Richey-Chrétien Collimation Made Easy

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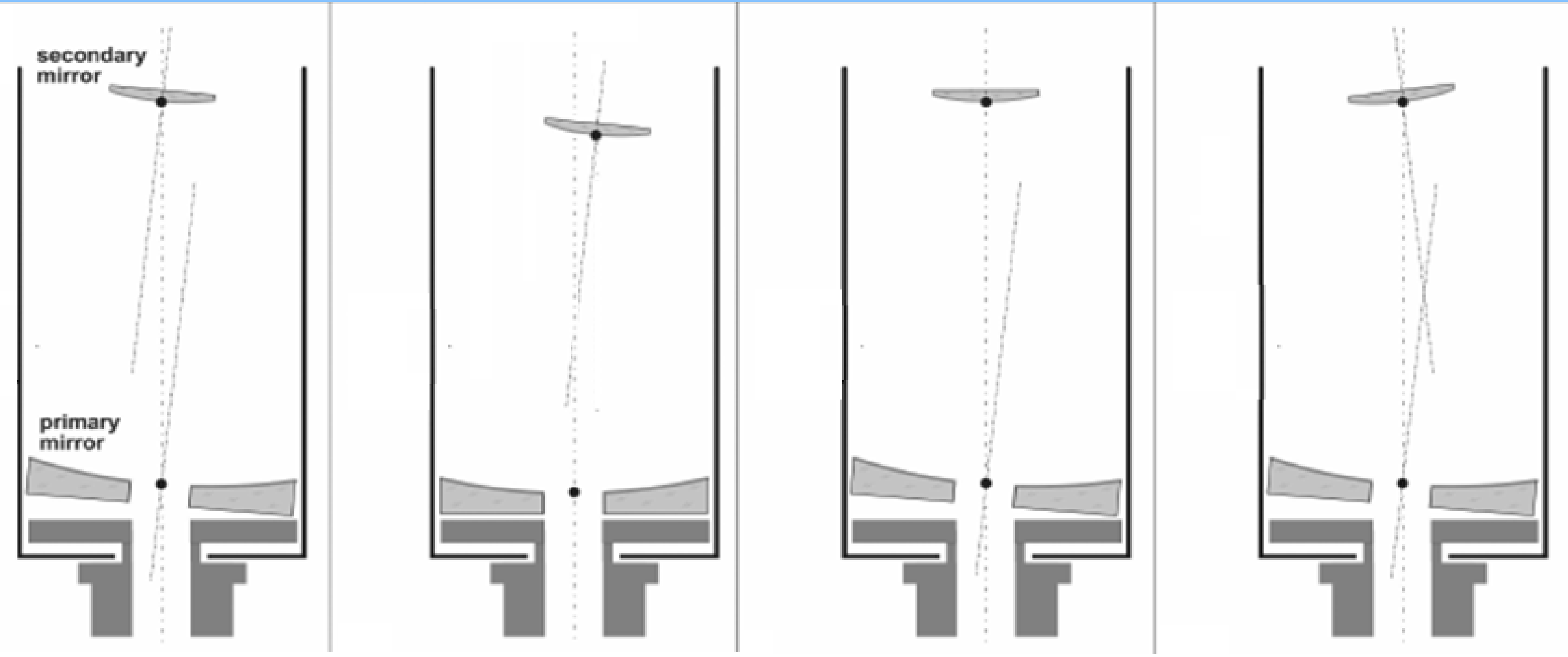
Dr. Gaston Baudat

Innovations Foresight, LLC

Adjunct Research Professor at
the Wyant College of Optical Sciences
University of Arizona, Tucson USA

Goal

Ensure that both mirror optical axes (A1 & A2) are superimposed, creating congruence. Ensure the correct spacing between mirrors.



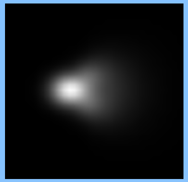
Out of alignment scope: Various misalignment scenarios (reflector)

Richey-Chrétien (RCT) Optics

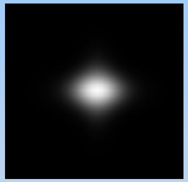
DAG 4m RCT (Turkey)

Key aspects

- RCTs are coma-free across the entire field at the expense of off-axis astigmatism & field curvature. They trade coma for astigmatism.



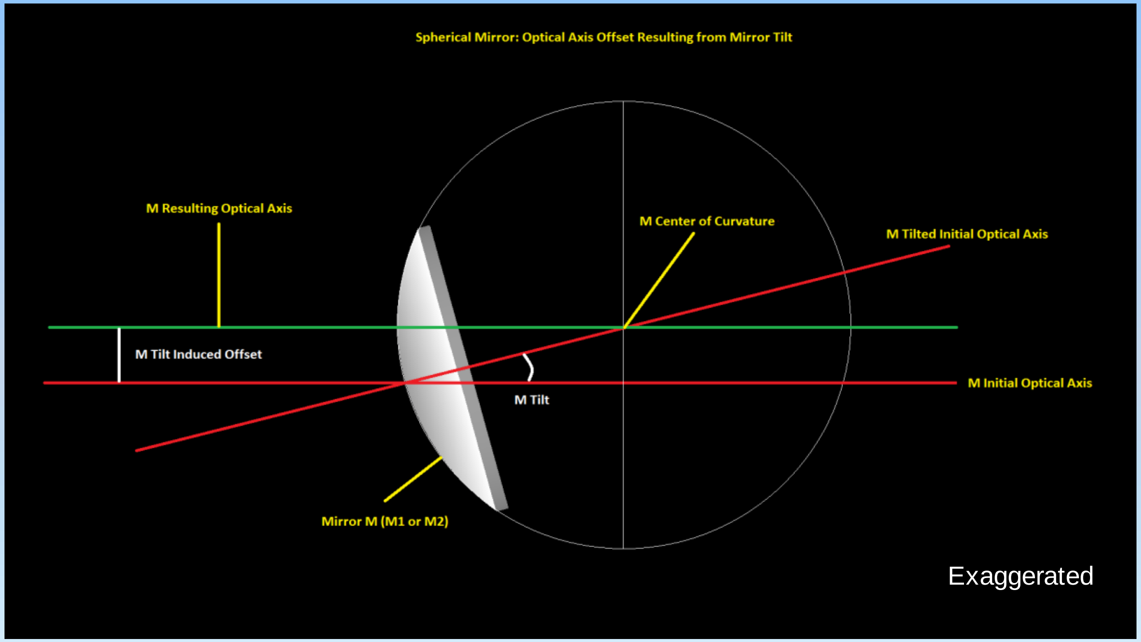
- Astigmatism is a more "friendly" aberration than coma. Both astigmatism & field curvature can be dealt with using a field lens (corrector).



- Corrected RCTs are well-suited for wide-field imaging and photometry.
- Both mirrors (M1 & M2) are hyperbolics (and hard to make and collimate)

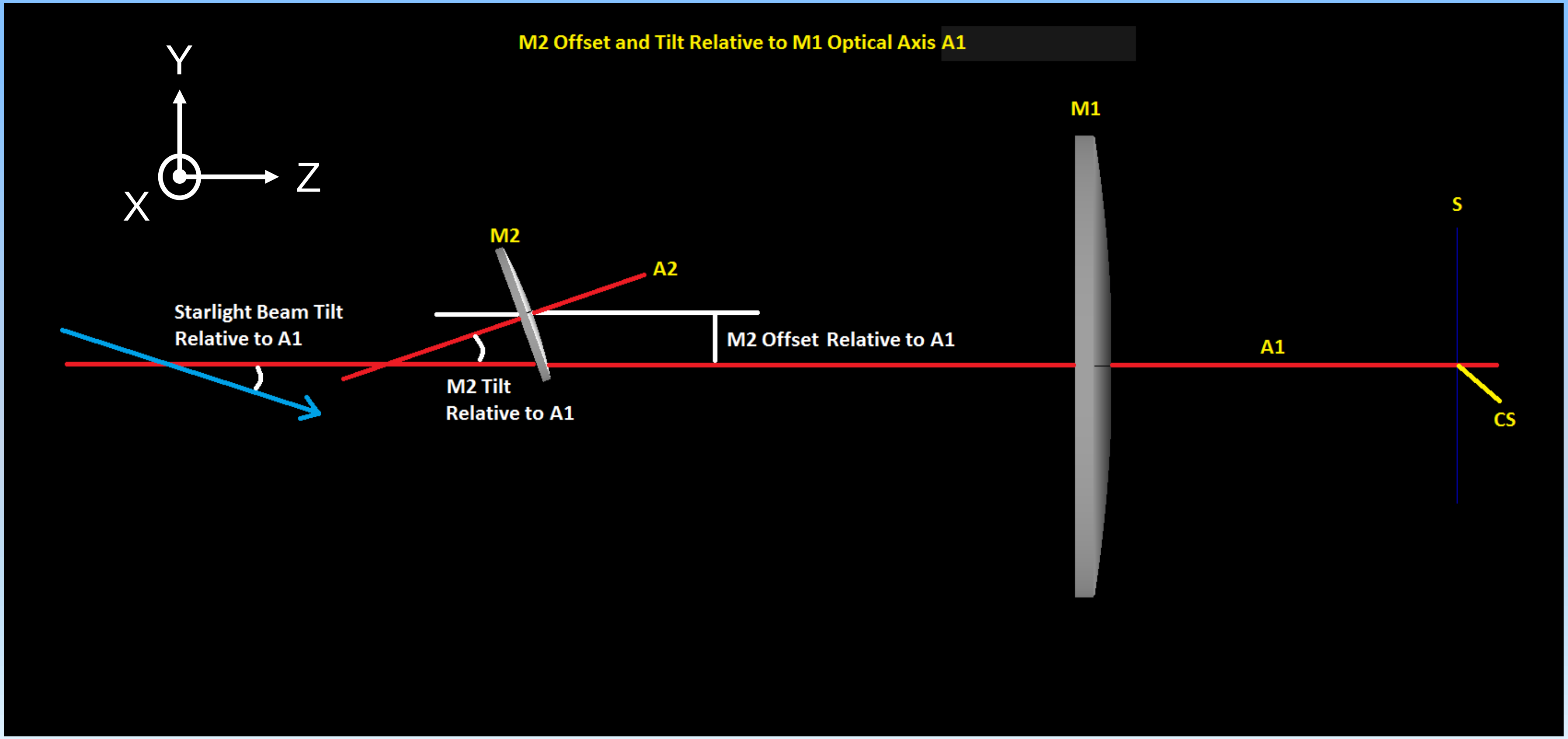
Congruence & spherical mirror

Any line passing through the center of curvature of a spherical mirror is an optical axis, tilts and offsets are alike reducing degrees of freedom to just **2**. Tilt control suffices for collimation. RCT feature hyperbolic mirrors with **only one** optical axis, resulting in **4** degrees of freedom (mirror spacing omitted).



