Cryogenic thermal mask for space-cold optical testing of space optical systems

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Introduction

How do the next generation space optical systems look like?

6.5m JWST

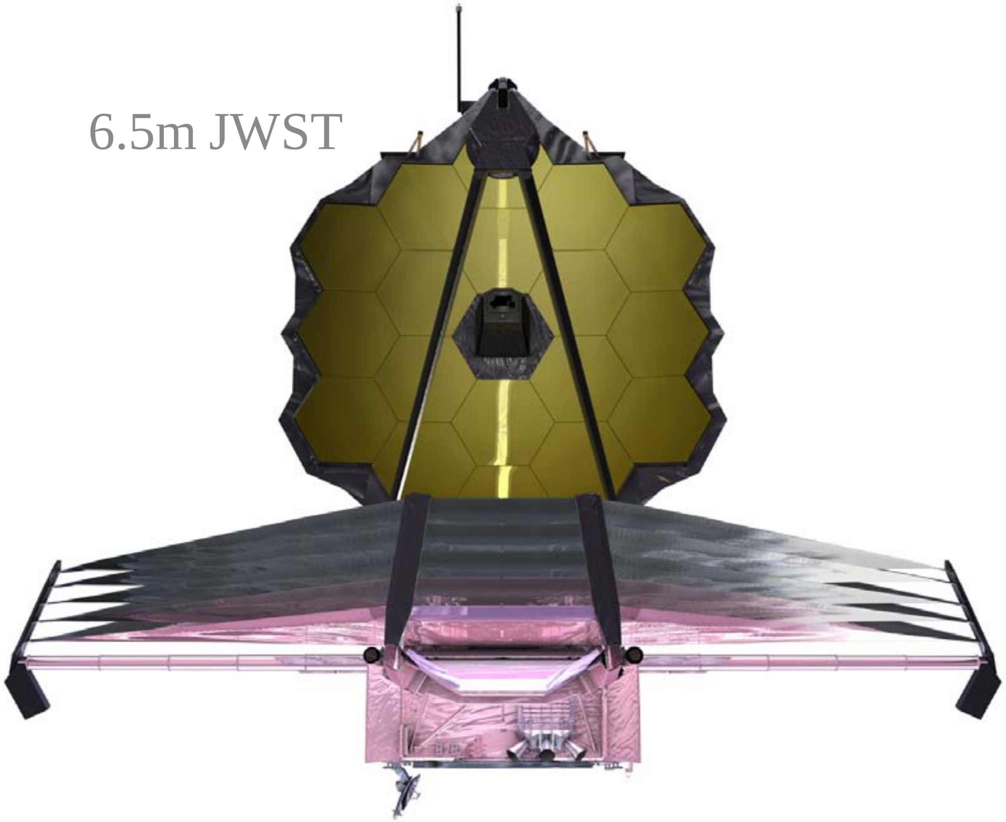


Image from http://www.jwst.nasa.gov/images2/013535_white.jpg

Large aperture size

-More light collecting

-Higher resolution

Cryogenic system

-working in space

-IR telescopes ~7K

No A/S

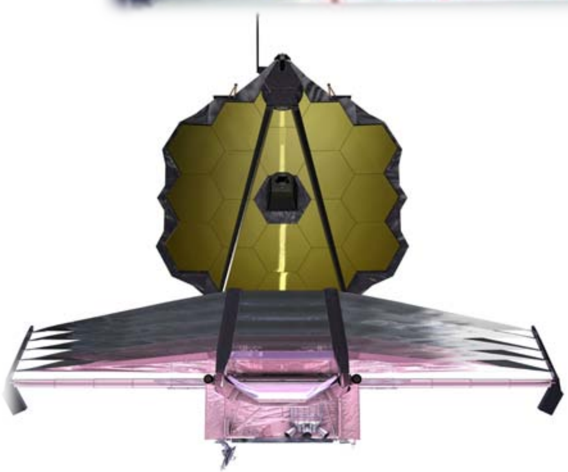
-Located at Lagrange 2

Motivation

We want to test the final performance before the launch.

LOTIS Vacuum Chamber

LOTIS 6.5m collimator



6.5m JWST

Images from

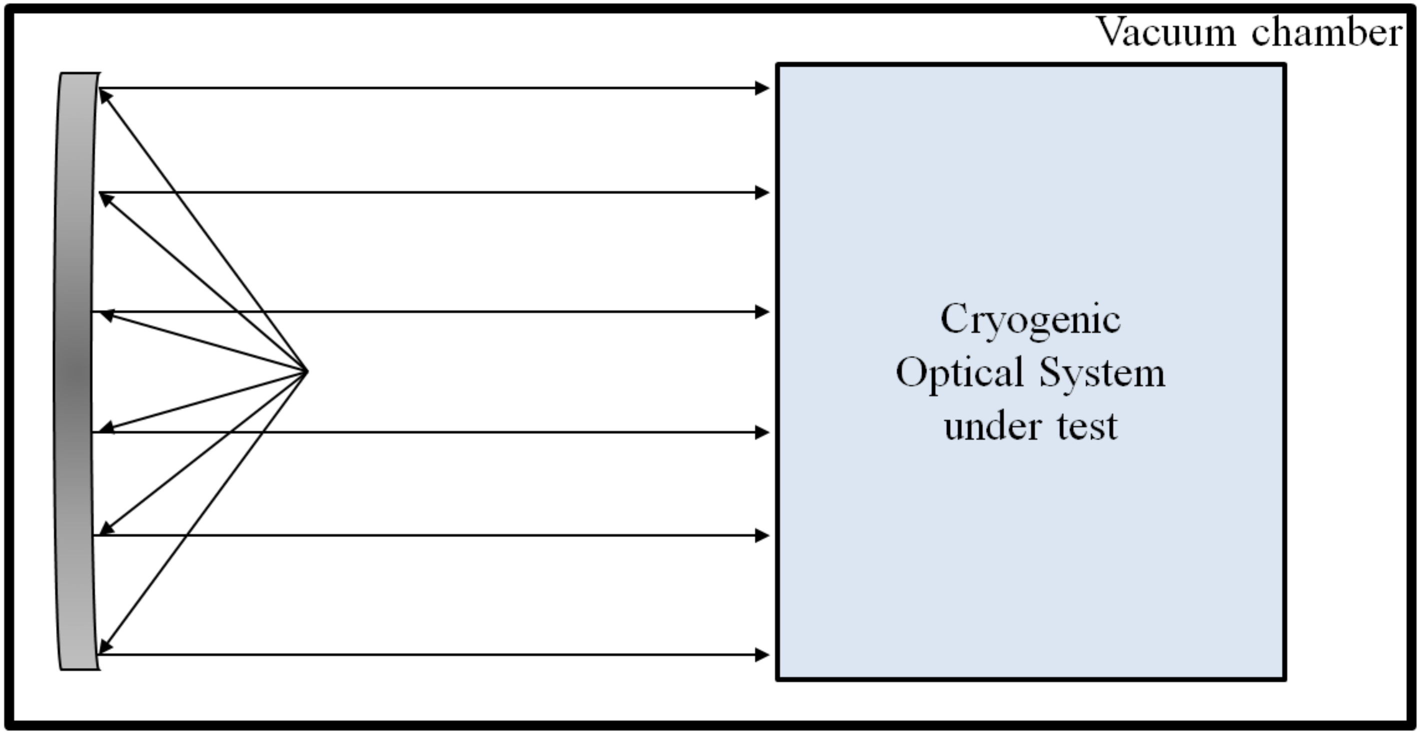
"LOTIS at Completion of Collimator Integration"

R.M. Bell, G.C. Robins, C. Eugeni, G. Cuzner, and S.B. Hutchison*

Lockheed Martin Space Systems Company

Proc. of SPIE Vol. 7017 70170D-1

Test the whole optical system in a space-cold cryogenic vacuum chamber with a collimator.



