Optimization of coupling between Adaptive Optics and Single Mode Fibers

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Non common path aberrations compensation through dithering

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Outline

- Problem statement
- Concept
- Results
- Conclusions
Context

- Long baseline optical interferometry, Space-to-ground Optical Communications
- Injection of optical signal into SMF
- Use of AO for correction of atmospheric turbulence induced perturbations
Problem statement

Correction of wavefront injected into SMF?

Adaptive Optics Loop: correction of wavefront seen by WFS

Non common path aberrations: alignment, thermo-mechanical effects.

Deformable mirror

Control

Wave Front Sensor

Beam splitter

Single Mode Fiber

Atmospheric turbulence

Plane wave front

Distorted wave front

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AO main loop (high frequency)

Secondary loop: dithering based optimisation of injected flux (low frequency)
**Concept of « sensorless » loop**

- Single measurement (coupled flux), Multi dimension correction using AO deformable mirror => use of dithering

- Correction through AO: can only be introduced by modification of setpoint = reference slopes

- From control point of view: Cascade control
  
  Main AO loop ($f_s > 100$ Hz)  
  « sensorless » loop ($f_s \# 1$ Hz)  

=> Modifications of DM shape introduced by the « sensorless » loop can be seen as quasi-static by the main AO loop (modification of setpoint of AO): temporal decoupling

- « sensorless » loop:
  
  - Control in the AO loop eigen modes: ($m$);
  
  - Application of sensorless loop control onto DM ($v$) by projection of modes ($m$) onto reference slopes ($\delta p$) of WFS: ($\delta p$) = $A$ ($m$) then ($v$) = $D$ ($\delta p$) ($D$ = AO command Matrix);
  
  - Iterative search of maximum along random directions of the eigen modes space ($m$)$_n$.

- Principle: dithering with parabolic fit. Can be related to Stochastic Parallel Gradient Descent (SPGD)
Optimization by dithering

**Coupling efficiency** $I$ in one direction of modulation $(m)_n$

$$I = F(\lambda (m)_n)$$

- Choice of direction of modulation in eigen mode space $(m)_n$,
  - For that direction:
    - a. Modulation of amplitude $\pm \delta\lambda$ in mode space,
    - b. Detection of associated signals $I_n^+, I_n^-$,
    - c. Determination of maximum by parabolic fit, $\lambda_{n+1}$
    - d. Conversion into slopes of associated mode vector and detection of output signal.

$\lambda_n$ amplitude on mode $(m)_n$

$I_n$ associated coupling efficiency
Impact of noise

Coupling efficiency $I$ in one direction of modulation $(m)_n$

$I = F(\lambda (m)_n)$

$I_{\text{max}}$ $I_{\text{est}}$ $\delta I$ $\delta \lambda$

$\sigma I$ $\lambda_{\text{max}}$ $\lambda_{\text{est}}$

Modulation of amplitude
$+/- \delta \lambda$ in mode space
$+/- \delta I$ in coupling efficiency

Internal source
$\sigma I \rightarrow$ Detection noise

External source
$\sigma I \rightarrow$ Turbulence

Attenuation: $<I_{\text{max}} - I_{\text{est}}>/I_{\text{max}} = 1/8$

$(\sqrt{\frac{N}{I/I_{\text{max}}}}) \uparrow 2 I_{\text{max}} /dI$

- Reduction of $\sigma I$: temporal averaging of coupled signal
- Increase of $\delta I$: increase of modulation amplitude $\delta \lambda$ in mode space
Optimization on sky with AO

fitting error limited AO case

- Assume modulation:
  \[ \frac{I_{\text{max}}}{dI} = 0.1 \]
- Consider \( \frac{I}{I} = 0.1 \)
- then \( \frac{<I_{\text{max}} - I_{\text{est}}}{I_{\text{max}}} = 0.01 \)

Experimental validation in the lab

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PSF
SMF output
internal source @ 635 nm

BOA bench @ONERA

Rotating phase screens

DM : 241 actuators ALPAO

RTC : PC fs= 200 Hz

WFS SH : 156 sub-apertures ANDOR CCD
Experimental validation in the lab: no turbulence case

Convergence of CE optimisation

- Optimisation of static aberrations.
- Can be performed with input source (no use for intermediate reference source as in AO)
- Convergence speed not critical.
Experimental validation in the lab: turbulent case

• Turbulence ON

Convergence of CE optimisation

Residuals mainly driven by AO performance!

Stability after convergence

If phase screen removed? Sensorless loop stopped

No turb: 56% CE
PS removed: 50% CE

Convergence speed and performance as function of number of actuators, amplitude of modulation, averaging to be analyzed
AO bench ODISSEE @ OCA

90 actuators
8x8 SH-WFS
Up to 1.5kHz

Validation of hybrid AO on ODISSEE (D = 1.5 m, 8x8 sous-pupilles, 1500 Hz)

**CESAR mission**: coupling of star light into SMF for long baseline interferometry (collaboration : ONERA/Lagrange).

**SOTA/SOCRATES mission**: coupling of telecom signal into SMF (collaboration : ONERA/CNES/NICT/OCA).
CESAR preliminary results (star @ 700 nm)

Cesar Module from Lagrange

Static (internal source) optimization of coupling

Significant gain obtained through AO and sensorless loop.
Performance limited by AO system

PSF from AO and SMF output image optically combined onto the same detector

AO closed loop internal

AO open loop (star)

AO Closed loop (star)

Coupling eff. measured ≈ 10 %
SR ≈ 11 %
Conclusion

Sensorless loop concept:

- A simple approach which goal is to simplify complex systems: use of single or no calibration source (improve transmission), ensure stability of system (reduce need for thermo-mechanical stabilisation), on the whole reduce costs.
- First demonstration: numerical analysis comforted by in lab experiment and first tests on sky
- Still a lot of job to be done:
  - Analysis of convergence wrt time averaging/nbr of actuator/modulation amplitude
  - Possibility to enhance strategy (choice of dithering basis, hierarchical approach …)
  - Investigate fully automatic use of sensorless loop

Applications:
- Long base interferometry, optical communication, …