CCAT
Optical Design

Germán Cortés-Medellín
National Astronomy and Ionosphere Center
Cornell University

Outline

- Telescope Optical Parameters and Design
- FOV Performance Analysis
- Sub-reflector Sensitivity Analysis
- Active Surface Segmentation Analysis
- Conclusions

CCAT Optical Design Parameters

Design: Ritchey-Chrétien/Nasmyth Focus

Input Design Parameters	Symbol	Value	Units
Aperture Diameter	D	**25**	[m]
Primary Focal Ratio	f_1/D	**0.6**	
System Focal Ratio	$f/\#$	**f/8**	
Back Focal Distance	B	**11**	[m]
Field of View	FOV	**20**	[arcmin]
Minimum Operating Wavelength	λ_{min}	**200**	[μm]

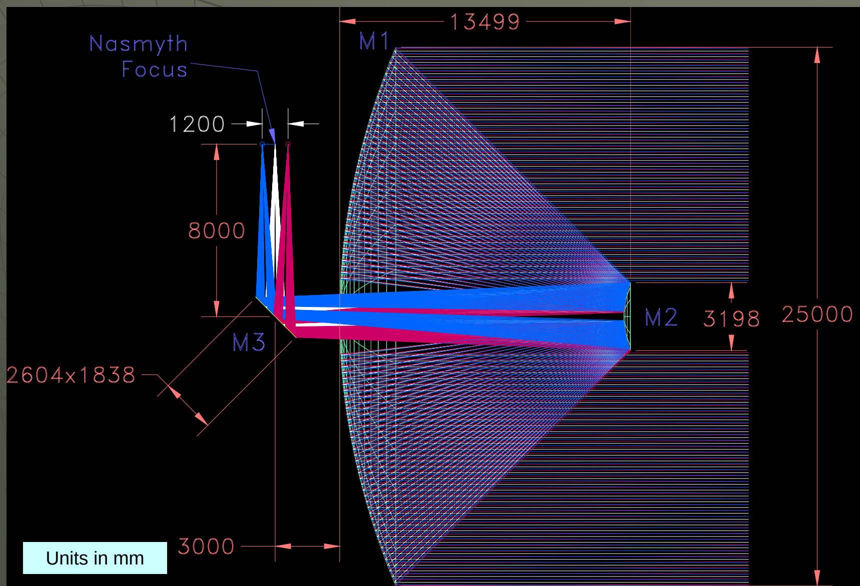
Ritchey-Chrétien Design Parameters

Design: Ritchey-Chrétien/Nasmyth Focus

Derived Design Parameters	Symbol	Value	Units
M1 Diameter	D_1	**25**	[m]
Eccentricity	ε_1	**1.000774**	
Vertex Radius of Curvature	R_{C1}	**30.000**	[m]
Focal Distance	f_1	**15.000**	[m]
Edge Angle from Prime Focus	θ_1	**45.24**	[deg]
M2 Diameter (with provisions for FOV)	D_2	**3.20**	[m]
Eccentricity	ε_2	**1.169098**	
Vertex Radius of Curvature	R_{C2}	**3.922**	[m]
Edge Angle from Secondary Focus	θ_2	**3.58**	[deg]

CCAT Feasibility/Concept Study Review 17-18 January 2006

CCAT 25m Optical Layout



FOV Characteristics

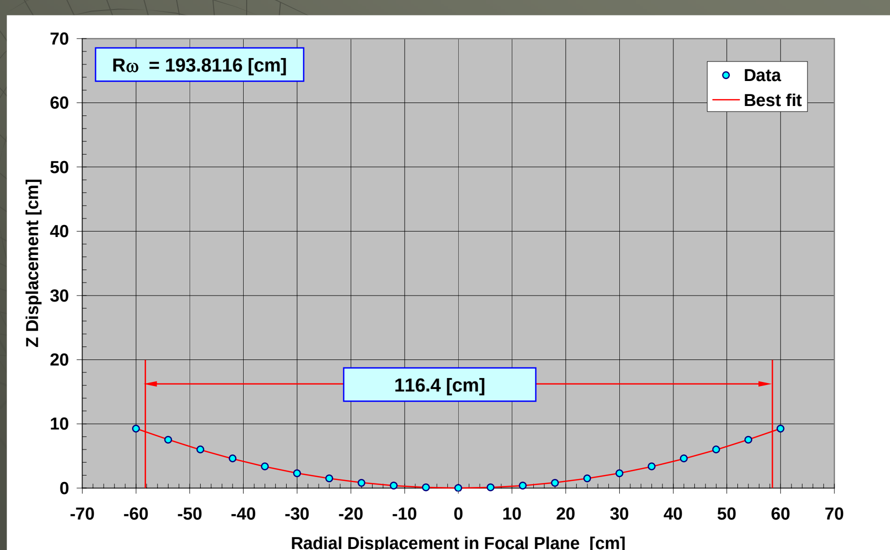
- FOV Size and radius of Curvature
- Performance on-axis and at edge of FOV
- Calculated Co-Pol and Cross-Pol performance
- Performance Variation across FOV
  - Strehl
  - HPBW
  - Sidelobe level
  - Antenna Gain loss (with –11 dB Edge Taper)
  - Antenna aperture efficiency (with –11 dB Edge Taper)
- Available Number of Beams in the FOV

CCAT Filed of View Parameters

Field of View Parameters	Symbol	Value	Units
Specified Field of View	FOV	**20.0**	[arcmin]
Image Scale at Nasmyth Focus	IMS	**1.031**	[arcsec/mm]
Optimum Radius of Curvature	R_{ω}	**1.938**	[m]
Size of 20 arcmin FOV		**1.164**	[m]
Diffraction Spot-size at 200 μm		**1.920**	[mm]

Calculated Angular Aberrations	Symbol	Value	Units
Specified Field of View	FOV	**20.0**	[arcmin]
Angular Tangential Coma	*ATC*	**0.00**	[arcmin]
Angular Astigmatism	*AAS*	**2.83**	[arcmin]
Angular Distortion	*ADI*	**0.48**	[arcmin]

FOV: Optimum Focal Surface Geometry



On Axis Performance

Wavelength: 200 [µm]
Frequency: 1499 [GHz]

