Correction of atmospheric turbulent effects with a double fast steering mirror system for fast free-space quantum communications

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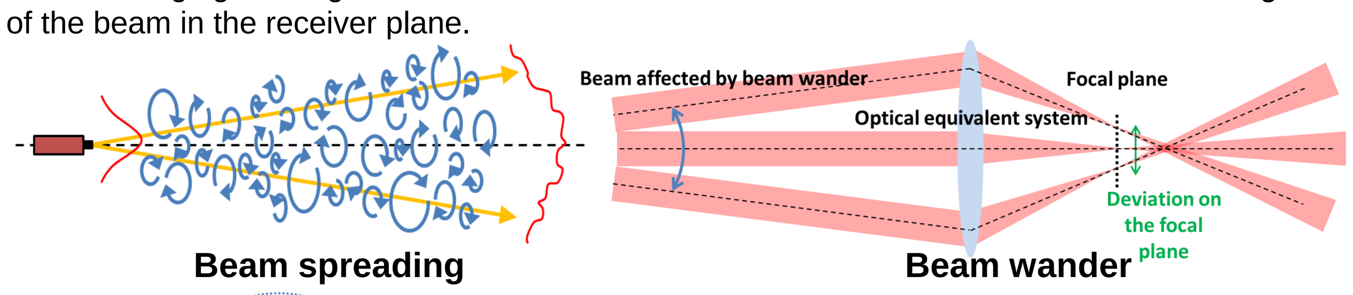
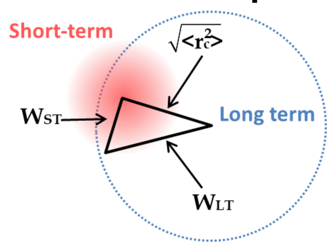
MOTIVATION

Free-space quantum communication systems require beam stabilization techniques to compensate for the effects of atmospheric turbulence, such as **beam wander**, which provokes random fluctuations of the beam centroid at the receiver, inducing optical losses of the quantum signal. These fluctuations are due to wavefront distortions or aberrations of the first order (*tip and tilt*) which can be corrected with fast actuators and position sensitive detectors. In moderate to high turbulent regimes (C_n^2 of 10^{-13}) correction on the receiver is sufficient to compensate turbulent effects in propagation distances of typically less than 1 km before active pre-compensation of the emitter is also necessary. The simplest configuration consist of a fast steering mirror in a PID loop to minimize the error caused by deviations measured on a position sensitive detector. However, this setup can only correct for deviations in the beam in a single spatial plane. A double mirror correcting system stabilizes the beam in the whole optical axis making its implementation ideal for a quantum receiver.

ATMOSPHERIC TURBULENCE EFFECTS

Refractive index fluctuations due to movements of air masses from therman gradients cause different effects on a beam, such as **beam spreading** and **beam wander**. The first is caused by small eddies compared to the beam diameter and originates an enlargement of the beam beyond that caused by natural diffraction. Larger eddies cause deflections of the beam, changing the angle of arrival at the receiver, which translates into a random 'dancing' of the beam in the receiver plane.



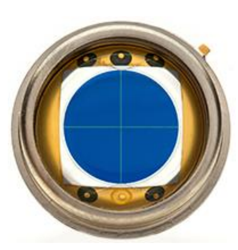


- **Beam spreading** causes the **short-term diameter**
- **Beam wander** causes the **long-term diameter**
- $\sqrt{\langle r_c^2 \rangle}$ **is the standard deviation of the beam displacements at the receiver**

CORRECTING WITH FSMS AND PSD

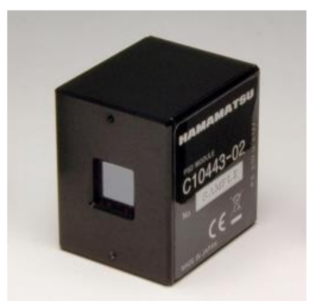
FAST STEERING MIRROR (FSM)

