Stability error budget for an aggressive coronagraph on a 3.8 m telescope

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Overview

- TPF-C Flight Baseline 1 (FB1) was an 8 x 3.5 m telescope with a coronagraph operating at 4 λ/D, about 60 mas.
  - We established that with an 8th order mask, the wavefront stability requirements were measured in nanometers.
- Recently, including the Decadal, there is discussion of a 4-m class telescope to do the same science.
  - Requires 2 λ/D
  - Precludes 8th-order mask. Need 4th-order.
  - Wavefront equirements are MUCH tighter.
  - Likely need a low-order wavefront sensor with extraordinary sensitivity to meet the requirements.

TPF-C Requirements (SPIE 5905)

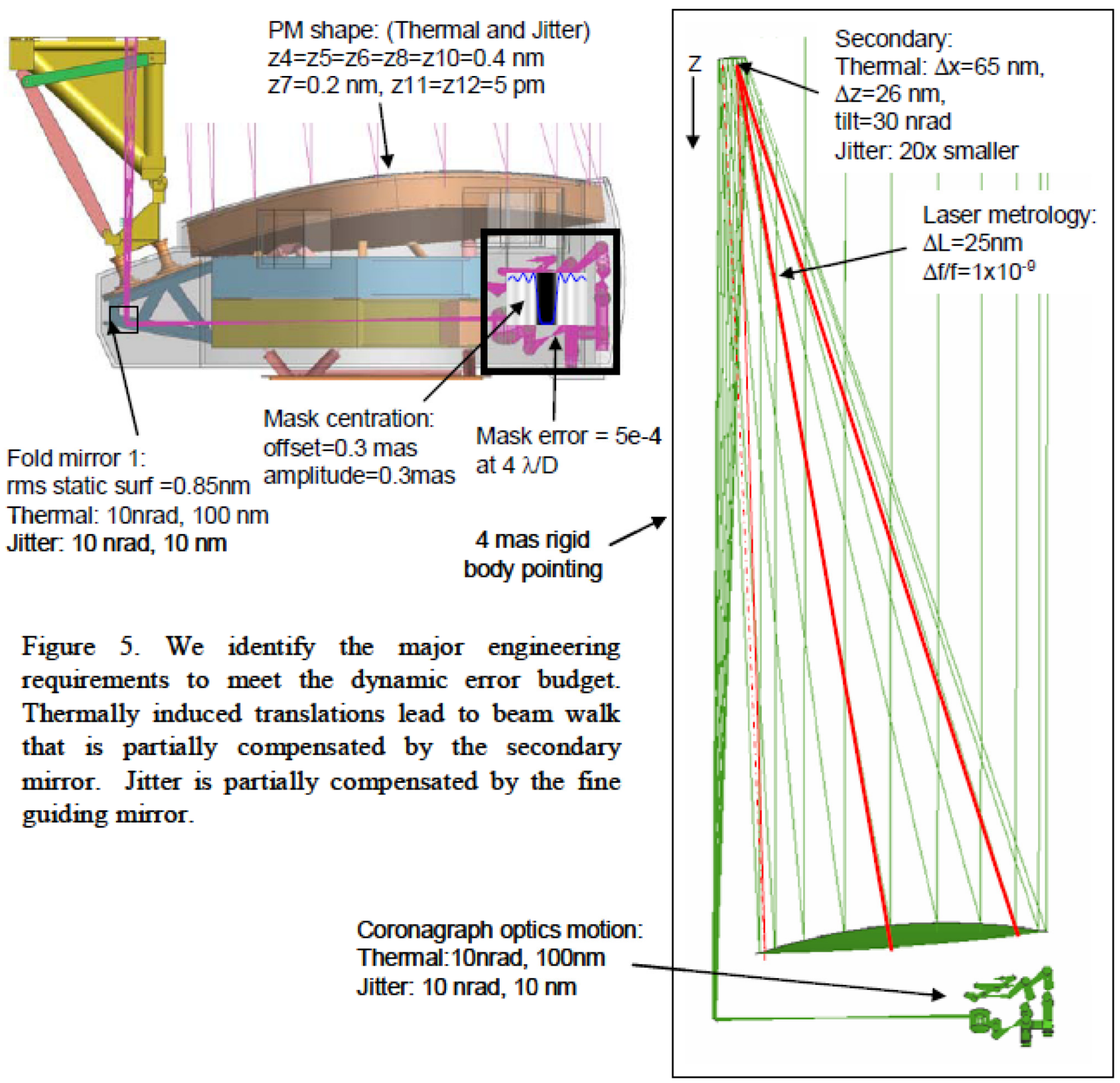

Figure 5. We identify the major engineering requirements to meet the dynamic error budget. Thermally induced translations lead to beam walk that is partially compensated by the secondary mirror. Jitter is partially compensated by the fine guiding mirror.

