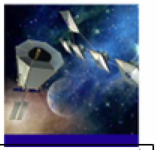
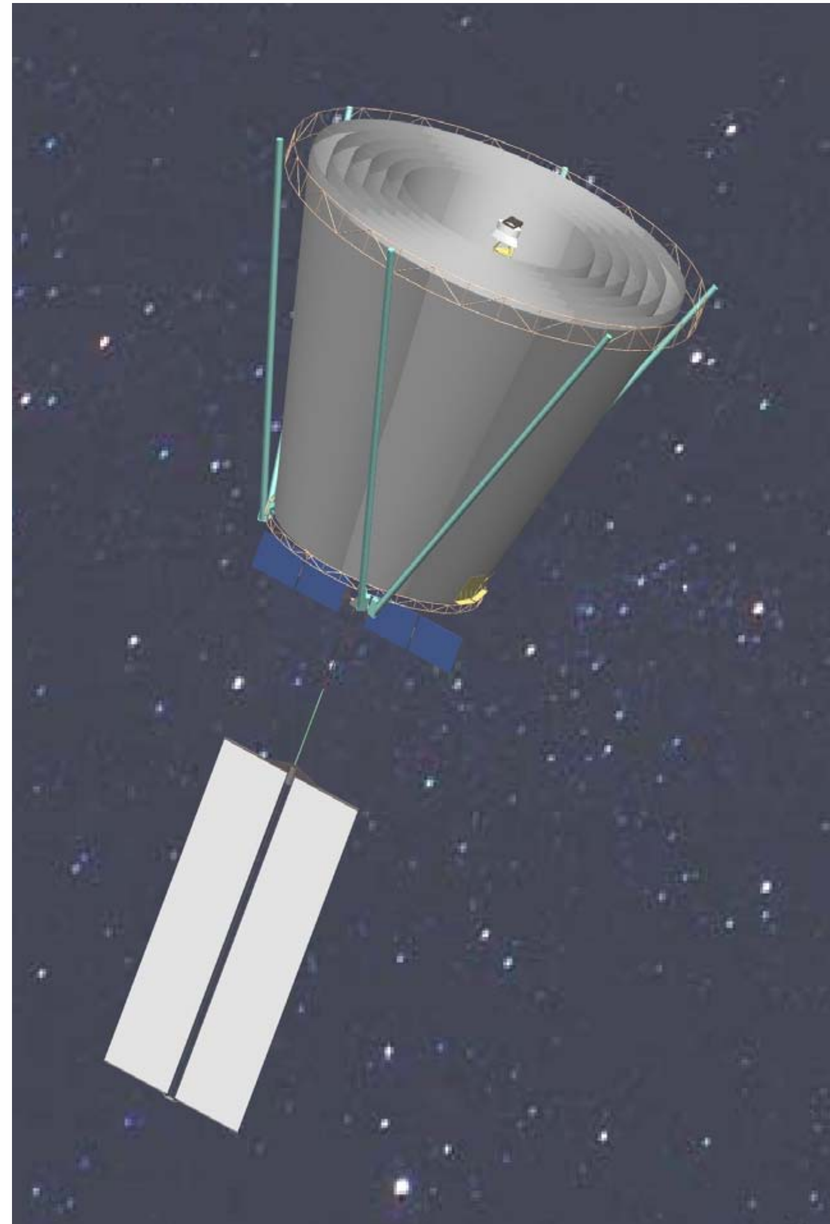


TPF Terrestrial Planet Finder

The Terrestrial Planet Finder Dynamics Error Budget

Stuart Shaklan, Luis Marchen, Joseph Green, and Oliver Lay

SPIE Meeting
San Diego, CA
August 2005
Paper 5905-13



High-Level Requirements

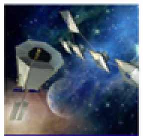
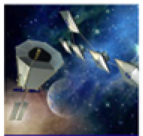


Table 1. TPF-Coronagraph Contrast Error Budget Requirements.

	Requirement	Comment
Static Contrast	6.00E-11	Coherent Terms
Contrast Stability	2.00E-11	Thermal + Jitter
Instrument Stray Light	1.50E-11	Incoherent light
Inner Working Angle	$4\ \lambda/D_{long}$	57 mas at λ=550 nm, $D_{long} = 8$ m
Outer Working Angle	$48\ \lambda/D_{short}$	1.5 arcsec at λ=550 nm, $D_{short} = 3.5$ m
Bandpass	500-800 nm	Separate observ. in three 100 nm bands.

