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Title: Latest Developments in the Field of Optical Communications for Small Satellites and Beyond

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Abstract *This paper introduces the latest trends in the field of space optical communications for small satellites including the National Institute of Information and Communications Technology (NICT) efforts to develop payloads for small moving platforms and the HICALI project for an optical feederlink between a Geostationary Earth Orbit Satellite and ground.*

Introduction

Space laser communication (lasercom) is gaining attention due to its capability to provide much wider and unlicensed bandwidth compared to the current RF systems. Recently, with a number of demonstrations around the globe not just from space agencies [1] but also from industry and academia [2], and first standardization documents published by the Consultative Committee for Space Data Systems (CCSDS), the technology is being considered mature enough for wide integration in the satellite networks. There are several distinguished trends in the field, such as satellite Quantum Key Distribution (QKD), Geostationary Earth Orbit (GEO) satellite-to-ground optical feederlinks, and GEO optical data relay satellites.

This paper emphasizes on the development of lasercom terminals for small Low Earth Orbit (LEO) satellites. The trend is particularly interesting because such payloads provide an attractive wide-bandwidth downlink alternative for observation satellites and with the growing number of LEO constellations – potentially the best solution for high-speed intersatellite links.

The Japanese National Institute of Information and Communications Technology (NICT) has a long history in the field starting with the world's first space-to-ground downlink experiment using the GEO satellite ETS-VI in 1994 [3]. This paper also presents the latest activities in NICT in the field. First, the development of Miniaturized lasercom-terminals series for small moving platforms such as drones, high-altitude platforms (HAPS) and small satellites is introduced. Also, the High-speed Communication with Advanced Laser Instrument (HICALI) payload and the newly prepared optical ground station (OGS) for experiments with it are summarized.

Recent Trends of Lasercom Terminals for Small Satellites

The main benefit of lasercom terminals for small LEO satellites is their low Size Weight and Power (SWaP) and high bandwidth. The recent efforts in decreasing the SWaP while allowing higher data rates has lead to multiple projects considering CubeSat-mounted payloads.

One such example is the OSIRIS4CubeSat (O4C) payload, developed by the German Aerospace Center (DLR)[4], which is a part of the OSIRIS series program and supports 100 Mbps downlink. The lasercom payload itself its within 1/3U of a CubeSat unit and has a weight of 395 g and power consumption under 9 W. O4C is demonstrated in the "PIXL-1" mission that was launched in January, 2021 and uses an OGS with 60-cm telescope.

The CubeSat Laser Infrared CrosslinK (CLICK) mission will demonstrate terminals capable of conducting fullduplex, high data rate crosslinks and enabling high precision ranging on 3U CubeSats in LEO [5]. CLICK-A is expected to launch no earlier than May 2022 for deployment from the International Space Station (ISS) in June 2022, while CLICK B/C is anticipated to launch in late 2022. The CLICK-A payload has a mass of less than 1.2 kg and fits a 1.2U envelope and allows 10Mbps downlink to an OGS with 28 cm aperture. CLICK-B/C payload fits in 1.5U and aims for data rates ≥ 20 Mbps.

NASA's TBIRD program has developed an optical communication architecture for direct downlinks at 100+ Gbps that leverages 1550-nm technology from terrestrial fiber telecommunications [6]. A 6U Cubesat will host the TBIRD space terminal payload, which is roughly 3U in volume. The spacecraft is planned to launch in Summer 2022. The TBIRD mission