Science Requirements Flowdown

- Unchanged since TPF-C
- Background below Zodi
  - Requires AVERAGE INSTRUMENT SCATTER < 1e-10
- Sensitivity to detect planets with Δmag = 26
  - Requires instrument SYSTEMATIC NOISE of 1e-11
  - Can be KNOWLEDGE to 1e-11.
- Requirements for characterization
  - Scatter unchanged since background limited
  - Systematic knowledge requirement may not have to change, depending on the spectral features.
- Inner Working Angle 60 mas
  - Requires IWA = 2 λ/D on a 3.8 m telescope at 550 nm.
  - Even tighter at longer wavelengths
- Bandpass 500-800 nm (broader is desirable)

3.8 m off-axis Telescope

- Why 3.8 m?
  - TPF-C study showed it was the largest diameter that could reasonably fit inside existing fairings.
- Why off-axis?
  - The coronagraph requires an unobscured aperture. At 2 l/D, an obscurations such as a secondary mirror and its supports would cause a large throughput loss.
- Length: 5.5 m
  - THEIA study found this was the maximum practical PM-SM separation that still allowed room for astrophysics instruments and the coronagraph.
  - NWO study came to the same conclusion, but for a different reason: needed room for front-end sun-shade.

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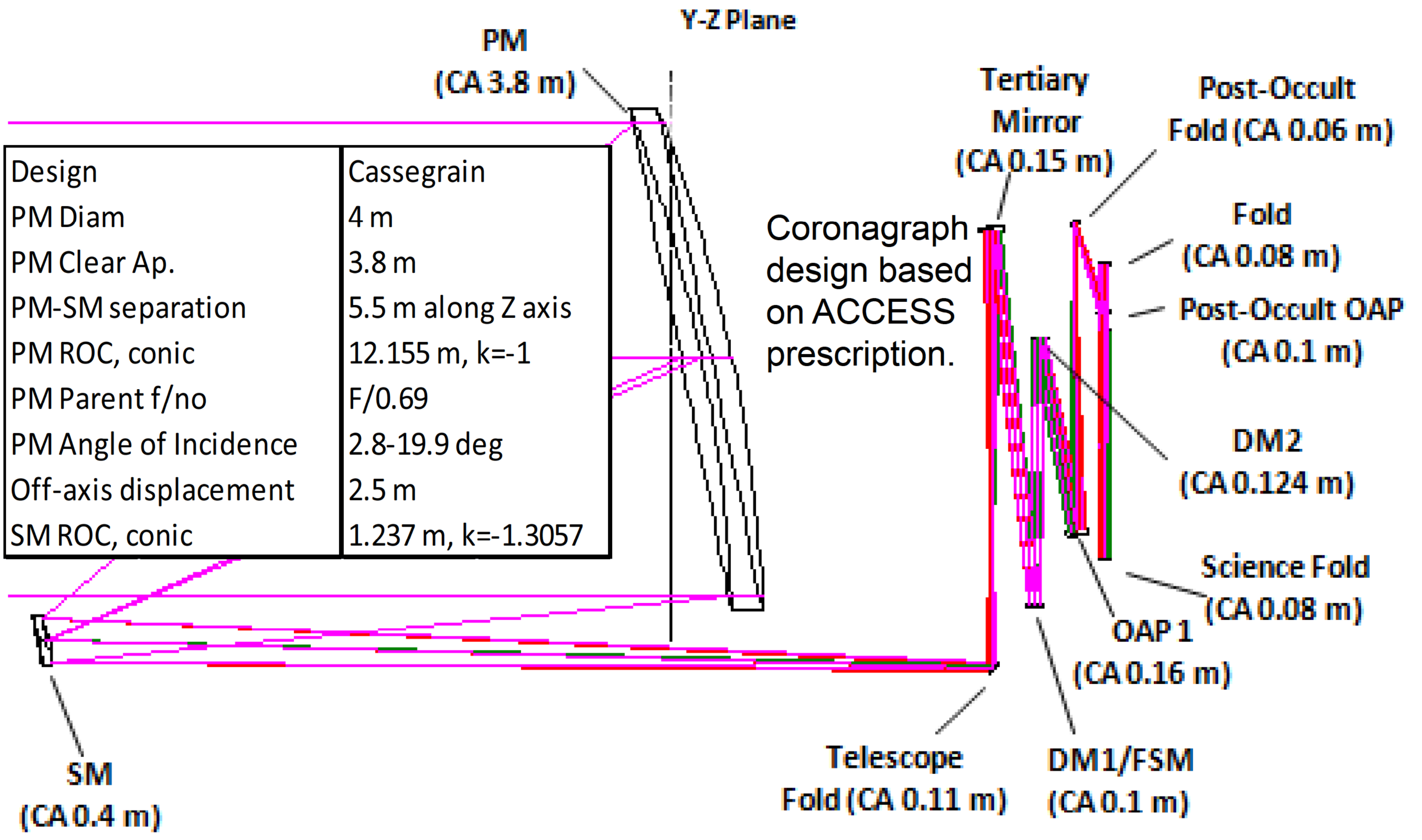
3.8 m off-axis Telescope