Static and Dynamic Terms



$$\text{Contrast} = I_s + \langle I_d \rangle$$

$$\text{Stability} = \text{sqrt}(2I_s\langle I_d \rangle + \langle I_d^2 \rangle)$$

I_s = Static Contrast	I_d = Dynamic Contrast
Wave Front Sensing Wave Front Control Gravity Sag Prediction Print Through Coating Uniformity Polarization Mask Transmission Stray Light Micrometeoroids Contamination	Pointing Stability Thermal and Jitter Motion of optics Beam Walk Aberrations Bending of optics Aberrations
Every item is unknown territory, new technology. Most are bandwidth-dependent	Solve with Design and Engineering, linear modeling. Bandwidth independent.

Error Budget Models

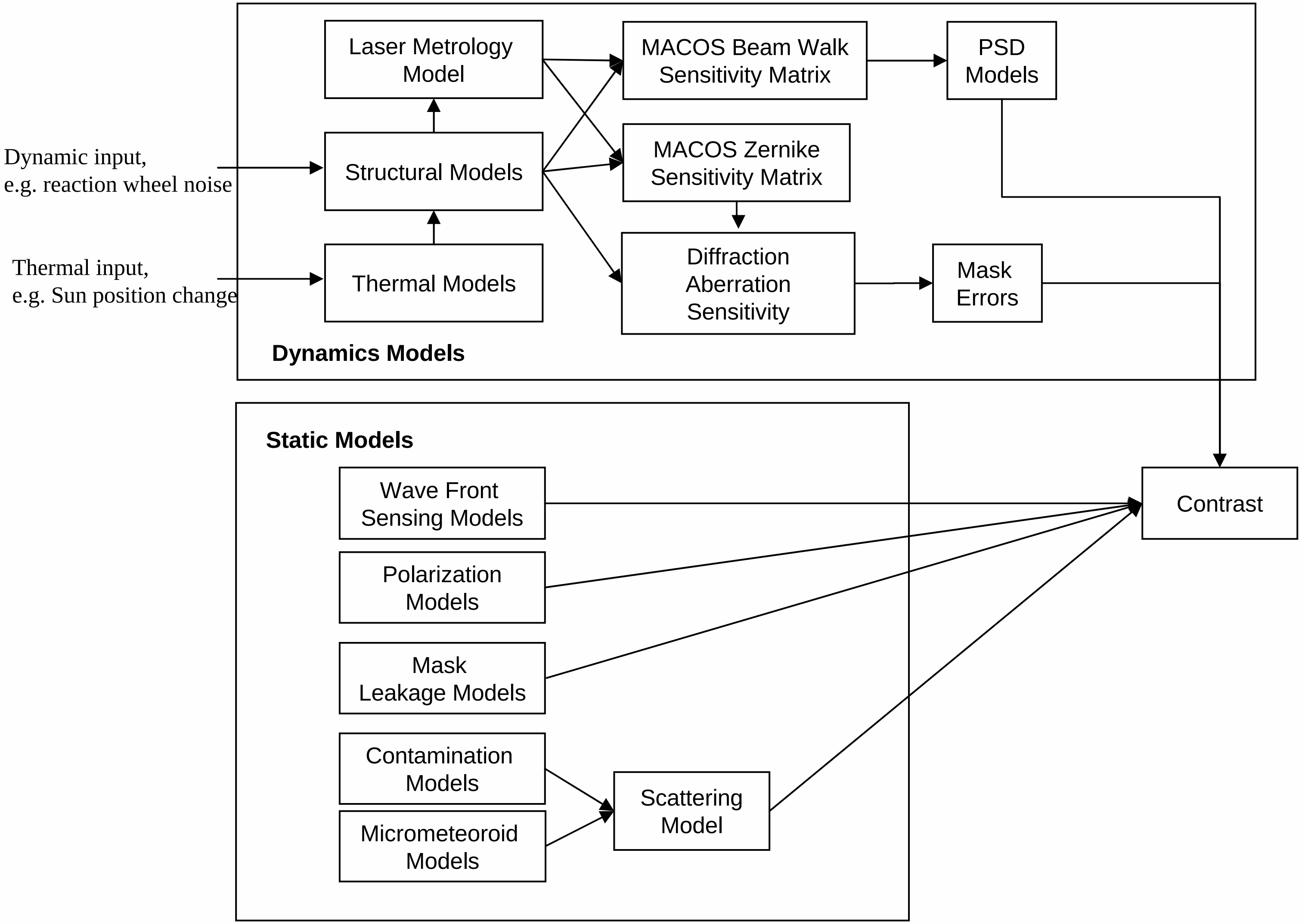


Figure 3. Models used to calculate static and dynamic contrast.

