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On-sky Image Quality Verification / Compensation Plan

March 27, 2015 (original)

April 3, 2015 (revised)

April 9, 2015 (revised)

Outline

- Overview
- HET system layout & error budget
- WFC-FPA alignment scheme
- Deployable Wavefront Sensor (DWFS) & tilt alignment to FPA
- Expected alignment error
- In-situ calibration & Measurement sequence
- Discussion on FPA tilt compensation & Example case studies.
- Summary
- Appendix

Overview

- **Expected alignment-driven aberrations contributing to the image quality degradation**
  - **Major terms : Field constant coma, Field linear curvature/astigmatisms.**
    - Additionally, field quadratic coma and field cubic astigmatisms can contribute.
  - All these terms are linearly coupled to alignment parameters.

- **Available compensators and their influences**
  - WFC motions
    - Decenter : Strongly image position, weakly field constant coma.
    - Tip/tilt : Strongly field constant coma, weakly field linear curvature/astigmatism.
  - Focal Surface (FS) motions
    - Decenter : Strongly image position, weakly field linear curvature.
    - Tip/tilt : Strongly field linear curvature.

- **First-order plan**
  - Align FS with respect to WFC.
  - Point HET to on-sky target (geostationary satellite) on-axis and minimize coma by tilting WFC.
  - Point to the target at off-axis FS positions and measure curvature.
  - If necessary, minimize field linear curvature by tilting the FP

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Layout & Error budget

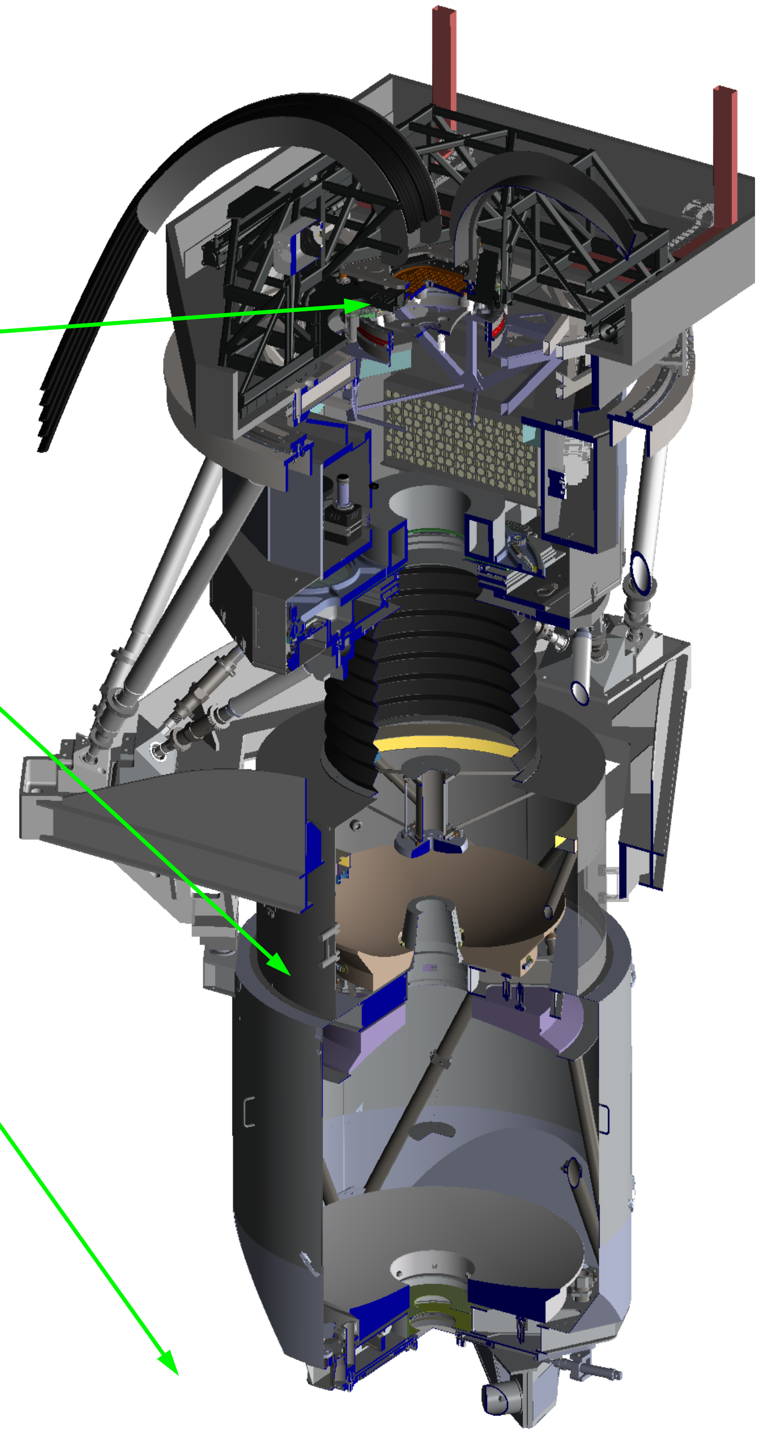
- **Three major subsystems**
  - Focal Plane Assembly (FPA)
  - Wide Field Corrector (WFC)
  - Primary Mirror (M1)

- **Critical alignment**
  - WFC – FPA
  - M1 – WFC

- **Static alignment error budget**
  - WFC-FPA
    - Focus: ±0.3mm
    - Centration: ±0.17mm
    - Tilt: ±90arcseconds

    (Centration and Tilt: 0.19wv linear curvature)
  - M1-WFC
    - Focus: ±0.01mm
    - Centration: ±0.01mm
    - Tilt: ±4arcseconds

    (Centration and Tilt: 0.33wv coma)



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WFC-FPA Alignment Scheme

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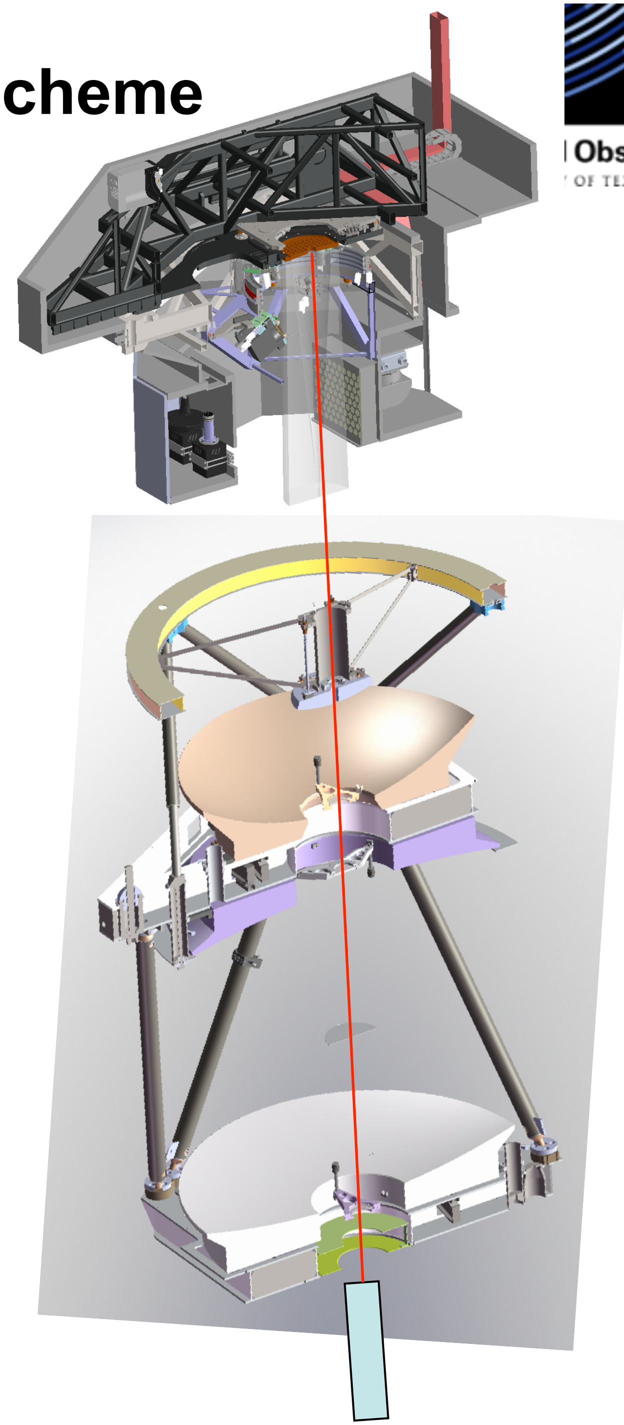
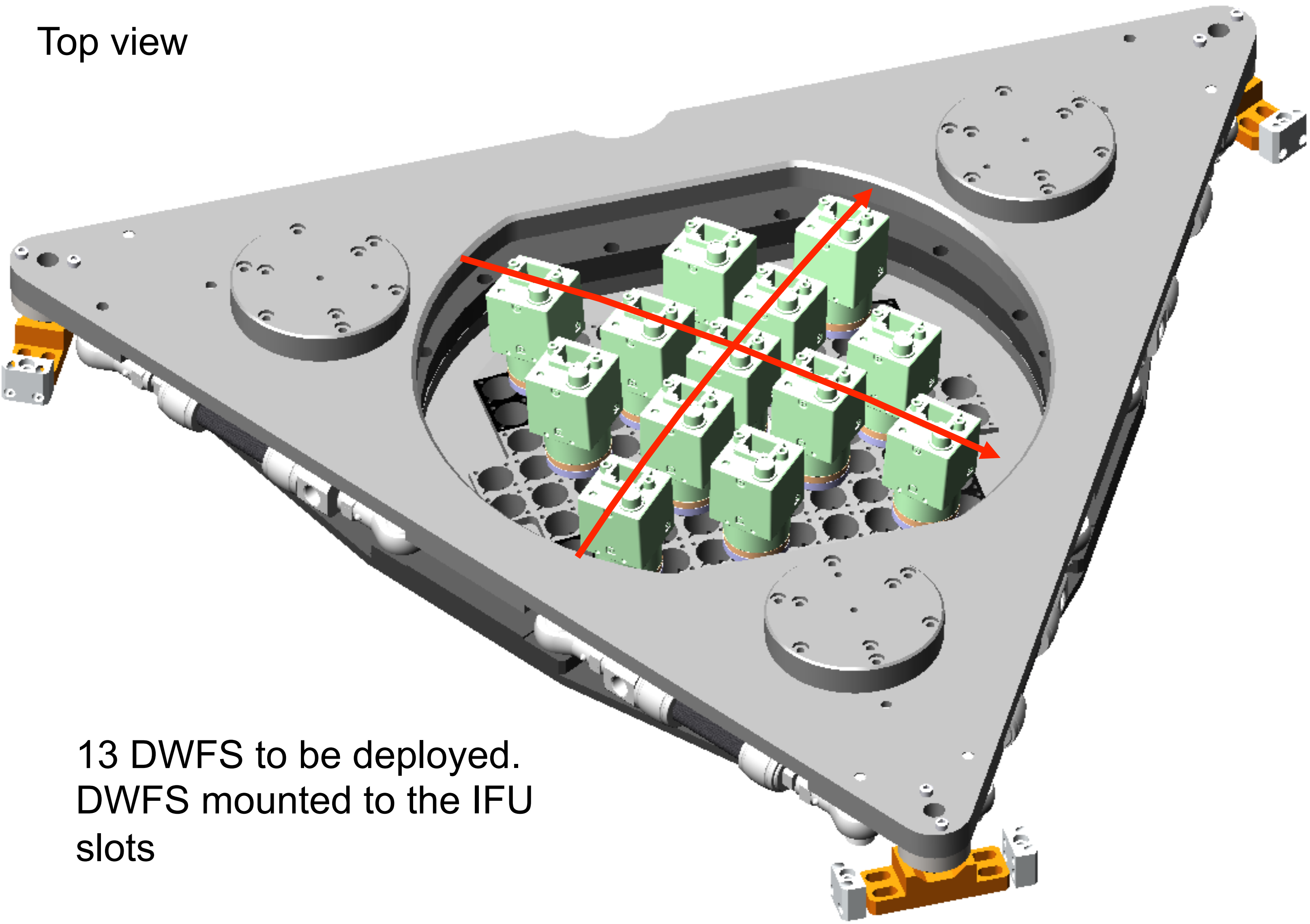
- Set up Video Alignment Telescope (VAT) at M3 Strongback centered/ normal to M4 CGH Reference.
- FPA Reticle target is aligned to M4 CGH Reference in tilt (using VAT)
- FPA SMR target is aligned to M4 Vertex Reference in centration/focus (using Laser Tracker).



Refer to Appendix for details of M4 references, VAT Laser Tracker, FPA targets (page 34-40).

Deployable Wavefront Sensor (DWFS)

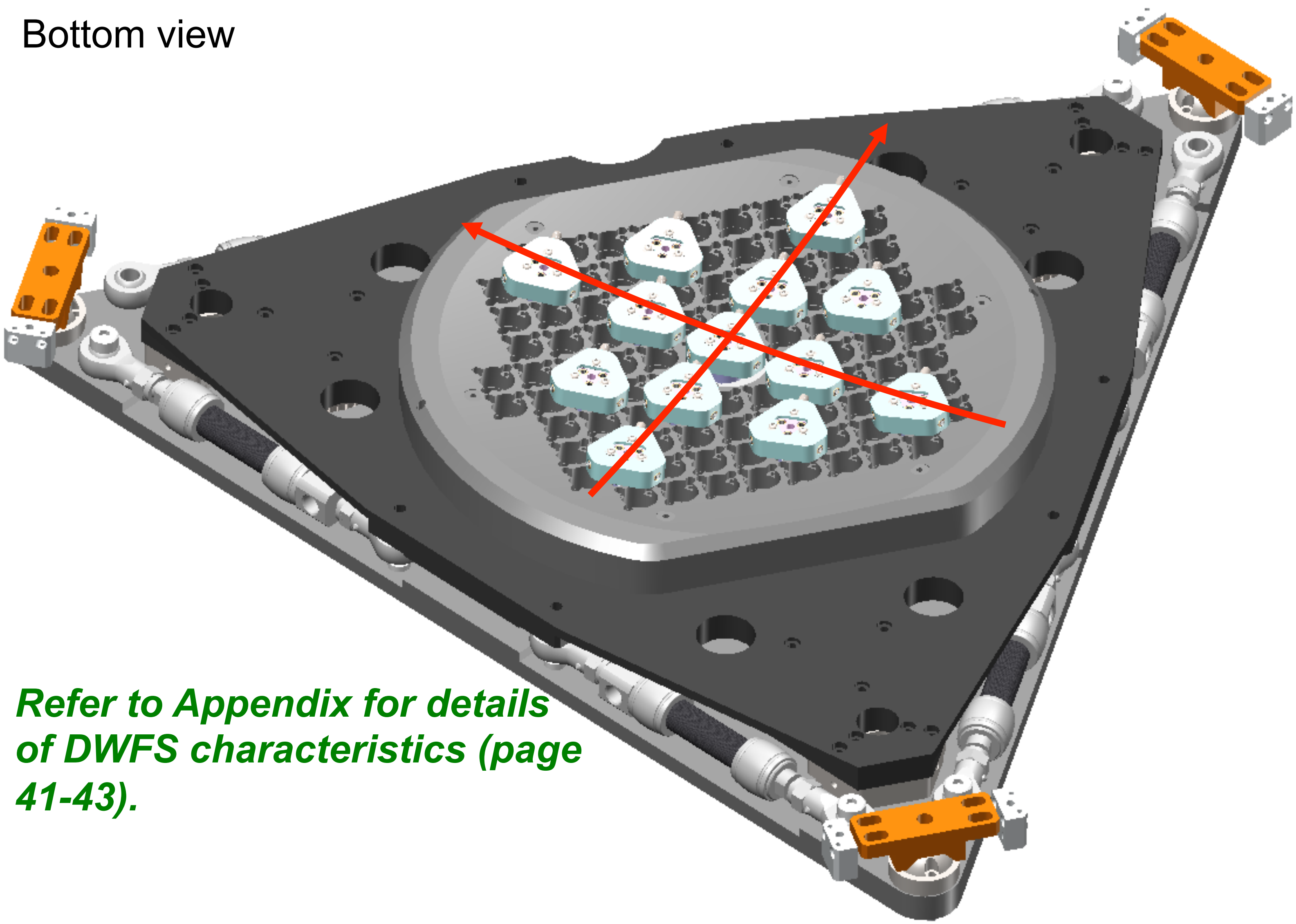
Top view



13 DWFS to be deployed.
DWFS mounted to the IFU slots

Deployable Wavefront Sensor (DWFS)

Bottom view



Refer to Appendix for details of DWFS characteristics (page 41-43).

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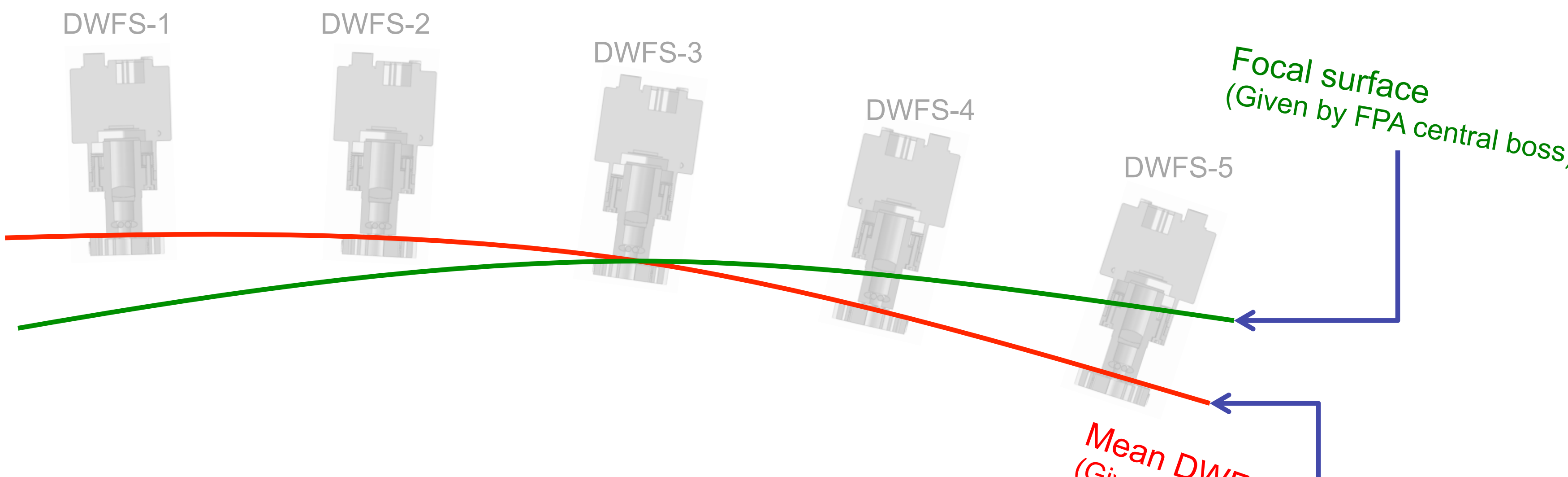
Critical alignment (tilt)



- **Tilt between the mean DWFS surface and the focal surface**
  - Focal surface tilt is used to correct the linear field curvature.
  - Systematic tilt between two surfaces results in error in the linear field curvature measurement
  - This tilt is a function of
    - Registration accuracy of the IFU seats (where DWFS are mounted) to the FPA central boss (+/- 0.01mm focus direction, +/- 0.05mm centration).
    - Registration accuracy of each DWFS calibration pinhole to each IFU seat (+/- 0.027mm in centration/focus)

Refer to Appendix for details of this tilt is determined (page 44-47).