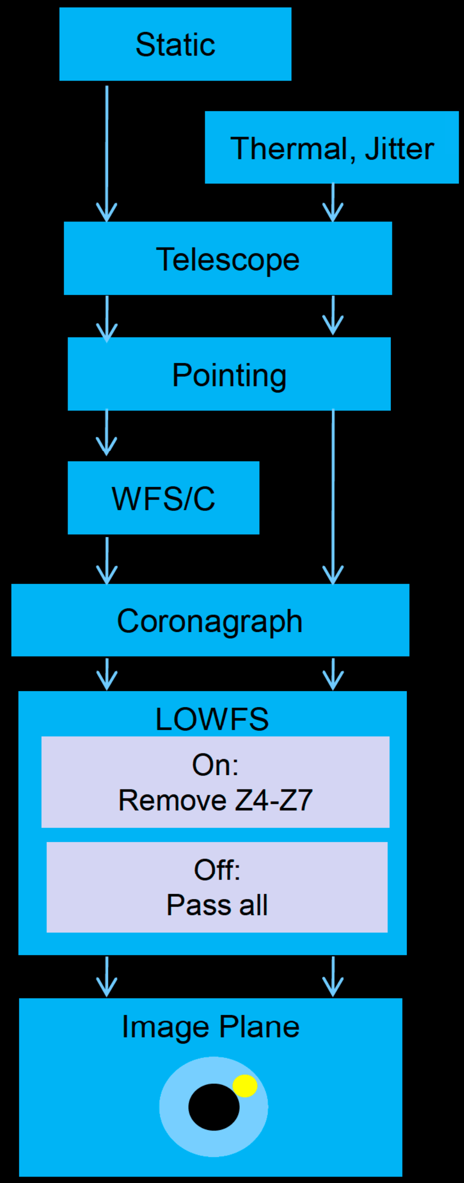


Design	Cassegrain
PM Diam	4 m
PM Clear Ap.	3.8 m
PM-SM separation	5.5 m along Z axis
PM ROC, conic	12.155 m, k=-1
PM Parent f/no	F/0.69
PM Angle of Incidence	2.8-19.9 deg
Off-axis displacement	2.5 m
SM ROC, conic	1.237 m, k=-1.3057

Coronagraph design based on ACCESS prescription.

Figure 2. Telescope and instrument layout.

Models



System WFE and pointing offset. *Allocation.*

Drift, slow oscillations, and vibrations induce warping and motion. *Allocation.*

3.8 m clear aperture, off-axis Cassegrain. *Code V, MACOS ray trace.*

Low-bandwidth rigid body pointing and high bandwidth FSM. *MACOS ray trace.*

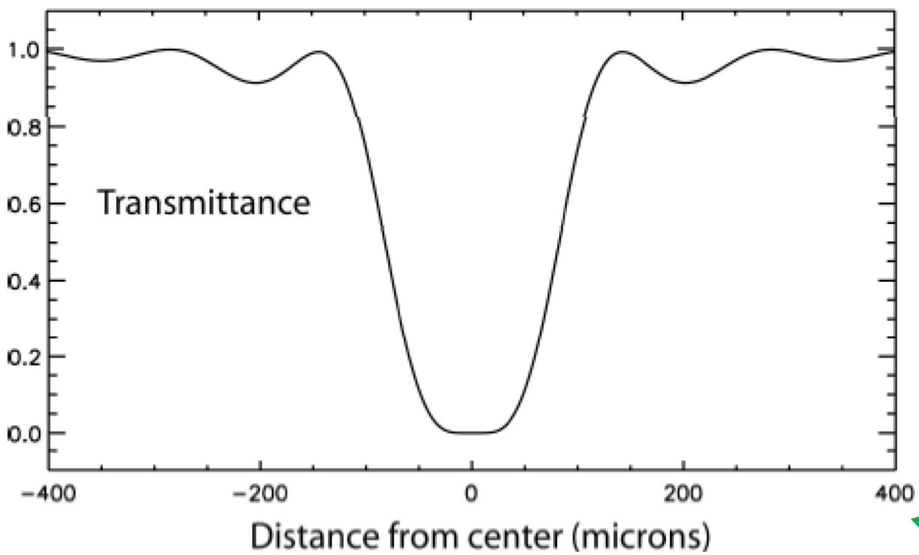
Set at beginning of observation,
Not commanded during observation. *Black box.*