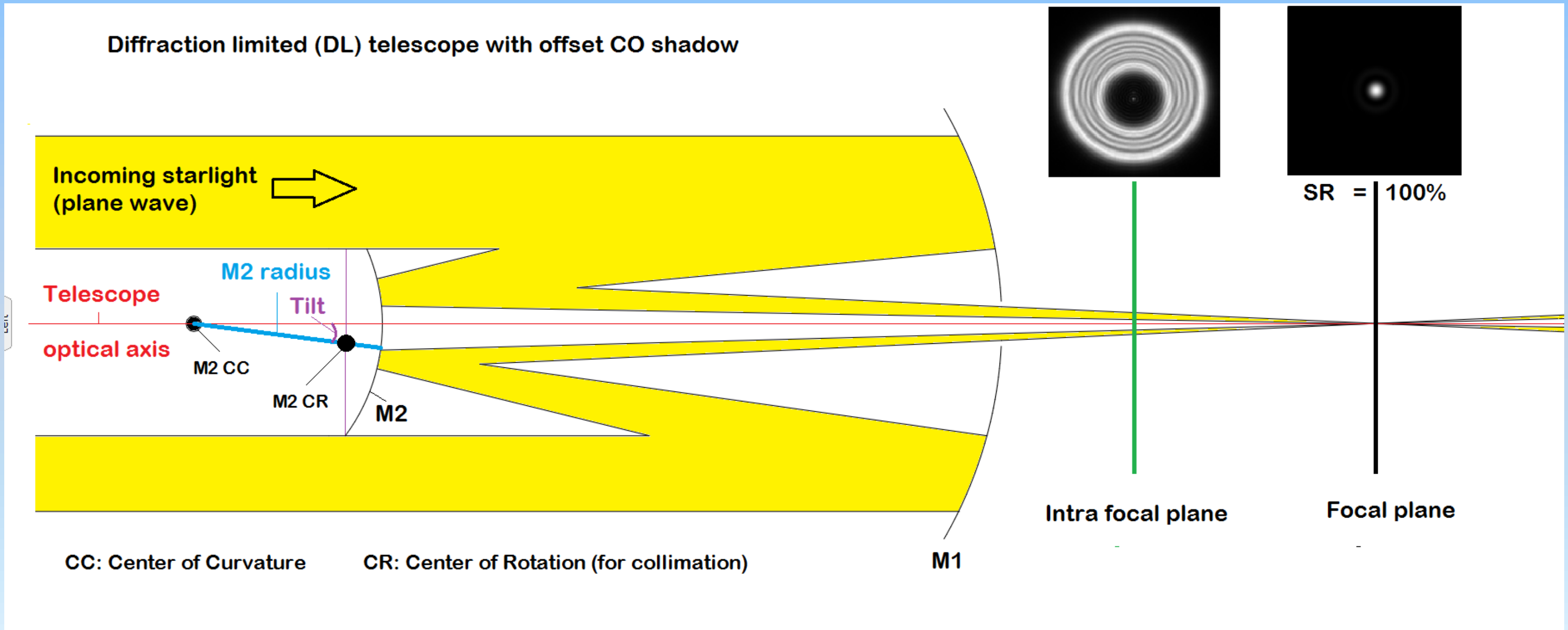
RCT congruence understand the challenge

In a mis-aligned RCT the M2 optical axis A2 exhibits, relative to M1 optical axis A1, offsets & tilts for a total of 4 degrees of freedom. Spacing omitted (Z).

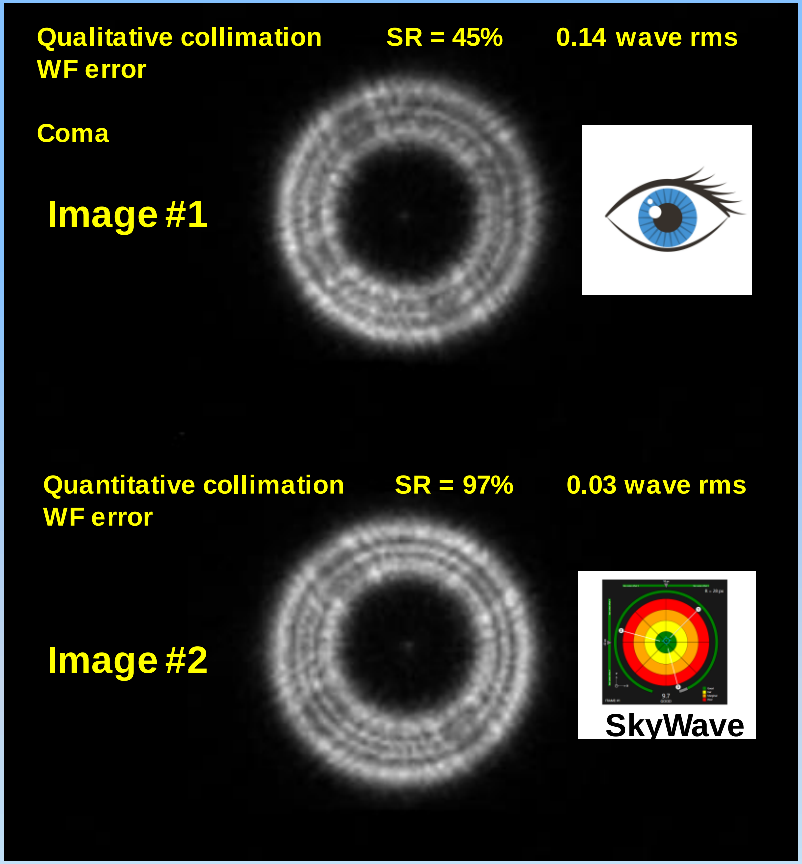


Collimation & Start test: A Word of Caution

- Mechanical offset of the secondary mirror & its mount (CO) causes an asymmetrical defocused star image in an otherwise perfectly collimated telescope.
- This occurrence is highly common in numerous telescopes.



Qualitative vs. Quantitative Collimation

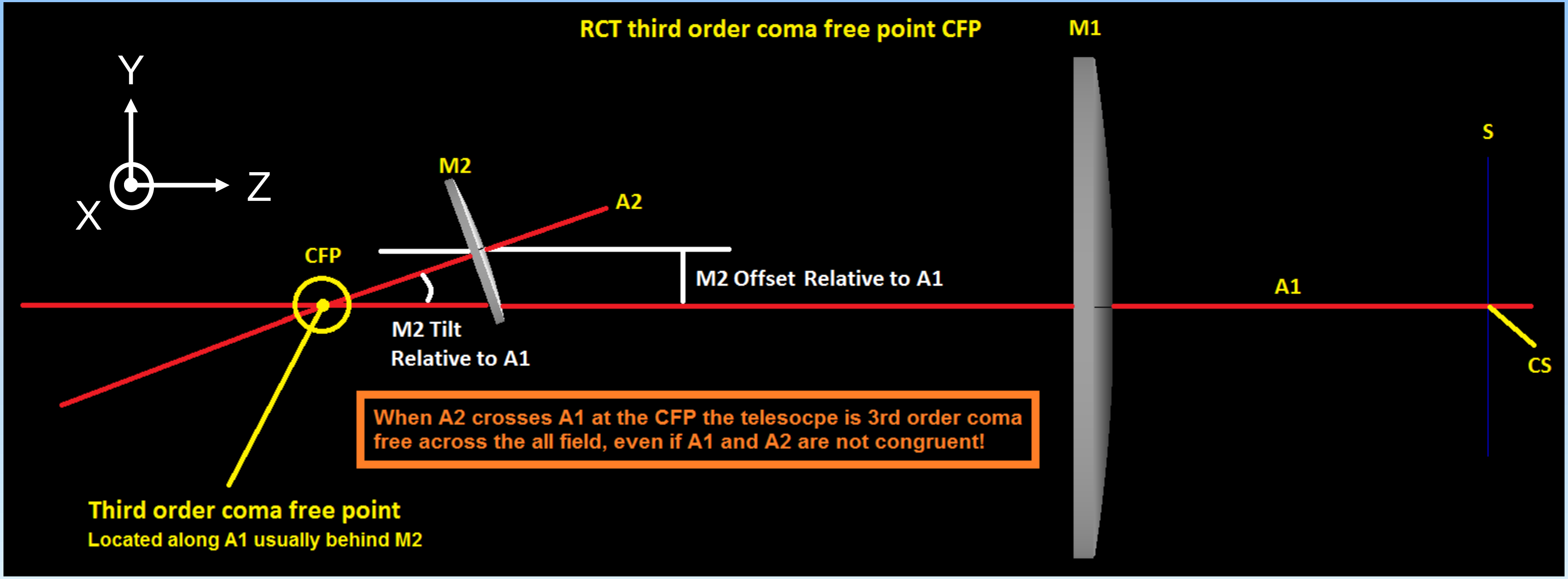


Credits: Vincent Suc, ObsTech (Chili)

