Simulated parametric study of coherent differential imaging for exoplanet detection with SPHERE

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- **Motivations:** Classical high-contrast imaging (ADI, RDI,...) always requires extensive observation time for speckle calibration. We investigate **Coherent Differential Imaging (CDI)**, a powerful alternative that relies on **active, user-controlled modulation** rather than passive diversity.
- **Method:** We implemented the **Pair-Wise Probing** algorithm within **COMPASS** simulations to actively modulate optical aberrations in a **VLT/SPHERE**-like environment.
- **Results:** We performed a comprehensive parametric analysis, demonstrated a contrast gain up to a **factor of 11** in simulations and identified distinct corrective regimes.
- **Perspective:** This work paves the way for CDI as a highly efficient strategy for next-generation instruments like **SPHERE+** and the **Roman Space Telescope**.

1. Scientific and technological context

- Detection of Super-Jupiters (≥ 5 AU) with **VLT/SPHERE** ($D = 8$m).
- **Adaptive Optics (AO):** N×N = 41×41 actuators on the **deformable mirror (DM)**.
- **COMPASS**: end-to-end numerical simulations (atmosphere + instrument).

2. The NCPAs limitation

- **NCPAs = Non-Common Path Aberrations.**
- **Uncorrectable** by adaptive optics, **static or quasi-static**.

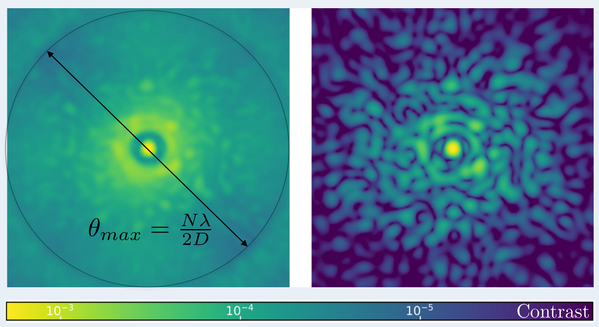


Fig 1: SPHERE focal plane simulations with COMPASS. **Left (Ground case)**: Residual AO halo and NCPAs speckles). The Fried parameter is r_0. **Right (space case)**: NCPAs speckles only (*Galicher & Mazoyer, 2023).*

3. Focal plane correction of NCPAs with CDI

- **Goal:** Estimate the intensity of NCPAS: $|E_s|^2$.
- **How?** Temporal modulation: **Pair-Wise Probing (PWP)**.
- **Principle:** Apply pairs of known phase probes $\pm\psi_m$ on the (DM) and linearize the intensity measurement $\Delta I_m = I^+ - I^-$.
- Solve inverse problem:

$$\underbrace{\Delta I_m}_{\text{Measurement}} = \underbrace{\mathcal{M}_{\text{model}}}_{\text{Modulation}} \cdot \underbrace{E_s}_{\text{Speckles}}$$

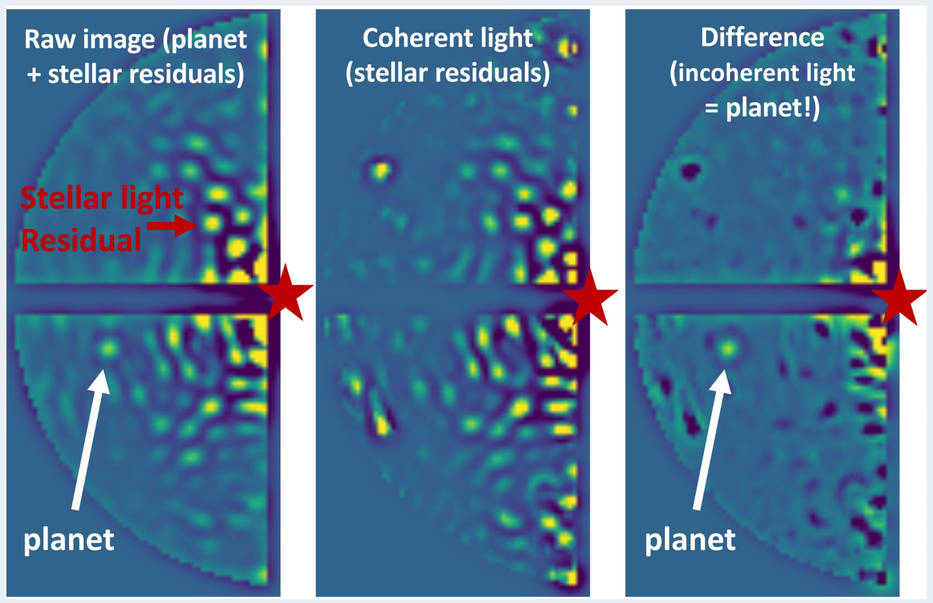
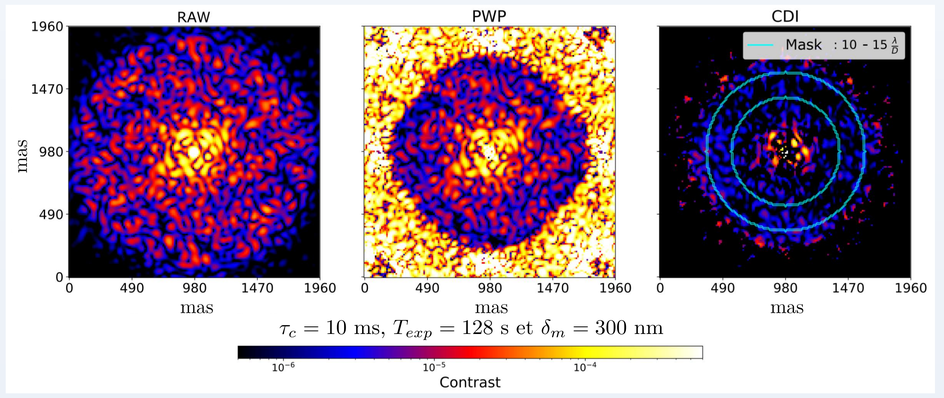