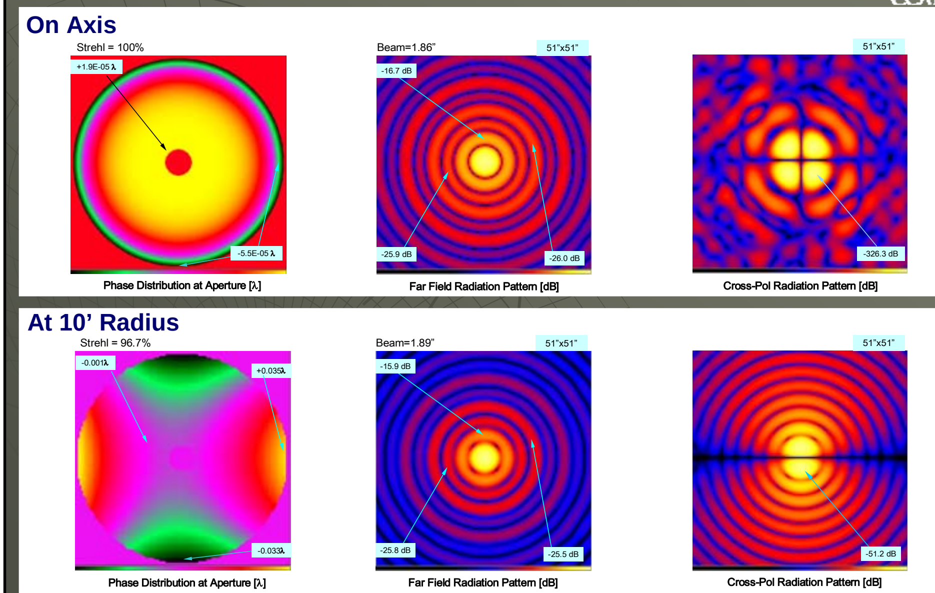
	Uniform Illumination	Edge Taper -11 dB	
HPFW Beam Width:	**1.861**	**1.983**	[arcsec]
Aperture Strehl:	**100.00**	**100.00**	[%]
Polarization Efficiency:	100.00	100.00	[%]
Beam Efficiency:	76.21	85.97	[%]
Aperture Plane Efficiency:	98.73	87.58	[%]
Spillover Efficiency	-------	88.37	[%]
Antenna Gain:	-------	110.76	[dB]
Overall Antenna Efficiency:	-------	**77.40**	[%]
Side Lobe Level (SLL):	**-16.70**	**-22.27**	[dB]
Cross-Polarization Level:	-326.30	-326.73	[dB]

Performance at Edge of 20’ FOV

Wavelength: 200 [µm]
Frequency: 1499 [GHz]

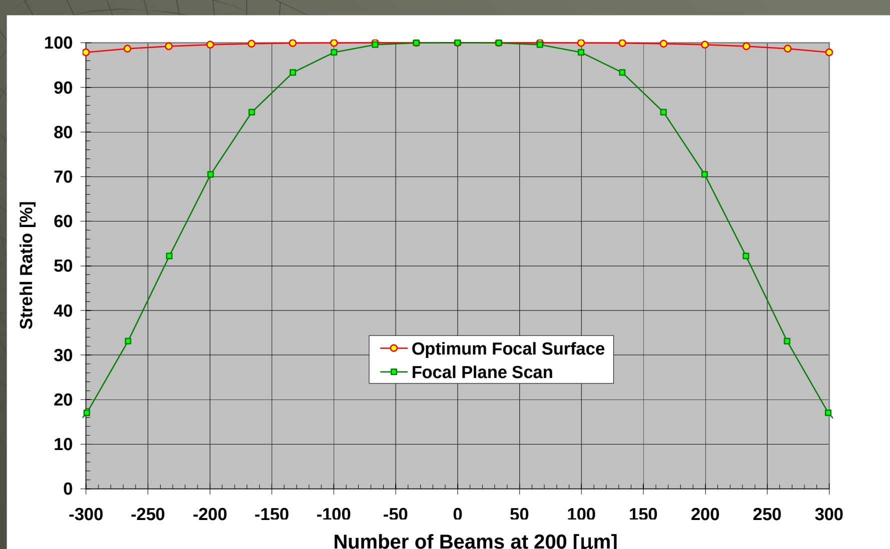
	Uniform Illumination	Edge Taper -11 dB	
HPFW Beam Width:	1.892	2.008	[arcsec]
Aperture Strehl:	**96.75**	**98.39**	[%]
Polarization Efficiency:	99.99	99.99	[%]
Beam Efficiency:	74.41	84.65	[%]
Aperture Plane Efficiency:	95.59	85.41	[%]
Spillover Efficiency	-------	88.37	[%]
Antenna Gain:	-------	110.66	[dB]
Overall Antenna Efficiency:	-------	**75.48**	[%]
Side Lobe Level (SLL):	**-15.71**	**-20.89**	[dB]
Cross-Polarization Level:	-51.21	-52.63	[dB]

FOV Performance at 200 µm



Strehl Ratio vs. Number of Beams

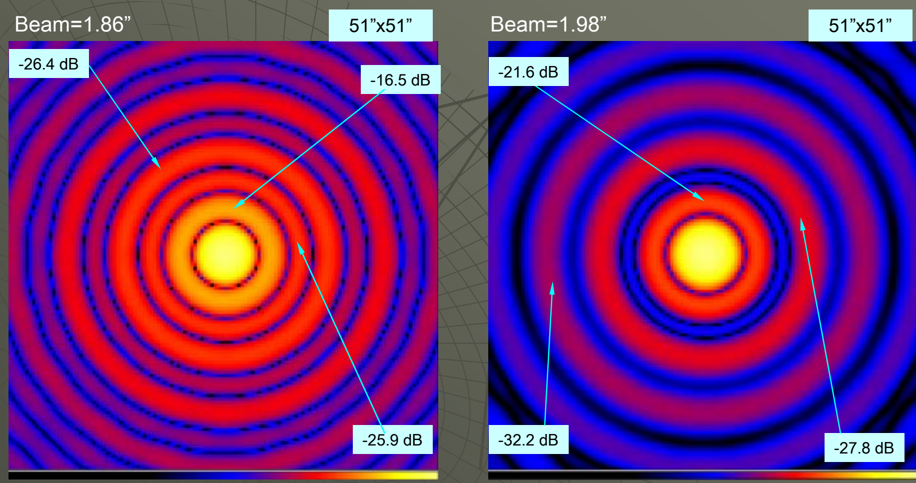
λ= 200 µm, Uniform Illumination



Co-Polar Beam Patterns Comparison

Uniform vs. –11 dB Edge Taper Illumination

(at 200 μm)