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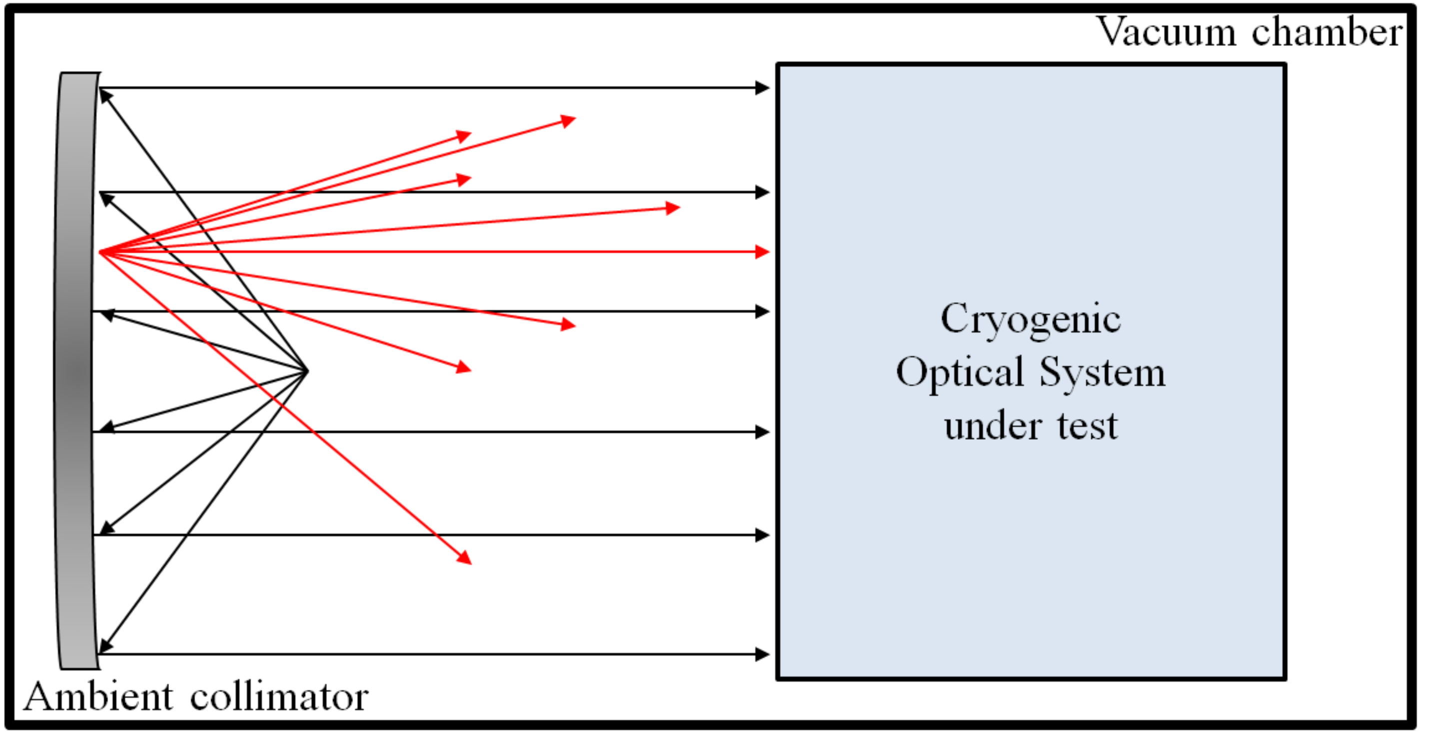
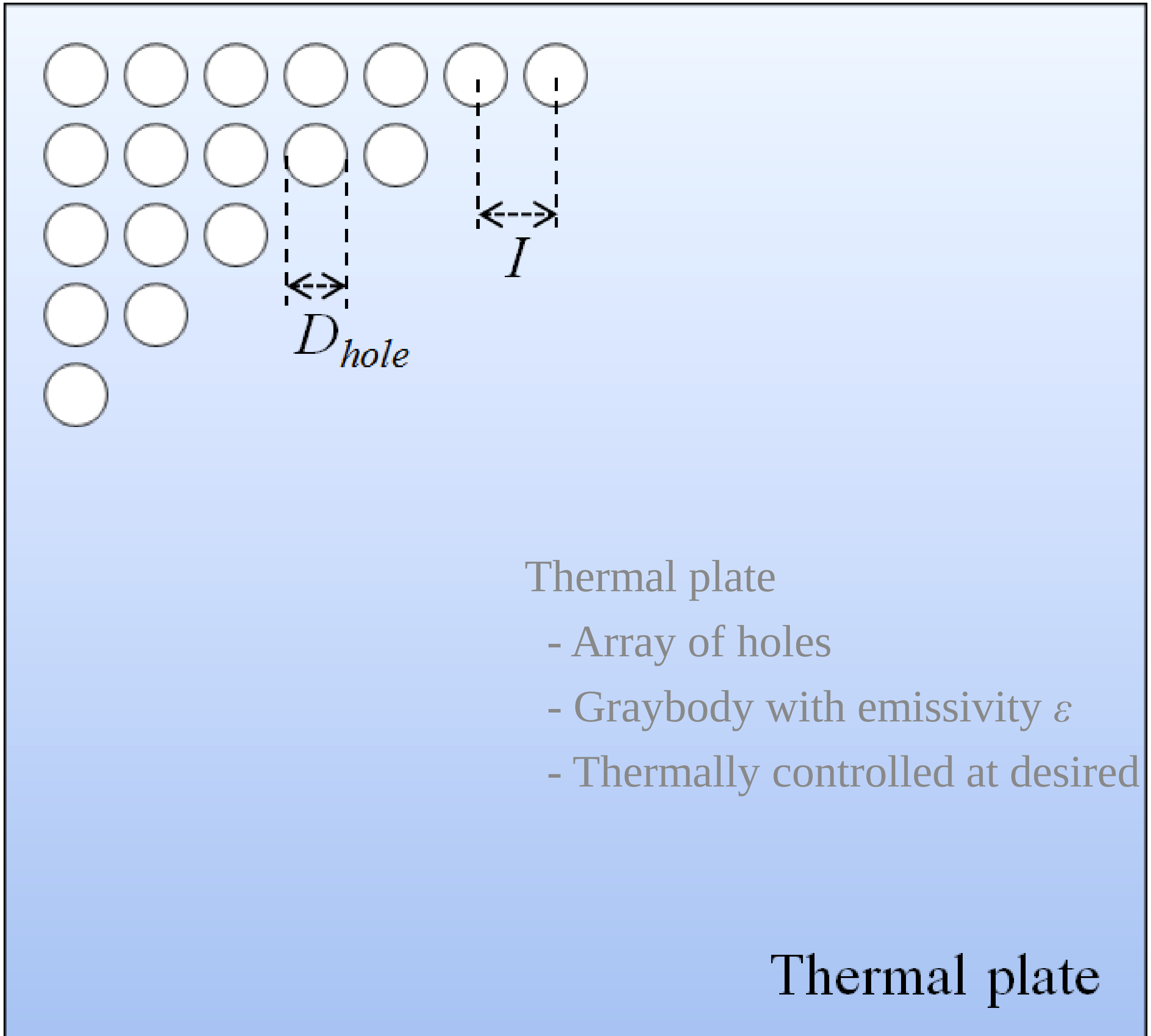


