Laser Beam Engineering & Atmospheric Turbulence Effects Mitigation with Fiber Array Systems: Overview

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Communications and Observations through Atmospheric Turbulence (COAT)

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Outline

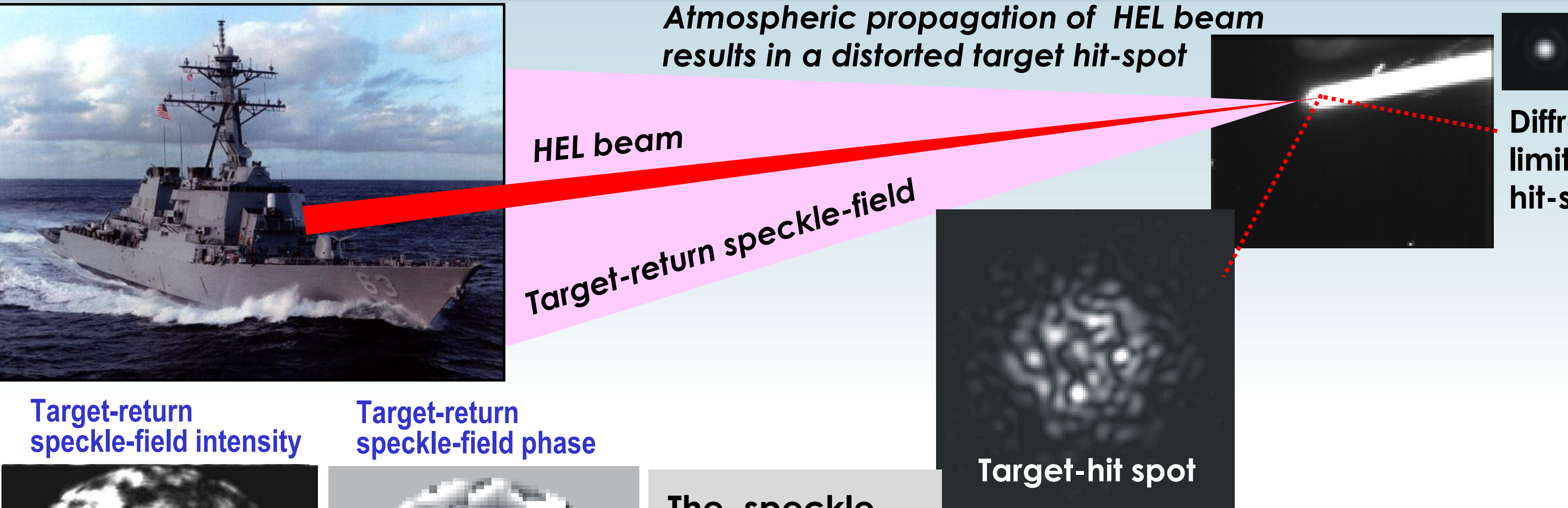
- Introduction into coherent fiber array technology
- Low- and high-power adaptive fiber array systems
- Double-pass time delay challenge: delayed-feedback SPGD control algorithm
- Target-in-the-loop turbulence effects mitigation with a coherent fiber array system (“cooperative” target)
- Coherent beam combining at an extended, non-cooperative target in atmosphere
- Engineering of laser beam with controllable coherence using fiber array systems
- Remote laser power beaming with adaptive beam shaping
- Concluding Remarks

A visionary chart “War in Air” (1908)

Krasnoyarsk Museum

Siberia, Russia

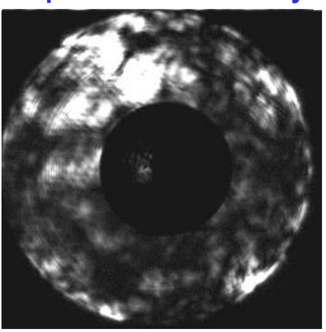
Limitations of Conventional Adaptive Optics (AO) Techniques



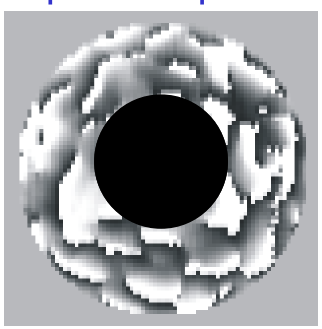
GOAL

Diffraction-limited target hit-spot

Target-return speckle-field intensity



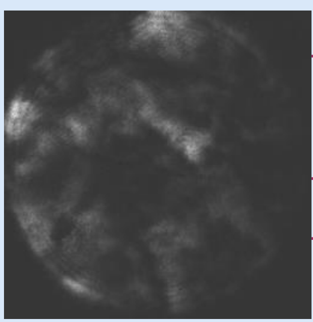
Target-return speckle-field phase



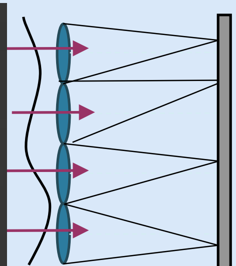
The speckle-field phase is a superposition of target-and turbulence-induced phase components.

For adaptive optics beam control the turbulence-induced phase component should be separated from the speckle-field phase. *How?*

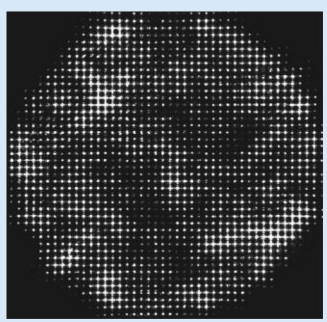
Wavefront sensing challenges in strong scintillations



Pupil plane intensity



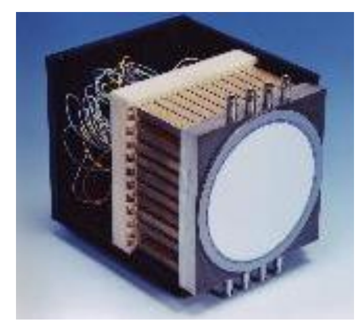
Shack-Hartmann wavefront sensor



Focal plane intensity

Wavefront control challenges in strong scintillations

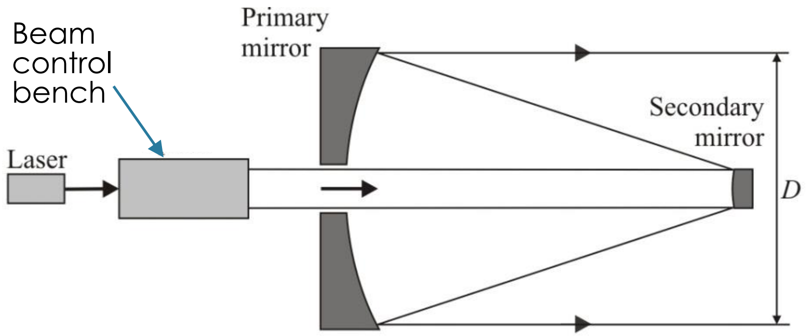
Wavefront phase



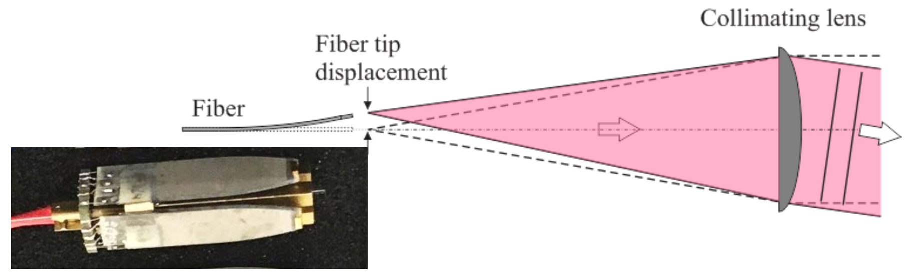
How to compensate this phase aberration with faceplate DM?

