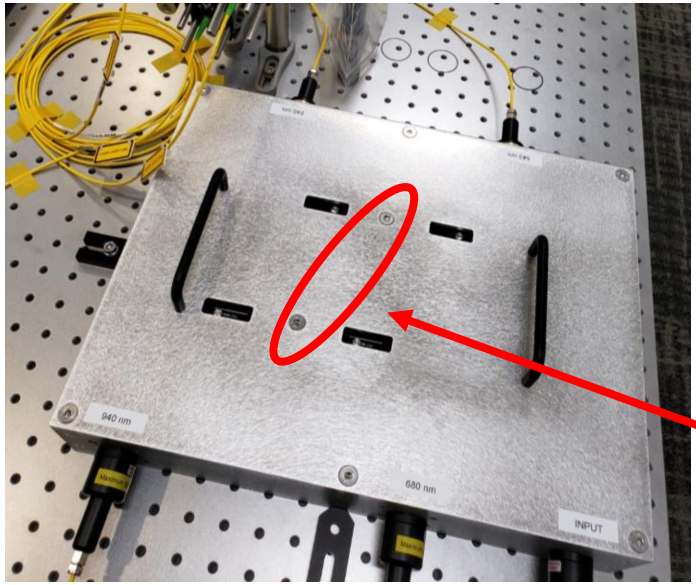
Tolerance analysis enables simple alignment requirements

- Final x-y-z position tolerances are +/- 1 mm for all components
  - Using the laser-cut stencil, we can achieve this precision in the x-z plane (on the optical table)
  - Using a ruler and/or calipers, we can achieve the proper height (y-position)
- Final tilt tolerances were translated into beam centration targets: +/- 2 mm on each optic
  - Direct angle measurements are not required
  - This should be easily achievable using the alignment guides from Thorlabs
- By using tolerance analysis in CODE V, we were able to arrive at realistic alignment requirements, which should reduce the time required to align the optical components

