CCAT Optical Design Trade-off Study

f_1/0.6 vs. f_1/0.4

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Outline

- Main Optics Image Quality Impact
- Sub Reflector Positioning Impact
- Re-Imaging Optics Impact
- Active Surface Segment Positioning Errors Impact
- SCUBA-II/SW/LW Cameras Location

Ritchey-Chrétien Design Parameters
f_1/0.6 vs. f_1/0.4

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Design: Ritchey-Chrétien/Nasmyth Focus

Derived Design Parameters

	Symbol	f_1/0.6	f_1/0.4	Units
M1				
Diameter	D_1	25	25	[m]
Eccentricity	ε_1	1.000774	1.000278	
Vertex Radius of Curvature	R_{C1}	30.000	20.000	[m]
Focal Distance	f_1	15.000	10.000	[m]
Edge Angle from Prime Focus	θ_1	45.24	64.01	[deg]
M2				
Diameter (with FOV provisions)	D_2	3.20	2.62	[m]
Eccentricity	ε_2	1.169098	1.108191	
Vertex Radius of Curvature	R_{C2}	3.922	2.105	[m]
Edge Angle from Secondary Focus	θ_2	3.58	3.58	[deg]

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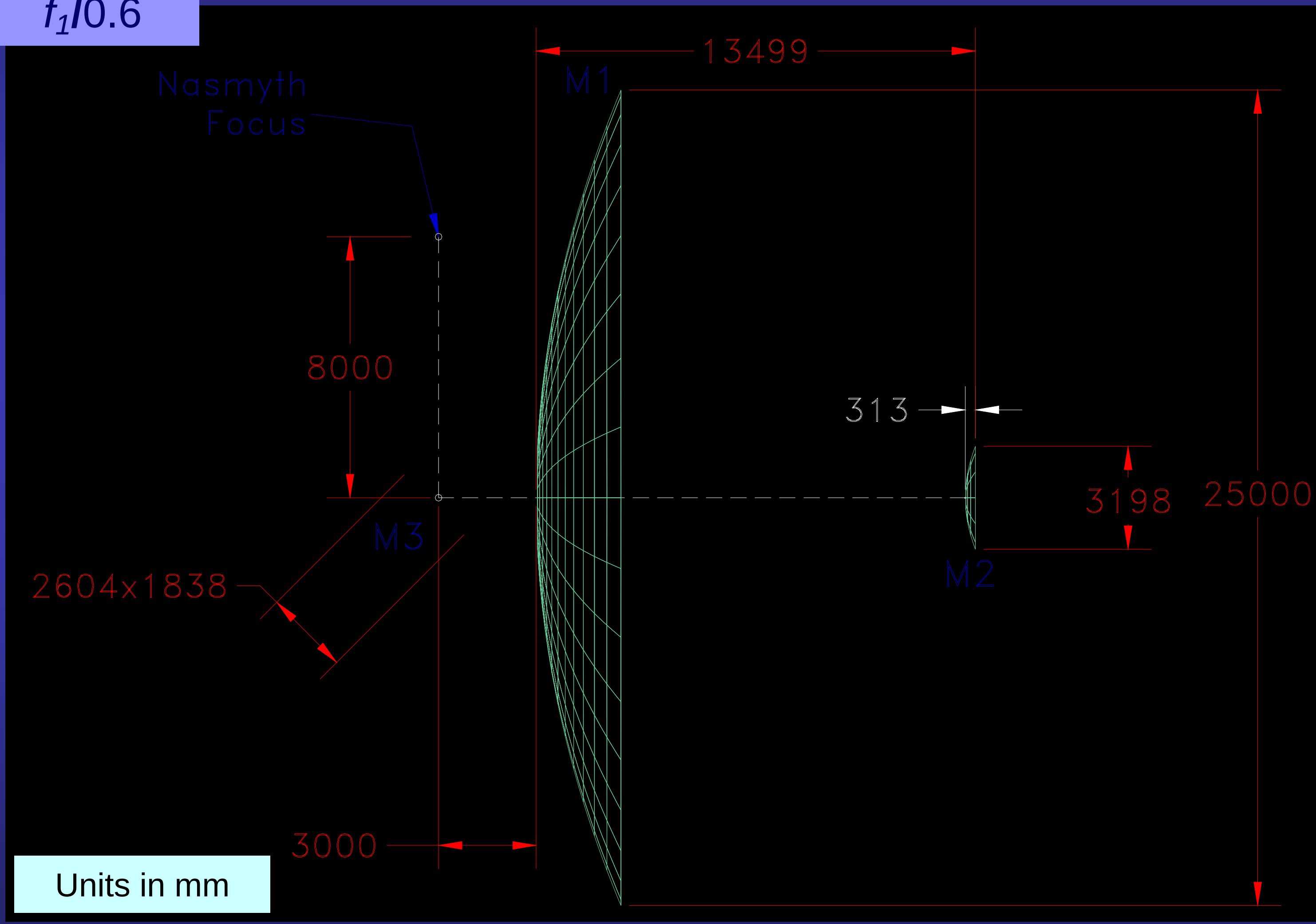
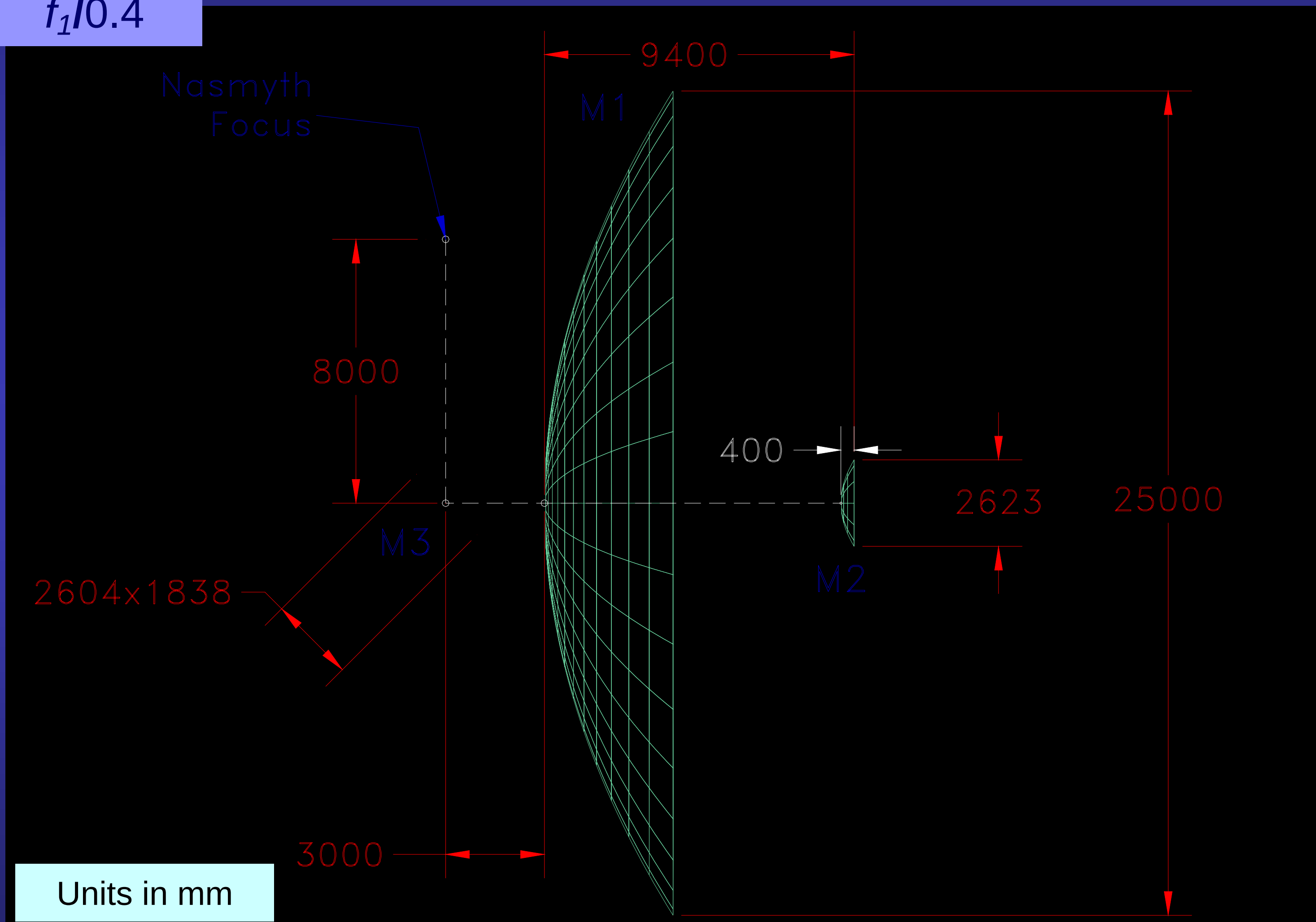
Ritchey-Chrétien Optical Layout
$f_1/0.6$ vs. $f_1/0.4$

$f_1/0.6$



Ritchey-Chrétien Optical Layout
$f_1/0.6$ vs. $f_1/0.4$

$f_1/0.4$



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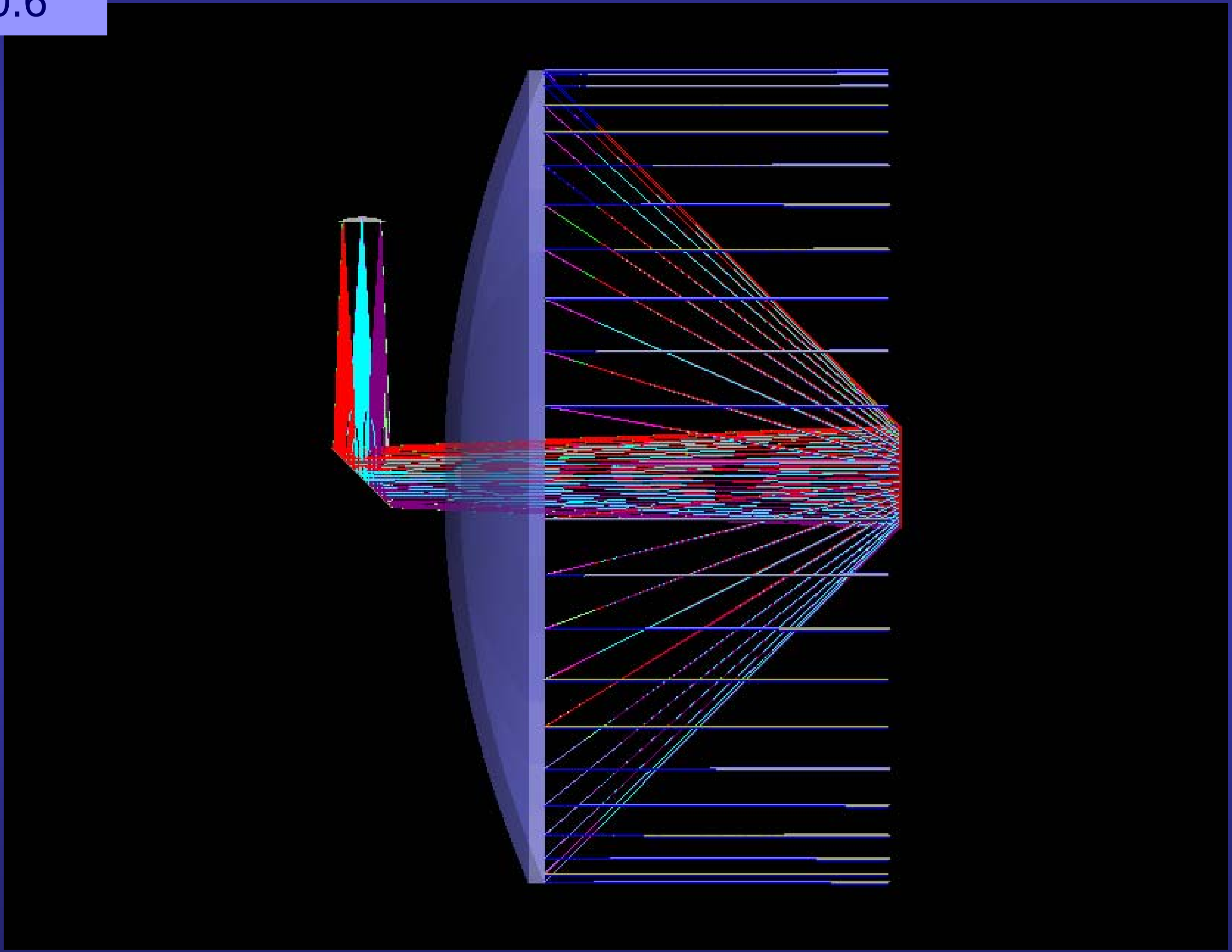
Ritchey-Chrétien Optical Layout
f_1/0.6 vs. f_1/0.4

f_1/0.6



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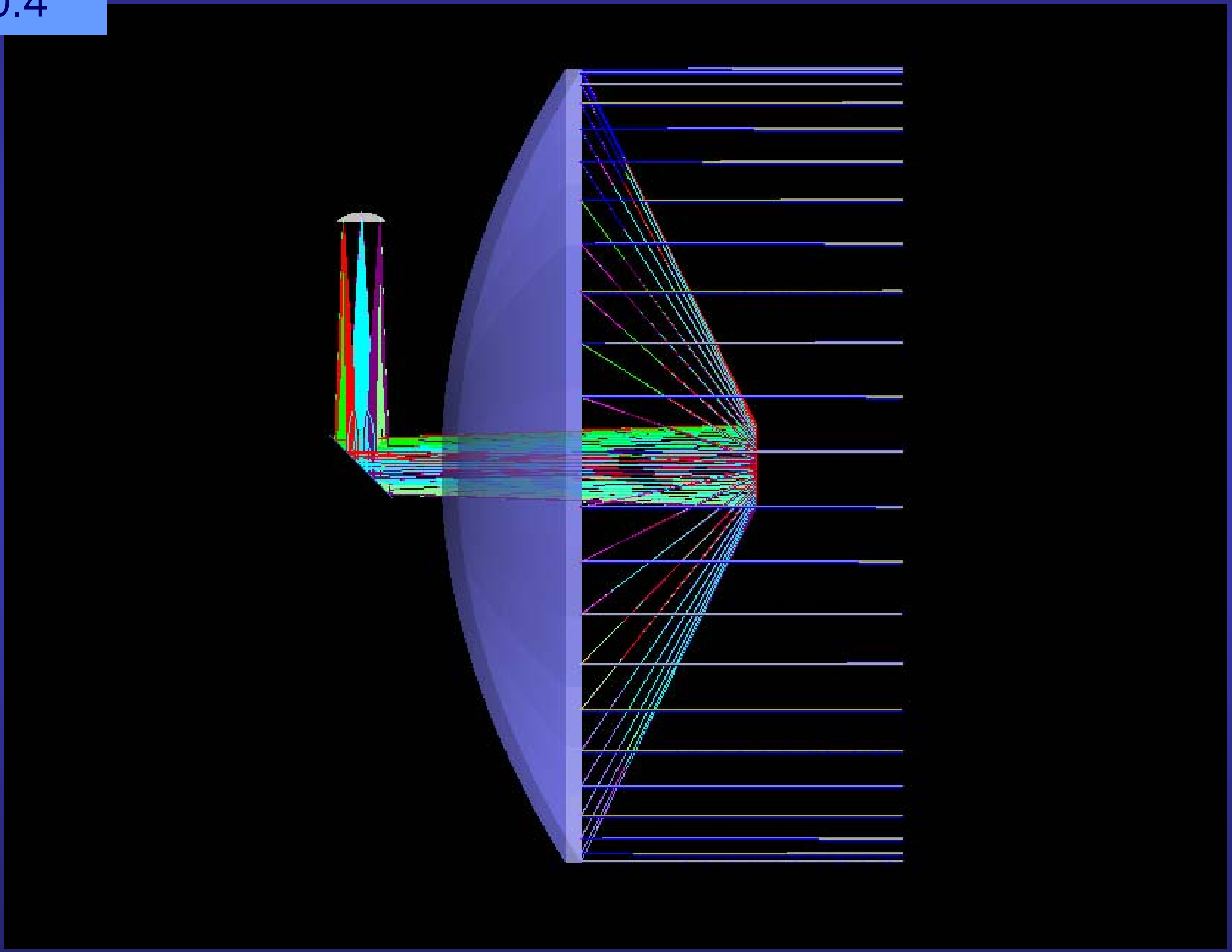
Ritchey-Chrétien Optical Layout
f_1/0.6 vs. f_1/0.4

f_1/0.4



FOV: Optimum Focal Surface Geometry

$f_1/0.6$ vs. $f_1/0.4$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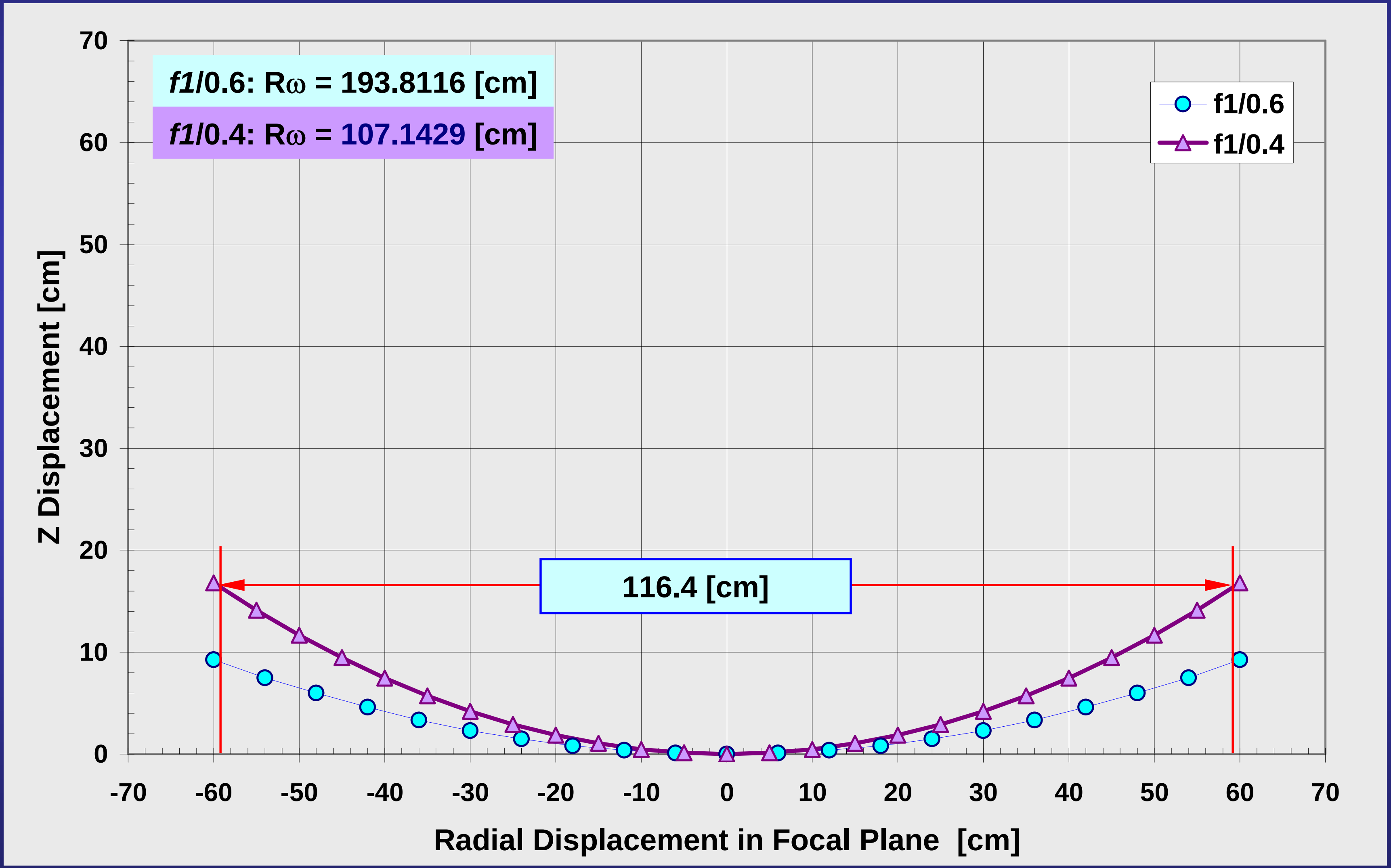