Fig 2: Real CDI result on sky with Beta Pictoris. Static speckles are **indistinguishable** from the planet. Post-process subtraction produces a cleaned post-processing **CDI image** (*Potier & Mazoyer, priv. comm.).*

4. Study and results

Variable parameters
Exposure time T_{exp} of PWP
Modulation amplitude: $\delta_m = \frac{\psi_m \lambda}{2\pi}$
Wind speed: $V_{wind} = 0.314 \times r_0/\tau_c$

Fig 3: Simulation with COMPASS. **Left:** Raw image (NCPAs only). **Center:** Closed-loop PWP image (atmosphere + NCPAs). **Right:** Final CDI residues. The mask annulus = area used for contrast estimation. **No exoplanets** in simulation = we aim to **minimize the CDI intensity**.



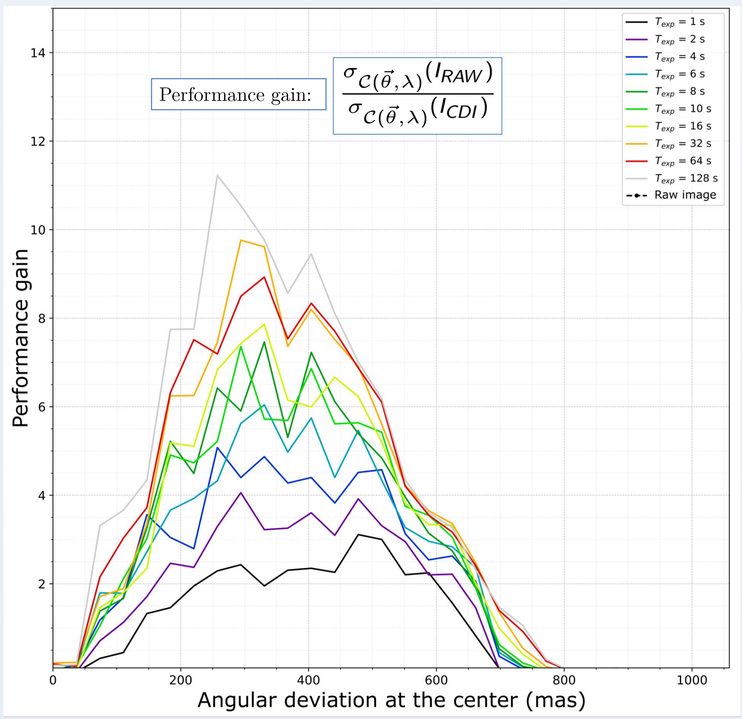


Fig 4: Impact of exposure time on performance gain simulated with COMPASS.

Increase PWP exposure time should **improve the quality of the speckle estimation**, but **decrease duty cycle**.