Error Budget Structure

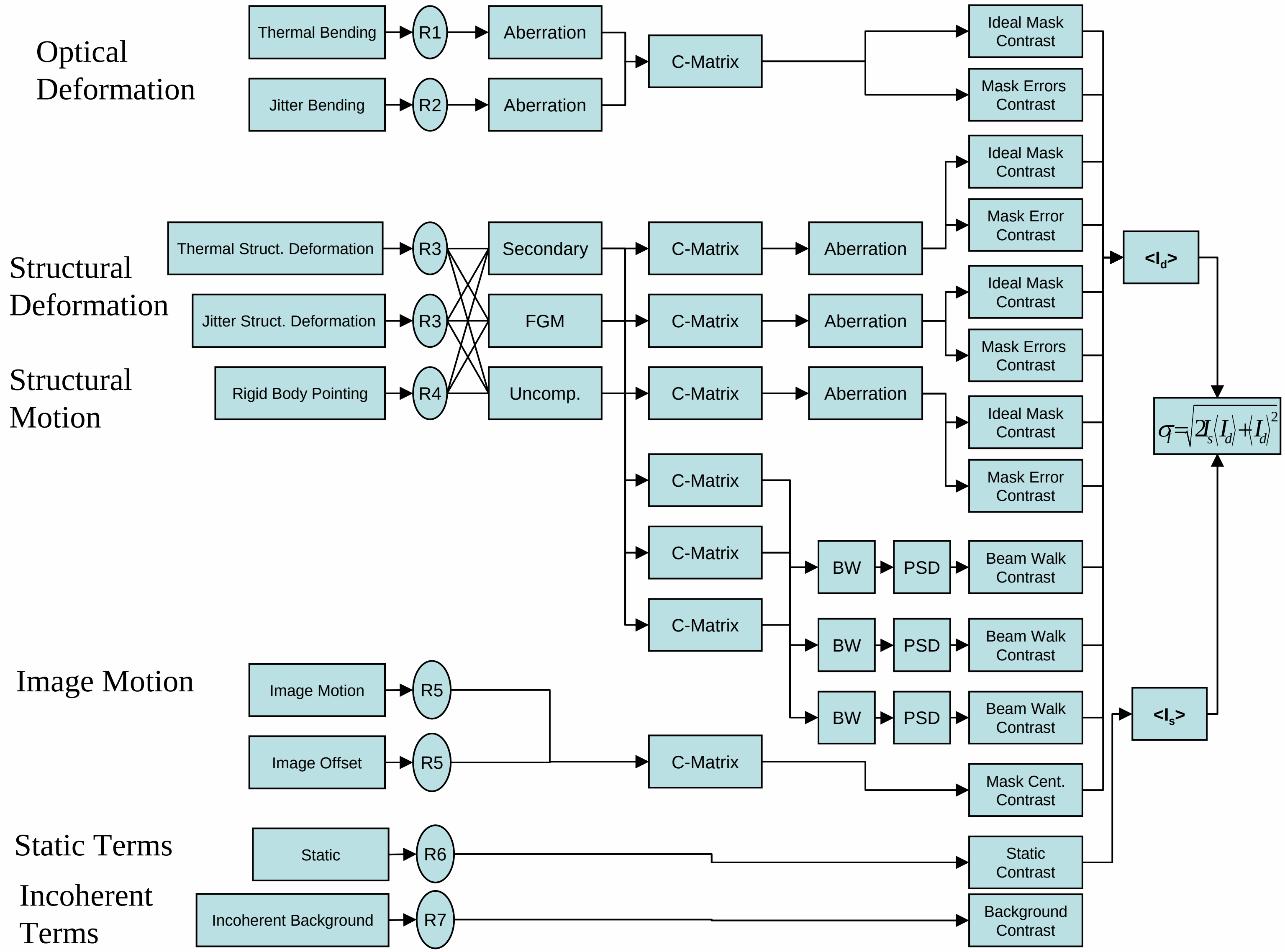