Conventional vs Coherent Fiber Array Based AO Laser Transmitter Systems

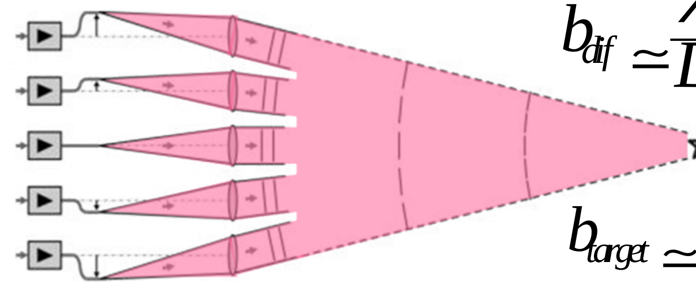
Conventional beam director



Precision beam pointing with fiber tip positioner



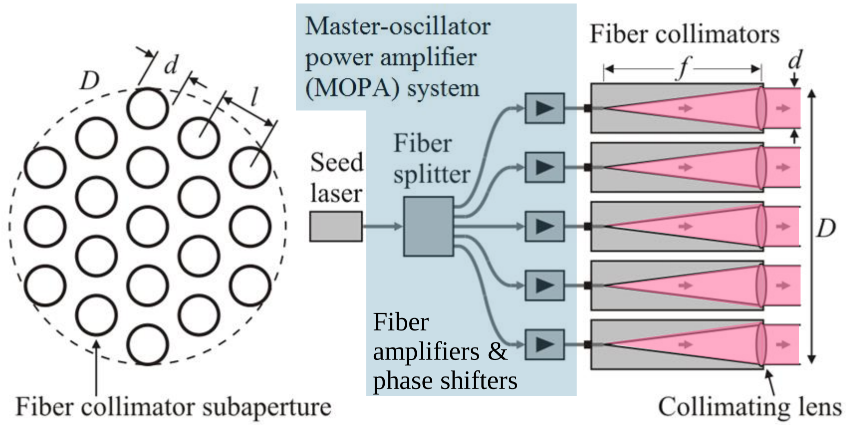
Electronic beam focusing and retargeting in fiber array beam director



$$b_{dif} \simeq \frac{\lambda}{D} L$$

$$b_{target} \simeq b_{dif} \frac{D}{r_0}$$

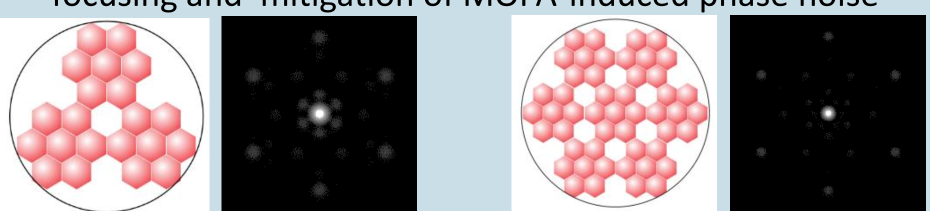
Fiber-collimator array based beam director



Fiber-collimator array can be phased either locally (at transmitter plane) or at the target (target-plane phasing) using adaptive control of piston phases with phase shifters.

Disadvantages of coherent fiber array systems

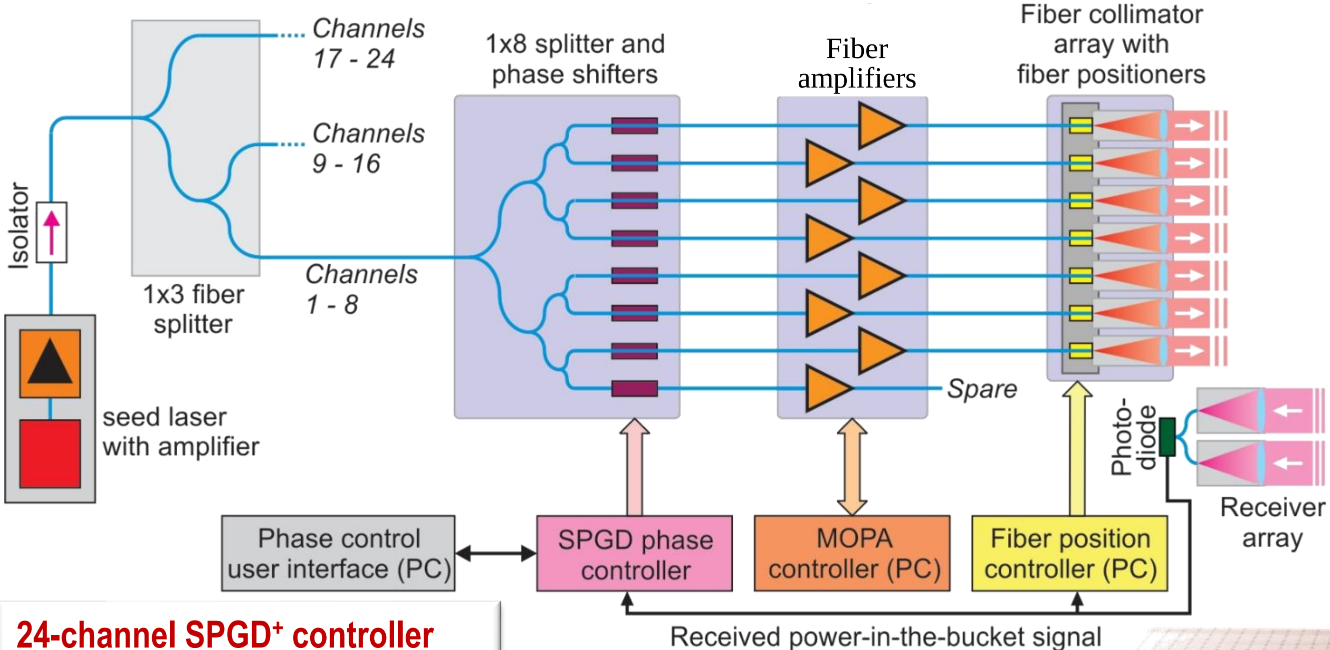
- Energy losses in side lobes
- Need for individual beams pointing, combined beam focusing and mitigation of MOPA-induced phase noise



Fiber-integrated phase shifters of the MOPA system allow extremely fast control (< 10^{-9} s time response) of piston phase at each fiber-array sub-aperture. The piston phase control is used for transmitted beams phasing.

Coherent Fiber Array Laser Transceiver Architecture: Example of Low-Power System Implementation

Fiber-array based laser transmitter: architecture & major modules



Key advantages:

- Scalability
- Compactness
- High quality beam
- No beam train
- Extremely fast AO
- Electronic beam focusing
- High wall-plug efficiency (>40%)

24-channel SPGD+ controller with integrated phase shifters

- 500 kHz iteration rate
- Accounts for propagation delay time
- Adaptive gain and perturbation amplitude

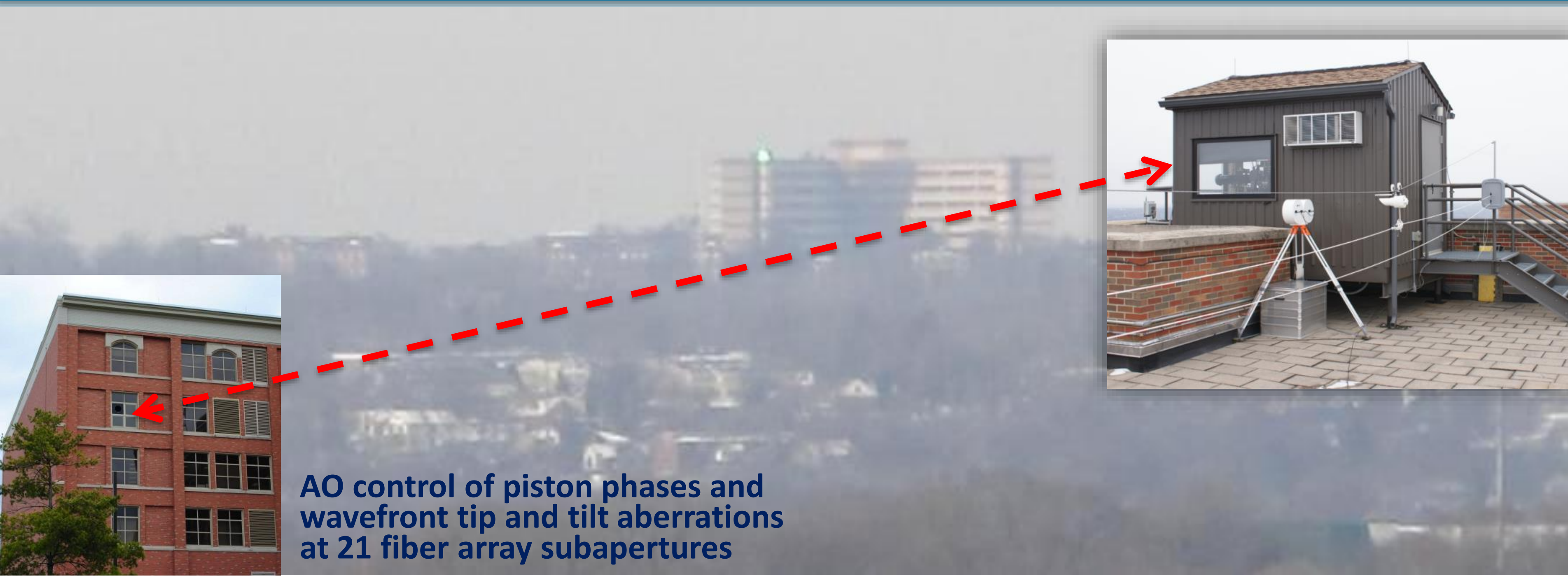
24-channel fiber system with fiber-amplifiers