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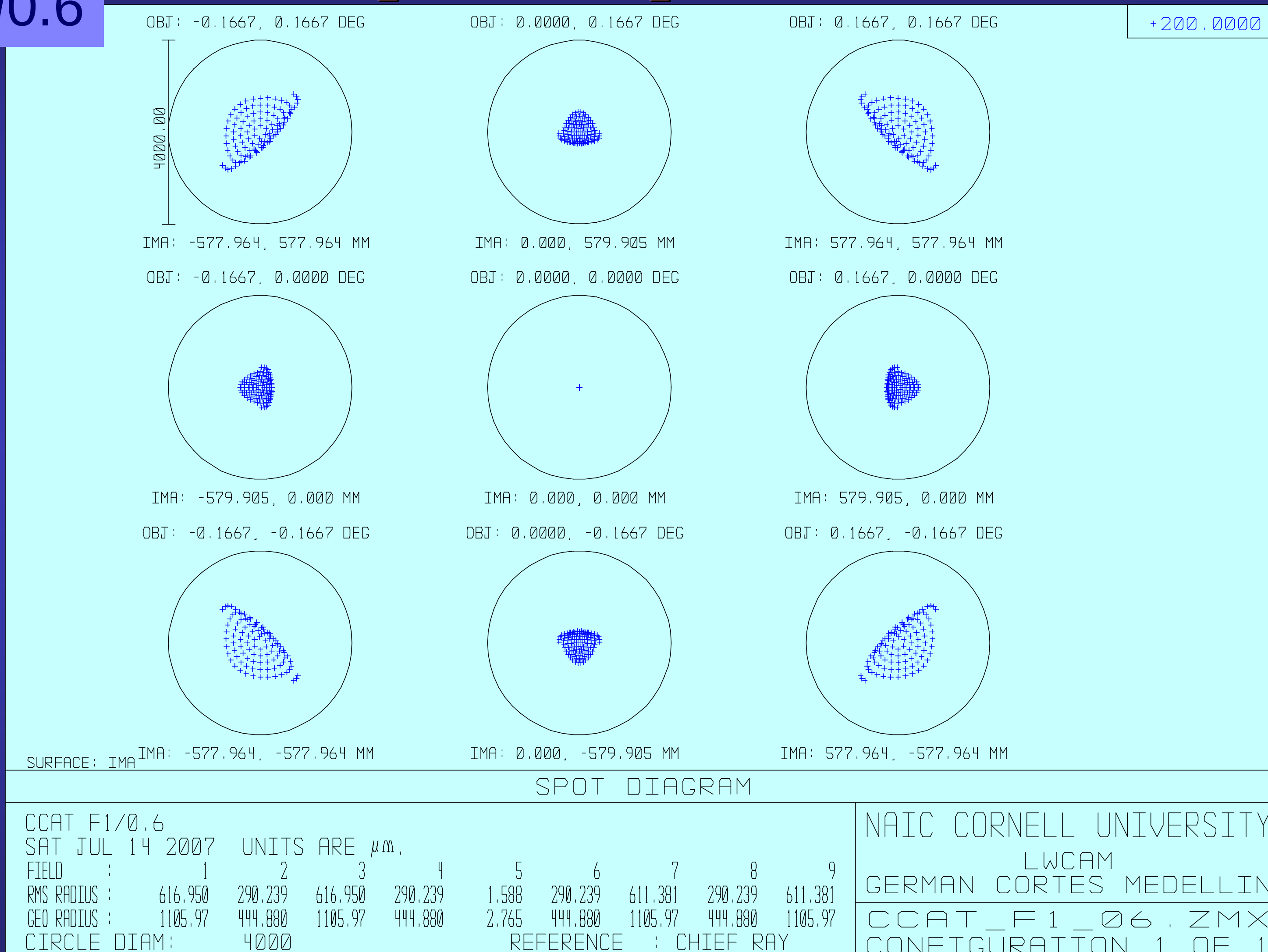
FOV: Spot Diagram

f_1/0.6 vs. f_1/0.4

f_1/0.6



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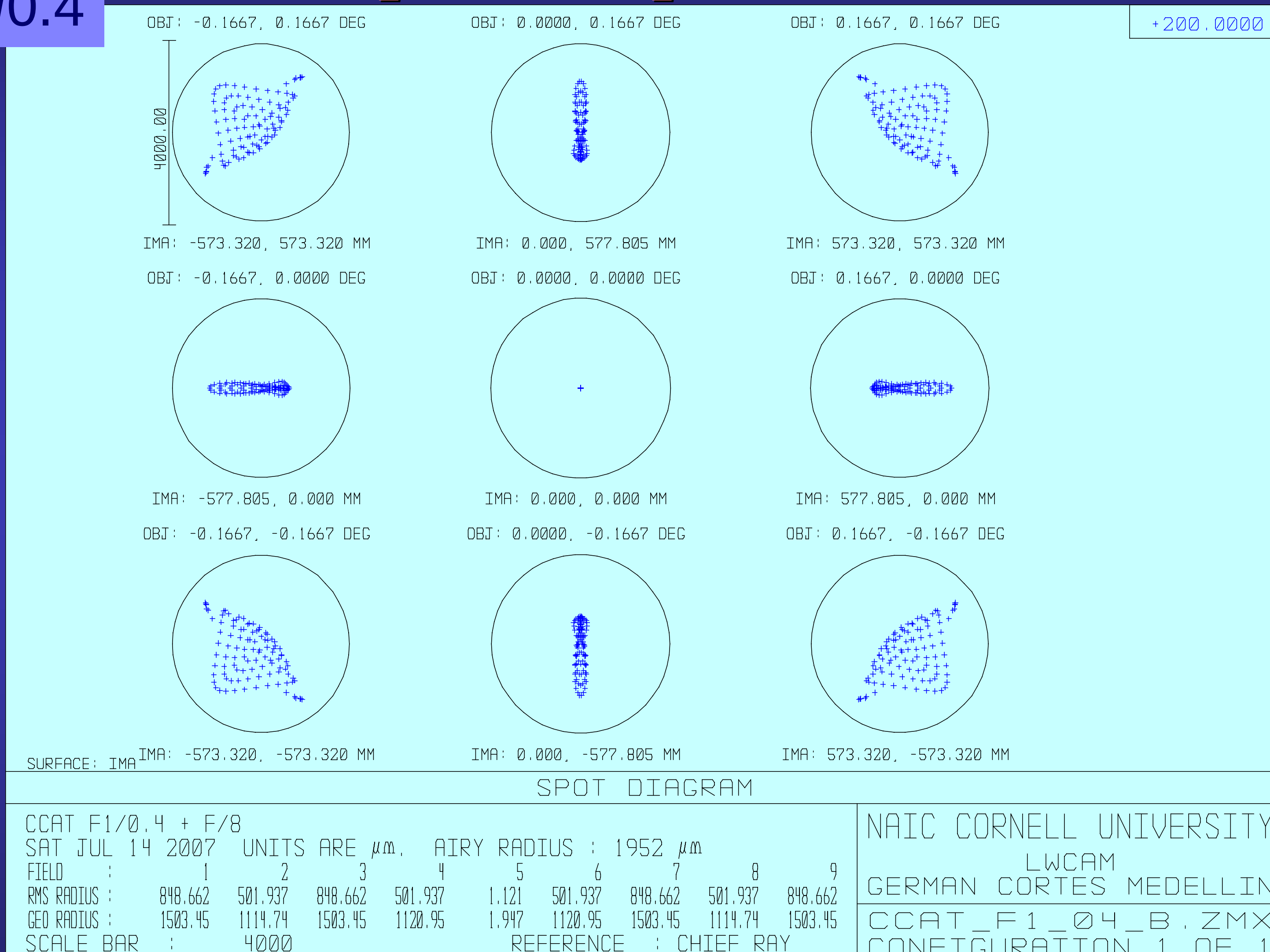
FOV: Spot Diagram

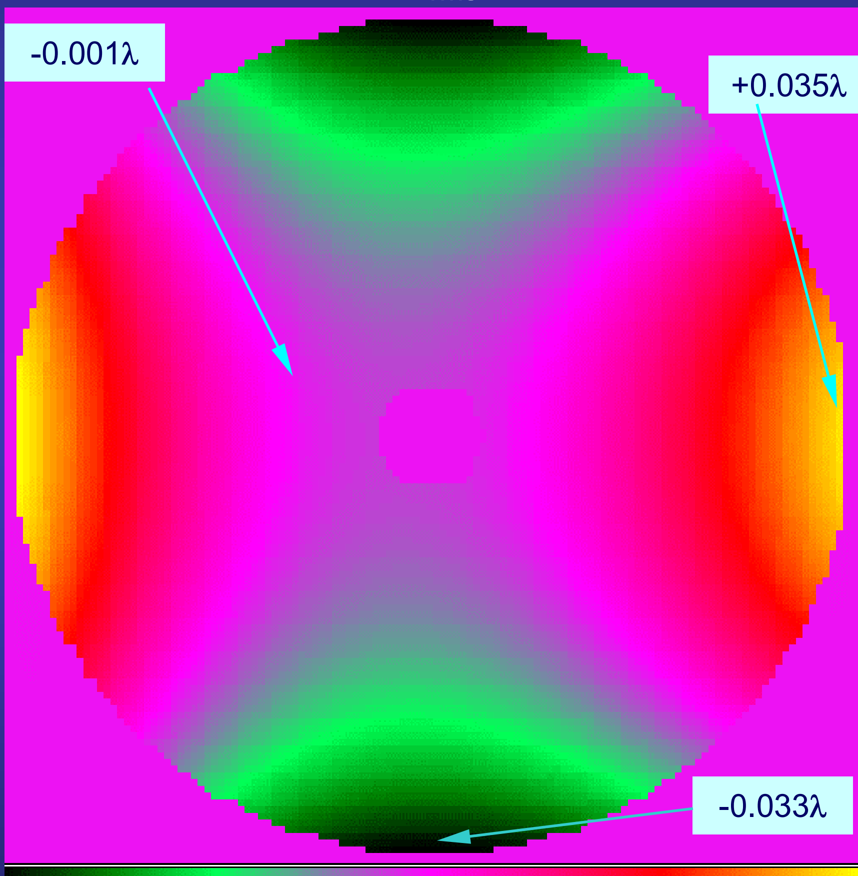
f_1/0.6 vs. f_1/0.4

f_1/0.4



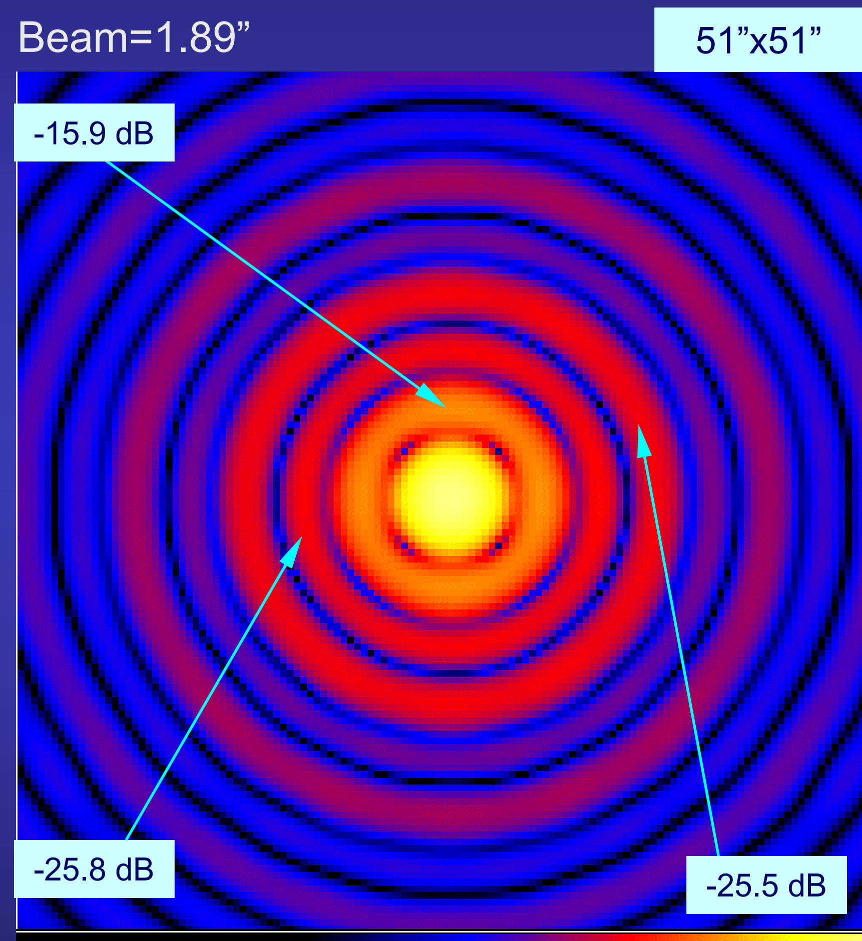
f_1/0.6 Uniform Illumination (at 200 μm)

Strehl=96.8% ε_{rms}= 0.0331λ = 6.6 μm



Phase Distribution at Aperture [λ]

Beam=1.89”



Far Field Radiation Pattern [dB]

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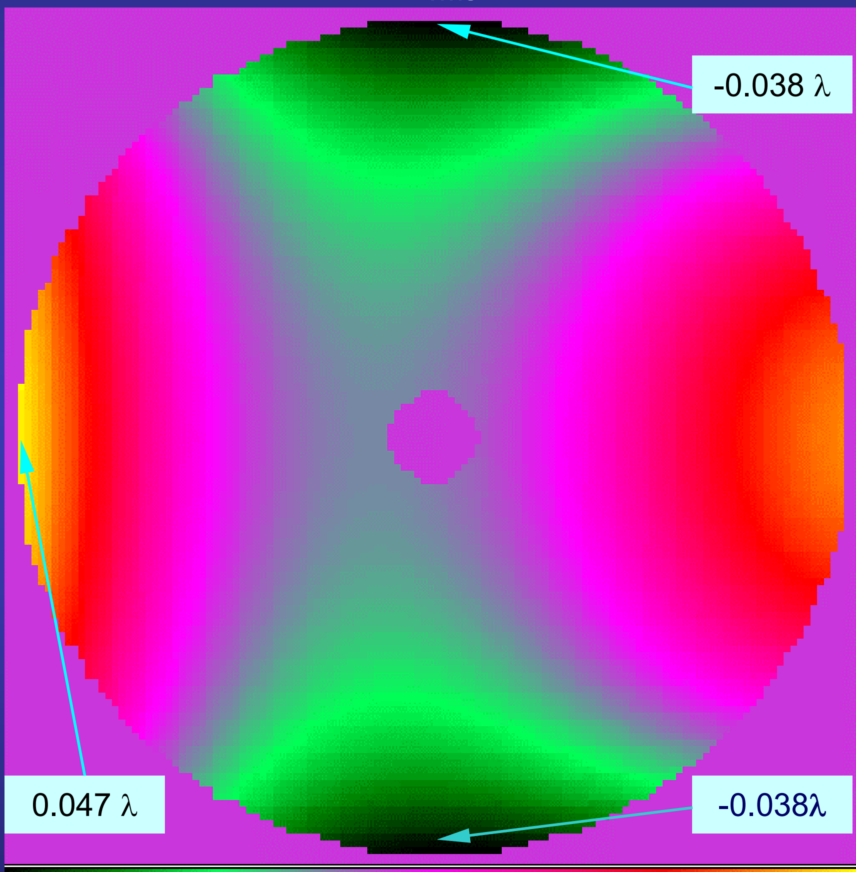
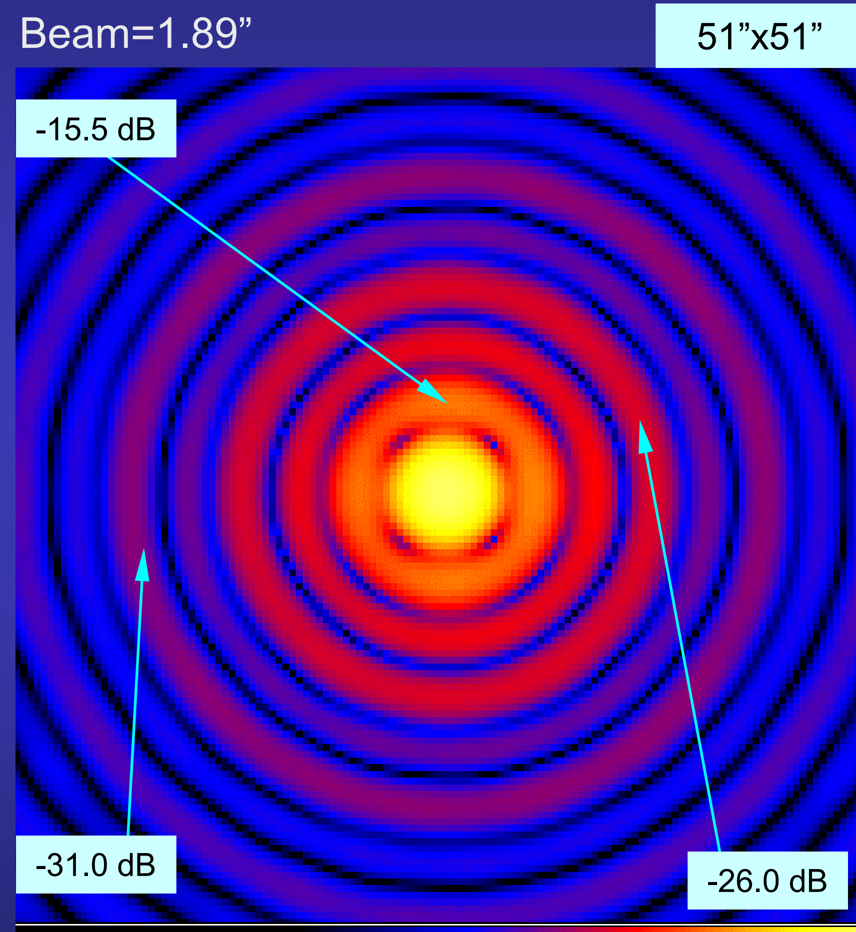
$f_1/0.4$ Uniform Illumination (at 200 μm)

Strehl=95.0% ε_{rms}= 0.0358λ = 7.2 μm



Phase Distribution at Aperture [λ]

Beam=1.89”



Far Field Radiation Pattern [dB]

Strehl Ratio vs. Number of Beams

$f_1/0.6$ vs. $f_1/0.4$

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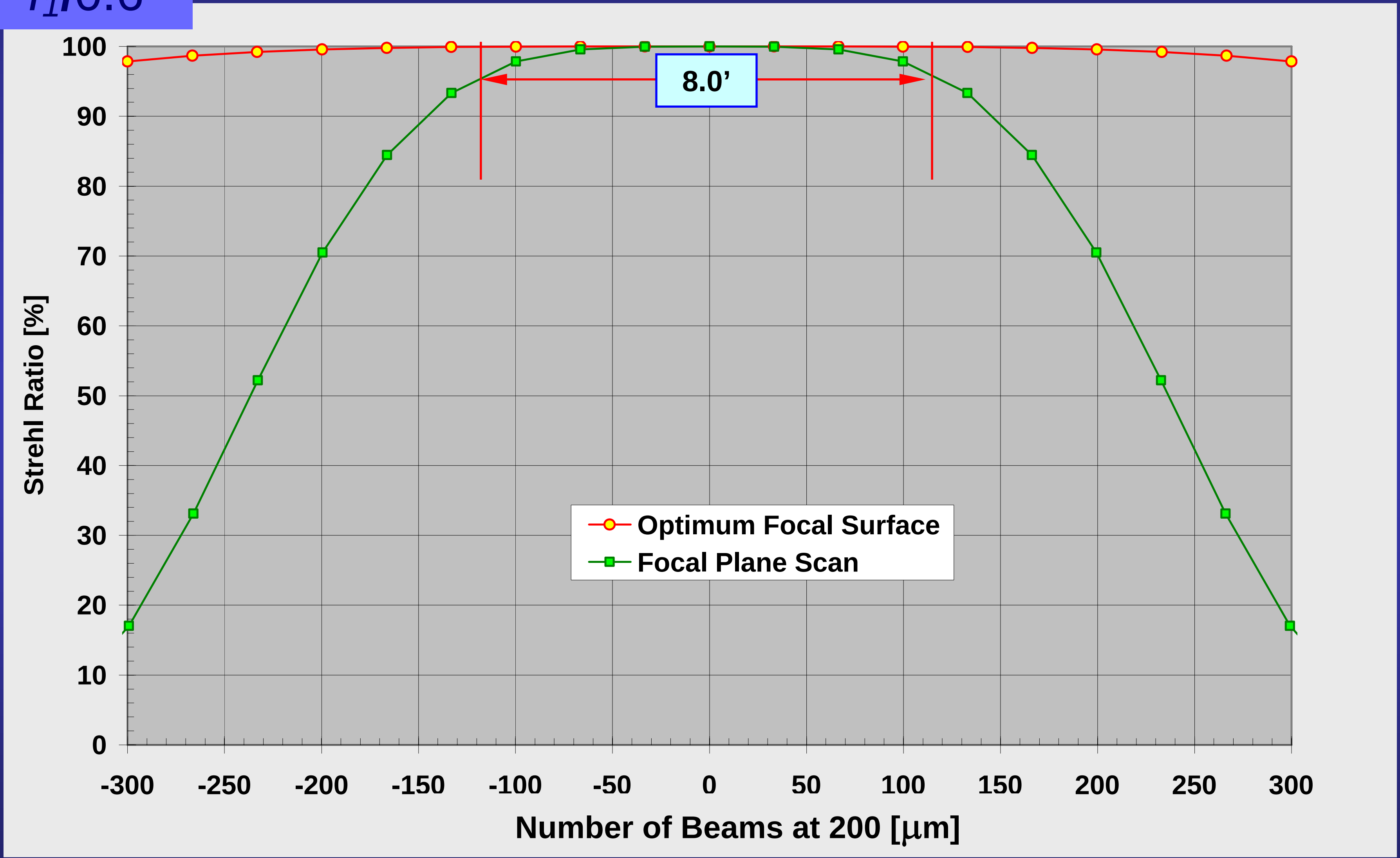
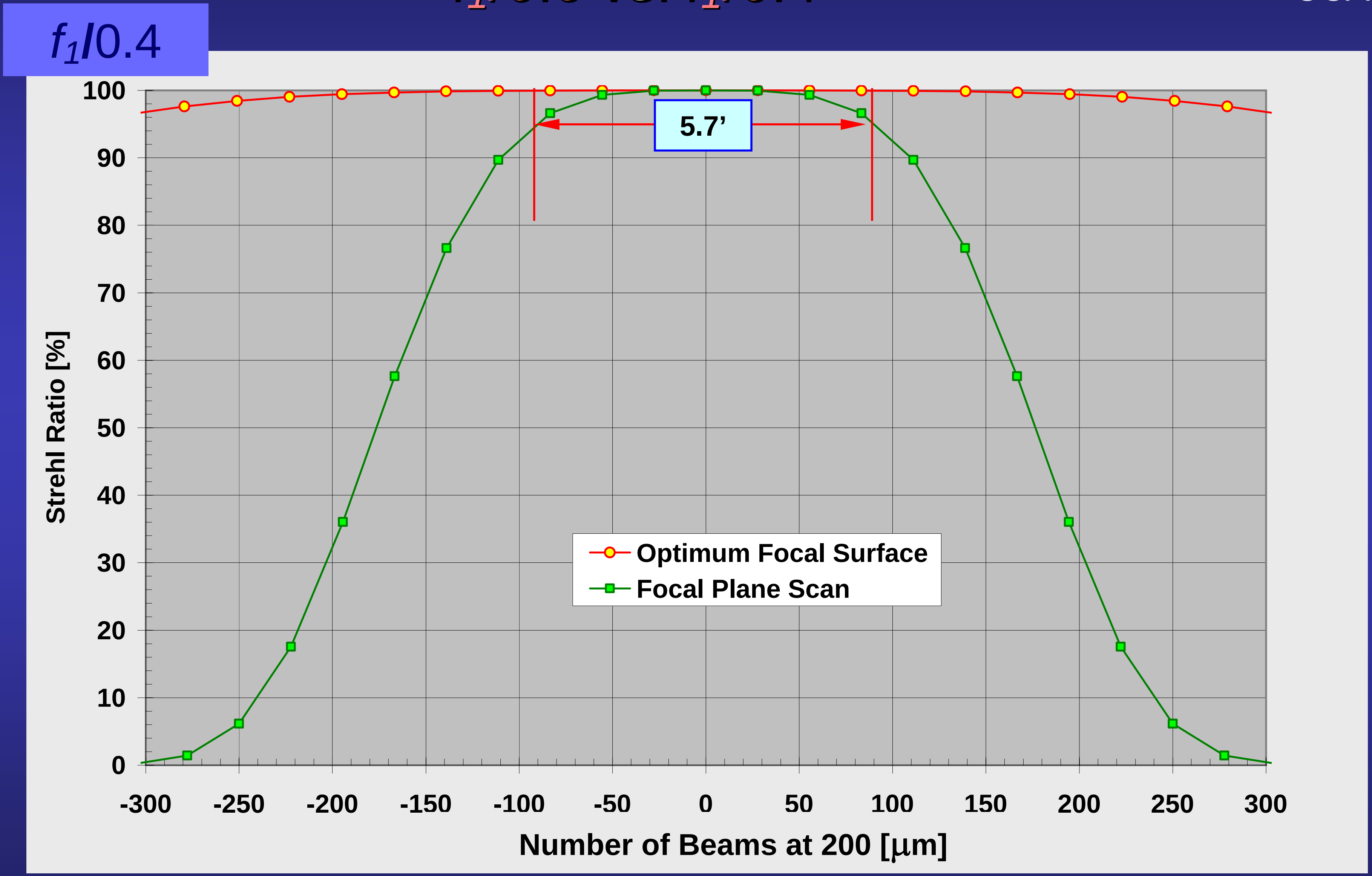
$f_1/0.6$