Alignment techniques for wavelength splitter box



splitter box before output fibers were installed

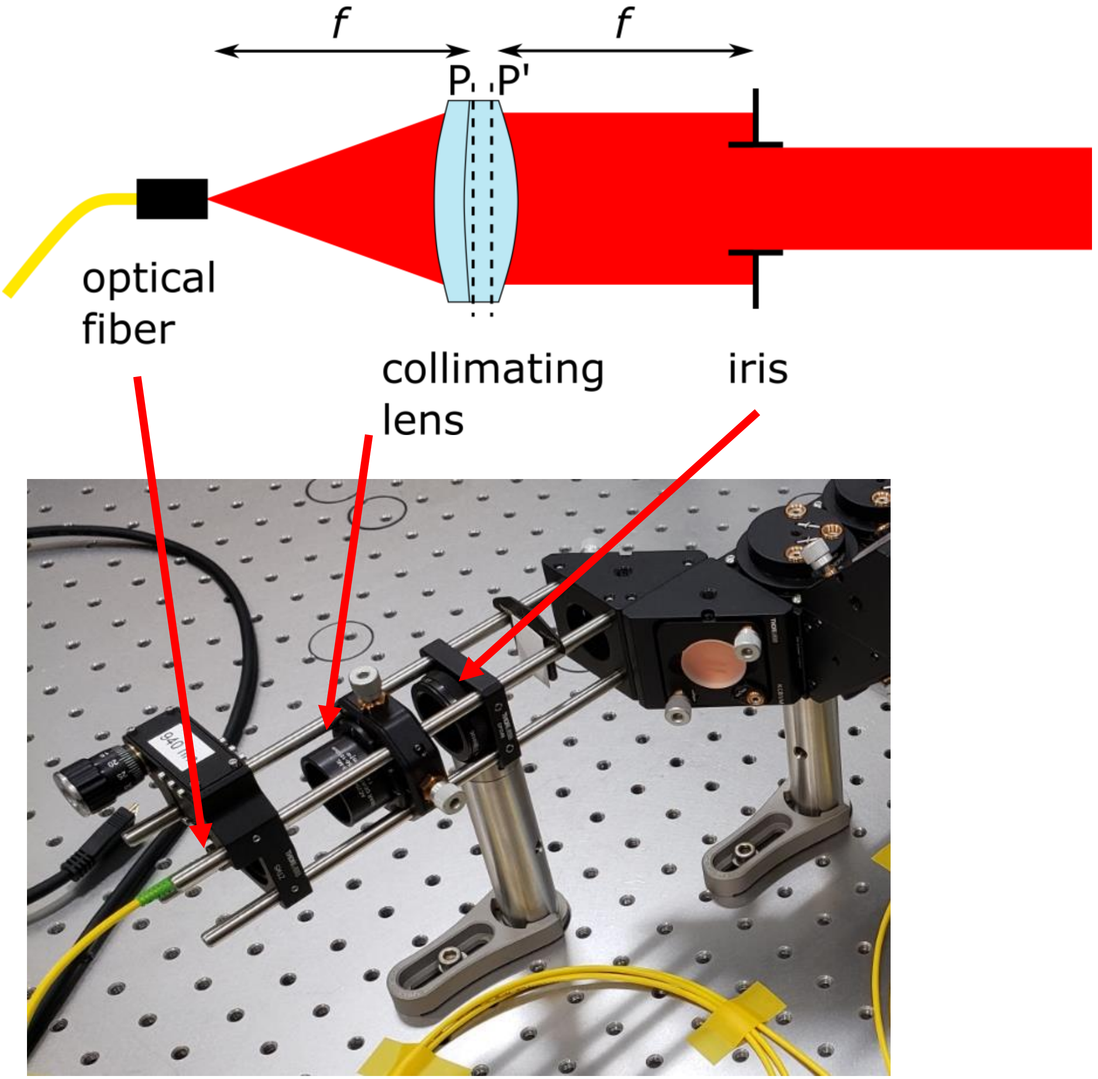


finished splitter box with output fibers installed and cover in place

- Each wavelength channel has a periscope, which is used to optimize alignment for coupling light into the fiber optic cable
  - Beam position and angle can both be adjusted using the periscope
  - Free-space alignment was performed first before attempting to couple into fiber
  - Iterative process
- Final coupling efficiency was > 70% for each channel (and within 1% of the theoretical efficiency for one channel)

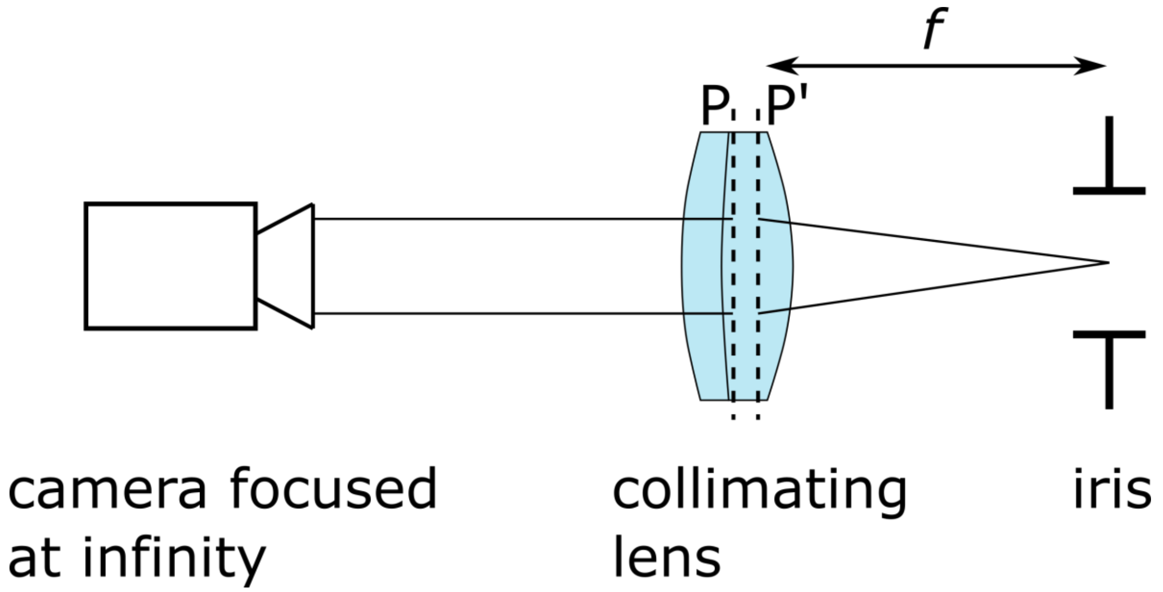
Lesson: do not fully tighten these screws. It causes the baseplate to deform and messes up the alignment.