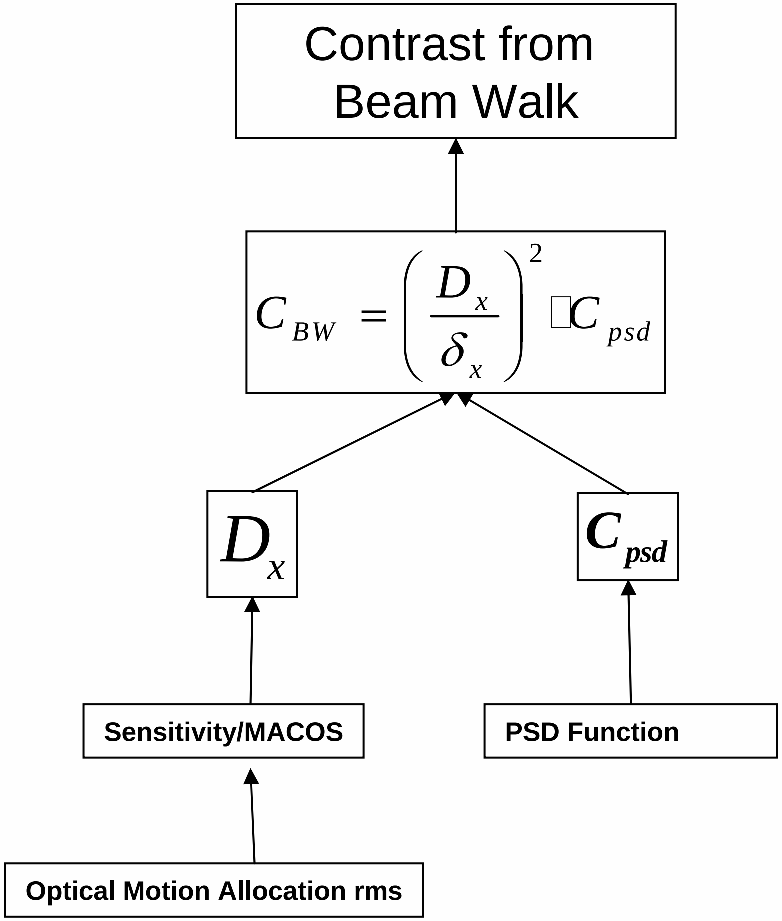