Strehl Ratio vs. Number of Beams

$f_1/0.6$ vs. $f_1/0.4$



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M2 Positioning and Image Quality

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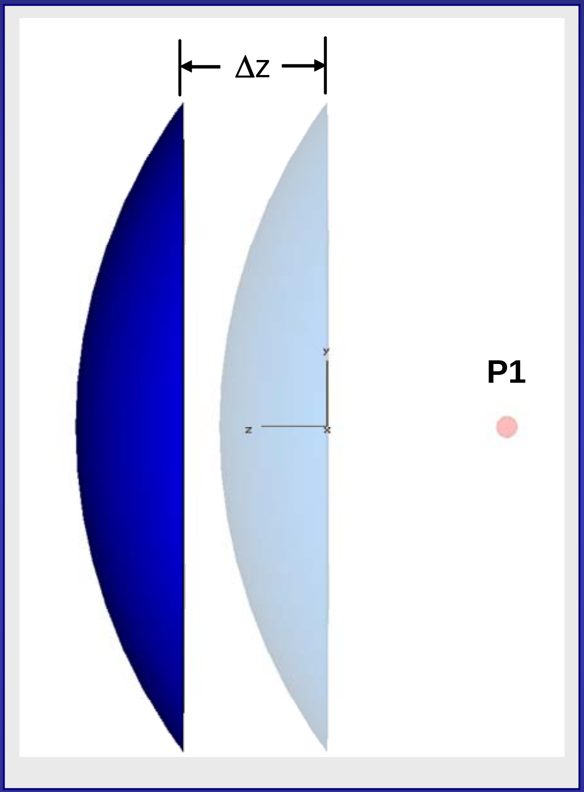
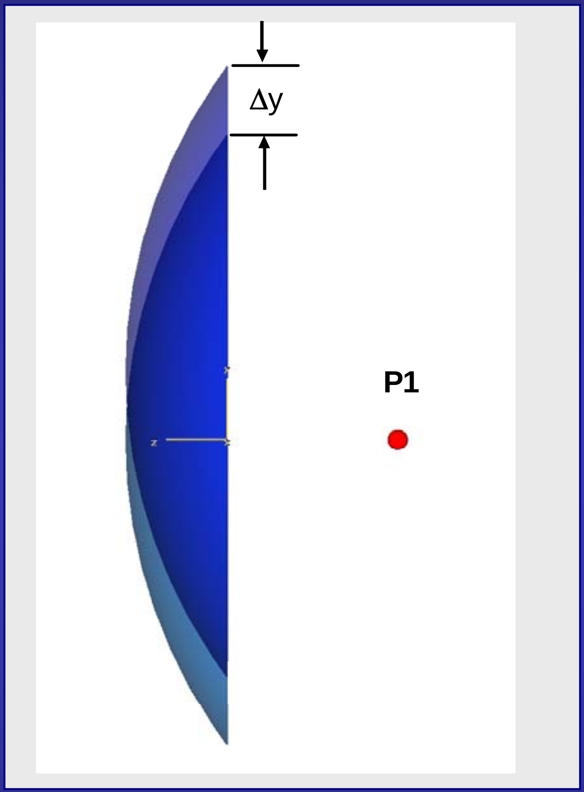
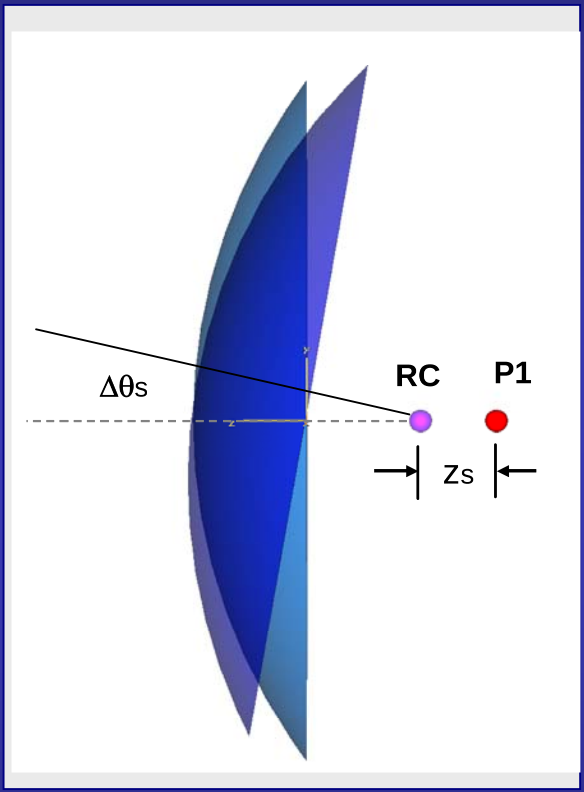


FOCUSING



DE-CENTER

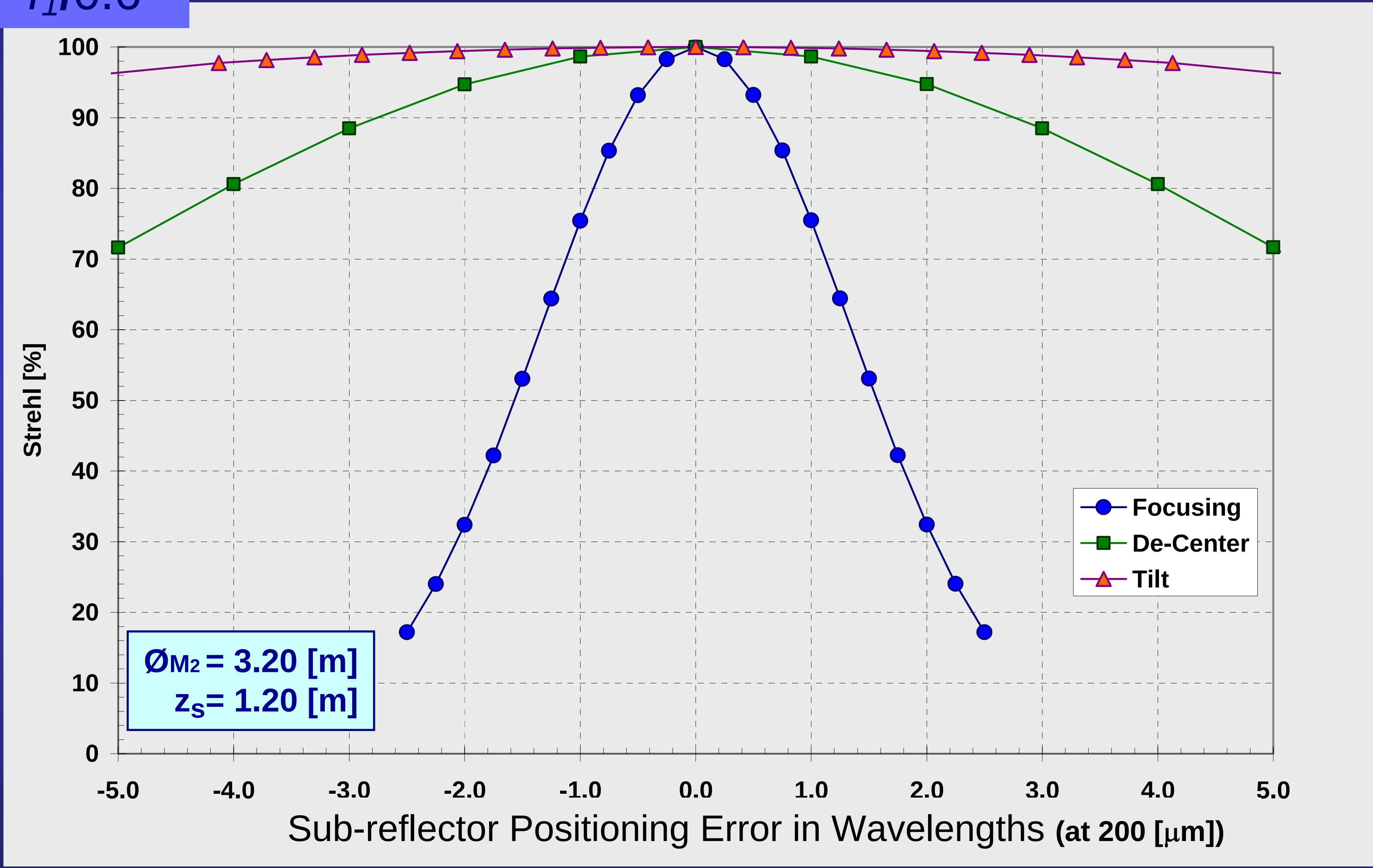


TILT

Strehl Ratio vs. M2 Positioning

f_1/0.6 vs. f_1/0.4

f_1/0.6



Strehl Ratio vs. M2 Positioning

f_1/0.6 vs. f_1/0.4

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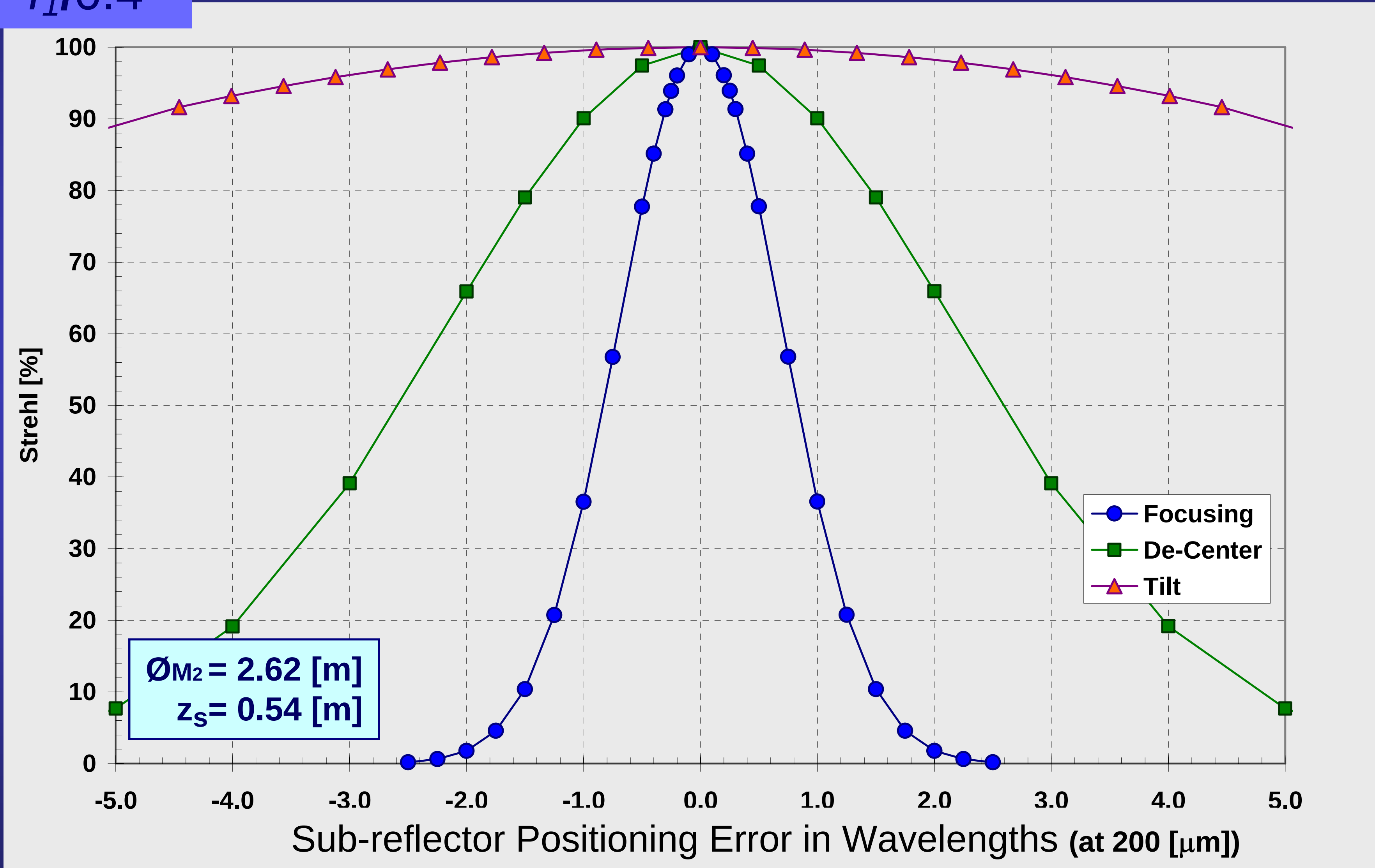
f_1/0.4



M_2 Positioning Requirements for Image Quality Strehl > 95% at 200 μm

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	Focus $\lvert\Delta z\rvert$ [μm]	De-center $\lvert\Delta x^2+\Delta y^2\rvert^{1/2}$ [μm]	Diameter $Ø_{M2}$ [m]
$f_1/0.6$	< 80.0	< 380.0	3.20
$f_1/0.4$	< 45.0	< 120.0	2.62

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M_2 Positioning and Beam Deviation

Beam Deviation vs. M2 Lateral Displacement

$f_1/0.6$ vs. $f_1/0.4$ at 200 μm

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	Lateral Sensitivity [arcsec/mm]	Diameter ØM2 [m]
$f_1/0.6$	-10.93	3.20
$f_1/0.4$	-14.33	2.62

Beam Deviation vs. M2 Tilt

$f_1/0.6$ vs. $f_1/0.4$

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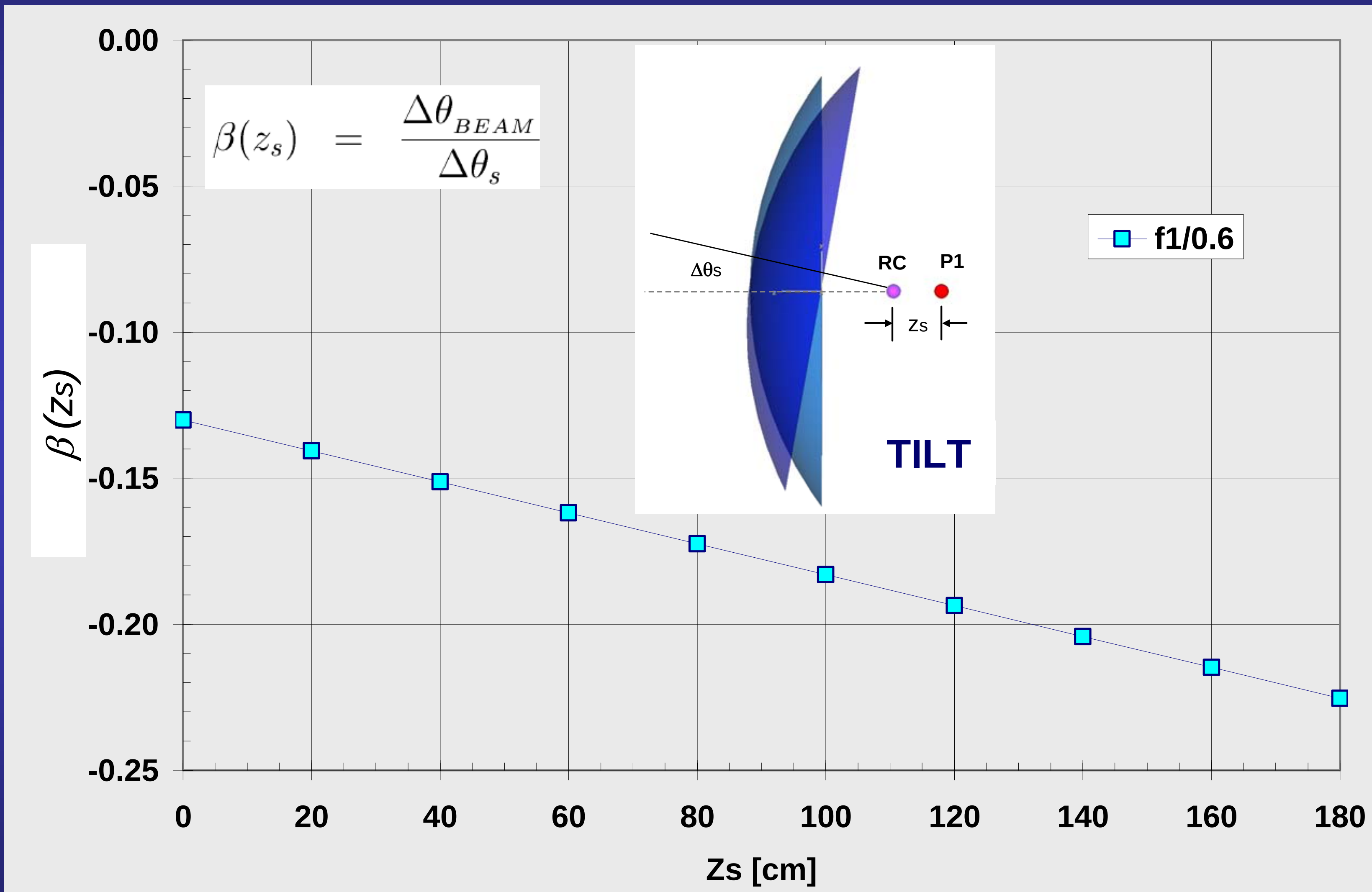
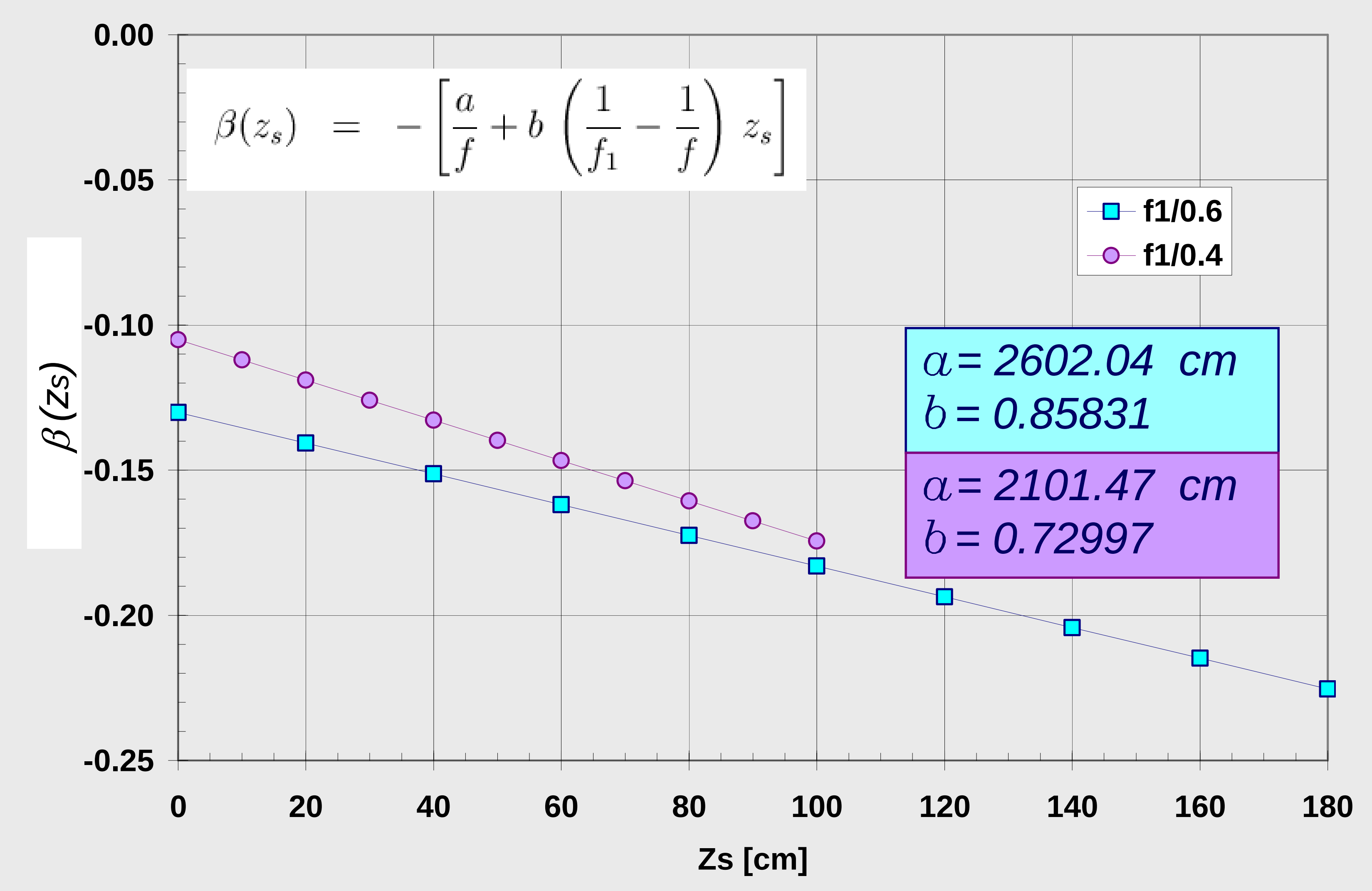


at 200 [μm]

Beam Deviation vs. M2 Tilt

$f_1/0.6$ vs. $f_1/0.4$


CCAT

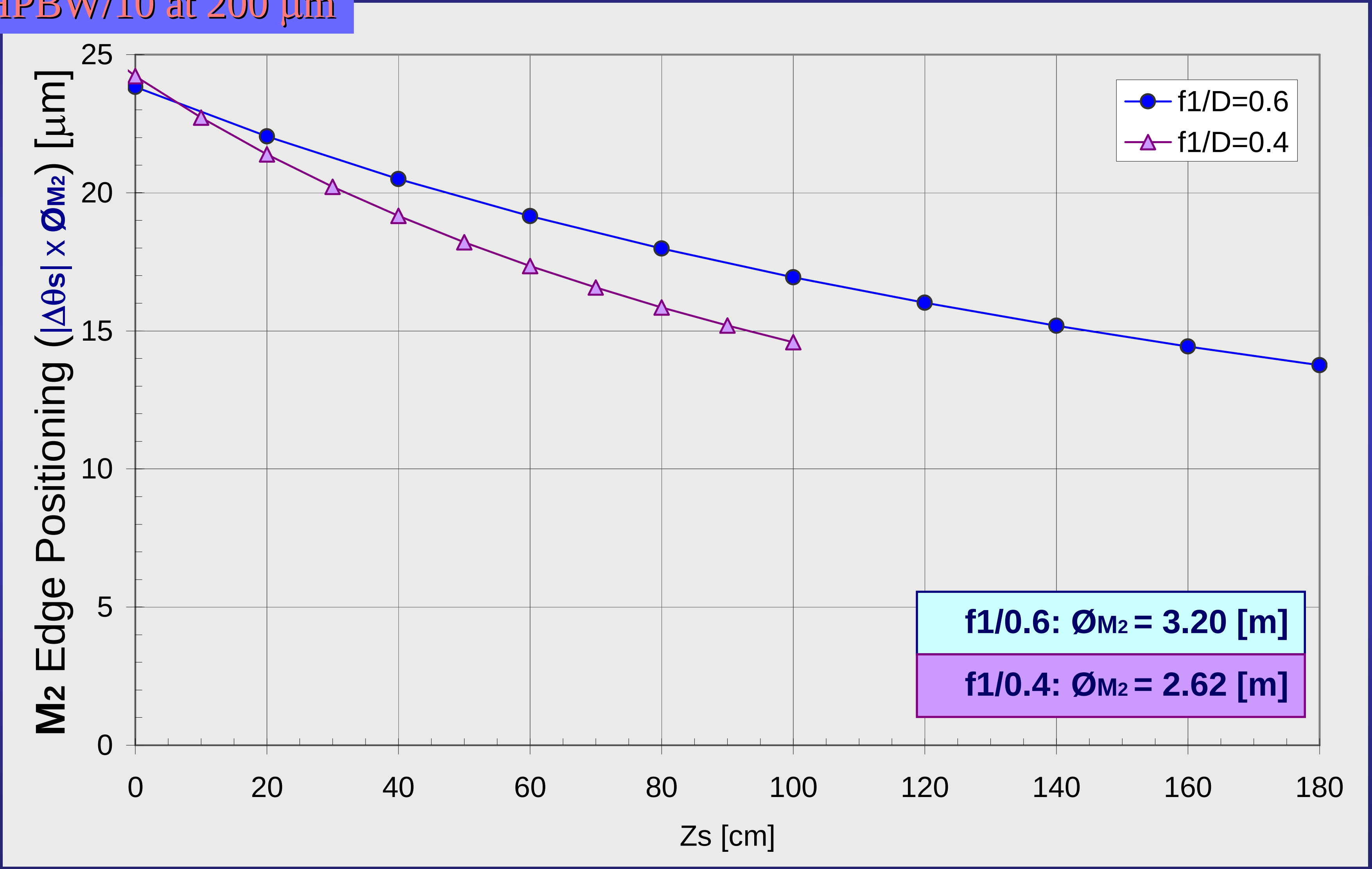


at 200 [μm]