- 0.25 W per channel
- Output power control

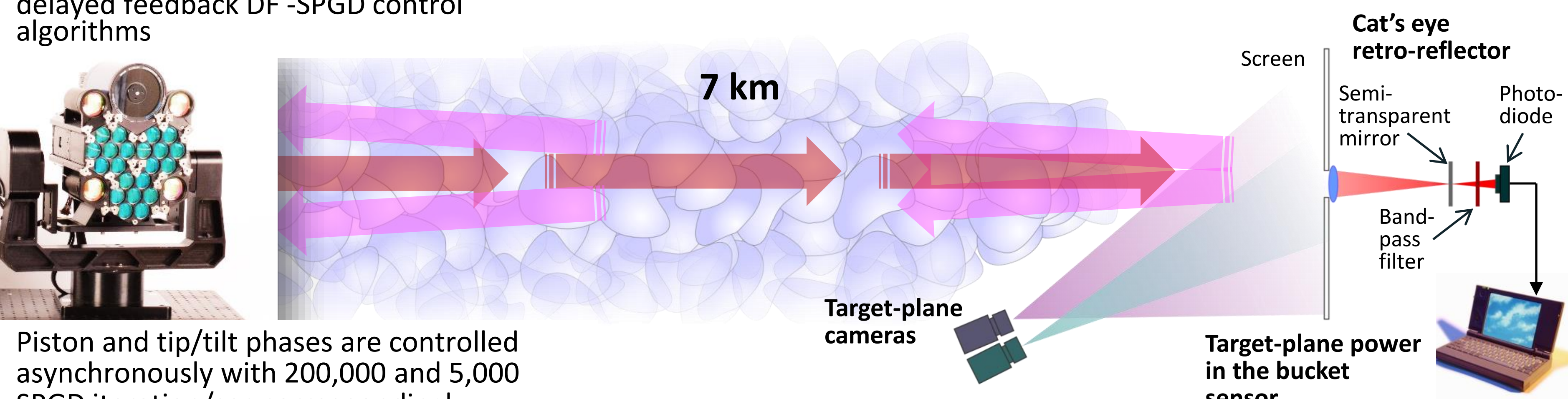
Key advantages:

- Transmitted beams coherence control for speckle mitigation in active imaging
- Fast star-mode beam steering
- Integration of target tracking and aim-pointing capability

Fiber Array Based AO: Coherent Beam Combining at Unresolved, Stationary Retro-Target over 7 km with DF-SPGD Control



Experiments were performed with delayed feedback DF -SPGD control algorithms

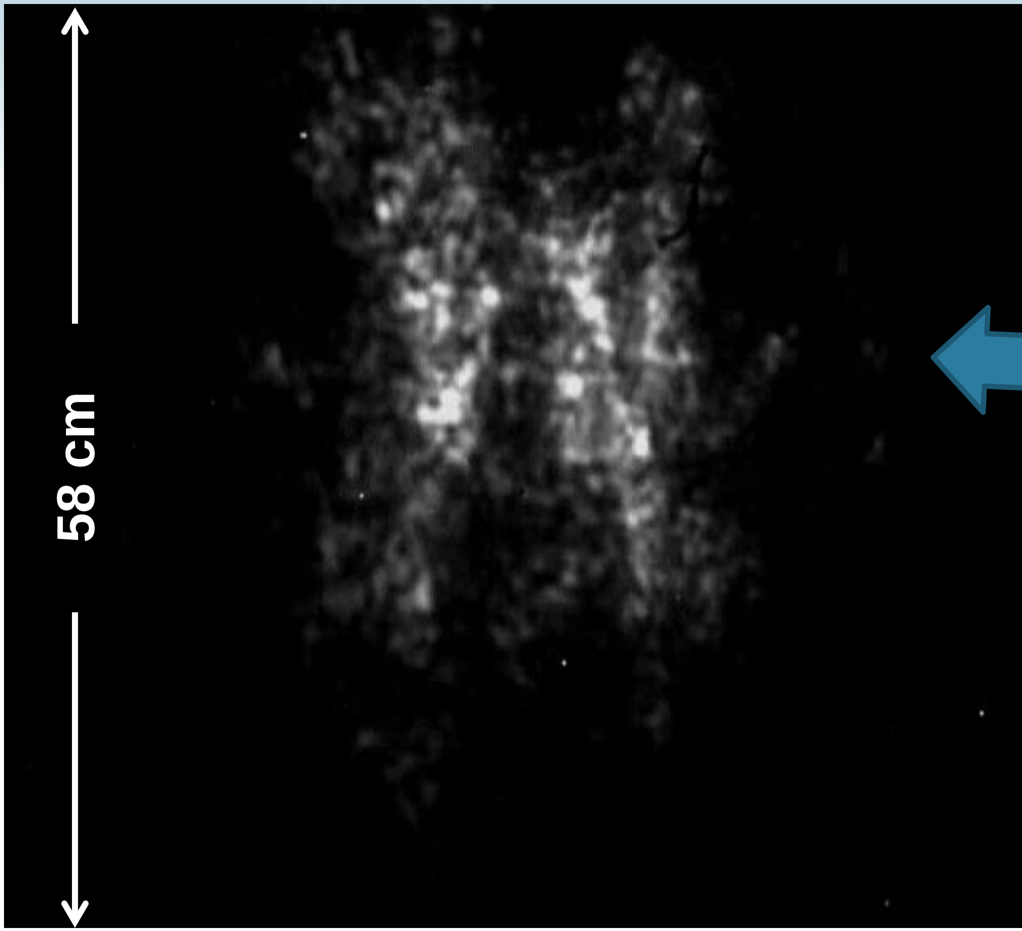


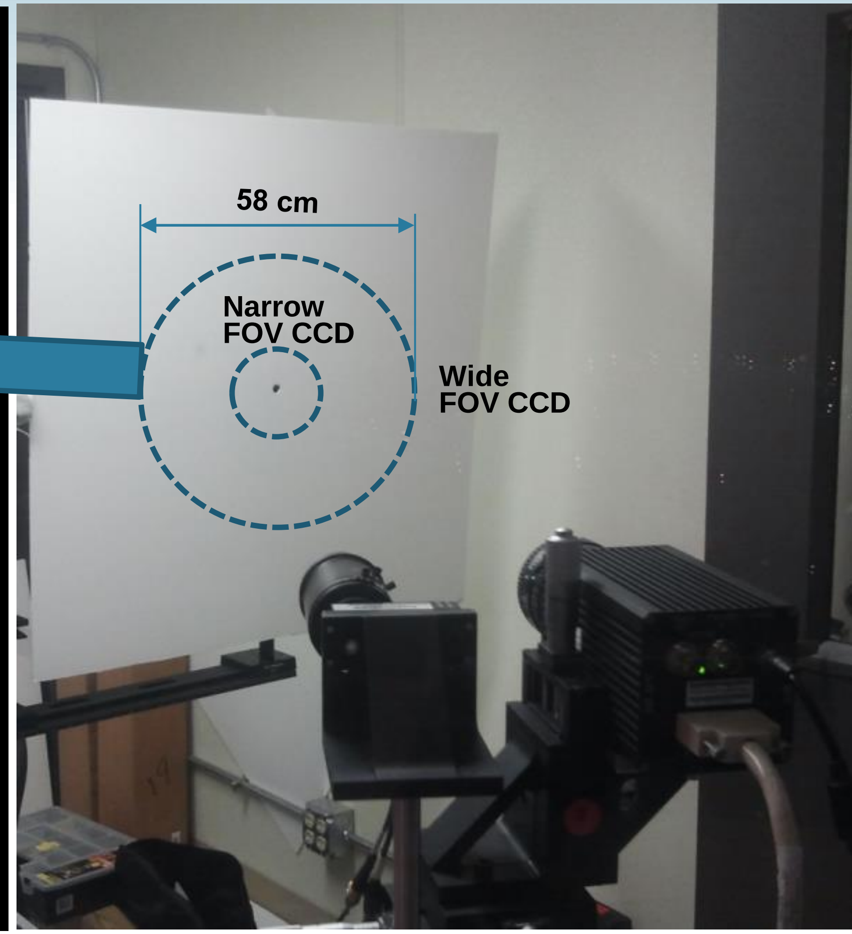
Piston and tip/tilt phases are controlled asynchronously with 200,000 and 5,000 SPGD iteration/sec correspondingly.

