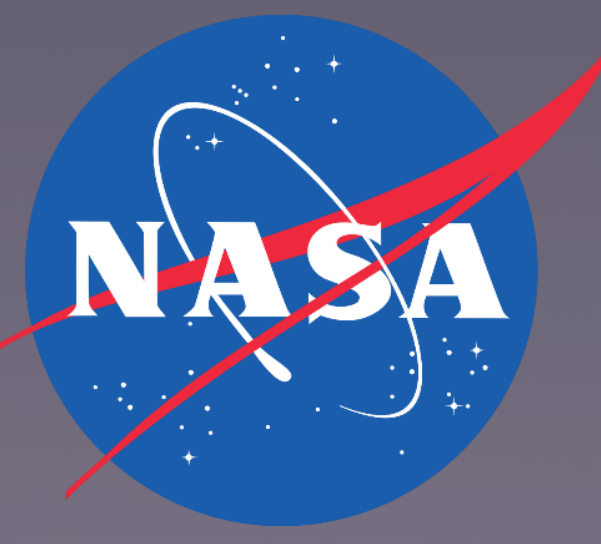


IMPACT OF NEAR-ANGLE SCATTERING ON EXO-EARTH CORONAGRAPHY

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ABSTRACT

Near-Angle Scatter (NAS) of the host star's light may limit the ability of a potential Habitable Worlds Observatory (HWO) to detect and characterize an Earth-like planet around a Sun-like star via coronagraphy. NAS from each optical surface produces an E-field across the dark hole that is coherent. These E-fields sum and could be as large or larger than the coronagraph mask leakage E-field. NAS E-fields contribute to the dark hole noise floor via both shot noise and heterodyne amplification of the wavefront instability. The amount of NAS is determined entirely by the statistical properties of the optical surface microroughness and the operating wavelength. Surface properties include not only the rms roughness, but also correlation length and the functional form of the distribution itself. We derive an expression that specifies the surface statistics required to achieve a given coronagraph error budget NAS throughput allocation.

INTRODUCTION

Direct imaging of exoplanets requires coronagraphs capable of rejecting host starlight and enabling imaging of its companions. Habitable Worlds Observatory (HWO) desires to detect and characterize Earth-like planets in the habitable zone of nearby sun-like stars. (Fig. 1)