- Push-pull coils
- Maximum angular displacement of ±1,5º
- Resolution < 2 µrad
- Internal PSD to monitor position
- Measured bandwidth ~500 Hz



QUADRANT Position Sensitive Detector (QD-PSD)

- Segmented or quadrant detectors
- Blind area or gap
- Better resolution and accuracy than lateral effect detectors
- Resolution NON dependent on SNR
- Response dependent on light spot profile



Lateral-Effect Position Sensitive Detector (LE-PSD) DETECTOR

- Non-segmented lateral-effect detectors
- Wider dynamic range (No gap)
- Independent on light spot profile
- Resolution dependent on SNR

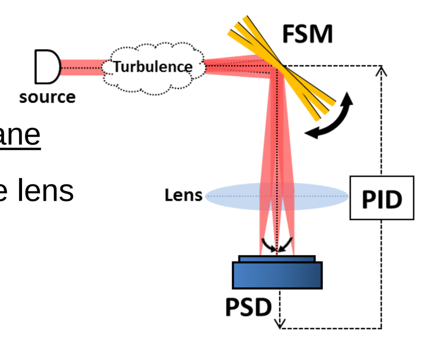
ONE-MIRROR CORRECTING STRATEGY

Simplests correcting system is a feedback PID loop between a single fast sterring mirror (FSM), an a position sensitive detector (PSD). The loop minimizes the deviations caused by turbulence from a predetermined aligned position on the PSD.

Limitations:

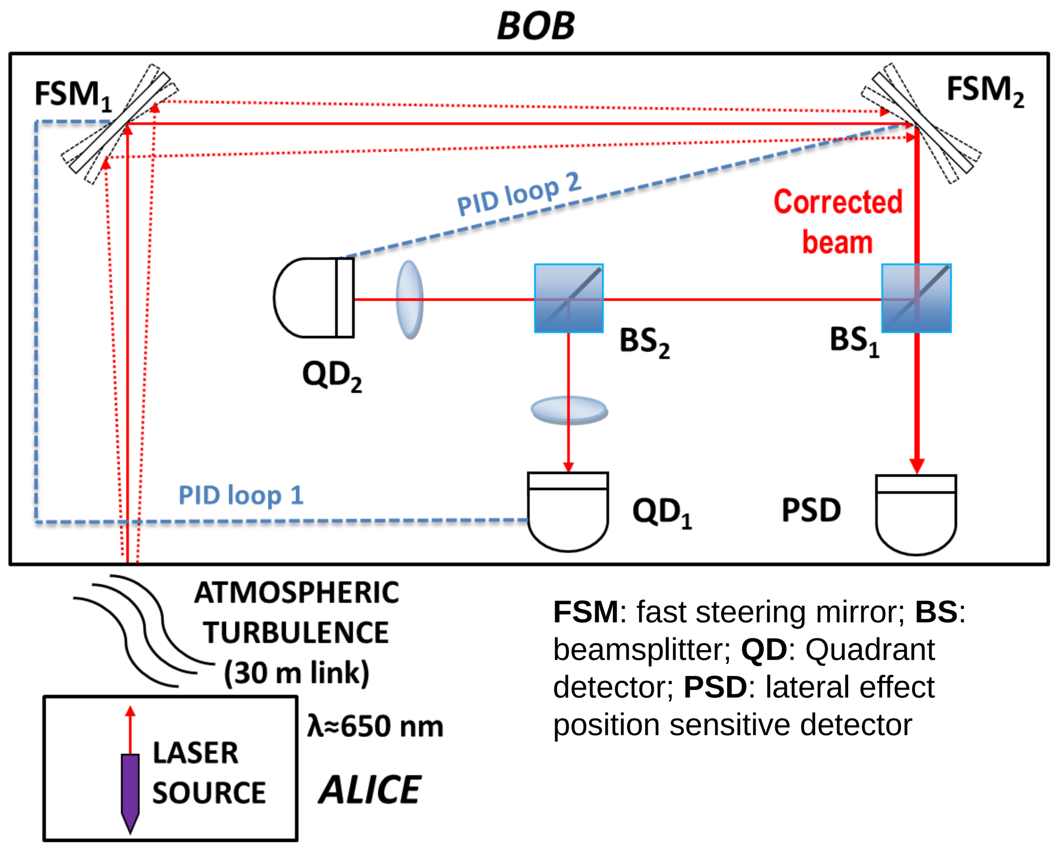
- Beam only stabilized in a spatial point of a single plane
- Corrected beam does not pass through center of the lens