RCT: The 3rd Order Coma Free Point

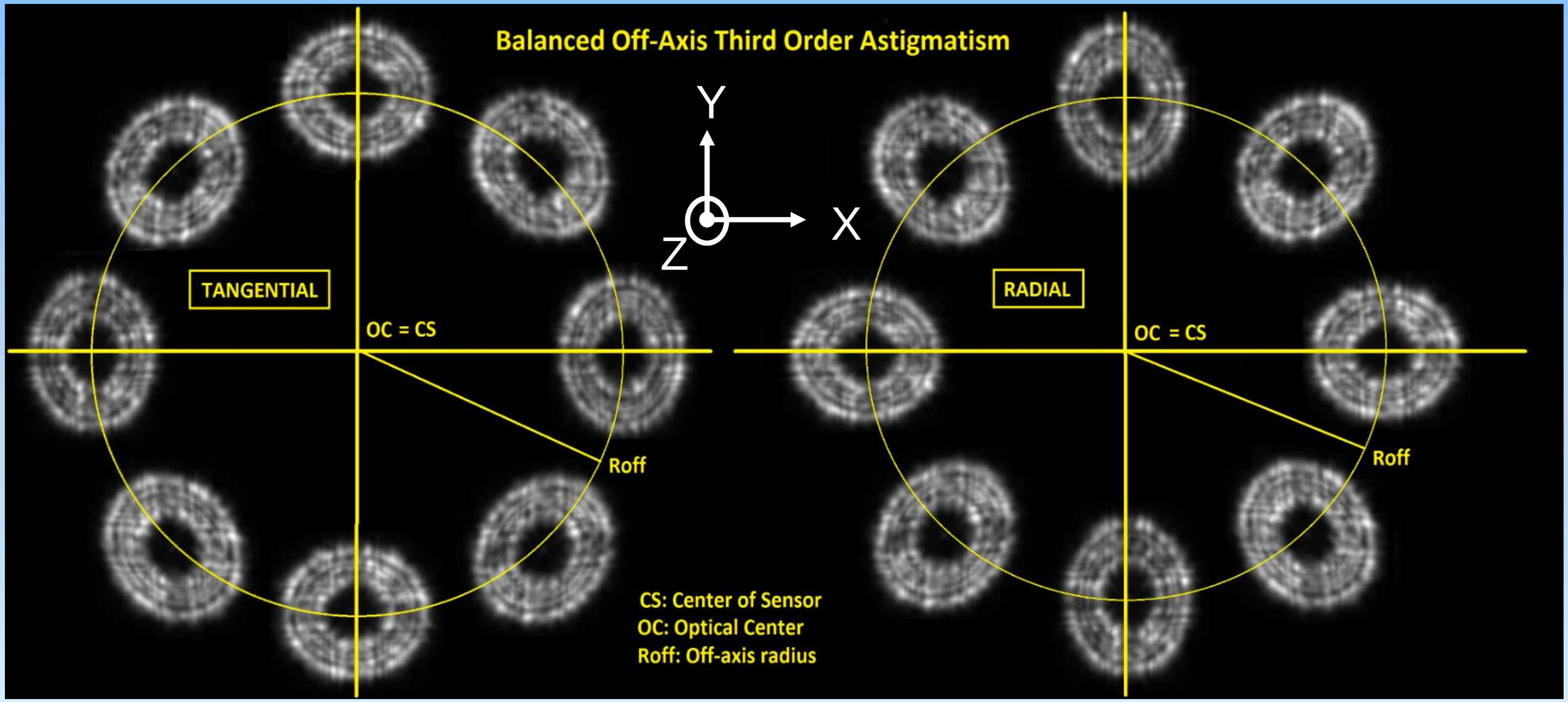
In any RCT is a point along A1, known as the coma free point (CFP). When A2 intersects A1 at the CFP the RCT is 3rd order coma free across the all field.

However, achieving **coma-free status doesn't guarantee collimation**; significant unbalanced off-axis astigmatism may exist if A 1& A2 are not congruent .



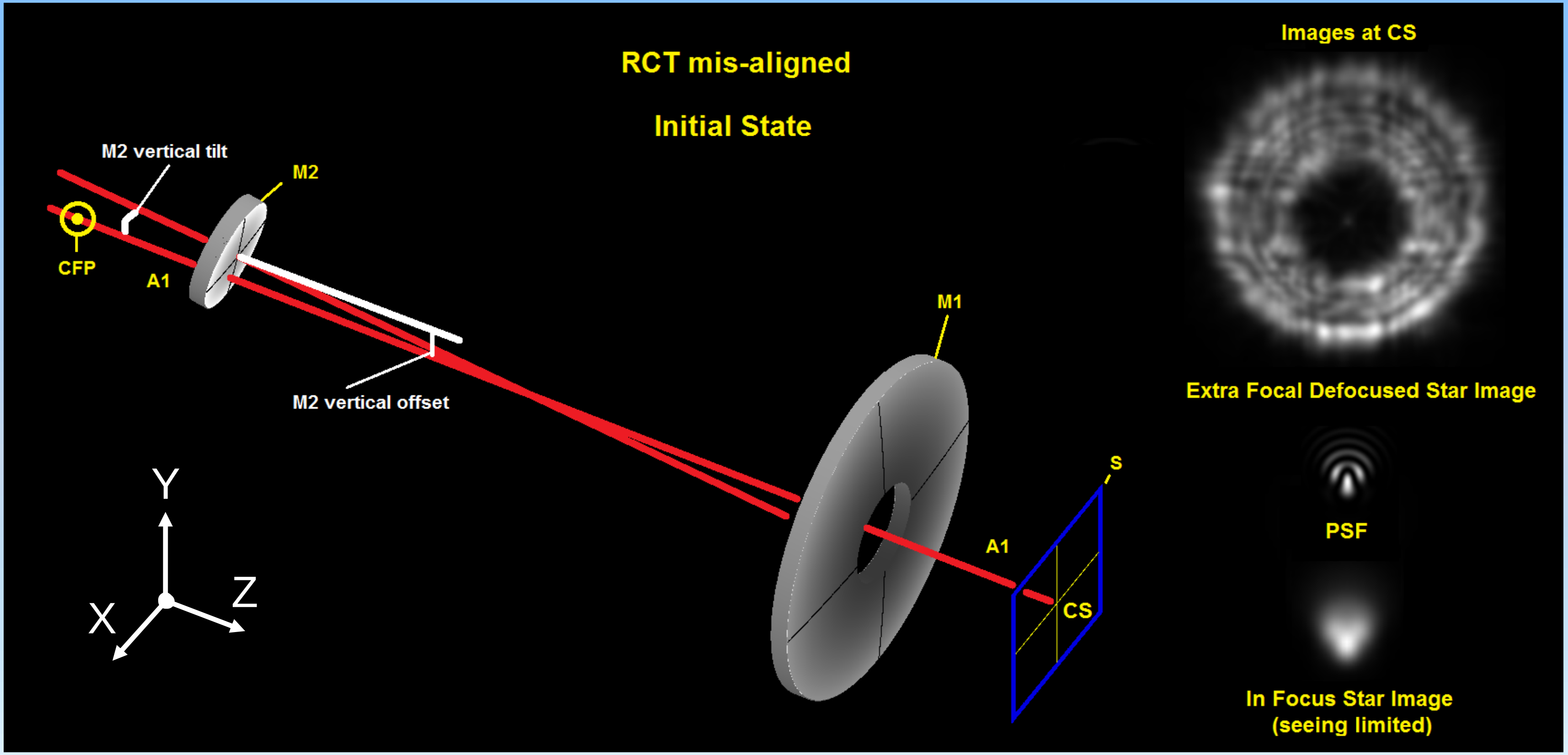
Congruence: Balanced Off-Axis Astigmatism

For a collimated RCT, at any given off axis radius, astigmatism is balanced. It is either tangential or radial symmetric with a **constant magnitude.**
Field lenses (corrector) may reduce it to a minimum.