The thermal radiation from the ambient (e.g. 300K) collimator will warm up the cryogenic optical system under test.

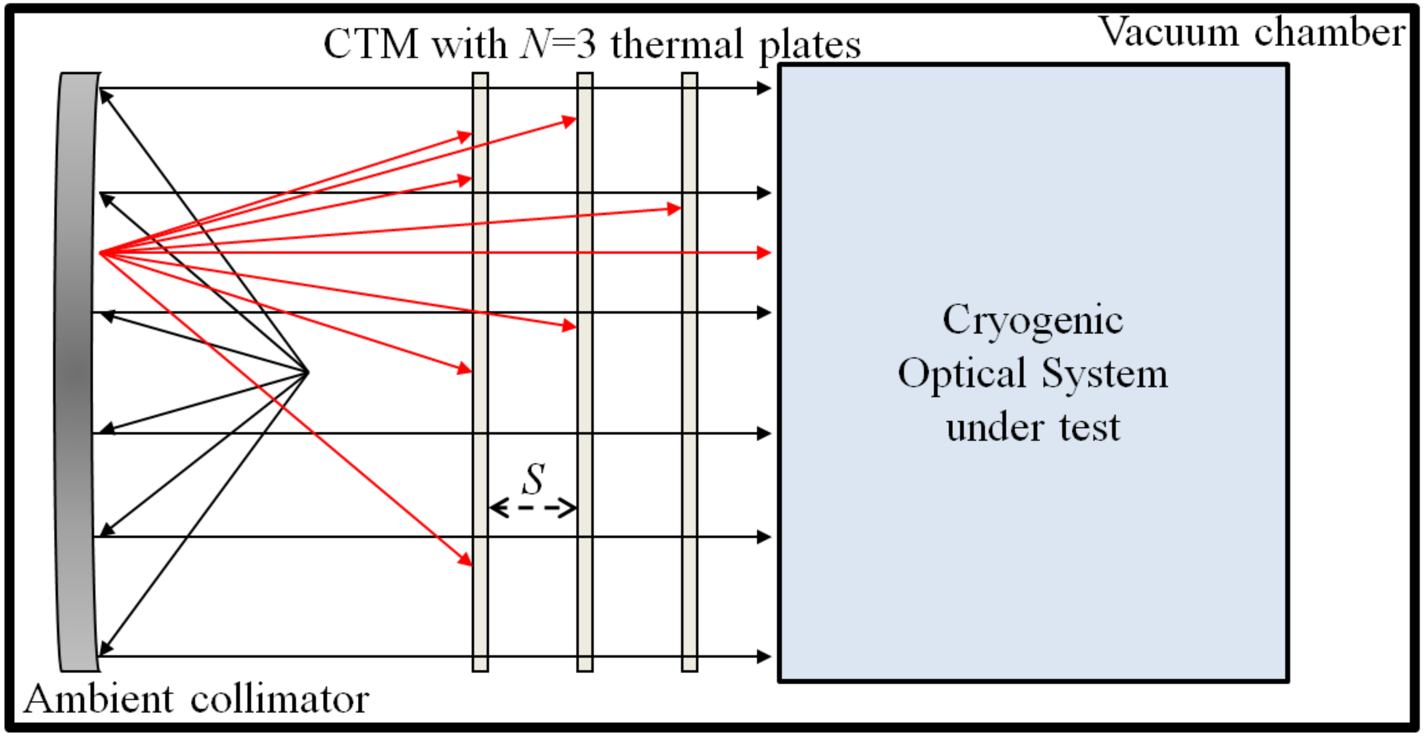
Proposed Solution: Cryogenic Thermal Mask

Can we block the thermal transfer while passing the test wavefront without significant degradation?



Thermal plate

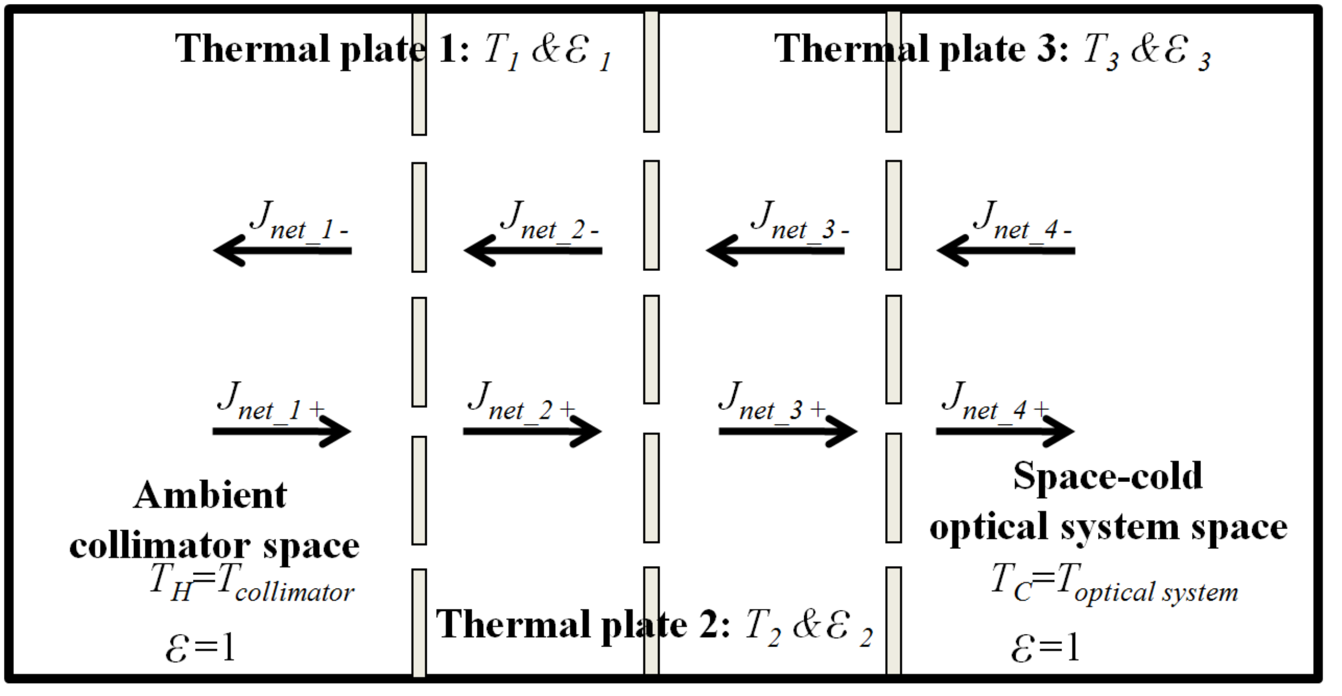
- Array of holes
- Graybody with emissivity ε
- Thermally controlled at desired temperature T