Figure 1. Error Budget Structure. 'C-matrix' is a sensitivity matrix or equation. R1-R7 are multiplicative reserve factors.

Beam Walk Model



$$C_{psd} = \left(\frac{2\pi}{\lambda} \cdot \sqrt{ \iint 16\pi^2 (\delta_x k_x)^2 \cdot \left[\frac{A}{1 + \left(\frac{\sqrt{k_x^2 + k_y^2}}{k_0} \right)^n} \right] dk_x dk_y } \right)^2$$

Figure 4. Beam walk calculation. C_{psd} is the contrast for a unit value of beam walk, δ_x at a spatial frequency (image plane position) of k_x.. D_x is the beam walk calculated from linear sensitivity matrices applied to allocated translation and tilt motions.

Control Systems

- 3-tiered pointing control
  - Rigid body pointing using reaction wheels or Disturbance-Free Payload
  - Secondary mirror tip/tilt (~ 1 Hz)
  - Fine-guiding mirror (several Hz)
- PM-SM Laser Metrology and Hexapod
  - Measures and compensates for thermal motion of secondary relative to primary.

Pointing Control

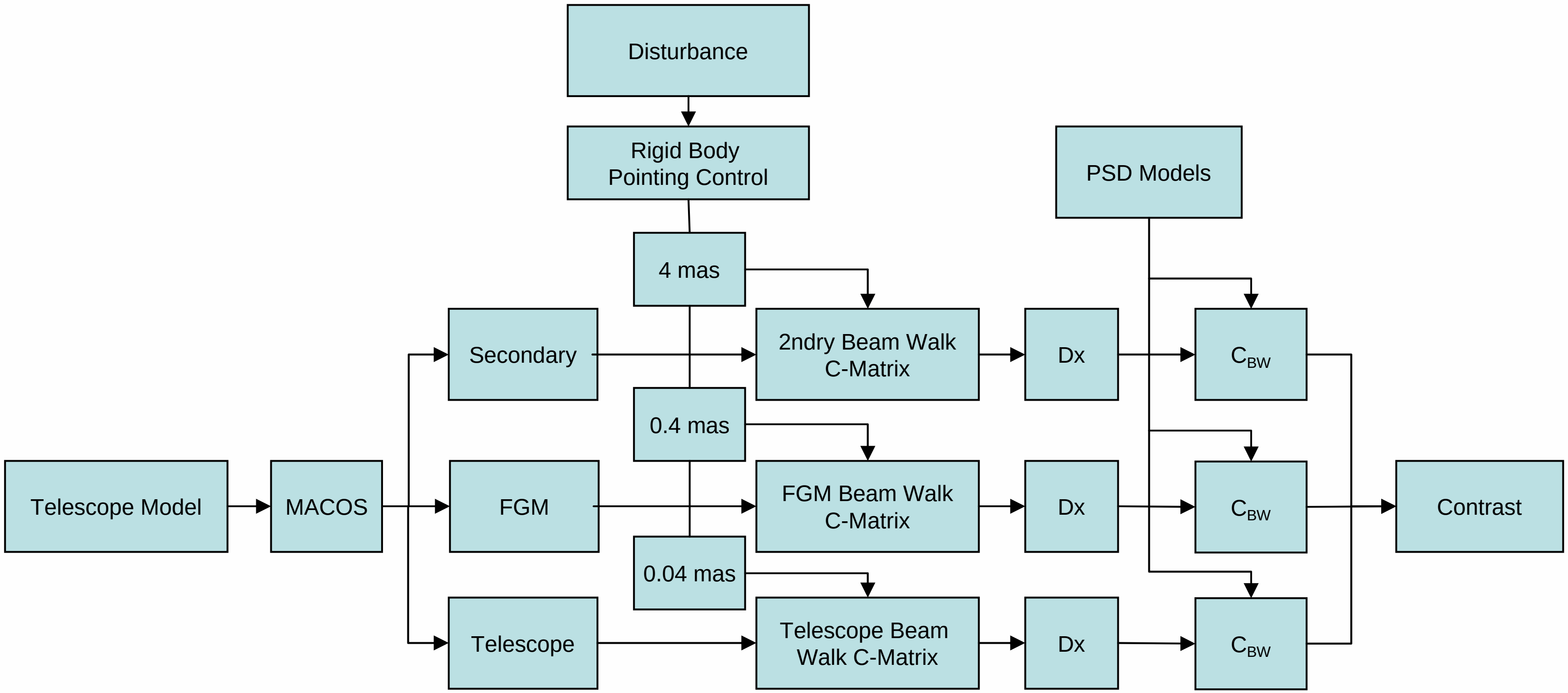


Figure 2. Pointing control. The CEB assumes a nested pointing control system. Reaction wheels and/or a Disturbance Reduction System control rigid body motions to 4 mas (1 sigma). The telescope secondary mirror tips and tilts to compensate the 4 mas motion but has a residual due to bandwidth limitation of 0.4 mas. A fine guiding mirror in the SSS likewise compensates for the 0.4 mas motion leaving 0.04 mas uncompensated.

Error Budget Screen Shot

TC Technology

nightsky systems

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Error Budget

			4 λ/D
Final Contrast	=	**WFE +Background**	**5.63E-11**
σ_I	=	$\sqrt{2 I_s \langle I_d \rangle + \langle I_d \rangle^2}$	**2.00E-11**
$\langle I \rangle$	=	$\langle I_d \rangle + \langle I_s \rangle$ **Total Contrast**	**4.13E-11**
$\langle I_d \rangle$	=	**Jitter/Thermal Error+Bending of Optics+Rigid Body+Image Position**	**5.14E-12**

Bending of Optics Jitter/Thermal (Includes Reserve)	**1.72E-12**
Jitter/Thermal Structural Deformation Aberrations and Beam Walk (Includes Reserve)	**1.49E-12**
Image Position Offset and Image Jitter (Includes Reserve	**6.37E-13**
Rigid Body Pointing (Includes Reserve)	**1.29E-12**
I_S = **Static Error (Includes Reserve)**	**3.62E-11**
Background Error	**1.50E-11**