(causes enlarged beams due to spherical aberration)

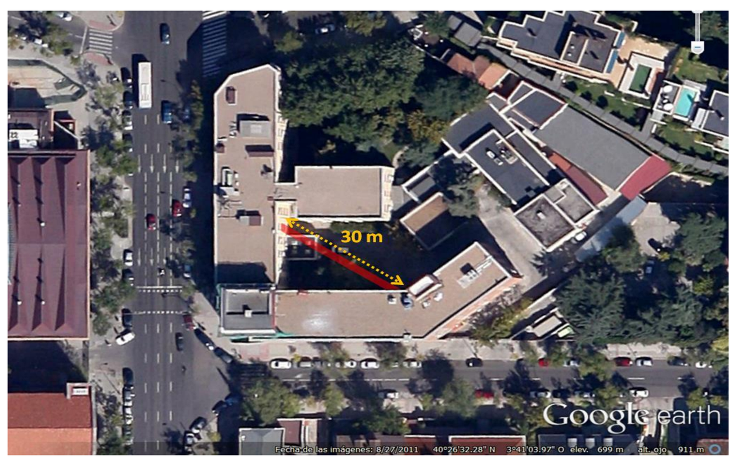


DOUBLE-MIRROR CORRECTING SYSTEM

- Fixing an optical beam spatially **in two points** allows stabilization along a **whole optical axis** (*corrected beam* in diagram).
- The correcting system in Bob has two Fast Steering Mirrors (FSMs) connected to two position sensitive detectors (quadrants).
- Each mirror fixes the beam in **one spatial point.**
- FSM_1 is PID *looped* with QD_1 and FSM_2 with QD_2.



FSM: fast steering mirror; **BS**: beamsplitter; **QD**: Quadrant detector; **PSD**: lateral effect position sensitive detector



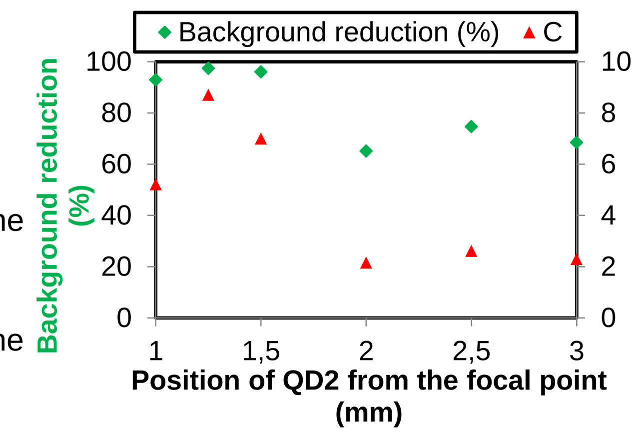
- The **corrected beam** is analysed by a lateral effect PSD

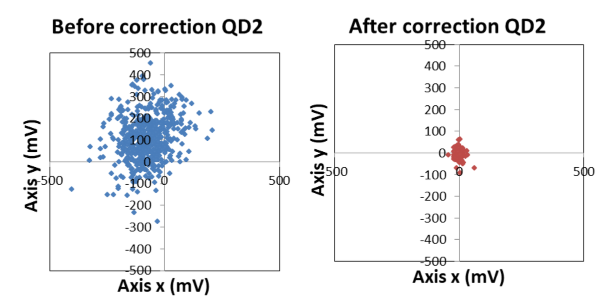
CALIBRATION OF THE SYSTEM

Setting up the positions of QD_1 and QD_2

- **Position of QD_1:** image plane of FSM_2.
- **Position of QD_2:** the closest to the focus of the lens.