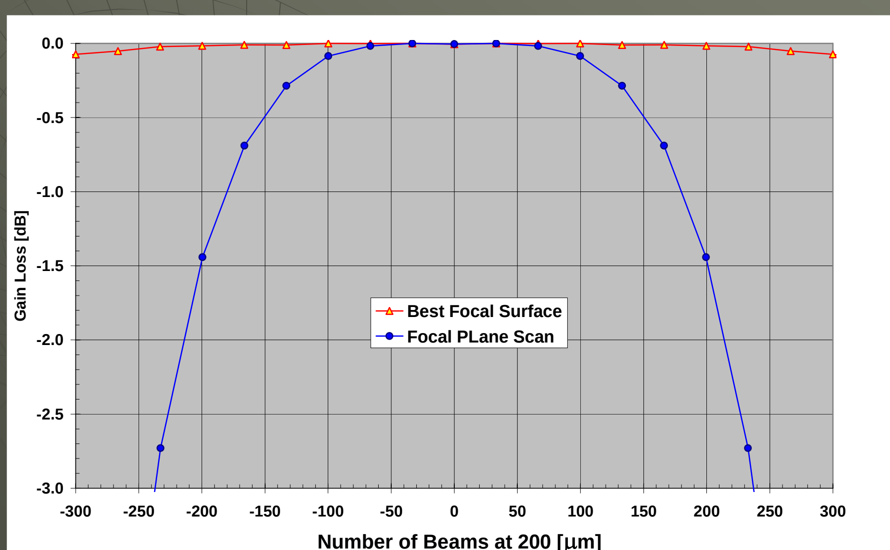


Uniform Illumination

Edge Taper –11.0 dB

Gain Loss vs. Number of Beams

λ= 200 μm, -11 dB Edge Taper at M2

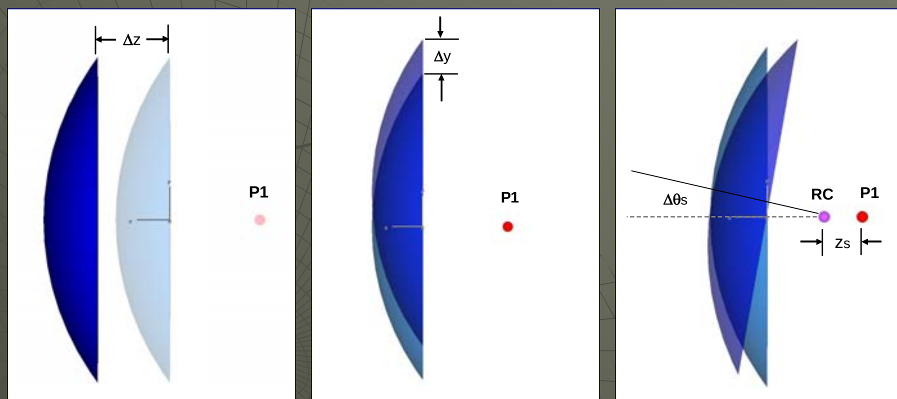


M_2 Sensitivity Analysis

Sub-Reflector Sensitivity Analysis

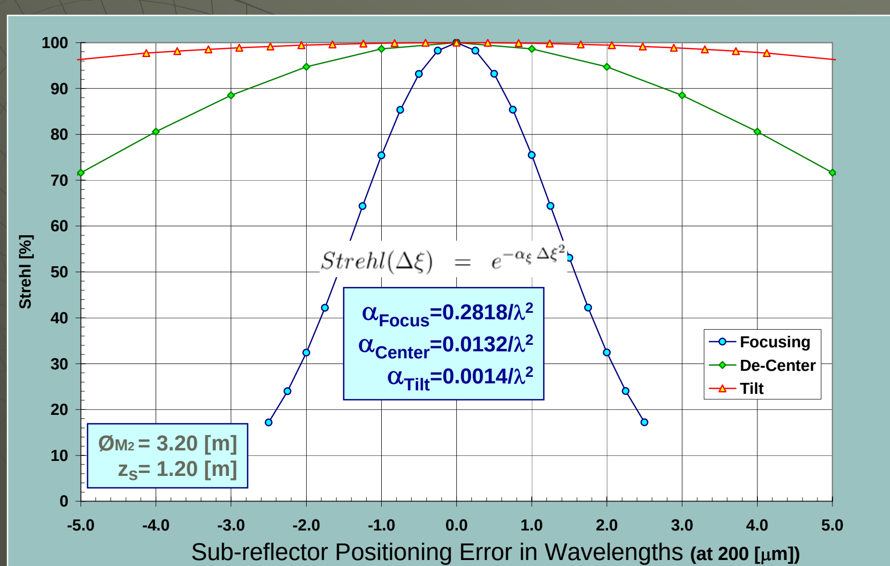
- Sub-reflector Sensitivity
  - focusing
  - De-Centering
  - Tilt/Tip
- Beam Deviation due to Sub-Reflector motion
- Set limits for sub-reflector positioning based on
  - Image quality
  - Pointing requirements.
- Analyzed the image characteristics for sub-reflector chopping

Sub-Reflector Sensitivity Analysis



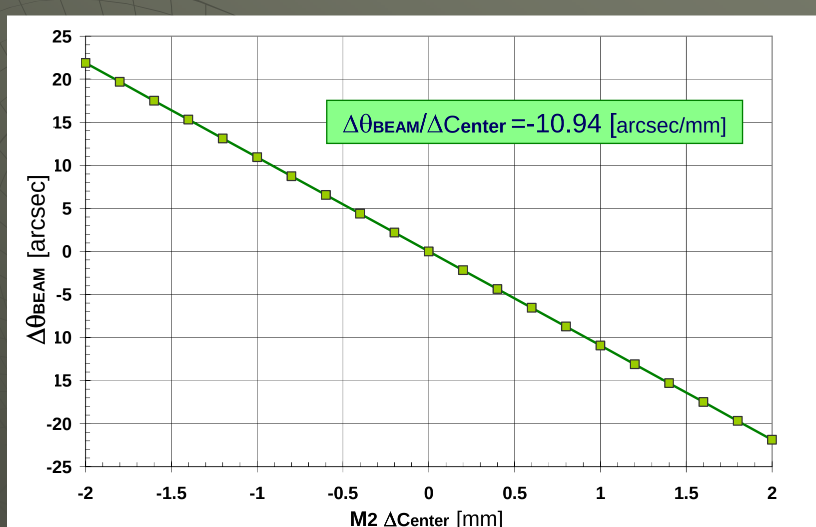
FOCUSING | DE-CENTER | TILT

Strehl Ratio vs. M2 Positioning



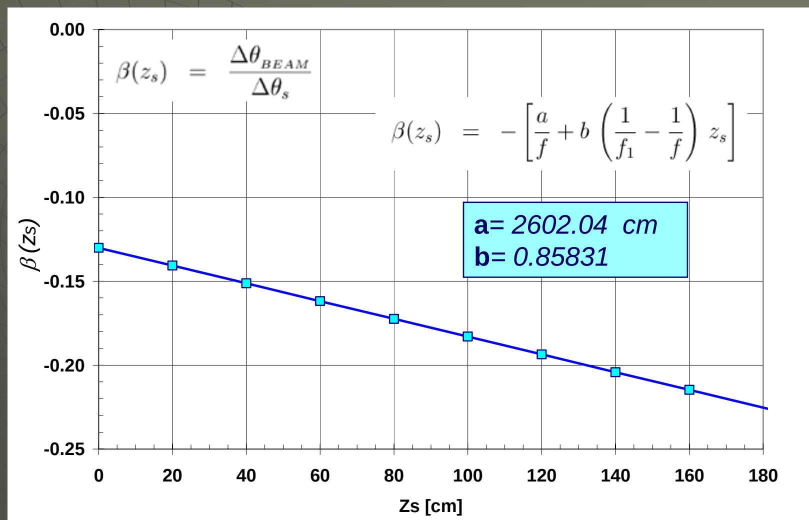
Beam Deviation and M2 Chopping

Beam Deviation vs. M2 De-Centering



at 200 [μm]

Beam Deviation vs. M2 Tilt



at 200 [μm]