Alignment techniques for irises and collimating lenses



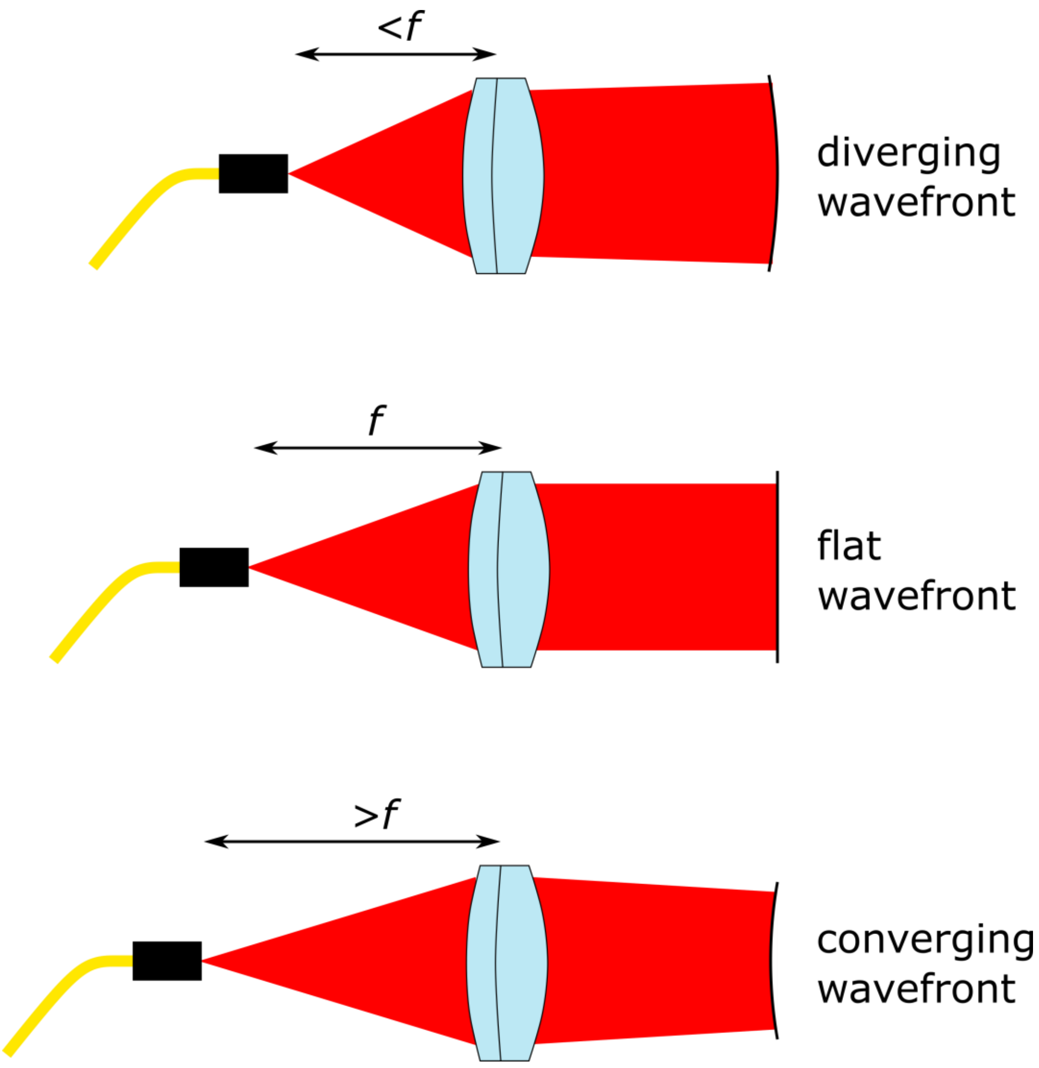
- Lens must be precisely positioned one focal length away from the fiber to properly collimate the light
- Iris must be placed one focal length away from the lens to ensure the proper pupil location and size
- The iris position is fixed in the system, so we'll start by moving the lens to the proper position and then adjusting the fiber location