This allows to increase the distance between the two fixed points to the maximum





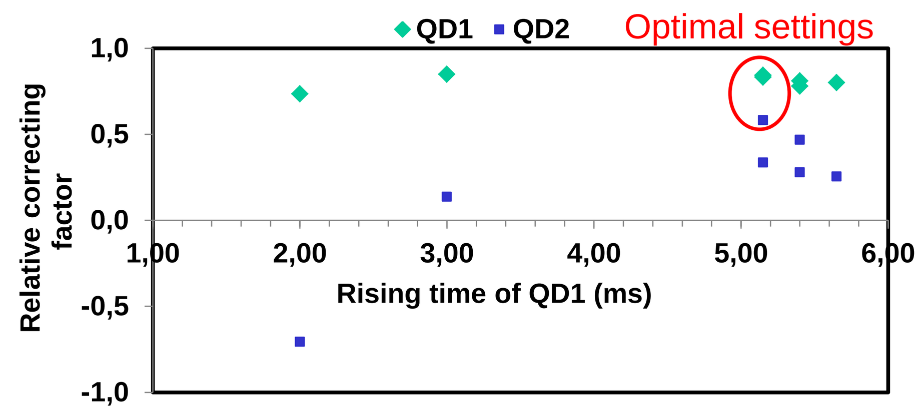
$$\text{Correcting factor} = C = \frac{\sqrt{\langle r_c^2 \rangle_{before\ correction}}}{\sqrt{\langle r_c^2 \rangle_{after\ correction}}}$$

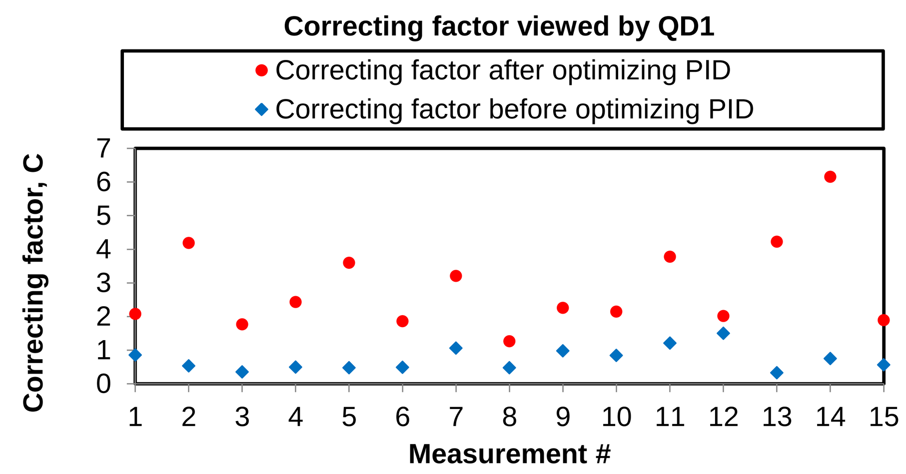
$$QBER\ reduction \propto \frac{Area\ (after\ correction)}{Area\ (before\ correction)}$$