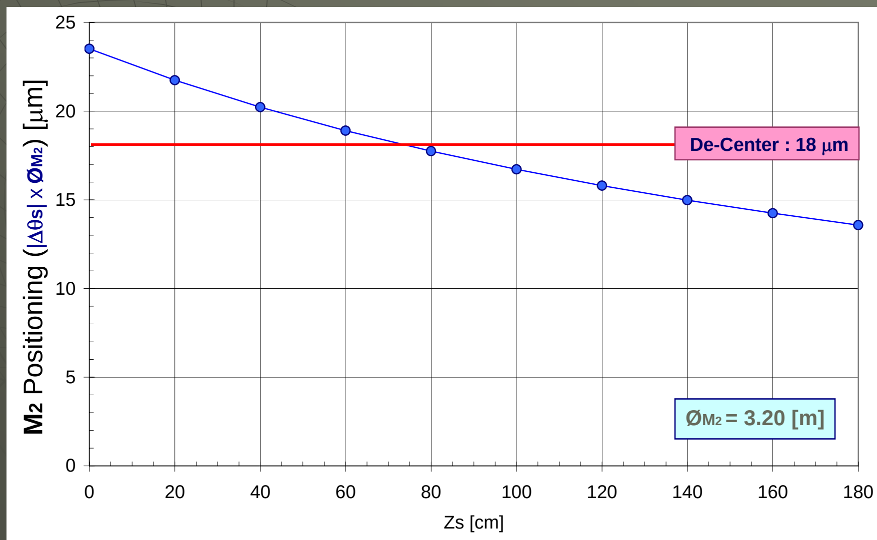
M2 Positioning Requirements at 200 μm

	Focus $\|\Delta z\|$ [μm]	De-center $\|\Delta x^2+\Delta y^2\|^{1/2}$ [μm]	Tilt eqv $\|\Delta\theta\| x Ø_{M2}$ [μm]	Tilt $\|\Delta\theta\|$ [arcsec]
Image Quality: Strehl > 95%	< 80.0	< 380.0	<1,085.	< 70.0
Pointing: $\Delta\theta_{BEAM}$ < HPBW /10	**--------**	**< 18.1**	**< 16.0**	**< 1.03**

$Ø_{M2}$ = 3.20 [m]
z_S= 1.20 [m]

M2 Positioning Requirements for Pointing

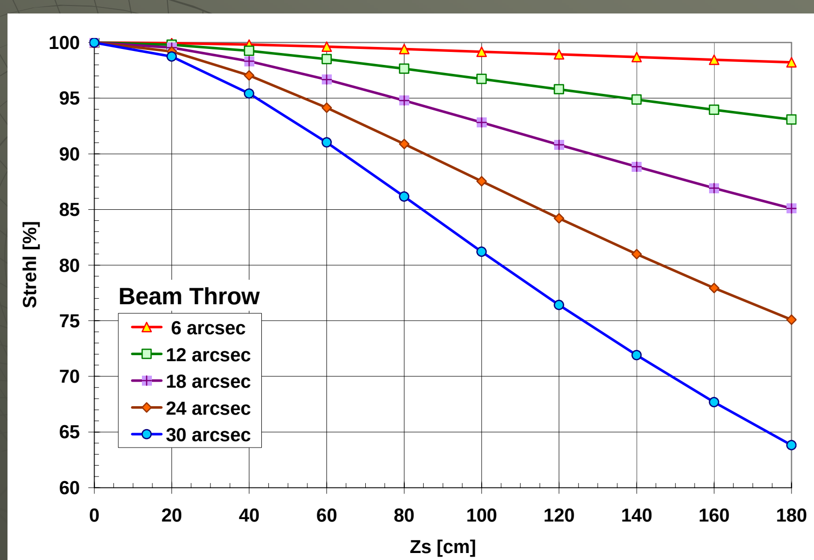
(1/10th of the HPBW at 200 μm)



CCAT Feasibility/Concept Study Review 17-18 January 2006

Strehl variation vs. Beam Deviation

due to Sub-Reflector Chopping



λ= 200 μm

CCAT Feasibility/Concept Study Review 17-18 January 2006

Active Surface Segmentation

CCAT Feasibility/Concept Study Review 17-18 January 2006

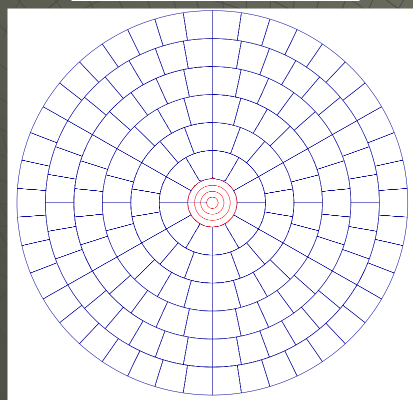
Active Surface Segmentation

- We analyzed an active surface composed of 162 pie-shaped segments distributed with 6-fold symmetry in 6 rings
- Grating lobes symmetry, power level and location in the far field.
- Segment Positioning Error Analysis
- For Segment Piston errors, tilt/tip errors, radial and azimuth segment positioning errors, segment twists.
- Characterization of Segment positioning errors in terms of Ruze's coefficients relating segment position standard deviation errors with optical performance.
- Thermal expansion effects.

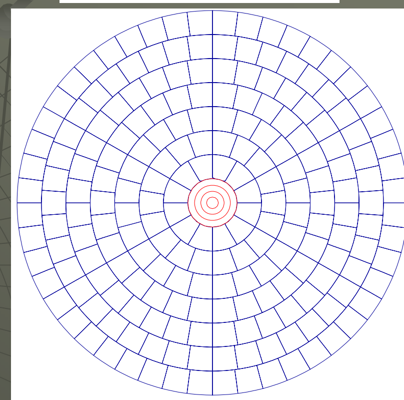
CCAT Feasibility/Concept Study Review 17-18 January 2006

CCAT M_1 Active Surface Layout

A. 162 Segments
6 Rings

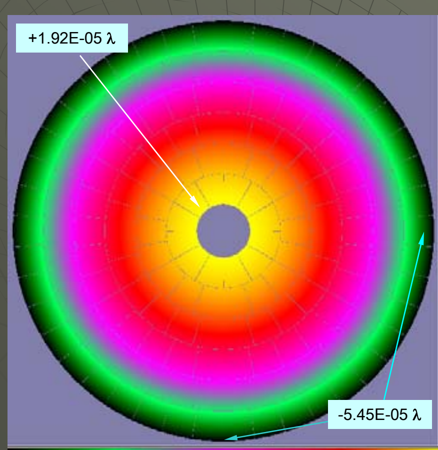


B. 210 Segments
7 Rings



Segmentation Effects

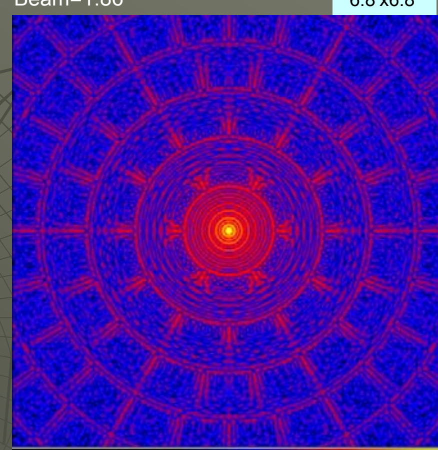
(λ=200 μm, Uniform Illumination)