Finding the correct lens position



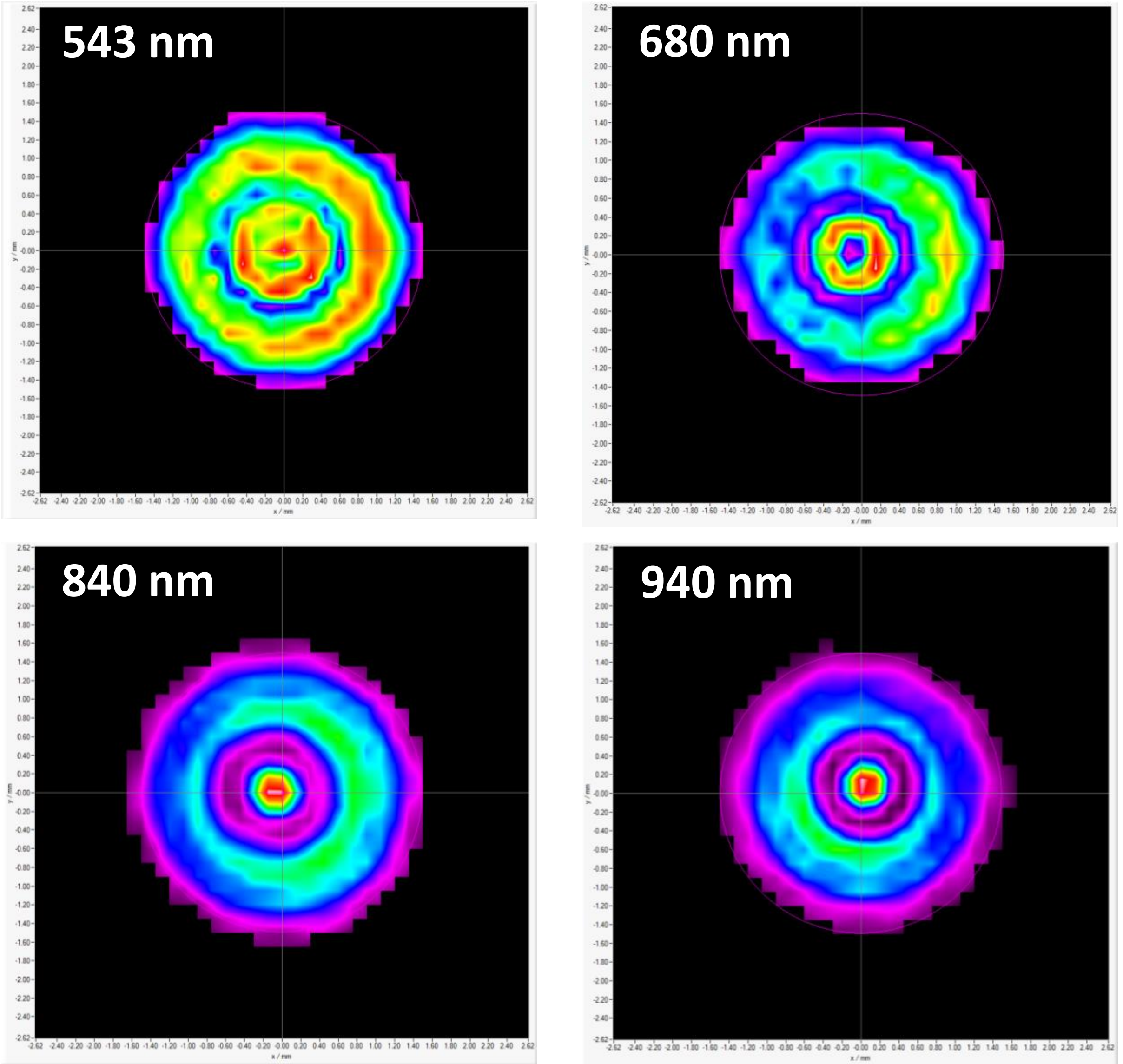
- Alignment instructions from Austin Roorda’s group recommended using a camera focused at infinity to find the correct lens position
  - When looking through the collimating lens with this camera, the back focal plane of the collimating lens is in focus
  - The lens position can be adjusted to achieve optimum focus on the edge of the iris

