Laboratory Validation of Sequential Optimization of Adaptive Receivers in Downlink Laser Communications

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Outline

- **Motivation**
- Speckle-based compensation system and method
- Experimental results
- Experimental results: Lasercoms
- Conclusions

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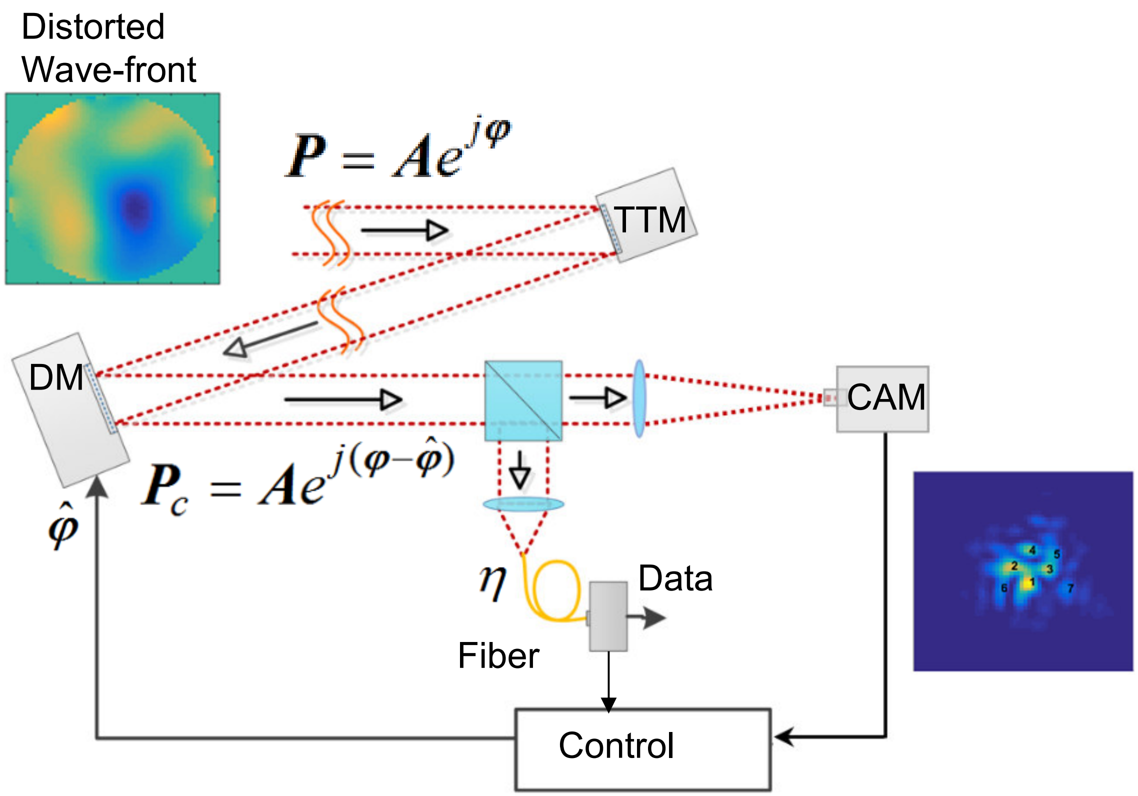
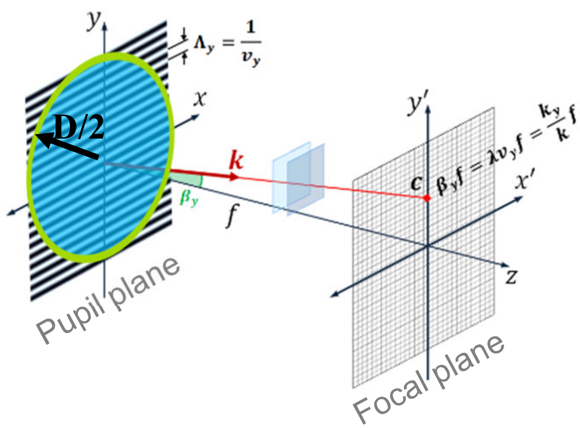
Compensation system and method



Main Steps:

- Acquire single image
- Detect speckle position and amplitude
- Create software-based plane waves (PW)
- Find optimum phase-shift of PW
- Use parabolic optimization of coupled power
- Sum optimized PW and extract argument to shape DM

Compensation system and method



$$u(x,y,z) = A\exp\left[j\left(k_x x + k_y y + k_z z\right)\right] = A\exp\left(j\boldsymbol{k}\cdot\boldsymbol{r}\right)$$

$$x' = \beta_x f = \lambda \nu_x f$$

$$y' = \beta_y f = \lambda \nu_y f$$

$$\boxed{F(\boldsymbol{k}) = \iint_{-\infty}^{\infty} W(\boldsymbol{r}) f(\boldsymbol{r}) \exp\left(-j\boldsymbol{k}\cdot\boldsymbol{r}\right)} \rightarrow \boxed{I_a(\boldsymbol{k}) = \left[\frac{2\pi J_1\left(\frac{D}{2}\sqrt{k_x^2+k_y^2}\right)}{\sqrt{k_x^2+k_y^2}}\right]^2}$$

BASIS:

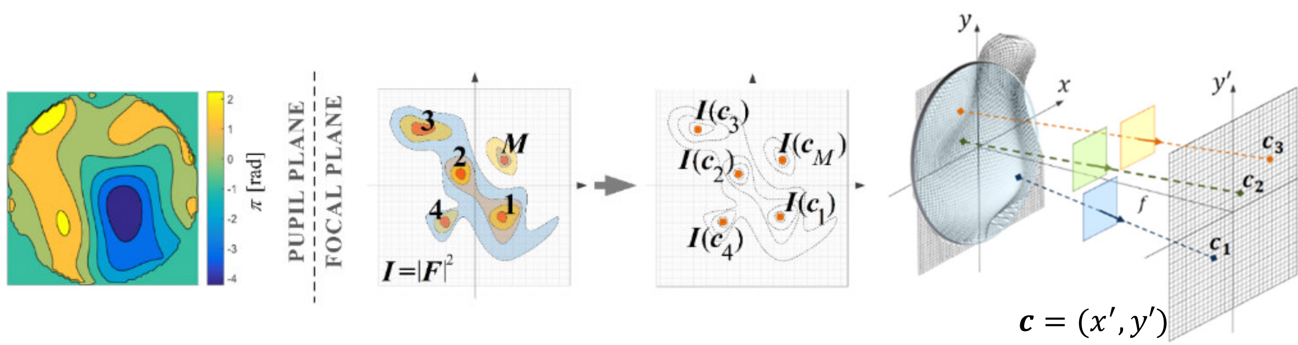
Plane wave propagates in a direction of $\boldsymbol{k}$ vector

Plane wave focuses in a single x', y'

Pupil/Focal planes are Fourier-related.

Pupil truncation results in a focal Airy pattern

Compensation system and method



$$P(\boldsymbol{r}) \approx \sum_{l=1}^{M} \left[b_l \exp(j\theta_l) \iint_{-\infty}^{\infty} \delta(\boldsymbol{k} - \boldsymbol{k}_l) \sqrt{I_a(\boldsymbol{k})} \exp(j\boldsymbol{k} \cdot \boldsymbol{r})\, d\boldsymbol{k} \right] \qquad \boldsymbol{k}_l = \left(\frac{2\pi x'_l}{\lambda f}, \frac{2\pi y'_l}{\lambda f} \right)$$

$$\boxed{P(\boldsymbol{r}) \approx W(\boldsymbol{r}) \sum_{l=1}^{M} b_l \exp(j\theta_l) \exp(j\boldsymbol{k}_l \cdot \boldsymbol{r})}$$

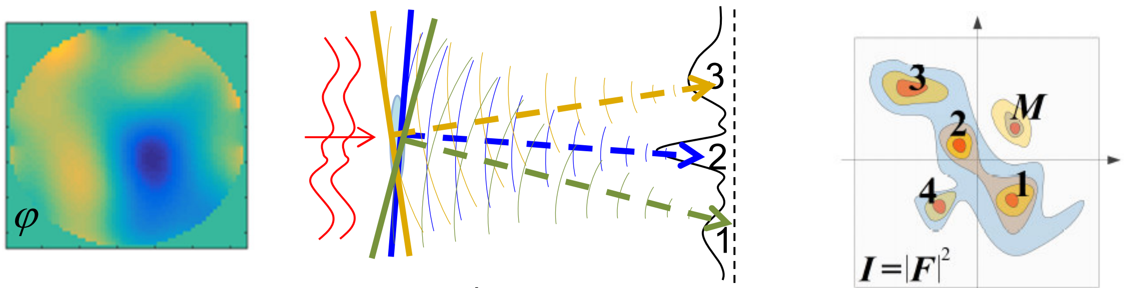
BASIS:
Distorted wave-front modelled as a discrete number of coherent regions

Decorrelated focal speckles modelled as a summation of airy patterns

Wave-front modelled as a summation of plane-waves

Compensation system and method

Pupil Plane   Focal Plane

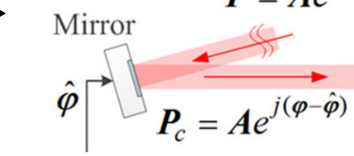


$$P = Ae^{j\varphi} \qquad F = Be^{j\theta}$$

$$P \approx b_1 \exp(j\boldsymbol{k_1}\cdot\boldsymbol{r} + \boxed{\theta_1}) + b_2 \exp(j\boldsymbol{k_2}\cdot\boldsymbol{r} + \boxed{\theta_2}) + b_3 \exp(j\boldsymbol{k_3}\cdot\boldsymbol{r} + \boxed{\theta_3}) + \cdots$$

$$\Downarrow$$

$$\hat{\varphi} = arg\{\boldsymbol{P}\} \quad \Rightarrow \quad \boldsymbol{P} = Ae^{j(\varphi - \hat{\varphi})} \longrightarrow$$