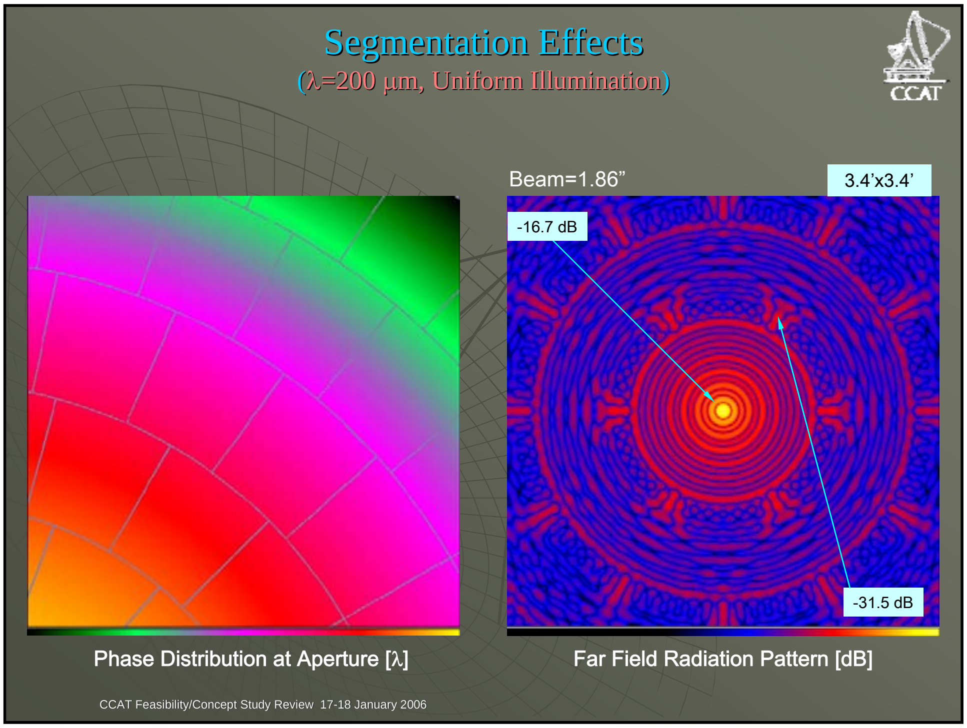
Phase Distribution at Aperture [λ]

Beam=1.86”

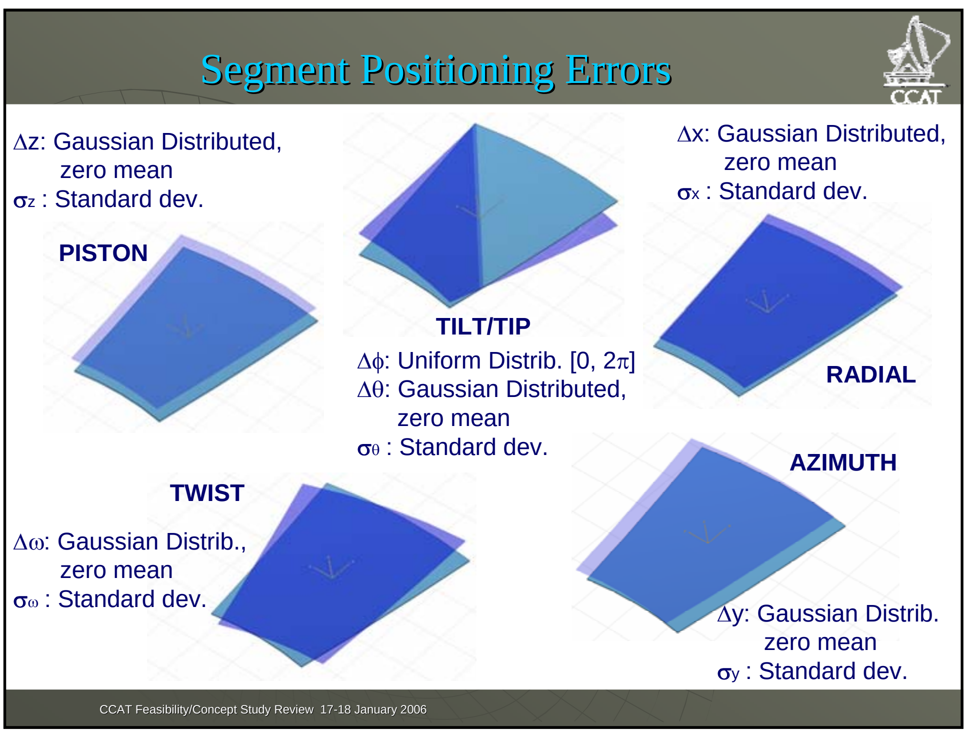
6.8’x6.8’



Far Field Radiation Pattern [dB]



Segmentation Effects
(λ=200 μm, Uniform Illumination)
CCAT
Beam=1.86”
3.4’x3.4’
-16.7 dB
-31.5 dB
Phase Distribution at Aperture [λ]
Far Field Radiation Pattern [dB]
CCAT Feasibility/Concept Study Review 17-18 January 2006

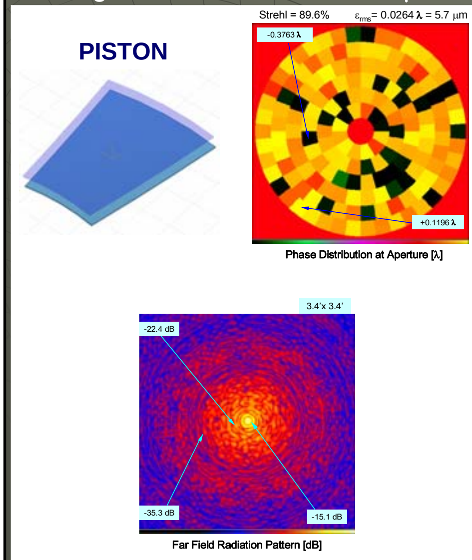


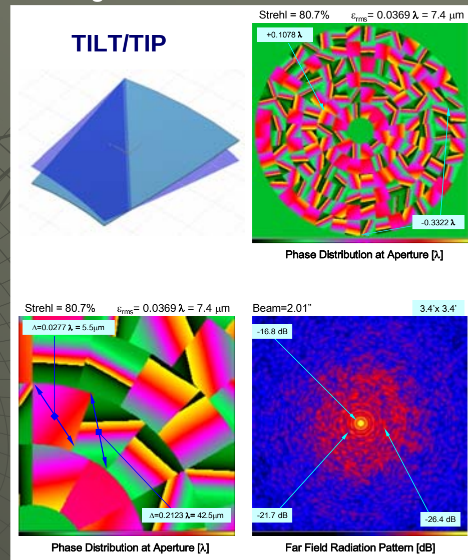
Segment Positioning Errors
CCAT
Δz: Gaussian Distributed, zero mean
σ_z : Standard dev.
PISTON
TILT/TIP
$\Delta\phi$: Uniform Distrib. [0, 2π]
$\Delta\theta$: Gaussian Distributed, zero mean
σ_θ : Standard dev.
Δx: Gaussian Distributed, zero mean
σ_x : Standard dev.
RADIAL
TWIST
$\Delta\omega$: Gaussian Distrib., zero mean
σ_ω : Standard dev.
AZIMUTH
Δy: Gaussian Distrib. zero mean
σ_y : Standard dev.
CCAT Feasibility/Concept Study Review 17-18 January 2006