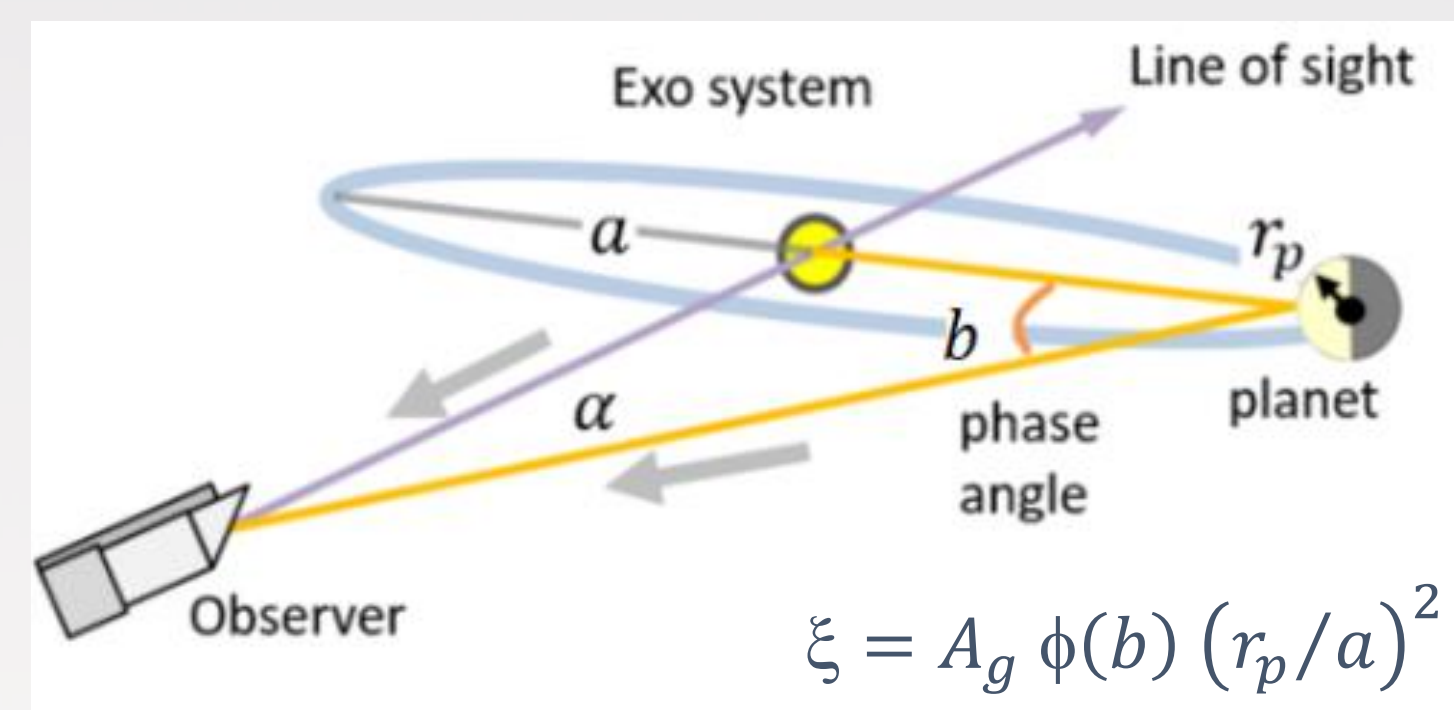


Fig. 1. Flux ratio, ξ , of an exoplanet depends on its radius, r_p , orbital semi-major axis, a , and phase angle, b . At 10 pc, an Earth-like planet near a sun-like star would have a maximum ang. separation of 100 mas, with $\xi = 2.1 \times 10^{-10}$ at quadrature phase.

Coronagraphs achieve this flux ratio by blocking the star's light with a focal plane mask (FPM). A Lyot mask removes most of the remaining on-axis star light, and the beam is focused onto a detector, creating a 'dark hole'. The key attributes needed for an error budget are core throughput, inner and outer working angles, and raw contrast.