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Roll-up of WFC-FPA-DWFS alignment error estimate

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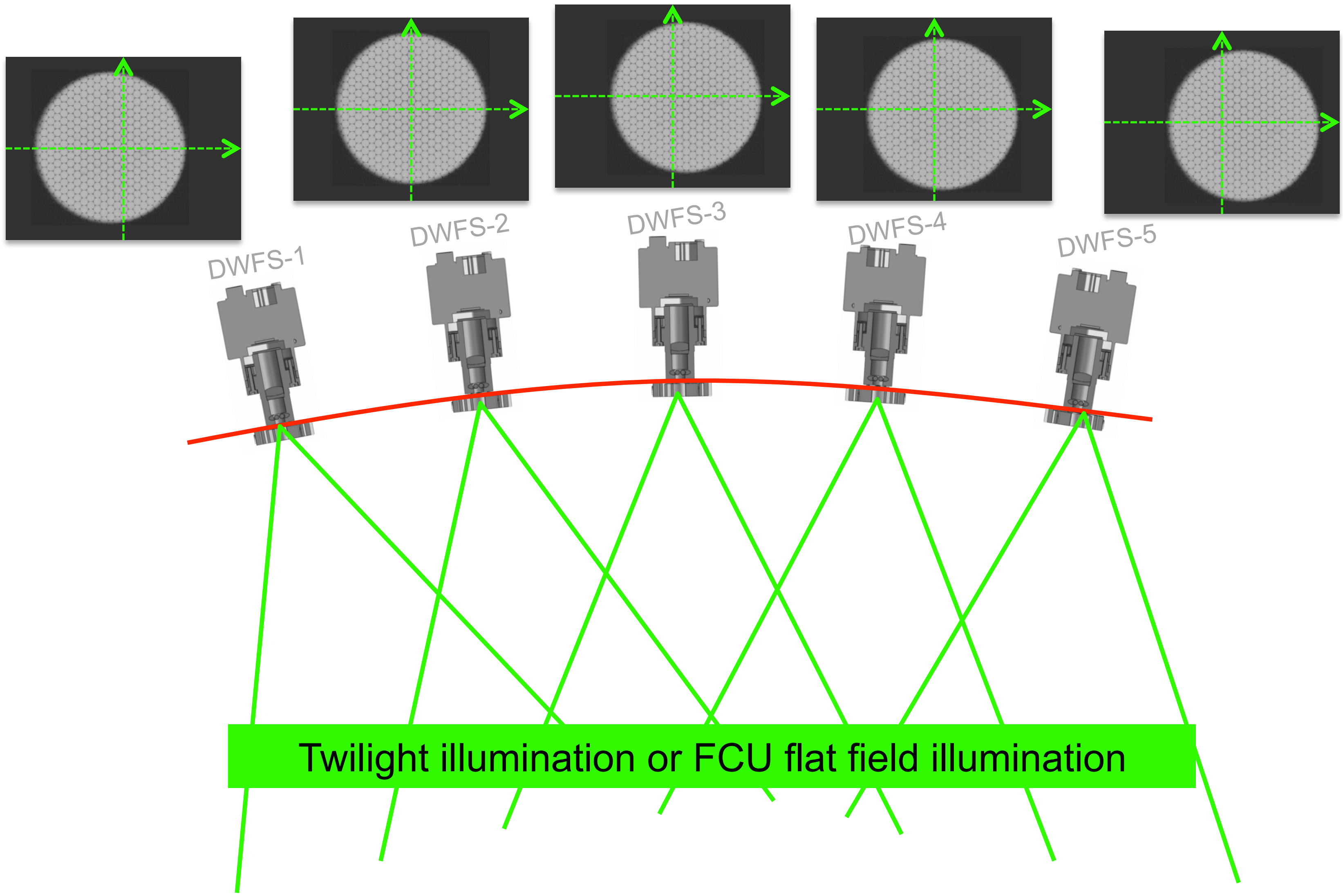
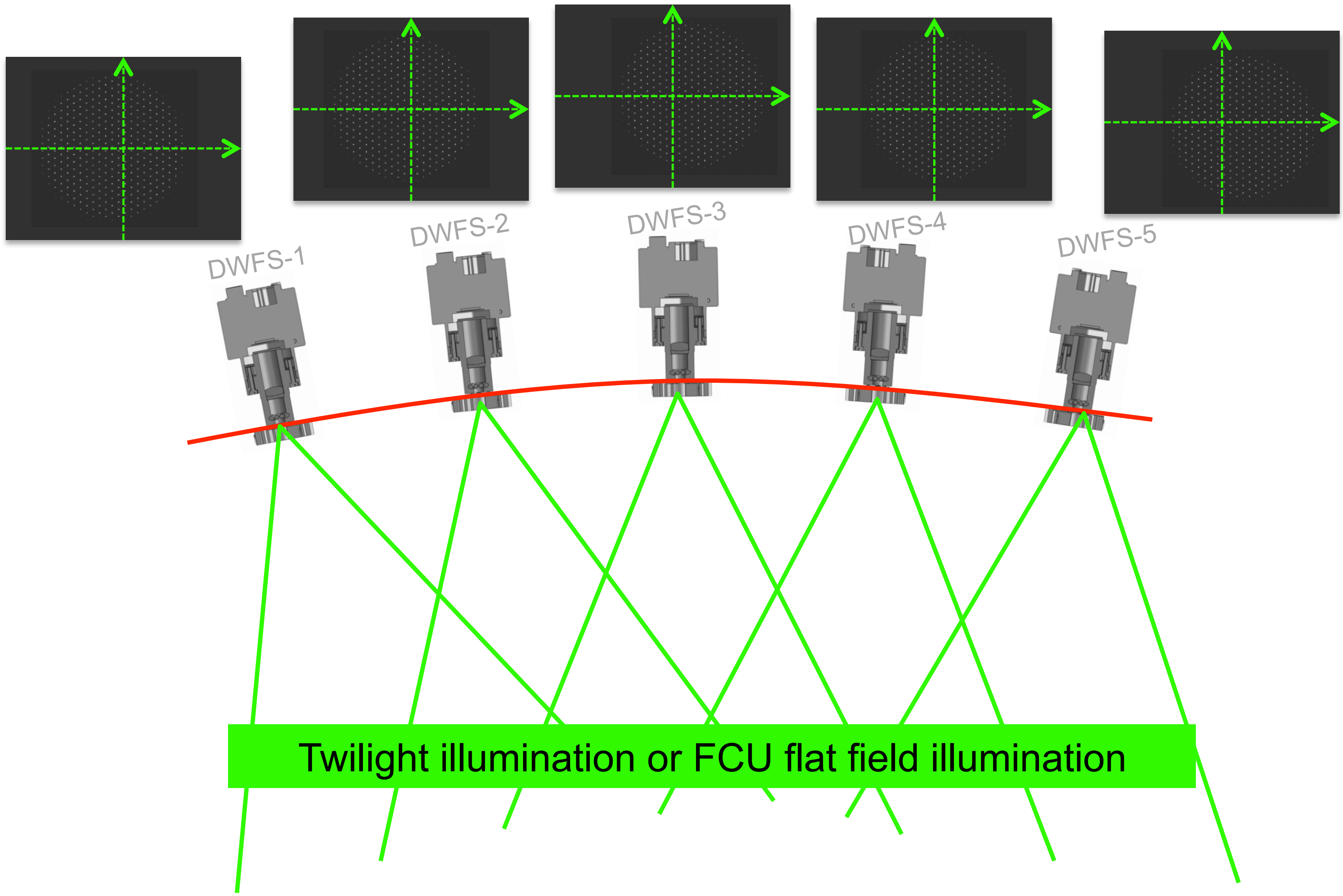
Contributor	Focus (mm)	Centration (mm)	Tilt (arcsec)	Comment
FPA Target setup wrt FPA central boss	0.015	0.025	10	Installation accuracy
VAT cent/tilt to M4 CGH	-	0.010	5	Measurement accuracy
VAT cent/tilt to FPA Reticle	-	0.050	5	Measurement accuracy
LT focus to M4 VTX	0.025	-	-	Measurement accuracy at 2m
LT focus to FPA SMR	0.050	-	-	Measurement accuracy at 4m
Manual hexapod control	0.007	0.003	1	Resolution
Registration of the mean DWFS surface wrt FPA central boss	0.029 (maximum)	0.058	52 (maximum)	Registration / measurement accuracy (assuming all errors go to either focus or tilt)
Cumulative	**0.061**	**0.081**	**66**	**RSS at 3σ**
Requirement	**0.3**	**0.17**	**90**	

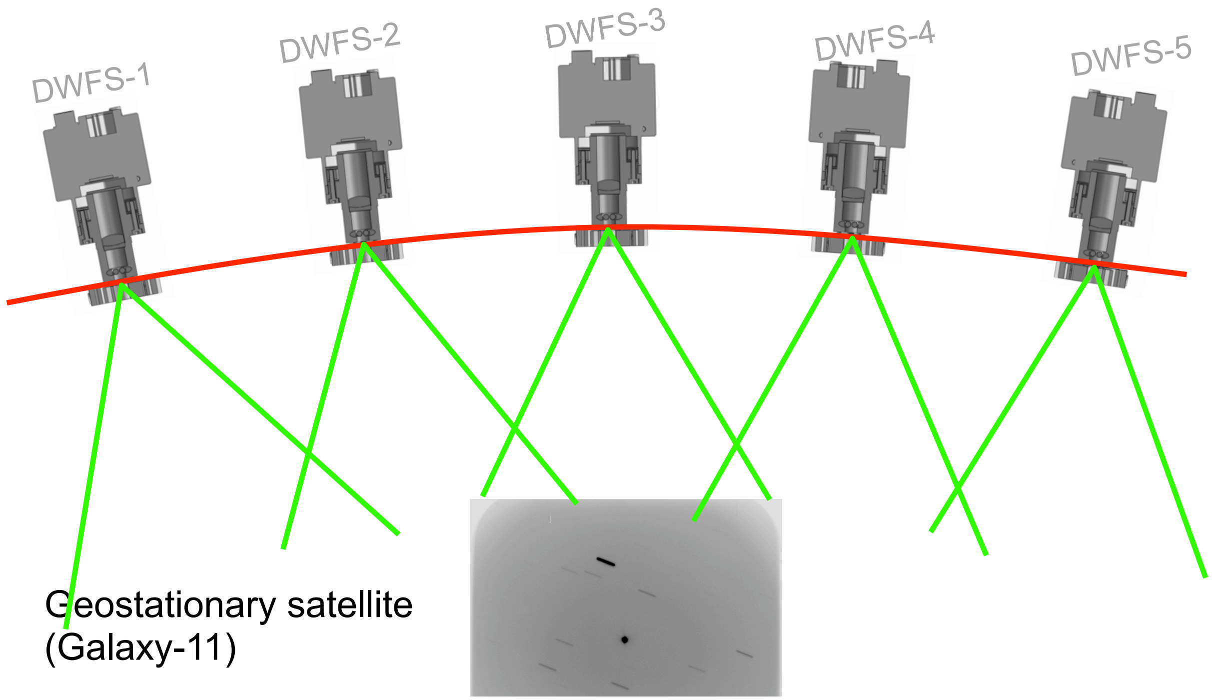
DWFS In-Situ Calibration
(Establish WFC Pupil/Sub-aperture Geometry with Field stop)

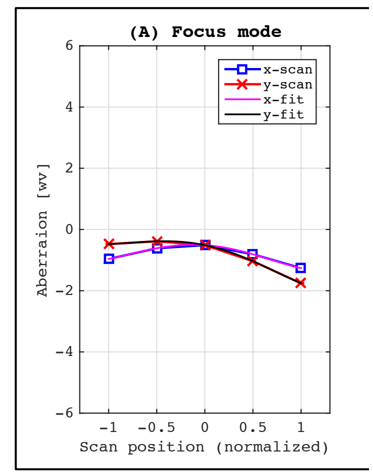


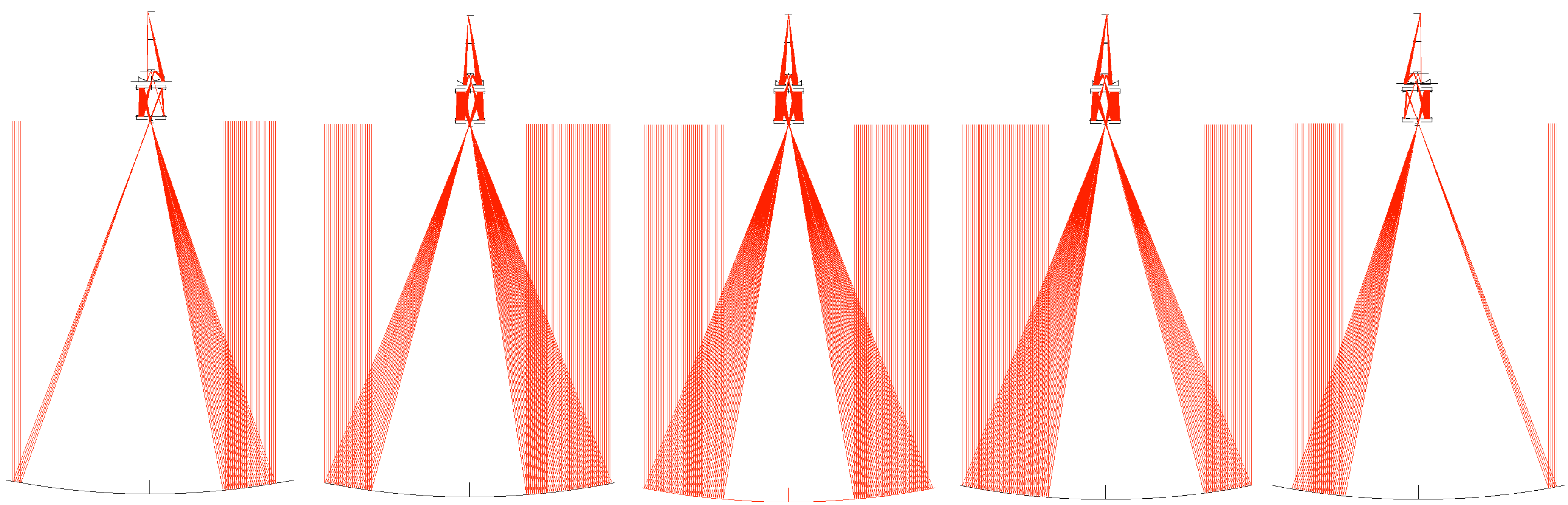
DWFS In-Situ Calibration
(Establish the calibration of DWFS internal aberrations with Calibration pinhole)



On-sky measurement sequence







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FPA tilt compensation

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- **Reduction of the linear curvature down to ±0.19wv over 22 arcmin.**
  - This is sufficient to compensate for the image quality.
  - Linear curvature is dominant cause of image quality degradation.
  - However, the linear astigmatism remains uncorrected → Ok for the expected cases.

- **FPA tilt (Δα) leads to**
  - Beam angle change (Δβ) to the focal surface, thus to the fibers. **(where Δα = Δβ)**
  - Focal Ratio Degradation (FRD) occurs at the output of the fibers (unless the fibers are tilted to match the incoming beam angle to the FPA).
  - Maximum marginal ray angle ~ nominal max. marginal angle + Δβ
  - For a perfect fiber, the output beam focal ratio would be, to the first order,

    $f/\#_{out}$ = 0.5 / sin(nominal max. marginal angle + Δβ)
  - Beam angle change → Pupil shift in Operation WFS / Calibration WFS / Pupil Viewer → Recalibration or adjustment is needed.

- **Azimuthal Image Quality Variation is uncorrected.**
  - FPA is rotated to follow sky rotation (rho angle) while the WFC is fixed.
  - FPA tilt compensation at one particular rho angle.
  - In Case 1, image quality / throughput will azimuthally vary.

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Uncorrected aberrations

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- **Most of the aberrations remains uncorrected after FPA tilt compensation.**
  - Mainly astigmatism
  - Elongated / asymmetric PSF shape (substantial in case 1)
  - Varying over the rho angle change and the track (due to varying obscuration)
  - Adding systematic error to the HET guiding systems

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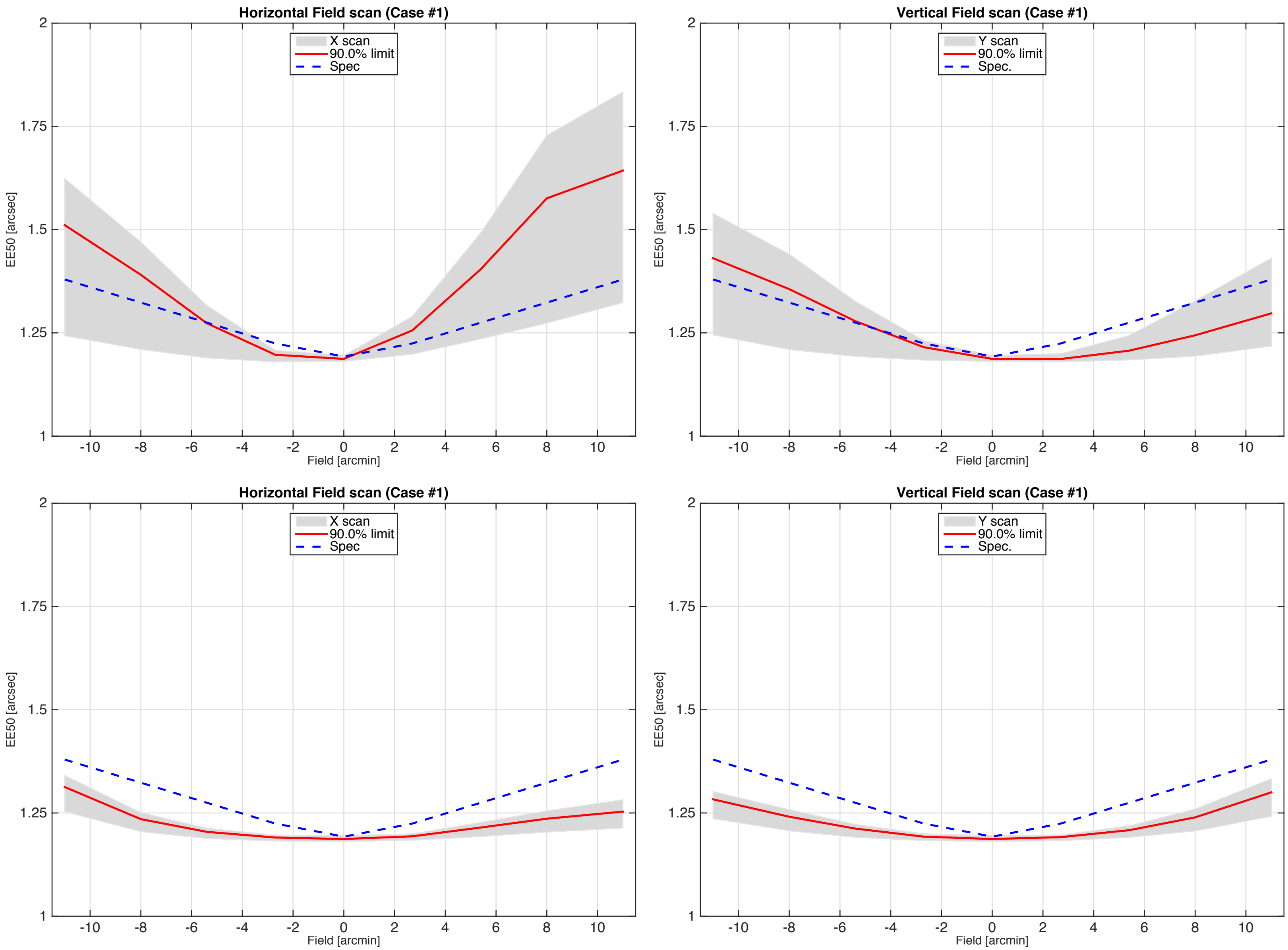
Case #1 post adjustment with just-in-spec setup error