Segment Positioning Errors Samples I

Segment Piston Errors: σz= 6 μm

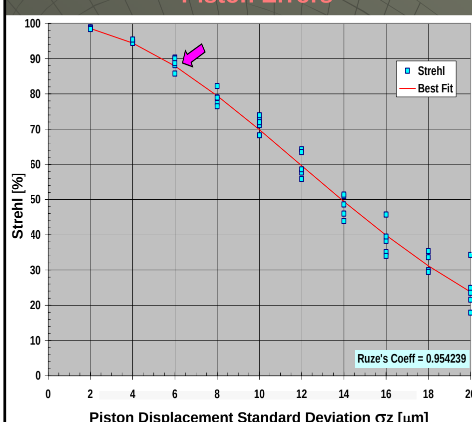
Segment Tilt Errors: $\sigma\theta$= 3 arcsec



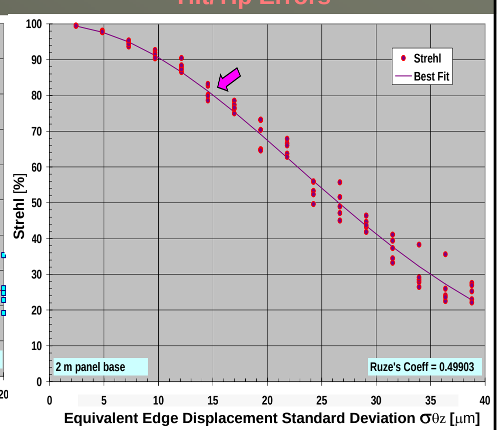


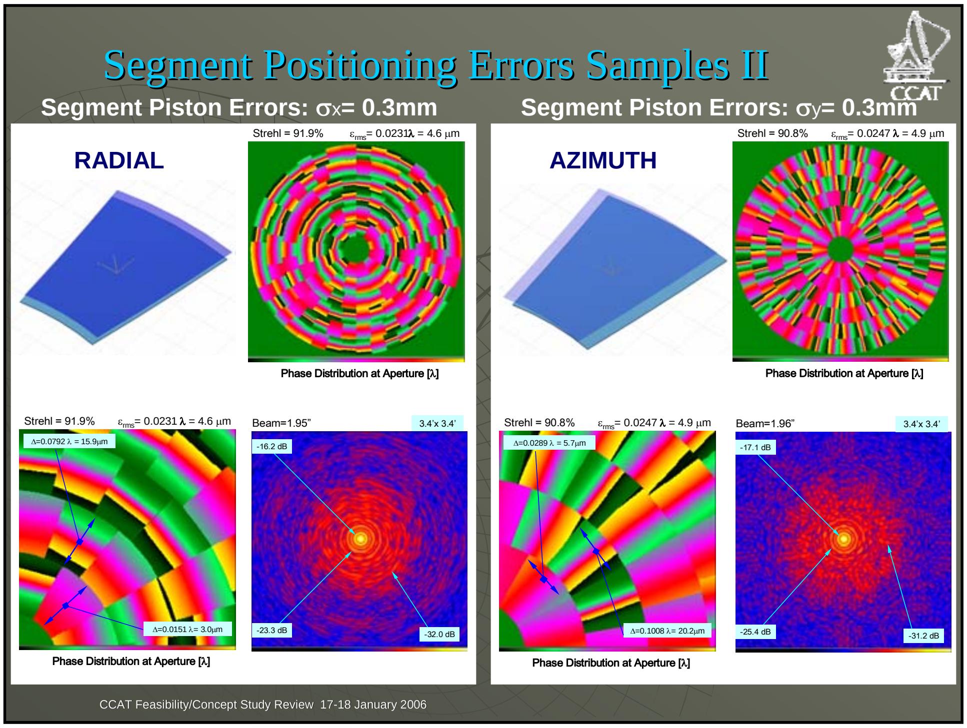
Strehl vs. Segment Positioning Errors

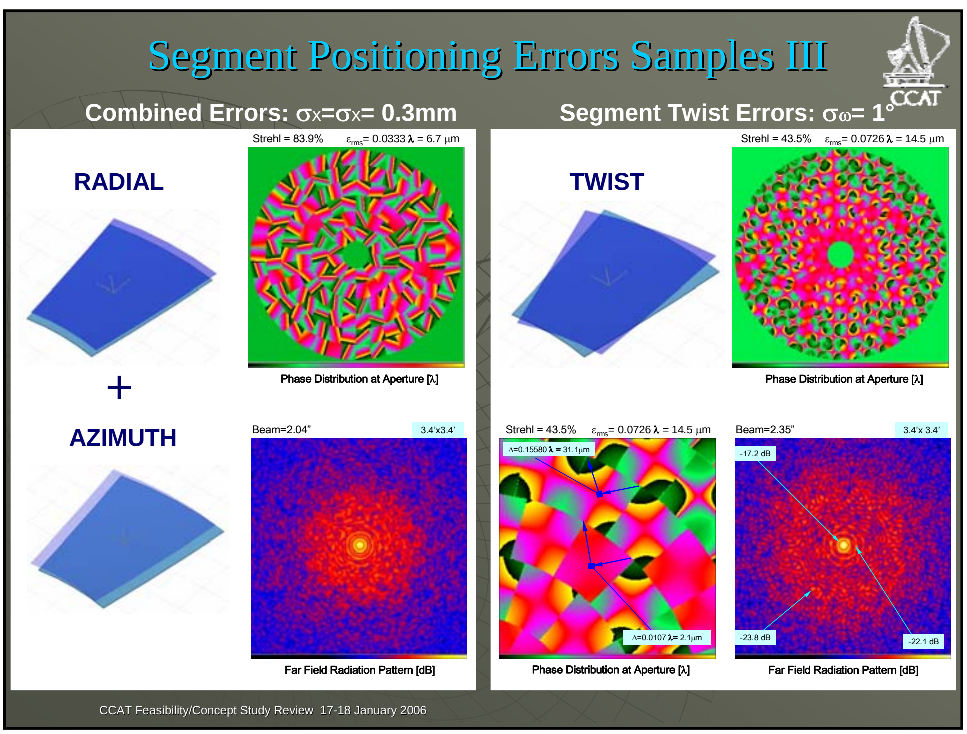
Piston Errors



Tilt/Tip Errors

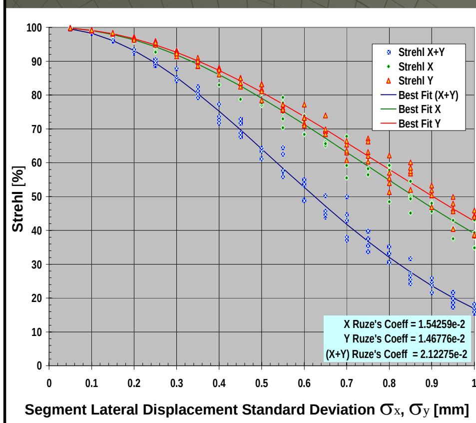



Segment Positioning Errors Samples II
CCAT
Segment Piston Errors: σx= 0.3mm
Segment Piston Errors: σy= 0.3mm
RADIAL
Strehl = 91.9% εrms= 0.0231λ = 4.6 µm
Phase Distribution at Aperture [λ]
Strehl = 91.9% εrms= 0.0231 λ = 4.6 µm
Δ=0.0792 λ = 15.9µm
Δ=0.0151 λ= 3.0µm
Phase Distribution at Aperture [λ]
Beam=1.95"
3.4'x 3.4'
-16.2 dB
-23.3 dB
-32.0 dB
AZIMUTH
Strehl = 90.8% εrms= 0.0247 λ = 4.9 µm
Phase Distribution at Aperture [λ]
Strehl = 90.8% εrms= 0.0247 λ = 4.9 µm
Δ=0.0289 λ = 5.7µm
Δ=0.1008 λ= 20.2µm
Phase Distribution at Aperture [λ]
Beam=1.96"
3.4'x 3.4'
-17.1 dB
-25.4 dB
-31.2 dB
CCAT Feasibility/Concept Study Review 17-18 January 2006