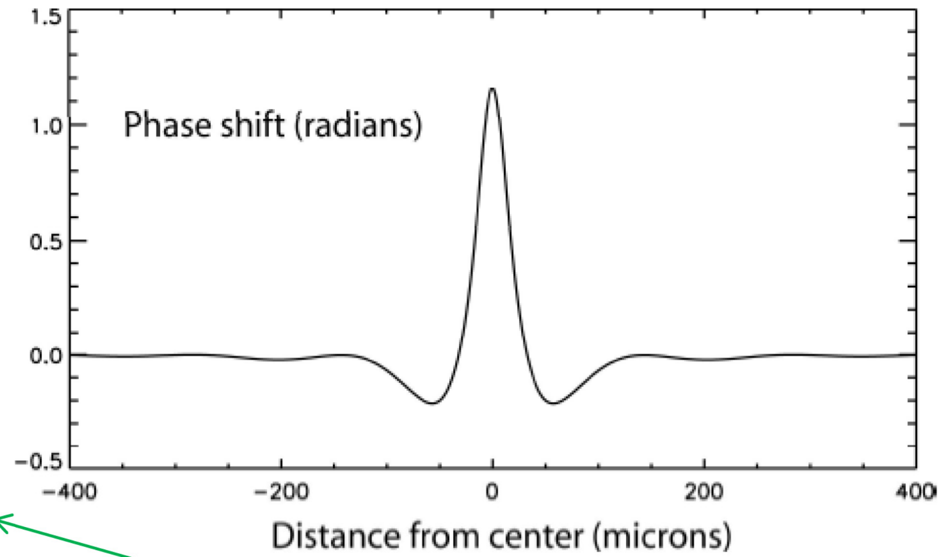
Radial, linear, amplitude, hybrid masks.
PROPER Diffraction analysis.

Low-order wavefront sensor assumed to perfectly measure focus, astigmatism, and coma. *Black box.*

Static & Thermal → systematic noise floor.
Static, Thermal, Jitter →photometric noise floor
Matlab analysis of diffraction leakage.

Mask and Throughput





$$A^R(x) = 1 - \mathrm{sinc}^2(\pi r/w)$$
$$A^I(x) = 0.49\,\mathrm{sinc}\left(\frac{2\pi r}{w} + \pi\right) + 0.49\,\mathrm{sinc}\left(\frac{2\pi r}{w} - \pi\right)$$

Moody & Trauger, SPIE 7010 (2008).

Throughput

IWA	w (λ/D)	D_{Lyot}/D_{pupil}	Circ. Trans.	Linear Trans
2	4.329	0.530	0.280	0.610
2.5	5.411	0.610	0.372	0.516
3	6.494	0.672	0.450	0.589
4	8.659	0.751	0.564	0.686

