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Review

Overview of Space-Based Laser Communication Missions and Payloads: Insights from the Autonomous Laser Inter-Satellite Gigabit Network (ALIGN)

Othman I. Younus [1,*], Amna Riaz [1], Richard Binns [1], Eamon Scullion [1], Robert Wicks [1], Jethro Vernon [1], Chris Graham [2], David Bramall [2], Jurgen Schmoll [2] and Cyril Bourgenot [2]

[1] Department of Mathematics, Physics and Electrical Engineering, Northumbria University, Newcastle upon Tyne NE1 8ST, UK; robert.wicks@northumbria.ac.uk (R.W.)
[2] NETPark Research Institute, Centre for Advanced Instrumentation, Durham University, Joseph Swan Road, Sedgefield TS21 3FB, UK
* Correspondence: othman.younus@ieee.org

Abstract: This paper examines the growing adoption of laser communication (lasercom) in space missions and payloads for identifying emerging trends and key technology drivers of future optical communications satellite systems. It also presents a comprehensive overview of commercially available and custom-designed lasercom terminals, outlining their characteristics and specifications to meet the evolving demands of global satellite networks. The analysis explores the technical considerations and challenges associated with integrating lasercom terminals into LEO constellations and the Inter-satellite communications service provision in LEO due to their power, size, and weight constraints. By analyzing advancements in CubeSat lasercom technology designed to cater for the emergence of future mega constellations of interacting small satellites, the paper underscores its promising role in establishing high-performance satellite communication networks for future space exploration and data transmission. In addition, a brief overview of our ALIGN planned mission is provided, which highlights the main key operational features in terms of PAT and link budget analysis.

Keywords: free-space optical communication; satellites; low-earth orbit; geostationary orbit

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1. Introduction

Wireless communications have recently undergone an exceptional surge in various areas. From cellular networks to satellite connections, wireless telecommunications have given rise to a multitude of novel services to provide communication and internet connectivity worldwide. Despite this, the "World Internet Development Report 2024" states that the global average internet penetration rate is approximately 67.1 percent, implying that approximately 32.9% of the global population lacks internet access. This means billions of people are still unconnected [1]. Traditional communication methods that utilize radio frequencies (RF) face data transmission capacity constraints due to technological and regulatory challenges [2]. From a technological perspective, these systems are mainly constrained by limited available bandwidth, signal attenuation, interferences, and hardware limitations in terms of weight and energy efficiency. On the regulatory front, they are bound by spectrum allocation, the necessity for licenses and coordination, and the international agreements governing the use of the RF spectrum and orbital slots [3]. Terrestrial networks, for example, make it impossible to deliver telecommunications services in isolated areas, the North and South Poles, and impoverished settlements due to high building costs. Likewise, for certain scenarios, such as high-speed trains and planes, terrestrial wireless communication networks deliver poor quality of service (QoS) due to a high call drop rate caused by high mobility and frequent cell handovers.

Satellite communications have received a lot of attention for offering abundant radio frequency resources, wide coverage areas, long communication distances, rapid deployment capabilities, and minimum interference from the ground network. However, the dependence on satellite communication highlights the inherent limits of present RF technologies. As an alternative to addressing these limits, the use of optical technology has demonstrably pushed the RF boundaries to enable data transmission with high bandwidth and secure channels.

Free-space optical (FSO) communication emerges as a subset of optical communication technology that is used to address the growing demand for high-speed data transmission in space applications. FSO, with its inherent advantages of large capacity, low detection likelihood, and minimal interception risk, provides an alternative solution to standard RF communication. It may also contribute to the deployment requirements of mega-constellations composed of multiple small-to-medium-sized satellites, thereby mitigating the issues related to spectrum congestion in RF communication [4]. The global space-based laser communication market, mostly commercial applications, is expected to reach USD 5 billion by 2031, i.e., a growth of about 26% per year since 2022 [5]. FSO links can be established between fixed or dynamic point-to-point systems or in interconnections between satellites, aircraft, maritime vessels, and ground terminals (stationary and mobile).