Fiber Array Based AO: Coherent Beam Combining at Unresolved, Stationary Retro-Target over 7 km

Atmospheric conditions: $\langle C_n^2 \rangle = 1.6 \times 10^{-15}\ \mathrm{m}^{-2/3}$ **Rytov number** $\langle \sigma_R^2 \rangle = 0.4$

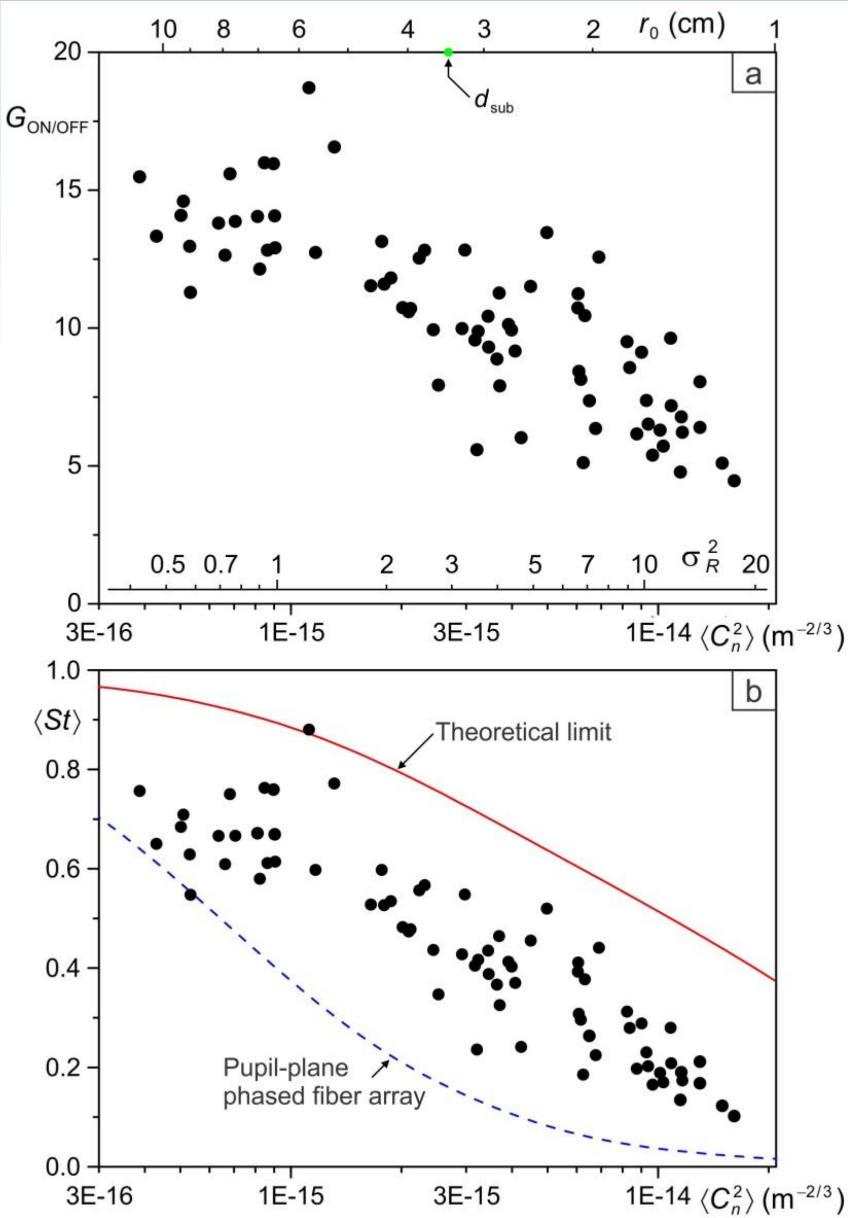
Rytov number (log-amplitude variance for plane wave) $\sigma_R^2 = 0.307 k^{7/6} L^{11/6} C_n^2$



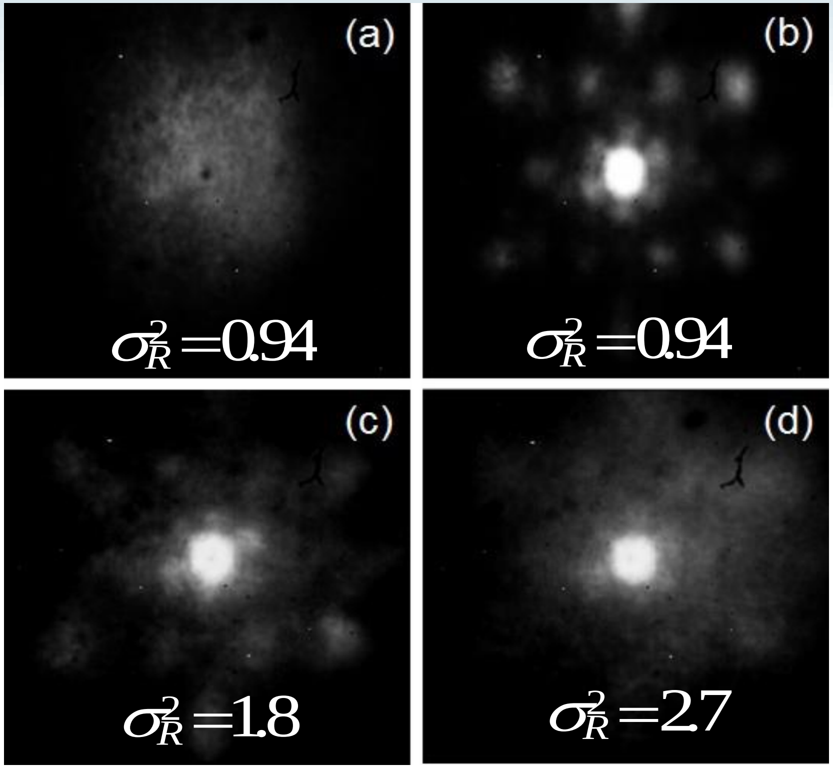


21-channel SPGD phase-locking controller OFF and ON (tip/tilt controller is OFF)

Turbulence Effects Mitigation via Coherent Combining of 21 Beams (7 km)



Experimental results (dots) for the gain factor Gin (a) and the Strehl ratio St (b) obtained during a number of target-in-the-loop phase locking trial over 7 km, under different atmospheric turbulence conditions with the fiber-array system composed of 21 subapertures

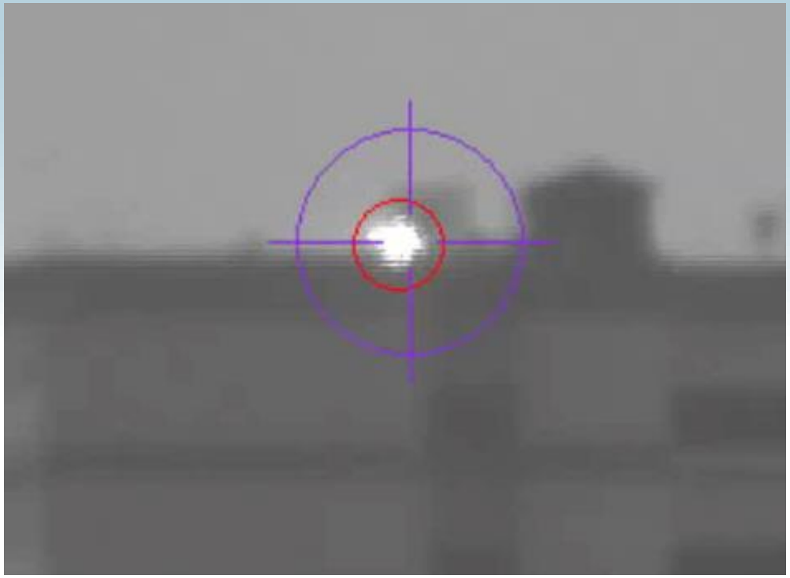


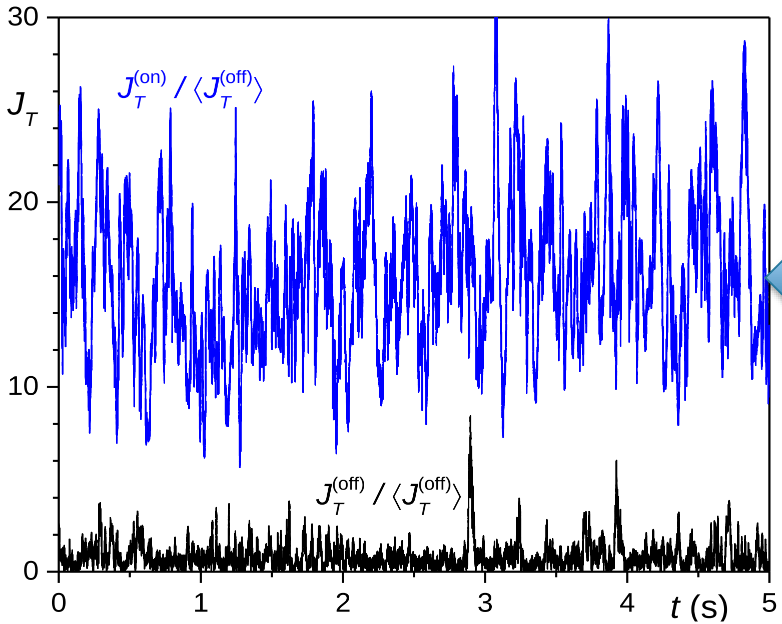
Atmospheric-averaged irradiance distributions on the target-plane screen (58 × 58 cm^2 area) as seen by the target-plane camera with the SPGD phase control off (a) and on (b, c, d)