Cryogenic Thermal Mask

- Series of thermal plates with array of holes
- Placed between the collimator and the optical system under test
- Temperature of thermal plates is independently controlled to gradually match the temperature difference two space.

Simplified Thermal Transfer Model



$$J = \varepsilon \cdot \sigma \cdot T^4 \quad [W/m^2]$$

$$J_{net\_2+} = \varepsilon_1 \cdot \sigma \cdot T_1^4 \cdot \alpha + J_{net\_1+} \cdot (1-\alpha) + (1-\varepsilon_1) \cdot J_{net\_2-} \cdot \alpha$$

Thermal Transfer Equation for a given CTM parameters

$$\begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ (\varepsilon_1 - 1)\alpha & 1 & 0 & (\alpha - 1) & 0 & 0 & 0 & 0 \\ (\alpha - 1) & 0 & 1 & (\varepsilon_1 - 1)\alpha & 0 & 0 & 0 & 0 \\ 0 & 0 & (\varepsilon_2 - 1)\alpha & 1 & 0 & (\alpha - 1) & 0 & 0 \\ 0 & 0 & (\alpha - 1) & 0 & 1 & (\varepsilon_2 - 1)\alpha & 0 & 0 \\ 0 & 0 & 0 & 0 & (\varepsilon_3 - 1)\alpha & 1 & 0 & (\alpha - 1) \\ 0 & 0 & 0 & 0 & (\alpha - 1) & 0 & 1 & (\varepsilon_3 - 1)\alpha \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} J_{net\_1+} \\ J_{net\_1-} \\ J_{net\_2+} \\ J_{net\_2-} \\ J_{net\_3+} \\ J_{net\_3-} \\ J_{net\_4+} \\ J_{net\_4-} \end{bmatrix} = \begin{bmatrix} \sigma T_H^{\ 4} \\ \sigma \varepsilon_1 T_1^{\ 4} \alpha \\ \sigma \varepsilon_1 T_1^{\ 4} \alpha \\ \sigma \varepsilon_2 T_2^{\ 4} \alpha \\ \sigma \varepsilon_2 T_2^{\ 4} \alpha \\ \sigma \varepsilon_3 T_3^{\ 4} \alpha \\ \sigma \varepsilon_3 T_3^{\ 4} \alpha \\ \sigma T_C^{\ 4} \end{bmatrix}$$

Thermal Loads to the cold (cryogenic optical system) space and to the hot space (ambient collimator)

$$\Delta J_C = J_{net\_4+} - J_{net\_4-} \; [W / m^2]$$

$$\Delta J_H = J_{net\_1-} - J_{net\_1+} \; [W / m^2]$$

Fraunhofer diffraction theory for the test beam propagation

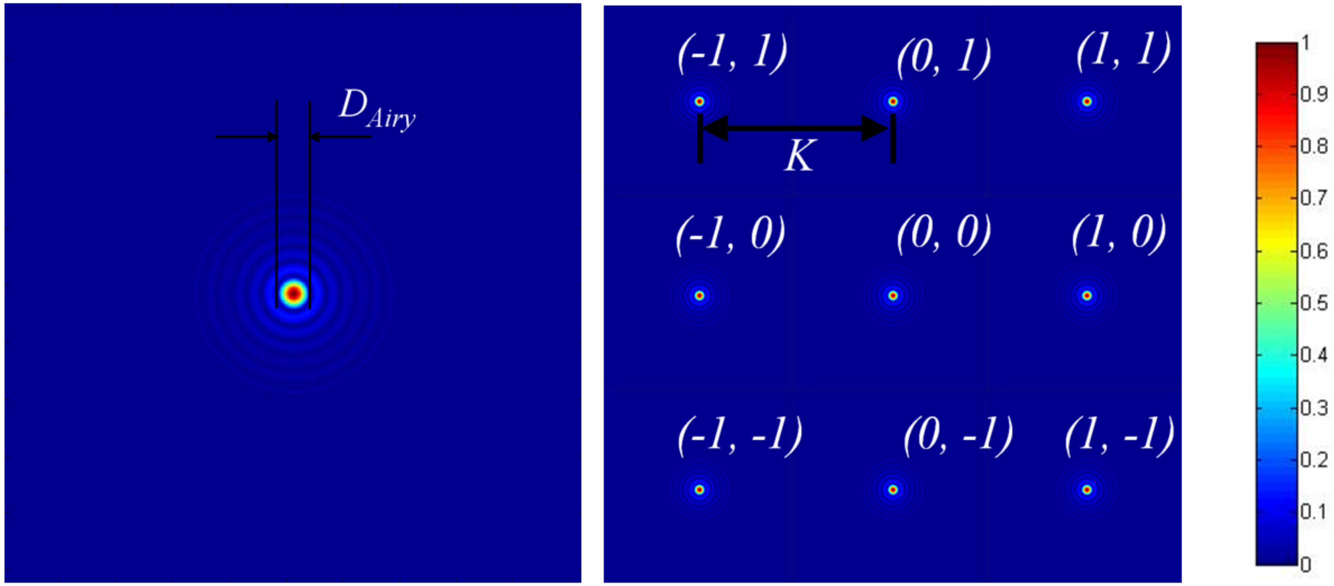
$$U_{focal}(x,y) \propto F_{\eta=\frac{y}{\lambda\cdot f_{eff}}} F_{\xi=\frac{x}{\lambda\cdot f_{eff}}} [cyl(\frac{\sqrt{x^2+y^2}}{D_{CTM}}) \cdot \{comb(\frac{x}{I},\frac{y}{I}) ** U_{hole}(x,y)\}]$$

$$= F_{\eta=\frac{y}{\lambda\cdot f_{eff}}} F_{\xi=\frac{x}{\lambda\cdot f_{eff}}} [cyl(\frac{\sqrt{x^2+y^2}}{D_{CTM}})] ** F_{\eta=\frac{y}{\lambda\cdot f_{eff}}} F_{\xi=\frac{x}{\lambda\cdot f_{eff}}} [comb(\frac{x}{I},\frac{y}{I}) ** U_{hole}(x,y)]$$

$$\propto somb(\frac{D_{CTM}\cdot\sqrt{x^2+y^2}}{\lambda\cdot f_{eff}}) ** \{comb(\frac{I\cdot x}{\lambda\cdot f_{eff}},\frac{I\cdot y}{\lambda\cdot f_{eff}}) \cdot F_{\eta=\frac{y}{\lambda\cdot f_{eff}}} F_{\xi=\frac{x}{\lambda\cdot f_{eff}}} [U_{hole}(x,y)]\}$$