M2 Positioning Requirements for Pointing

f_1/0.6 vs. f_1/0.4

HPBW/10 at 200 μm



M2 Positioning Requirements for Pointing
f_1/0.6 vs. f_1/0.4

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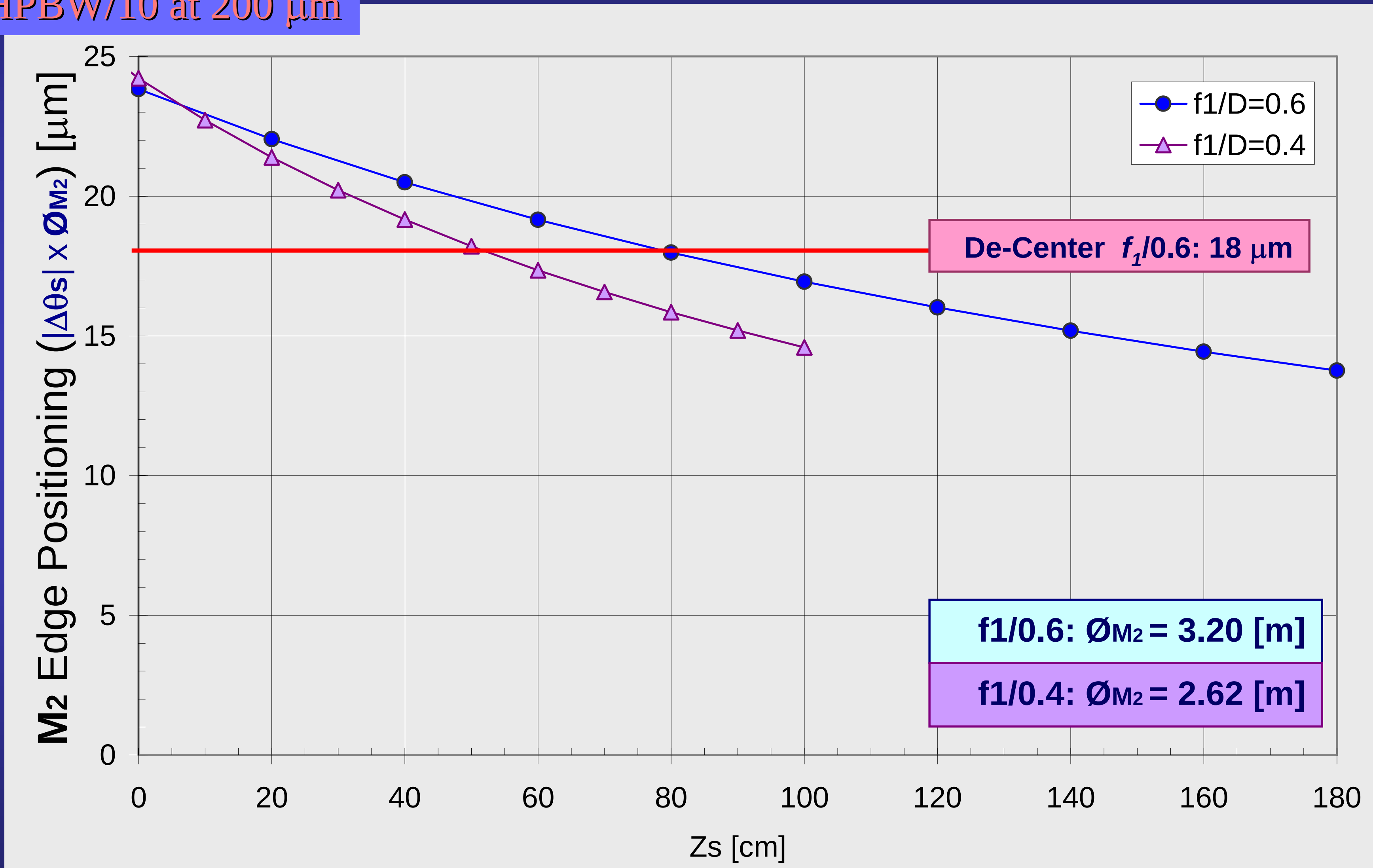
HPBW/10 at 200 μm



M2 Positioning Requirements for Pointing
f_1/0.6 vs. f_1/0.4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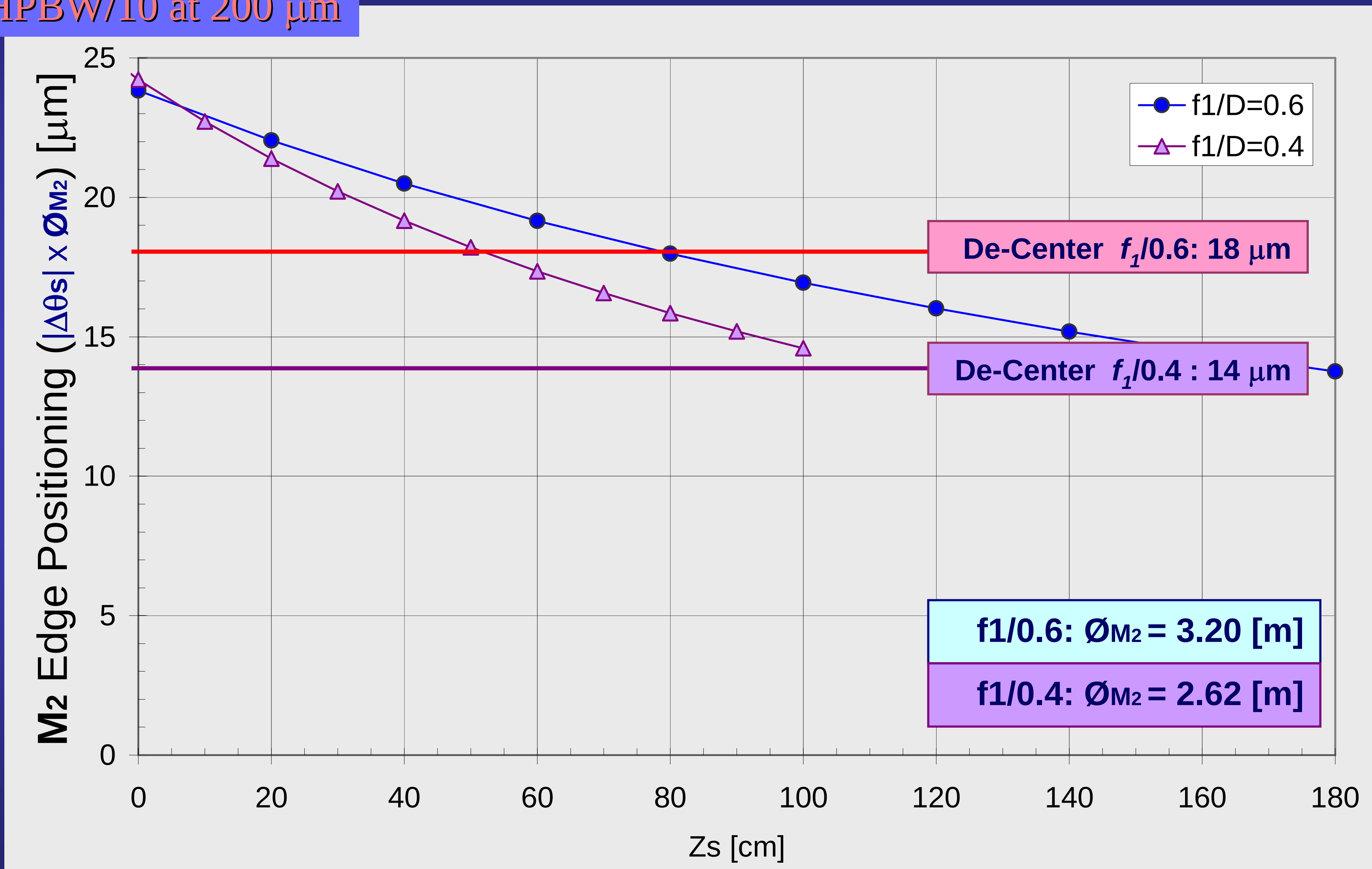
HPBW/10 at 200 μm



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M2 Nutation and Image Quality

M2 Nutation and Image Quality

$f_1/0.6$ vs. $f_1/0.4$


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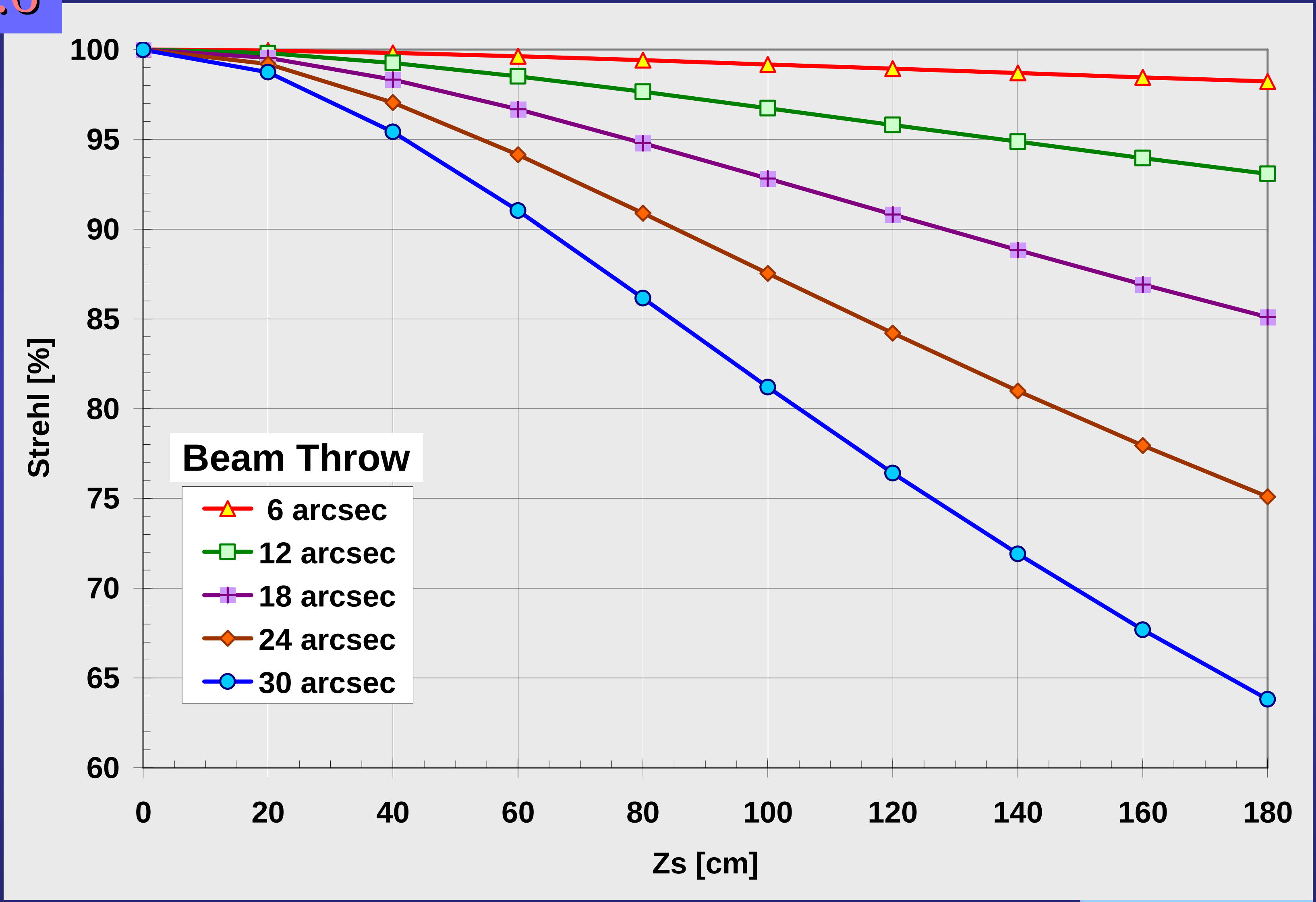
$f_1/0.6$



λ= 200 µm

M2 Nutation and Image Quality

$f_1/0.6$ vs. $f_1/0.4$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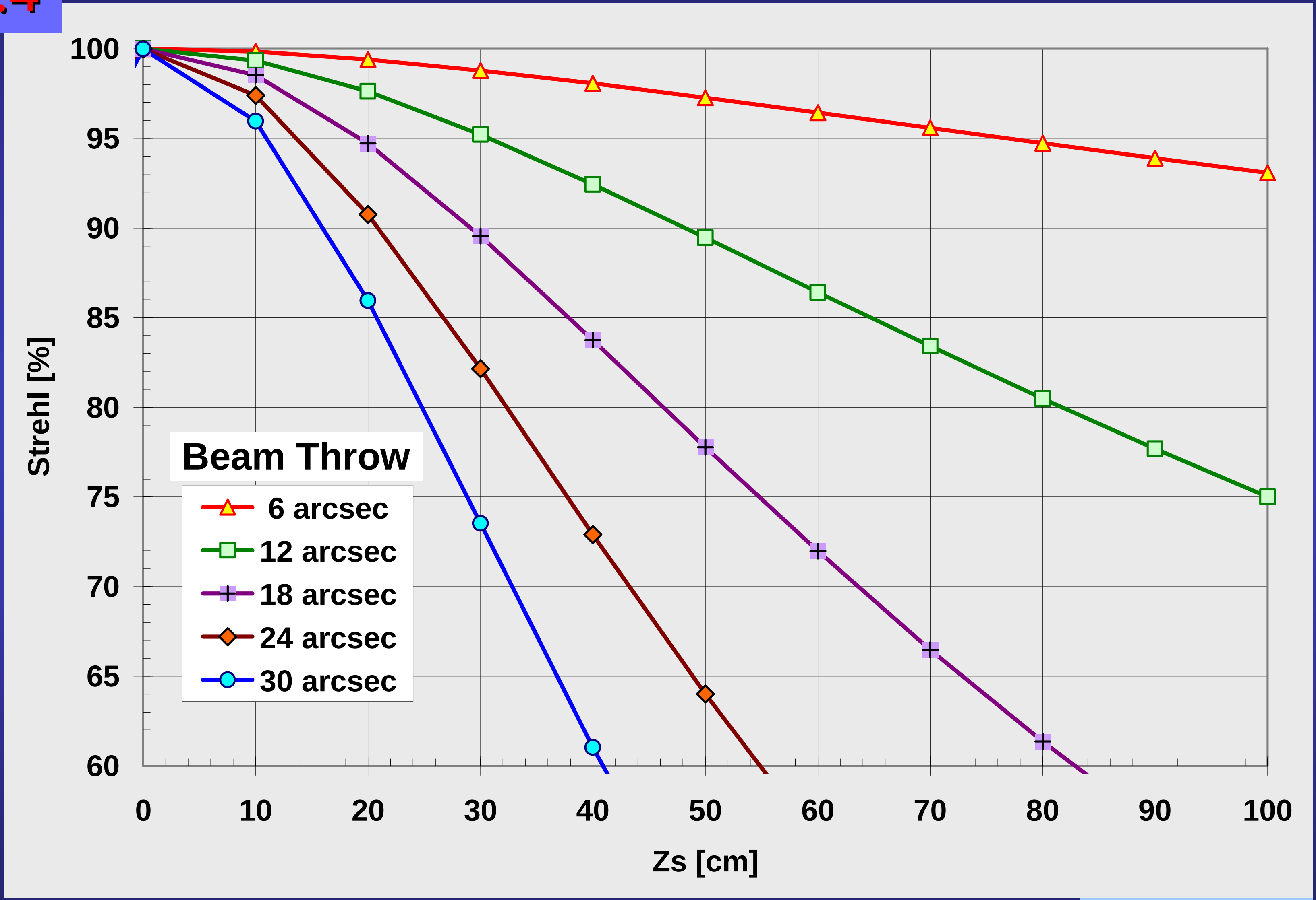
$f_1/0.4$



λ= 200 μm

Conclusions I

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- There is reduction in the distance between the main reflector vertex and the edge of M2 from 13.5m with an f1/0.6 design to a 9.4m with a f1/0.4 design.
- Reduction in M2 diameter:
  - for f1/0.6 design is 3.2m
  - for f1/0.4 design is 2.6m.
- The calculated Strehl ratio variations over the 20’ FOV
  - for f1/0.6 design are better than 97% (optimal focal surface).
  - for f1/0.4 design are better than 95% (optimal focal surface).
- Size of FOV on a flat focal plane:
  - for f1/0.6 is 8.0 arcmin, with a Strehl ≥ 95%
  - for f1/0.4 is 5.7 arcmin, with a Strehl ≥ 95%
- Radius of curvature of the optimal focal surface at Nasmyth Foci
  - for f1/0.6 is 1.94m, and
  - for f1/0.4 is 1.07m.

Conclusions I   Cont…

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- M2 Positioning and Image Quality at 200μm:
  - Both cases are dominated by M2 focusing sensitivity, but while for the f1/0.6 it requires maintain the M2 focusing errors <80 μm, for an f1/0.4 it requires <45 μm, in order to maintain an Strehl ≥ 95%.
- M2 Positioning and Pointing requirement of θ_{HPFW}/10 at 200μm:
  - For f1/0.6 it requires M2 edge-to-edge displacement due to tilts be between 14 μm and 24 μm, depending the location of the center of nutation. While M2 lateral displacements have to be < 18 μm.
  - For f1/0.4 it requires M2 edge-to-edge displacement due to tilts be between 14.5 μm and 24 μm, depending the location of the center of nutation. While M2 lateral displacements have to be < 14 μm.
- M2 Chopping:
  - Distance between M2 vertex and Prime Focus is almost half for f1/0.4 compared with f1/0.6, which for chopping kinematics and control purposes is better.
  - Number of beam throws with Strehl ≥ 95% is 8 beams for f1/0.6 and 4 beams for f1/0.4, when the center of nutation is located halfway between M2 vertex and prime focus

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Re-Imaging Optics Impact

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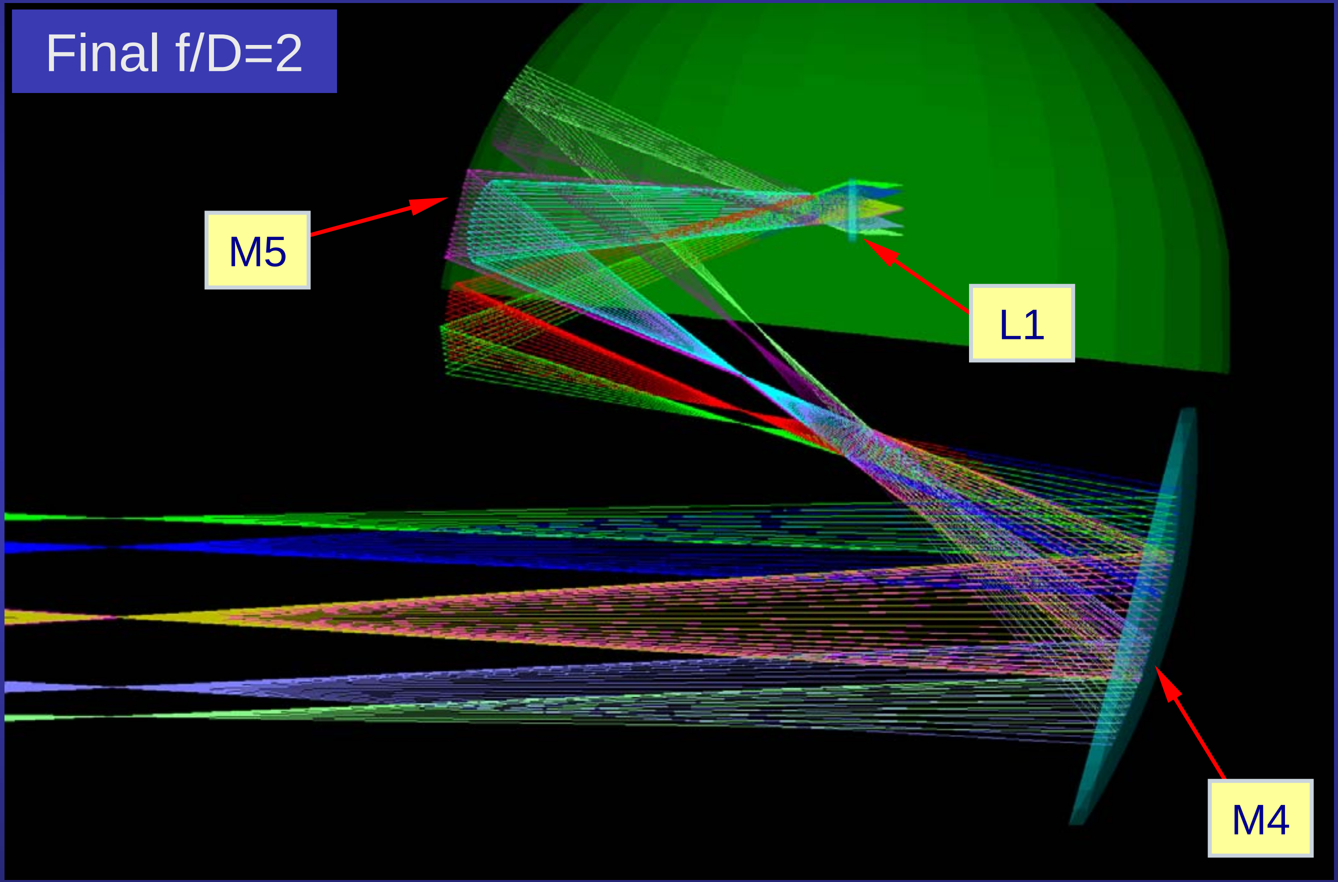
LW-Cam Re-imaging Optics