Jitter/Thermal Reserve (Beam Walk and Structural)						2.00
Reserve Factor Bending of Optics						2.00
Reserve Factor (Image Position Jitter and Offset)						2.00
Reserve Factor Mask Transmission Errors						2.00
Reserve Factor Rigid Body Pointing						2.00
Reserve Factor for WFS/C						2.00
Reserve Factor Amplitude Uniformity						2.00
Reserve Factor Polarization Leakage						2.00
FGM-Residual						0.10
Secondary-Residual						0.10
					No Reserve	Reserve
ΔM	The no reserve ΔM can be changed here				5.00E-04	1.00E-03

ON — FGM ON/OFF

ON — Secondary ON/OFF

Turn off 2ndary Mirror Pointing Control

LOCKHEED MARTIN
Ball Aerospace & Technologies Corp.
NORTHROP GRUMMAN Space Technology
TC Technology
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Error Budget

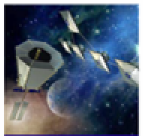
		4 λ/D
Final Contrast =	WFE +Background	2.19E-10
$\sigma_I = \sqrt{2I_s \langle I_d \rangle + \langle I_d \rangle^2}$		2.00E-10 ←
$\langle I \rangle$ = $\langle I_d \rangle + \langle I_s \rangle$	Total Contrast	2.04E-10
$\langle I_d \rangle$ =	Jitter/Thermal Error+Bending of Optics+Rigid Body+Image Position	1.67E-10
Bending of Optics Jitter/Thermal (Includes Reserve)		1.72E-12
Jitter/Thermal Structural Deformation Aberrations and Beam Walk (Includes Reserve)		3.63E-11
Image Position Offset and Image Jitter (Includes Reserve		6.37E-13
Rigid Body Pointing (Includes Reserve)		1.29E-10
I_S = Static Error (Includes Reserve)		3.62E-11
Background Error		1.50E-11

Jitter/Thermal Reserve (Beam Walk and Structural)			2.00
Reserve Factor Bending of Optics			2.00
Reserve Factor (Image Position Jitter and Offset)			2.00
Reserve Factor Mask Transmission Errors			2.00
Reserve Factor Rigid Body Pointing			2.00
Reserve Factor for WFS/C			2.00
Reserve Factor Amplitude Uniformity			2.00
Reserve Factor Polarization Leakage			2.00
FGM-Residual			0.10
Secondary-Residual			0.10
		No Reserve	Reserve
ΔM	The no reserve ΔM can be changed here	5.00E-04	1.00E-03

ON
FGM ON/OFF

OFF
Secondary ON/OFF

Power Spectral Density of Optics

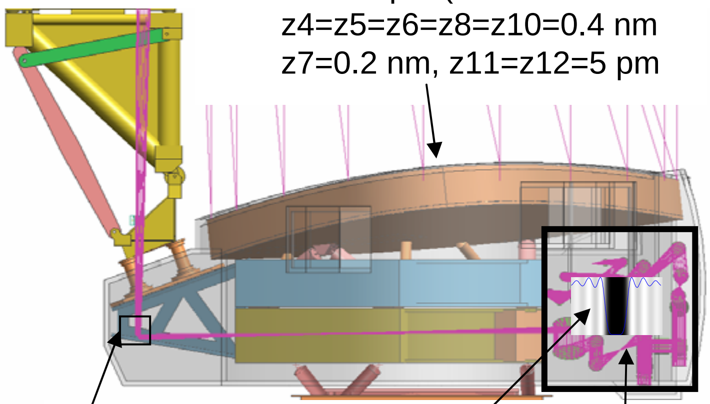


- Fold mirrors 1 and 2 are 'super fold'
- First off-axis-parabola is 'Super OAP'
- Cylindrical mirrors are 'anamporphic'
- DM is r.s.s. of all optics. K0 is scaled value from PM (8 m scaled to 10 cm)

Table 2: PSD specifications for optics modeled in the CEB.