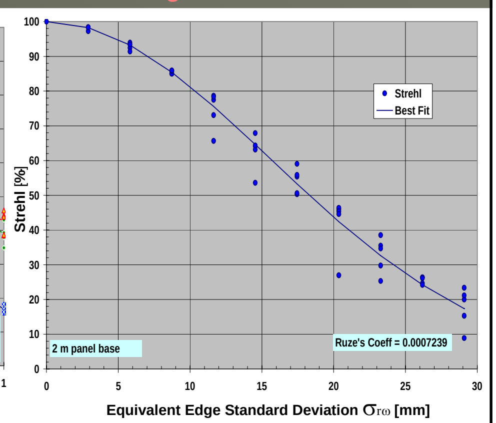

Segment Positioning Errors Samples III
CCAT
Combined Errors: σx=σx= 0.3mm
Segment Twist Errors: σω= 1°
RADIAL
+
AZIMUTH
Strehl = 83.9% εrms= 0.0333 λ = 6.7 µm
Phase Distribution at Aperture [λ]
Beam=2.04"
3.4'x3.4'
Far Field Radiation Pattern [dB]
TWIST
Strehl = 43.5% εrms= 0.0726 λ = 14.5 µm
Phase Distribution at Aperture [λ]
Strehl = 43.5% εrms= 0.0726 λ = 14.5 µm
Δ=0.15580 λ = 31.1µm
Δ=0.0107 λ= 2.1µm
Phase Distribution at Aperture [λ]
Beam=2.35"
3.4'x 3.4'
-17.2 dB
-23.8 dB
-22.1 dB
Far Field Radiation Pattern [dB]
CCAT Feasibility/Concept Study Review 17-18 January 2006

Strehl vs. Segment Positioning Errors

Combined Radial + Azimuth Errors



Segment Twist Errors



Best Fitted Ruze's Coefficients

Ruze's Coefficient

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

	Symbol	Best Fitted Value
Segment Piston Displacement	κ_z	0.95424
Segment Tilt/Tip (Equiv. Edge Displacement*)	κ_{TILT}	0.49903
Segment Radial Displacement	κ_x	0.01543
Segment Azimuth Displacement	κ_y	0.01468
Segment Twist (Equiv. Edge Displacement*)	κ_{TWIST}	0.00073

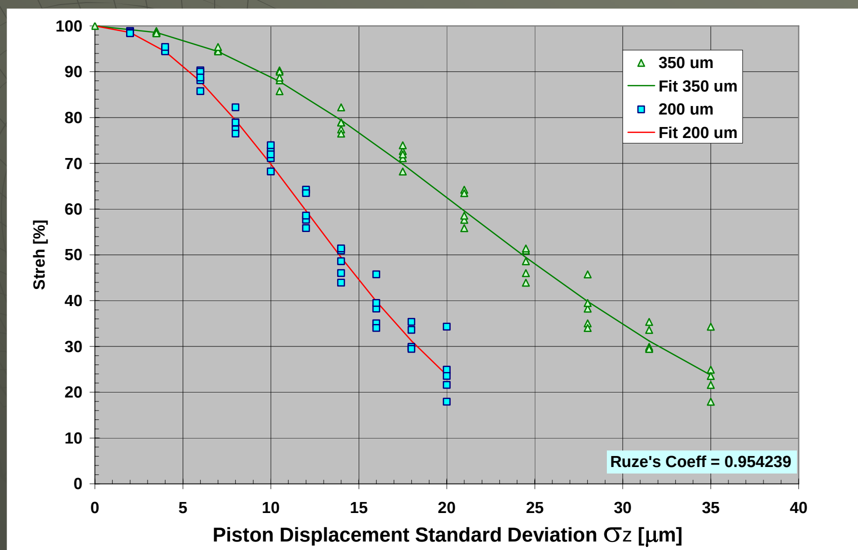
$$\epsilon_{rms} = \sqrt{(\kappa_z\,\sigma_z)^2 + (\kappa_{tilt}\,\sigma_{tilt})^2 + (\kappa_x\,\sigma_x)^2 + (\kappa_y\,\sigma_y)^2 + (\kappa_\omega\,\sigma_\omega)^2}$$

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

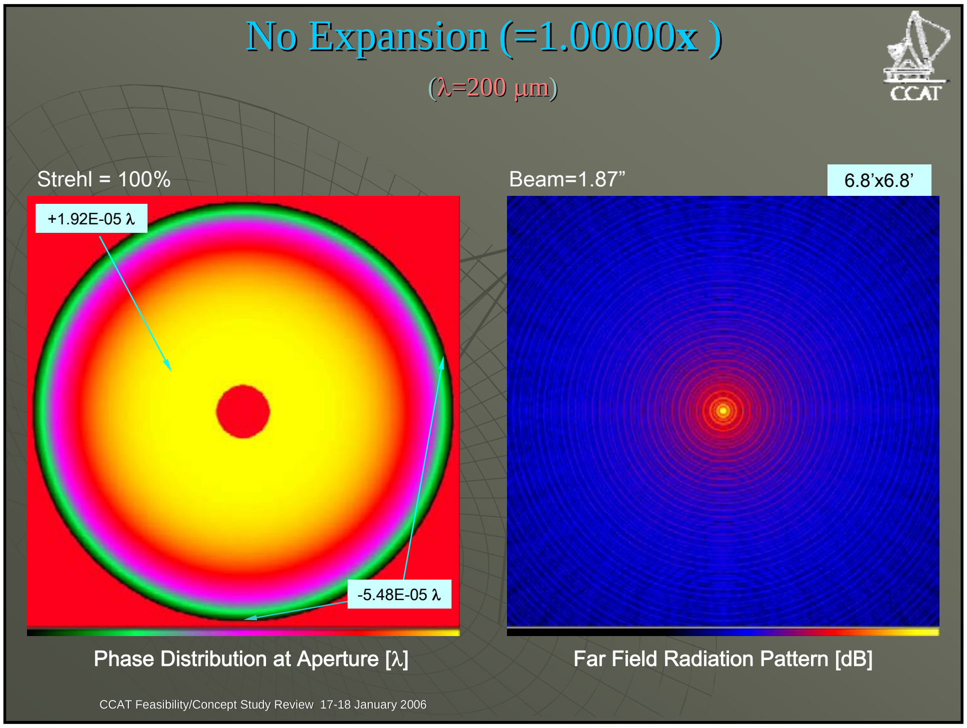
CCAT Feasibility/Concept Study Review 17-18 January 2006