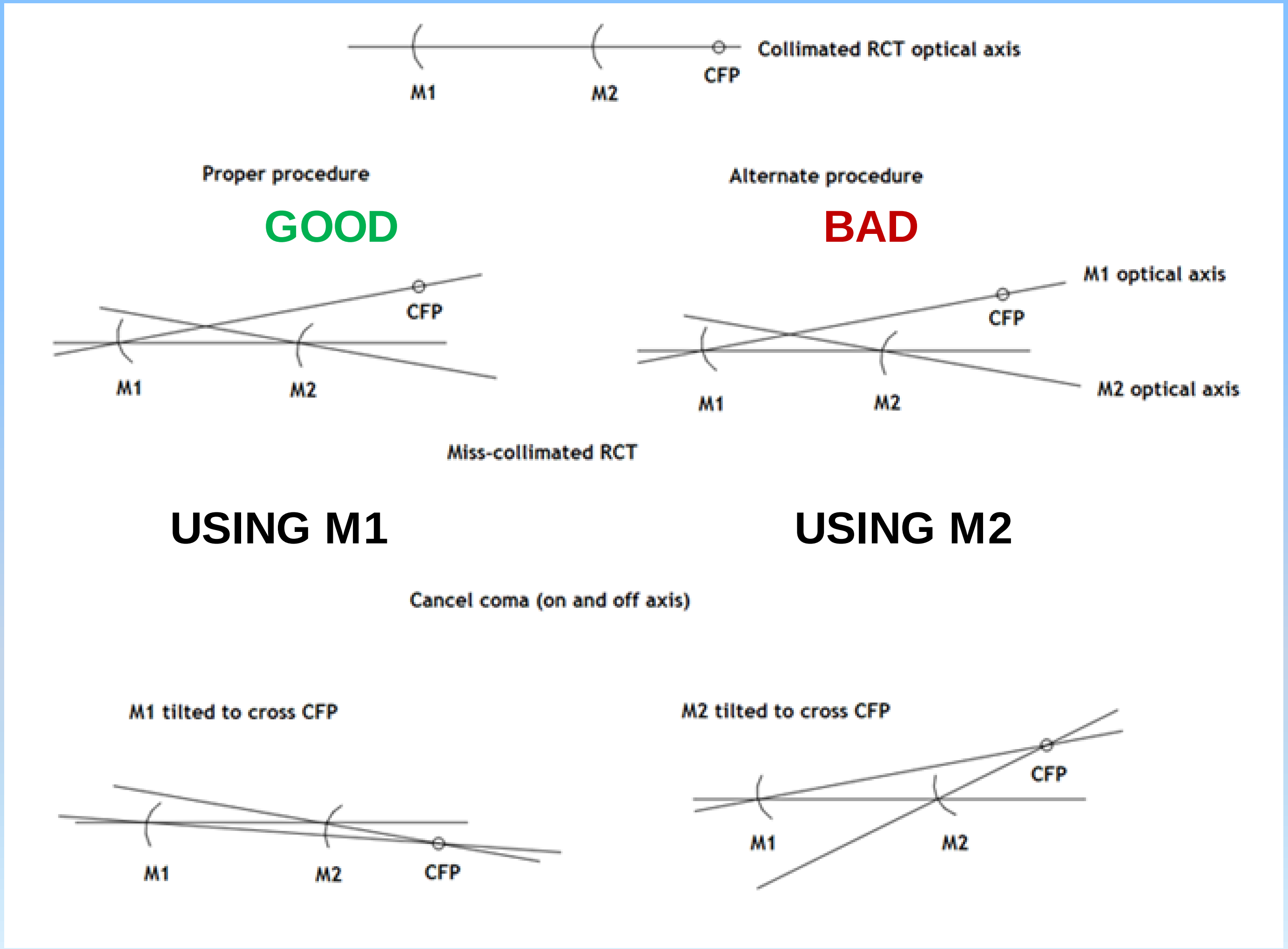


Mis-aligned RCT: Initial State

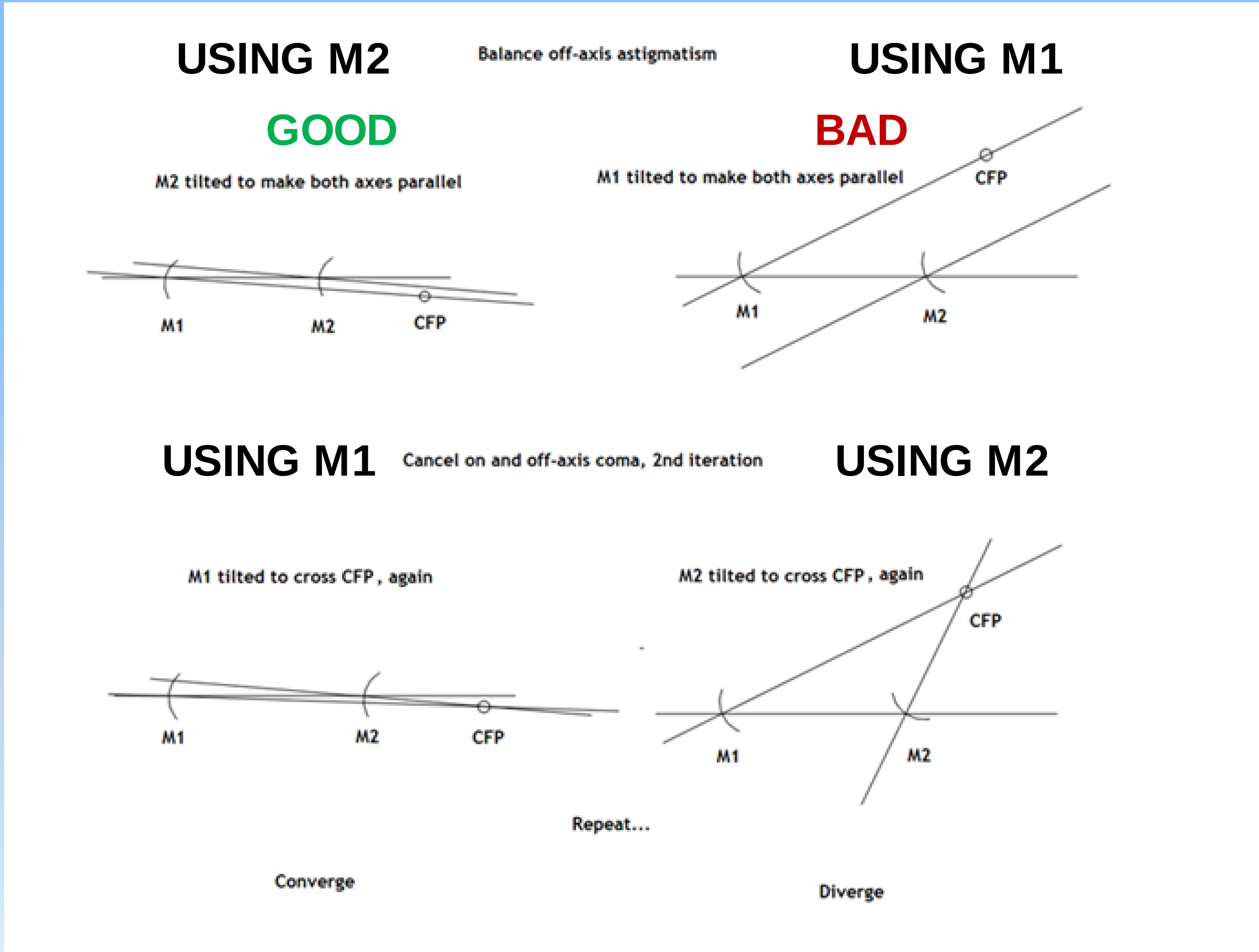
Here, A2 is tilted vertically by 0.1° and offset by 0.5mm, not to scale. The star in the center of the image shows a large coma induced by mis-collimation, measured at 0.2 wave rms (SR=21% only).



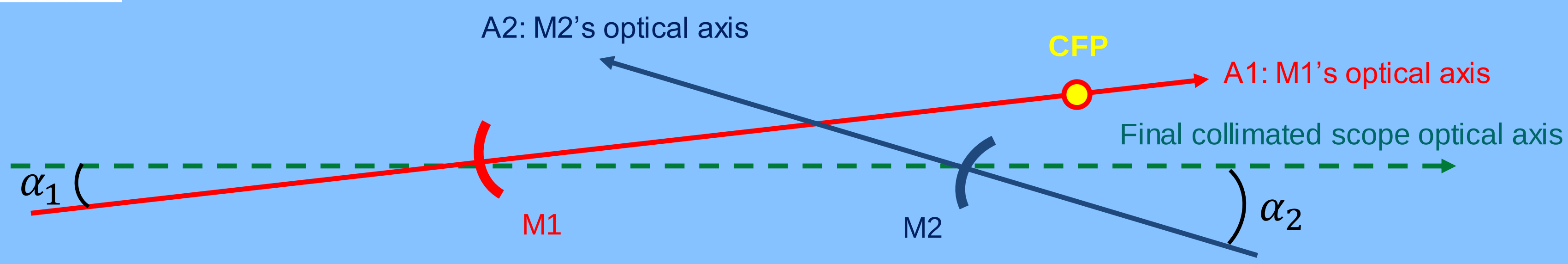
Cancel Coma:
Using Collimation Tilt Control Screws



Balancing Off-Axis Astigmatism Converging v.s. Diverging Procedures



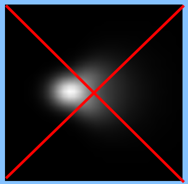
RCT Collimation:
The good (and bad) Procedure



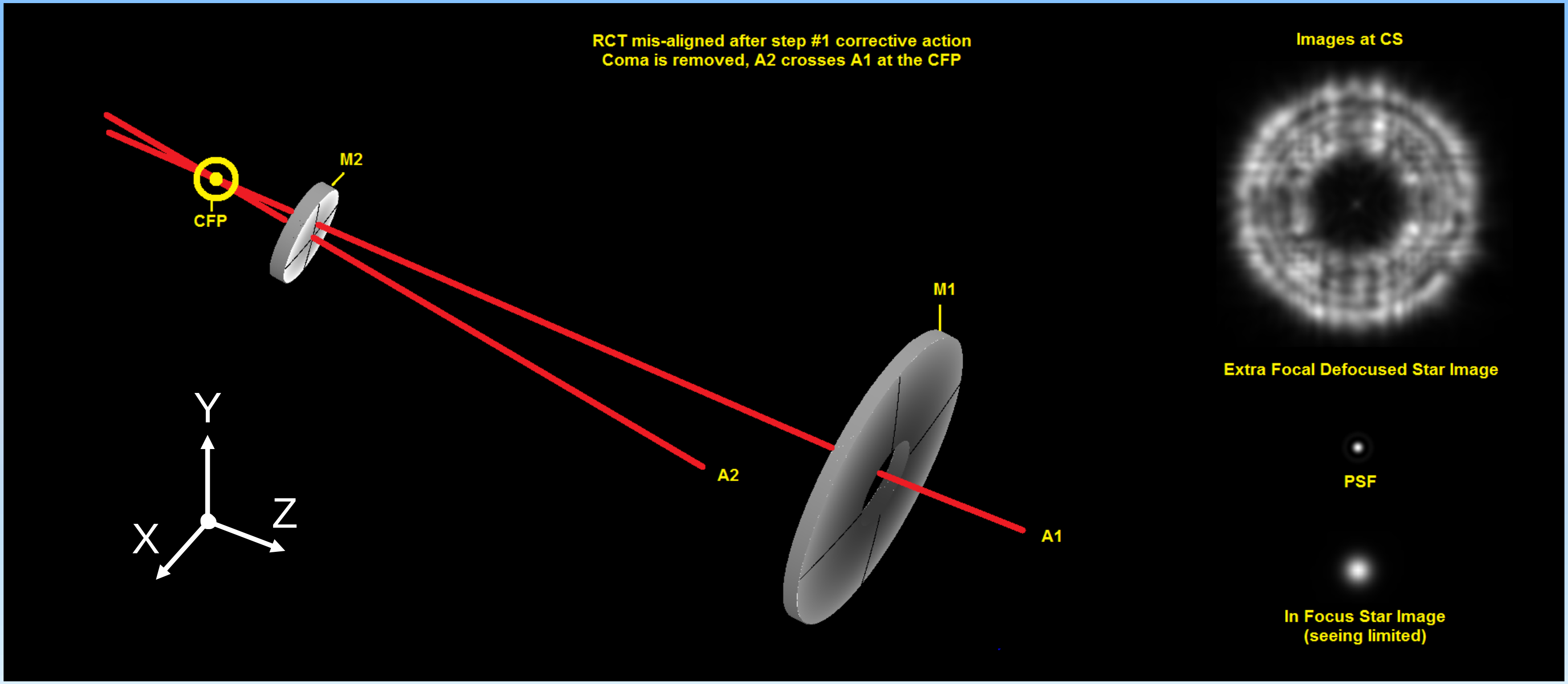
Collimation goal: $\alpha_1 = \alpha_2 = 0$ **Initial condition:** $\alpha_1\ or, and\ \alpha_2 \neq 0$