T. Weyrauch, M.A.Vorontsov, et al *Optics Letters*, Vol. 41, No. 4, 840-843 (2016).

Fiber Array Based AO: Coherent Beam Combining at Unresolved, Moving Retro-Target over 7 km

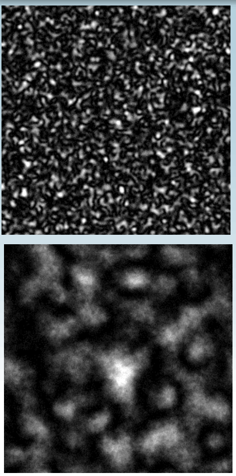
Coherent beam combining at a moving target

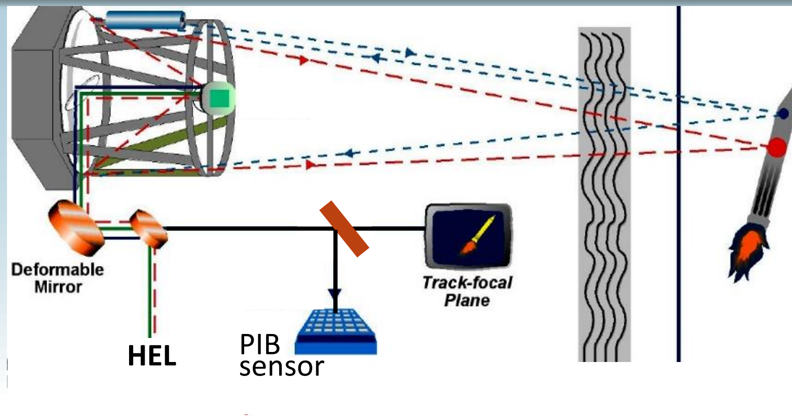


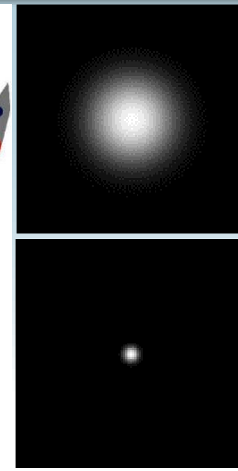


First five seconds of the target plane power-in-the-bucket (PIB) signals without and with TIL SPGD control of beamlets' piston phases. Both signals are normalized to the average of the control-off state.

Coherent Beam Combining at Extended ("Speckle") Fast Spinning Target: Speckle Metric Beam Control Basics







Time-varying component of the power-in-the-bucket (PIB) signal:

$$\delta J_{PIB}(t) \equiv J_{PIB}(t) - \langle J_{PIB}(t) \rangle = \int P(\mathbf{r})\,\delta I(\mathbf{r},t)\,d^2\mathbf{r}$$

$I(\mathbf{r},t)$ - backscattered field intensity at the receiver aperture

Temporal correlation function of the PIB signal time varying component:

$$\Gamma_{PIB}(\tau) \equiv \langle \delta J_{PIB}(t)\,\delta J_{PIB}(t+\tau) \rangle_{sp} = \int P(\mathbf{r}_1)P(\mathbf{r}_2)\,\Gamma_{\delta I}(\mathbf{r}_1,\mathbf{r}_2,\tau)\,d^2\mathbf{r}_1\,d^2\mathbf{r}_2$$

It can be shown [1] that for moving target with flat randomly rough surface

$$\Gamma_{PIB}(\tau) = C\int I_T(\mathbf{r})\,I_T(\mathbf{r}+\mathbf{v}_S\tau)\,d^2\mathbf{r}$$

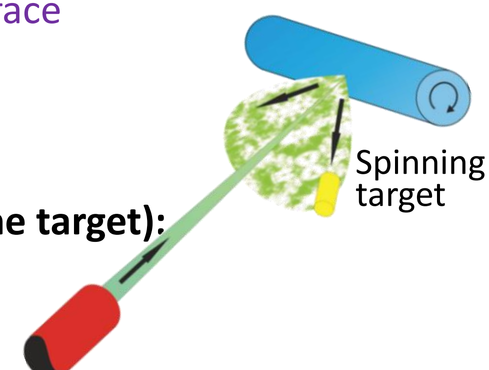
target surface transversal speed

intensity at the target surface

Variance for PIB signal fluctuations:

$$\sigma^2_{PIB} = \Gamma_{PIB}(0) = \langle \delta J^2_{PIB} \rangle_{sp} = c\int I^2_T(\mathbf{r})\,d^2\mathbf{r} = cJ_2$$

Speckle metric



PIB signal fluctuation power spectrum (for Gaussian beam of width b_s on the target):

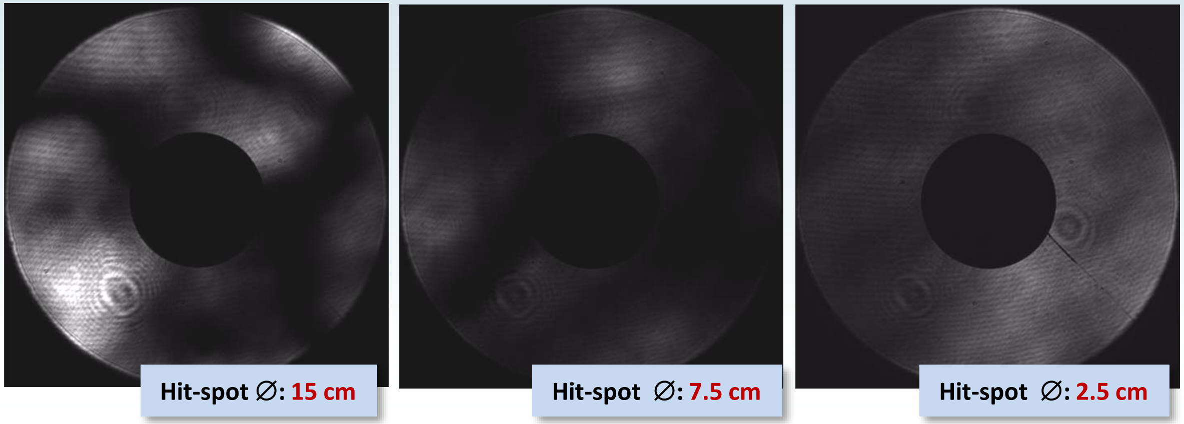
$$G_{PIB}(\omega) = G_{PIB}(0)\exp\left[-\frac{\omega^2}{\omega^2_{PIB}}\right], \quad \omega_{PIB} = v_S/b_S$$

PIB signal spectrum width depends on target plane beam width b_s

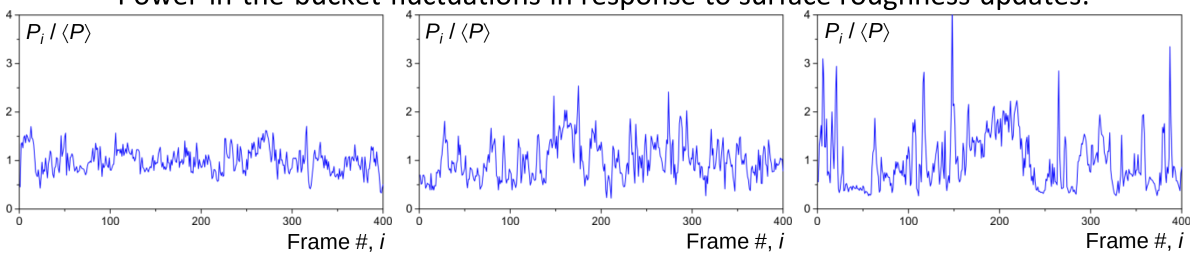
[1] M.A. Vorontsov, "Speckle effects in target-in-the-loop laser beam projection systems," Adv. Opt. Techn. **2**(5-6), 369–395, (2013)

