ALASCA simulations in PASSATA:
geometrical versus physical optics propagation

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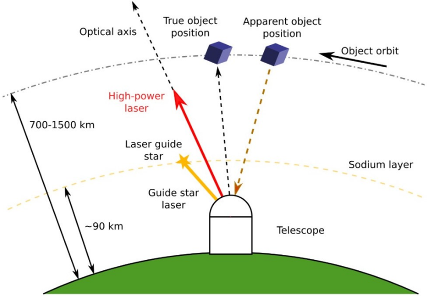
Advanced Laser guide star Adaptive optics for Satellite Communication Assessments (ALASCA)

Design and implementation of an OFL system for ESAs optical ground station in Tenerife
→ 1m telescope pupil with 35% central obstruction



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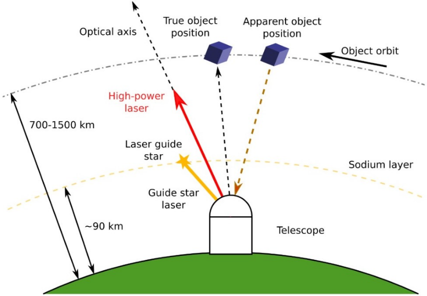

- Based on the **CaNaPY** project: Demonstrator for LGS-AO at visible wavelength
- **LGS-AO** for 24/7 operation time
- **Uplink laser beam pre-compensation** to have a smaller spot
- **Pyramid LGS-AO** closed loop

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Laser beam configuration

- **LGS**: 589nm wavelength, 90km height, on axis, for high order correction
- **Satellite**:
  - Uplink: 1075nm wavelength, 38000km height, on-axis
  - Downlink: 1064nm wavelength, 38000km height, 4" off-axis, for TT correction

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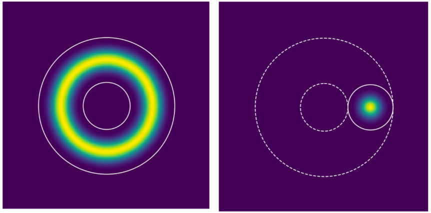
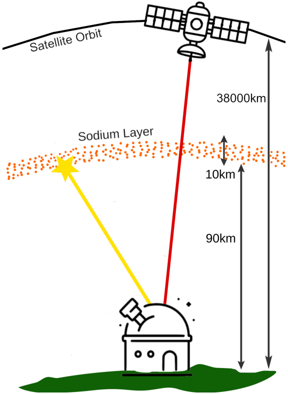
Launch configuration:

1. Launch of a donut shaped (axicon) beam from the full 1m OGS aperture
2. Launch from a 30cm sub-pupil of the OGS allowing an unobstructed Gaussian launch beam



Axicon launch (left) and sub-pupil launch (right).

Light propagation



- Optical field is propagated from layer to layer
- **Geometrical optics**: particle nature of light
- **Physical optics**: wave nature of light

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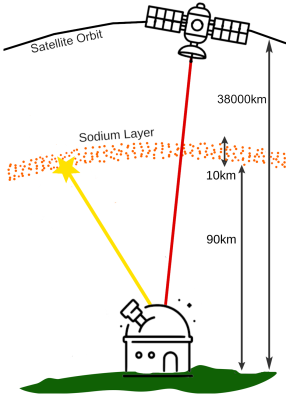
[1] R. M. Clare et. al. "Modeling low order aberrations in laser guide star adaptive optics systems", Opt. Express 15 (2017).

[2] R. Holzlöhner et. al. "Physical optics modeling and optimization of laser guide star propagation", Proc. Adaptive Optics Systems (2008).

Light propagation



- Optical field is propagated from layer to layer
- **Geometrical optics**: particle nature of light
- **Physical optics**: wave nature of light
- Most AO simulation tools use geometrical optics
- LGS aberrations studied using geometrical optics[1]
- Diffraction effects are significant for LGS light propagation[2] → physical optics
- Physical optics propagation takes scintillation into account

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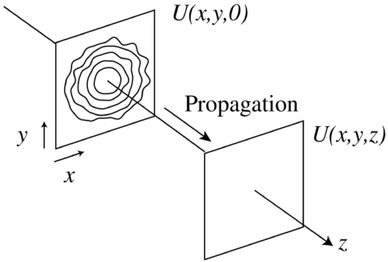
Angular Spectrum Propagation method (ASP)

… describes how an optical field $U(x, y, z)$ is propagated from one layer to another.