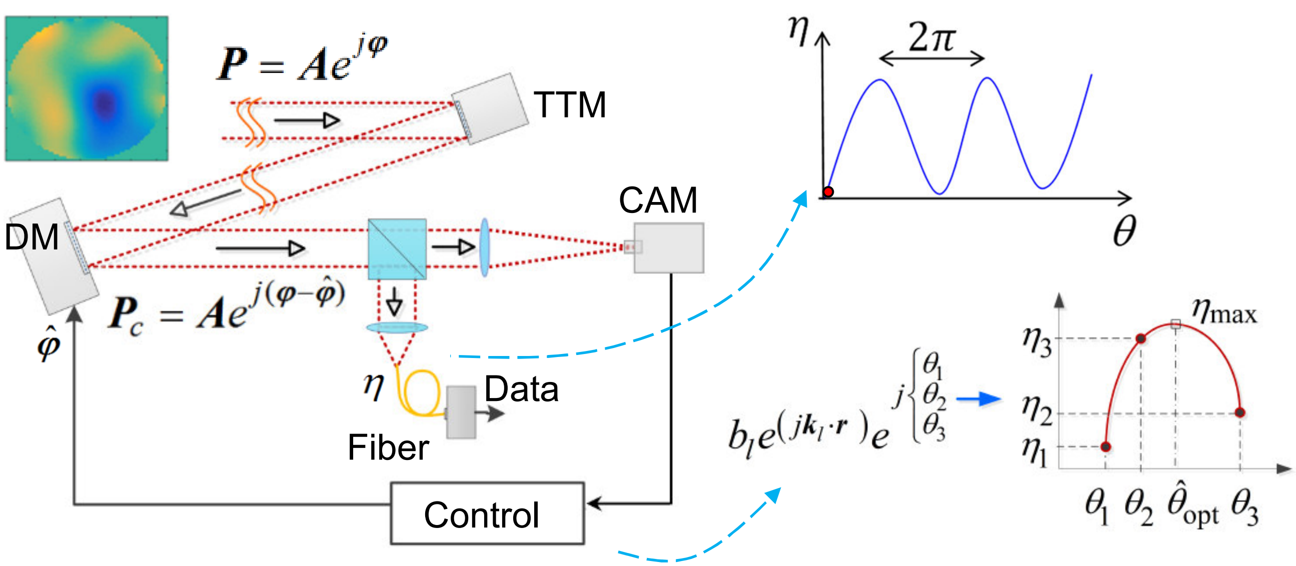


BASIS:

Each focal speckle is associated to a pupil plane wave.

The argument of $\boldsymbol{P}$ is the shape the DM

Compensation system and method



$$\boldsymbol{P} \approx \boxed{b_1 e^{j\left(\boldsymbol{k}_1\cdot\boldsymbol{r}_1+\cancel{\theta_{opt\ 1}}\right)}} + b_2 e^{j\left(\boldsymbol{k}_2\cdot\boldsymbol{r}_2+\theta_{opt\ 2}\right)} + b_3 e^{j\left(\boldsymbol{k}_3\cdot\boldsymbol{r}_3+\theta_{opt\ 3}\right)} + \cdots$$

$$N_{iter} = 3(M - \boxed{1}) + 1$$

Continuous variation of θ results in an oscillating coupled signal

Only 3 iterations to optimize a each plane wave

Total number of iterations proportional to the M treated speckles

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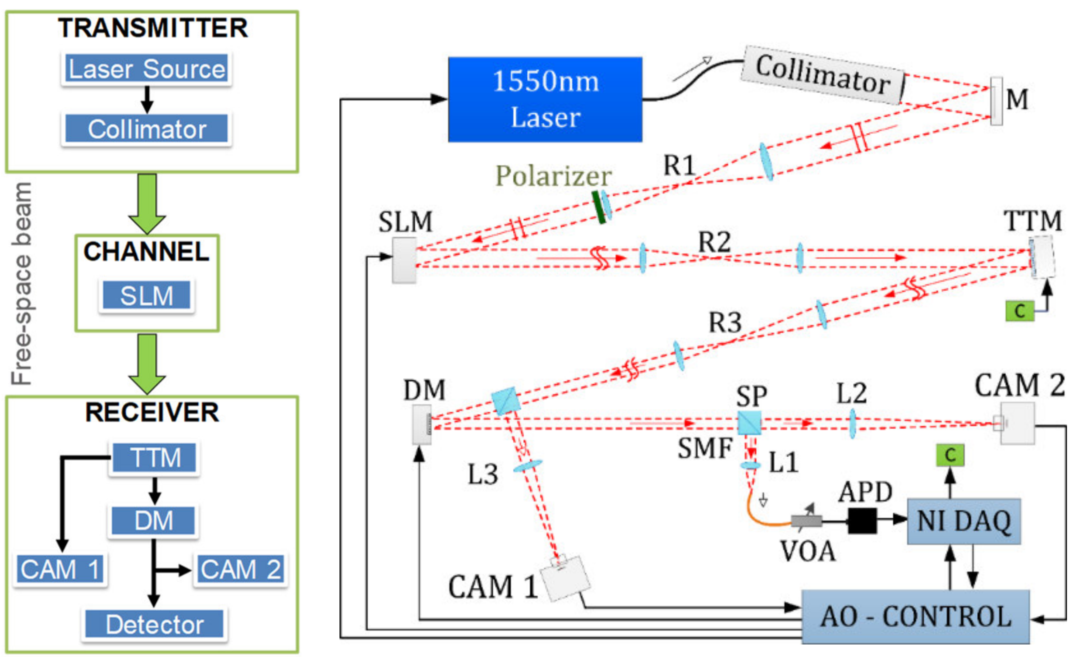
Experimental results: setup