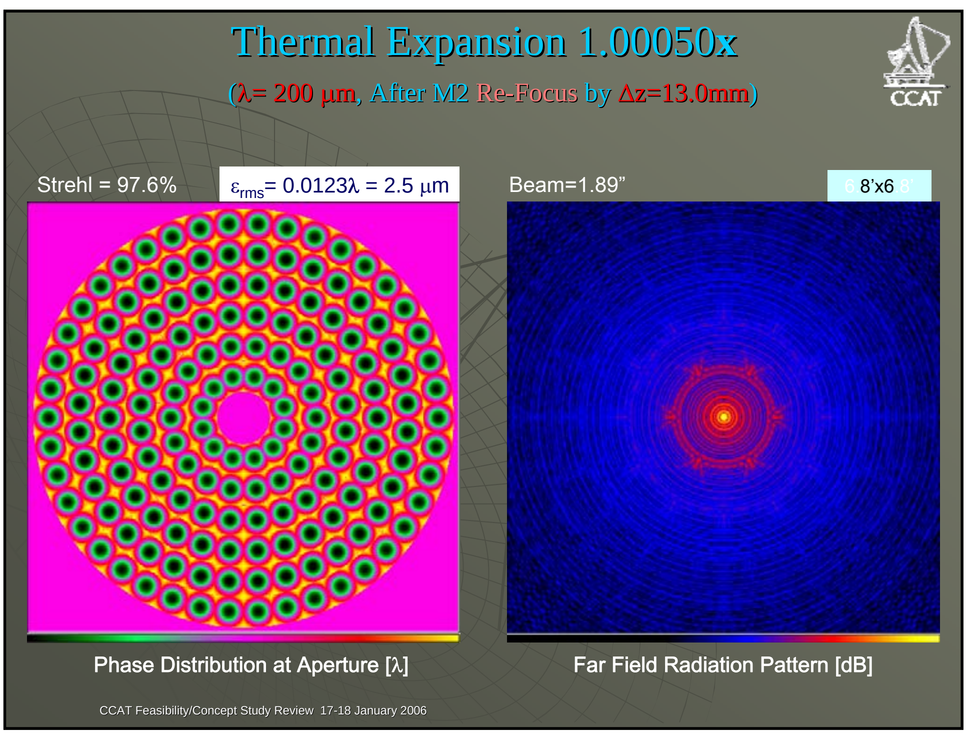
Strehl vs. Piston Displacement

λ= 200 μm and 350 μm



Thermal Expansion Effects

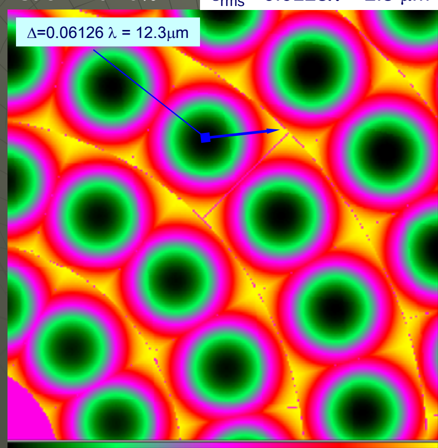

No Expansion (=1.00000x)
(λ=200 μm)
CCAT
Strehl = 100%
+1.92E-05 λ
-5.48E-05 λ
Beam=1.87”
6.8’x6.8’
Phase Distribution at Aperture [λ]
Far Field Radiation Pattern [dB]
CCAT Feasibility/Concept Study Review 17-18 January 2006


Thermal Expansion 1.00050x
(λ= 200 μm, After M2 Re-Focus by Δz=13.0mm)
CCAT
Strehl = 97.6%
ε_rms= 0.0123λ = 2.5 μm
Beam=1.89”
8’x6
Phase Distribution at Aperture [λ]
Far Field Radiation Pattern [dB]
CCAT Feasibility/Concept Study Review 17-18 January 2006

Thermal Expansion 1.00050x

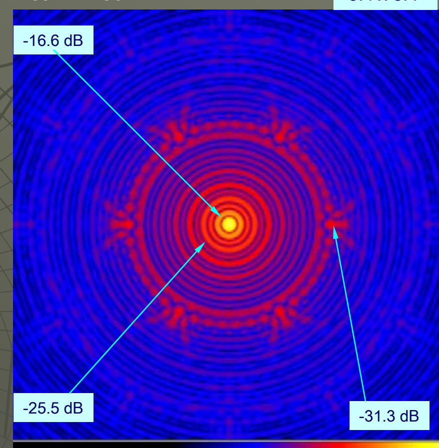
(λ= 200 μm, After M2 Re-Focus by Δz=13.0mm)

Strehl = 97.6% ε_{rms}= 0.0123λ = 2.5 μm



Phase Distribution at Aperture [λ]

Beam=1.89” 3.4’x 3.4’



Far Field Radiation Pattern [dB]

Conclusions

- We have designed a 25m f/8 Symmetric Reflector Sub-Millimeter telescope in a double Nasmyth Ritchey-Chrétien configuration with a FOV of 20’.
- The optimal focal surface has a diameter of 1.16 m, and a radius of curvature of 1.94 m. The calculated Strehl ratio variations over this FOV are better than 97%.
- The 20 arcmin FOV is capable to accommodate up to 1200x1200 (Nyquist Sampled) Pixels at 200 μm.
- The calculated maximum Cross-polar level at the edge of FOV are –51 dB and –52 dB for uniform and Gaussian illumination, respectively.
- The Far Field Side-Lobe Level (SSL) over the FOV is > –16 dB with an uniform Illumination, and better than –20 dB with a –11.0 dB Gaussian illumination taper.
- We have obtained the sub-reflector sensitivities for focusing, de-centering and tilt/tip motion.
- A pointing requirement of θ_{HPFW}/10 at 200μm, imposes a maximum de-centering of the sub-reflector of < 18μm, and maximum edge-to-edge displacements of the sub-reflector, resulting from tilt/tip, between 14μm and 24μm, depending on the location of the center of rotation.
- Maximum chopping amplitude is limited to 10 beam widths for 90% or better Strehl ratio at 200μm, and maximum defocusing of < 80μm.

Conclusions Cont…

- We have analyzed the segmentation effect of an active surface CCAT. The gaps between segments produce a series of grating lobes levels about –31 dB down, and are distributed with a six-fold symmetry in the far field pattern.
- We have calculated the effects, in terms of Strehl ratio, of random segment positioning errors of the active surface, including piston, tilt/tip, lateral displacement and twist segment errors.
- We have found a set of coefficients relating the standard deviation of a particular segment positioning error with its resultant structural rms surface error. We have concluded that the piston errors have the largest effect on the antenna performance, followed by tip/tilt errors being half as important.
- Although, segment piston, and tilt/tip errors are directly controllable by the active surface actuators, we found that un-controllable lateral segment displacements may be compensated by tip/tilt corrections.
- Segment twist errors are not controllable, neither can be compensated by a piston-tilt actuator system alone. Nevertheless, telescope performance is very insensitive to twist errors.
- We have calculated the effects of a uniform thermal expansion of the back-structure by a factor of 1.0005x. This produces a quadratic phase error distribution across of each of the segments, and a overall defocusing of the telescope. After refocusing the achievable Strehl ratio is better than 97%.

End

CCAT Feasibility/Concept Study Review 17-18 January 2006