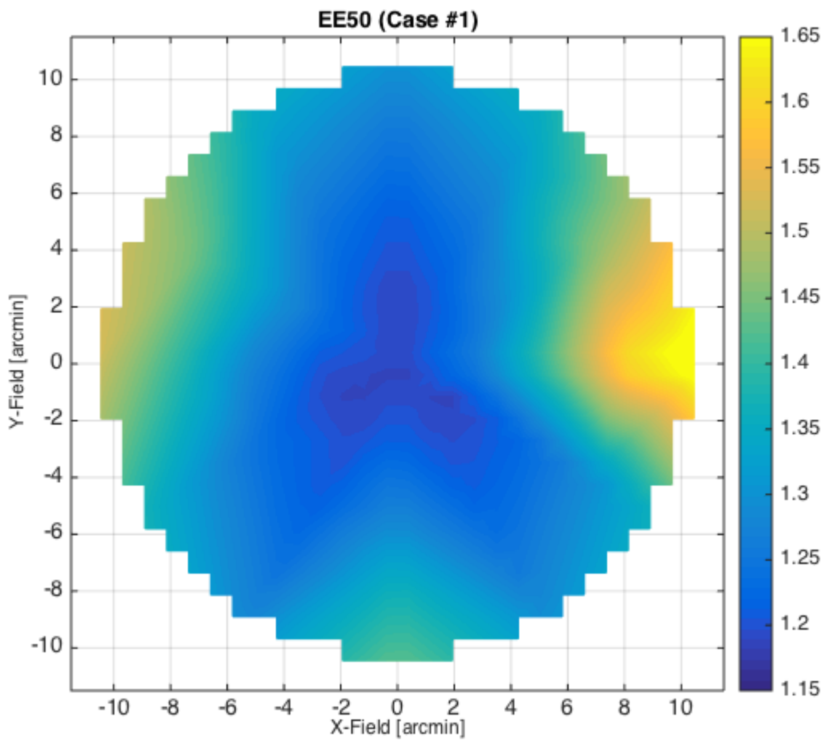
Before

After

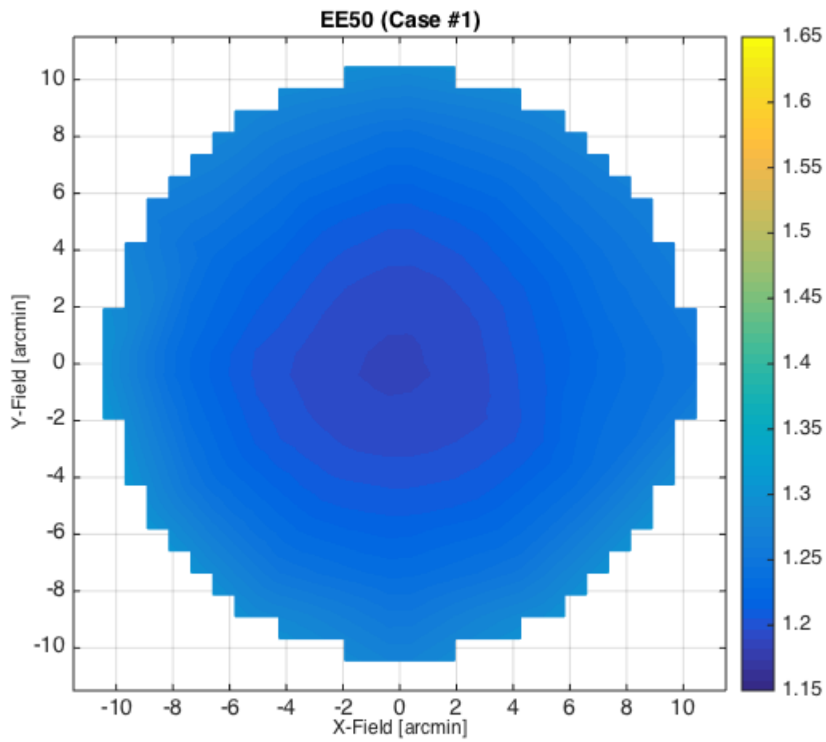
Case #1 post adjustment with just-in-spec setup error

EE50 Diameter

Before



After



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Case #1: other requirements

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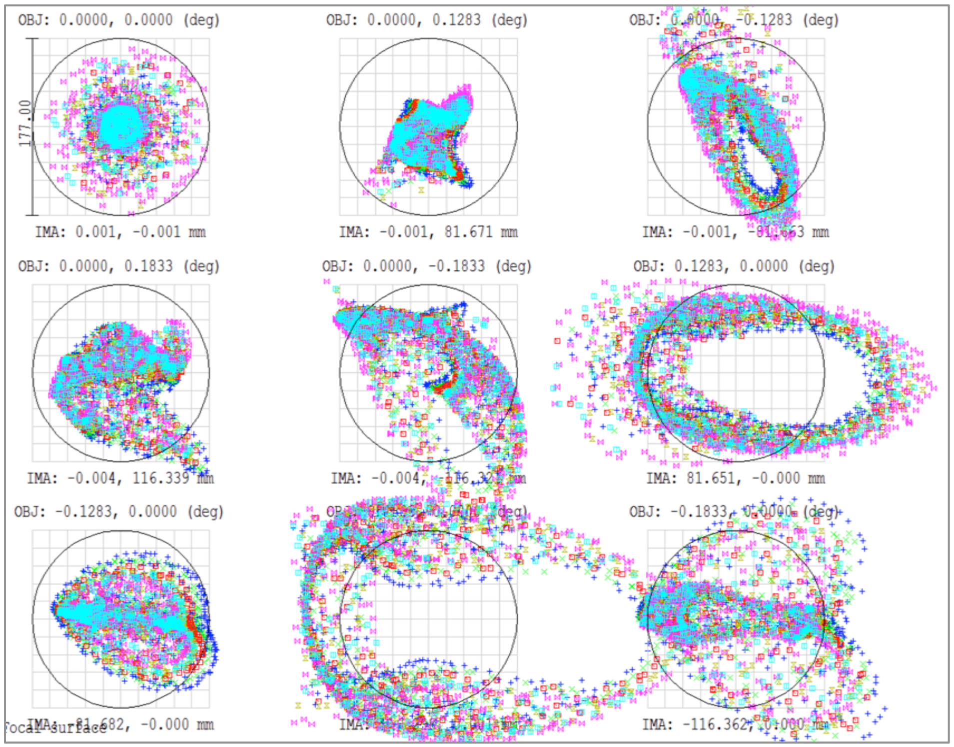
Metric	Requirement	Expectation	PASS/FAIL	Unit
Effective focal length	36450 – 36550	36492 – 36530	PASS	mm
Focal ratio**	3.645 – 3.655	3.321 (max)	FAIL	--
Max. marginal ray angle	7.863 – 7.884	8.659 (max)	FAIL	degrees
Max. telecentric angle	0.0 – 0.01	0.951 (max)★	FAIL	degrees
Max. distortion	0.0 – 1	< 0.585	PASS	%
Un-vignetted portion of beam	> 80 on-axis > 64 at edge	> 80 on-axis > 64 at edge	PASS	%

** Focal ratio is 0.5 / sin(max. marginal ray angle)

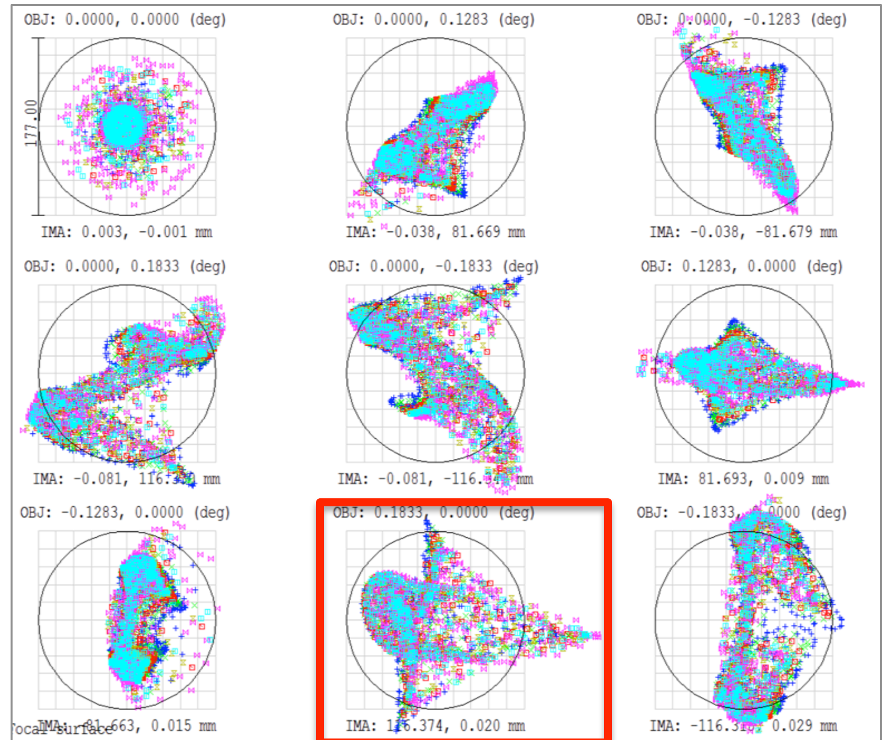
★ Telecentric angle closely corresponds to FPA tilt compensation.

Case #1 – 496 Spot diagram (guiding drift)

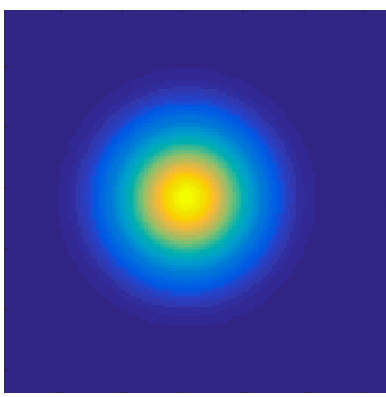
Before



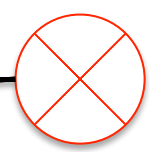
After



Centroid on this PSF



Convolve



1'' Seeing

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Case #1 – 496 Guiding drift (post-adjustment)

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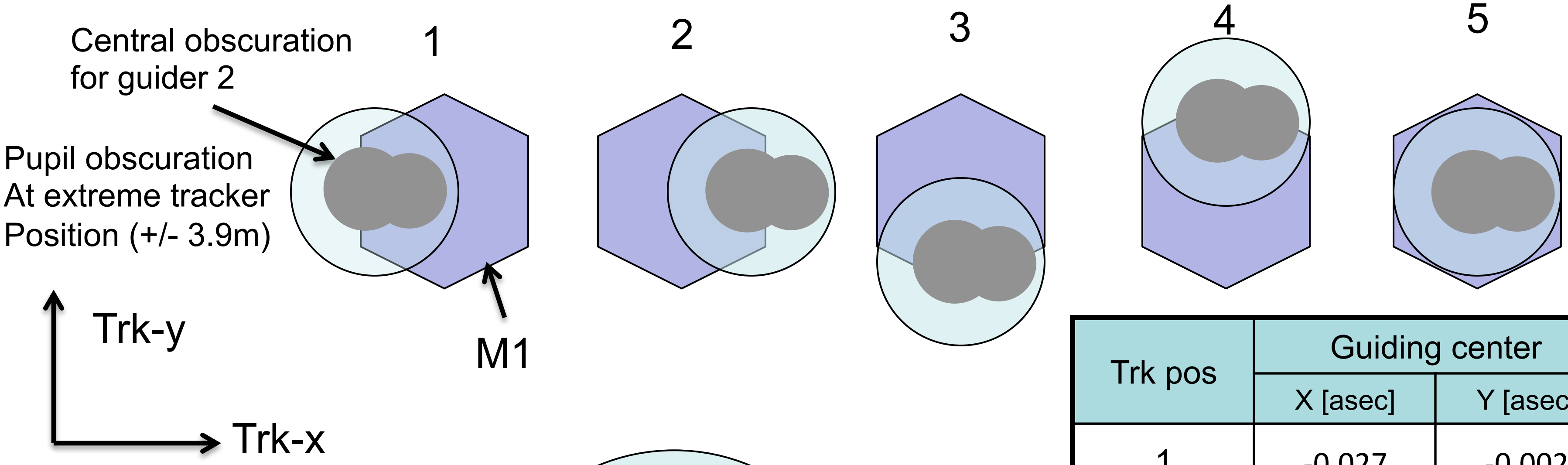
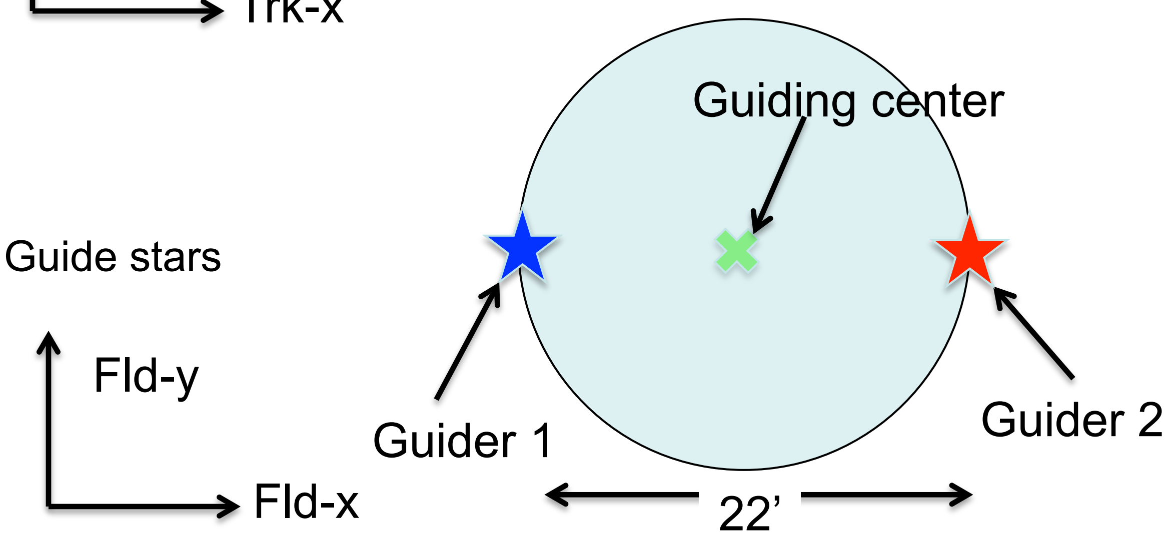
Refer to Appendix for examples of pupil obscurations (page 47).





Trk pos	Guiding center	
	X [asec]	Y [asec]
1	-0.027	-0.002
2	0.067	-0.002
3	-0.009	0.180
4	-0.018	-0.178
5	-0.013	0.003
Mean	0.000	0.000
Range	-0.02 ~ 0.07	-0.18 ~ 0.18

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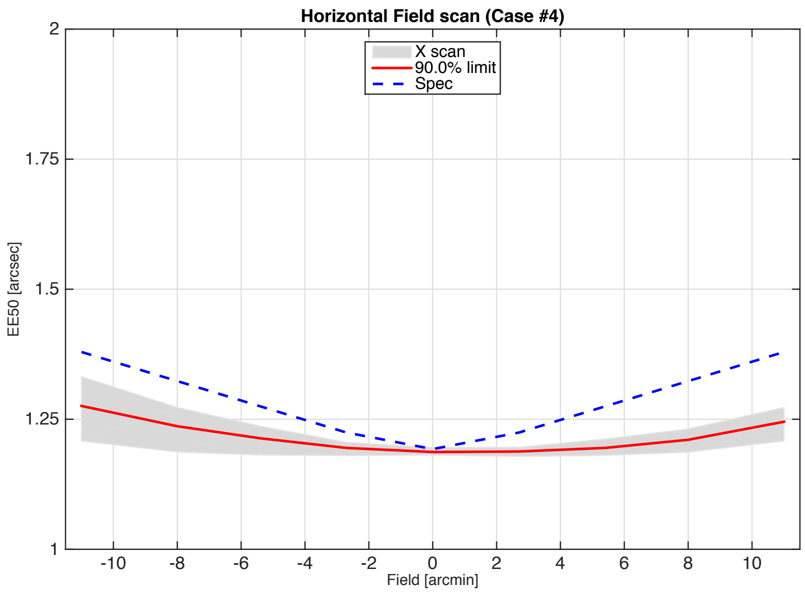
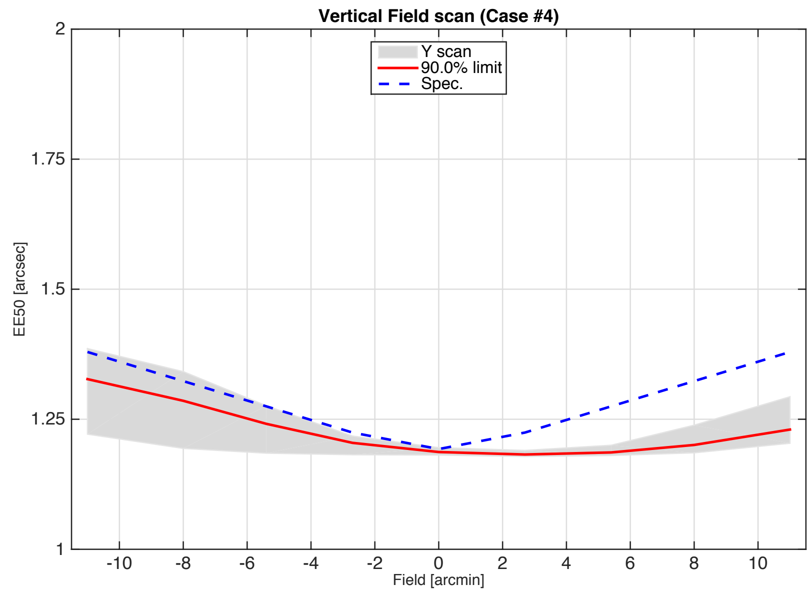
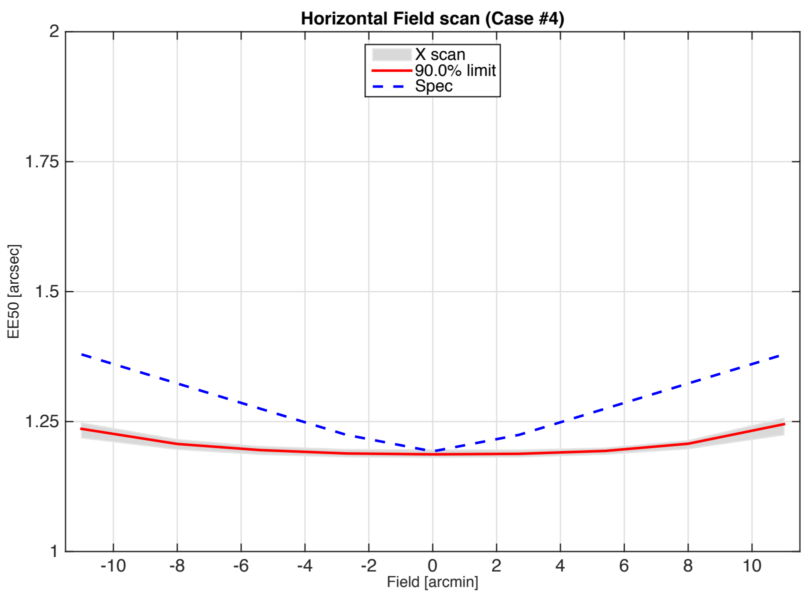
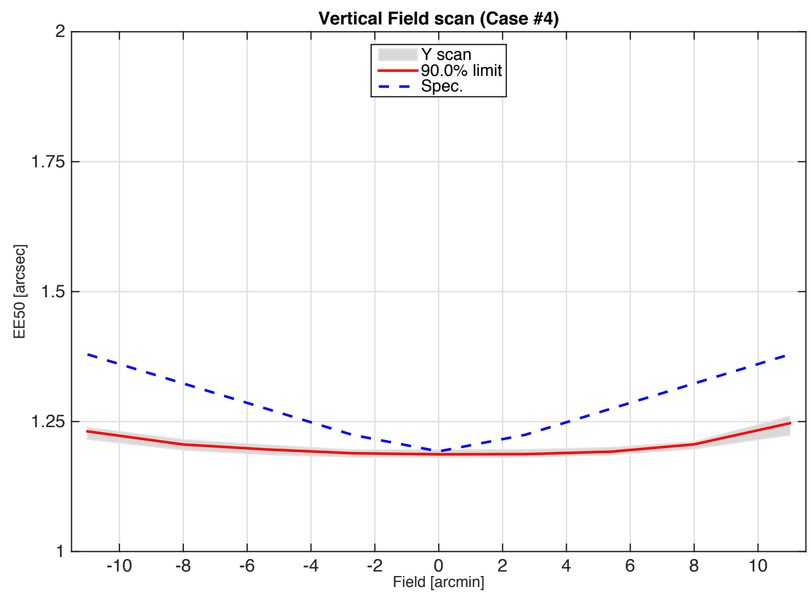
Case #4 post adjustment with just-in-spec setup error