	Proper procedure:	**Alternate procedure: DON'T !**
Cancel Coma	$\lvert\alpha_1[1]\rvert \leq \lvert\alpha_2[0]\rvert$ with **M1**	$\lvert\alpha_2[1]\rvert \geq \lvert\alpha_1[0]\rvert$ with M2
Balance Astigmatism	$\lvert\alpha_2[1]\rvert = \lvert\alpha_1[1]\rvert$ with **M2**	$\lvert\alpha_1[1]\rvert = \lvert\alpha_2[1]\rvert$ with M1
Cancel Coma	$\lvert\alpha_1[2]\rvert \leq \lvert\alpha_2[1]\rvert \leq \lvert\alpha_1[1]\rvert$ with **M1**	$\lvert\alpha_2[2]\rvert \geq \lvert\alpha_1[1]\rvert \geq \lvert\alpha_2[1]\rvert$ with M2
	⋮	⋮
Balance Astigmatism	$\lvert\alpha_1[n]\rvert \leq \lvert\alpha_1[n-1]\rvert \ldots \leq \lvert\alpha_1[1]\rvert$	$\lvert\alpha_2[n]\rvert \geq \lvert\alpha_2][n-1]\rvert \ldots \geq \lvert\alpha_2[1]\rvert$
	CONVERGE	**DIVERGE**

Mis-aligned RCT: Canceling Coma

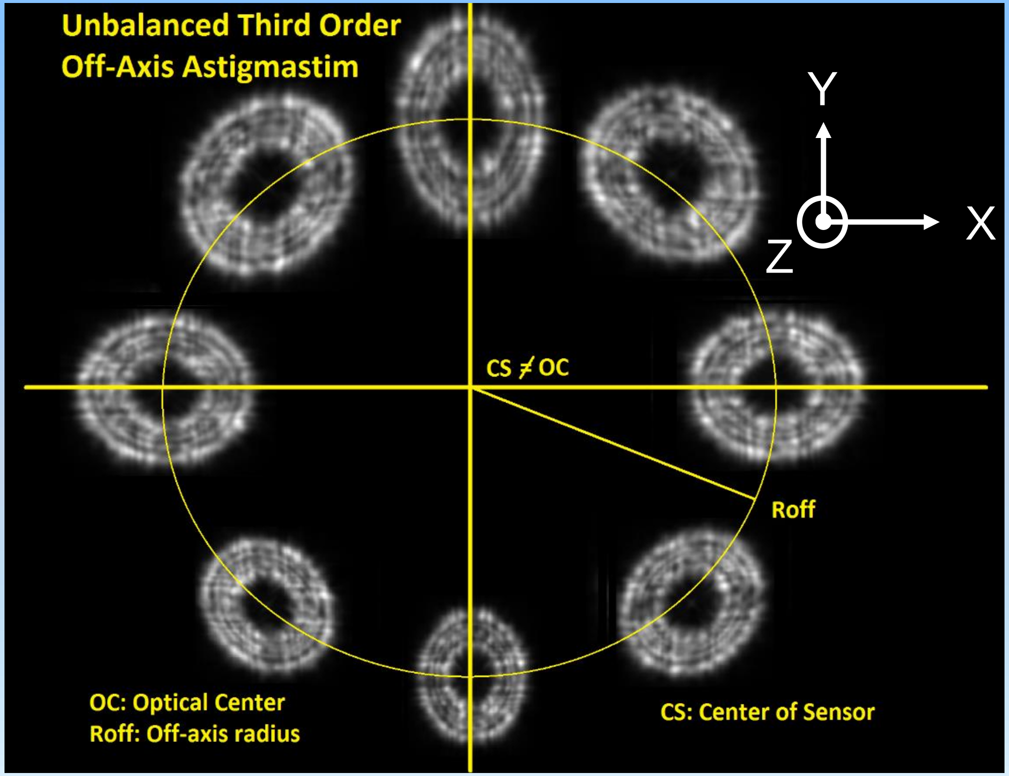


Coma has been removed across the all field. For a star at the center of the image the SR>99%. A1 crosses A2 at the CFP. However **A1 & A2 axes are not congruent** yet, they are still tilted leading to unbalanced off-axis astigmatism.



Unbalanced Off-Axis Astigmatism

At a given off axis radius astigmatism is neither tangential nor radial symmetric & it has **variable magnitude**.
Use M2 tilt control screws to balanced off-axis astiagmatism.



RCT Collimation: A Summary

- RCT telescopes are 3rd order coma free across the all field when aligned**, the converse is not necessarily true**.
- Both M1 and M2 tilt/tip adjustments are necessary for reaching congruence (unless the M2 mount has 4 degrees of freedom).
- Failing to follow the proper alignment procedure below leads to an ever-increasing off-axis astigmatism **even in the absence of coma.**

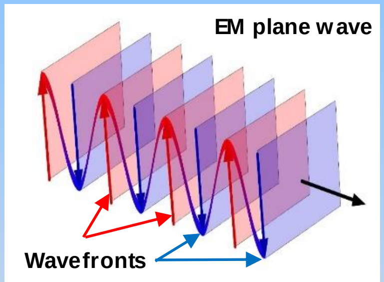
Step #1: Adjusting M1 to remove on-axis coma

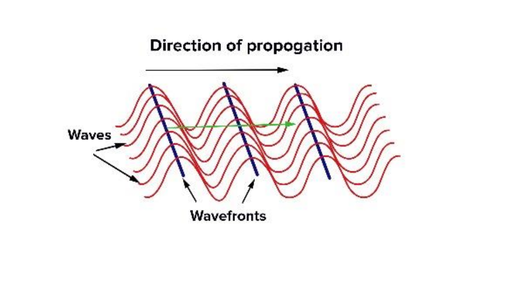
Step #2: Adjusting M2 to balance off-axis astigmatism

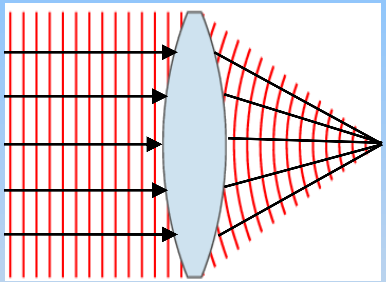
- Repeat step #1 and #2, in this order, until the on-axis coma is removed, and the off-axis astigmatism is balanced. Convergence takes usually 2 to 3 iterations.

Wave Optics

Wave optics (WO) treats light with explicit recognition of its wave nature. A plane wave is imaged as a spherical wave (SW) centered at the focal plane



