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Long-distance free-space quantum key distribution in daylight towards inter-satellite communication

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SMF coupling

Compared with previous attempts, we used the least amount of optics to design the receiving telescope and to reduce most optical abbreviation. A $420\ mm$ diameter off-axis parabolic mirror with $2\ m$ focal length is used as the primary mirror of receiving telescope, perfectly matched the numerical aperture of a single mode fiber (0.11 for most widely used SMF). Furthermore, a better focus effect could be expected with a parabolic mirror due to no chromatic aberration and spherical aberration. Meanwhile, the coma owing to optical axis deviation could be reduced to the least with a fine calibration.

To make single-mode coupling efficiently, Higher tracking bandwidth and smaller angle error is demanded to reduce the effects from atmosphere and environmental vibration. With our updated tracking technique, the feedback frequency and tracking error for our fine tracking system are about $300\ Hz$ and less than $3\ \mu rad$, respectively as shown in Fig. 1a and Fig. 1b. Meanwhile, Fig. 1c and Fig. 1d show the X-Y distribution of the centroid position of 671 nm beacon light photo taken by the CMOS camera with and without fine tracking, respectively.

Besides tracking in the X-Y plane (parallel to the focal plane), an electric controlled translation stage is used to make the coupling fibre in the best place at the Z axis (perpendicular to the focal plane). We also have a strong light at $1570\ nm$ emitting from the transmitter used for optical power remote scanning. Fig. 2 shows the the coupled telecomband light power distribution with different light spot over the CMOS camera. The peak coupled power with

$250\mu m$ shift at z axis was less than half of that at zero shift location. Because of thermal expansion and contraction effect, the location of the focal plane is found linearly depends on the temperature of the receiver, which can be easily compensated using the temperature data.

In our test, the beam spot's width at focal plane is usually several times larger than ideal case, very depending on the atmosphere. For this case, we cannot make the SMF coupling efficiency much higher, and utilizing the adaptive optics maybe a solution for this conundrum. However, considering current technique, the closed-loop frequency of usual adaptive optical system is not high enough to improve our coupling efficiency for long distance optical link steadily. Luckily, on account of no turbulence will be appear in space with vacuum, an adaptive optical module may help for such a measurement during a satellite-ground link or a satellite-satellite link.

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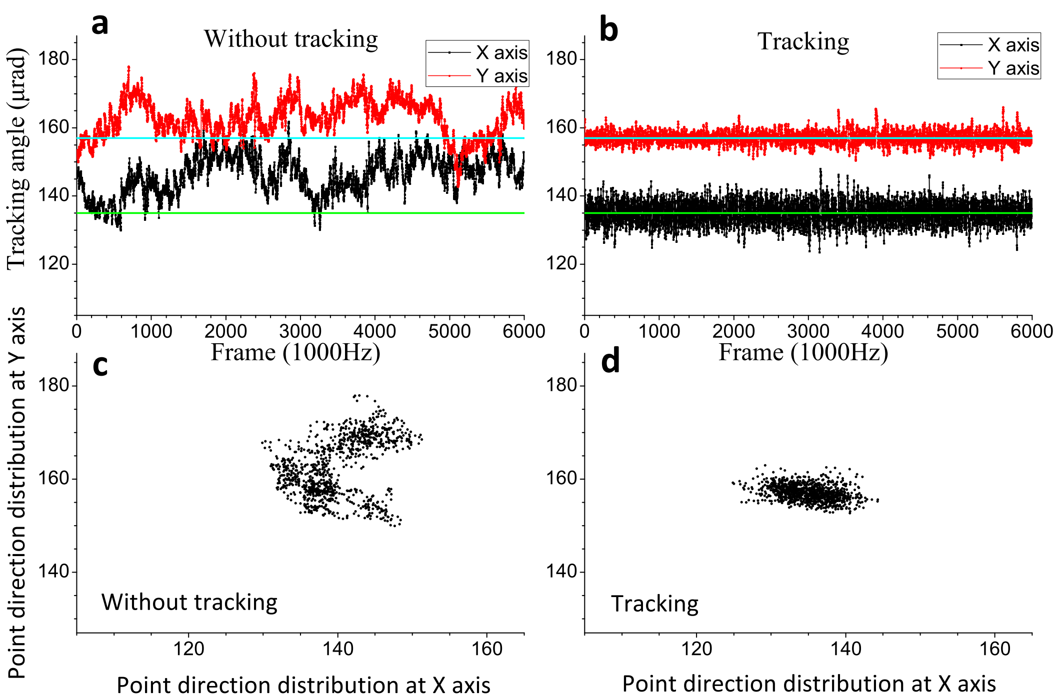

Figure 1: **Comparison for angle of arrival error with or without tracking during 6 seconds at transmitter. a (b)**, Targeted angle for X and Y axis (green and blue line) and tracking angle of arrival for X and Y axis (black and red points) without (with) fine tracking. **c (d)**, Distribution for the angle of arrival without (with) fine tracking during 1 second. Certain deviation exists between the angle of arrival and targeted angle without fine tracking. With a longer statistical time, the distribution was more dispersed for c (without tracking).

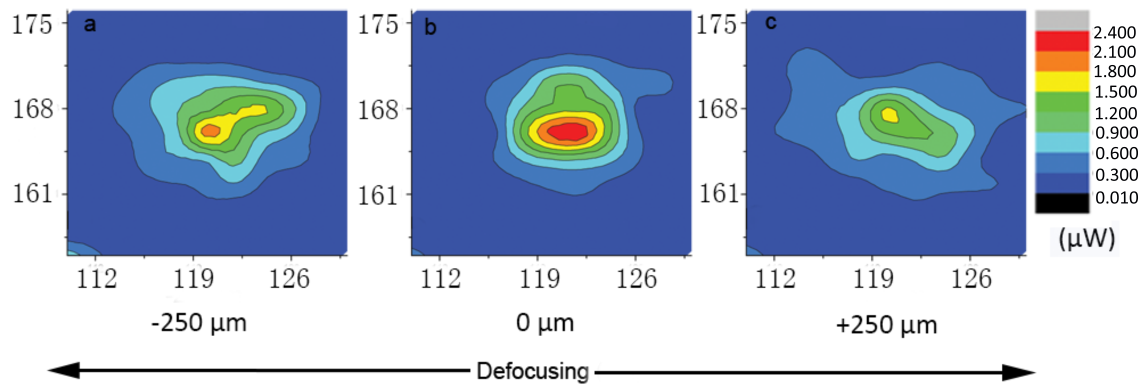

Figure 2: **Energy distribution contours at different planes near the focus plane of the receiver's collection system.** These energy distribution contours for arrival light are acquired with a power meter during scanning procedure of our tracking software. The size of a pixel is $5.5\ \mu m\ \times\ 5.5\mu m$. **a**, Energy distribution contour $500\mu m$ before the focus plane. **b**, Energy distribution contour at the focus plane. **c**, Energy distribution contour $500\mu m$ after the focus plane.