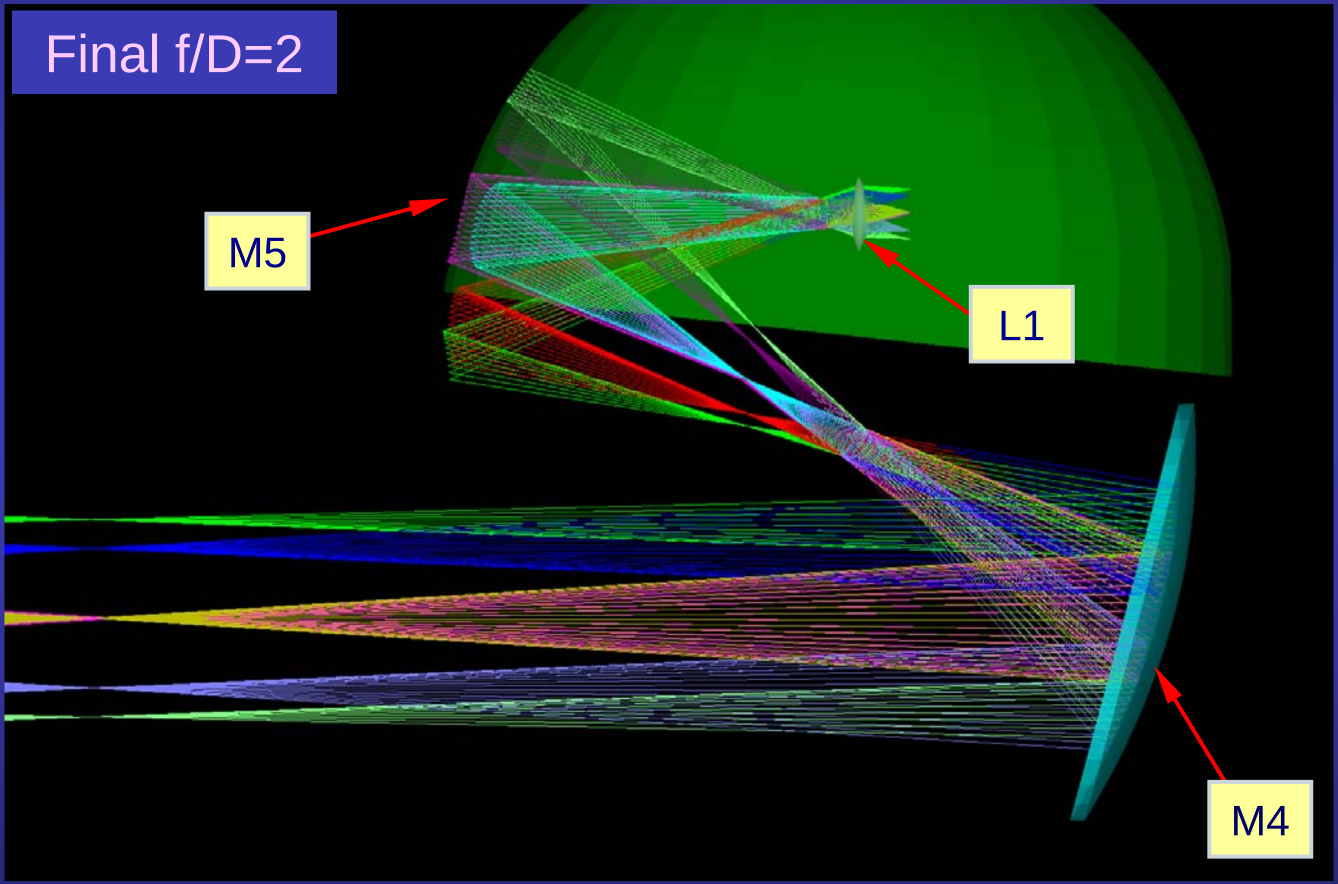
for 20’ Diameter FOV, θ_{inc}=15°, f_1/0.6



LWCam f_1/0.6, θ_{inc}=15°, f/2

LW-Cam Re-imaging Optics

for 20’ Diameter FOV, θ_{inc}=15°, f_1/0.4



LWCam f_1/0.4, θ_{inc}=15°, f/2

LW-Cam Strehl Ratio over FOV

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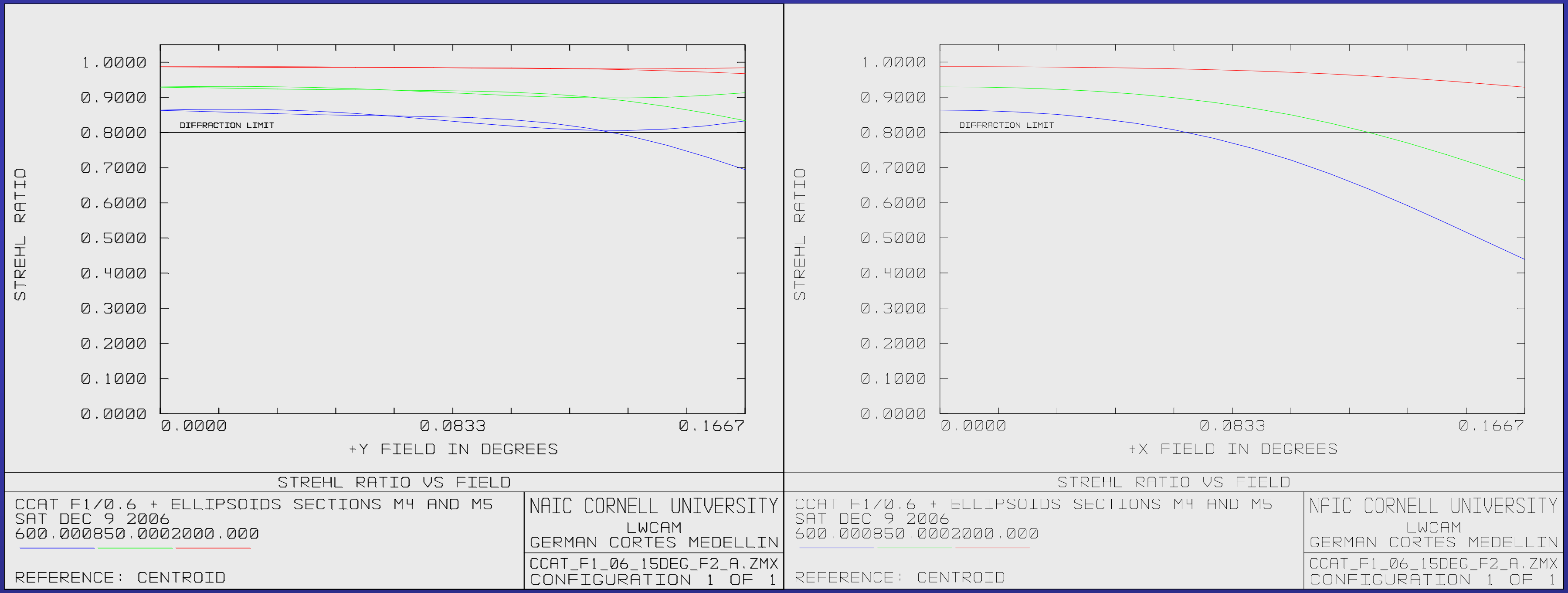
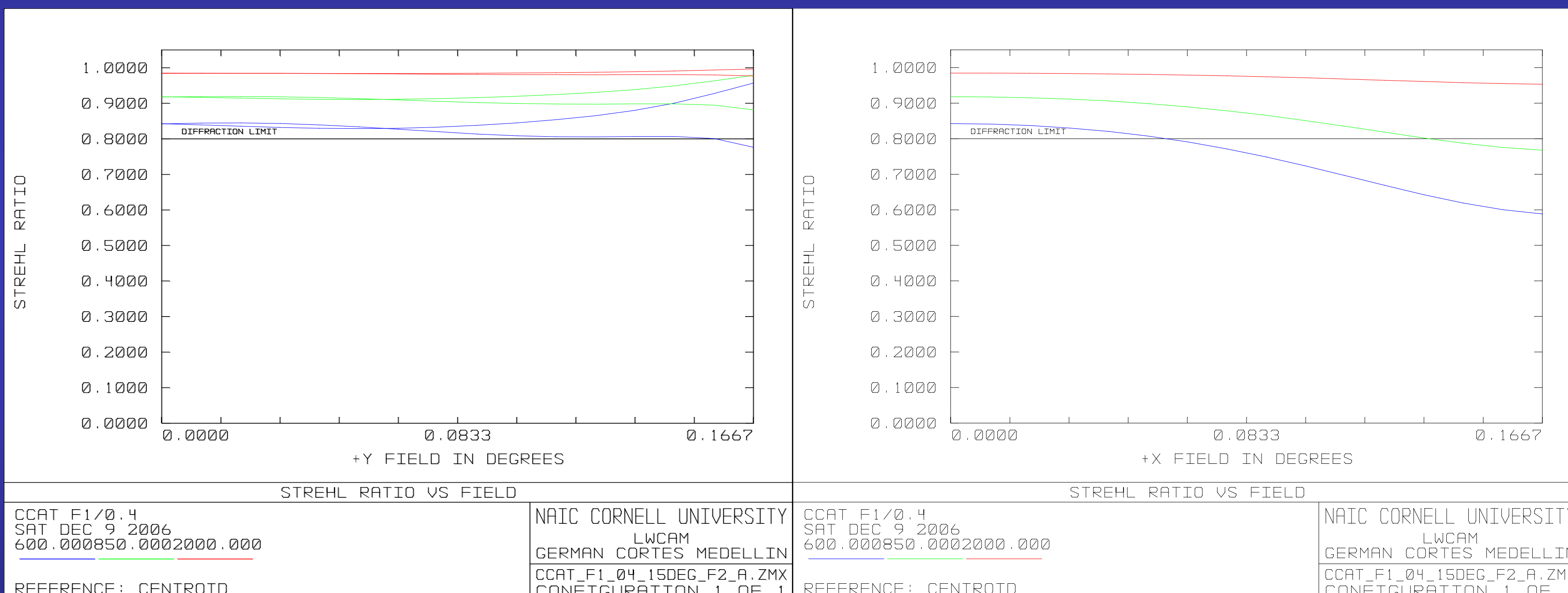
θ_{inc} = 15°, f_1/0.6



CCAT

LW-Cam Strehl Ratio over FOV

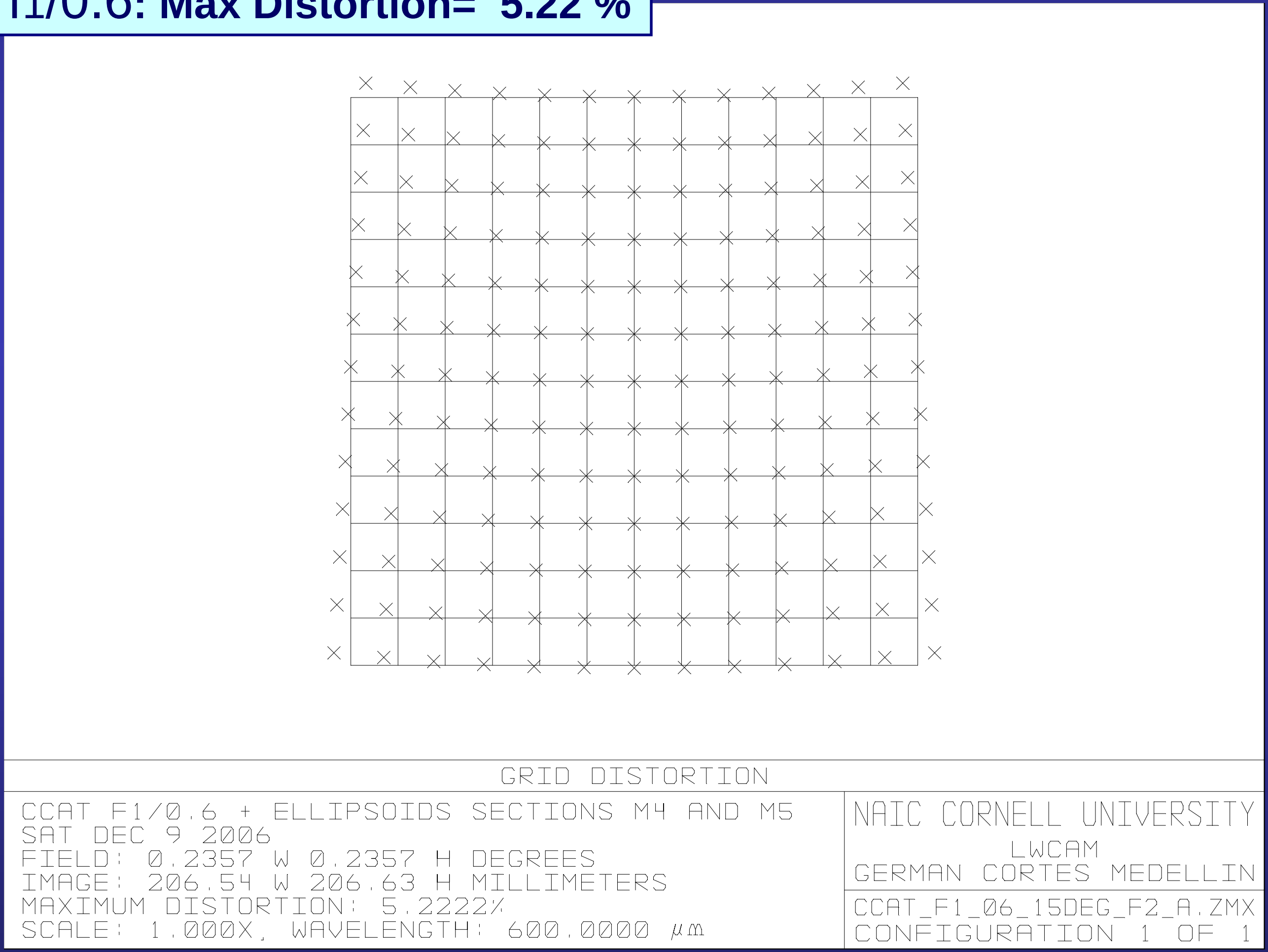
θ_{inc} = 15°, f_1/0.4



LW-Cam Distortion over FOV

$\theta_{inc} = 15°$, $f_1/0.6$

$f_1/0.6$: Max Distortion= 5.22 %



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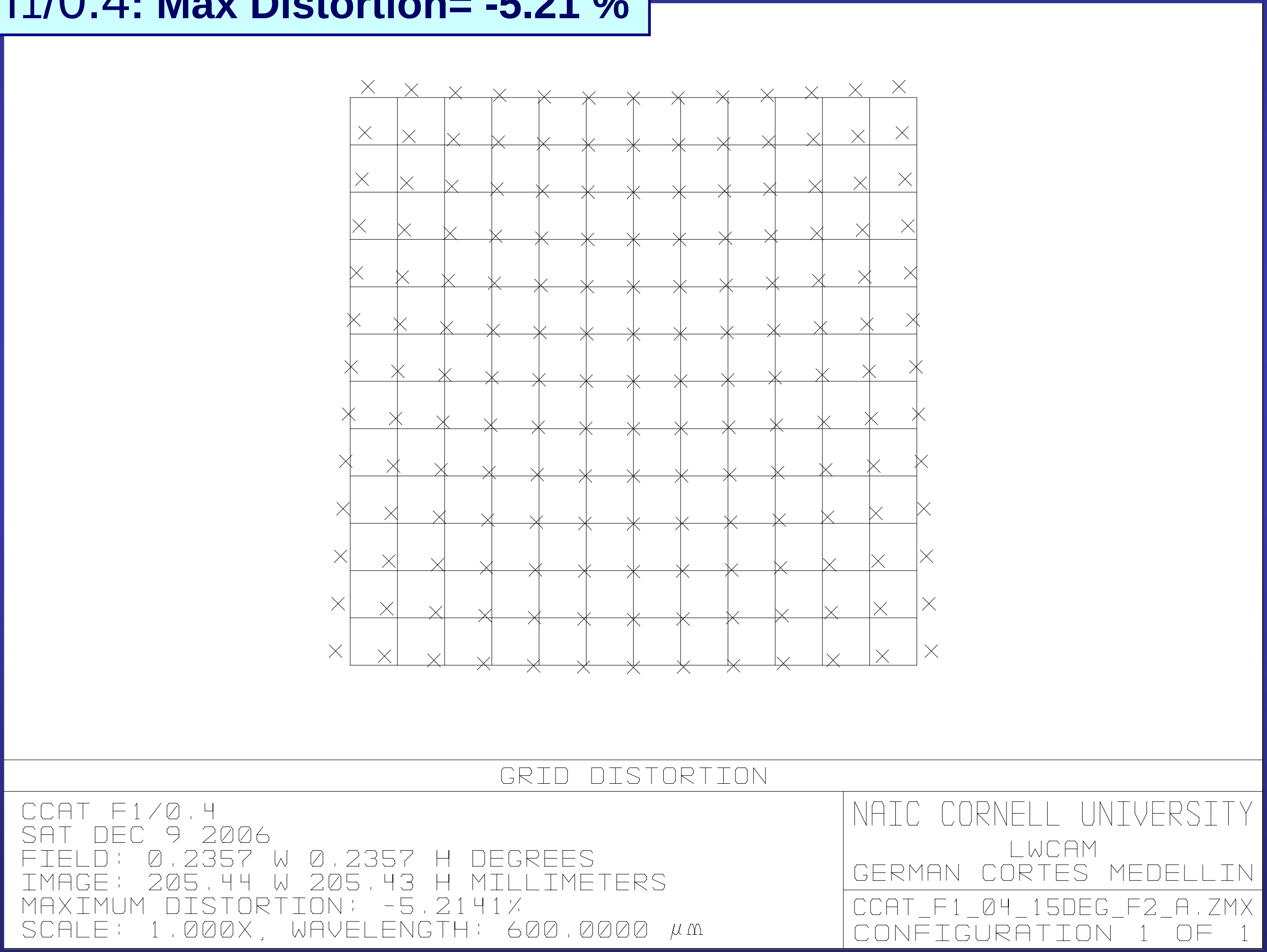
LW-Cam Distortion over FOV

$\theta_{inc} = 15°$, $f_1/0.4$

$f_1/0.4$: Max Distortion= -5.21 %



LW-Cam Spot Diagram

θinc = 15°, f1/0.6

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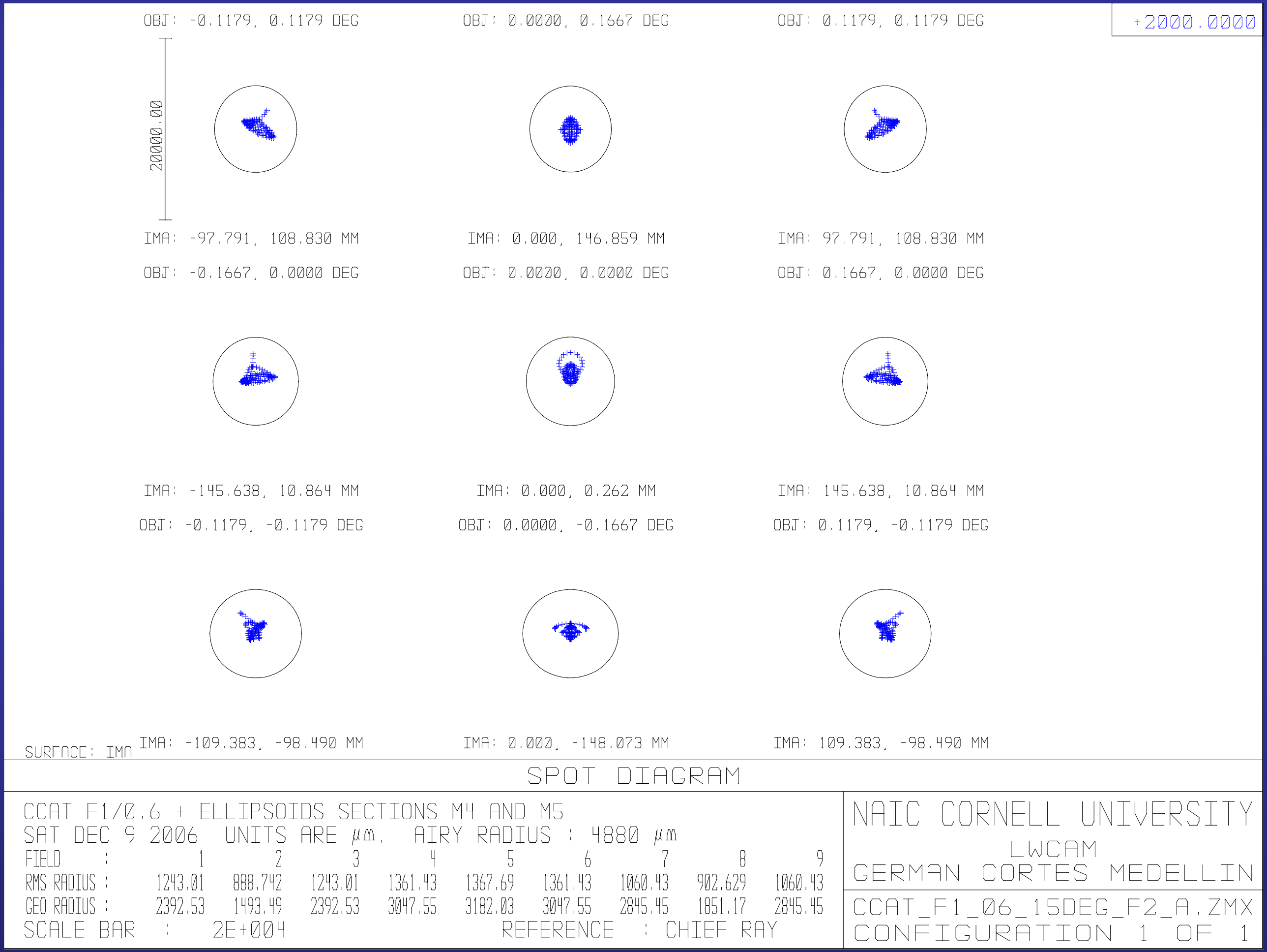

LW-Cam Spot Diagram

θ_{inc} = 15°, f_1/0.4

Active Surface Segment Positioning Errors and Strehl

f_1/0.6 vs. f_1/0.4

Segment Positioning Errors $f_1/0.6$ vs. $f_1/0.4$

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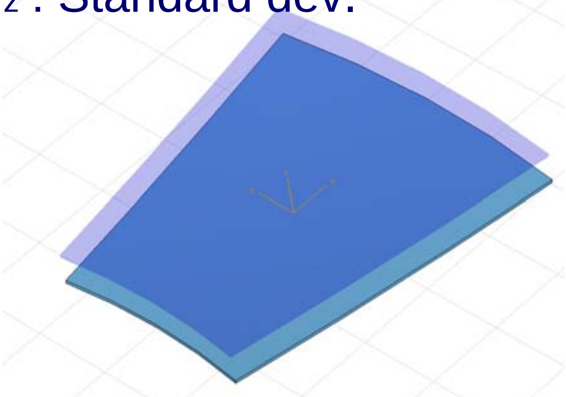
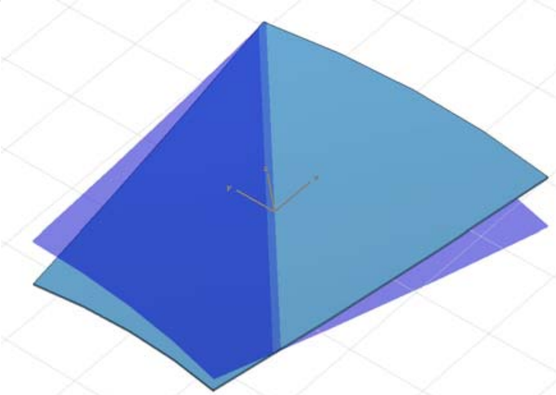
Δz: Gaussian Distributed,
zero mean
σ_z : Standard dev.