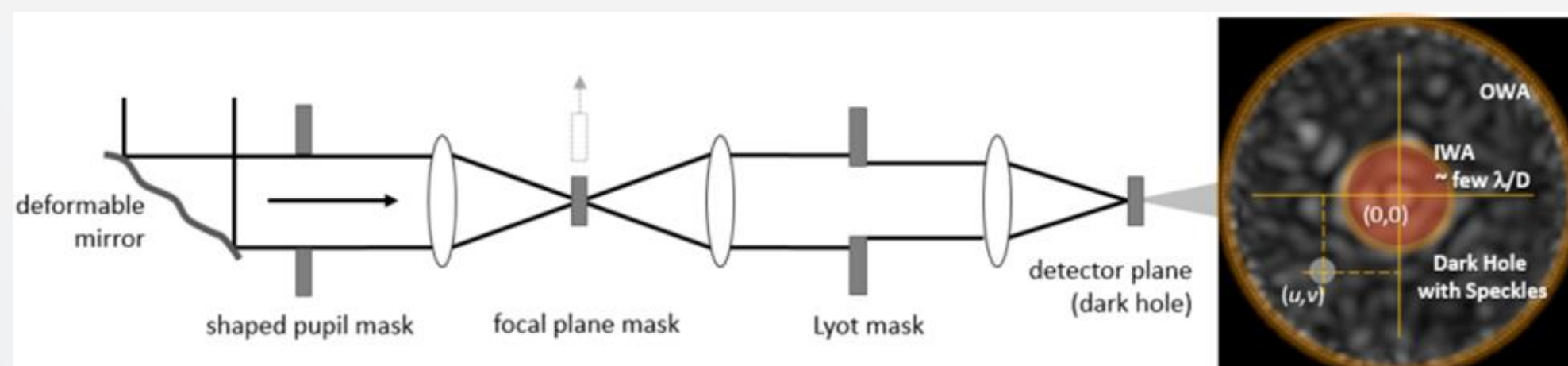
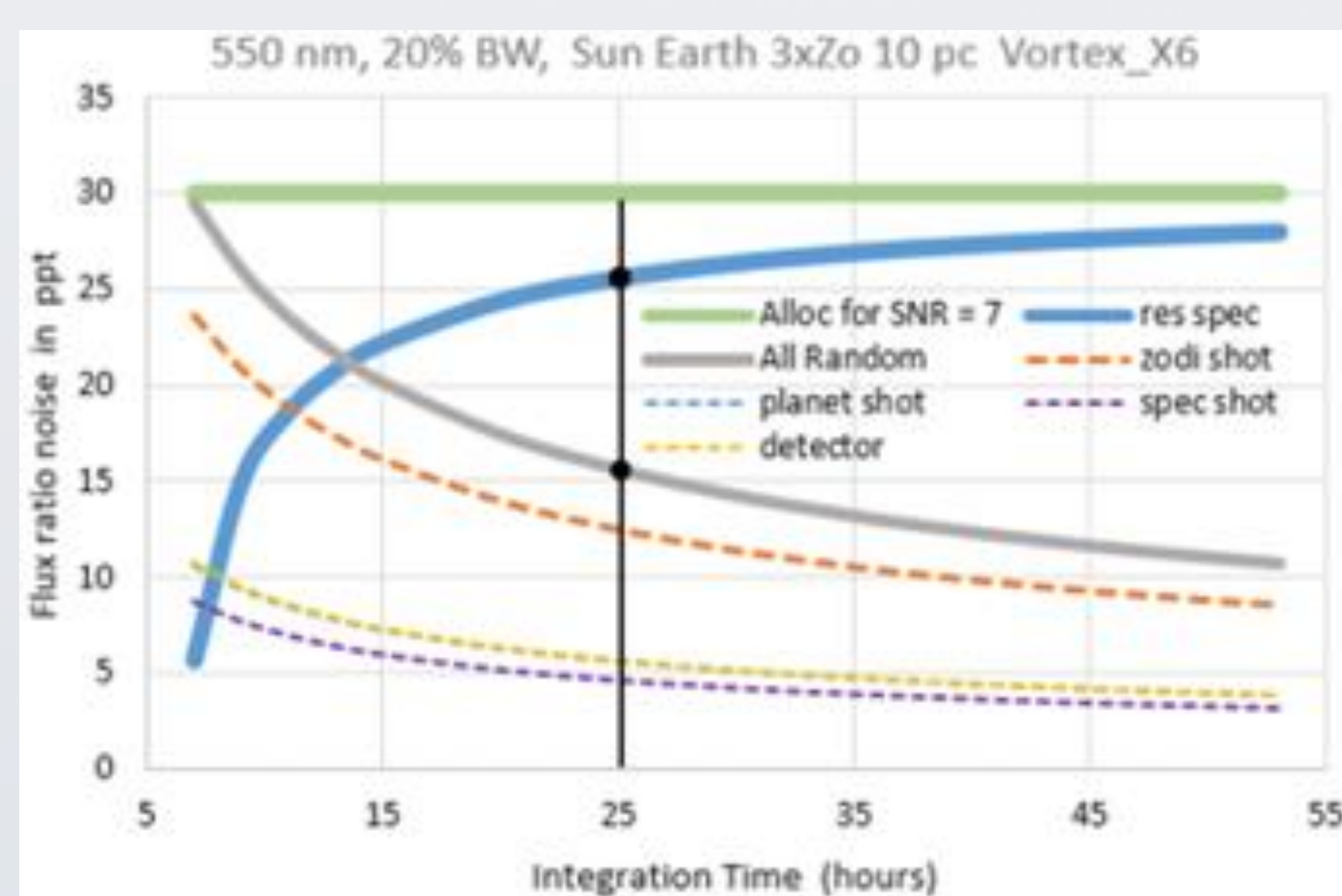


Fig. 2. Typical coronagraph setup. Incoming light from the left is shaped in phase (and potentially amplitude) by a deformable mirror(s) then sent through a succession of masks. The result is a 'dark hole' where (on-axis) starlight is strongly suppressed relative to the (off-axis) planet light.