Because of the diffraction from the periodical hole array in the CTM, multiple diffraction orders are generated.

Multiple diffraction orders at the focal plane



Condition to spatially block unwanted orders

$$D_{Airy} = \frac{2 \cdot \lambda \cdot f_{eff}}{D_{system}} << \frac{\lambda \cdot f_{eff}}{I} = K$$

$$I << \frac{D_{system}}{2}$$

Performance

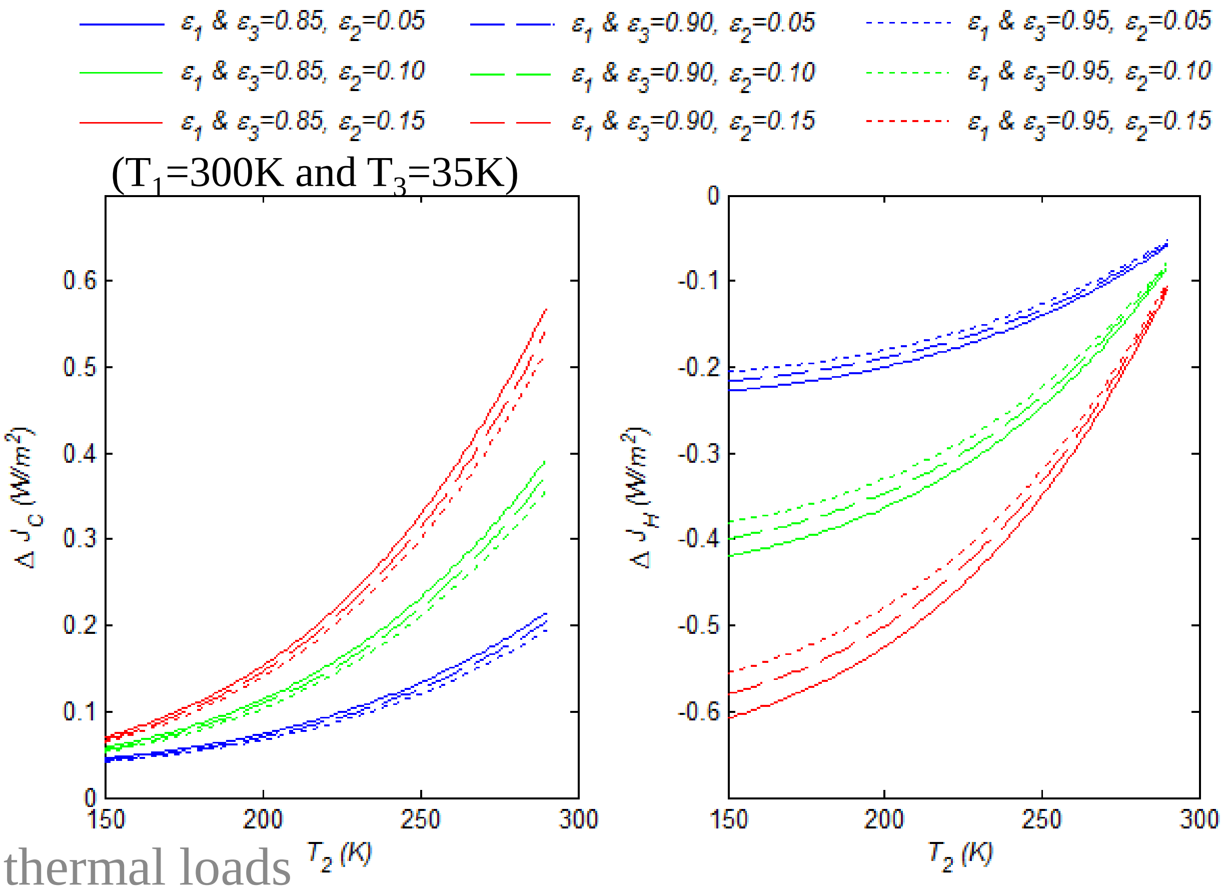
Will it work thermally and optically?

Nominal CTM parameter

Parameters	Symbol	Value
Temperature of hot space	T_H	300 K
Temperature of cold space	T_C	35 K
Wavelength	Λ	1 µm
Diameter of hole	D_{hole}	0.002 m
Interval between holes	I	0.02 m
Spacing between plates	S	0.25 m
Number of thermal plates	N	3
Diameter of optical system	D_{system}	6.6 m
Number of hole-sets	$N_{hole\text{-}set}$	~85500
Obscuration ratio	A	~0.99