SLM: imprints turbulence effects

TTM: corrects beam Tilt

DM: corrects beam phase distortion

CAM 1: captures initial focal speckle

CAM 2: captures focal speckle after each iteration

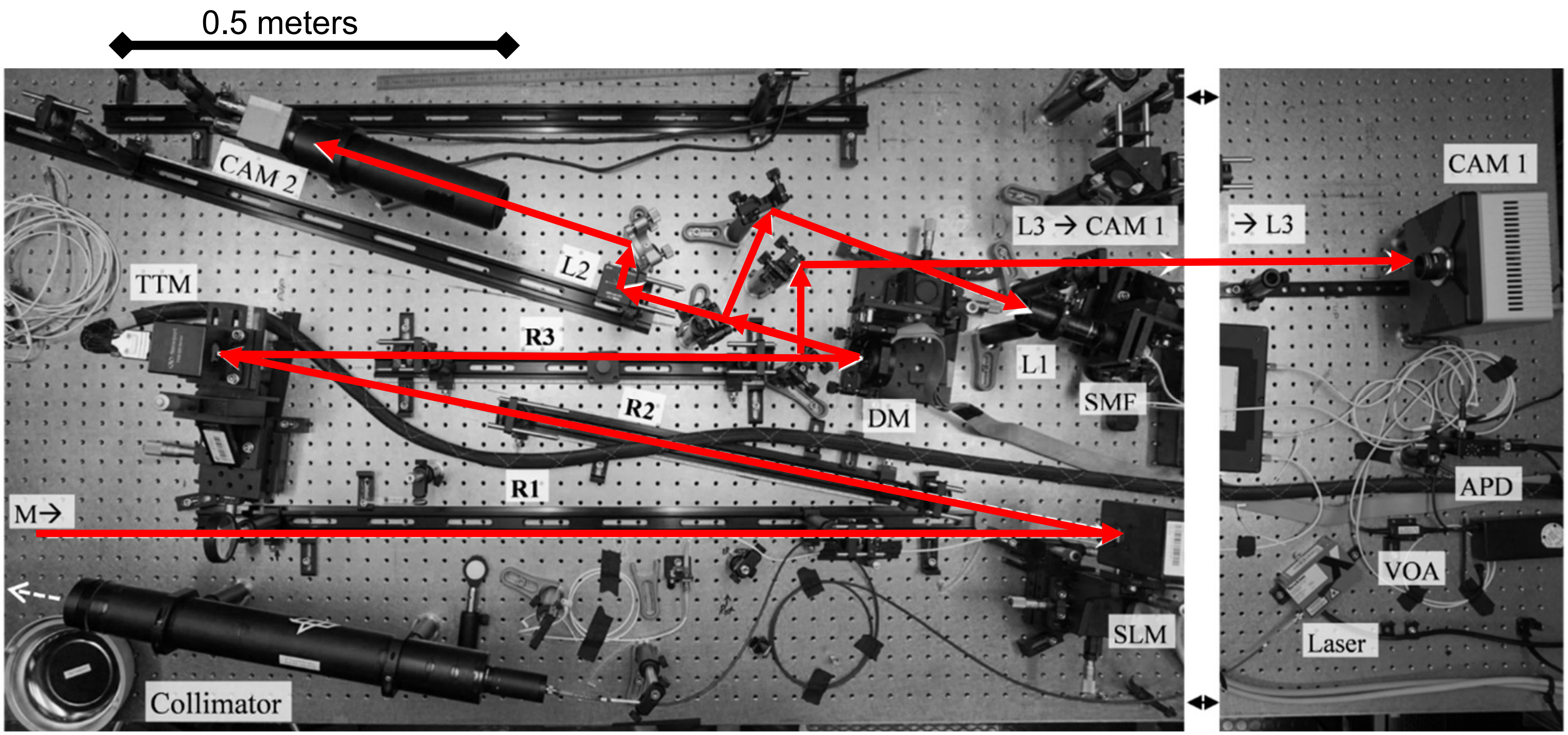
SMF: power measurement

VOA: attenuates coupled power

APD: avalanche photo detector

CONTROL: run algorithm

Experimental results: setup



Experimental results: Coupling vs. Corrected speckles

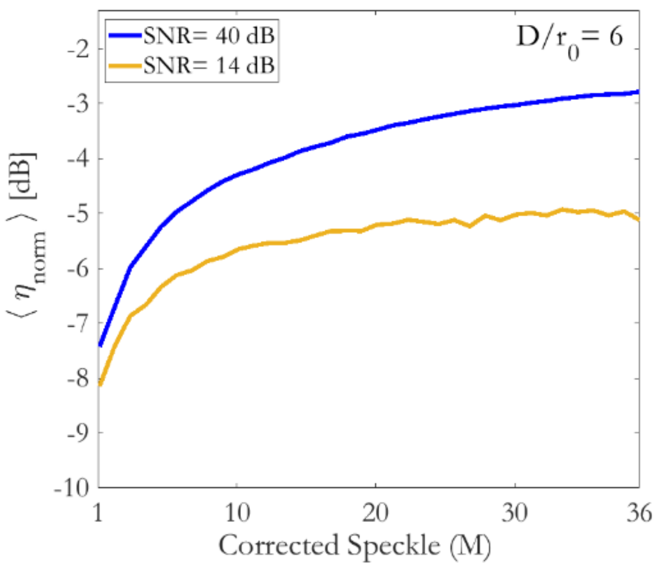


Fig.1- *Normalized coupling vs. corrected speckles for different SNR.*