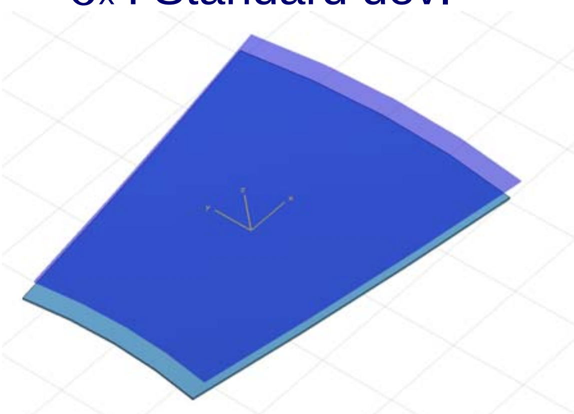
PISTON



TILT/TIP

$\Delta\phi$: Uniform Distrib. $[0, 2\pi]$
$\Delta\theta$: Gaussian Distributed,
zero mean
σ_θ : Standard dev.

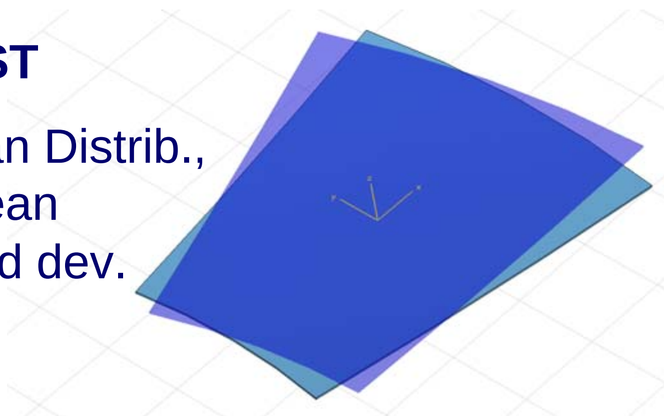
Δx: Gaussian Distributed,
zero mean
σ_x : Standard dev.

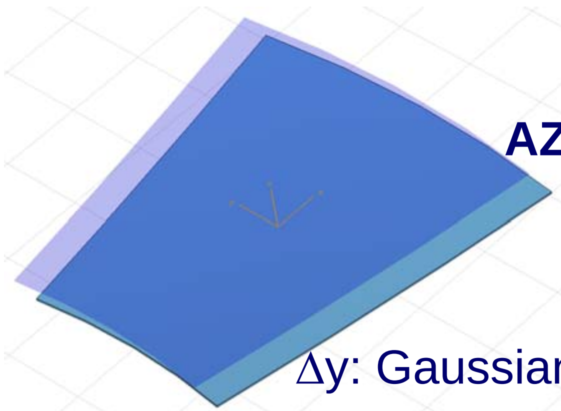


RADIAL

TWIST

$\Delta\omega$: Gaussian Distrib.,
zero mean
σ_ω : Standard dev.



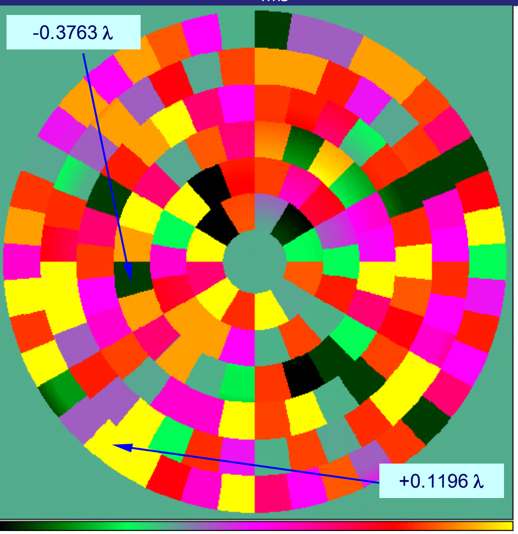


AZIMUTH

Δy: Gaussian Distrib.
zero mean
σ_y : Standard dev.

Segment Positioning Errors *f_1/0.6* vs. *f_1/0.4*

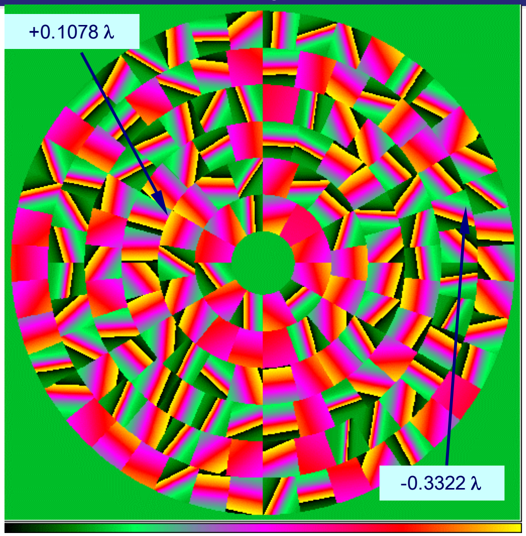
Strehl= 89.6% ε_{rms}= 0.0264λ = 5.7 µm



Aperture Phase Distribution [λ]

PISTON

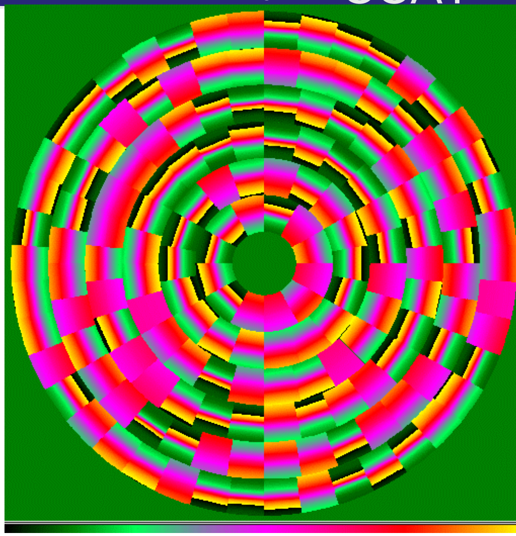
Strehl= 80.7% ε_{rms}= 0.0369λ = 7.4 µm



Aperture Phase Distribution [λ]

TILT/TIP

Strehl= 91.9% ε_{rms}= 0.0231λ = 4.6 µm



Aperture Phase Distribution [λ]

RADIAL

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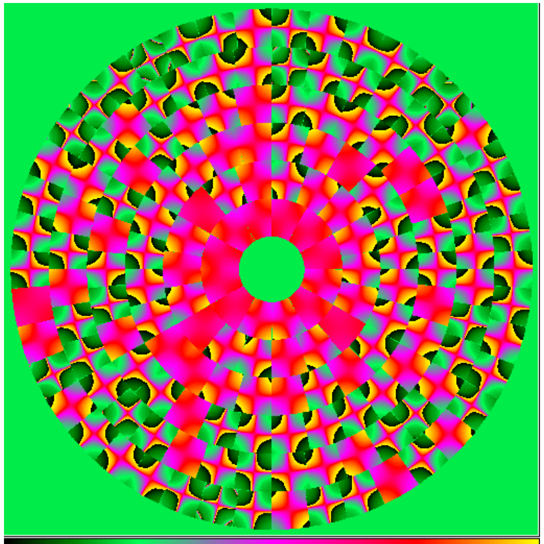
Strehl= 43.5% 14.5 µm



Aperture Phase Distribution [λ]

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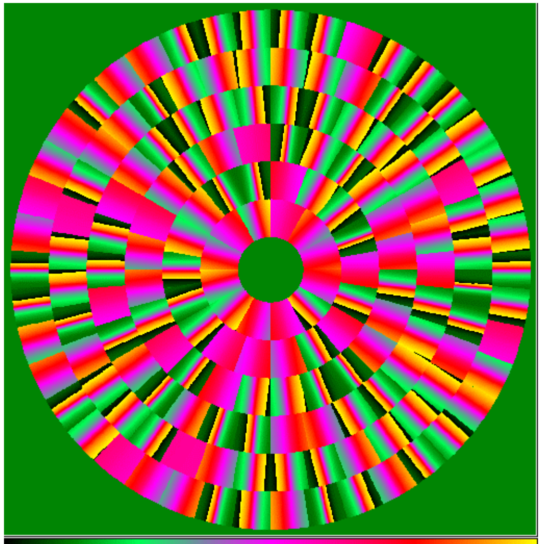
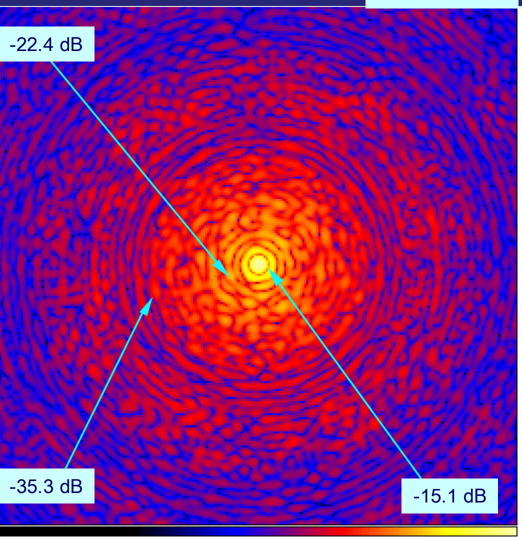
Strehl= 90.8% 4.9 µm



Aperture Phase Distribution [λ]

Segment Positioning Errors $f_1/0.6$ vs. $f_1/0.4$

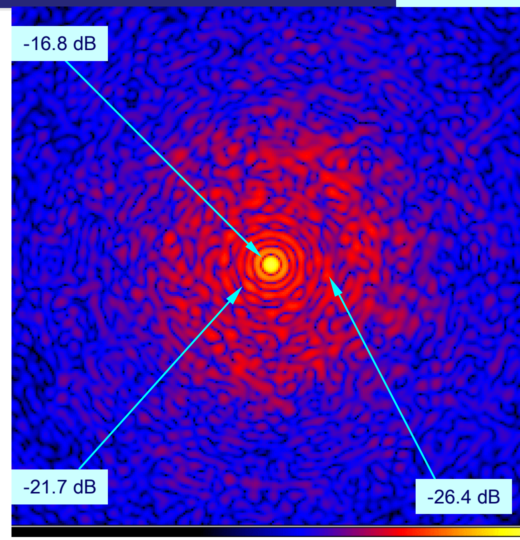
Beam=1.97” 3.4’ x 3.4’



Far Field Radiation Pattern [dB]

PISTON

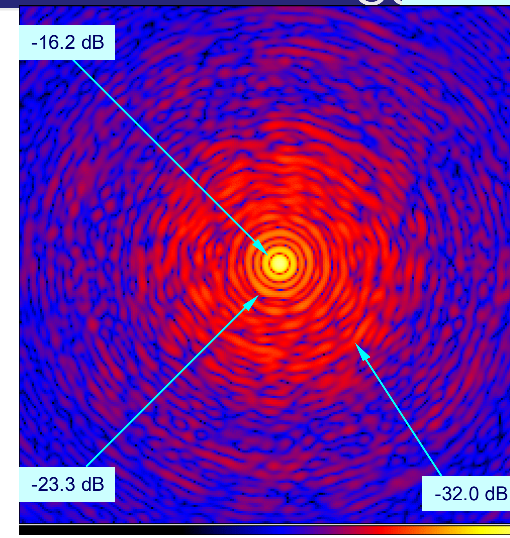
Beam=2.01” 3.4’x 3.4’



Far Field Radiation Pattern [dB]

TILT/TIP

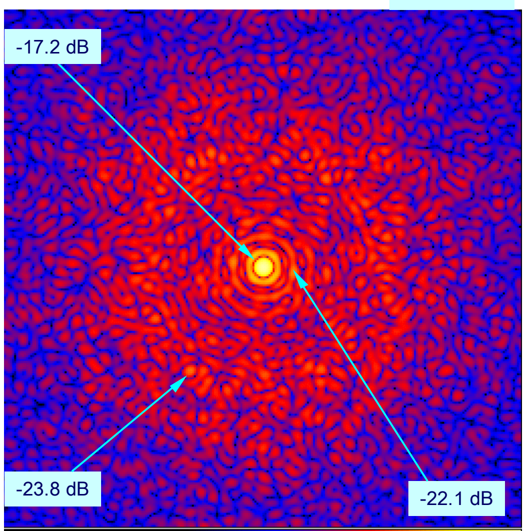
Beam=1.95” 3.4’x 3.4’



RADIAL

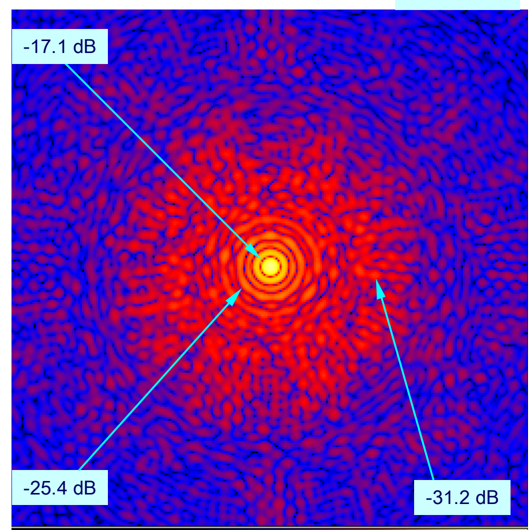
TWIST

3.4’x 3.4’



Far Field Radiation Pattern [dB]

3.4’x 3.4’



AZIMUTH

Segment Piston Errors

$f_1/0.6$ vs. $f_1/0.4$

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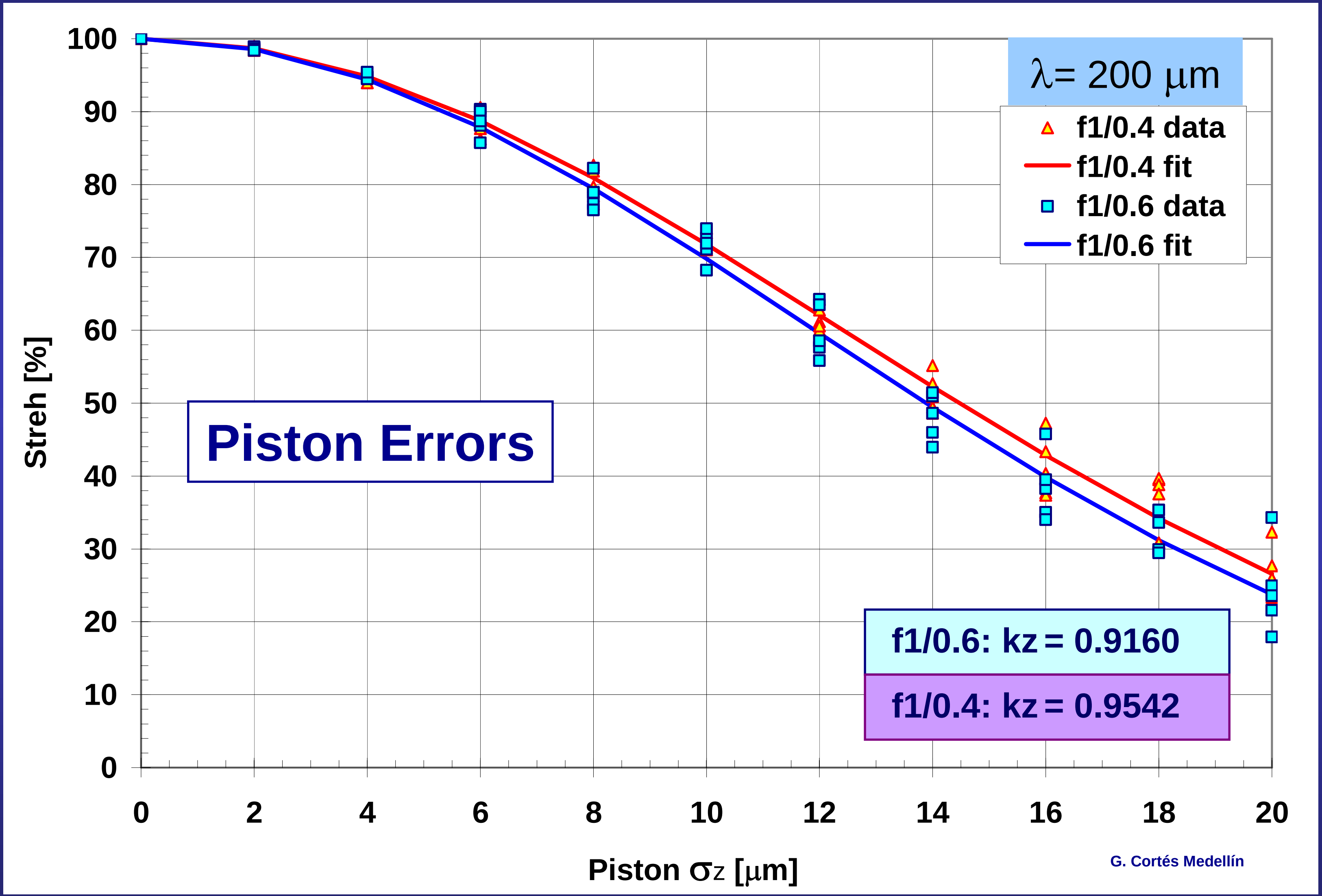
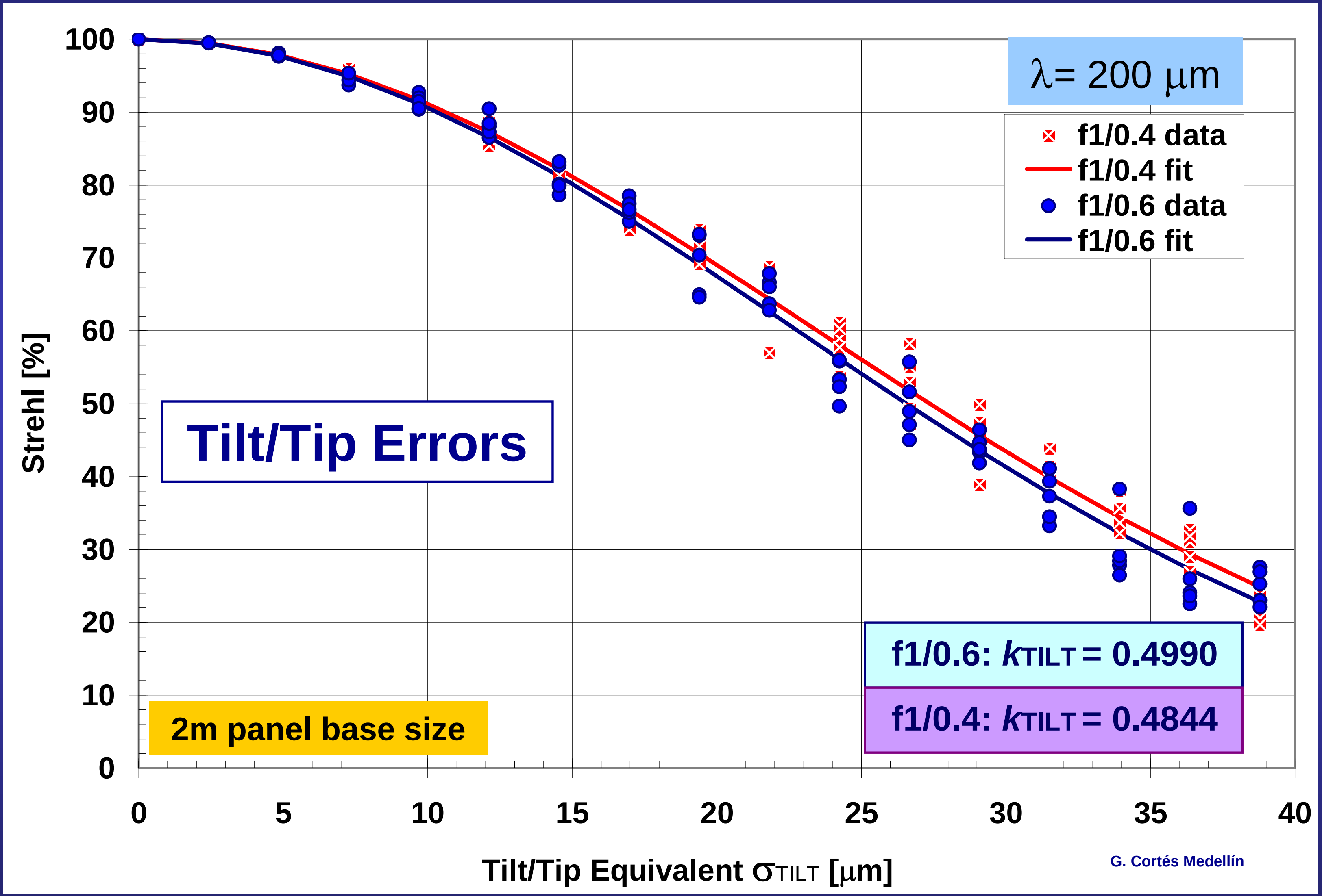