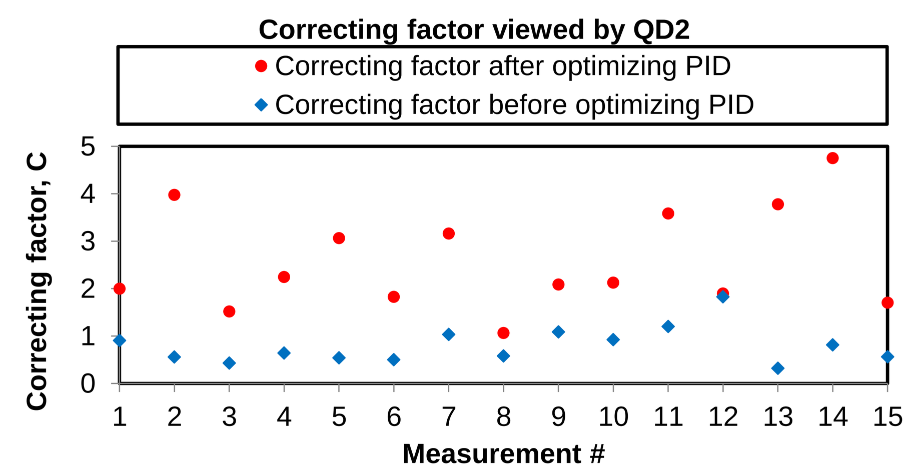
$$\text{Relative correcting factor} = 1 - \frac{1}{C}$$

Setting up the values of PID_1 and PID_2

- **Rising times slow** to reject high frequency turbulent effects due to scintillation.
- **FSM_2 faster than FSM_1:** to enable a more efficient correction.