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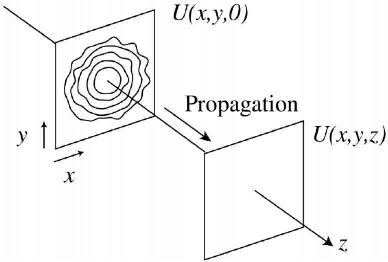

- Optical field is decomposed in plane waves using the 2D FT

$$U(x, y, 0) = \mathcal{F}^{-1}(\mathcal{F}(U(x, y, 0)))(x, y)$$

with spatial frequencies (k_x, k_y)

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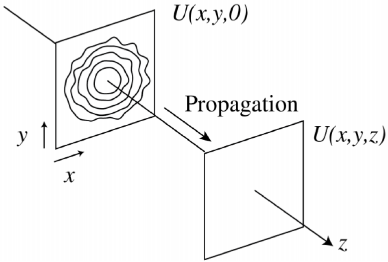

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$$U(x, y, z) = \mathcal{F}^{-1}(\mathcal{F}(U(x, y, 0)) \exp(ik_z z))(x, y)$$

with $k_z = \sqrt{k^2 - k_x^2 - k_y^2}$, $k = \frac{2\pi}{\lambda}$

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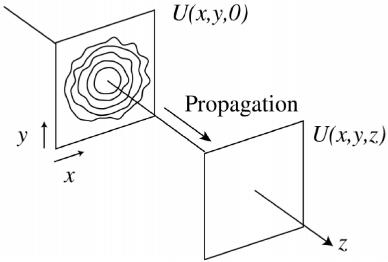

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- **Fresnel approximation**: propagator $\exp(\frac{ik(x^2+y^2)}{z})$

PASSATA Simulations

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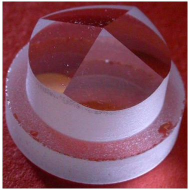
PyrAmid Simulator Software for Adaptive opTics Arcetri (PASSATA)[3]is an IDL and CUDA based library/software capable of doing Monte-Carlo end-to-end Adaptive Optics (AO) simulations.

→ Originally only geometrical optics propagation implemented
→ Added Angular Spectrum Propagation method in the framework of the ALASCA project



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[4] G. Agapito et. al. "Advances in control of a Pyramid Single Conjugate Adaptive Optics system", Oxford University Press, Volume 508 (2021).

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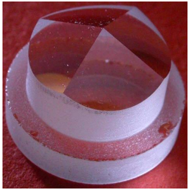

- **2 Pyramid WFSs**: 40×40 pixels, $0\lambda/D$ modulation (LGS + downlink)
- **Deformable mirror**: 57 KL modes, ALPAO 97 measured influence functions
- **Cn2 profile**: Measured (full 1m pupil) and synthetic (sub-pupil) by Durham Univ.
- **Laser launch configuration**: Axicon or sub-pupil
- **Seeing conditions**: 0.7", 1.0" and 2.5"
- **AO loop**: Modal integrator with automatic gain optimization[4]
  2 frames delay, 1kHz (0.7" seeing) or 2kHz (1.0", 2.5" seeing)

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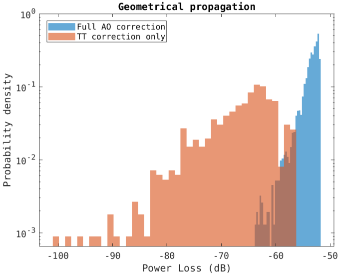
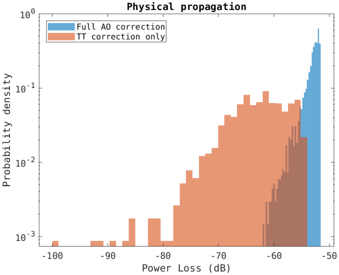
PASSATA simulations: Axicon launch, nighttime



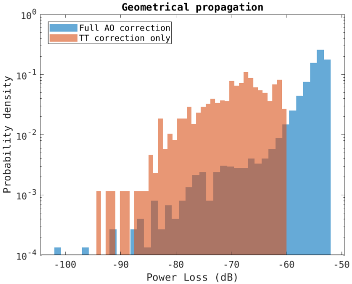


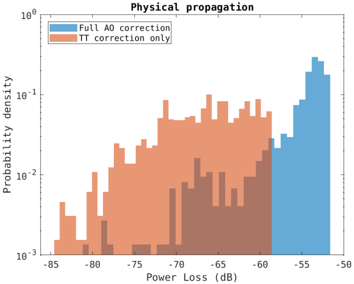
Parameter	Value
Diameter	1m
Central obstruc.	0.35
Launch	Axicon
Seeing	0.7"
Frame rate	1kHz
Simul. duration	1s

	Geometrical propagation		Physical propagation	
	full AO	TT only	full AO	TT only
Long exposure Strehl ratio [%]	65.515	6.233	72.509	12.809
FWHM [μrad]	0.2175	1.212	0.222	0.598
Power loss 3σ width [dB]	9.428	37.515	8.766	37.514
Minimum flux [μW/m^2]	29.365	0.0055	40.559	0.0058
Laser power [W] to reach 1.5μW/m^2	0.051	271.899	0.037	257.920

Plots computed with the last 1000 iterations of the 5000 iterations AO loop with modal optimization.