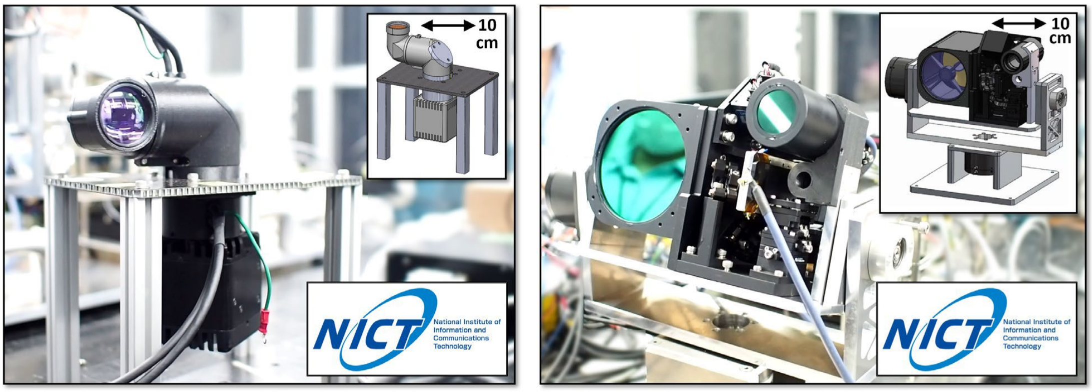

Fig. 1: Early prototypes of ST terminal (left) and FX terminal (right) for preliminary validation.

will be capable of performing downlinks to a ground terminal with 1-meter aperture at burst rates up to 200 Gbps during.

To increase the link availability, instead of LEO-to-ground direct links it is better to use a GEO data relay satellite that has much longer direct line of sight to the LEO satellite. Such projects include the European Data Relay System (EDRS) [7], operational since 2016, the Laser Communications Relay Demonstration (LCRD) [8], launched at the end of 2021, Laser Utilizing Communication System (LUCAS) [9], launched in 2020. A challenge for the small satellite payload is the long LEO-GEO link (in the order of 30000-40000 km) compared to LEO-ground links (normally under 1000km) or inter-satellite links (5000-10000-km).

Miniaturized Lasercom-Terminals in NICT

Free-space optical communications are expected to play important role in the future 5G/Beyond 5G networks which rely on LEO satellite constellations and drone/HAPS non-terrestrial networks. This urges the development of small lasercom terminals that can be mounted on such small moving platforms with stringent requirements in terms of Space Weight and Power (SWaP). NICT has started the development of series of lasercom payloads called Full Transceiver (FX) and Simple Transmitter (ST) with main characteristics as shown in Table 1 (Fig. 1).

The FX terminal development has started with the plan to be mounted on a LEO satellite that requires a one-way link towards a GEO relay satellite allowing very high connection availability, as described in the CubeSOTA concept [10-11]. For links in the order of several thousands of kilometers, for example in a LEO-Ground scenario or a LEO-LEO scenario for LEO constellations, the terminal is able to support bi-directional communication. The key component of the FX terminal, which enables it for high-speed bidirectional long-range communications is the 9-cm miniaturized telescope that allows collimating a very-narrow beam to cover long distances with small geometrical losses, as well as providing enough receiving gain to close the link at high speed. The design has been limited to 9 cm in order to be compatible with Cubesat platforms where the frame dimension may be limited to 10 cm.

The ST terminal is a further-miniaturized version of the FX terminal able to support LEO-ground downlinks. The smaller aperture allows to significantly miniaturize the gimbal. However, the low receiving gain together with much wider divergence angle for the transmitted beam prevent this design from achieving a bidirectional operation at moderate distances such as LEO-ground. Nevertheless, the terminal allows one-way LEO-ground optical links that are useful for observation satellites in need for high-speed downlink channels. In the case of dense satellite constellation or HAPS-ground scenarios where the distance are significantly shorter, the FX terminal can support bidirectional links since its internal optical configuration is equivalent to the FX terminal, including the receiving part.

Tab. 1: Optical-head assemblies of NICT's space laser-communication terminals.

	FX terminal	ST terminal
Maximum distance range	LEO-GEO (1 way) LEO-LEO (2 ways)	LEO-ground (1 way) HAPS-ground (2 ways)
Aperture size	9 cm	3 cm
Mass (OHA)	~6 kg	~3 kg
Data rate (max)	2 optional modems: 10 Gbps & 100 Gbps	
Wavelength	C-band	
Direction discr.	Wavelength (tx side polarization compatible)	
Field of regard	±90°	

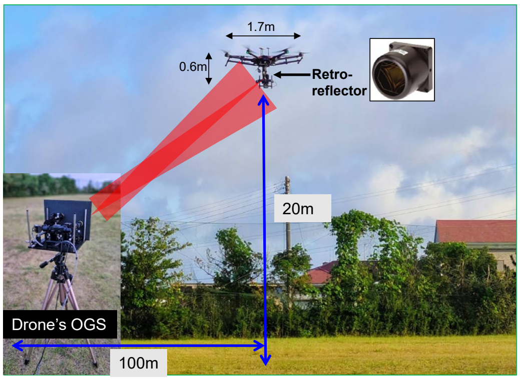

Fig. 2: .Free-space optical link between a hovering drone and a simple optical ground station

NICT has further performed initial tracking system tests with a simple optical ground station and a small drone flying at a 20-meters altitude (Fig. 2), [9]. Apart from the atmospheric turbulence effects that need to be compensated for single mode fibre coupling, in the shown scenario there are additional factors to be considered such as platform vibrations due to the rotor blades of the drone, and drone random hovering due to local wind bursts, and GPS accuracy.