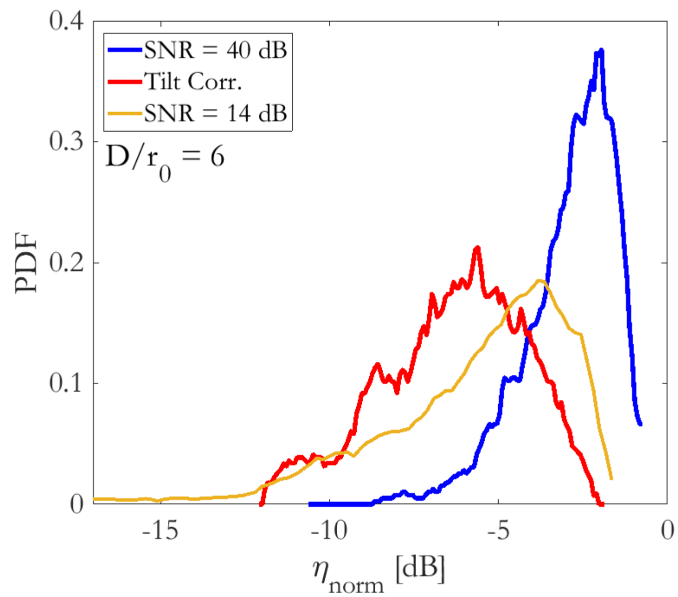


Fig.2- *PDF of the normalized coupling efficiency.*

Coupling improves with each corrected speckle.

20 corrected speckles (58 iterations) deliver 4.5 dB signal gain

There is a penalty with low SNR

Experimental results: Coupling vs. Turbulence regimes

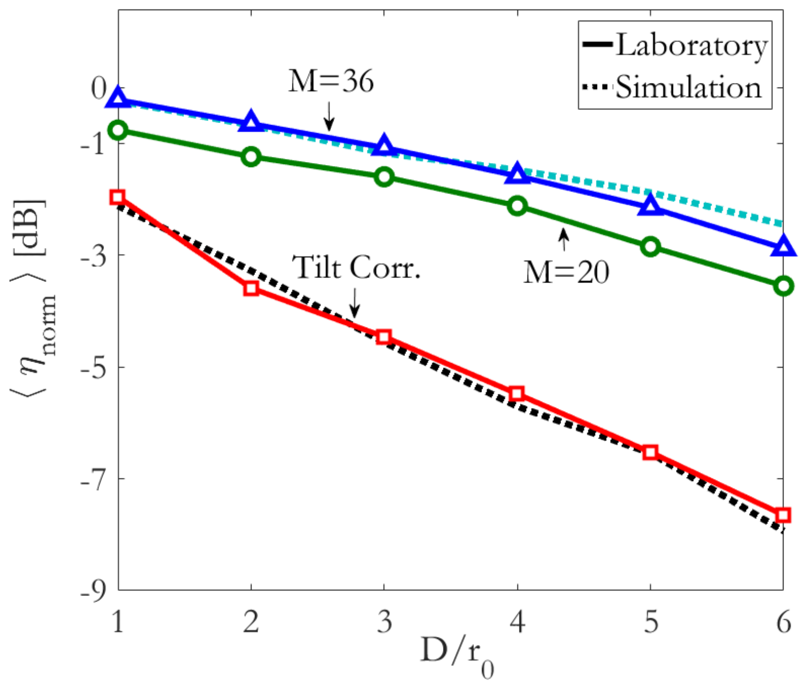


Fig.1- Overall coupling performance for different turbulent scenarios

Normalized coupling efficiency for different turbulent scenarios

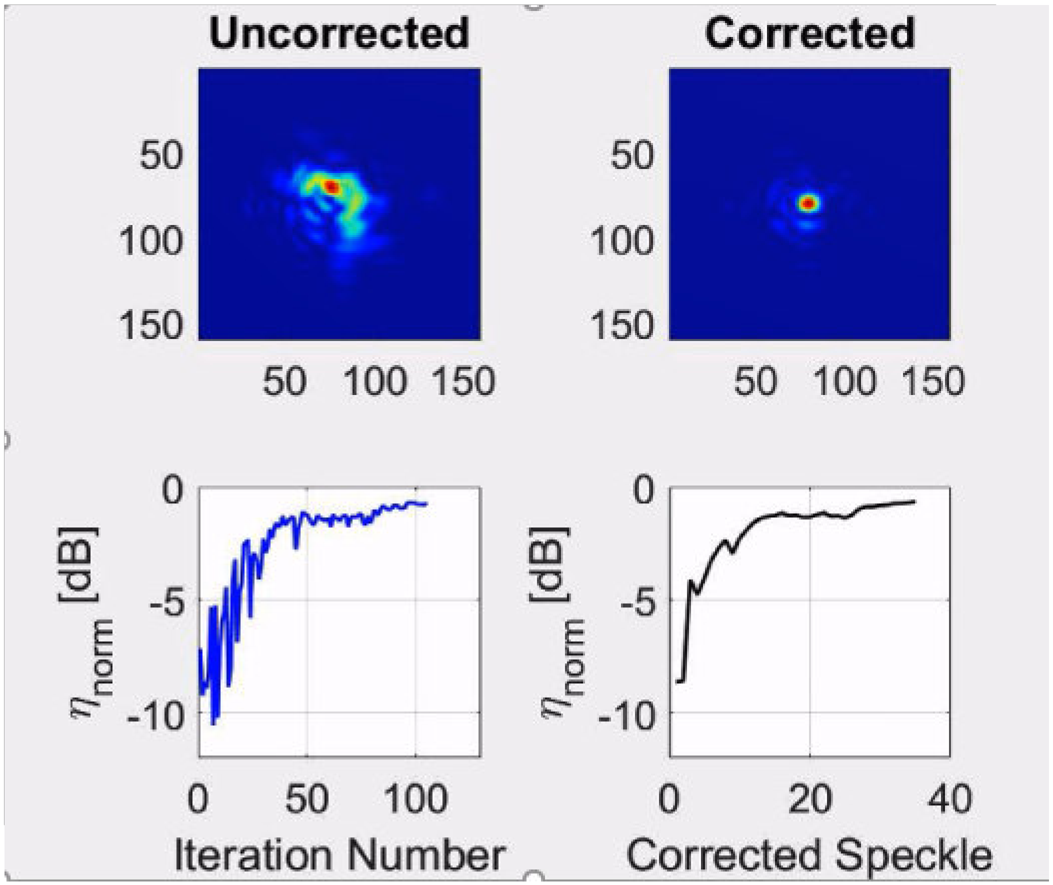
Fields corrected with:

106 iterations (M=36)

57 iterations (M=20)

Penalty of 0.4 dB

Experimental results: Signal behavior during correction

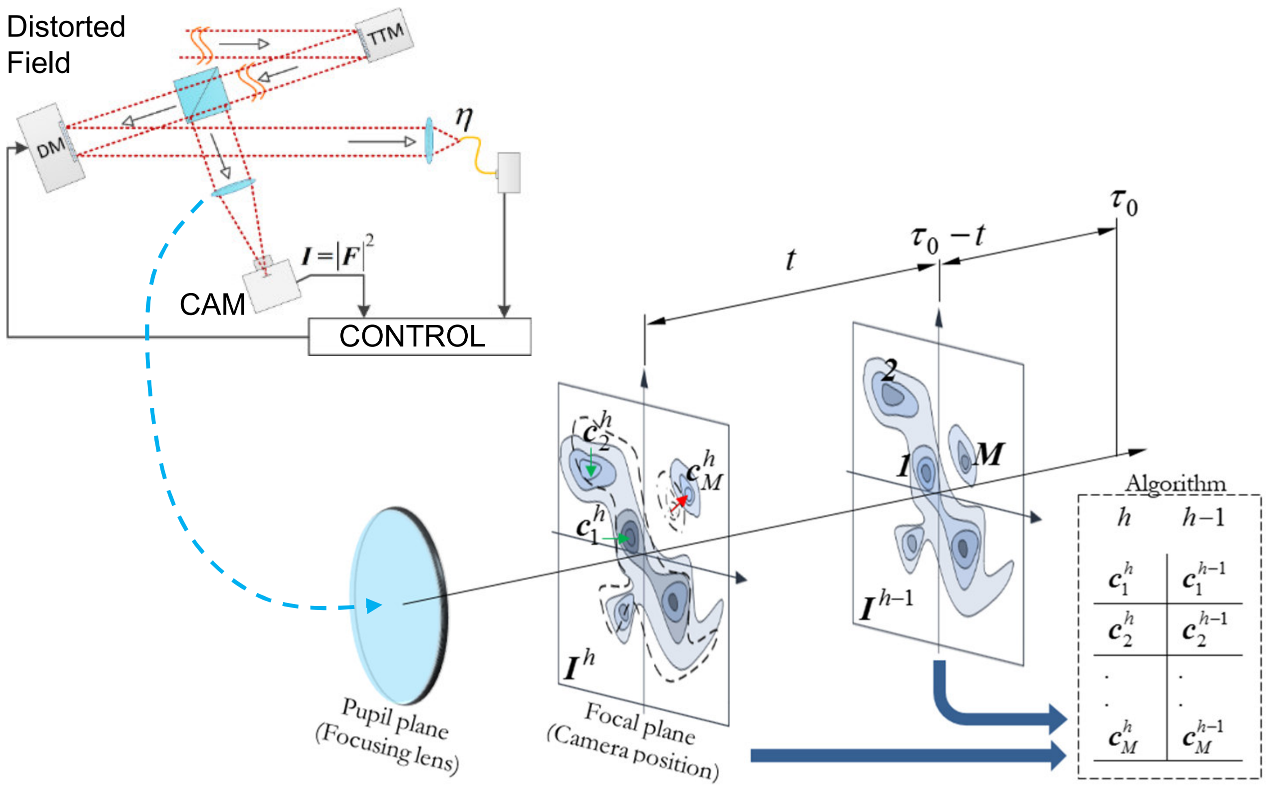


Scenario $D/r_0 = 4$

Each focal image is corrected with M speckles

Coupled signal is shown after each iteration and after each corrected speckle

Concept for dynamic correction



Focal images captured before the DM

Position of speckles are tracked

Small changes in position use previous optimized phase

Large change in position need new optimization

Experimental results: Dynamic Correction

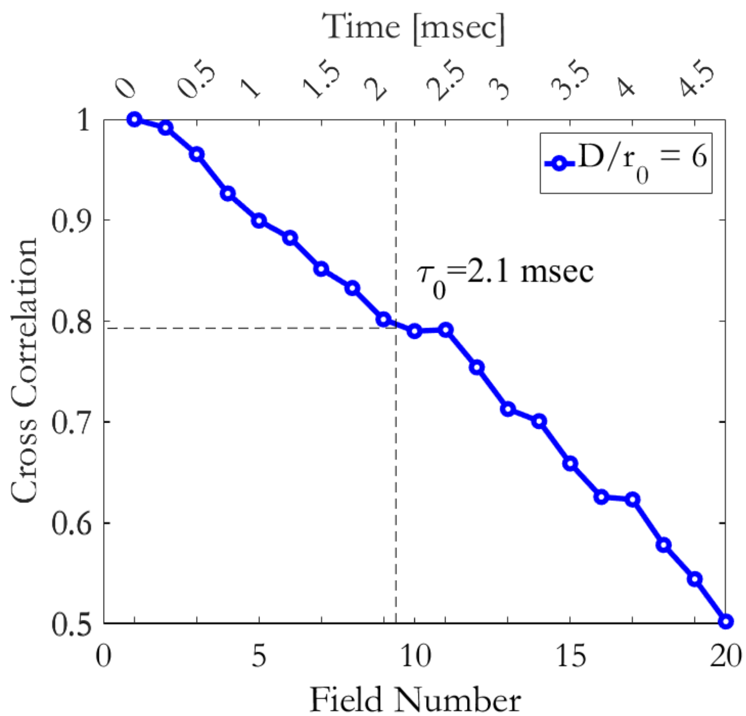


Fig.1*- Cross-correlation between correlated pupil phase wave-fronts.*

Correlated pupil fields are generated and propagated every $250\mu sec$ with a coherent time $t_0 = 2.1msec$ every 9 fields.