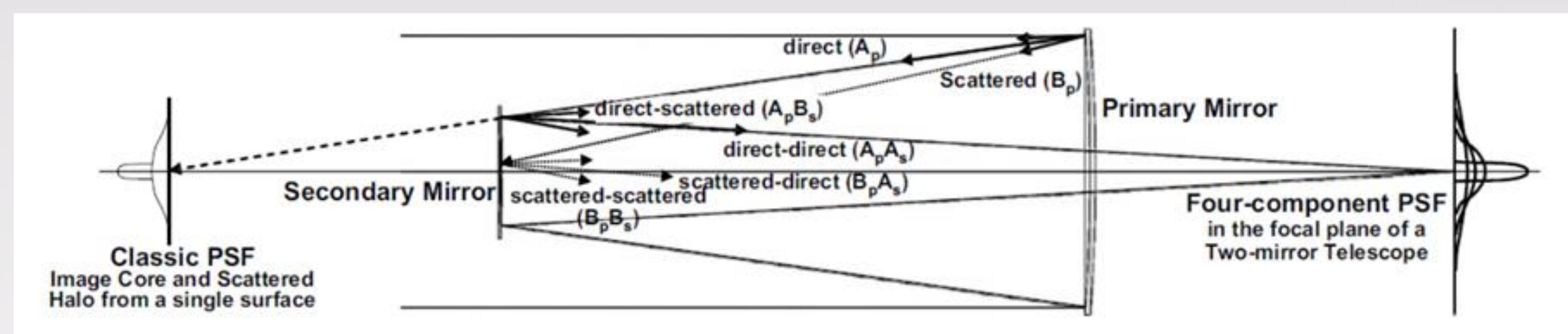


$$\tau(u, v) \equiv \frac{\Phi(u, v)}{\Phi_i(0, 0)} \quad \tau_{NAS} < 10^{-11}$$

Fig. 3. Relative contributions to the flux ratio noise versus integration time. This analysis leads to a rough specification for NAS core throughput, τ_{NAS} .

NAS IN THE DARK HOLE

Every optical surface before the coronagraph focal plane mask can scatter host star light directly into the dark hole. Because of the coronagraph's optical design, each scattering site on the primary mirror produces a collimated wavefront in the dark hole. Secondary mirror scatter produces wavefront with 30-m radius.



$$\text{Revised Specification: } \tau_{NAS} < 10^{-12}$$

Fig. 4. Each surface in telescope/coronagraph is a source of NAS which sums (it does not RSS).

HETERODYNE AMPLIFICATION

After wavefront control 'digs' the dark hole, a 'leakage' field $E(u, v)$ remains. Any $\Delta E(u, v, t)$ disturbance or drift error coherently mixes with the original E-field to creates a speckle pattern:

$$|E + \Delta E|^2 = |E|^2 + |\Delta E|^2 + 2 \mathcal{R}\{E^* \cdot \Delta E\}$$

It is this mixed or heterodyned term for which error budgets allocate a maximum value.

Near-angle scatter can increase the static E-field. And consequently, to keep the heterodyne term constant, the wavefront instability must become smaller.

Also, if NAS increases the static E-field, then it also increases its shot noise.

SCATTERING THEORY

Rayleigh-Rice theory relates the PSD of an isotropic (i.e. polished) surface to BRDF. Both are constant across the dark hole, equal to their values at zero spatial frequency and angle:

$$PSD_0 = \left(\frac{\lambda^2}{4\pi}\right)^2 BRDF_0, \quad \text{where } BRDF_0 = \frac{\tau_{NAS}}{\Omega_{Core}} \quad (1)$$

Model surface PSD by ABC power law model

$$PSD_0 = \frac{C-1}{2\pi} (B\sigma)^2 \quad \{\text{for } C > 1\} \quad (2)$$

$$B = L_c; \quad C = \begin{cases} 2\pi^2 + 1 & \text{Gaussian} \\ 2 & \text{Lorentzian} \end{cases} \quad \text{PSD Bounds}$$

