Calibration of residual aberrations in coronagraphic instruments with ZELDA: validation in VLT/SPHERE

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Context

• Direct imaging and spectroscopy of exoplanets
  ‣ VLT/SPHERE, Gemini/GPI, Subaru/SCExAO, etc
  ‣ disks, warm or massive gas giant planets
  ‣ high contrast ($\Delta$mag>10) at small separations (0.1‰”-0.5‰”)

• Instrument limitations
  ‣ quasi-static aberrations
  ‣ temporal stability

• Need of a clean PSF for optimal starlight rejection
  ‣ Calibration of pre-coronagraph aberrations

Direct imaging of colder or lighter exoplanets

• Residual aberrations:
  ‣ How to calibrate them?
  ‣ Their origin?
  ‣ Their temporal evolution?

• Our solution:
  ‣ Zernike wavefront sensor
Zernike wavefront sensor

- Conversion of the phase aberrations into intensity variations
  - $I_c = \alpha \sin \varphi + \beta$
  - Small aberrations: $I_c = \alpha \varphi + \beta$

![Diagram of Zernike wavefront sensor](image)

N'Diaye et al. 2013
Linearity range of the sensor

- Linearisation of the amplitude ↔ expression valid only near zero phase error
- Limited capture range: $-0.14\,\lambda_0 \rightarrow 0.36\,\lambda_0$
- Possible extension of the capture range in closed loop

![Graph showing WFE in nm at $\lambda_0=1.642\,\mu m$ with corrections for different piston values.](image)

$Vigan\ et\ al.\ 2011,\ N'Diaye\ et\ al.\ 2013$
Implementation in VLT/SPHERE

**ZELDA**

Zernike sensor for Extremely accurate measurements of **Low-level Differential Aberrations**

- Original measurement strategies:
  - VLT/SPHERE: off-line phase diversity
  - GPI: Mach-Zehnder interferometer behind coronagraph

- Our proposal:
  - ZELDA a concept based on phase-contrast technique
Current implementation in SPHERE

J.-L. Beuzit’s talk Thursday morning
ZELDA prototype in SPHERE

- Fused silica substrate
- Mask by photolithographic reactive ion etching (SILIOS, France)
- Within 1% of the specifications

Installation during SPHERE reintegration at Paranal in April 2014

\[ \lambda = 1.62 \ \mu m \ (H\text{-band}) \]

\[ D = 70.7 \ \mu m \]

\[ z = 0.815 \ \mu m \]
Validating ZELDA in SPHERE

- Internal point source
- IRDIS pupil-imaging mode, $\lambda = 1642$ nm (Fe II filter)
- PSF centered manually + closed loop on near-IR DTTS
- Zernike and Fourier modes, amplitude ramps: -250 $\rightarrow$ 600 nm PtV

Zernike modes introduced with 400 nm PV on the DM

N'Diaye et al. 2016
Quantitative performance assessment

• theory vs. measurements:
  ‣ excellent agreement!
• low sensitivity to wavelength of measure

N'Diaye et al. 2016
NCPA measurement and compensation

45 nm RMS

Before correction

Phase errors [nm]

30 nm RMS

Before correction [filtered]
NCPA measurement and compensation

45 nm RMS

30 nm RMS

35 nm RMS

16 nm RMS

Tip-tilt: ~12 nm RMS

Manual centering + tip-tilt closed loop

N'Diaye et al. 2016
Impact on coronagraphic images

Apodised pupil Lyot coronagraph, H-band

Before calibration
Impact on coronagraphic images

Apodised pupil Lyot coronagraph, H-band

After calibration

0.85"

0.20"
Contrast gain after ZELDA calibration

perf. limit of SPHERE coronagraph

x10 gain @ 0.2"

→ ZELDA will be used for NCPA calibration in SPHERE this year

N'Diaye et al. 2016
Towards ZELDA on sky

**New tests in March 2017**

- Internal performance
- On-sky performance

**Procedure**
- Internal NCPA calibration
- Calibrated reference slopes applied on-sky

**Internal performance**
- On-par with 2015
- 5-10 contrast gain

Vigan et al. in prep
Towards ZELDA on sky

**New tests in March 2017**

- **Internal performance**
- **On-sky performance**

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**Procedure**

- internal NCPA calibration
- calibrated reference slopes applied on-sky

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**Internal performance**

- on-par with 2015
- 5-10 contrast gain

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**On-sky performance**

- no contrast gain yet!
- reason unknown:
  - chromatic beam-shift?
  - near-IR ADCs?
  - amplitude aberrations?
ZELDA in E-ELT/HARMONI high-contrast mode

- **Goal:**
  - spectro-imaging of young giants
  - $R=3000-20000$; $10^{-6}$ contrast at 0.2" and closer, in H & K bands

- **No ADC in the instrument:**
  - Dispersed beam & PSF
  - SCAO sensing at 0.8 um & science at 1.45-2.45 um:
    - *significant NCPA*

- **ZELDA @ 1.25 um, prospects:**
  - NCPA calibration: less constraints on surface quality of upstream optics
  - Pupil centering follow-up (0.5% accuracy): good for pupil masking
  - Fine E-ELT cophasing
ZELDA-Phasing Sensor

• Fine phasing sensor in diffraction-limited regime
  ‣ For each segment, measurements of piston, tip, tilt

• ZELDA-Phasing sensor
  ‣ Mode estimation with nanometric accuracy
  ‣ Closed-loop wavefront control for fine segment alignment
  ‣ promising option for fine cophasing of ELTs

Janin-Potiron et al. 2017
Conclusions

• **ZELDA for the calibration of residual aberrations**
  ‣ easy to manufacture
  ‣ simple alignment
  ‣ no calibration required
  ‣ fast and straightforward data analysis

• **Validation in VLT/SPHERE**
  ‣ excellent agreement between measurements and theory
  ‣ NCPA compensation: gain x10 in contrast at 0.2"
  ‣ implementation in the calibration plan of SPHERE in 2017

• **Powerful diagnostic tool for current and future AO facilities**
  ‣ internal and on-sky measurements
  ‣ several SPHERE examples: low-wind effects, internal turb., derotator behavior