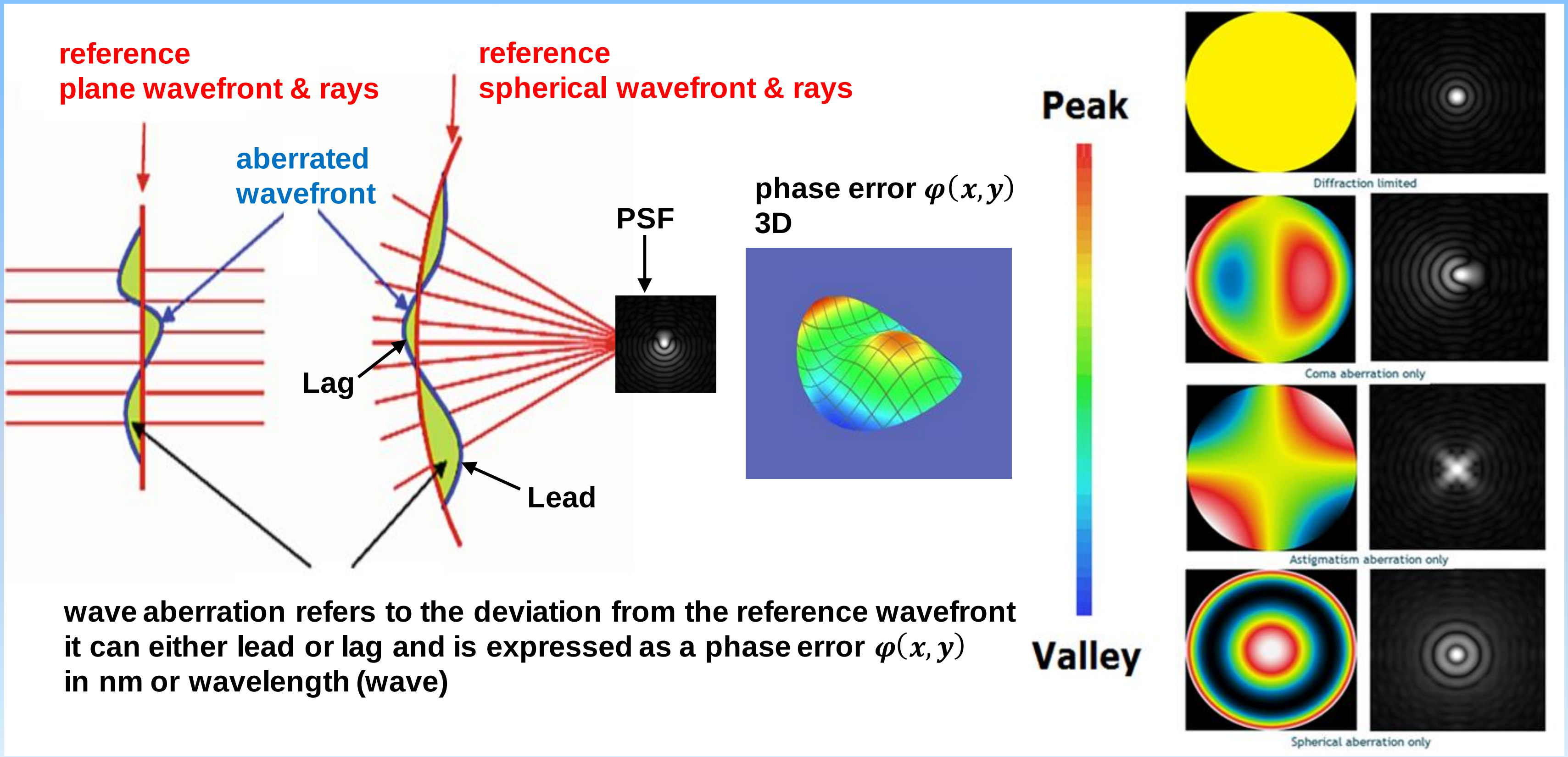




Rays are perpendicular to the wavefronts (WF).
Phase information is present. WO can predict and explain diffraction (Fourier optics).

Perfect versus Aberrated Imaging Optics

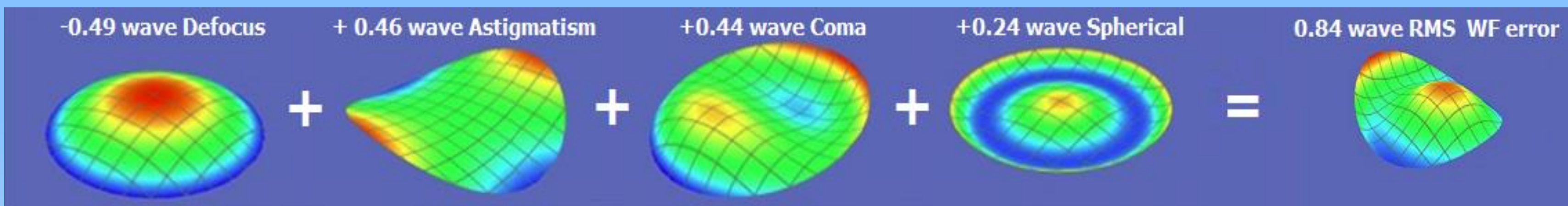
Departure from an ideal WF leads to a wavefront phase error $\varphi(x, y)$ and related optical aberrations.

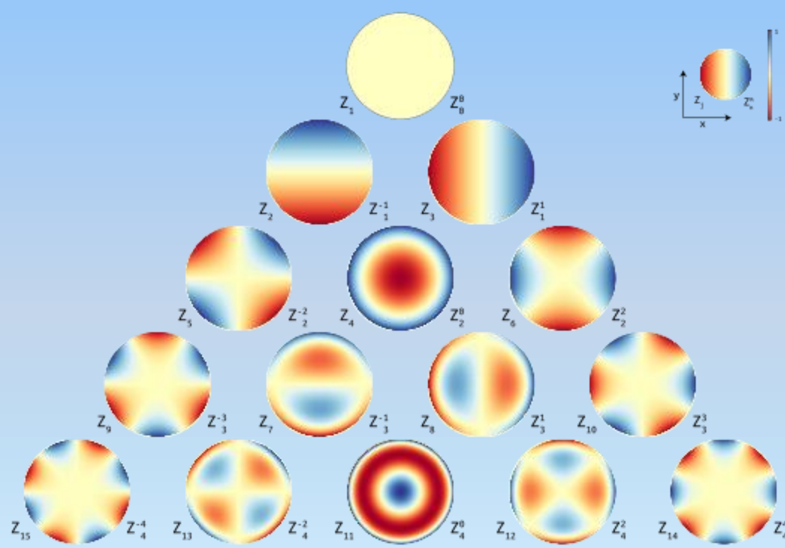


wave aberration refers to the deviation from the reference wavefront
it can either lead or lag and is expressed as a phase error $\varphi(x, y)$
in nm or wavelength (wave)

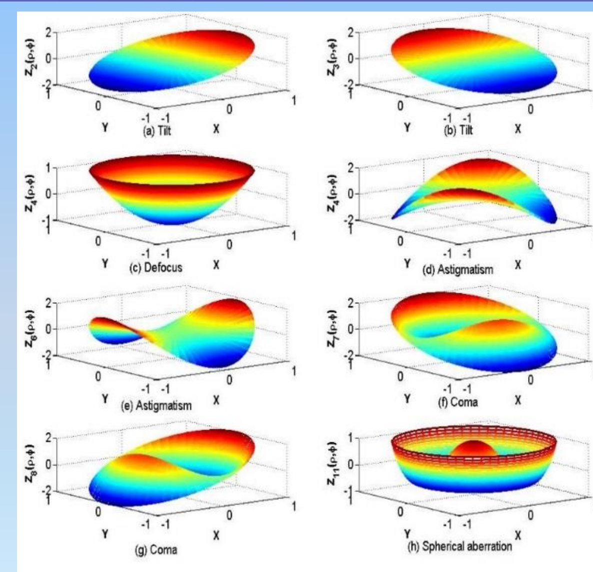
Aberration Analysis
The Zernike's Polynomials

The wavefront phase error $\varphi(x, y)$ can be expressed as the weighted sum of elementary phase functions (aberrations).





Zernike's Polynomials

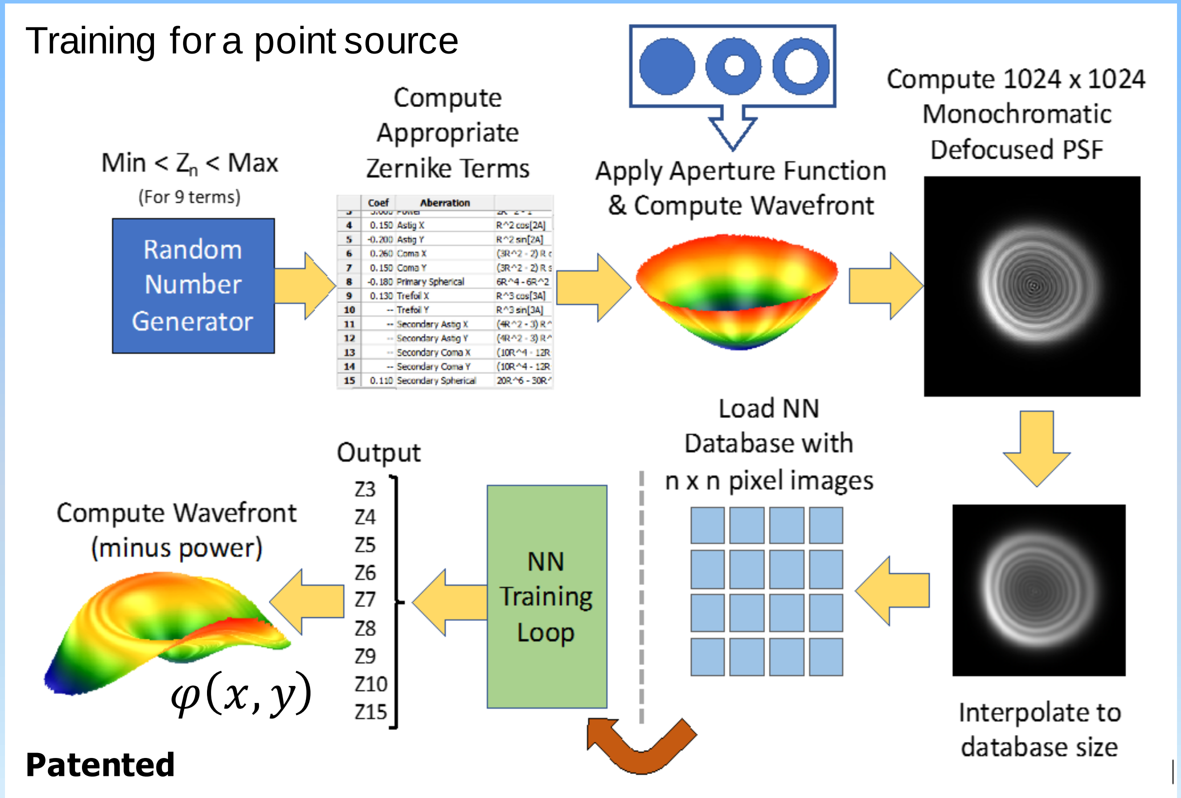


Related 3D wavefront errors

AI Based Wavefront Sensing
AIWFS (patented)

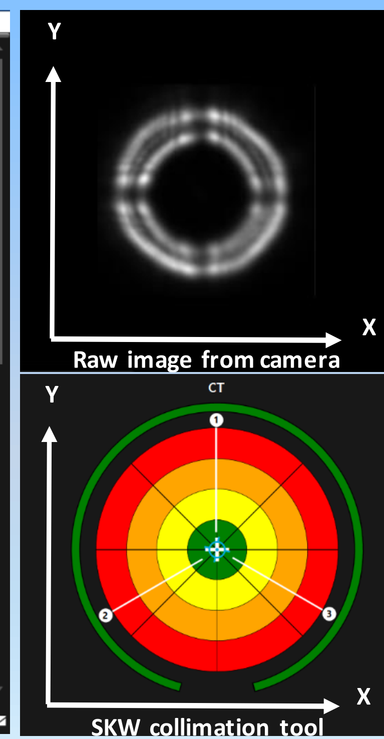
SPIE Photonics Europe 2020 conference, Strasbourg, France

A feedforward neural network (NN) is trained using **only** synthetic (simulated) data. Databases can be arbitrarily large. Relevant noises are added (seeing, scattering, speckle, read noise, …).