Before





After

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Case #4 post adjustment with just-in-spec setup error

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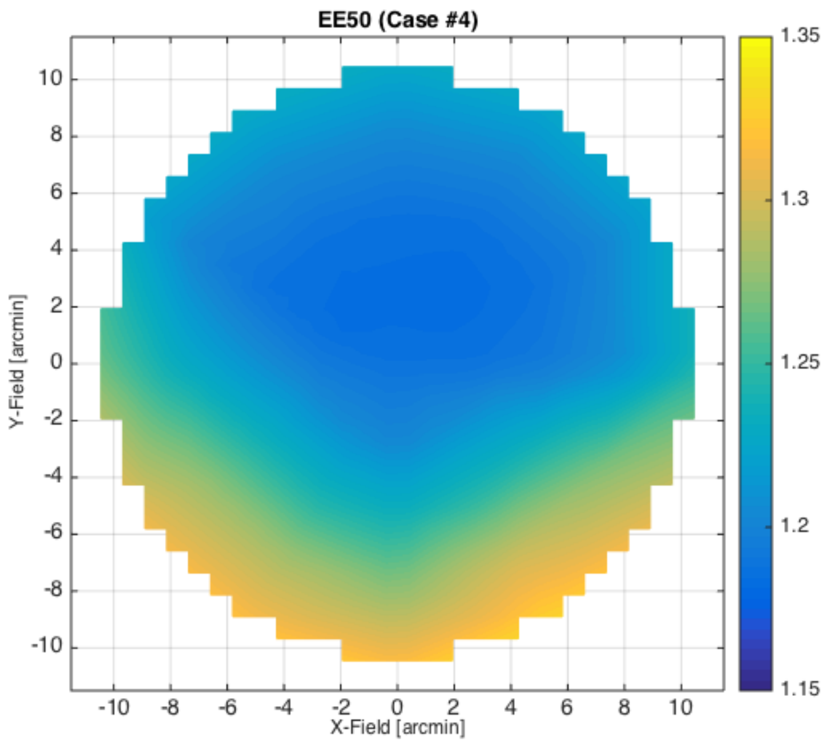
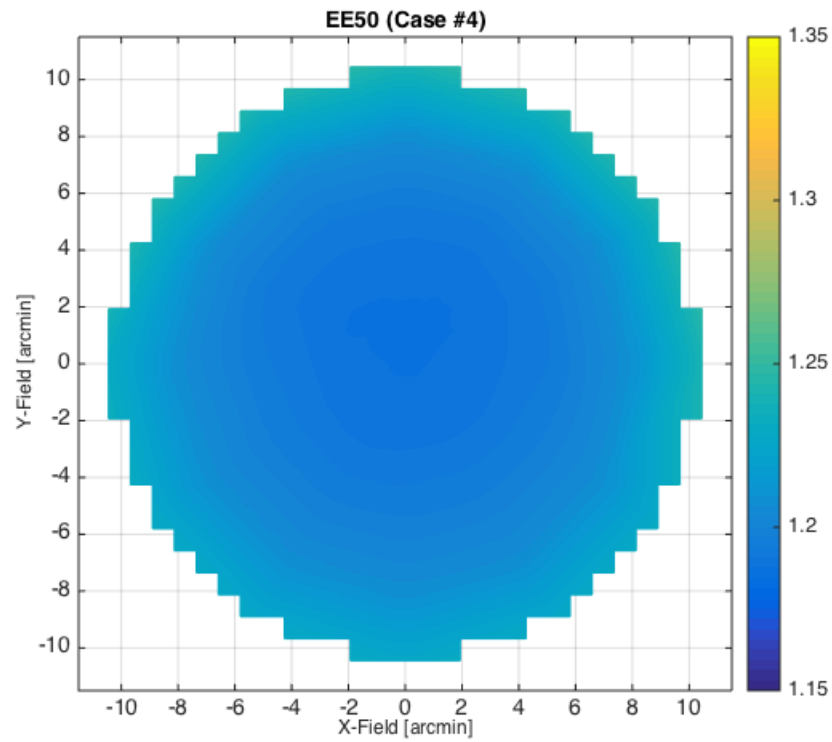
Before



After



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Case #4: other requirements

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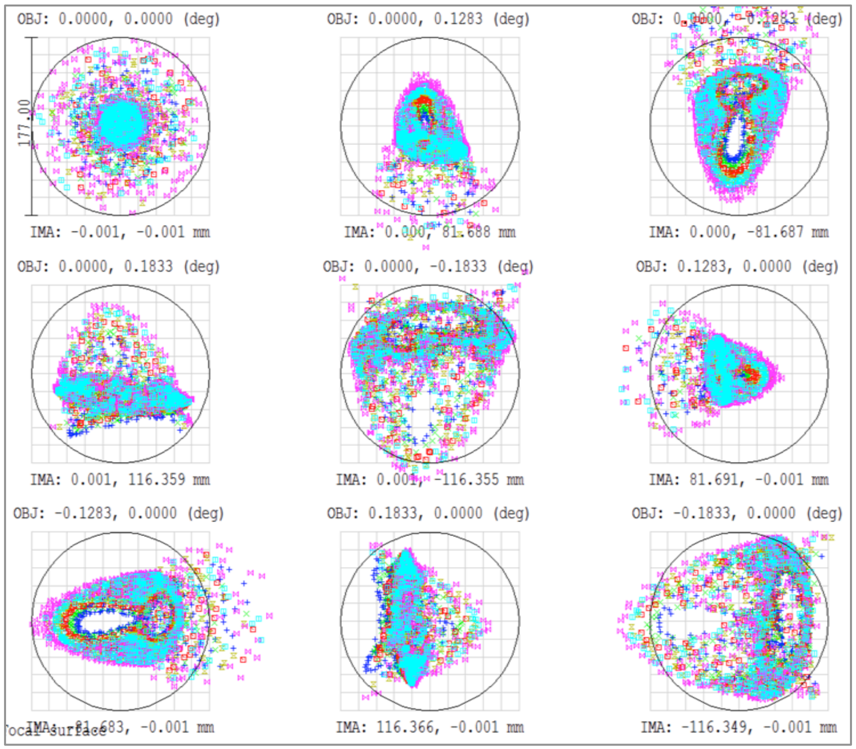
Metric	Requirement	Expectation	PASS/FAIL	Unit
Effective focal length	36450 – 36550	36492 – 36530	PASS	mm
Focal ratio**	3.645 – 3.655	3.505 (max)	**FAIL**	--
Max. marginal ray angle	7.863 – 7.884	8.201 (max)	**FAIL**	degrees
Max. telecentric angle	0.0 – 0.01	0.414 (max) ★	**FAIL**	degrees
Max. distortion	0.0 – 1	< 0.585	PASS	%
Un-vignetted portion of beam	> 80 on-axis > 64 at edge	> 80 on-axis > 64 at edge	PASS	%

** Focal ratio is 0.5 / sin(max. marginal ray angle)

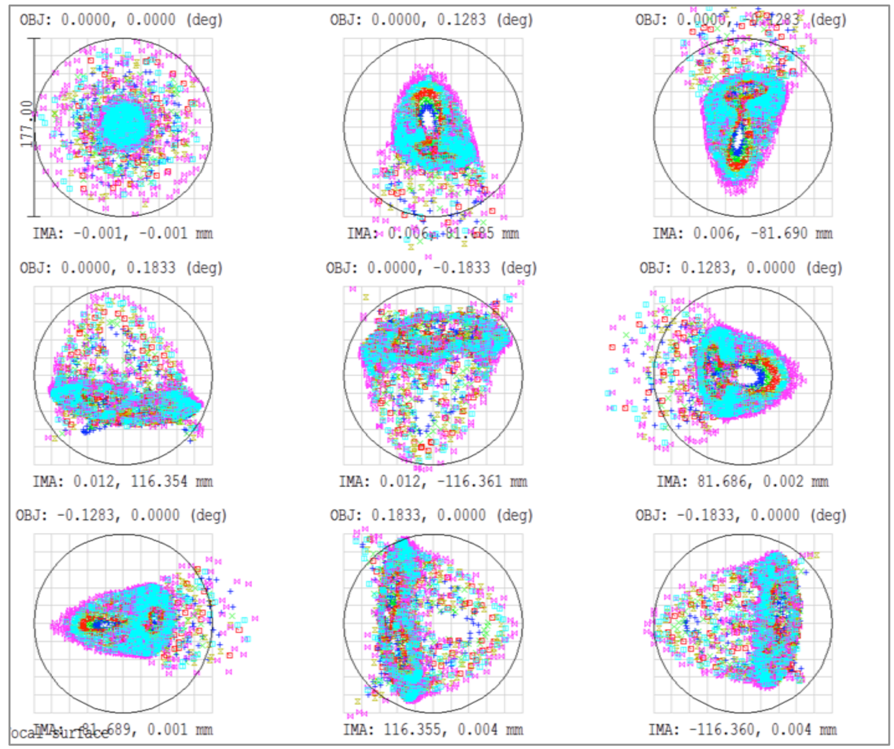
★ Telecentric angle closely corresponds to FPA tilt compensation.

Case #4 – 162 Spot diagram (guiding drift)

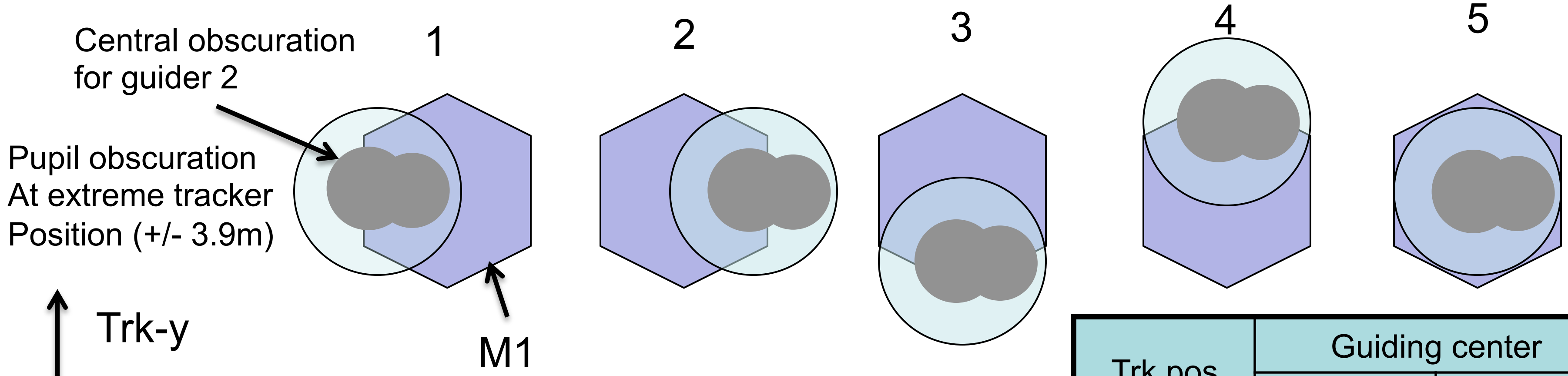
Before

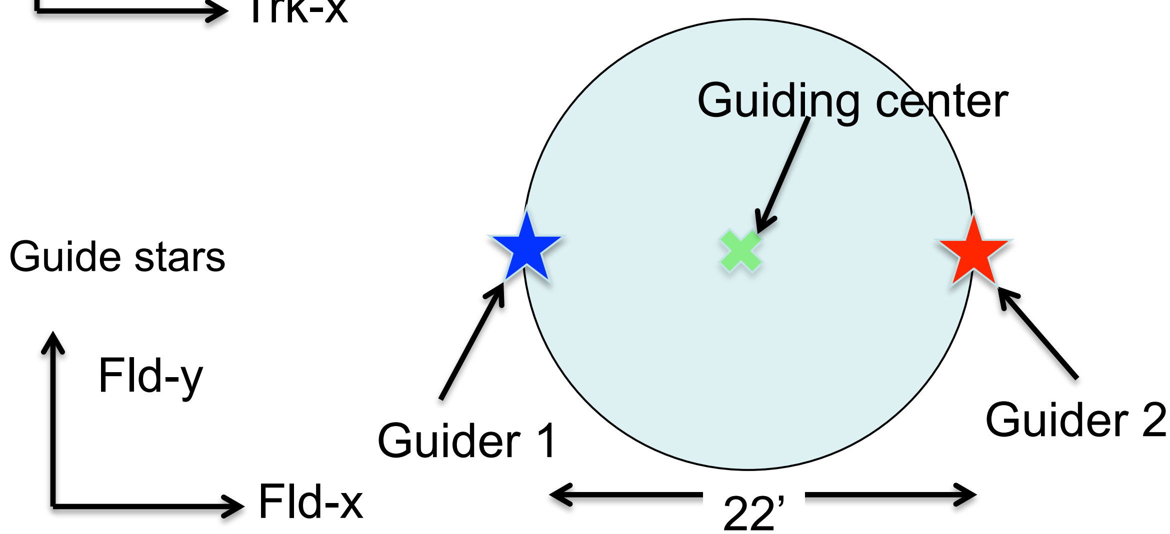


After



Case #4 – 162 Guiding drift (post-adjustment)

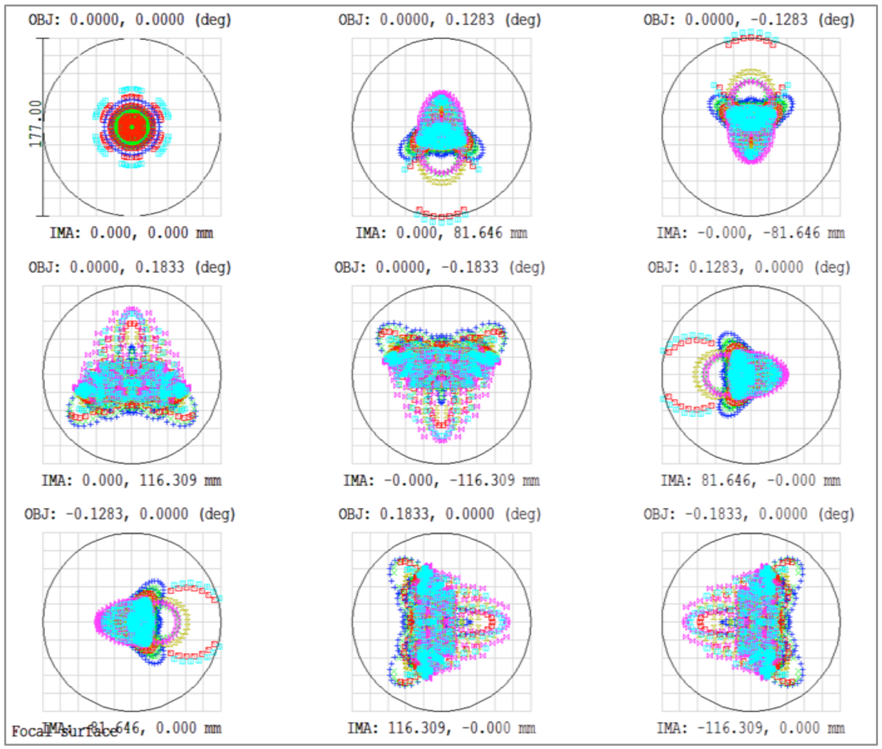




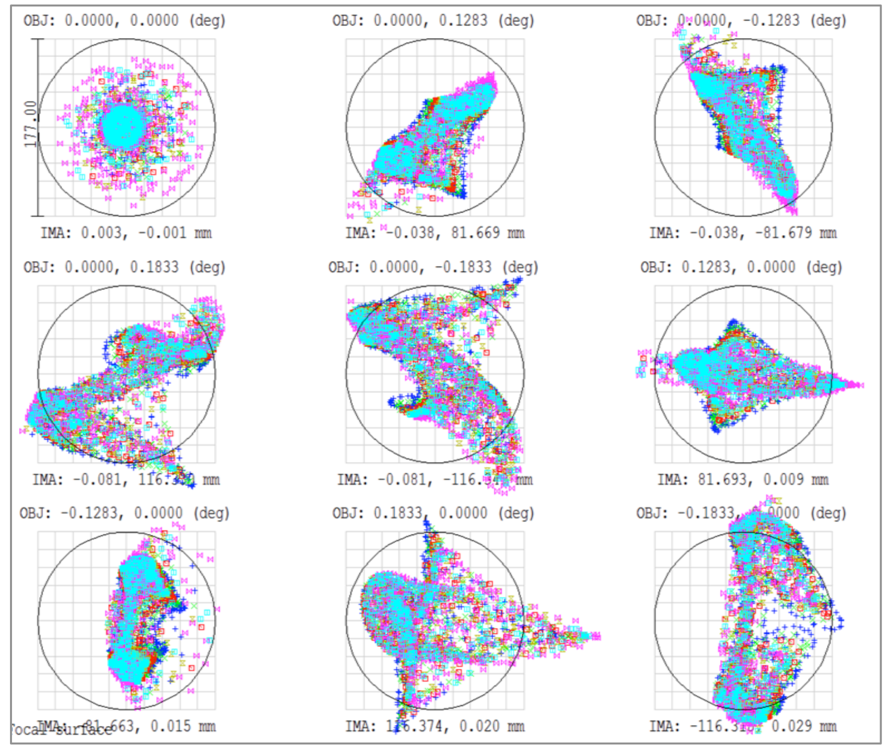
Trk pos	Guiding center	
	X [asec]	Y [asec]
1	-0.087	-0.002
2	0.084	0.000
3	0.001	0.195
4	0.001	-0.193
5	0.000	0.001
Mean	0.000	0.000
Min/max	-0.087~0.084	-0.193~0.195