Beam Projection on Extended Target with Coherent Fiber Array: Speckle Metric-based Phase Control

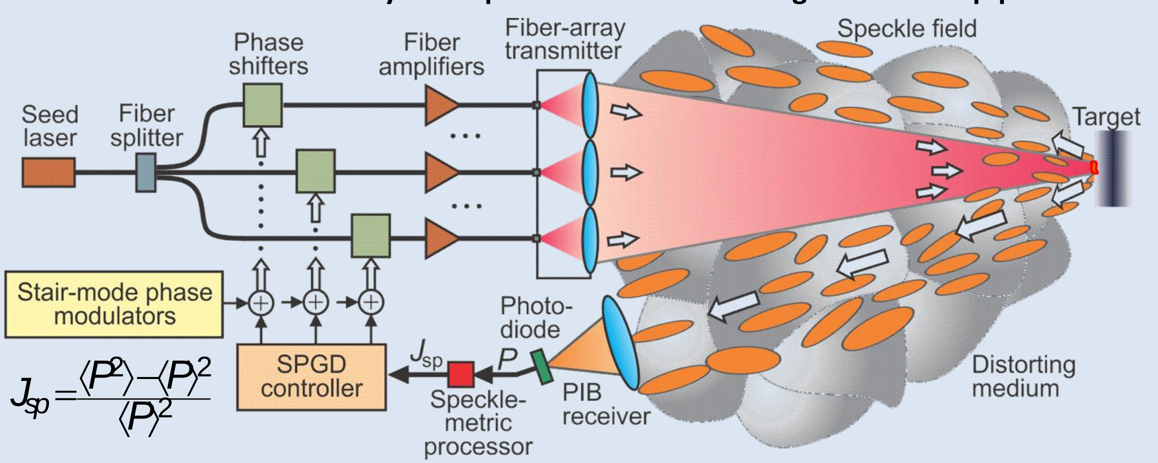
Speckle field in receiver telescope during surface roughness updates at target



Power-in-the-bucket fluctuations in response to surface roughness updates:

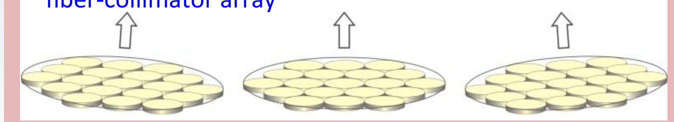


Notional schematic of fiber array with speckle-metric based target-in-the-loop phase locking

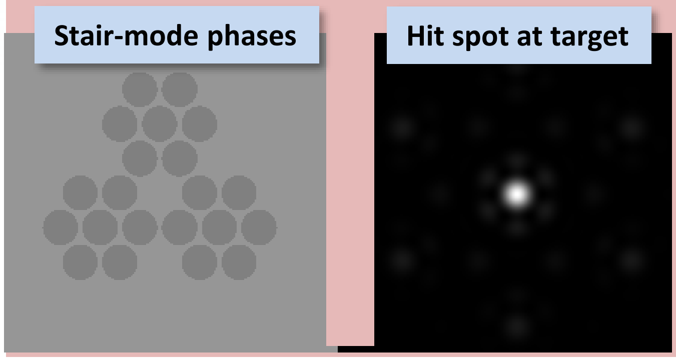


Stair-mode hit-spot position dithering in coherent fiber arrays

Example: Generation of global tilts through local piston phase control of the beamlets in a hexagonal 19-channel fiber-collimator array



Stair-mode dithering with Optonicus 3-cluster fiber array:



- Stair-mode dithering in fiber arrays can be performed at RF frequencies (up to GHz)
- Speckle metric, e.g., variance of power-in-the bucket signal, can be integrated over short time scales (~µsec) to enable fast SPGD control

Combined metrics

$$J_{\Sigma} = J_{sp} + \gamma < J_{PIB} >$$

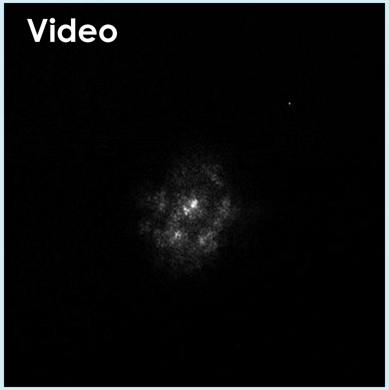
Speckle metric　　PIB metric

M. Vorontsov, et al, Opt. Let, V. 37, N. 14, (2012)

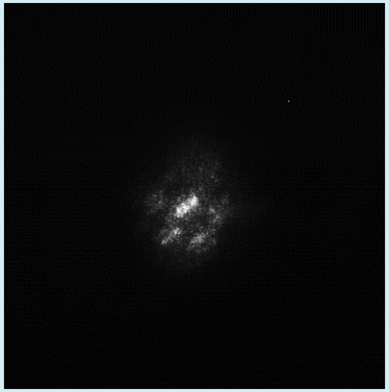
“Litmus-test” of AO Technology: Laser Beam Projection onto Flat Metallic Surface in Atmosphere

SPGD ON: speckle metric maximization (target CCD)

Short-exposure video sequence

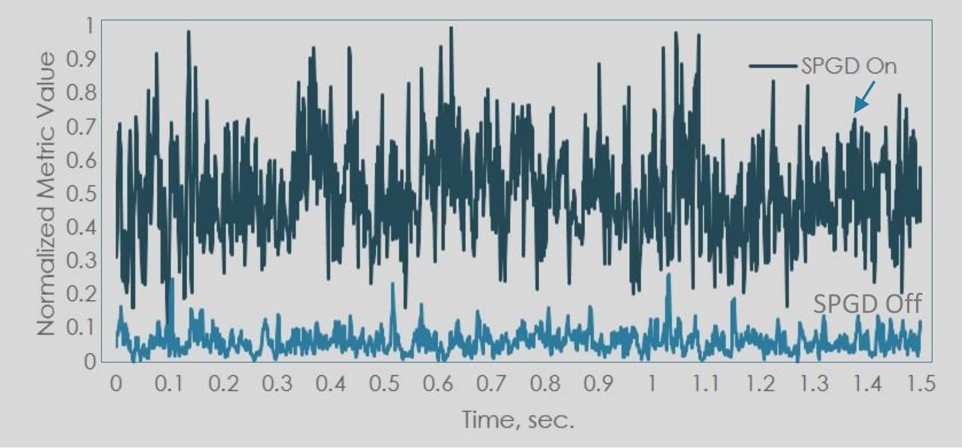


Long-exposure (averaged) frame



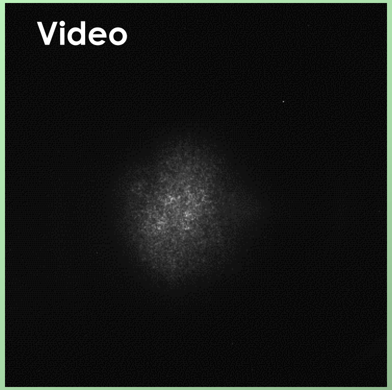
The most “unfriendly” HEL DE target (flat 12x12 inch still-plate)

Speckle metric time-evolution with SPGD control ON and OFF

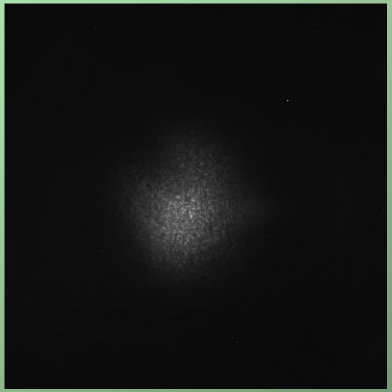


Incoherent combining: (target CCD)