SkyWave for a Quantitative Collimation

The SKW uses our patented AI4Wave technology for precise wavefront sensing, accurately measuring wavefronts and related aberrations from a single frame, even under seeing-limited conditions.

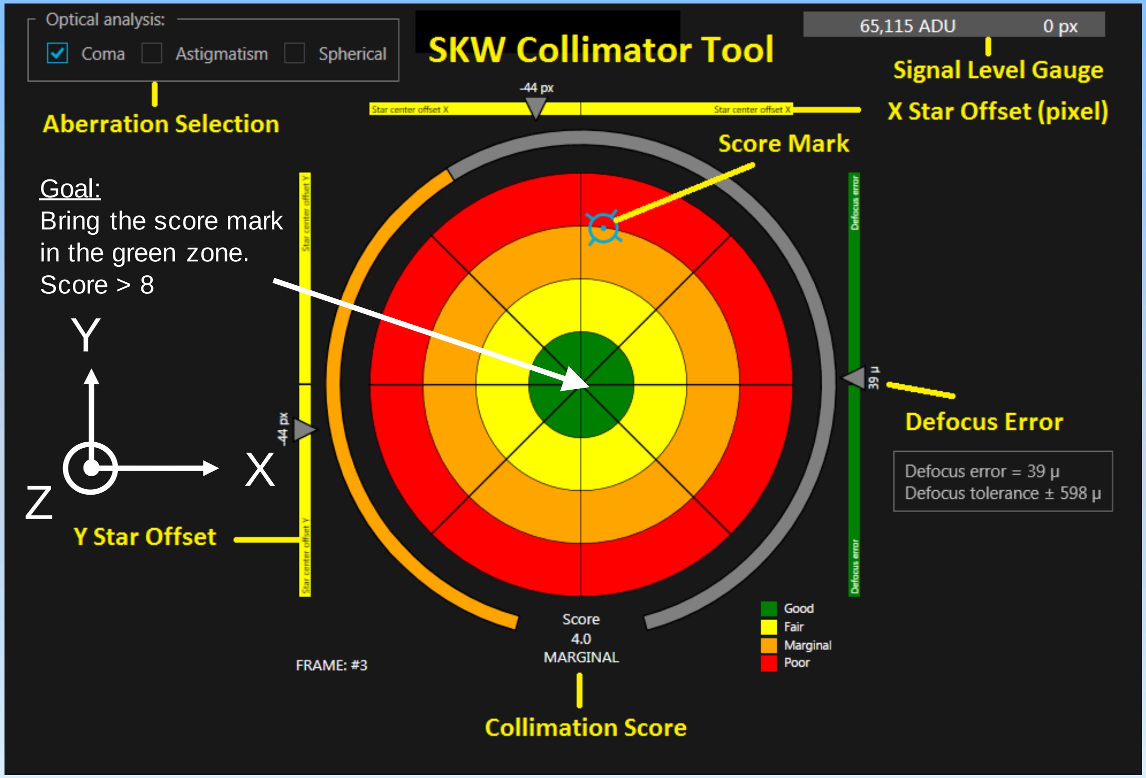


Congruence Collimation using SKW
Step #1: Removing coma

The SKW features a tool named collimator for alignment which displays a score mark inside a target. Here coma only should be selected. The mark is oriented toward the point where **M2** is the most tilted forward (in this RCT example the +Y direction).

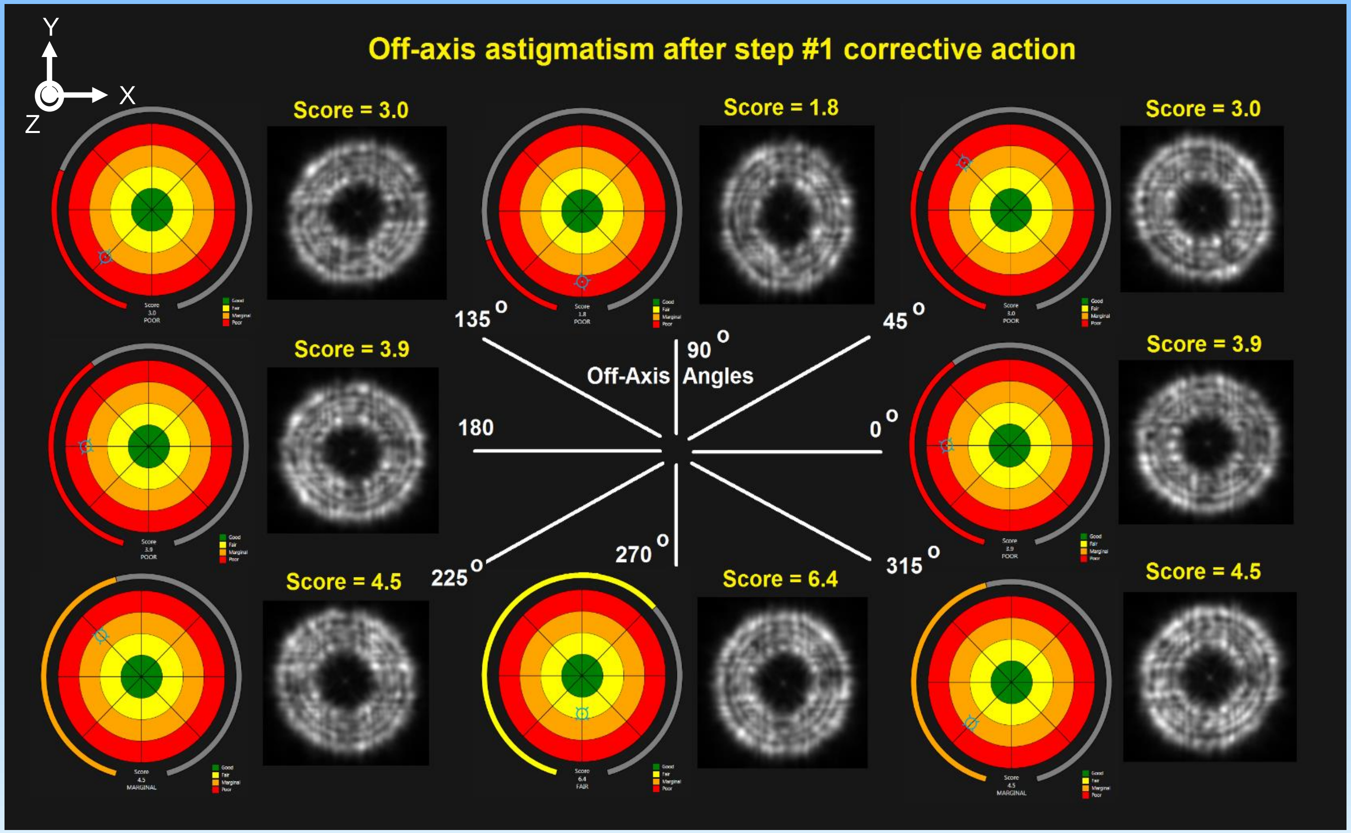
SKW collimator provides angular information in relation with the collimation screws.

Corrective action:
Pull **M1** at the position indicated by the SKW score mark angular direction



Congruence Collimation using SKW
Step #2: Balancing off-axis astigmatism

Analyze stars at a given off-axis radius. Astigmatism only should be selected. Corrective Action: Pull **M2** at the angular position indicated by the lowest SKW score (here at 90º , +Y)



INNOVATIONS
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Congruence Collimation using SKW
After balancing off-axis astigmatism

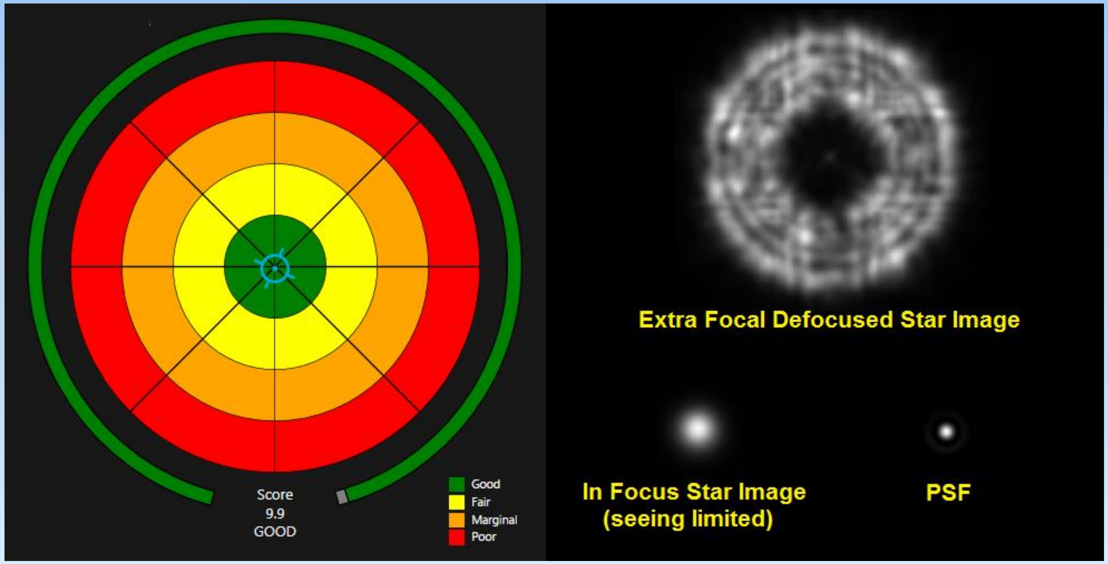
After balancing off-axis astigmatism with SKW using M2, the scope is essentially collimated. Adjusting M2 didn't reintroduce much coma.