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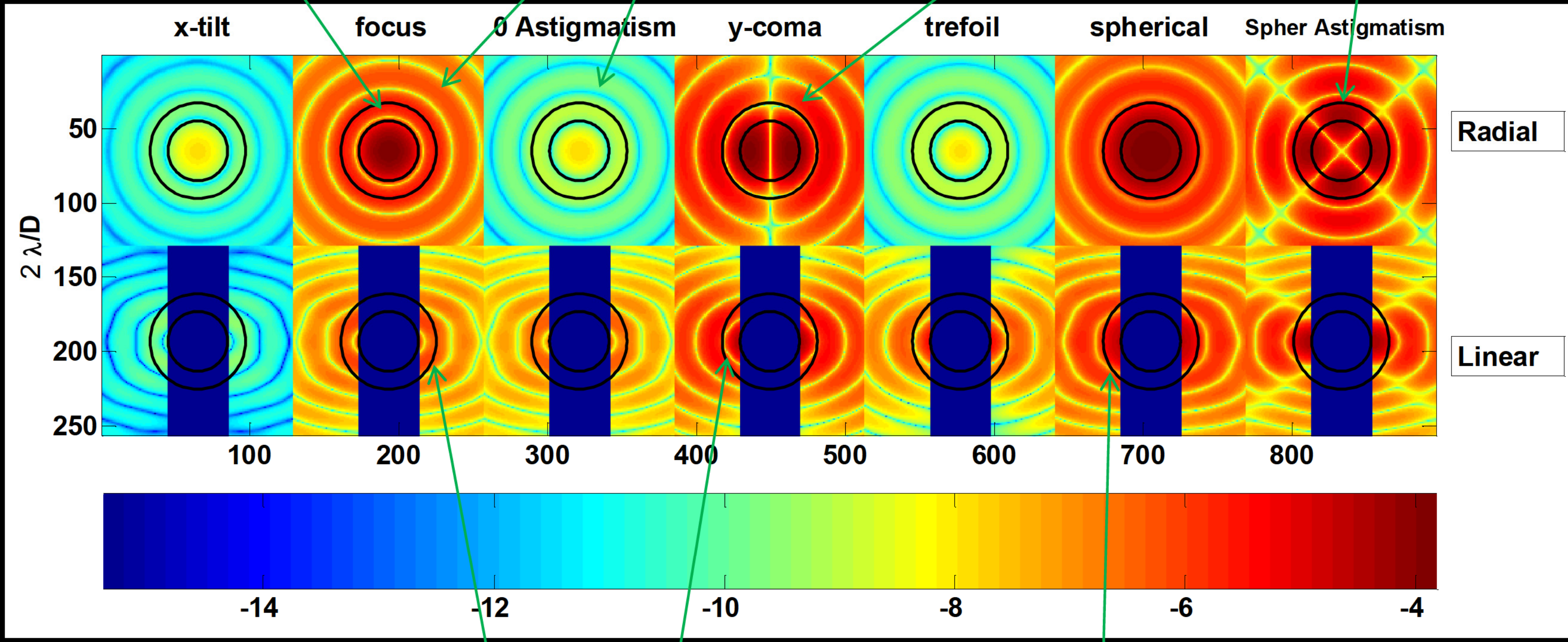
Aberration Sensitivity

Annulus for planet search

Focus and Astigmatism have radial leakage

Coma and Spherical Astigmatism have azimuthal leakage



With a linear mask, a central bar is blocked. All aberrations have leakage lobes that are difficult to distinguish from a planet.

Image Plane Variance

$$\sigma^2 = \sigma_{S,a}^2 + \sigma_{T,a}^2 + 2I_{S,a}\left(\langle I_{T,a}\rangle + \langle I_{T,r}\rangle\right) + 2I_{S,r}\langle I_{T,a}\rangle$$

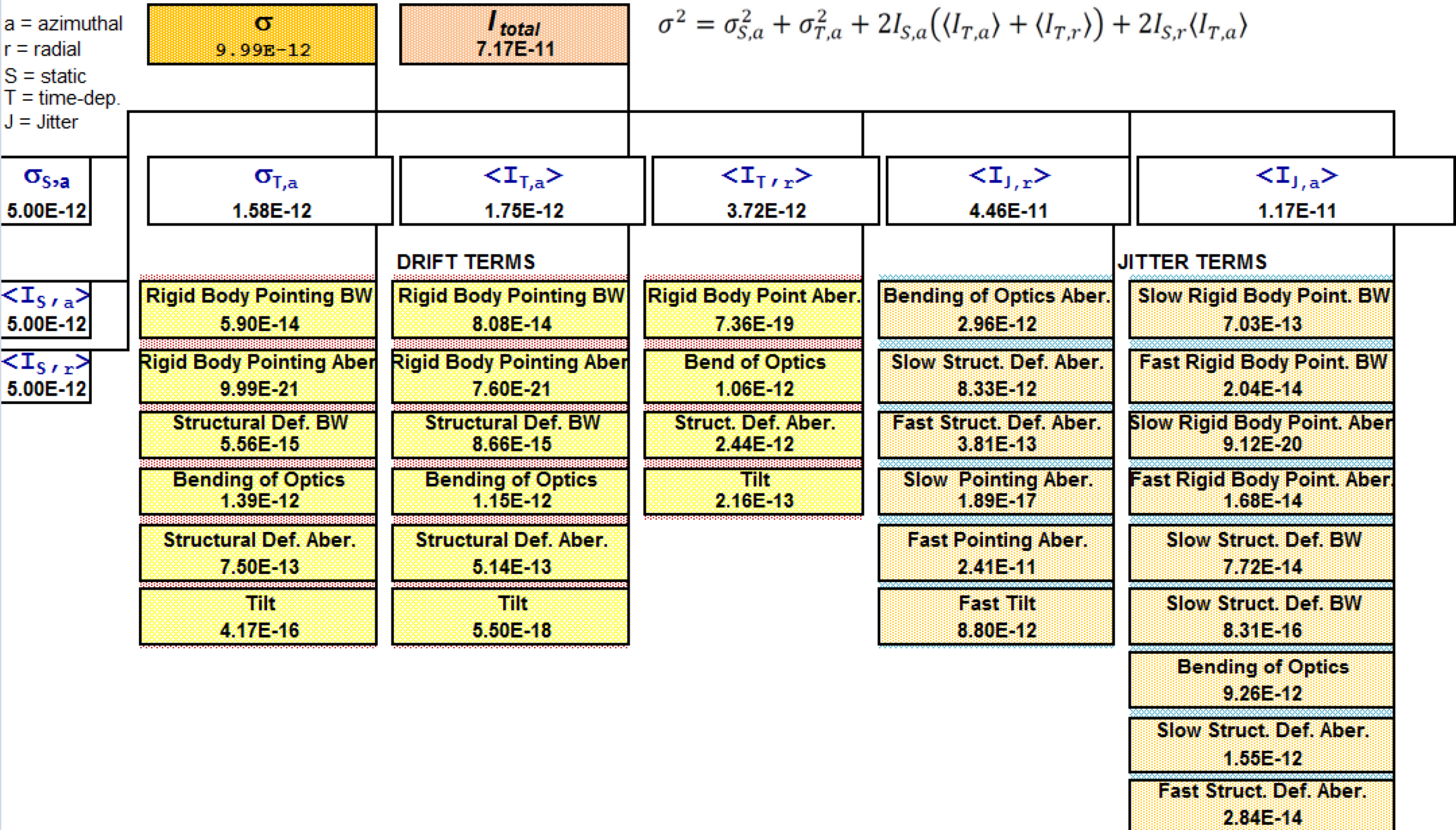
'a' subscript mean azimuthal component.
'r' subscript means radial component.
<I> is the expectation of the scatter.
σ^2 is the variance of the scatter.