As-design WFC spot diagram (guiding drift)

As-designed WFC (no errors)



Corrected case 1 as comparison



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As-design WFC spot diagram (guiding drift)

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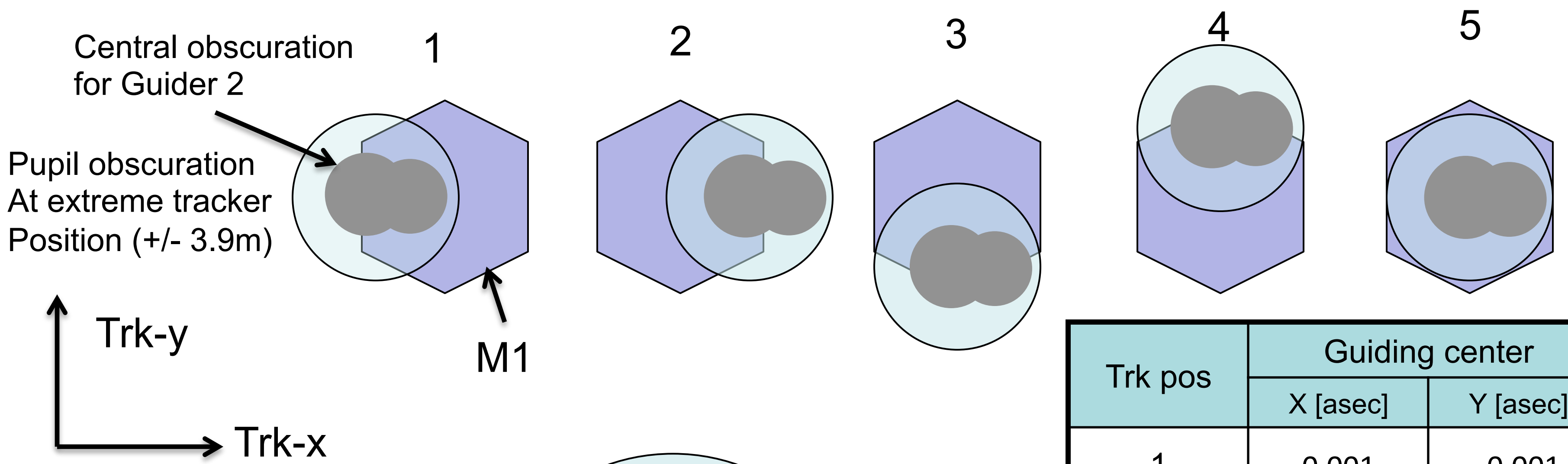

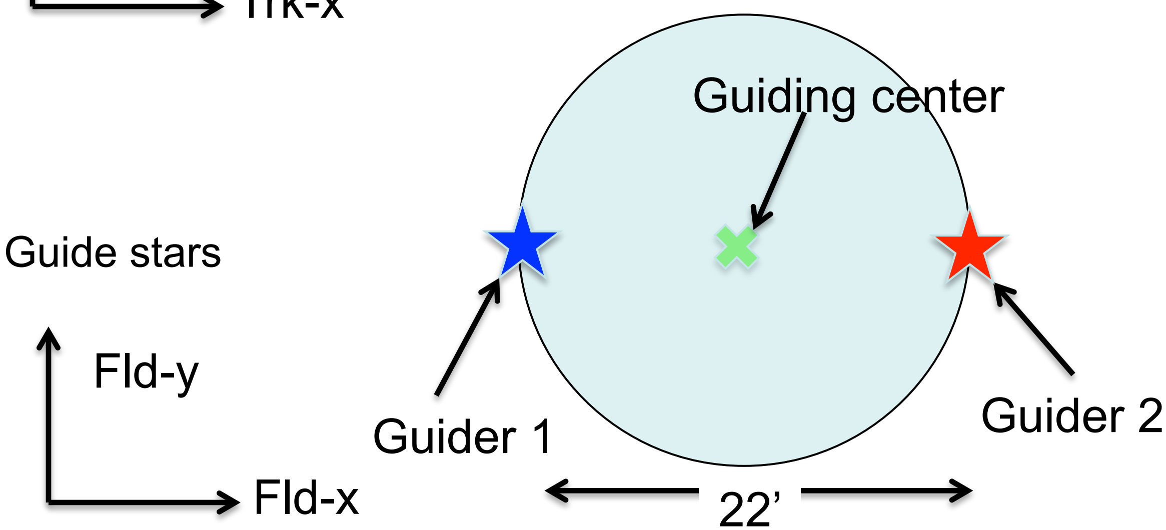

Trk pos	Guiding center	
	X [asec]	Y [asec]
1	0.001	-0.001
2	-0.003	0.000
3	0.001	0.095
4	0.001	-0.094
5	-0.001	0.001
Mean	0.000	0.000
Min/max	-0.003~0.001	-0.094~0.095

Adjustment

Case1-42	X[mm]	Y[mm]	Z[mm]	Rx[degree]	Ry[degree]
WFC	0.545	-0.038	0.066	-0.0027	-0.0013
FPA	0.0	0.0	0.0	0.1752	0.4908

Case4-500	X[mm]	Y[mm]	Z[mm]	Rx[degree]	Ry[degree]
WFC	-0.109	0.067	0.010	-0.0002	-0.0007
FPA	0.0	0.0	0.0	-0.0382	-0.1225

Alternative compensation

- **Should the HET performance fall significant short of the requirement, the following two compensations can be considered.**
  1. M4 adjusted to “optimally compensate” the image quality & telecentric error (based on Lee, Optics Express, 2010)
     - Knowing the exact misalignment state is not necessary.
     - However, the compensation can be made to optimally remove the dominant aberrations or errors.
     - Use the on-sky linear field curvature data
     - Use M4 tilt (& WFC rigid-body motion) as the compensators

       Example case in the next page
       - 5 available measurements: Coma, 2 Astigmatisms, Field Curvature, Star position
       - 6 available adjustment (per axis): M4 decenter/tilt, M5 decenter/tilt, WFC ridgid-body decenter/tilt.
       - We only target the minimum set and FPA will not be tilted.
       - It will take several months minimum and multiple take-down/installation of the WFC → Risk to the hardware.
       - HET will not be operable during this.
  2. Or the FPA IFU/fiber feed seats can be re-machined to “re-align” the fibers to the incoming beam angle to minimize the telecentric error.
     - Additional time/money for remaking the fiber feed mounts for all instruments.
     - HET can be operated with the existing fiber feed mount and reduced throughput while the new fiber feed mount is fabricated / tested.
     - This will require additional metrology to properly identify the incoming beam angle from the WFC.

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On-sky based compensation example (case 1 – 496)

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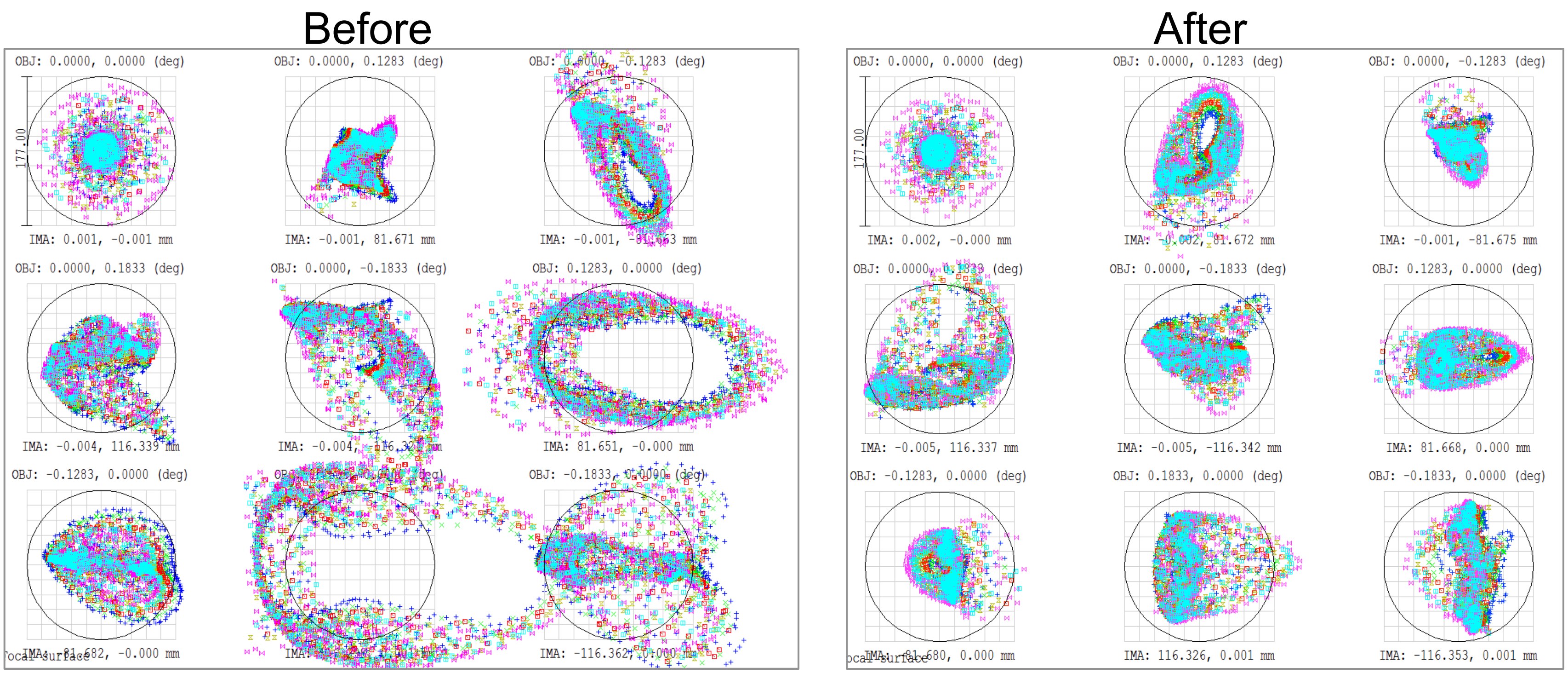
- **Strategy**
  - Adjusting M4 tilt to remove linear field curvature
  - Then adjust WFC rigid-body decenter/coma to null out Coma and image position shift



Case1-496	X[mm]	Y[mm]	Z[mm]	Rx[degree]	Ry[degree]
WFC	-0.187	0.092	0.0	0.0035	0.0074
M4	0.0	0.0	0.0	-0.0106	-0.0325

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On-sky based compensation example (case 1 – 496)

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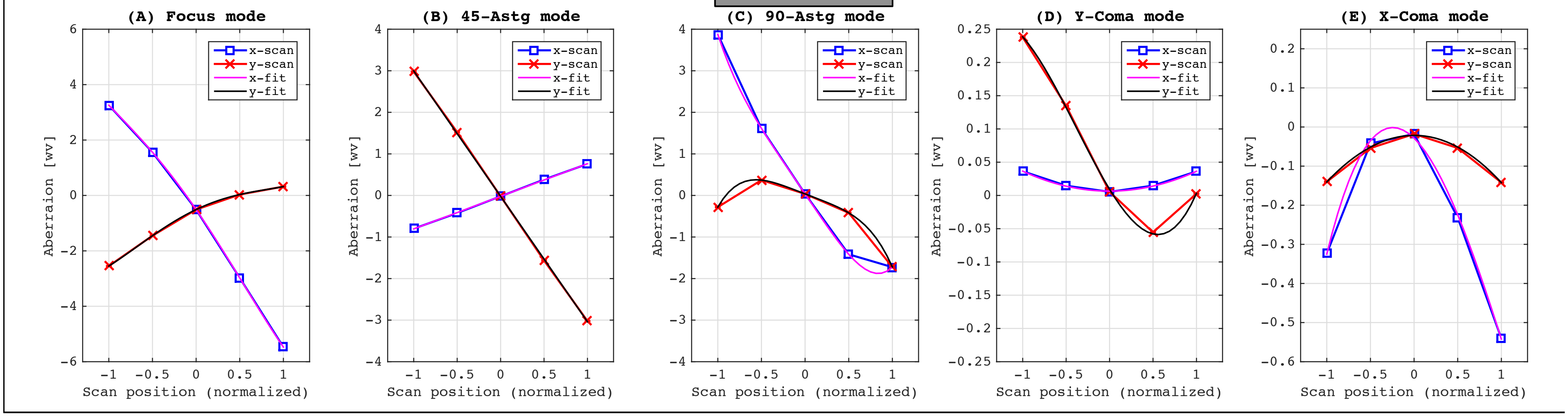
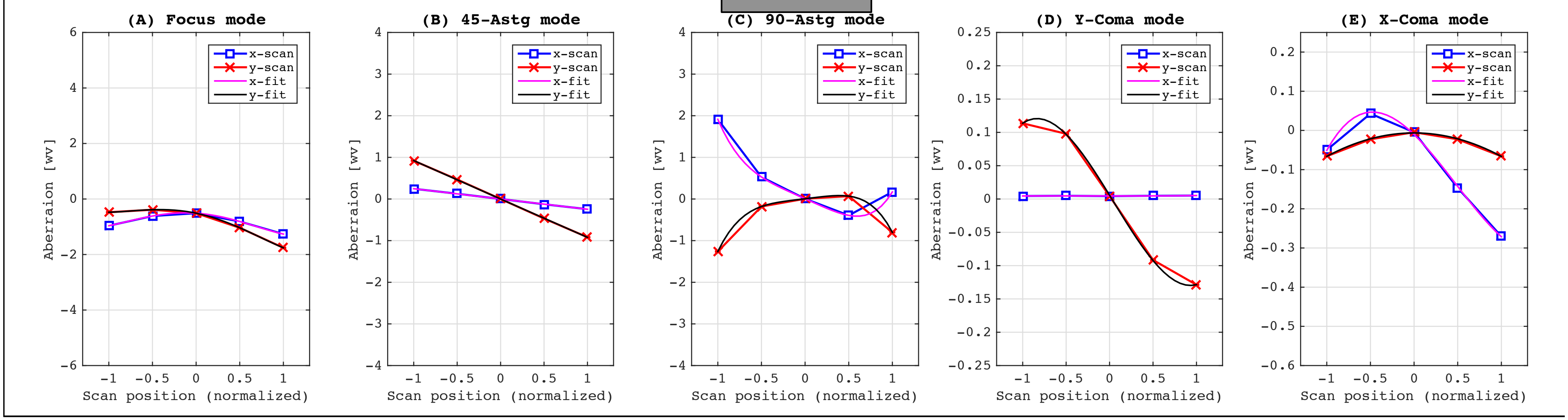
- **Field Aberrations**

BEFORE



AFTER



On-sky based compensation example (case 1 – 496)

Metric	Requirement	Expectation	PASS/FAIL	Unit
Effective focal length	36450 – 36550	36514	**PASS**	mm
Focal ratio**	3.645 – 3.655	3.687	**ACCEPTABLE**	--
Max. marginal ray angle	7.863 – 7.884	7.786 (max)	**ACCEPTABLE**	degrees
Max. telecentric angle	0.0 – 0.01	0.0043 (max)	**PASS**	degrees
Max. distortion	0.0 – 1	< 0.573	**PASS**	%
Un-vignetted portion of beam	> 80 on-axis > 64 at edge	> 80 on-axis > 64 at edge	**PASS**	%

** Focal ratio is 0.5 / sin(max. marginal ray angle)

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Summary

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- **Alignment between DWFS and FPA is the most critical**
  - Based on our best current knowledge, we think that we should have sufficiently accurate measurement & motion control and thus be able to compensate the image quality even in the current worst, Case 1.

- **Impact of FPA tilt compensation on throughput for fiber-fed instruments**
  - Potentially large telecentric angle into IFUs / fiber feeds of the HET instruments, that violates the specification.
  - This results in the Focal Ratio Degradation (FRD) at the output end of the fibers, thus loss of photons on the order of 15 percent.
  - Trade-off between the image quality and the telecentric angle.

- **Impact of extended & asymmetric PSF shape on HET guiding**
  - Note that FPA tilt only corrects linear field curvature. Astigmatism remains uncorrected and results in elongated / asymmetric PSF.
  - Case studies:
    - Two opposite guiders along the tracker X-axis.
    - Extreme tracker obscuration along the tracker axes.
    - Max. ±0.125'' centroid drift across extreme tracker positions
      - When tracker obscuration is at max in the orthogonal direction to the axis formed by two opposite guiders.

- **Alternative compensation is possible with risks**
  - Using the minimum number of mirror motions to reduce specific aberration(s).
  - Refabricating FPA fiber feed mount plate.