HICALI Mission

NICT vision for the future High-Throughput Satellites, implementing robust RF links for the user side and optical feederlink is shown in Fig. 3. While optical feederlinks offer very high throughput, they can be severely affected by clouds. To increase the link availability, site-diversity technique can be implemented, and the link can be switched between different OGS depending on the weather on the sites. Apart from GEO-ground links, GEO-LEO experiments are also considered using CubeSOTA [10].

The main characteristics of the HICALI payload are shown in Table 2. One of the main goals for the HICALI mission is to use commercial-off-the-shelf (COTS) parts for terrestrial network. For this purpose, the HICALI payload is using the mature technology and widely available components for ground fiber networks at 1550 nm wavelength.

NICT has also initiated OGS preparation for the HICALI mission in its facility in Koganei, Tokyo. A 40-cm sub-aperture of a 1-meter telescope, is planned to be used (Fig. 4). The optical bench, shown in Fig. 5, is mounted on the telescope nasmyth and allows pointing errors in the order of 1 microradian. Adaptive-optical system is also being developed to compensate the wavefront errors due to atmospheric turbulence so that high coupling efficiency for the single-mode fiber coupling can be achieved.

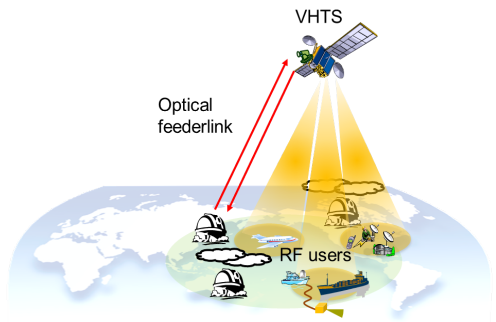

Fig. 3: High-throughput satellite concept with optical feederlink.

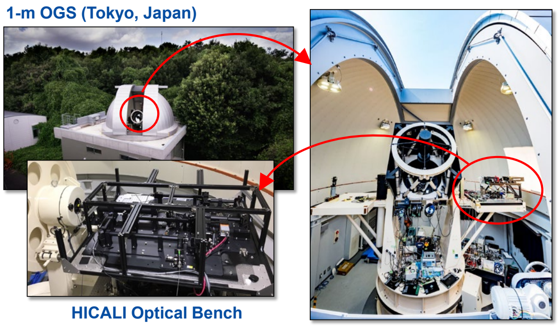

Fig. 4: NICT OGS with 1-meter telescope.

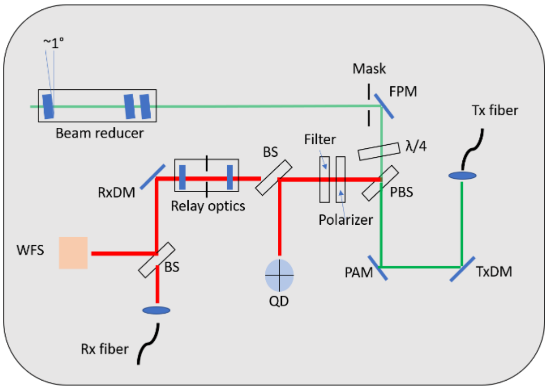

Fig. 5: NICT optical bench.

Tab. 2: HICALI Payload Specification.

Transmit power	34 dBm
Tx diameter	0.15 m
Wavelength	Downlink: 1540 nm
	Uplink: 1560 nm
	1530 nm (Beacon)
Polarization	Downlink: LHCP
	Uplink: RHCP
Modulation	Downlink: NRZ-DPSK
	Uplink: RZ-DPSK
Received power	-44 dBm
Pointing angle range	± 10 °
Mass	80 kg
Power	340 W

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