The azimuthal light at the start of the observation mixes with the thermally scattered radial and azimuthal components, and the radial light at the start mixes with the thermally scattered azimuthal component to boost the final variance.

It is important to start the observation with very good contrast to reduce sensitivity to changes in the state of the system.

Coronagraph Error Tree:
2λ/D

$$\sigma^2 = \sigma_{S,a}^2 + \sigma_{T,a}^2 + 2I_{S,a}\left(\langle I_{T,a}\rangle + \langle I_{T,r}\rangle\right) + 2I_{S,r}\langle I_{T,a}\rangle$$



Key Requirements, Systematic Noise Floor

Table 5. Key requirements for systematic noise floor, radial masks, at 2, 2.5, and 3 λ/D.

	2 λ/D radial complex		2.5 λ/d radial complex		3 λ/d radial amplitude	
Allocation	Reqmnt.	ΔContrast	Reqmnt.	ΔContrast	Reqmnt.	ΔContrast
PM x-coma drift, picometers	1.00	2.0E-12	2.50	2.0E-12	5.00	2.7E-12
PM y-coma drift, picometers	1.00	2.0E-12	2.50	2.0E-12	5.00	2.7E-12
Secondary Mirror z-motion drift, nm	0.40	1.9E-12	0.80	2.0E-12	1.60	1.8E-12
Secondary Mirror y-motion drift, nm	0.80	1.7E-12	1.60	2.0E-12	3.00	1.4E-12
PM spherical aberration drift, picometers	1.00	1.1E-12	2.00	1.3E-12	4.00	4.8E-13
Secondary Mirror x-motion drift, nm	0.80	7.6E-13	1.60	4.1E-13	3.00	6.1E-13
Pointing zero-point x-offset drift, milliarcsec	0.10	4.5E-13	0.14	6.4E-13	0.30	7.5E-13
Pointing zero-point y-offset drift, milliarcsec	0.10	4.5E-13	0.14	6.4E-13	0.30	7.5E-13
PM focus drift, picometers	2.00	3.7E-13	4.00	4.9E-13	8.00	3.3E-13
Secondary Mirror x-tilt drift, milliarcsec	0.17	2.6E-13	0.34	1.4E-13	0.62	2.2E-13
Secondary Mirror y-tilt drift, milliarcsec	0.17	2.2E-13	0.34	1.2E-13	0.62	1.9E-13
Line-of-sight x-drift, milliarcsec	2.00	1.5E-13	2.00	2.2E-13	2.00	2.8E-13