Segment Tilt/Tip Errors

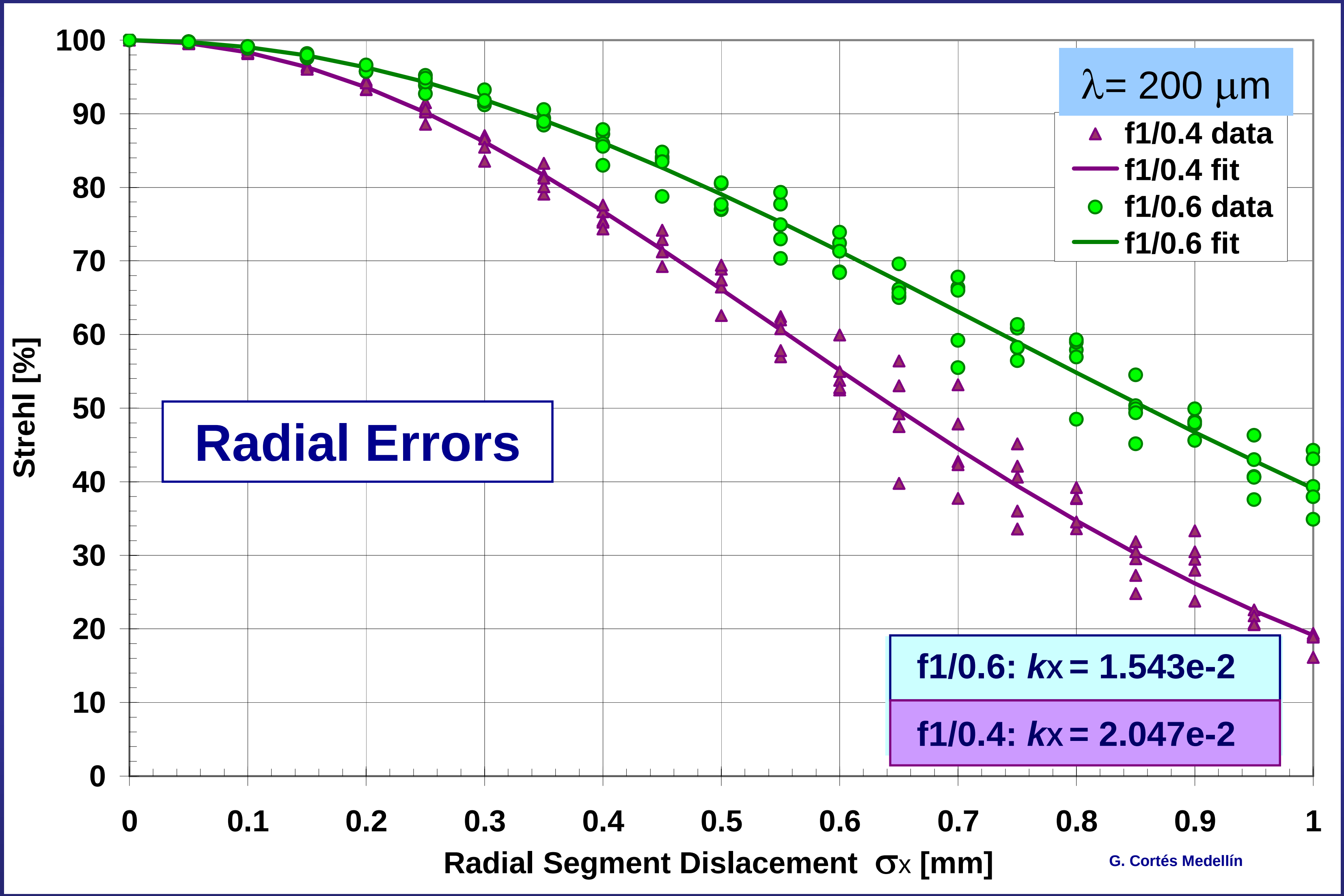
$f_1/0.6$ vs. $f_1/0.4$


CCAT



Segment Radial Positioning Errors

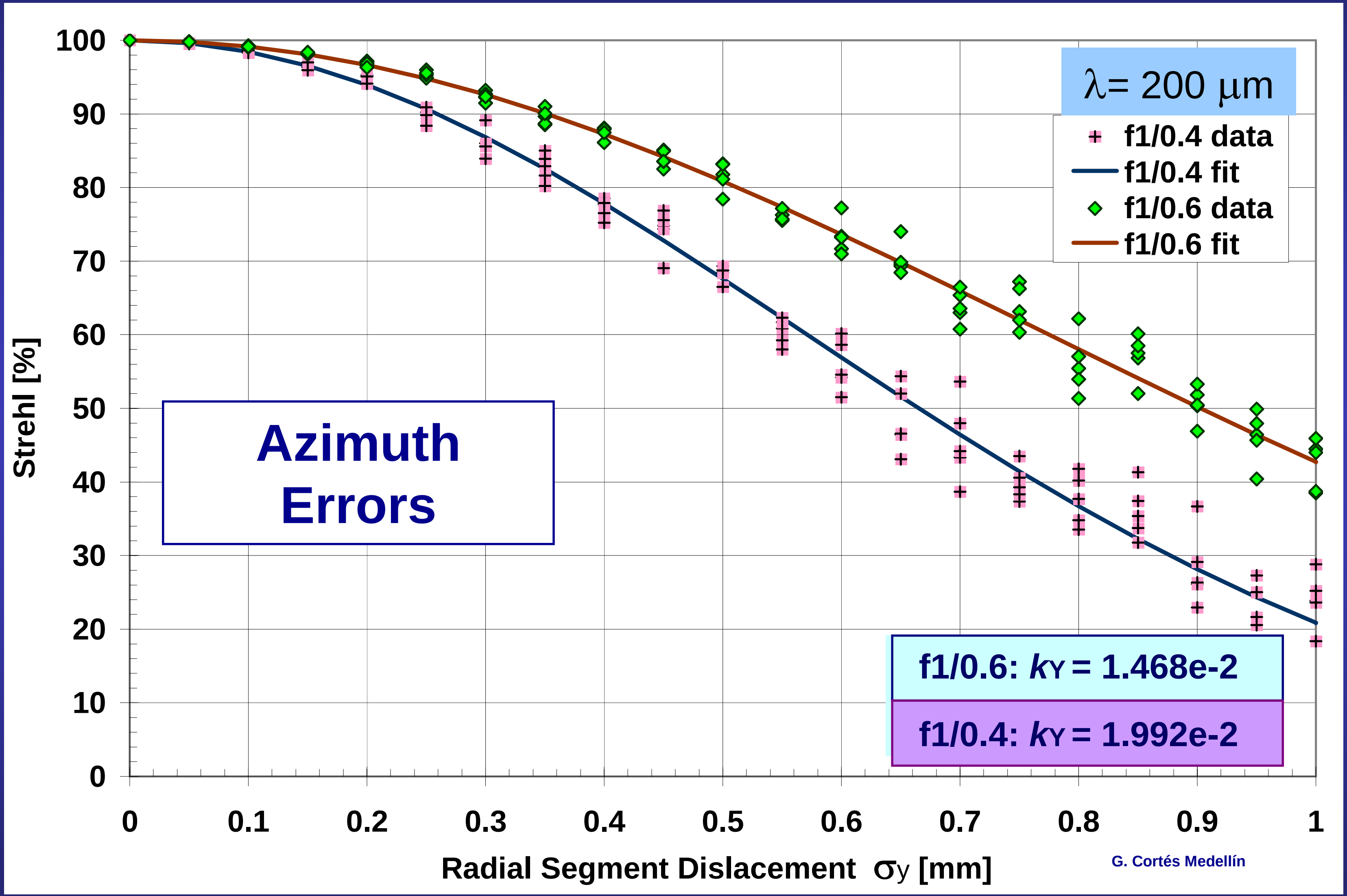
$f_1/0.6$ vs. $f_1/0.4$



Segment Azimuth Positioning Errors

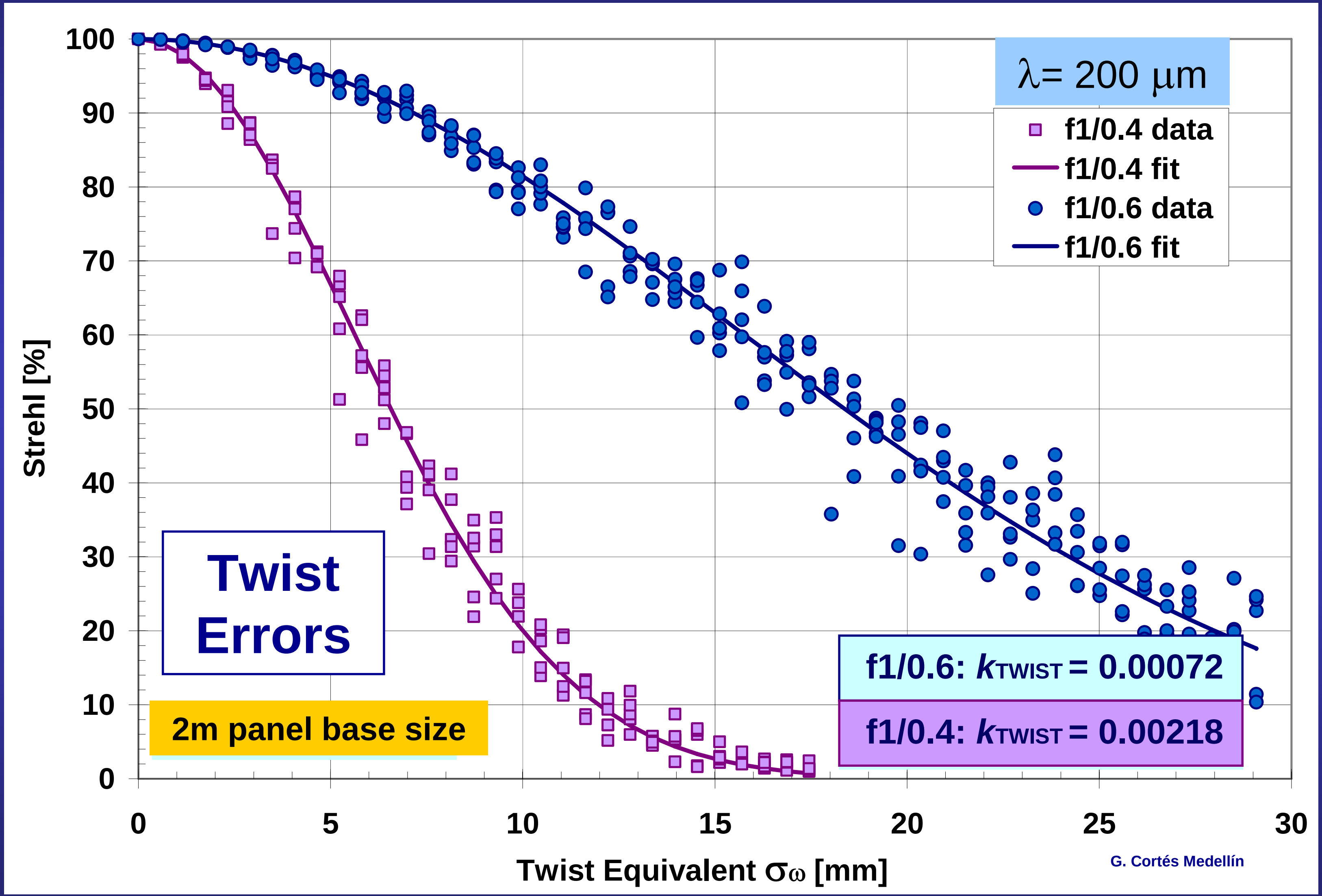
$f_1/0.6$ vs. $f_1/0.4$


CCAT



Segment Twist Positioning Errors

$f_1/0.6$ vs. $f_1/0.4$



Best Fitted Ruze's Coefficients

$f_1/0.6$ vs. $f_1/0.4$

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Ruze's Coefficient

$$\eta_{RUZE_i} = e^{-\left(\frac{4\pi\,\kappa_i\,\sigma_i}{\lambda}\right)^2}$$

	Symbol	$f_1/0.6$	$f_1/0.4$
Segment Piston Displacement	κ_z	0.95424	0.91602
Segment Tilt/Tip (Equiv. Edge Displacement*)	κ_{TILT}	0.49903	0.48435
Segment Radial Displacement	κ_x	0.01543	0.02047
Segment Azimuth Displacement	κ_y	0.01468	0.01992
Segment Twist (Equiv. Edge Displacement*)	κ_{TWIST}	0.00073	0.00202

$$\epsilon_{rms} = \sqrt{(\kappa_z\,\sigma_z)^2 + (\kappa_{tilt}\,\sigma_{tilt})^2 + (\kappa_x\,\sigma_x)^2 + (\kappa_y\,\sigma_y)^2 + (\kappa_\omega\,\sigma_\omega)^2}$$

*** Panel Base Size = 2.0 [m]**

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Conclusions II

Segment Positioning Errors and Image Quality at 200μm:

- Again, piston errors dominate the contribution to Strehl, followed by tilt/tip segment errors.
- There is a slight reduction in Ruze's piston coefficient from 0.954 at f1/0.6 to 0.916 at f1/0.4
- There is also a slight reduction in Ruze's tilt/tip coefficient from 0.499 at f1/0.6 to 0.484 at f1/0.4.
- In contrast, there is an increase in Ruze's coefficient for both, radial and azimuth segment positioning errors. For radial errors it changed from 0.0154 at f1/0.6 to 0.0247 at f1/0.4, and for azimuth errors it changed from 0.0147 at f1/0.6 to 0.0199 at f1/0.4, respectively.
- The largest change occurs in Ruze's twist coefficient by a factor of three: from 0.00073 at f1/0.6 to 0.00202 at f1/0.4. In other words, in order to have 95% Strehl ratio at f1/0.6, twist alignment errors should be 5mm or less at the edges of a 2m base size panel; and with f1/0.4, they must be maintained below 2mm.


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End

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Additional Material

SCUBA-2 and SW/LW Camera Locations

SCUBA-2 Location I

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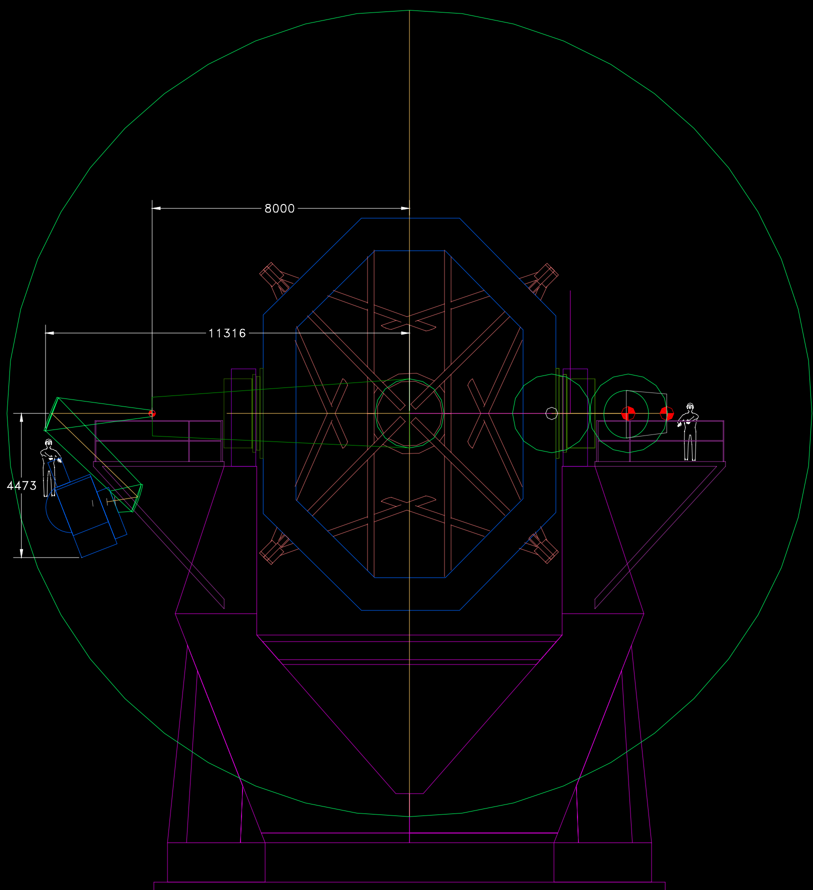
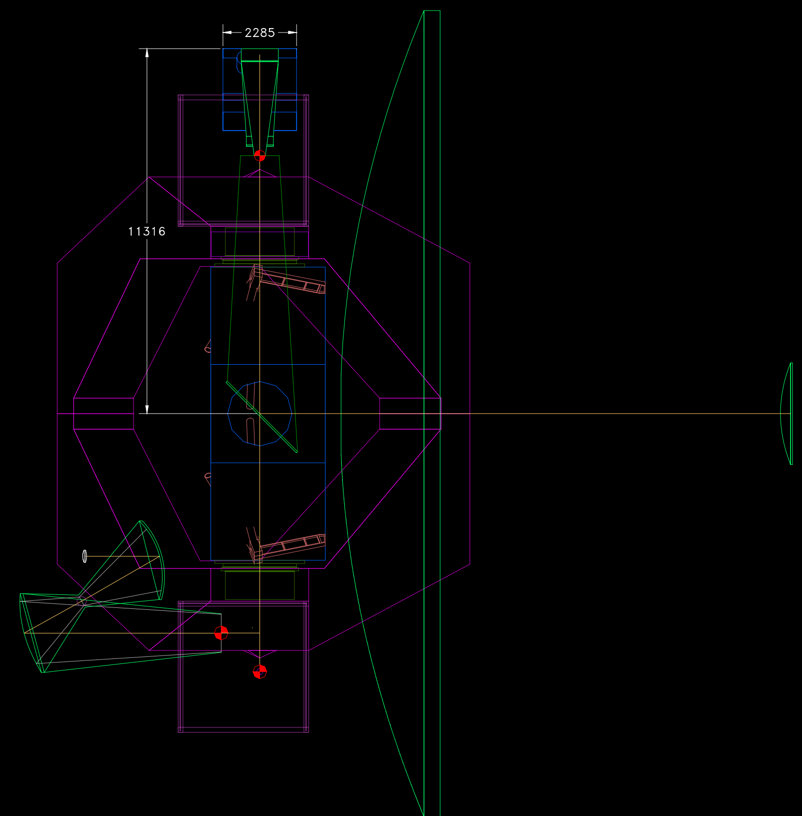
Back View



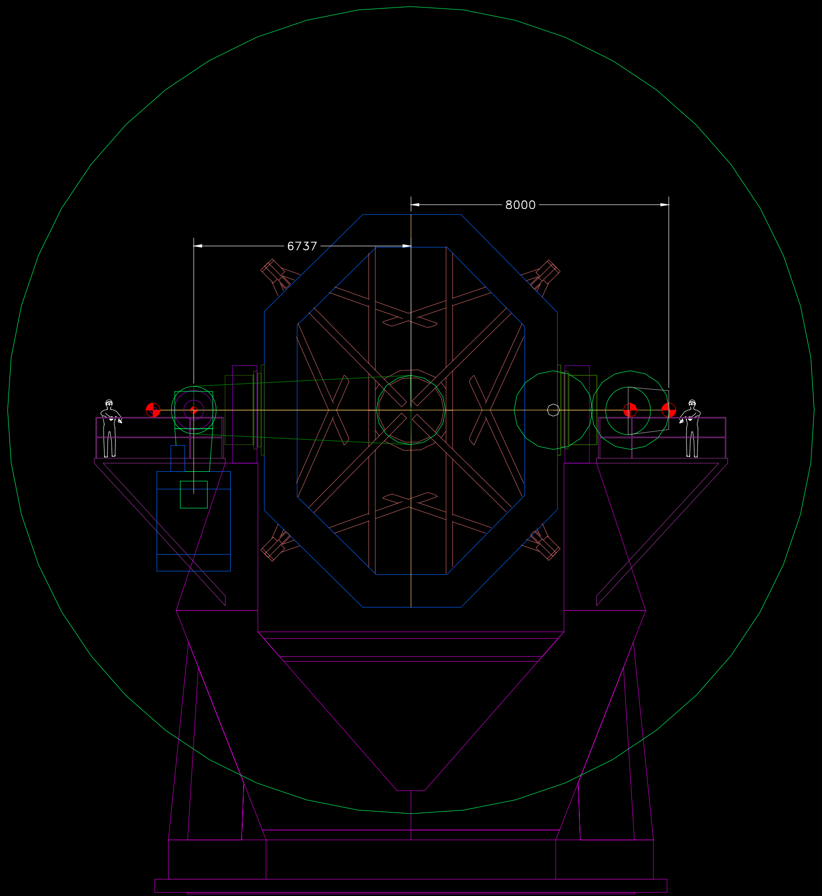
Top View

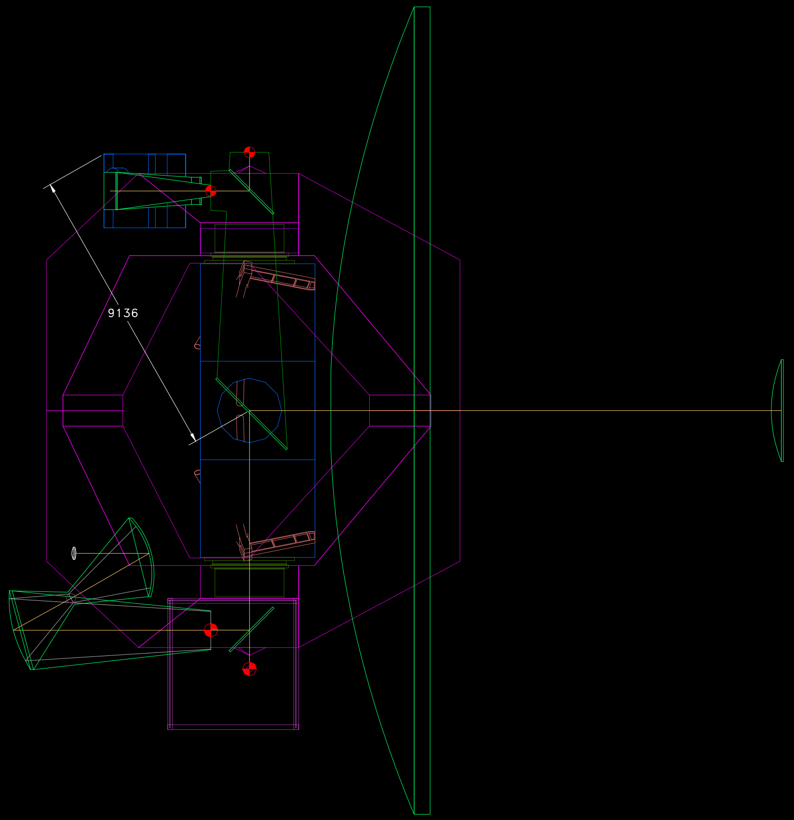


SCUBA-2 Location II

Back View

Top View





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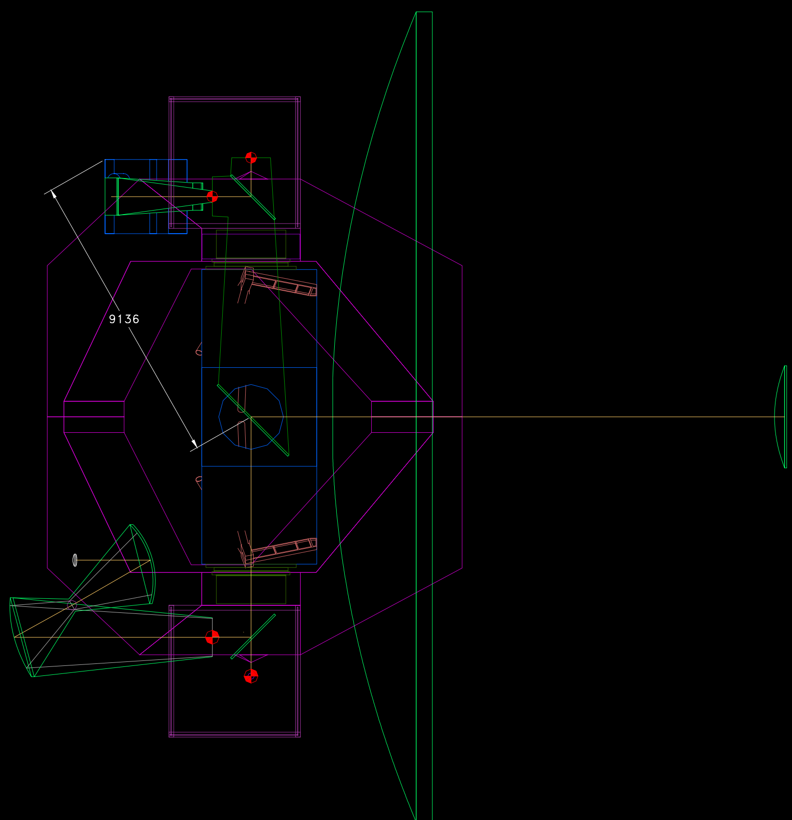
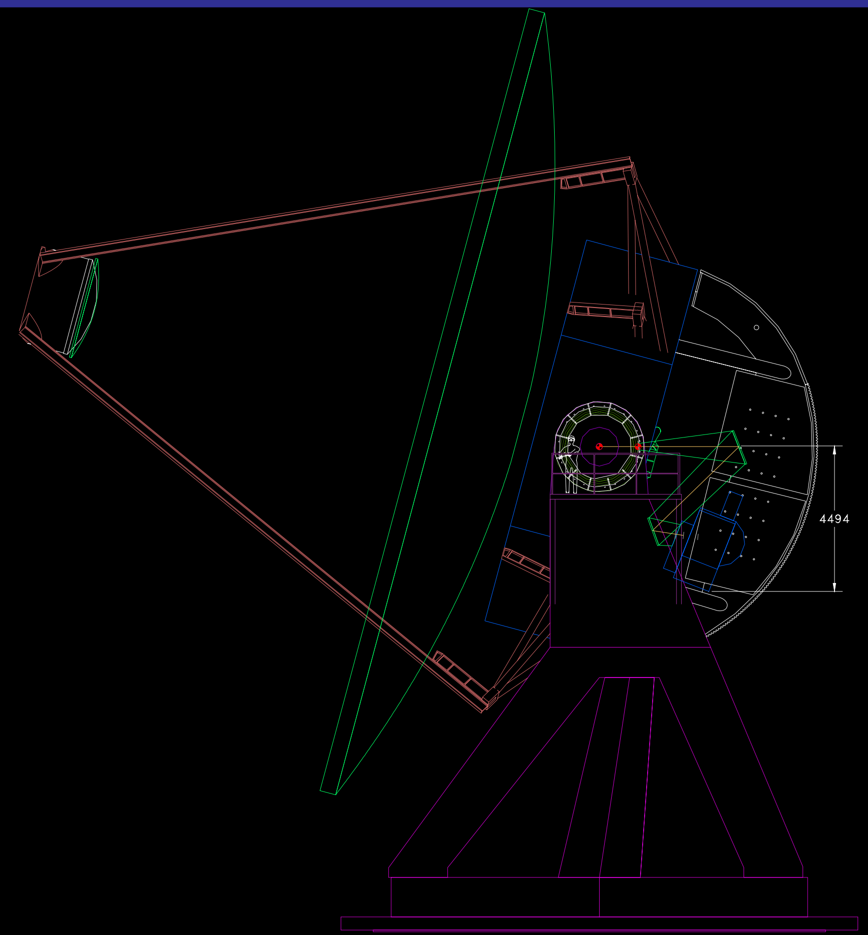
SCUBA-2 Location II