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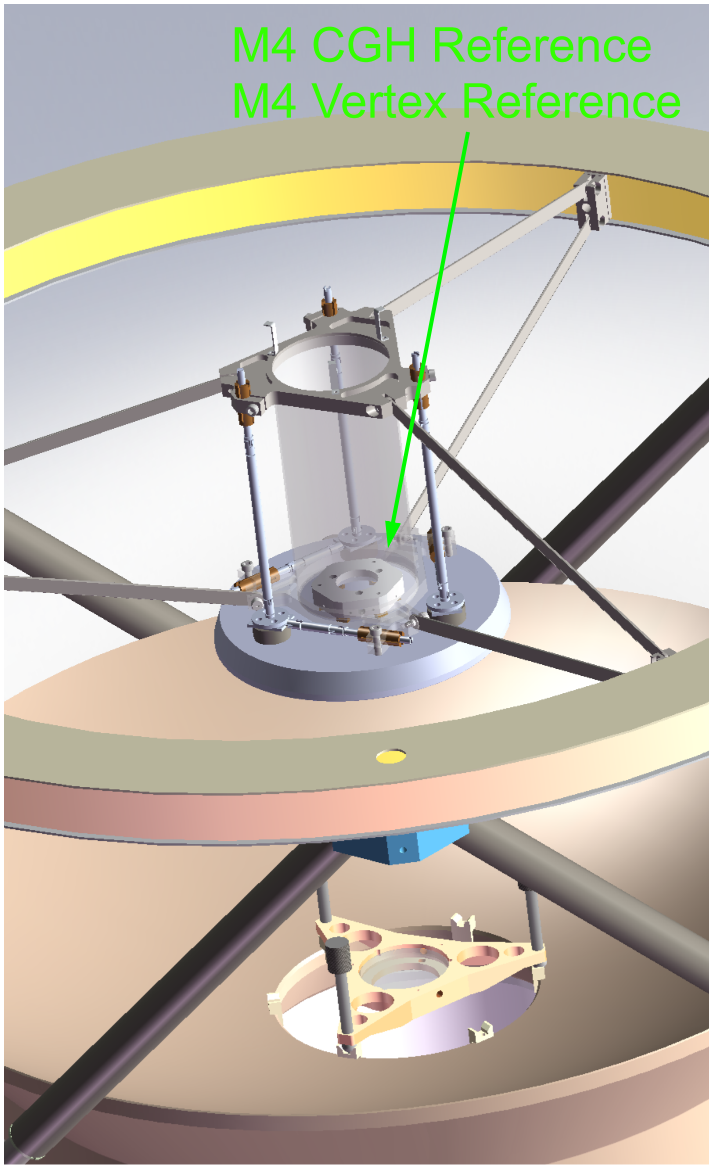
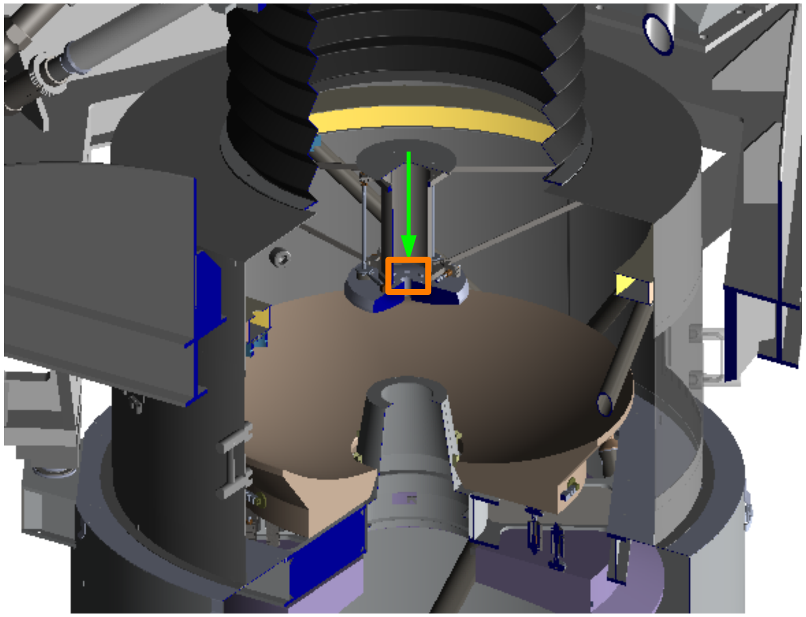
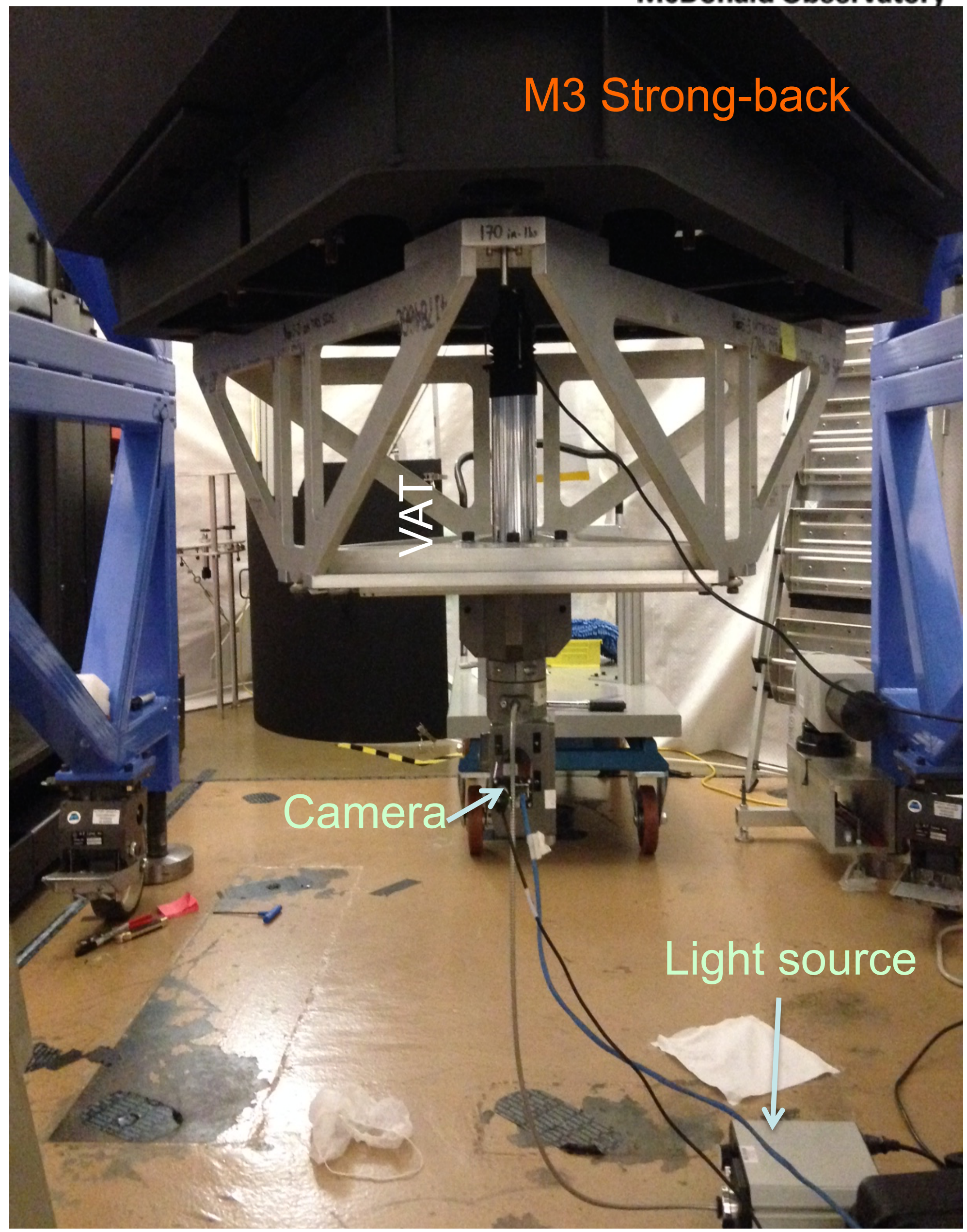
Appendix

Alignment Reference



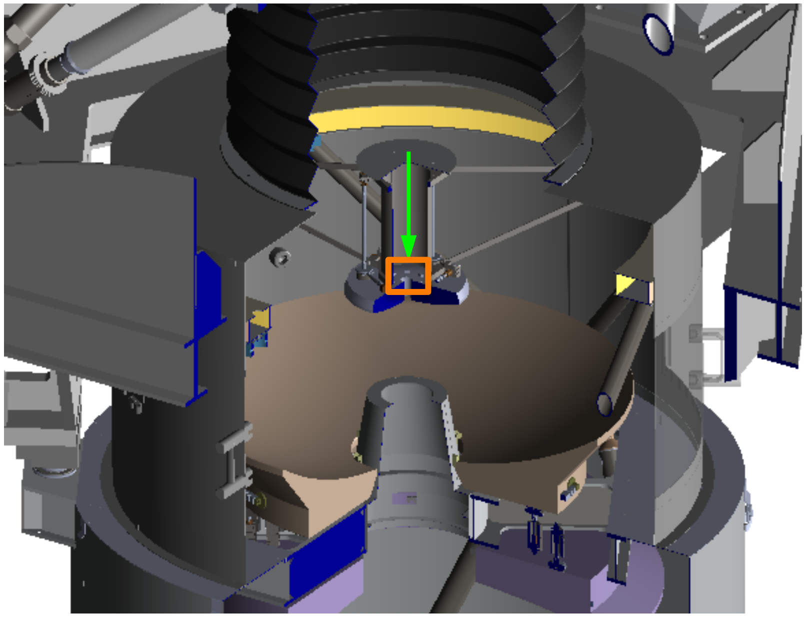
Video Alignment Telescope



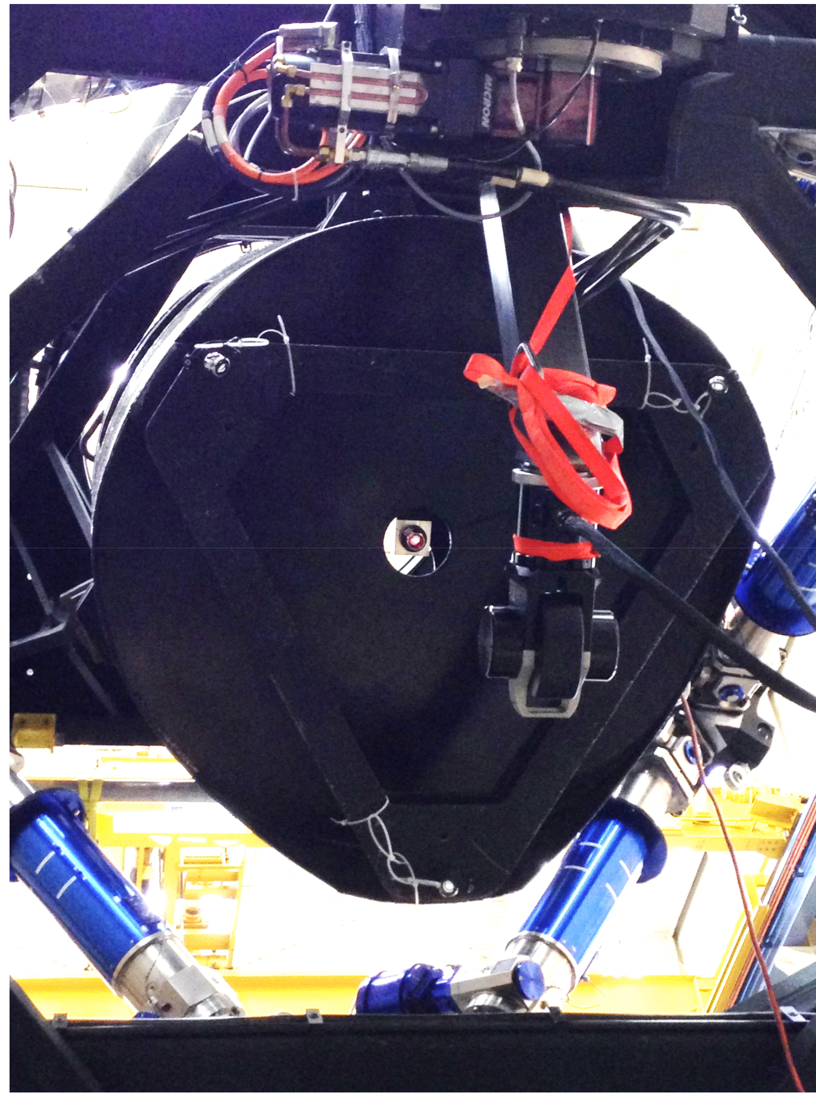


- **VAT aligned to M4 CGH Reference to the following accuracy estimate (based on previous tests)**
  - Centration: ±0.01mm at 3σ
  - Tilt: ±5arcseconds at 3σ

API Laser Tracker



Laser tracker mounted on Tracker Carriage



- **LT to M4 Vertex Reference**
  - Focus: ±0.025mm at 3σ worst case.

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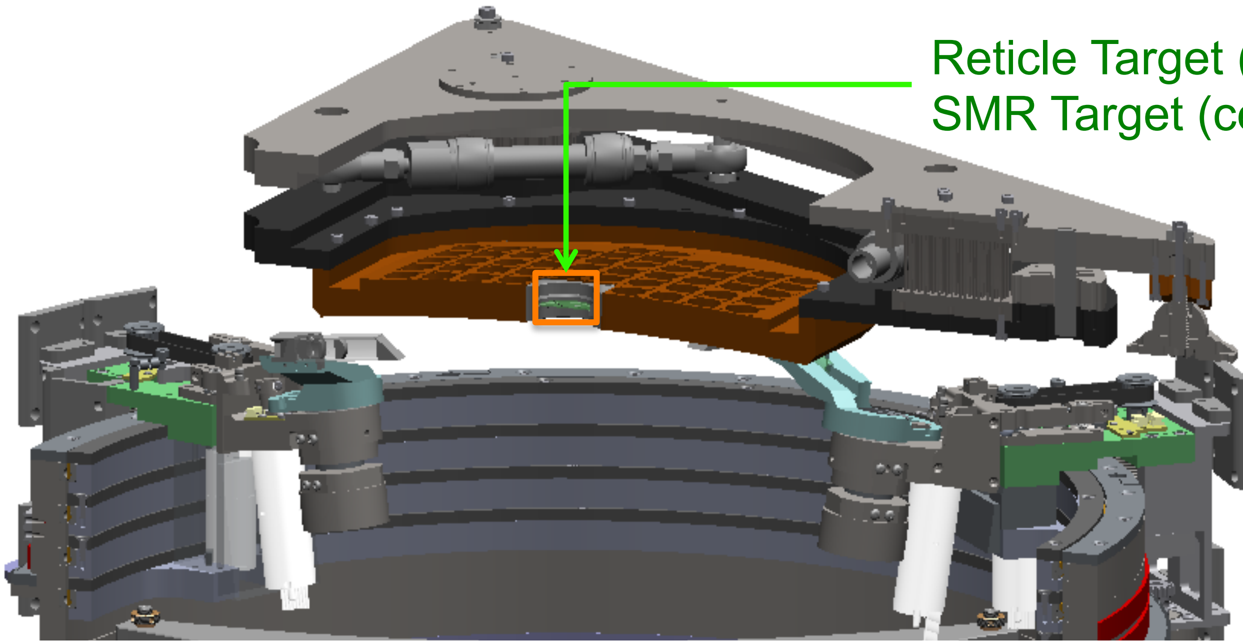
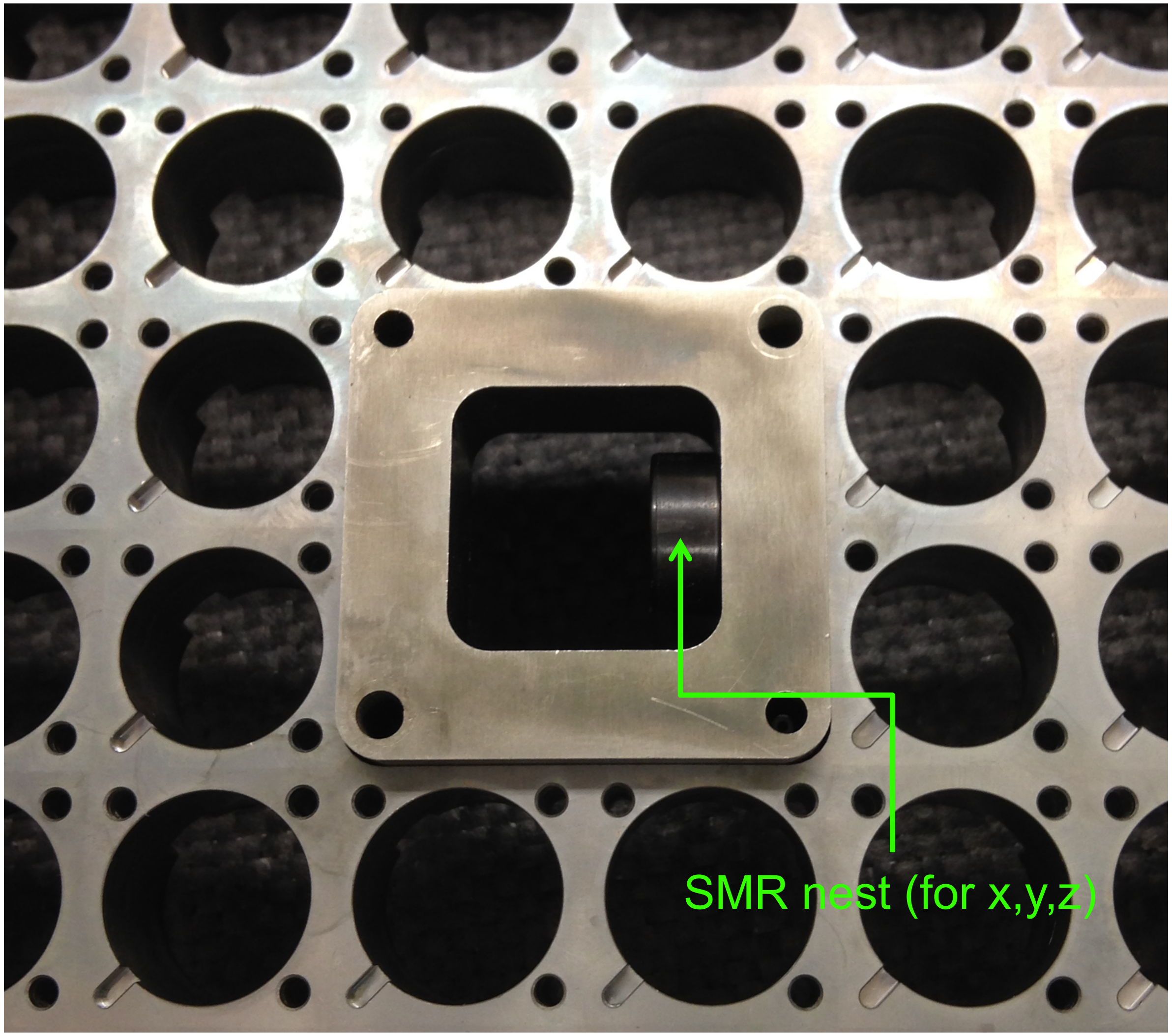
FPA Targets



- **FPA targets installed to the focal surface**
  - Centration accuracy:±0.025mm at 3σ (SMR)
  - Tilt accuracy: ±10arcseconds at 3σ (Reticle)
  - Focus accuracy: ±0.015mm(?) at 3σ (SMR)
- **Using VAT (wrt M4 CGH reference), align FPA Target in tilt**
  - Tilt measurement accuracy: ±5arcseconds at 3σ
- **Using Laser Tracker (wrt M4 Vertex reference), align FPA target in focus**
  - Centration measurement accuracy: ±0.05mm at 3σ
  - Focus measurement accuracy: ±0.05mm(?) at 3σ