Optimizing the collimation

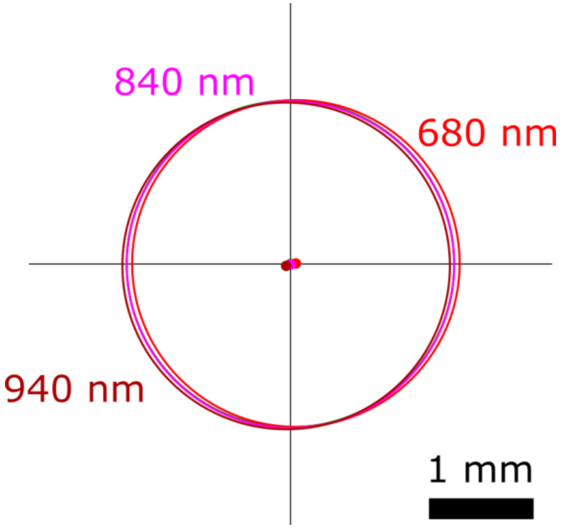


- The fiber position was adjusted to optimize the collimation for each channel
- Initially, a shear plate was going to be used (this was recommended by Austin Roorda's group)
  - However, I forgot to account for the temporal coherence of our sources
  - Shear plates work on interference, and they require a long coherence length (which means a narrow spectral bandwidth)
  - To use a shear plate, we would need to use a separate alignment laser (such as HeNe)
- I ended up using the wavefront sensor to measure the wavefront curvature directly

Co-aligning the different colors

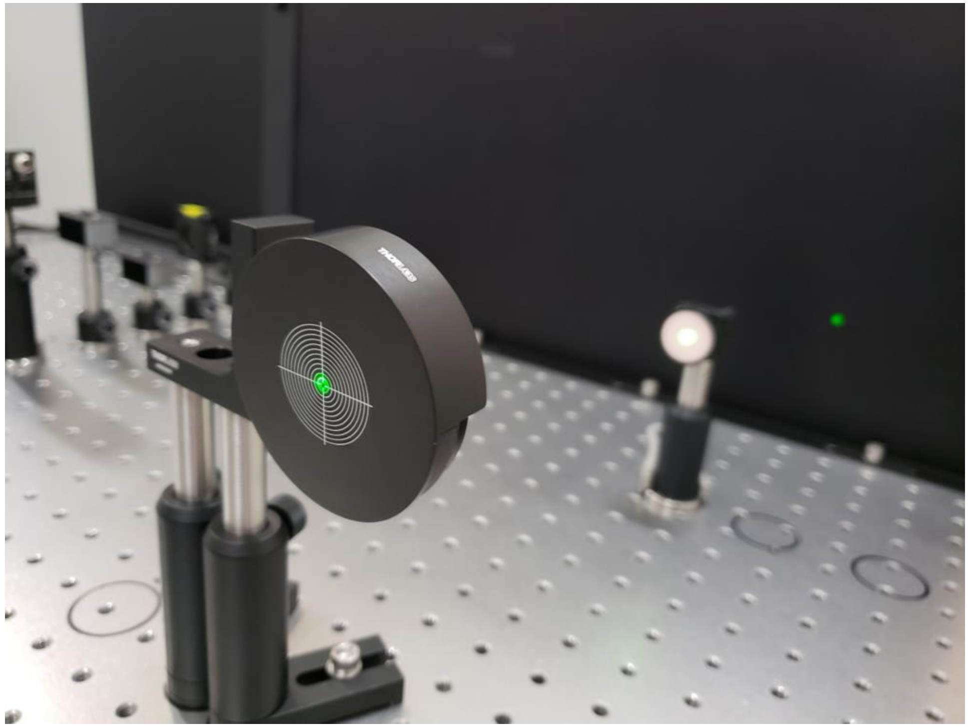


- Near-field beam positions were matched by maximizing power through a fixed iris just smaller than the beam diameter
- Far-field positions were matched using the beam profile feature of the wavefront sensor
  - Sensor location was adjusted to center the 543 nm beam on the detector
  - Next, all other colors were matched to this location
  - Maximum centroid deviation: 0.052 mm
  - Maximum centroid difference: 0.096 mm