Short-exposure video sequence

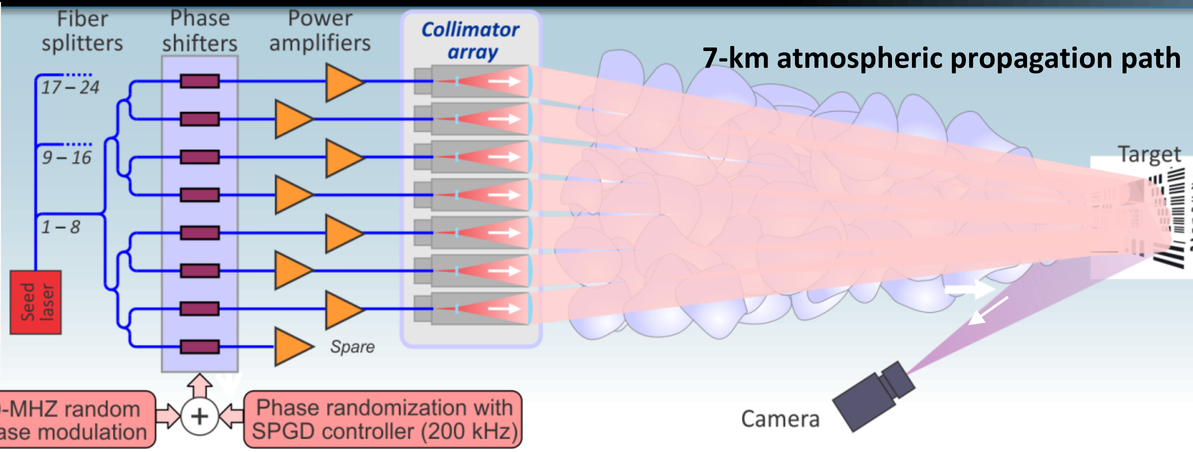


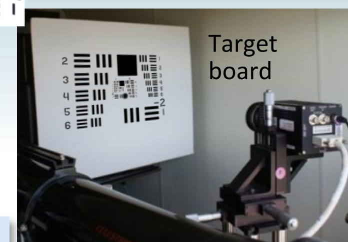
Long-exposure (averaged) frame



Fiber-Array Based Speckle-Free Laser Illuminator for Active Imaging

Fiber array-based laser illuminator

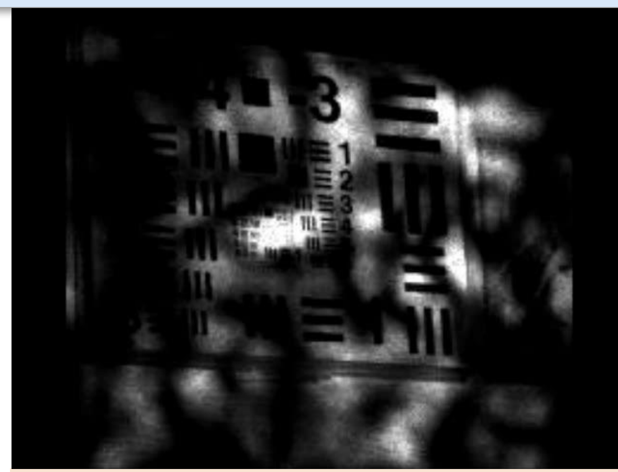




Side-by-side comparison of target image quality with a conventional laser illuminator using a Cassegrain telescope and the fiber-array with 21-subapertures

$$C_n^2 = 1.8 \times 10^{-15}\ \mathrm{m}^{-2/3}$$

Short-exposure image obtained with target illumination by conventional (Cassegrain telescope) beam director



Short-exposure image obtained with target illumination by fiber array-based beam director (incoherent combining)

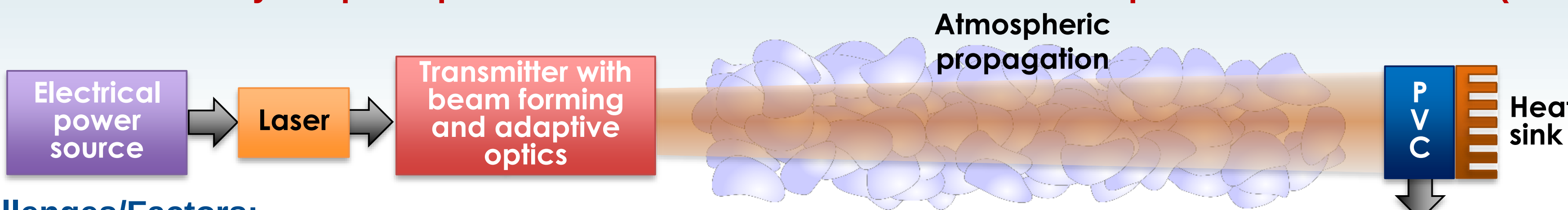
Short-exposure image obtained with target illumination by fiber array using randomized piston phases

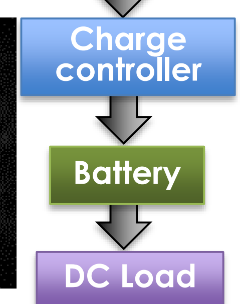
Applications: Active imaging (space-objects identification), directed energy (speckle-free wavefront sensing)

Optical Power Beaming Through the Atmosphere: Objectives & Challenges

Objectives:

- Efficient power transfer from an electrical power source to a remote electrical load using laser beams
- Example: enabling continuous enduring flight of an electrically powered UAV
- Requirements: Low losses in power conversion and delivery
- **Focus: Efficiency of optical power transfer from the laser source to the photovoltaic converter (PVC)**

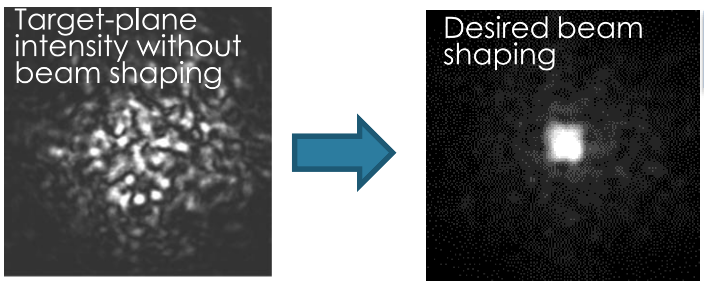


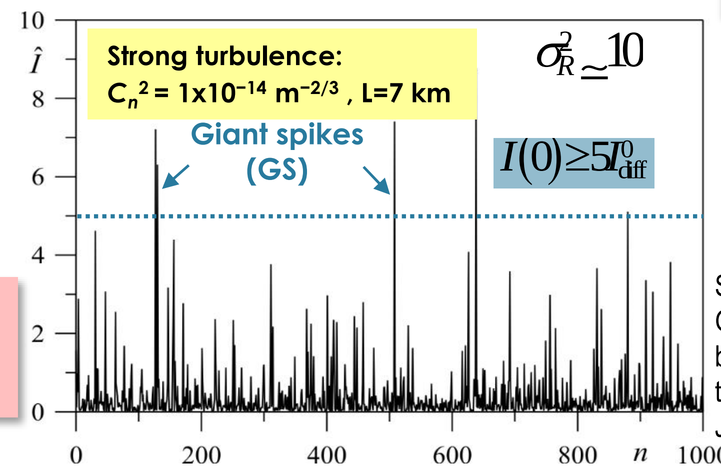


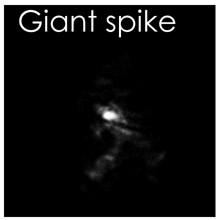
Challenges/Factors:

- **Power losses from a non-optimal match between photovoltaic cell and the projected laser beam footprint due to tracking errors, turbulence-induced beam wander and widening**
- **Atmospheric absorption**
- **Spatial inhomogeneity of the intensity distribution at the photovoltaic (PV) receiver cell**
- **Turbulence-induced large amplitude (giant) laser beam intensity spikes that can damage PV cells**

A need for adaptive wavefront phase shaping leading to maximization of both the overall laser power inside the PV cell assembly and its spatial uniformity.