FPA Target



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FPA Reference

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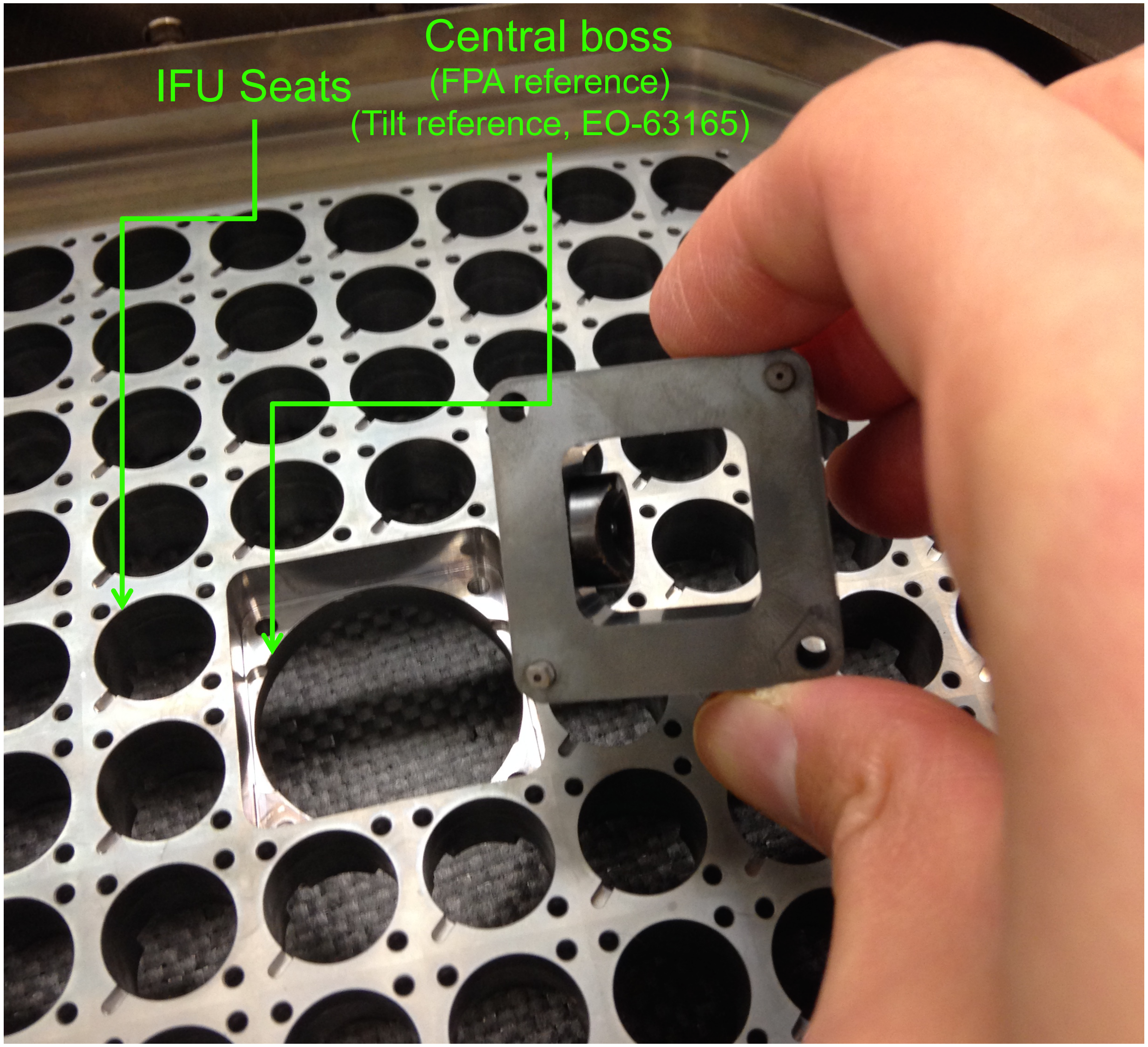
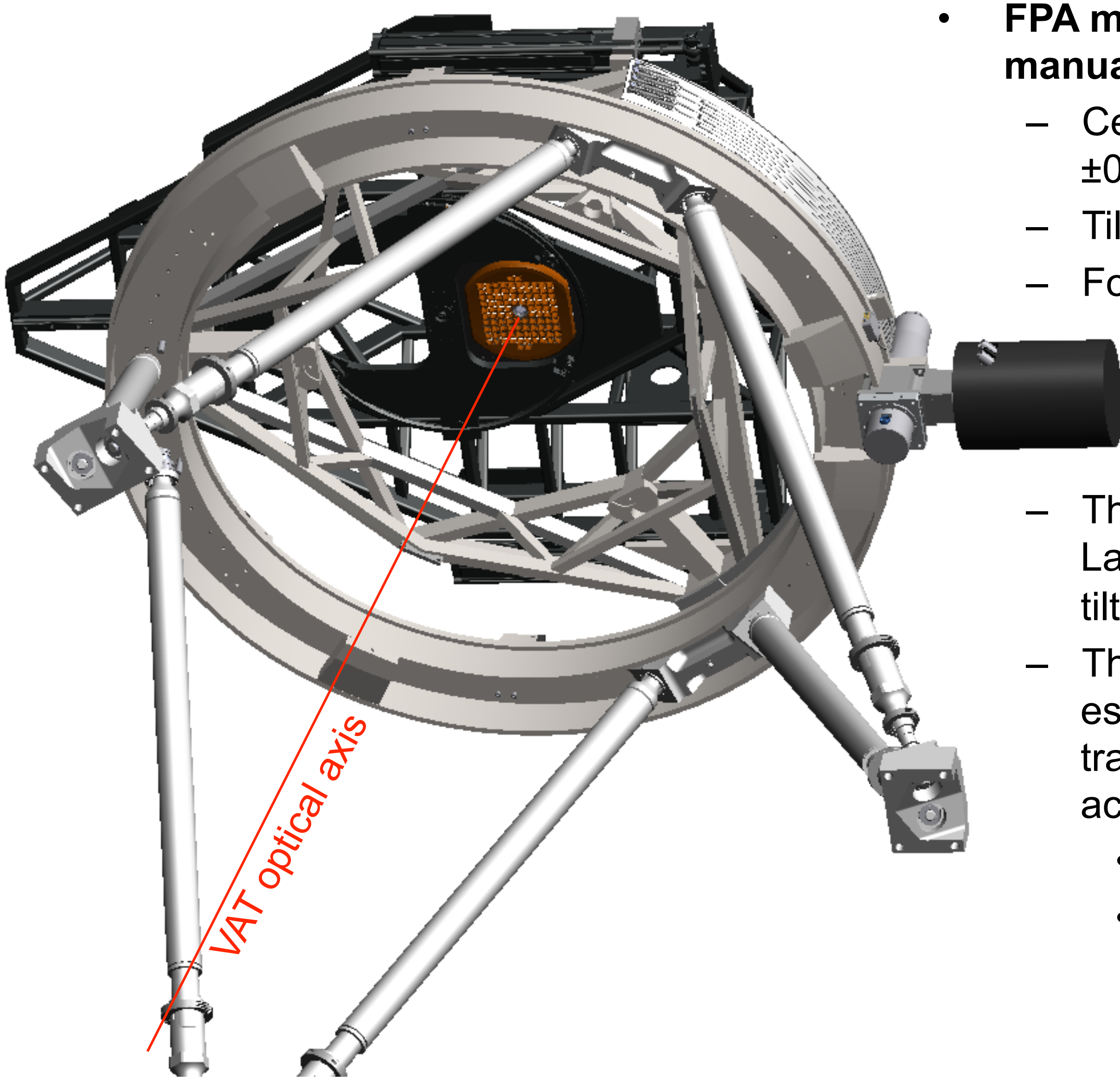


- Central boss is the reference surface.
- This is where the tilt reference mirror will be directly mounted.
- Each IFU seat is referenced to the central boss. → When each IFU is mounted, their input face is tangent to the focal surface.
- Seats registered to the central boss to the accuracy of ±0.01mm

FPA Target alignment control



- **FPA mounted to the Rho stage on a manual hexapod**
  - Centration control resolution: ±0.007mm
  - Tilt control accuracy: ±1arcsec
  - Focus control accuracy: ±0.003mm
  - The motion control is guided by Laser tracker in x,y,z and VAT in tip/tilt feedback
  - Therefore, the control accuracy is essentially equivalent to the laser tracker and VAT measurement accuracy
    - ±0.05mm in x,y,z.
    - ±5arcsec in tip/tilt

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DWFS characteristics

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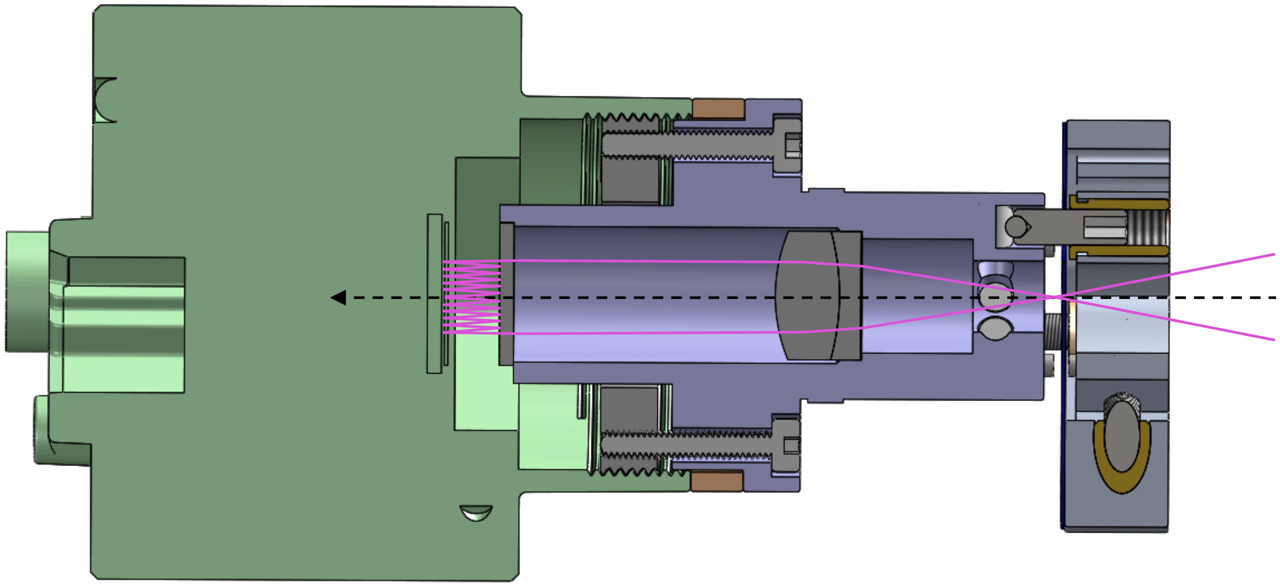
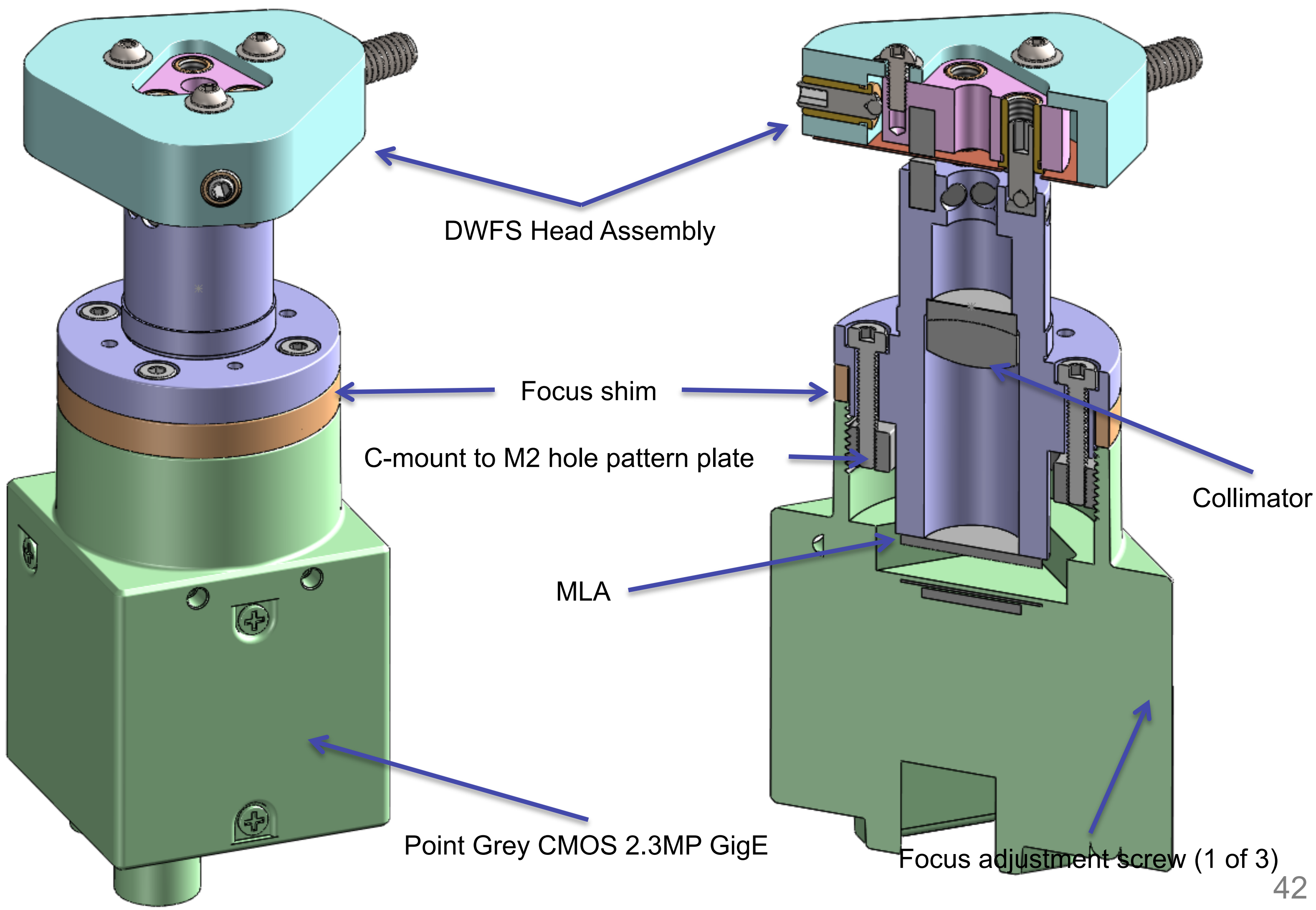
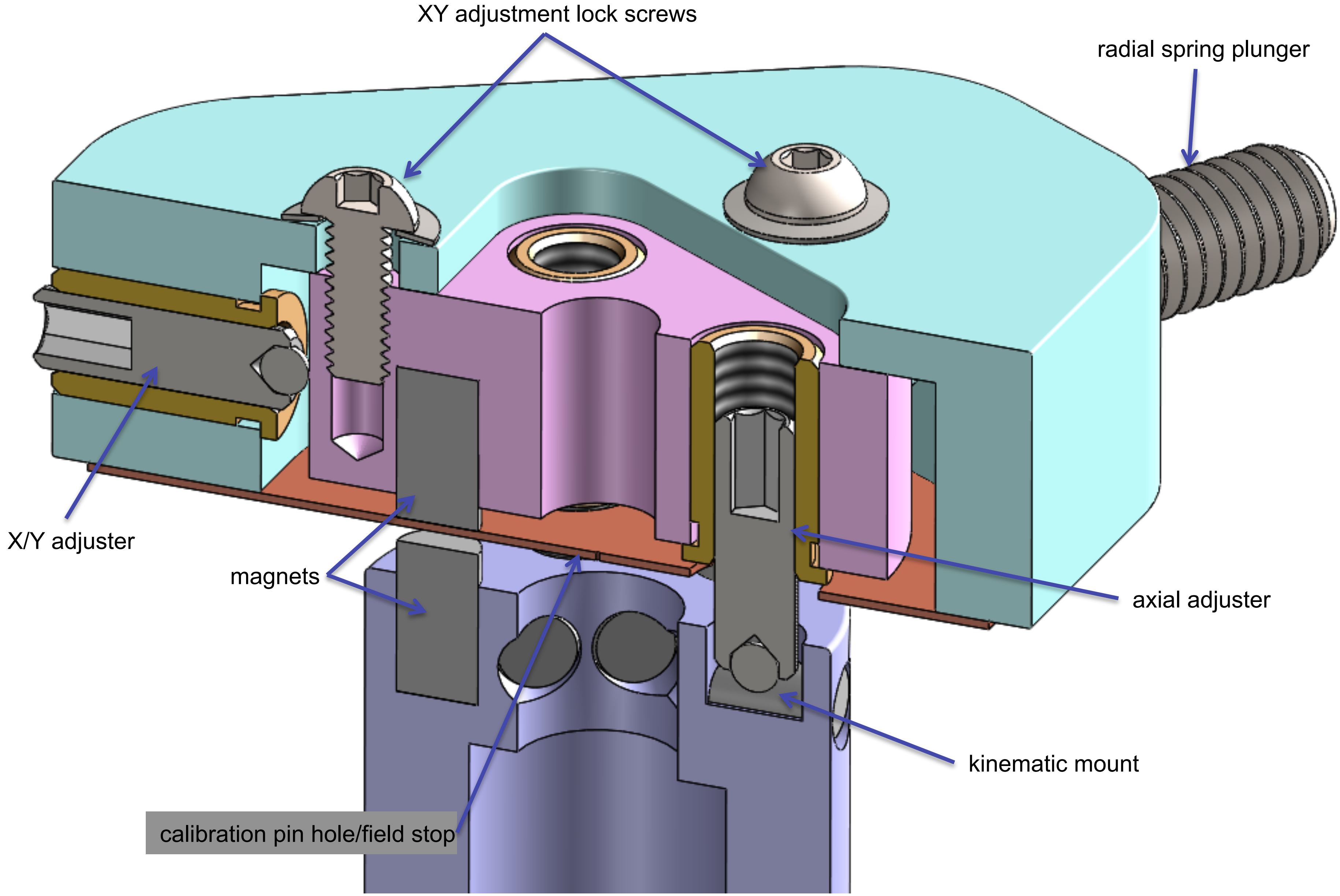


- **DWFS parameters (Hartmann-Shack Sensor)**
  - Detector: 5.86 microns pixel, CMOS, 82% QE, 41fps, Global shutter, 1900x1200
  - Pixel scale: 0.14 arcsec.
  - Field of View: 6 arcsec diameter.
  - MLA pitch: 0.25mm diameter (Hexagonal shape)
  - Sub-aperture density across HET pupil: 19 (Hexagonal grid) (798px diameter)
  - Maximum mode to be sensed: Up to Zernike #56 (radial order 10).
  - Calibrated accuracy: better than 0.01wv per mode at 3σ
  - Measurement repeatability: better than 0.05wv per mode at 3σ
    - Worst case: adding 0.05wv linear field curvature.