Part A. Thermal Performance Analysis

Thermal Performance Analysis I – Emissivity and T_2



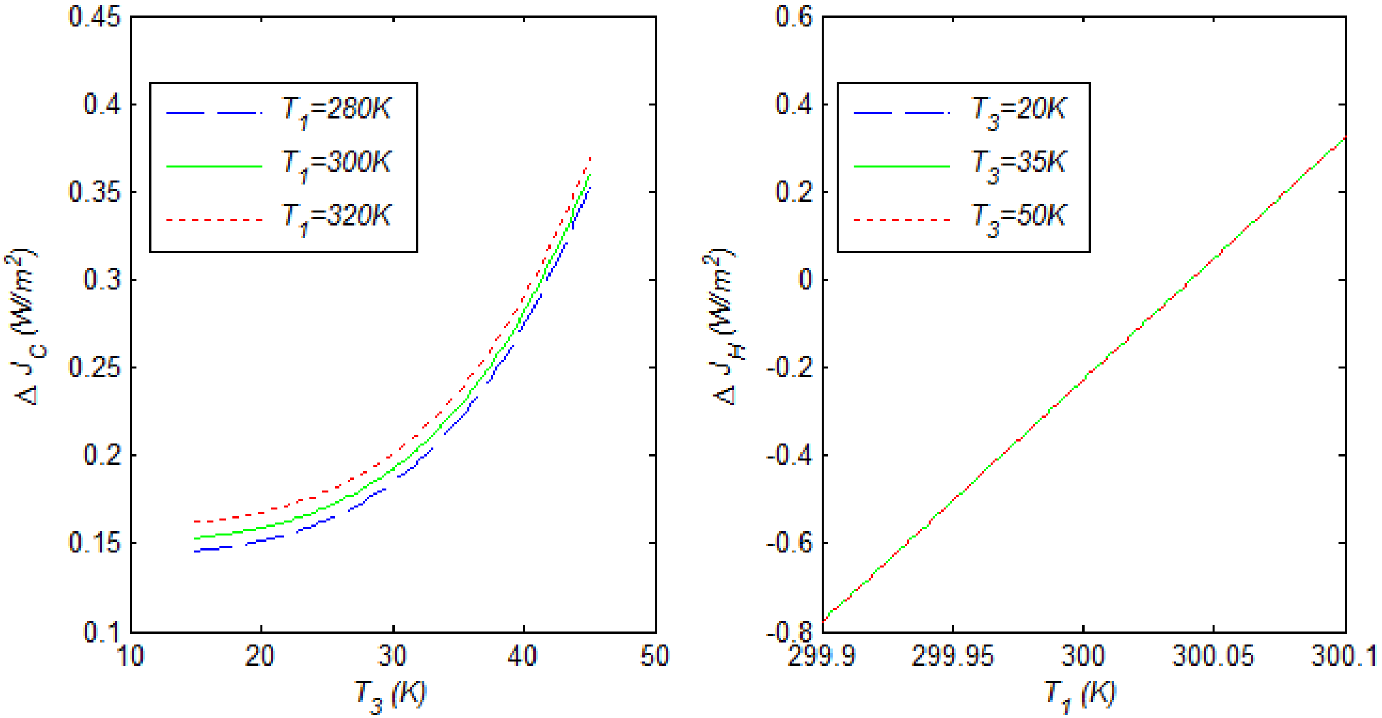
Less thermal loads

- More blackbody-like first and third plate
- More reflective second plate

T_2 needs to be compromised for ΔJ_C and ΔJ_H

Thermal Performance Analysis II – T_3 and T_1

(T_2=252K and $\varepsilon_1=\varepsilon_3=0.9$, $\varepsilon_2=0.1$)

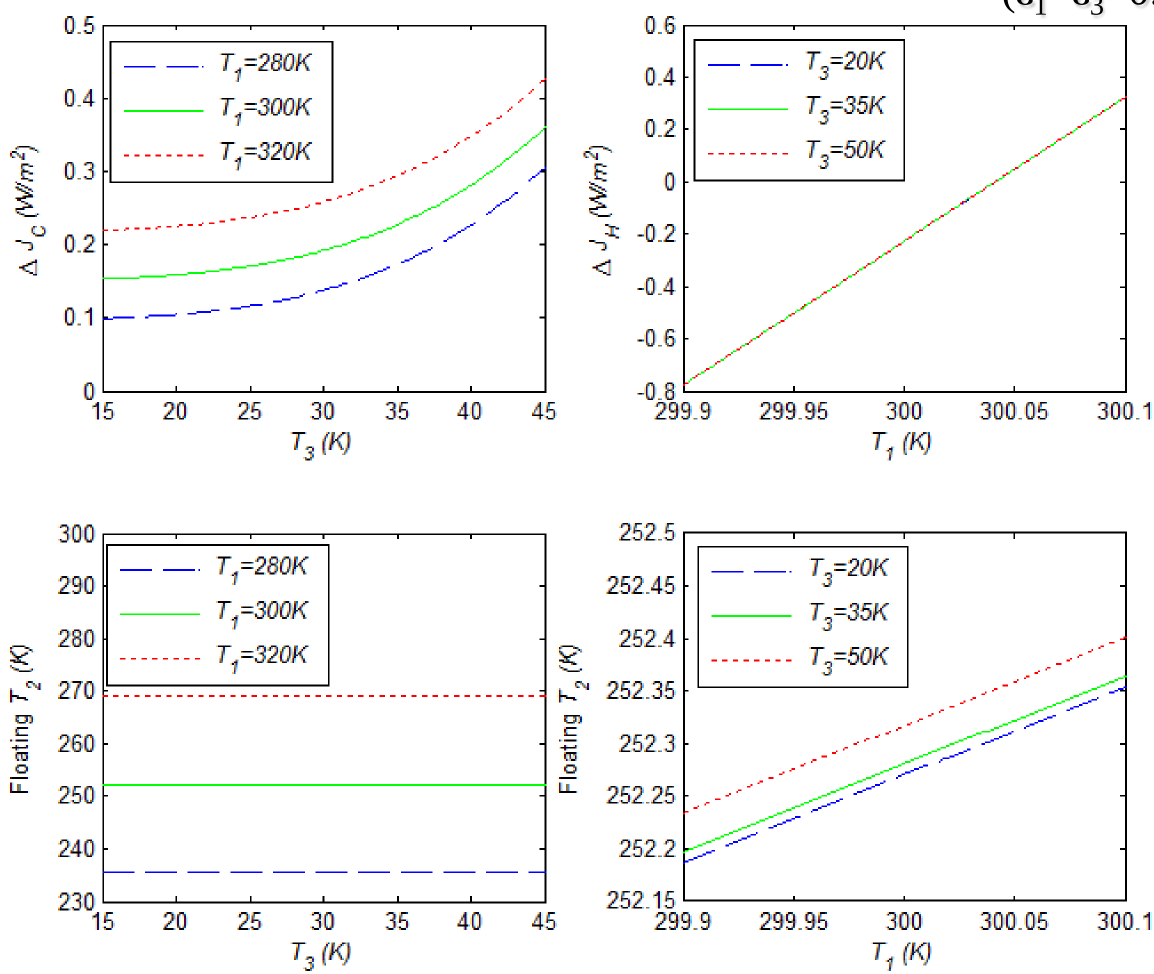


T_3 is useful knob to tweak the thermal load to the optical system side ΔJ_C

T_1 is useful knob to tweak the thermal load to the collimator side ΔJ_H

Thermal Performance Analysis III – Floating T_2

($\varepsilon_1=\varepsilon_3=0.9$, $\varepsilon_2=0.1$)