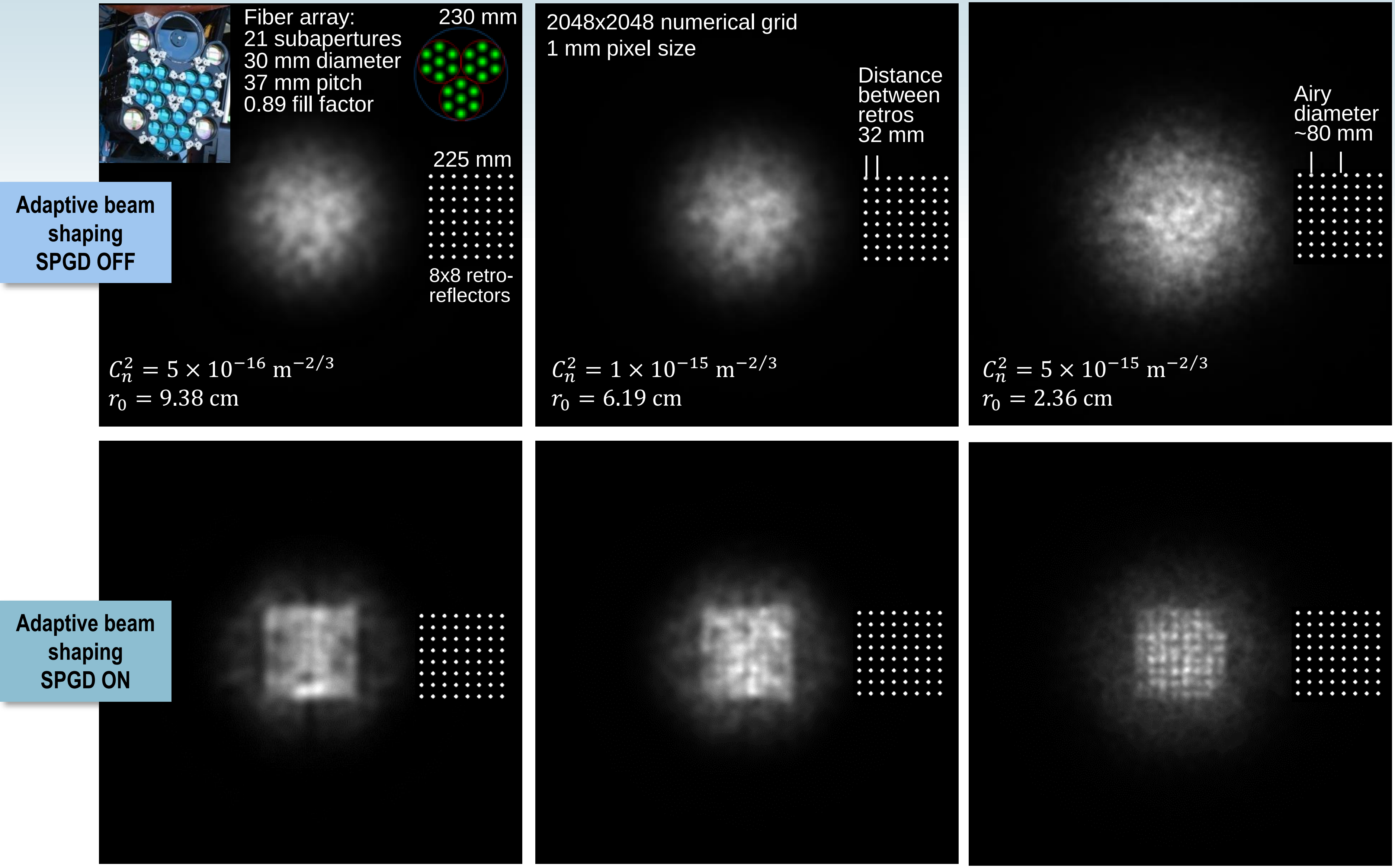




S. Lachinova and M. Vorontsov
Giant irradiance spikes in laser beam propagation in volume turbulence: analysis and impact
J. Opt., V. 18, 2, 025608 (2016)

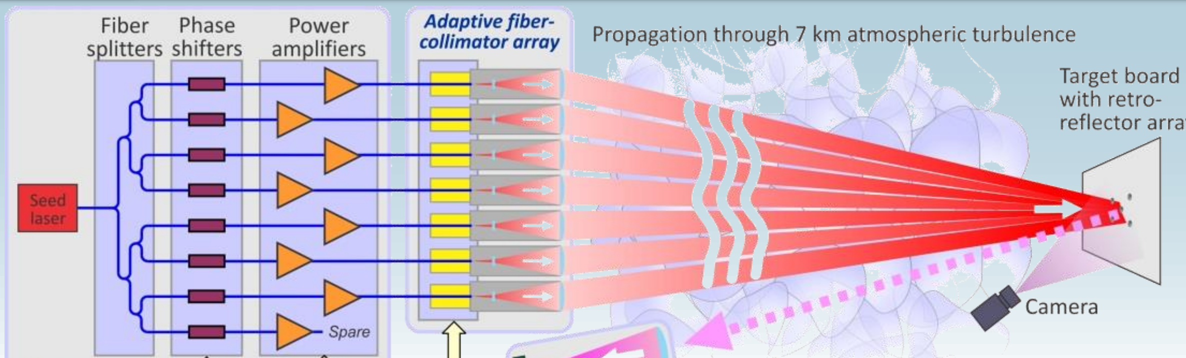
Power Beaming with Adaptive Beam Shaping: Numerical Simulation Results

Laser beam footprint at PVC array over 7 km with feedback control OFF and ON: horizontal propagation path

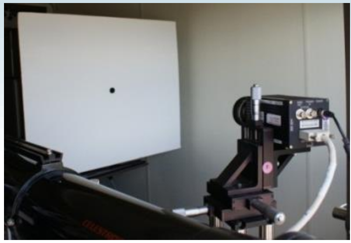


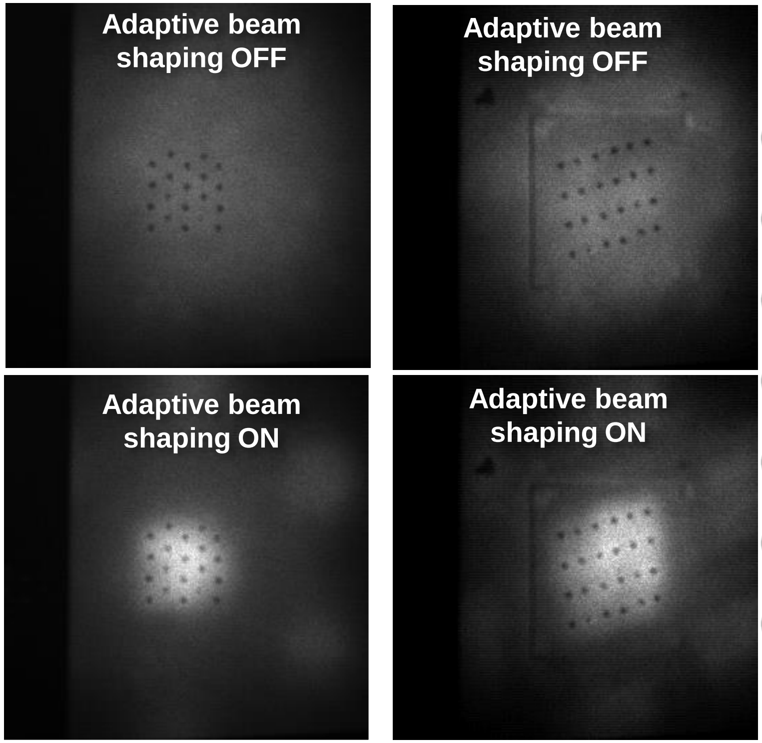
Power Beaming over 7 km with Adaptive Beam Shaping with Optical Feedback: Proof-of-Concept Experiments

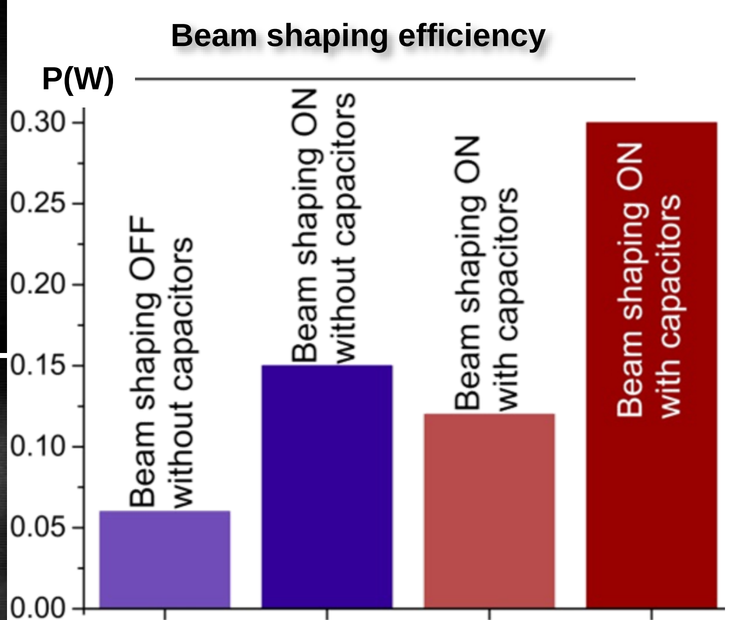
Fiber array-based laser illuminator used in the experiments (21x0.2W)



Maximizing PIB signal received from retroreflectors shapes beam at the PVC/retro-reflector array







Integration of capacitors to each PV cell allows partial mitigation of turbulence-induced scintillations

Custom laser power converter assembly (Spectra Lab) optimized for λ = 1064 nm

Summary

Coherent fiber-array-based laser beam directors offer unique opportunities for:

- Engineering of a variety of laser beams with controllable spatio-temporal distributions of phase and polarization;
- Dynamic control of laser beam coherence in time and across the beam aperture (beams with space-varying coherence);
- Mitigation of speckle effects for beacon illuminator laser (BIL) systems used for wavefront sensing and for speckle-free imaging with target illuminator laser (TIL) systems;
- Mitigation of intensity scintillations and adaptive beam shaping for optical power beaming applications
- Adaptive compensation of turbulence and aero-optics effects