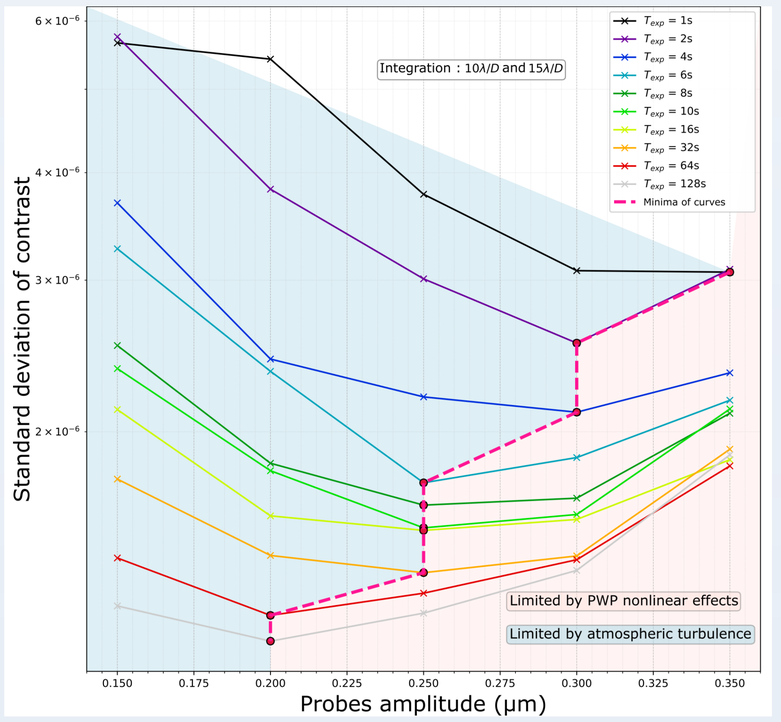


Fig 5: Visualization of two correction regimes simulated with COMPASS. Contrast integrated into the mask.

Amplitude of the probes provides a **better signal for modulation**, but introduces **nonlinear effects by pushing too hard**.

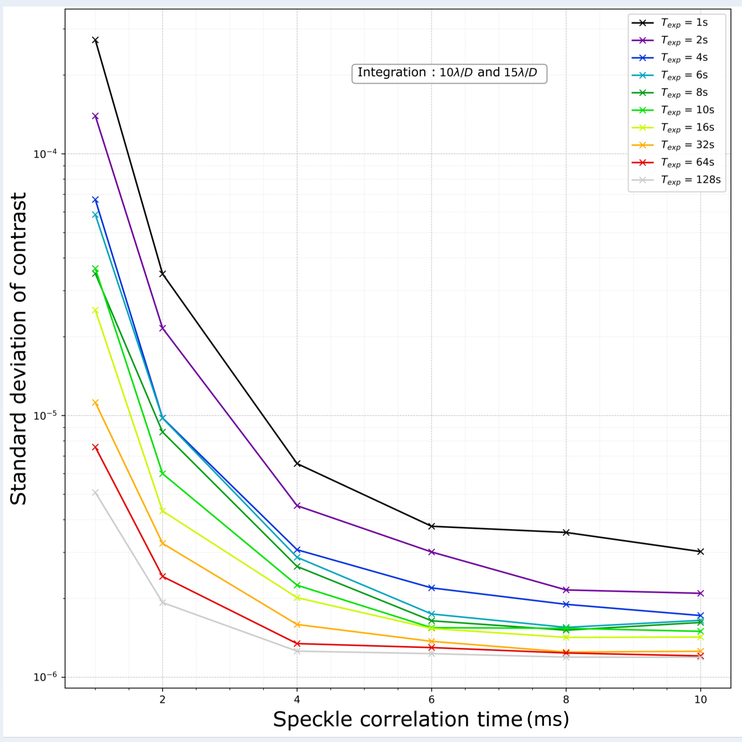


Fig 6: Impact of speckle correlation time τ_c on contrast simulated with COMPASS. Contrast integrated into the mask.

CDI can optimally be used for V_{wind} below **20** km/h.

5. Conclusion and outlook

Key Results:

✓ **High Performance:** Demonstrated a contrast gain up to a **factor of 11** in simulations.

✓ **Regime Analysis:** Identified distinct corrective regimes (Linearity vs. Turbulence dominated e.g.).

Perspectives with COMPASS:

➢ **Ultimate Limits:** Implementation of **science detector noise**.

➢ **Next Generation:** Application to the **SPHERE+**.

References

❖ Galicher & Mazoyer, Comptes Rendus. Physique. (2023)
❖ Ferreira et al., HPCS IEEE (2018)
❖ Give'on et al., Optics Express (2007)
❖ Goulas et al., Adaptive Optics Systems, SPIE (2024)
❖ Groff et al., JATIS (2016)

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