PASSATA simulations: Axicon launch, nighttime



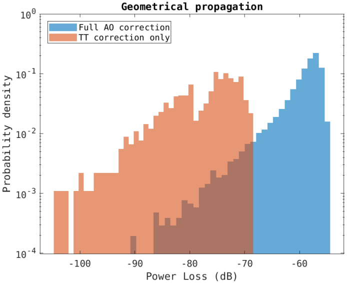


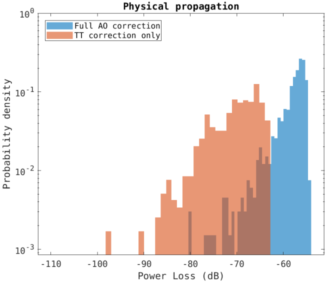
Parameter	Value
Diameter	1m
Central obstruc.	0.35
Launch	Axicon
Seeing	**1.0"**
Frame rate	**2kHz**
Simul. duration	**0.5s**

	Geometrical propagation		Physical propagation	
	full AO	TT only	full AO	TT only
Long exposure Strehl ratio	46.523	3.311	56.249	5.493
FWHM [μrad]	0.241	1.387	0.249	0.8129
Power loss 3σ width [dB]	25.014	34.790	25.055	32.108
Minimum flux [μW/m^2]	0.0036	0.0241	0.466	0.223
Laser power [W] to reach 1.5μW/m^2	417.684	62.281	3.214	6.699

Plots computed with the last 1000 iterations of the 5000 iterations AO loop with modal optimization.

PASSATA simulations: Axicon launch, daytime


Geometrical propagation

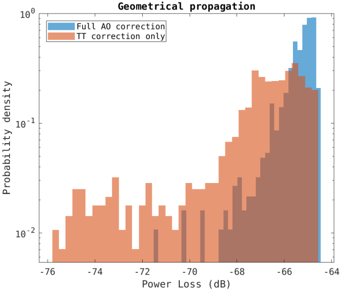

Physical propagation

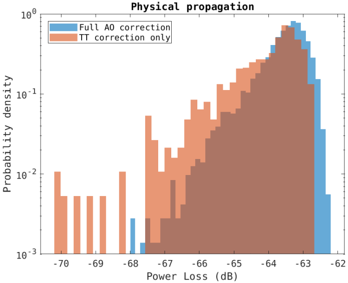
Parameter	Value
Diameter	1m
Central obstruc.	0.35
Launch	Axicon
Seeing	2.5"
Frame rate	2kHz
Simul. duration	0.5s

	Geometrical propagation		Physical propagation	
	full AO	TT only	full AO	TT only
Long exposure Strehl ratio	19.746	1.497	28.883	2.766
FWHM [μrad]	0.248	2.446	0.264	1.487
Power loss 3σ width [dB]	23.223	36.888	20.212	34.162
Minimum flux [μW/m^2]	0.0144	0.0019	0.522	0.0007
Laser power [W] to reach 1.5μW/m^2	104.074	770.8826	2.874	2207.095

Plots computed with the last 1000 iterations of the 5000 iterations AO loop with modal optimization.

PASSATA simulations: Sub-pupil launch, nighttime


Geometrical propagation

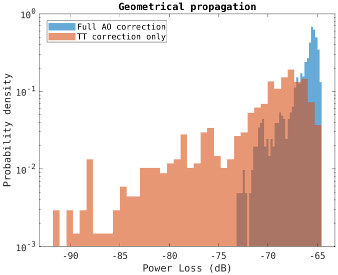

Physical propagation

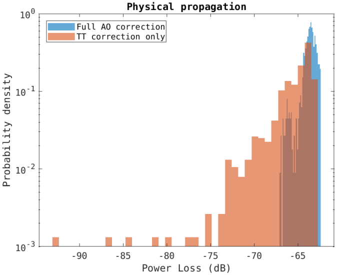
Parameter	Value
Diameter	30cm
Central obstruc.	no
Launch	Sub-pupil
Seeing	0.7"
Frame rate	1kHz
Simul. duration	1s

	Geometrical propagation		Physical propagation	
	full AO	TT only	full AO	TT only
Long exposure Strehl ratio	77.239	60.235	79.898	66.627
FWHM [μrad]	1.196	1.345	1.001	1.041
Power loss 3σ width [dB]	5.933	13.656	5.143	6.522
Minimum flux [μW/m^2]	3.384	1.732	9.141	5.461
Laser power [W] to reach 1.5μW/m^2	0.443	1.463	0.642	0.865

No automatic modal gain optimization. Gains optimized by hand.