	Primary	Secondary	Fold	Super Fold	OAP	Super OAP	Anamorphic 1	Anamorphic 2	DM
D (m)	8.02	0.83	0.1	0.1	0.1	0.1	0.23	0.10	0.10
k0 (cy/m)	4	4	10	10	10	10	10	10	320
A (m^4)	9.60E-19	9.60E-19	1.25E-20	7.58E-21	1.25E-20	1.09E-20	5E-20	7.5E-20	8.52E-22
n	3	3	3	3	3	3	3	3	3
RMS WF	8.51E-09	9.55E-09	2.15E-09	1.67E-09	2.15E-09	2.00E-09	5.24E-09	5.27E-09	1.62E-08

Key Dynamics Requirements



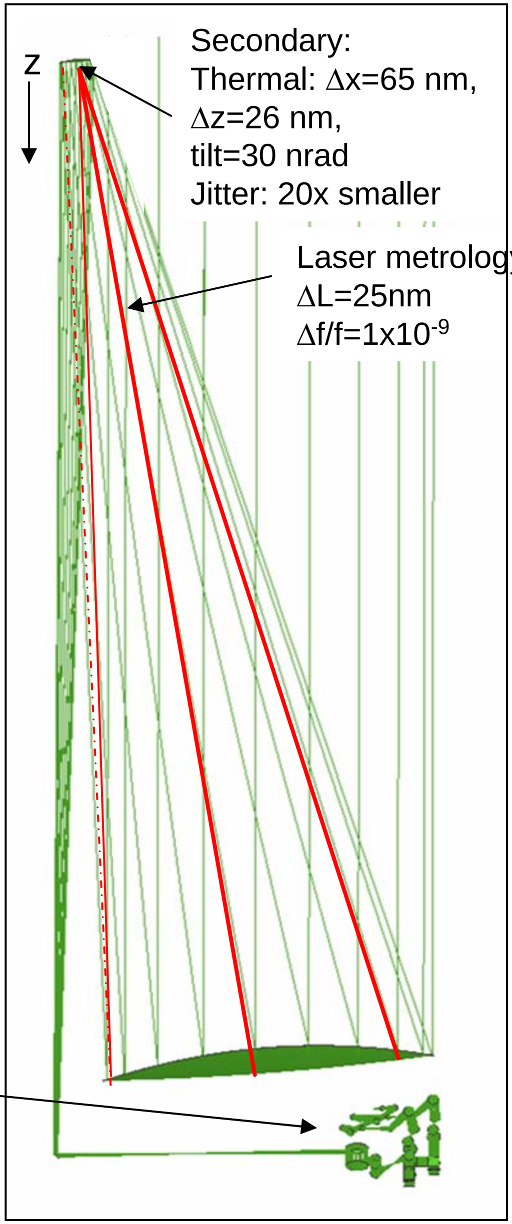


Figure 5. We identify the major engineering requirements to meet the dynamic error budget. Thermally induced translations lead to beam walk that is partially compensated by the secondary mirror. Jitter is partially compensated by the fine guiding mirror.

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Contrast Roll Up

Table 4: Rolled up Dynamic Contrast Contributors

Perturbation	Contributor	Nature	Contrast	Fraction
Structural Defomation	Beam Walk	Thermal	8.29E-13	16.12%
		Jitter	6.33E-13	12.31%
	Aberrations	Thermal	3.28E-14	0.64%
		Jitter	4.43E-17	0.00%
Bending of Optics	Aberrations	Thermal	8.60E-13	16.72%
		Jitter	8.60E-13	16.72%
Pointing	Beam Walk		1.29E-12	25.10%
	Image Motion		9.04E-14	1.76%
	Mask Error		5.46E-13	10.63%
SUM			5.14E-12	

Static Terms: Work in Progress

- SPIE 5905, San Diego August 2005
  - "Coronagraph Mask Tolerances For Exo-Earth Detection," Oliver Lay et al.
    - Broad band limitations in binary mask design, 2-DM control
  - "Measurement of Wavefront Phase Delay and Optical Density in Apodized Coronagrapic Mask Materials," P. Halverson et al.
    - HEBS masks, broad band response
  - "Polarization-Compensating Protective Coatings for TPF-Coronagraph Optics to Control Contrast Degrading Cross-Polarization Leakage" K. Balasubramanian et al.
    - Broad-band polarization control

Plans

- Re-evaluate requirements
  - Set limiting_delta_magnitude = 26?
  - 2-3x change in structural stability requirements
- Static Error Budget
  - Broad-band limitations
  - Gravity Sag
  - Chromatic Mask Errors
  - Mask Polarization Effects
- Incoherent Light
  - Stray light study underway at GSFC (Ed Frenier)
- Dynamic Error Budget
  - Re-allocate to match modeling results
- Detection vs. Characterization
  - Same structure, but characterization requirements may be more challenging because spectral line depth is small (signal contrast << 1E-10).