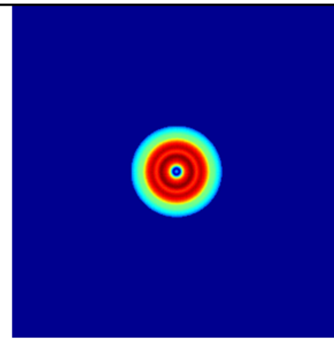
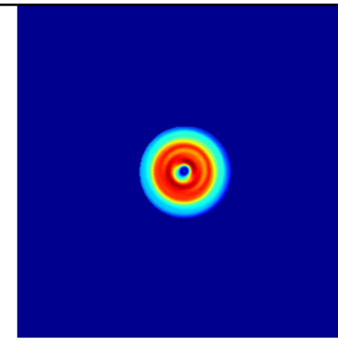
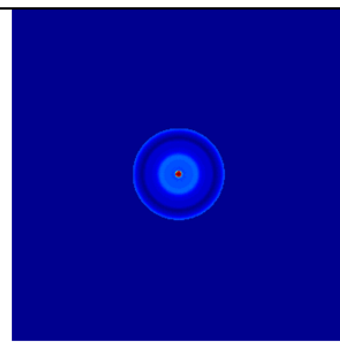
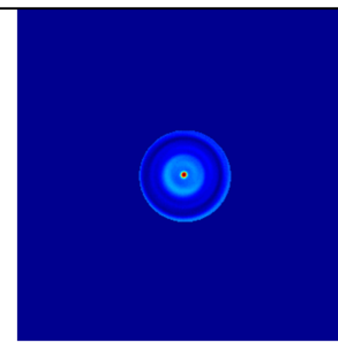


Floating T_2 is still gives good thermal performance (e.g. $<300 mW/m^2$) .

T_2 does not need to be thermally controlled.

Part B. Optical Performance Analysis

Optical Performance Analysis I – Tolerance in a single hole in the CTM

	Perfect case	Perturbed case
Amplitude Map		
Phase Map		

Tolerance

- Misalignment: $\delta x = 50\ \mu m$, $\delta y = 50\ \mu\ m$
- Hole diameter: $\delta D_{hole} = 20\ \mu\ m$

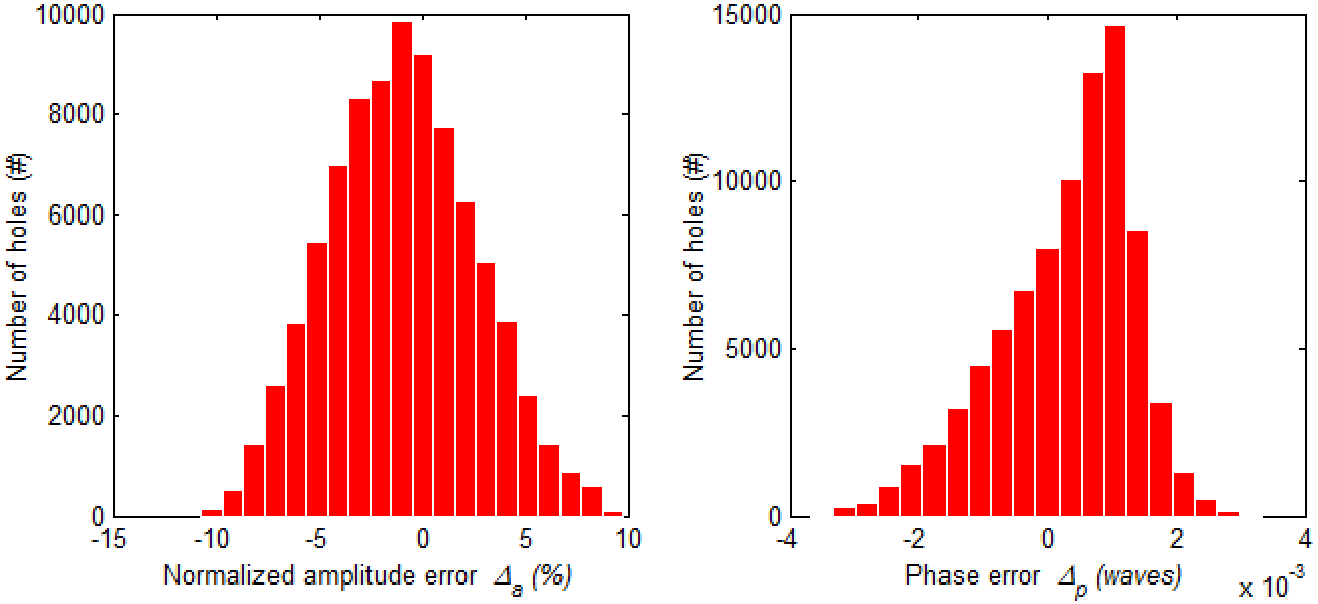
Optical Performance Analysis II – Normalized amplitude error and phase error

$$\Delta_a = \frac{\left|\iint\limits_{hole} U_{hole\_perturbed}(x,y)\,dx\cdot dy\right| - \left|\iint\limits_{hole} U_{hole\_perfect}(x,y)\,dx\cdot dy\right|}{\left|\iint\limits_{hole} U_{hole\_perfect}(x,y)\,dx\cdot dy\right|}\cdot 100\ (\%)$$

$$\Delta_p = \frac{phase\ angle\ of\ \iint\limits_{hole} U_{hole\_perturbed}(x,y)\,dx\cdot dy - phase\ angle\ of\ \iint\limits_{hole} U_{hole\_perfect}(x,y)\,dx\cdot dy}{2\cdot\pi}\ (waves)$$

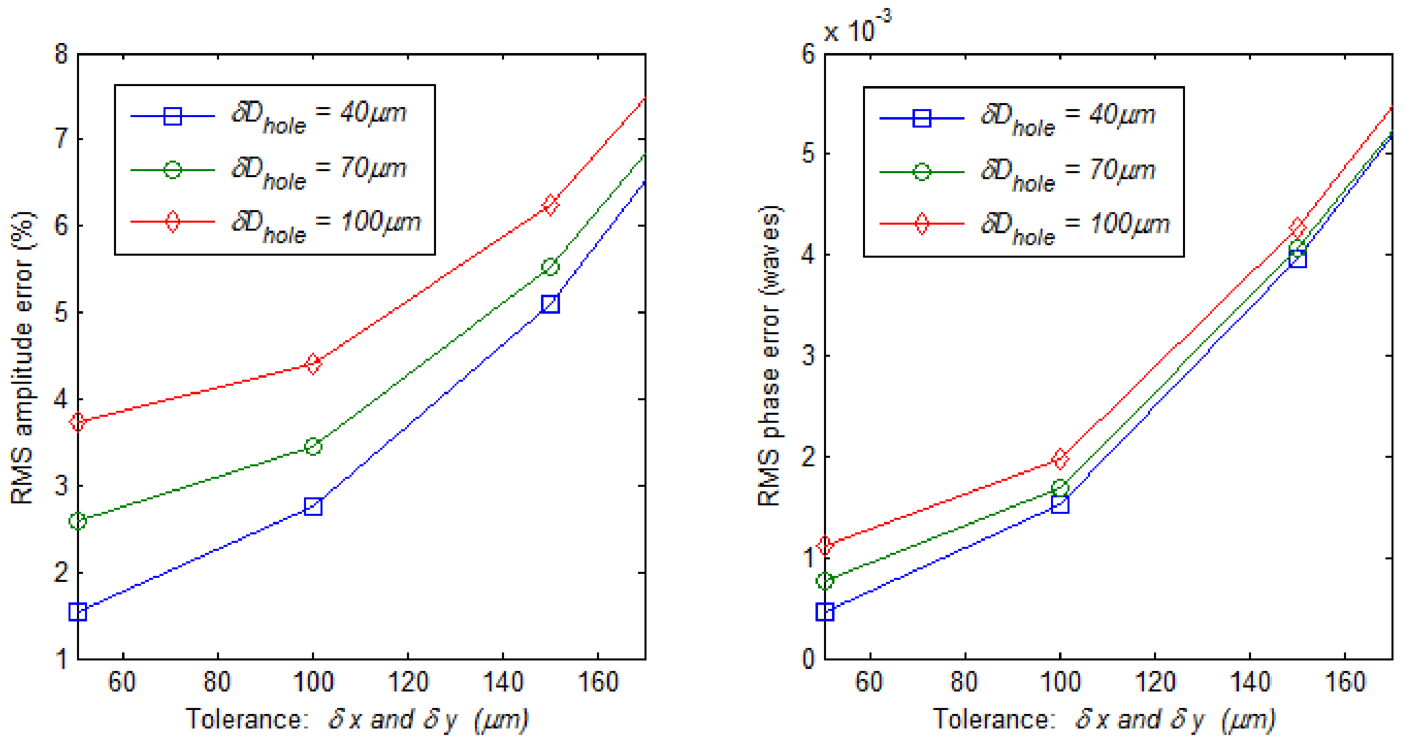
The normalized amplitude error Δ_a and the phase error Δ_p were defined to quantitatively asses the optical errors in the test beam compared to the perfect case.