DWFS Opto-mechanical layout



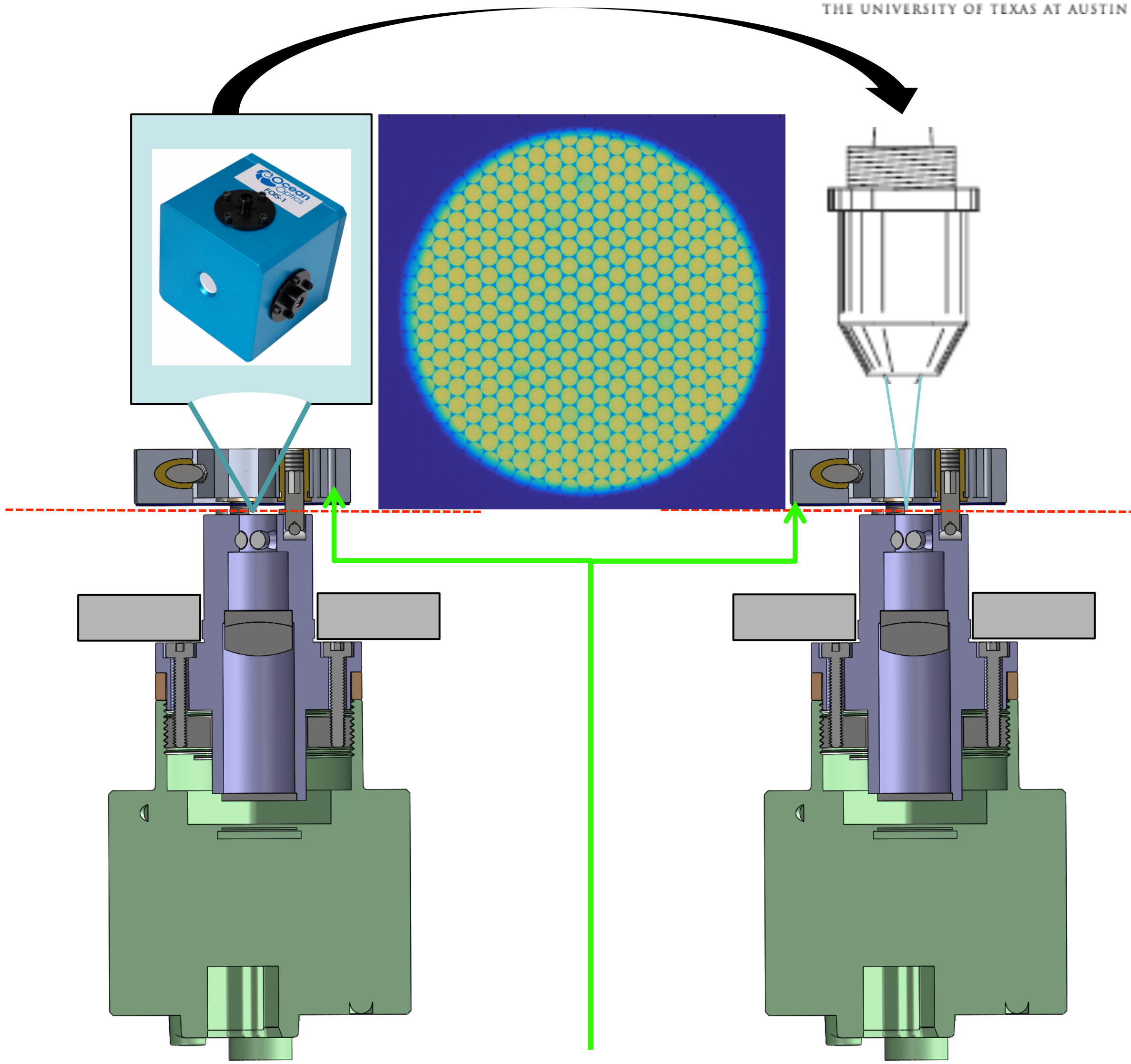
DWFS Head Assembly



DWFS Lab registration
(Field Stop Registration to Detector)

- Define DWFS field stop in X/Y/Z for calibration (Field stop is a 1.05mm dia. pinhole).

1. Set field stop in Z to minimize separation of field stop images (thru MLA) on the detector.
2. Set field stop in X/Y to center the field stop images (thru MLA) on the detector.
3. Establish MLA geometry projected on the detector using the field stop images.
4. Measure field stop position under the microscope and set this as the reference position.



Field stop assembly

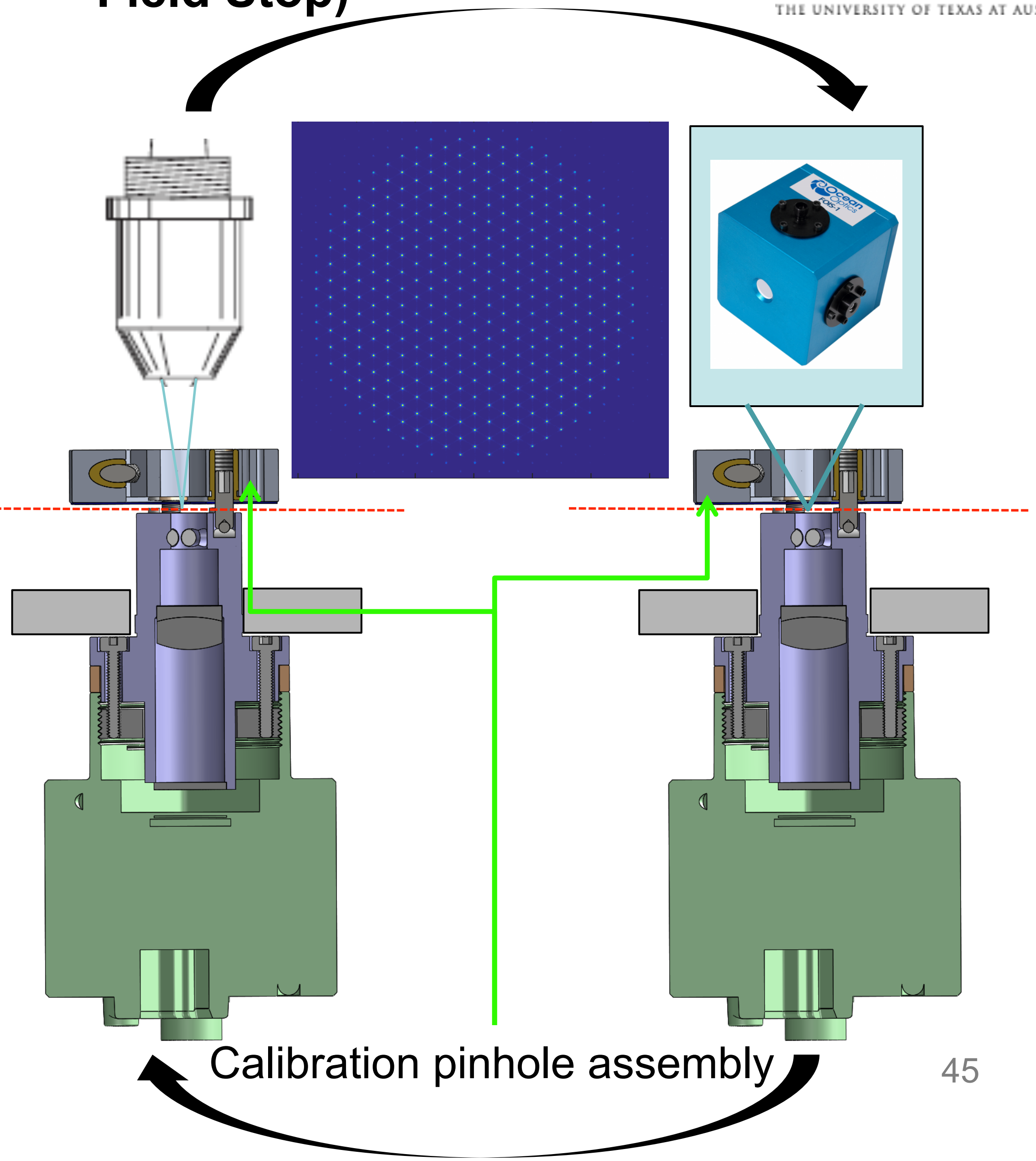
DWFS Lab Registration
(Calibration Pinhole Registration to Field Stop)

1. Position the calibration pinhole to the center of the field stop in X/Y/Z (Calibration pinhole is 0.05mm dia.).

2. Further refine X/Y/Z by minimizing the spot centroid deviation wrt MLA geometry constructed by the field stop image.

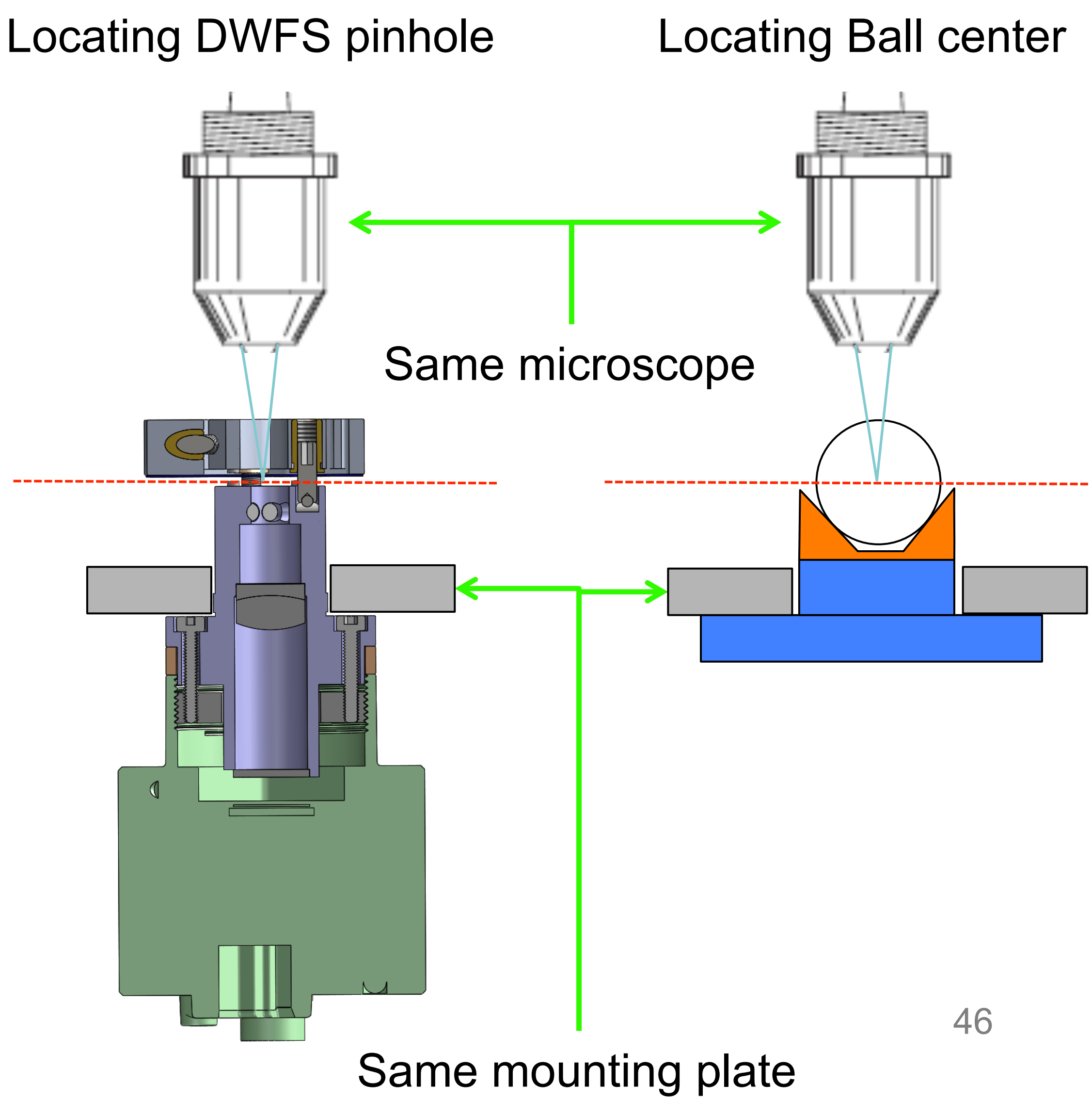
3. Locate the final X/Y/Z position of the calibration pinhole.

4. This is the position at which the DWFS internal optics aberration are to be calibrated in-situ.



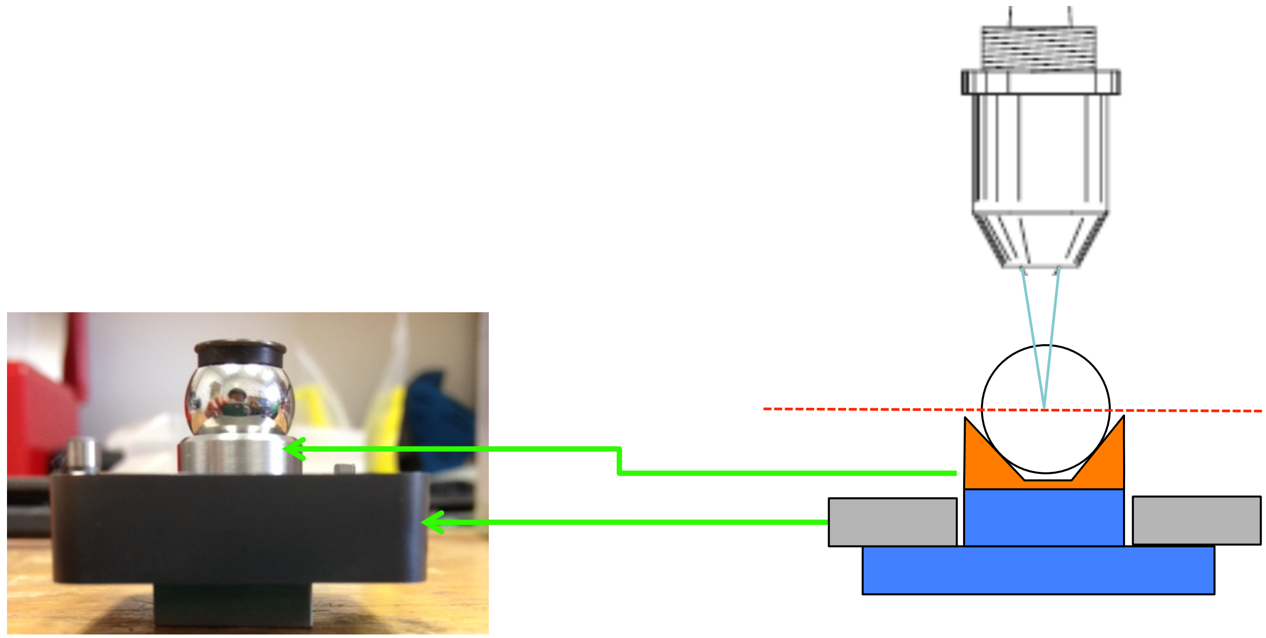
Calibration pinhole registration fixture

- Register the DWFS calibration pinhole center to the IFU seat.
- Use separate fixture where a ball center is accurately registered to the mounting seat (+/-0.025mm).
- Under a point source micro scope, locate the ball center (+/-0.005mm)
- Mount each DWFS to the same seat and locate its field stop center relative to the center of the ball using the same point source microscope. (+/- 0.005mm)
- Repeat these steps multiple times to determine the uncertainty bound of the measurement. (+/- 0.01 mm)



Calibration pinhole registration fixture

Locating Ball center



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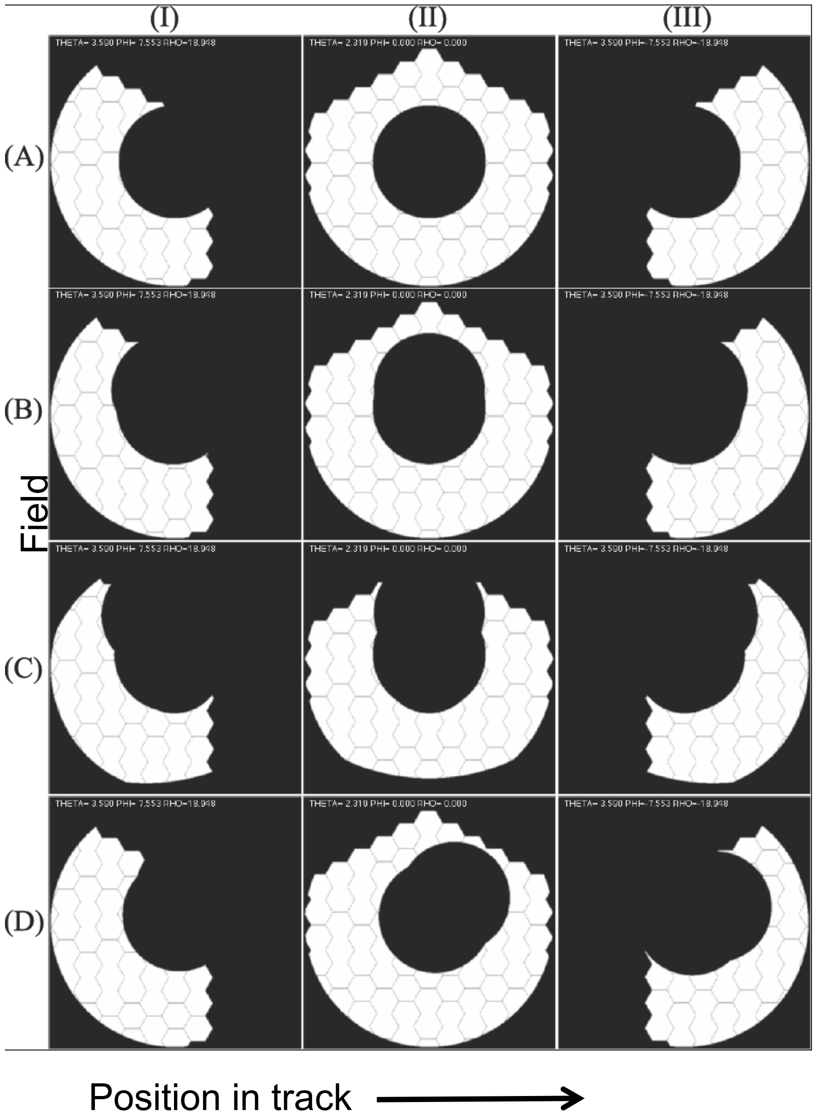
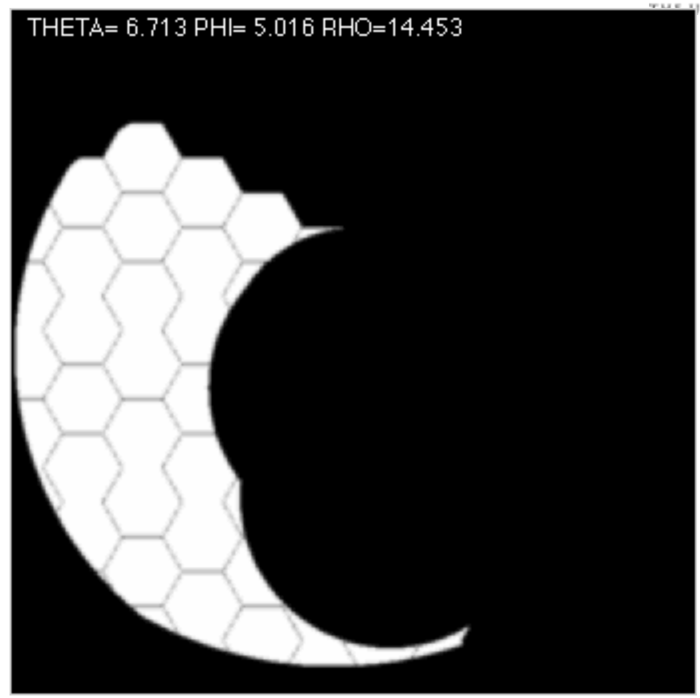
Pupil illumination





- As HET tracks, the pupil illumination changes due to the WFC position relative to the primary
- M1 illumination combines with the WFC fixed obstruction and vignetting to create a complex, time variable pupil illumination as a function of field position
- The convolution of the illumination with wavefront creates a time-variable point spread function in the outer field which can result in centroid shifts for the guiders
- Misalignment of WFC makes this effect worse.