Focal speckles will evolve within t_0

Tracking of the speckle position can be used for the dynamic correction in the iterative process

Experimental results: Dynamic Correction

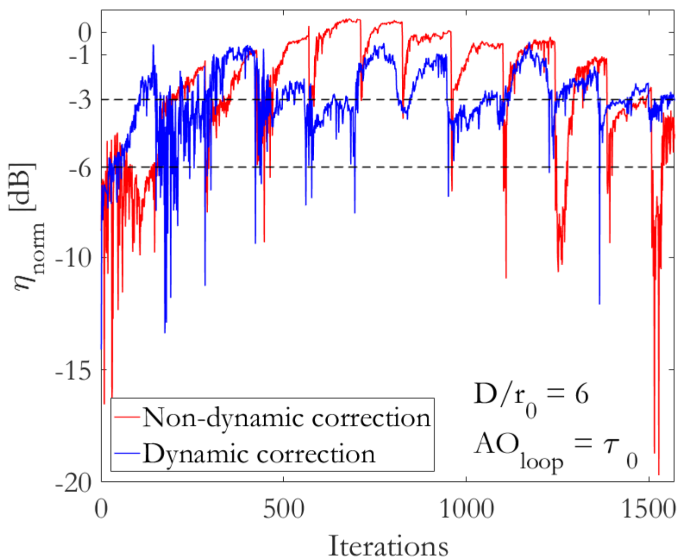


Fig.1- Comparison between the dynamic/non-dynamic correction of correlated fields.

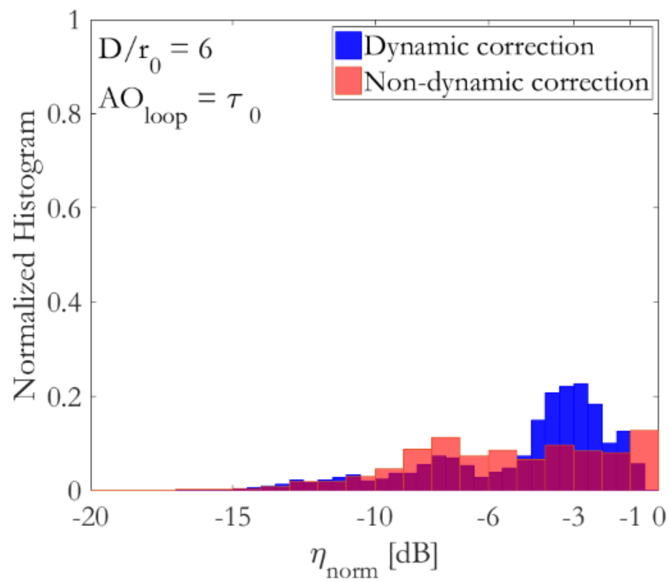


Fig.2- Normalized histogram of the dynamic/non-dynamic correction of correlated fields.

Fields are sent to the SLM every τ_0

Algorithm fails to maintain the correction

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Experimental results: Coherent communication test

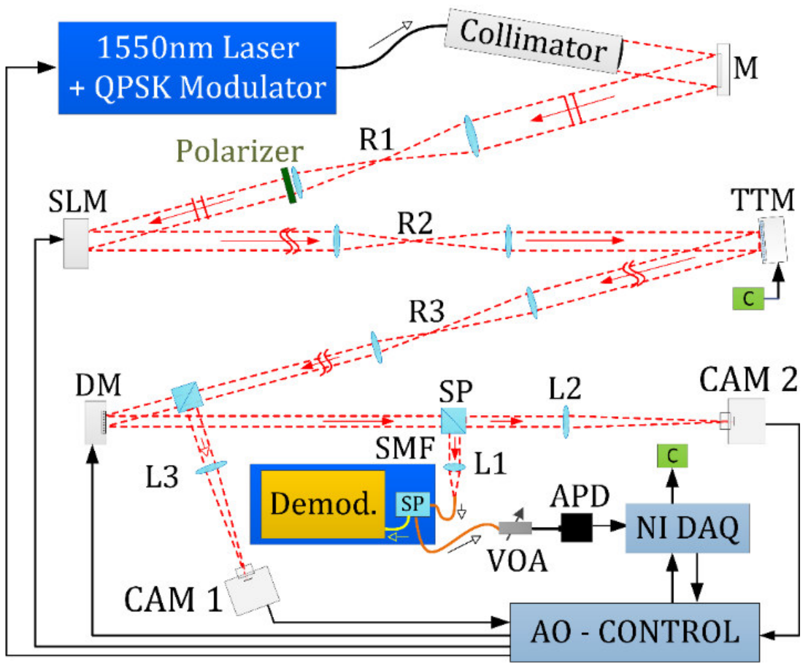

Fig.1 *- Schematic of the laboratory setup for the coherent data communication test.*

