7 Concluding Remarks

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The National Institute of Information and Communications Technology (NICT) has worked toward the research and development of various satellite communications and broadcasting technologies since the 1970s. We have established the basis of broadband satellite communications since the beginning of satellite communications: we realized broadband communications with the 200 MHz bandwidth transponders of CS (Medium-capacity experimental communications satellites) series which led the way to worldwide communication technologies in the Ka-band. Moreover, we achieved a maximum transmission capacity of 1.2 Gbps per channel with the WINDS satellite launched in 2008. However, in recent years, there has been an increased demand for higher capacity satellite communications. For example, while Earth observation satellites with high-resolution-observation sensors have been launched recently, the communication capacity increases year by year. It has been reported that the required speed for data transmissions will need a capacity of more than 20 Gbps by the year 2015. Although the recent Ka-band-satellite communication systems such as KA-SAT and ViaSat both include a large capacity of transmission having a total capacity of 70 to 100 Gbps, they can only provide 3~4 channels if the 20 Gbps channel is used. Now, big expectations have been placed on laser communications, which enables the ultra-high capacity of satellite communications to adequately satisfy future communications requirements.

NICT developed the basic laser communication experimental equipment (LCE) for the Engineering Test Satellite-Ⅵ (ETS-Ⅵ) and performed the world's first laser communication experiment using a satellite in orbit in 1994. The transmission rate was 1 Mbps, and a link between an optical ground station at NICT and a satellite having a similar altitude to geostationary orbit was successfully established.

The Optical Inter-orbit Communications Engineering Test Satellite (OICETS), called "Kirari" in Japanese, was developed by the Japan Aerospace Exploration Agency (JAXA). Researchers at NICT joined the JAXA's OICETS project team to develop the technology for ground-to-satellite optical communications, and mainly pursued the development of the payload equipment for laser communication missions. Laser communications need to realize ultra-fine acquisition and tracking. Therefore, researchers have encountered various difficulties in the development phase: for example, desired performance could not be attained because of thermal distortion in the estimates of the space environment in orbit. However, they overcame these difficulties after developing the payload equipment to satisfy the essential interface requirements of laser satellite communications with the ARTEMIS satellite of the European Space Agency (ESA). The developed payload equipment made a significant contribution to the attainment and development of satellite onboard laser communication technology. This process also showed the advanced technology in Japan, considering that this payload equipment applied to the satellite "Kirari" was developed using original Japanese technology.

The Kirari faced many difficulties not only in the development phase but also in the launch phase. Although it was originally planned to launch with the J-Ⅰ rocket, the

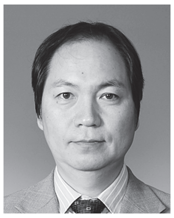
Kirari project was put on hold after the protoflight test was completed. However, the Kirari was launched successfully in August 2005 after the launch vehicle was changed to the Dnepr rocket. This success owes to unceasing efforts from staff and engineers involved in the project, which led to maintaining and improving the reliability of the satellite, and to ensuring the opportunity to launch during the freeze-period. After the Kirari was put in orbit, it yielded the world's leading results in this field: with the cooperation of ESA, it succeeded in the world's first experiment of bi-directional inter-satellite laser communications at 50 Mbps. Moreover, it successfully achieved the world's first experiment of laser communications between the optical ground station at NICT and the Kirari in orbit.

After this, NICT guided and realized a joint international project of laser communication experiments between the Kirari and each of the four optical ground stations in various locations on the ground, including the NICT station, with the cooperation of JAXA. The foreign optical ground stations belonged to the NASA Jet Propulsion Laboratory (JPL), ESA and the German Aerospace Center (DLR). As a result, we obtained a lot of valuable data on the atmospheric propagation characteristics of lasers in different site-conditions from ground-to-satellite laser propagation data which had not be obtained before. The data obtained was important basic information because it will be utilized for modeling atmospheric turbulence on the various site conditions. The standardization of the satellite-to-ground laser propagation model will lead considerable progress toward the actual use of laser communication, providing a valuable tool for system design for telecommunication carriers and space users.

It has always been reported that laser communications cannot be established in bad weather. However, if a number of optical ground stations are placed on Earth, the data from a satellite in orbit can be transmitted to the ground using an optical ground station that has good weather. Fortunately, in the international joint project of laser communication experiments, we were able to confirm that the probability of establishing a link from a satellite to at least one of the four ground stations was more than 99%, although the probability of establishing a link from a satellite to one ground station was small. These results show the effectiveness of site diversity. Considering the rapid progress of optical fiber networks on the ground, we will be able to easily realize applications where high capacity remote sensing data is received without interruption by connecting the number of optical ground stations via optical fiber networks on Earth.

The future of technology in laser communication places its hopes on highly secured wireless communications using quantum cryptography. Quantum key distribution via optical fibers on Earth has a limit value of a distance that is around 100 km and this cannot distribute quantum keys all over the world because the signal cannot be copied due to the uncertainty principle. However, a Low Earth Orbit (LEO) satellite makes quantum key distribution possible using space transmission. Thus, global quantum key distribution will be available using satellites. The polarization property of the space-to-ground channel is important because quantum key distribution generally utilizes this. However, in the past there was no measured data related to the polarization property. NICT made the research of quantum key distribution using satellites feasible, and obtained the polarization property of the space-to-ground channel using Kirari, which led to extra successes that were not in the original plan. The whole content of laser communications using Kirari might not be easily accessible because of the challenging technology and its variety. We have tried to cover and summarize most of the results of in-orbit experiments using Kirari in this feature article. In addition, we expect that many interested readers know the above information and have utilized it in various fields. The in-orbit demonstration of the Kirari laser communications experiment was performed by staff and engineers in related ministries and agencies in many organizations. I appreciate their continued diligence in this project and thank them all from my heart.

The disaster of the Great East Japan Earthquake and tsunami happened in Japan on March 11, 2011. At that time, satellites made a significant contribution to society by sending observational data, which was utilized to learn about the disaster areas. In the future, observational data in higher-resolution will be able to be obtained in near real time when the ultra-high capacity of downlink channels is realized in laser communications between observation satellites and ground stations. It will be possible to quickly learn in detail about areas at times of disaster, and satellites will make a significant contribution to society by providing observational data which can help the planning of appropriate rescue operations immediately after a disaster. There is no doubt that it is important to develop a downlink channel with the ultra-high capacity of tens of Gbps in Japan, and this development will lead not only to ensuring superiority in engineering development but also to securing the safety of society. We initialized the new mission plan of onboard satellite laser communications and will make every effort to proceed to the next step by using the successful results of the development of the Kirari and the demonstration experiment of the NICT Wireless Network Institute. Finally, I hope related organizations give us their understanding and supports to push our new missions going forward.



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Satellite Communications System