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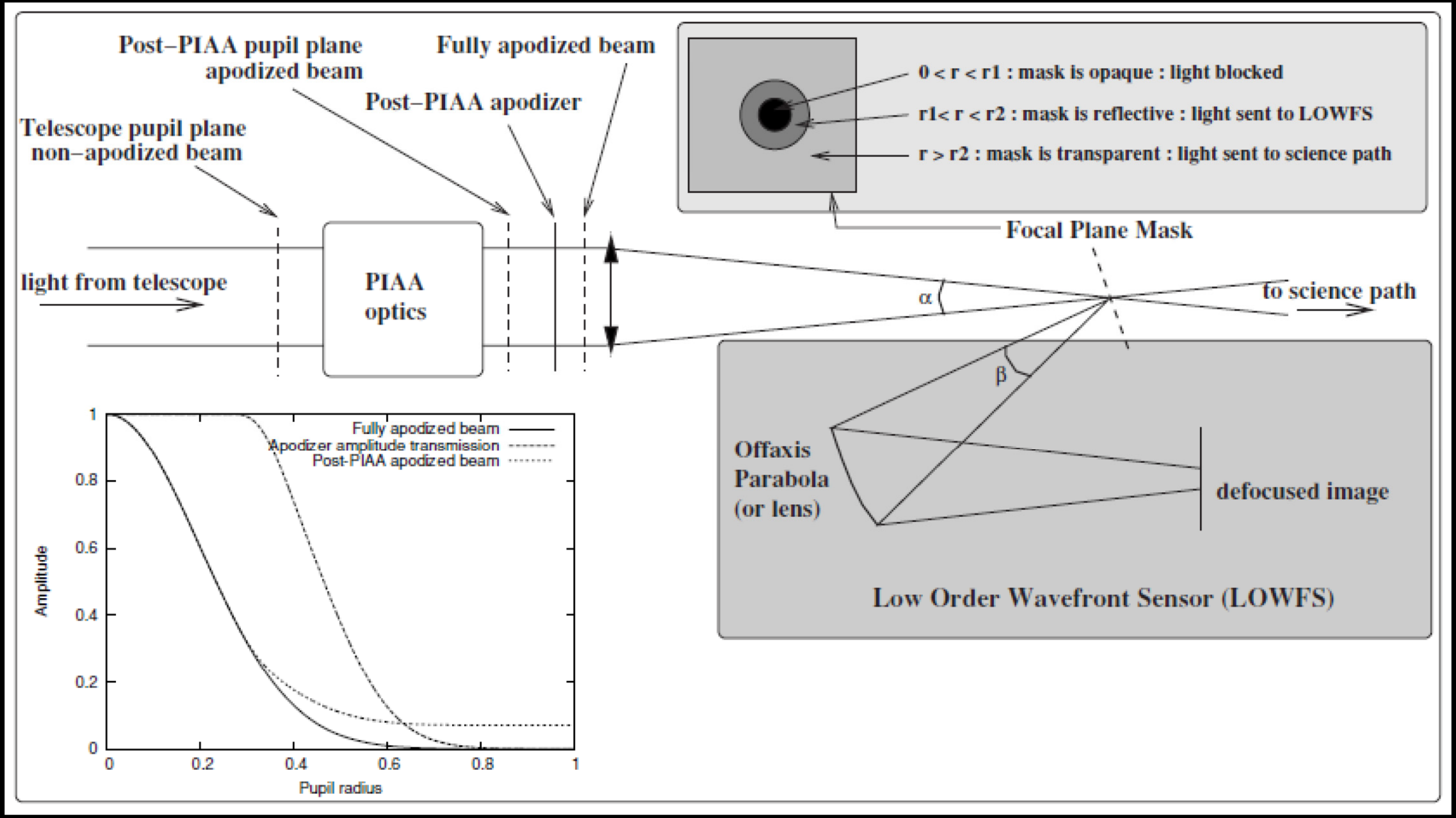
Key Requirements, Photometric Noise Floor

Table 6. Key requirements for photometric noise floor.