PASSATA simulations: Sub-pupil launch, nighttime





Parameter	Value
Diameter	30cm
Central obstruc.	no
Launch	Sub-pupil
Seeing	**1.0"**
Frame rate	**2kHz**
Simul. duration	**0.5s**

	Geometrical propagation		Physical propagation	
	full AO	TT only	full AO	TT only
Long exposure Strehl ratio	66.520	37.065	69.948	54.118
FWHM [μrad]	1.247	2.097	1.001	1.151
Power loss 3σ width [dB]	9.239	29.160	4.998	15.612
Minimum flux [μW/m^2]	2.833	0.041	11.177	0.0325
Laser power [W] to reach 1.5μW/m^2	0.529	36.666	0.134	46.145

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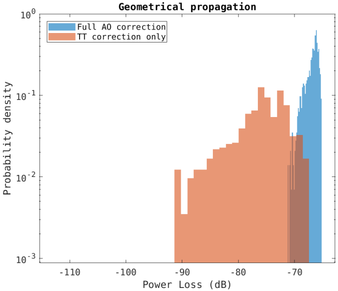
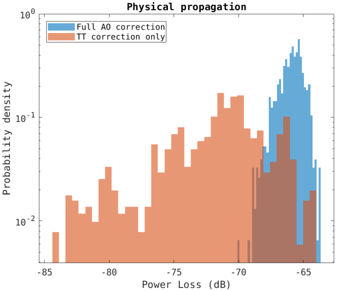
PASSATA simulations: Sub-pupil launch, daytime





Parameter	Value
Diameter	30cm
Central obstruc.	no
Launch	Sub-pupil
Seeing	2.5"
Frame rate	2kHz
Simul. duration	0.5s

	Geometrical propagation		Physical propagation	
	full AO	TT only	full AO	TT only
Long exposure Strehl ratio	56.107	9.238	67.102	19.885
FWHM [μrad]	1.236	2.261	1.204	1.809
Power loss 3σ width [dB]	6.955	30.797	5.838	24.788
Minimum flux [μW/m^2]	4.3333	0.0003	5.591	0.217
Laser power [W] to reach 1.5μW/m^2	0.346	4946.75	0.268	74.090

No automatic modal gain optimization. Gains optimized by hand.

Summary

- Simulations in PASSATA showed that the ALASCA requirements can only be met with AO.
- **Sub-pupil launch**: Using LGS-AO the ALASCA requirements on the 3σ width and the minimum flux are met for all test cases studied.
- **Axicon launch**: The 3σ distribution width is larger and the requirement that it is below 10dB can only be fulfilled in the $0.7"$ seeing case.
- Zero padding and apodization improved the results for physical optics propagation.
- Using physical optics propagation provided better results than geometrical optics propagation.

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Thank you!

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Photometric histogram at the satellite

1. We take the central value of the short exposure PSF from PASSATA $\left[\frac{\mathrm{W}}{\mathrm{pixel}}\right]$.
2. **Spacing at the satellite**: $\mathrm{dxSat} = \frac{\mathrm{wavelength} \cdot \mathrm{propDist}}{\mathrm{imWidth} \cdot \mathrm{pixelPitch}} \left[\frac{\mathrm{m}}{\mathrm{pixel}}\right]$
3. **Flux at the satellite**:

$$\mathrm{flux} = \frac{\mathrm{psf}}{\mathrm{dxSat}^2} \left[\frac{\mathrm{W}}{\mathrm{m}^2}\right]$$

4. **Power at the satellite:** $\mathrm{power} = \mathrm{flux} \cdot \mathrm{areaReceiver} = \mathrm{fluxSat} \cdot \pi \cdot (\frac{15}{2}\mathrm{cm})^2 [\mathrm{W}]$
5. **Power loss**: $\mathrm{powerLoss} = 10 \cdot \log(\mathrm{power})\ [\mathrm{dB}]$
   Assuming 1W initial power.