Optical Performance Analysis III – Optical errors from the whole CTM



One of the tolerance analysis histograms for 85500 holes in the nominal CTM (Tolerance: δx = 50 um, δy = 50 um, and δDhole = 100 um)

Optical Performance Analysis IV – Tolerance vs. optical errors



Within the realistic tolerance ranges, the induced RMS phase error was <0.006 waves, which may be sufficient for most optical testing applications.

Summary & Future Works

What do we have now,

and what needs to be done next?

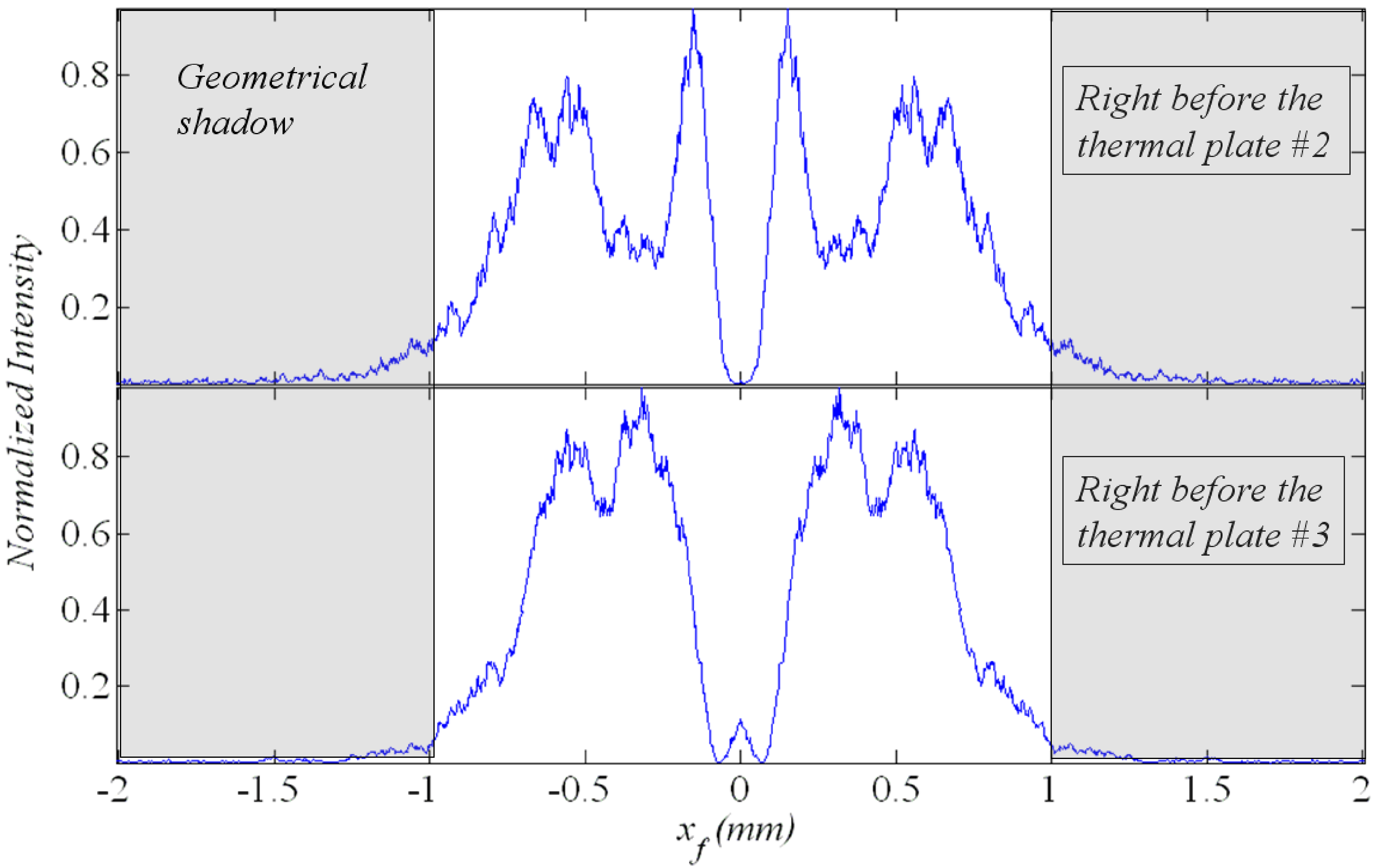
The analysis shows a good thermal and optical performance of the nominal CTM.

- A three plate CTM with holes occupying ~1% of the thermal plate area and with two black and a polished intermediate thermal plates caused thermal loading less than 300mW/m^2 for both the 300K ambient and the 35K cryogenic sides of the system.
- The induced RMS phase error with some realistic CTM tolerance values was <0.006waves, which may be sufficient for most optical testing applications.

There are remaining future works.

- The normalized amplitude error Δ_a and the phase error Δ_p may not exactly represent the actual errors in the test beam after passing through a CTM.
- The simplified thermal model is only the first order calculation.
- An actual experimental demonstration using a sub-scale CTM will be made to answer those issues.

Thank you.



Geometrical shadow
Right before the thermal plate #2
Right before the thermal plate #3
Normalized Intensity
0.8
0.6
0.4
0.2
0.8
0.6
0.4
0.2
-2
-1.5
-1
-0.5
0
0.5
1
1.5
2
x_f (mm)