A coherent QPSK Tx/Rx system is integrated in the AO setup

GOAL:

Verify that field correction allows 80 Gbps data transmission.

Coherent System development ref. [4]

Experimental results: Coherent communication test

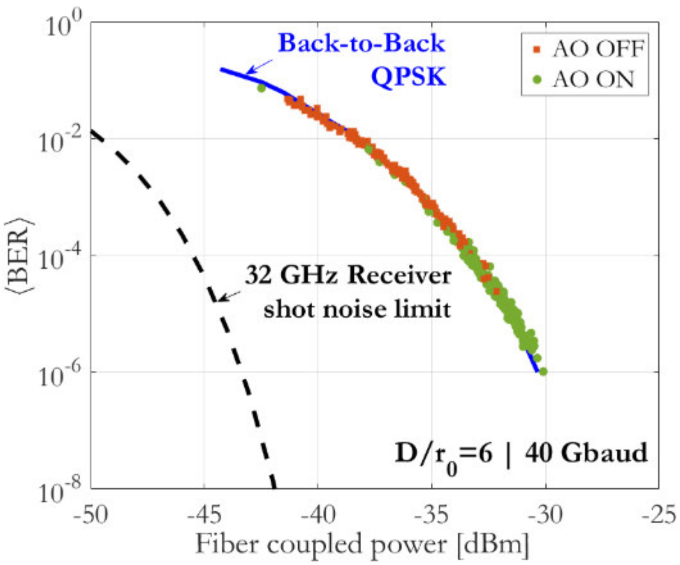

Fig.1- Receiver sensitivity for 80 Gbps QPSK data transmission corrected with AO system.

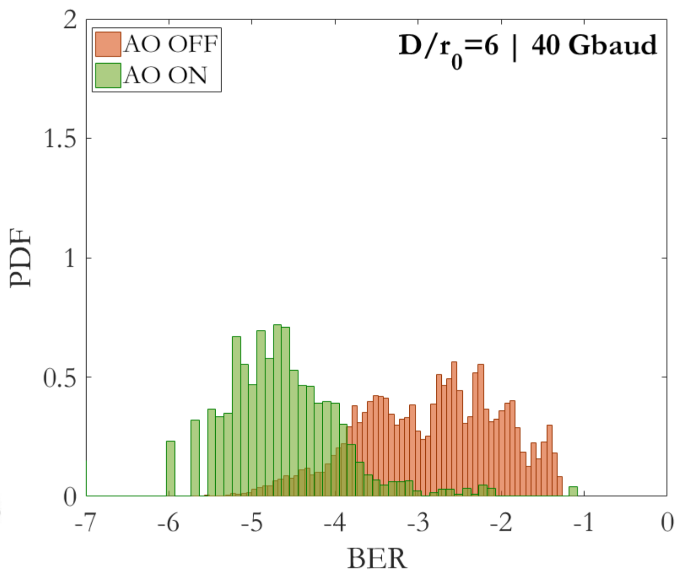

Fig.2- PDF of the BER before and after AO correction.

Experiment is performed over 200 uncorrelated fields.

On each field: 50 data sequences of 10^6 $bits$ (PRBS7) are sent, received, demodulated, and stored.

With AO correction, the coupled signal and BER improves beyond 10^{-3}.

This assures error-free transmission if coding is applied

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- The speckle pattern can be used to accelerate an iterative correction, reducing by 40% the AO bandwidth requirements. The method is non-stochastic, well-defined, and tracktable.

- Signal gain of 4.5 dB obtained for scenario $D/r_0 = 6$, using only 58 iterations

- This AO method can correct wave-front distortions in week to strong turbulences, allowing 80 Gbps coherent data transmission.

- BER better than 10^{-3} are obtained with the AO, allowing FEC error-free performance

- The method shows robustness facing signal noise, low received, and it allows dynamic management of the loop bandwidth

Publications & Patent

[1] C. E. Carrizo, R. Mata Calvo, and A. Belmonte, “Intensity-based adaptive optics with sequential optimization for laser communications,” Opt. Express, 2018

[2] C. E. Carrizo, R. Mata Calvo, and A. Belmonte, “Proof of concept for adaptive sequential optimization of free-space communication receivers,” App. Optics, 2019

[3] C. E. Carrizo, R. Mata Calvo, and A. Belmonte, “Method for determining altering parameters for altering the optical features of an optical element for compensation of distortions in a beam for optical free-space communications (EU patent - EP3493430)

[4] Janis Surof, Juraj Poliak, and Ramon Mata Calvo, "Demonstration of intradyne BPSK optical free-space transmission in representative atmospheric turbulence conditions for geostationary uplink channel," Opt. Letters, (2017)

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