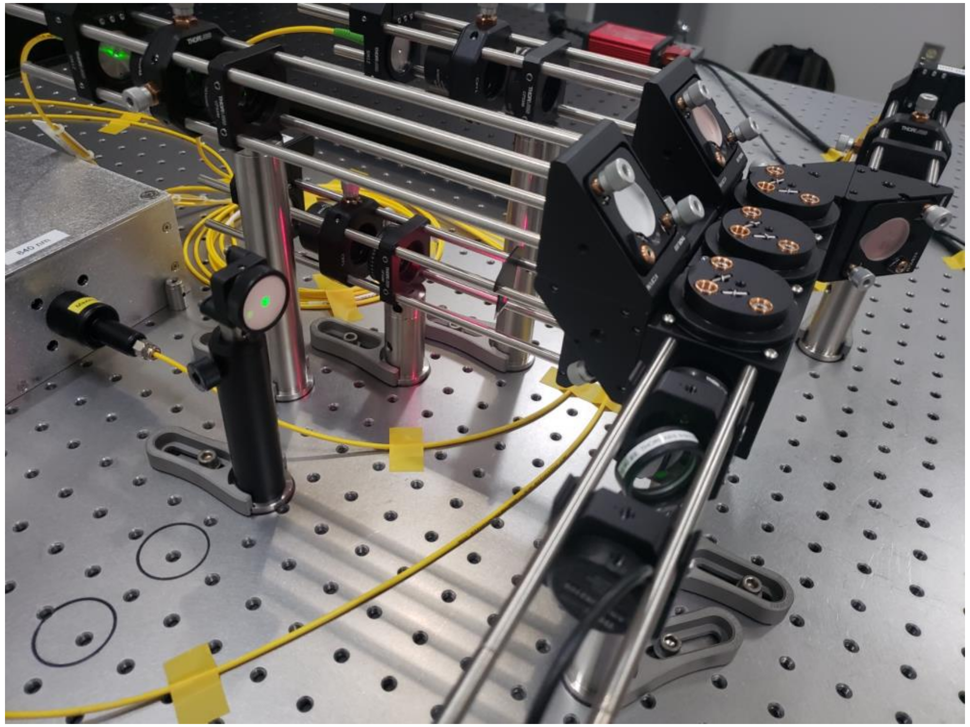


Aligning telescopes

- The first pair of spherical mirrors has been installed and aligned
- Since all colors are co-aligned, we can use the green beam because it's easiest to see
- We can use the wavefront sensor to check collimation and aberrations during alignment



using an alignment guide to center the beam on a 2” mirror



using an alignment pinhole to center the beam on a 1” mirror

Progress update

- I've completed several tasks on my original plan for resuming work in the lab (from March presentation)
  - ☑ Install optics in wavelength splitter assembly
  - ☑ Align wavelength splitter and verify proper performance
  - ☑ Finish building light delivery stage and align optics
  - in progress ☐ Assemble the relay telescopes and verify alignment of each subsystem
  - in progress ☐ Install scanning and adaptive optics hardware
  - ☐ Implement adaptive optics control algorithms
  - ☐ Begin testing performance of full system

  waiting on electronics hardware from Austin Roorda's group

- We still have work to do on alignment, and we can install some of the software, but then we will be waiting on electronics hardware, which is still in production

Summary and review

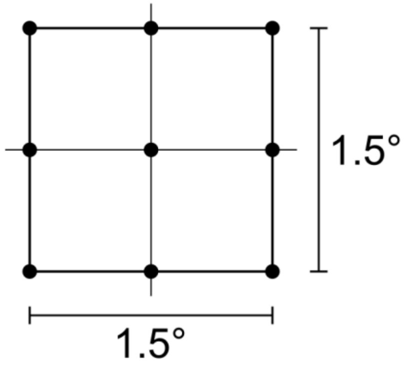
- Modeling the optical system in CODE V
- Tolerancing and sensitivity analysis in CODE V
- Optical alignment requirements
- Alignment techniques
- Alignment progress
- Project status updates

I look forward to your questions and suggestions regarding this project

Extra slides

CODE V model was compared to Zemax model to verify that system had been properly entered

field of view as seen by the subject



- Good agreement between models: similar residual aberrations
- All spots are well within the diffraction-limited spot diameter (black circle)
- Square grid with a ray density of 20 rays across aperture was used for both models