Top View



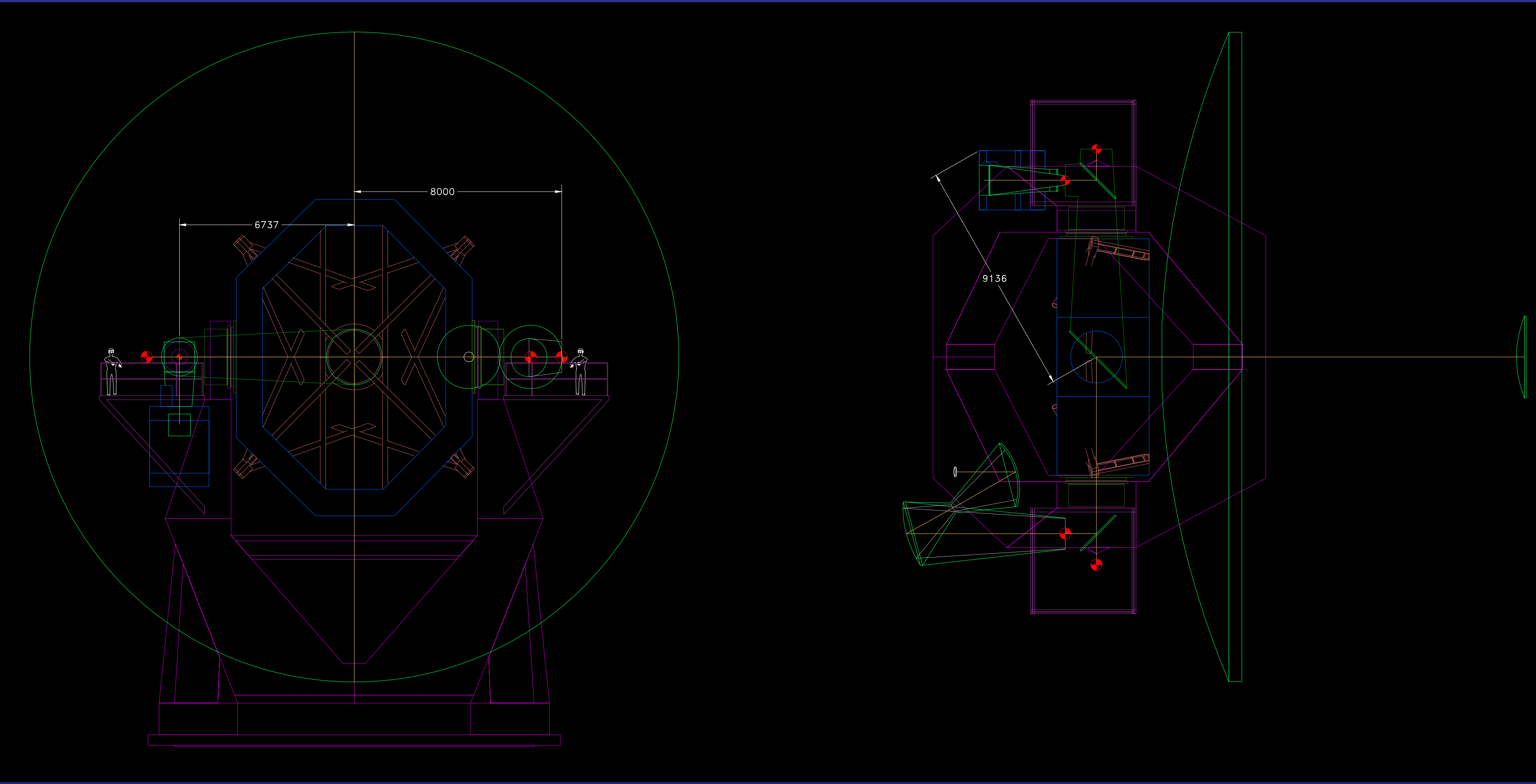
Side View



SW-Cam + SCUBA-2 Location I

Back View

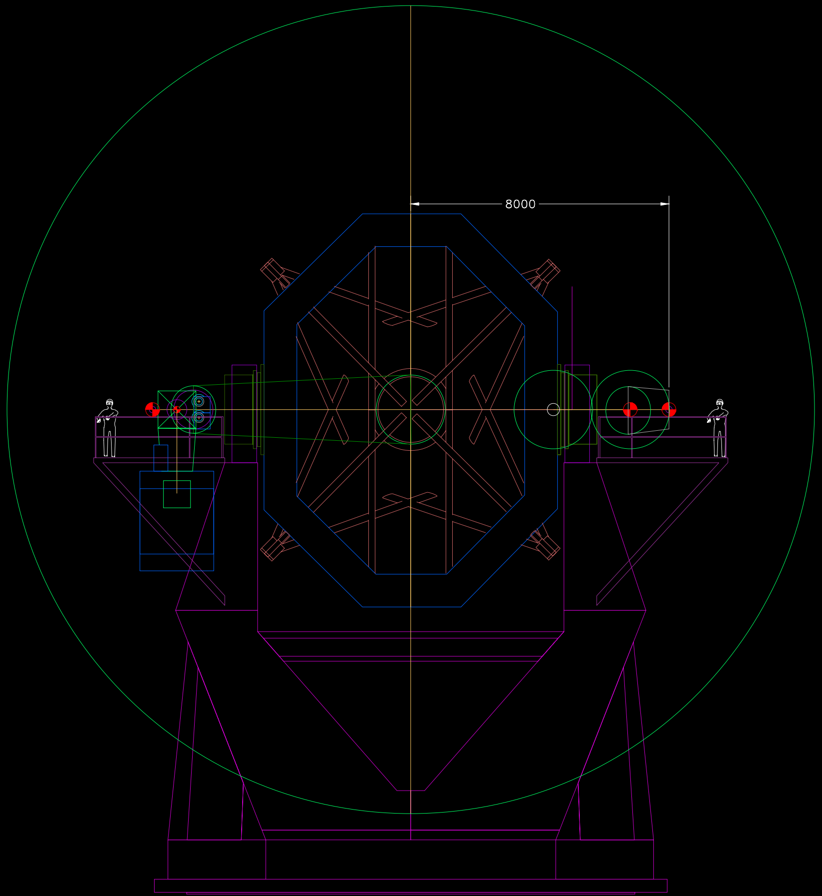
Top View



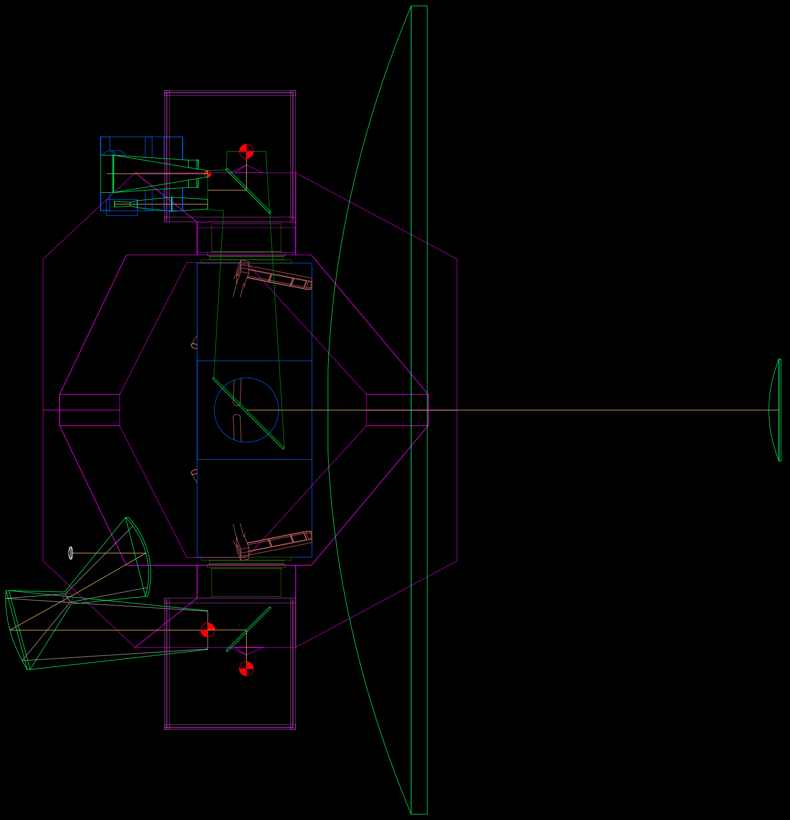
SW-Cam + SCUBA-2 Location I

CCAT

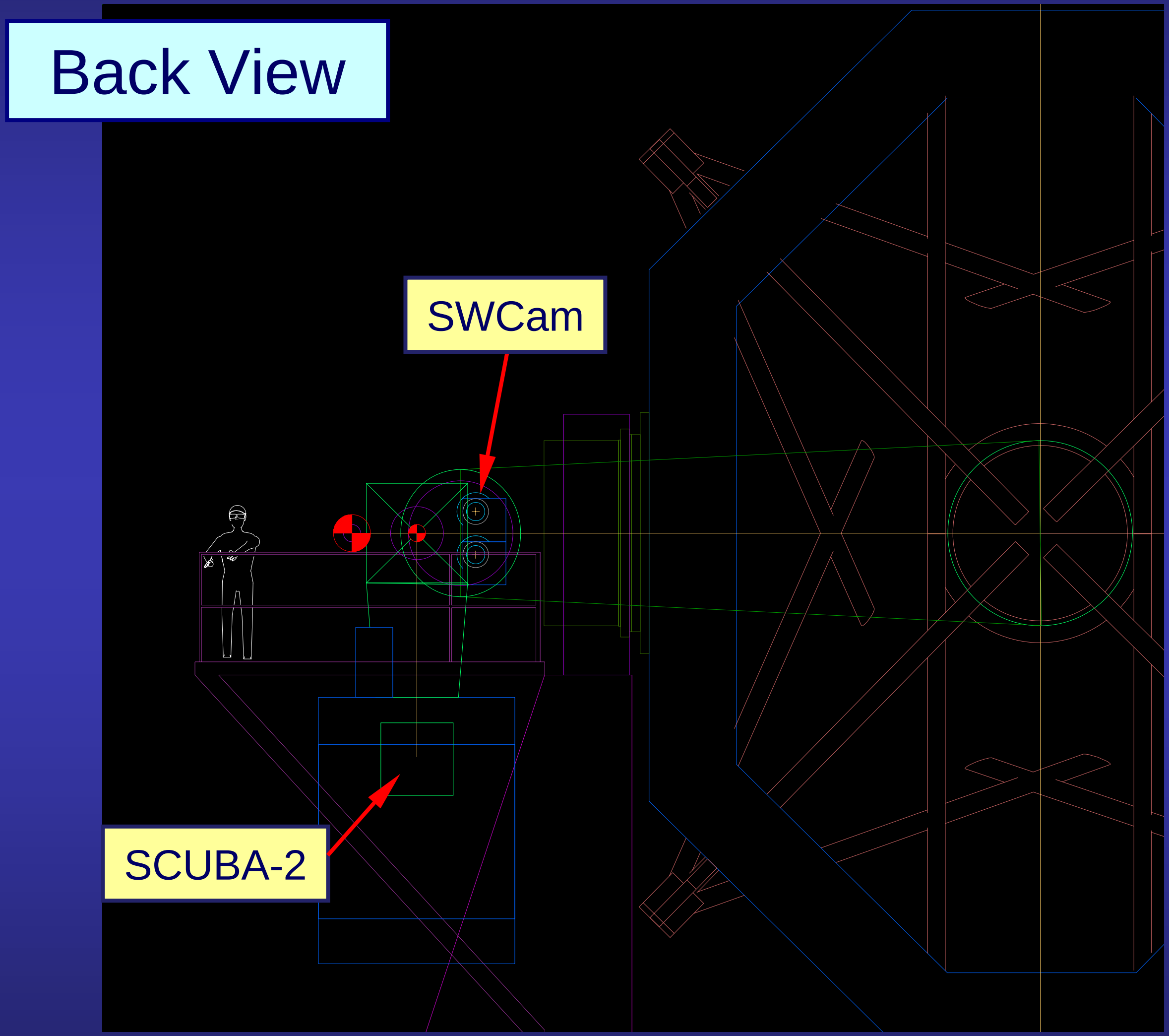
Back View



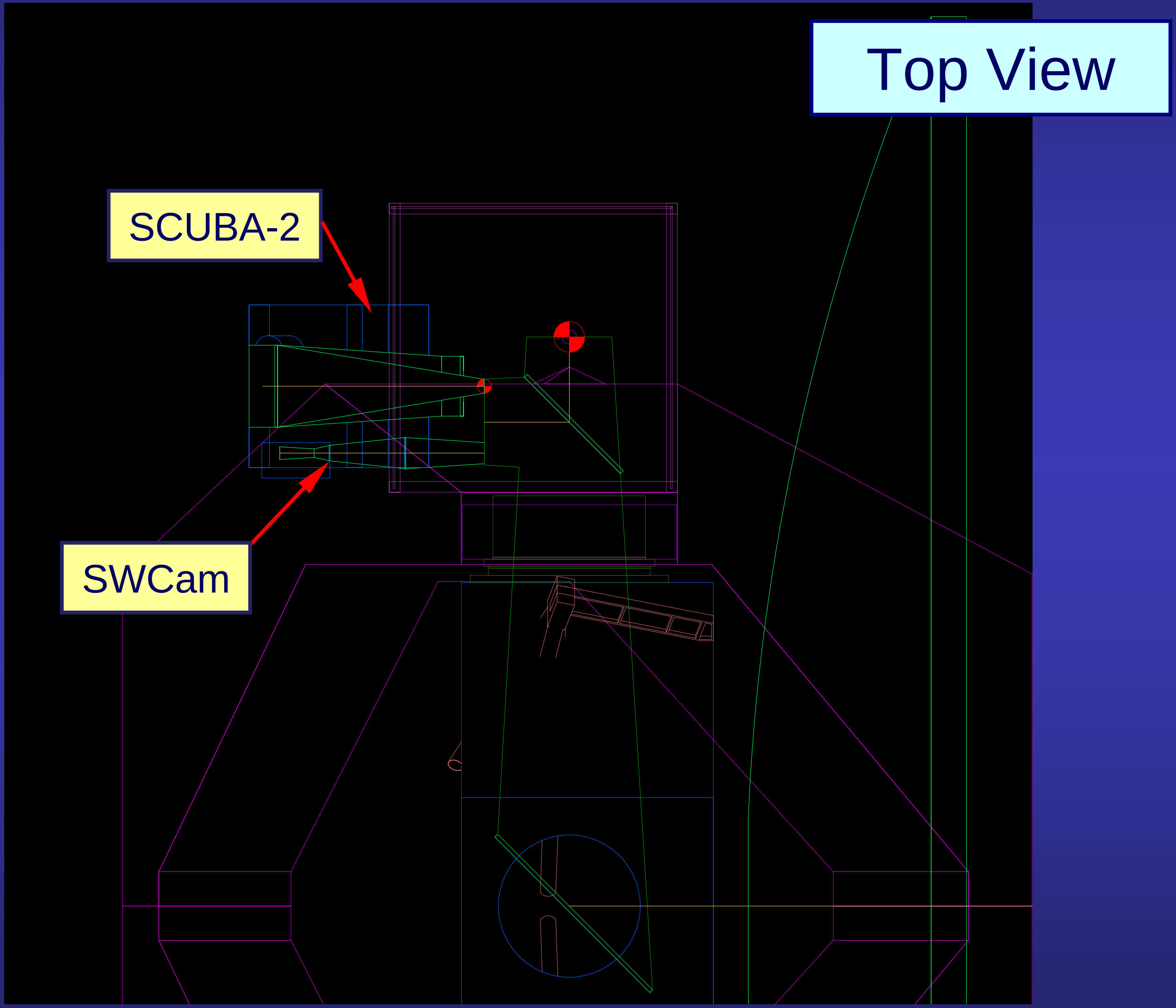
Top View



SW-Cam + SCUBA-2 Location I



SW-Cam + SCUBA-2 Location I



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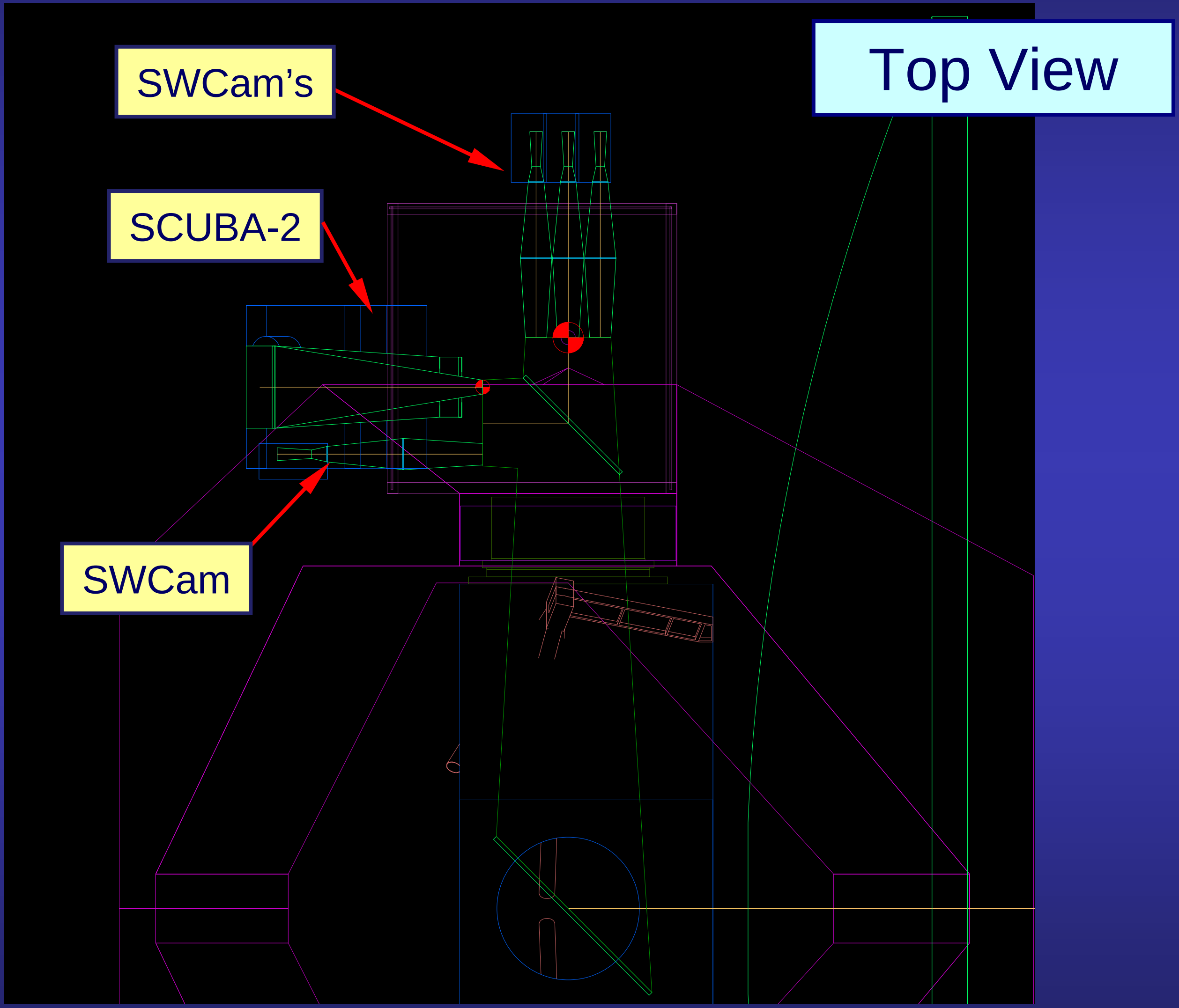
SW-Cam + SCUBA-2 Location II



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End II