This RCT does not have any corrector leading to some native off-axis astigmatism when collimated.

Off-Axis Astigmatism Scores

135º off-axis SCORE = 4.8	90º off-axis SCORE = 4.8	45º off-axis SCORE = 4.8
180º off-axis SCORE = 4.9	“On-axis” at CS near OC SCORE = 10.0	0º off-axis SCORE = 4.9
225º off-axis SCORE = 5.0	270º off-axis SCORE = 5.0	315º off-axis SCORE = 5.0

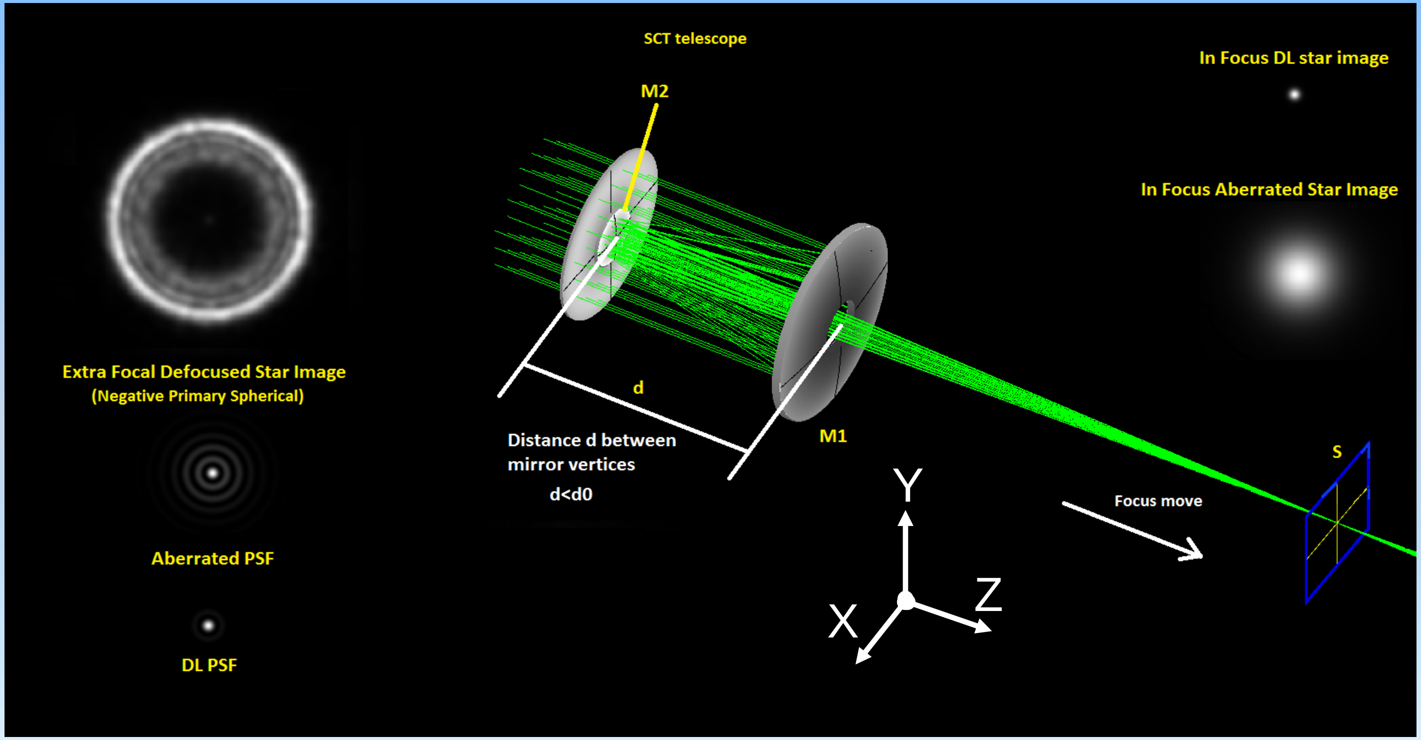
On-Axis Coma Score



Mirror Spacing and Spherical Aberrations

Spherical aberration from mirror spacing error or sensor not at the back-working distance of a corrector look like poor seeing, making them challenging to identify and quantify.

⚠ Measured focal length is a bad proxy for mirror spacing ⚠



Collimation with SKW
Summary

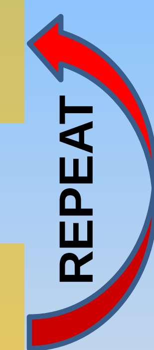
- SKW determines wavefront allowing for an accurate and fast quantitative optical alignment of telescopes using the relevant aberrations.

- Step #1 <u>Congruence using **coma only**</u>

Pull <u>M1</u> at the position indicated by the SKW score mark angular direction.

- Step #2 <u>Congruence using **astigmasim only**</u>

Pull <u>M2</u> at the angular position indicated by the lowest SKW score of the off axis defocused stars.



- 2. <u>Spacing using **spherical only**</u>

Increase the mirrors spacing if the SKW spherical aberration sign is negative, decrease it if positive.

INNOVATIONS FORESIGHT

SKW collimation of a 16" RCT + corrector

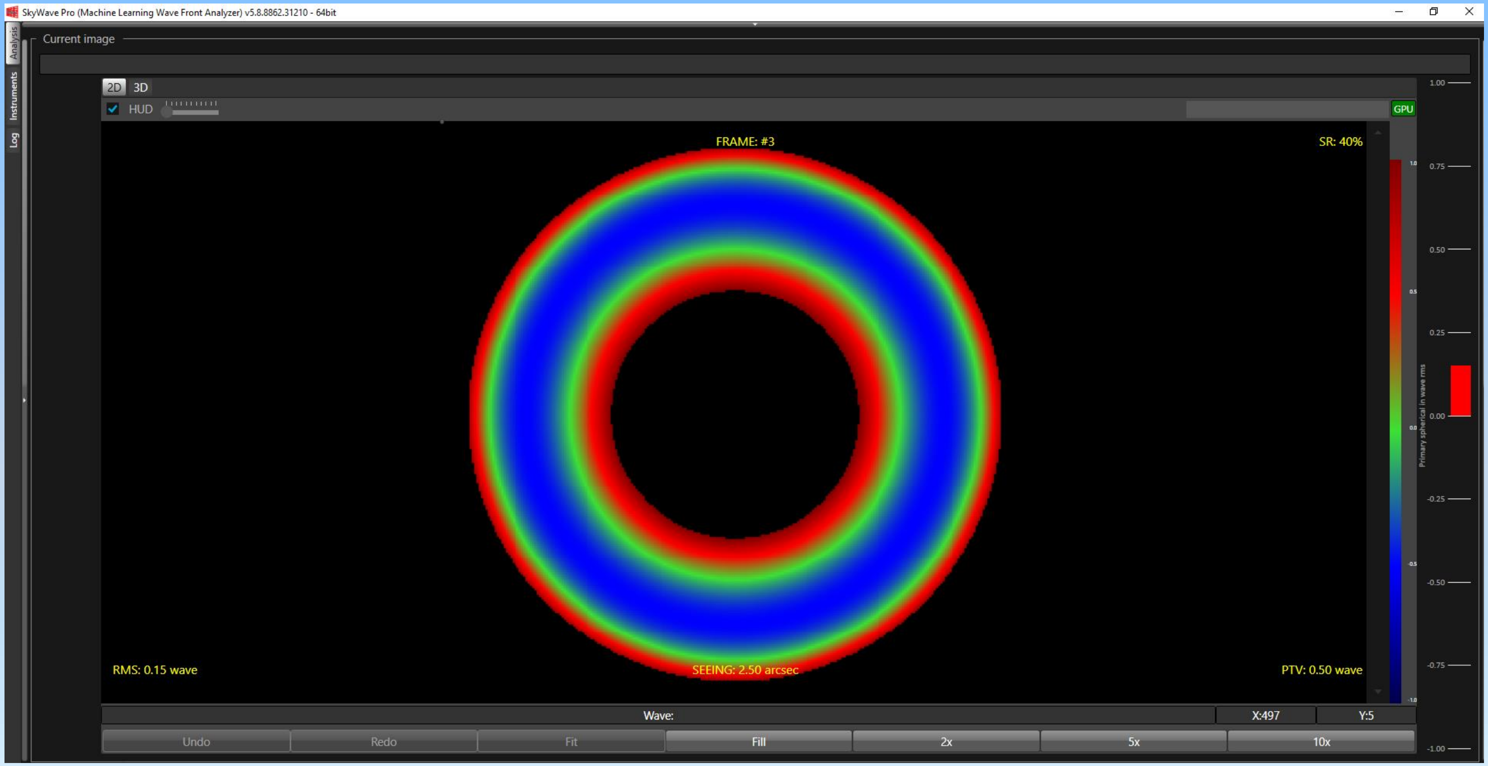
Collimation of a RCT Officina Stellare RC400 with Riccardi 0.75x Corrector/focal reducer.

Credit:

Sébastien Kuenlin, Switzerland.

Spherical Aberration

In addition to collimation-related aberrations, SKW revealed significant spherical aberration due to **incorrect spacing** between the corrector and the sensor plane.



Results

The stars FWHM improved by about 1” over all field.