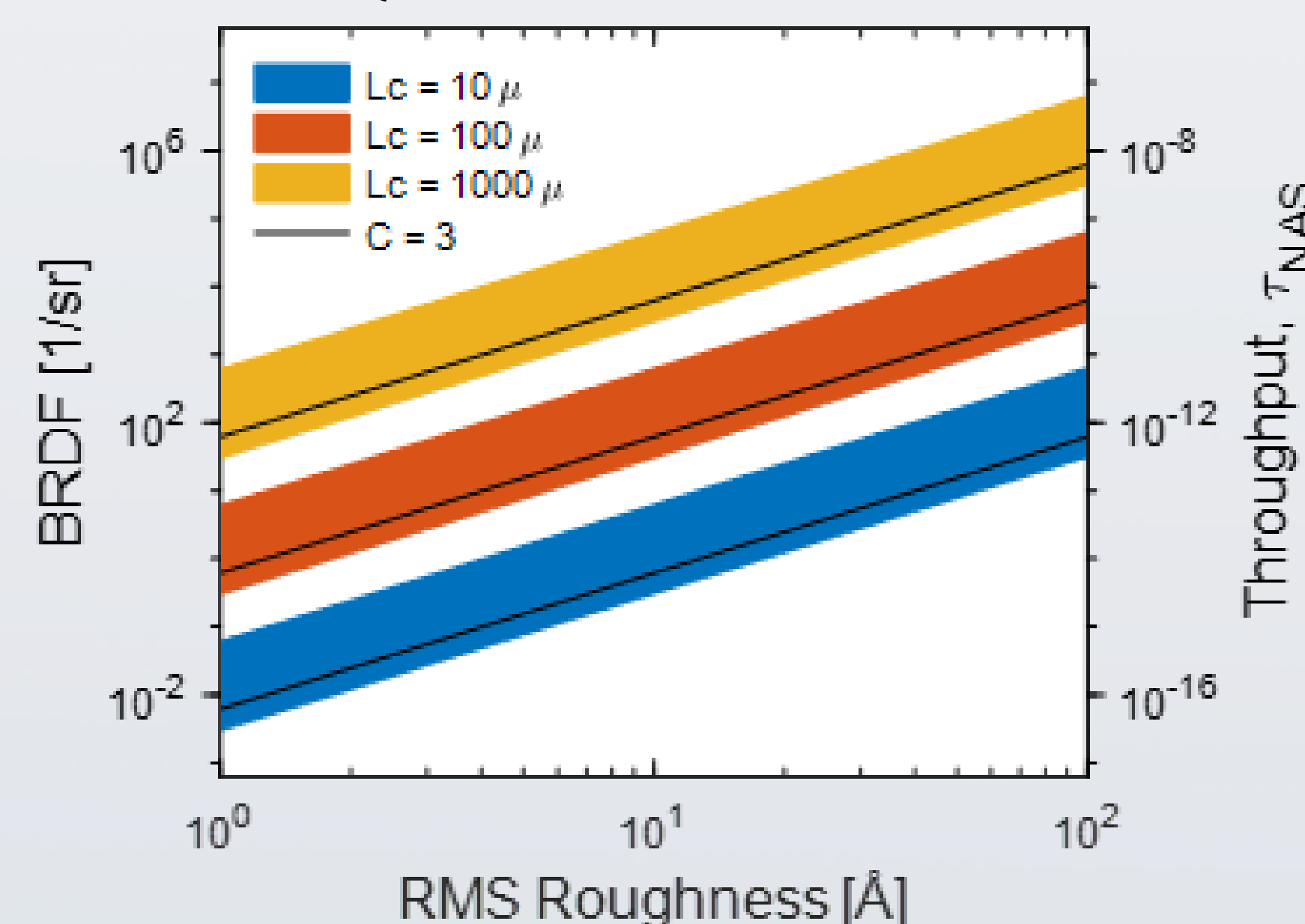


Fig 5: BRDF and core throughput vs. RMS roughness, σ , for NAS at three different correlation lengths, L_c . The bands represent the PSD bounds, ranging from Gaussian ($C = 2\pi^2 + 1$) at the top to Lorentzian ($C = 2$) at the bottom. The wavelength is 300 nm (shortest coronagraph wavelength) and the core solid angle was 10^{-14} sr.

SURFACE SPECIFICATION

From Eqs. (1) and (2) we obtain a specification for the Gaussian surface statistics:

$$\sigma < \frac{\lambda^2}{4\pi L_c} \sqrt{\frac{\tau_{NAS}}{\pi \Omega_{core}}}$$

Table 1. RMS [\AA] for NAS Throughput $< 1E-12$, assuming surface with Gaussian PSD

Correlation Length, L_c [μm]	Wavelength, λ [μm]			
	0.30	0.68	1.00	1.80
10	180.0	924.8	2000.0	6480.0
100	18.0	92.5	200.0	648.0
1,000	1.8	9.2	20.0	64.8
10,000	0.2	0.9	2.0	6.5

$$\text{RMS Slope} = \sqrt{2} \frac{\sigma}{L_c}$$

Table 2. RMS Slope [μrad] for NAS Throughput $< 1E-12$, assuming surface with Gaussian PSD

Correlation Length, L_c [μm]	Wavelength, λ [μm]			
	0.30	0.68	1.00	1.80
10	572.8	2942.7	6364.0	20619.2
100	5.7	29.4	63.6	206.2
1,000	0.1	0.3	0.6	2.1
10,000	0.0	0.0	0.0	0.0