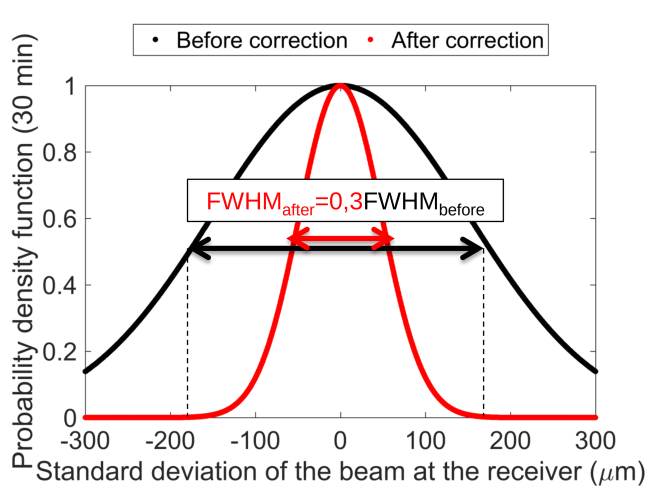


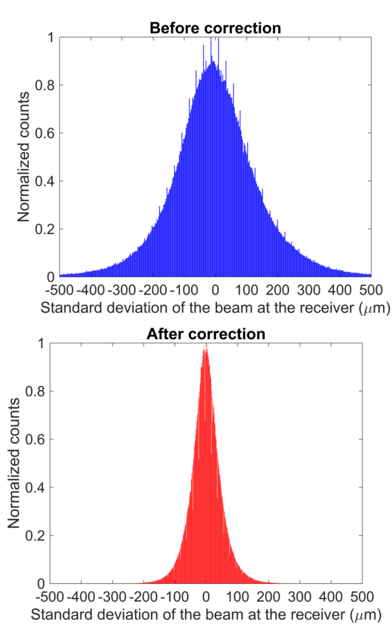




EXPERIMENTAL RESULTS

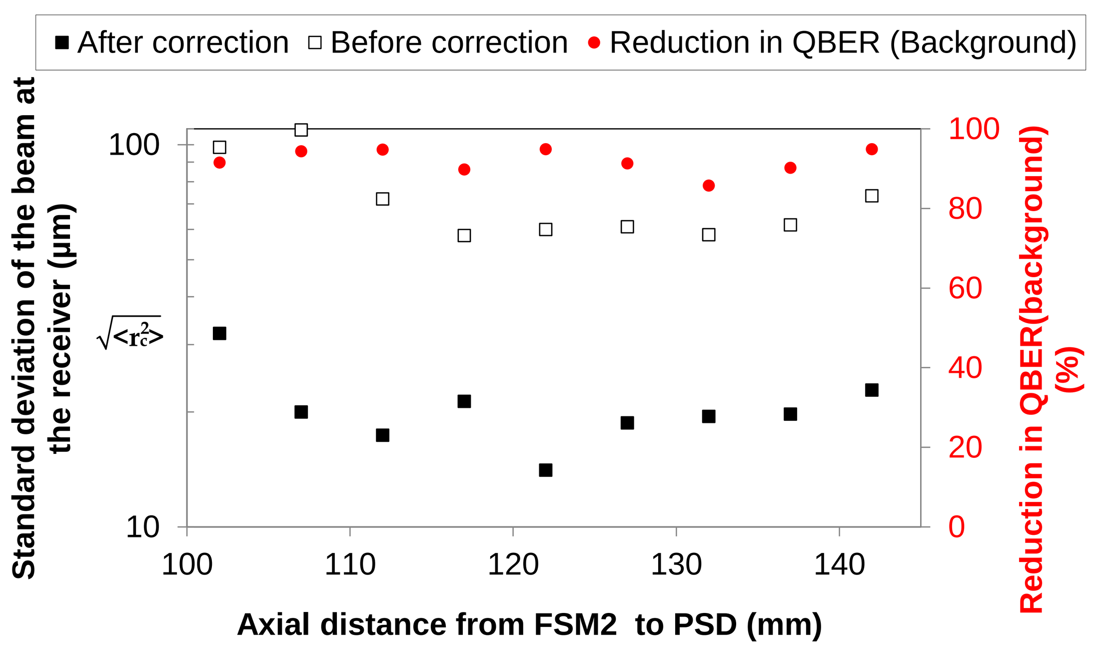
Probability density function of the correction



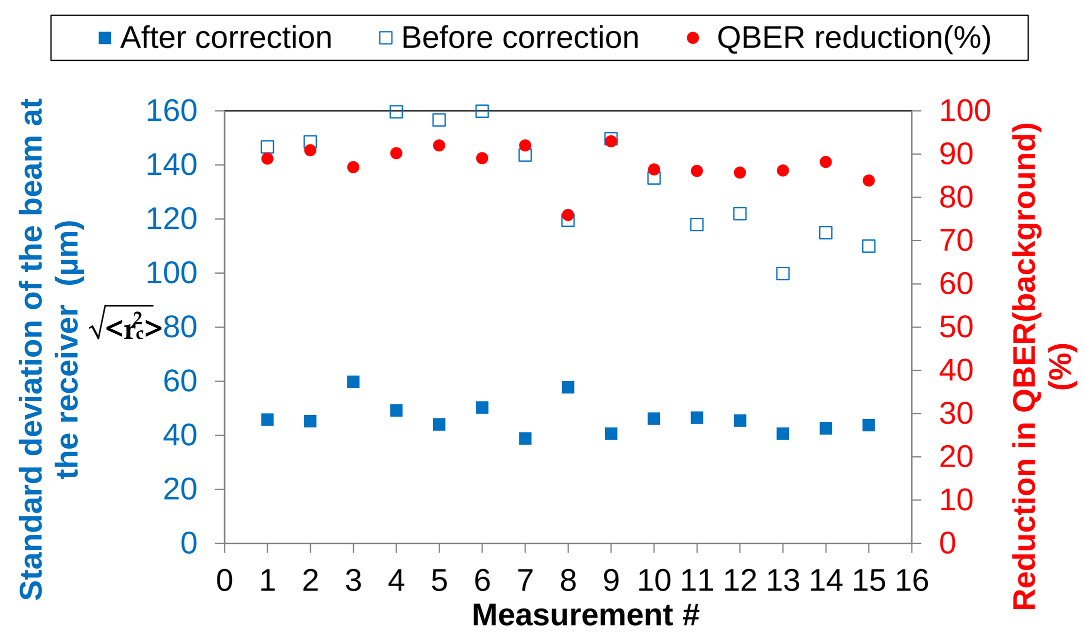


Histograms taken over 30 min (2x10⁶ points).

Correction along the optical axis of the receiver



Stability of the correction



Measurements taken over 30 min.

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