Adaptive Optics for Satellite Laser Communications

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Abstract: The development of laser communication technology between satellites and ground stations has been paid attention recently. On the other hand, the laser communication between satellites and ground stations is always affected by the atmospheric condition. We can compensate this effect by applying the technology of Adaptive Optics that is used for astronomical observation.

We started the development of Adaptive Optics for laser communication in NICT from 2019 and completed the manufacture of Adaptive Optics for Koganei 1-m telescope in 2021 fiscal year. We performed the initial inspection of the performance of this system in March 2022. Although it was just simulation using artificial light source in our inspection, we can confirm the performance of AO of Koganei 1-m telescope is enough to improve the fiber coupling efficiency. In this paper, we describe the detail of Adaptive Optics for laser communication in NICT.

1. Introduction

The development of laser communication technology between satellites and ground stations has been attracted attention not only for high-speed, large-capacity data transmission and reception, but also as for a method of the cryptographic key delivery. On the other hand, the atmosphere exists between the satellite and the ground, and the laser communication beam is always affected by it. If it were cloudy condition, the beam must be blocked, and communication could not be established. And, if it were fine condition, the beam should be affected by loss due to scattering and the wave front of the beam should be disturbed by atmospheric turbulence.

To avoid the presence of clouds, for example, it is possible to increase the number of ground stations and select a ground station located in a place with good weather to establish communication. the transportable ground station can also help to increase the possibility of communication.

In fine condition, even if the scattering loss is unavoidable, is available to correct the effect of atmospheric turbulence. We can apply the technology of Adaptive Optics (AO) that is used for astronomical observation to improve the spatial resolution by correcting the wave front of the light received by the telescope.

The efficiency and stability of the fiber coupling with the received communication beam will also be improved by the technology of the AO. We describe the research and development of the AO systems for laser communications in NICT in this paper.

2. The Effect of Atmospheric Turbulences

Since the atmosphere has inhomogeneous density, the beam coming from space has a phase difference at each point of the wave front. It causes the direction shift at each point of the wavefront. As a result, at the focal point, the photon that is collected by telescope is spatially scattered. Therefore, the time integrated image of the point source should be spatially spread, and the diffraction limit of the telescope could be not achieved.

In the case of the communication, photons are not integrated in time, this effect appears in the form of an unstable fiber coupling efficiency. Unless this effect is corrected, a stable communication environment cannot be constructed although the photons collected by the telescope is enough to establish the communication.

3. The Concept of Adaptive Optics

It is difficult to correct the influence of the atmospheric fluctuation by a static optical system. The atmospheric fluctuation has a speed of about kHz order fluctuation, and how to dynamically correct the influence is a problem to be resolved. [1] The AO system for dynamically correcting a wavefront by close loop system is one of techniques for resolving this problem. The AO system has been successfully developed and implemented in astronomy to drawing out the original performance of a large-aperture telescope [2] and is still provided as an essential device in a large-aperture telescope.

Figure 1 shows the concept of the AO system. First, the phase deviation at each point of the wavefront is measured by a wavefront sensor (WFS) for evaluating the disturbed wavefront. From the measurement result, a mirror called a deformable mirror (DM) is deformed and the disturbed wavefront is reflected to adjust the wavefront. By close loop controlling this process according to the speed at which the wavefront changes, it becomes possible to approach the ideal wavefront in real time.

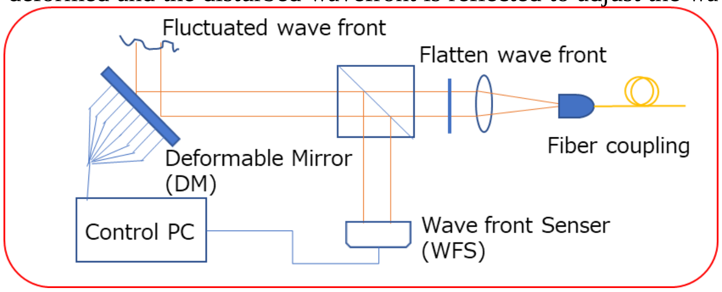

Figure 1. Concept of Adaptive Optics

4. Development of Adaptive Optics for Koganei 1m telescope

Based on the above concept, we have developed AO system for communication in Koganei 1m telescopes of NICT. In the optical communication for between satellites and ground stations, since a satellite moving on a celestial sphere faster than celestial objects is an object to be connected, it is first necessary to improve the tracking performance. Therefore, in 2019, we developed a fine pointing system (FPS) for Koganei 1m telescope. To install an AO system to this FPS for correcting atmospheric fluctuation to a beam after performing the fine pointing, we started the development of AO system on optical bread board in 2020, and in 2021, we installed this AO system in the FPS. This AO system is provided with the unit capable of performing calibration using a beam in which a wavefront fluctuation has occurred by rotating phase plate. This unit could be used for checking the performance of AO in case of no light source coming from satellites or stellar objects.

The initial performance test was carried out using artificial light source in March 2022. Fig. 2 shows the result of comparing the fiber coupling efficiency when the AO system is working and when it is not working, if the beam diameter called the Fried parameter, which can be regarded as a plane wave on the wavefront affected by atmospheric fluctuation, is 3 cm, and the condition of wind velocity of 20m/s.

In this figure, the vertical axis indicates the coupling efficiency of light through the optical system to the fiber, and the horizontal axis indicates time, which is data for 0.4 second. The reason of such a short time width is to be easy to understand the effects of correcting fast fluctuations. From this result, the coupling efficiency in the case of operating the AO system is improved by about two orders of magnitude on average, and the peak of the coupling efficiency is also improved by about three times at least.

Figure 2. Variance of fiber coupling efficiency. Green line shows the case of AO working and purple line shows the case of without AO.

5. Future work

In the future, the correction performance will be verified using the light source that comes from space such as stars or planets, and the performance will be quantitatively evaluated. In addition, for communication use, not only receiving downlink, but also transmitting uplink is required for the AO system. In the case of transmission to a satellite, the transmission light must be emitted in a direction different from the reception in consideration of the fact that the satellite is moving in the orbit. We show the optics included uplink AO in figure 3. How to correct the case where the light is emitted in a direction different from the reception is a problem for uplink, and research and development are currently being progressed.

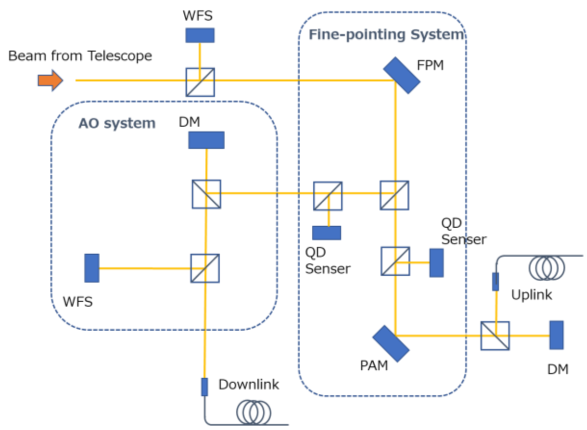

Figure 3. Design of Adaptive Optics for Koganei 1m telescope.

6. References

[1] J.W. Hardy, J.E. Lefebvre, and C.L. Koliopoulos: Real-time atmospheric compensation, Journal of the Optical Society of America, 67–3, 360/369 (1977)
[2] R. Davies and M. Kasper: Adaptive Optics for Astronomy, Annual Review of Astronomy and Astrophysics, 50, 305/351 (2012)