	2 λ/D radial complex	
Allocation	Reqmnt.	ΔContrast
Secondary Mirror z-motion, slow jitter, nm	1.0	7.8E-11
Secondary Mirror y-motion, slow jitter, nm	1.5	3.4E-11
PM spherical aberration jitter, picometers	2.0	2.7E-11
PM x-coma jitter, picometers	2.5	2.7E-11
PM y-coma jitter, picometers	2.5	2.7E-11
Rigid body pointing, high-freq, y-axis, milliarcsec	0.1	1.5E-11
Rigid body pointing, high-freq, x-axis, milliarcsec	0.1	1.5E-11
PM x-spherical astigmatism jitter, picometers	1.0	9.6E-12
PM y-spherical astigmatism jitter, picometers	1.0	9.5E-12
PM focus jitter, picometers	4.0	9.0E-12
Secondary Mirror x-motion slow jitter, nm	1.5	6.6E-12
Secondary Mirror z-motion drift, nm	0.4	4.2E-12
Secondary Mirror y-motion drift, nm	0.0	3.3E-12
Secondary Mirror x-tilt slow jitter, milliarcsec	0.3	2.4E-12
PM spherical aberration drift, picometers	1.0	2.2E-12
Secondary Mirror y-tilt slow jitter, milliarcsec	0.3	2.1E-12
PM x-coma drift, picometers	1.0	1.4E-12
PM y-coma drift, picometers	1.0	1.4E-12

Low Order Wavefront Sensor (LOWFS)

Assume we have an ideal LOWFS capable of perfectly measuring changes in Pointing, Focus, Astig, and Coma on timescales of minutes.
This eliminates the thermal drift but not the jitter for these terms.



Guyon, Matsuo, & Angel, ApJ 693 (2009)

Key Requirements, Systematic Noise Floor assuming an ideal LOWFS

Table 8. Key requirements for radial complex mask systematic noise floor, with LOWFS.

	2 λ/D radial complex	
Allocation	Reqmnt.	ΔContrast
PM spherical aberration drift, picometers	2.00	3.8E-12
Pointing zero-point x-offset drift, milliarcsec	0.20	3.7E-12
Pointing zero-point y-offset drift, milliarcsec	0.20	3.7E-12
Secondary Mirror x-motion drift, nm	15.00	1.1E-12
Secondary Mirror y-motion drift, nm	15.00	1.1E-12
Secondary Mirror z-motion drift, nm	10.00	5.9E-13
Secondary Mirror y-tilt drift, mas	3.00	3.4E-13
Secondary Mirror x-tilt drift, mas	3.00	3.3E-13
Line-of-sight x-drift, milliarcsec	2.00	1.4E-13
PM spherical astigmatism drift, picometers	0.20	1.3E-13
Line-of-sight y-drift, milliarcsec	2.00	9.5E-14

Key Requirements, Photometric Noise Floor assuming an ideal LOWFS

Table 9. Key requirements for photometric noise floor, with LOWFS.

	2 λ/D linear complex	
Allocation	Reqmnt.	ΔContrast
Secondary Mirror z-motion, slow jitter, nm	1.0	7.8E-11
Secondary Mirror y-motion, slow jitter, nm	2.0	6.1E-11
PM x-coma jitter, picometers	2.0	1.7E-11
PM y-coma jitter, picometers	2.0	1.7E-11
Rigid body pointing, high-freq, y-axis, milliarcsec	0.1	1.5E-11
Rigid body pointing, high-freq, x-axis, milliarcsec	0.1	1.5E-11
Secondary Mirror x-motion slow jitter, nm	2.0	1.2E-11
PM x-spherical astigmatism jitter, picometers	1.0	9.6E-12
PM y-spherical astigmatism jitter, picometers	1.0	9.5E-12
PM spherical aberration drift, picometers	2.0	9.1E-12
PM focus jitter, picometers	4.0	9.0E-12
Line-of-sight x-drift, milliarcsec	2.0	8.9E-12
Line-of-sight y-drift, milliarcsec	2.0	8.9E-12
PM spherical aberration jitter, picometers	1.0	6.7E-12
Secondary Mirror x-tilt slow jitter, milliarcsec	0.4	4.3E-12
Secondary Mirror y-tilt slow jitter, milliarcsec	0.4	3.7E-12
Secondary Mirror y-motion drift, nm	15.0	1.7E-12

Robustness

- Requirements discussed above have zero reserve
  - model uncertainty
  - Mask imperfections (a main driver in TPF-C)
  - Initial contrast at start of observation
    - 5e-12 mean and σ=5e-12 non-uniformity

Conclusions

- Searching for earth-like planets at 2 l/D is extremely challenging.
  - Wavefront requirements are measured in single-digit picometers
  - Secondary mirror position stability requirements is sub-nm.
  - Pointing offset drift is 0.1 mas.
- A circular coronagraph mask allows some relaxation of low-order aberrations, but not Coma.
- A LOWFS can significantly relax the stability requirements so that they apply to shorter timescales (the LOWFS measurement time).
  - Needs sensitivity to 5e-12 contrast for drift of focus, astigmatism, and coma while maintaining calibration traceable to the start of the observation.
- HCIT experiments: 5e-10 contrast achieved is 3.5 pm stability at any spatial frequency.