FSO links for space communication require beam tracking and locking prior to data transmission. In inter-satellite communications, where there is no need for ground stations, FSO links with wavelength division multiplexing (WDM) and relays can be deployed [6]. Recent space missions have demonstrated in orbit the core principles of space-based optical communication, which paved the way for its real-time deployment in both academic and business sectors [7]. These missions have demonstrated a range of optical communication links that are classified based on their separation from the Earth's surface and have investigated both the dynamic and stationary conditions of the transmitters and/or receivers. For instance, in geostationary Earth orbit (GEO), the satellite is typically deployed at about 36,000 km above the Earth's equator. GEO was the preferred technology used by satellite operators to execute their commercial satellite communication systems due to the advantages of fixed position relative to the Earth, coverage, and practically constant latency [8]. However, communication systems encounter multiple issues. The first issue is a bad user experience caused by high latency and channel attenuation. Second, it is inappropriate for mobile communications at high latitudes, not least because the elevation angle (the angle between the user's satellite and the horizon) of the user equipment is so narrow that terrain shelter should not be disregarded. Also, the system's coverage and capacity are constrained by a lack of orbital and frequency resources. Finally, the costs of satellite launch and operation are relatively high. Few missions were established between the GEO to ground. A Laser Communication Experiment (LCE) aboard the Japanese Engineering Test Satellite-VI (ETS-VI) was an example of the bi-directional laser communications link between the GEO and ground station [8,9]. Even though medium Earth orbit (MEO) satellite communications have a shorter propagation delay than GEO (closer to the Earth than GEO satellites, with distances ranging from 2000 km to 20,000 km), more MEO satellites are required to continually cover the region. It also requires a higher transmit power than low Earth orbit (LEO) systems to overcome path loss and other atmospheric losses [10]. O3b/SES "other 3 billion" has launched over 15 MEO satellites to provide Ka-band communication services [11], while Laser Light Communications plans to create an all-optical worldwide MEO communications network [10,11].

Unlike their GEO and MEO predecessors, LEO satellites orbit between 500 and 2000 km above the Earth's surface [12]. This low altitude translates into a variety of advantages, making LEO a suitable candidate for the satellite communication business, which include lower latency, reduced signal path loss, and lower production and launch costs. Prior demonstrations have successfully established FSO communication links between LEO to Ground Station. Examples include the Laser Utilizing Communications Equipment (LUCE) [13], Optical Payload for Lasercomm Science (OPALS), and Tesat LCT links facilitate optical communication capabilities from entities like the International Space Station (ISS) or LEO satellites to terrestrial stations [12]. The next section will further discuss these demonstrations and what they mean for future FSO communication installations employing LEO satellites.

The potential applications of FSO communication systems extend beyond traditional point-to-point links and established orbital altitudes. As shown in Figure 1, FSO can facilitate various array of interconnected links across different communication paths, including (i) Satellite-to-Satellite Links, as it may involves connections between LEO to GEO Satellite, which is established through the Semiconductor-laser Inter-satellite Link Experiment (SILEX) and the European Data Relay System (EDRS) [14,15]. Inter-satellite Links (ISLs) between satellites positioned in various orbits, including LEO, MEO, and GEO, are demonstrated by the Optical Inter-Orbit Communications Engineering Test Satellite (OICETS) and SILEX, with the Laser Communications Relay Demonstration (LCRD) showcasing optical inter-satellite links bridging LEO and geosynchronous orbit [16,17]. In addition ground to deep space connections were demonstrated by the Lunar Laser Communication Demonstration (LLCD) and Laser Communications Relay Demonstration (LCRD), showcasing optical communication capabilities from terrestrial stations to lunar orbit and deeper space regions [7,18,19]. (ii) Air-to-Ground/Ground-to-Air Link establishes a bidirectional laser communication between aircraft and LEO satellites, enabled by the Optical Communications and Sensor Demonstration (OCSD) [20]. Similarly, an optical downlink from high-speed aircraft to ground stations has been demonstrated, displaying integrated laser terminals suitable for free-space optical communications even under jet fighter vibrations conditions [21,22]. In addition, airborne free-space experimental laser terminals, such as those used in the stratospheric Optical Payload Experiment (STROPEX) [23], show data transmission from balloons to LEO satellites. CAPANINA, a project focused on broadband technology development from High Altitude Platforms (HAPs), extends coverage to users potentially marginalized by geography and infrastructural limitations, achieving burst data rates of up to 120 Mbit/s within a 60 km coverage area [24]. Stratobus and other projects have shown broadband internet connectivity via optical lines from a HAP balloon to ground [25]. (iii) The deep-sea-based OWC link was demonstrated by Japan Agency for Marine-Earth Science and Technology (JAMSTEC) with Trimatiz Limited (Trimatiz), which demonstrates an underwater vehicle at a depth of 900 m [26]. Table 1 illustrates instances of optical space communication links, organized across a variety of platforms.

A number of survey papers have discussed in detail the potential of FSO links in space [4,6,27]. For instance, the requirements to establish positioning, navigation, and timing (PNT) systems within LEO as a part of the FSO systems were analyzed [6]. The survey covered several areas of the signal design across space, ground, and user segments. The merits and limits of various instruments and techniques were evaluated to identify viable solutions for deploying LEO-based navigation systems. Thus, addressing the limitations of PNT systems in LEO is crucial for resolving current challenges in navigation, positioning, and timing, which can be directly reflected on the improvement of urban and indoors navigation. Likewise, the recent mega-constellation systems planned and launched from various countries were addressed in [28], in which the authors predict that the use of CubeSat laser communication will expand and that the deployment of the mega-constellation systems is subject to having sufficient number of operational in-orbit satellites. These papers highlight the significant advantages of optical communication over traditional radio frequency (RF) communication, in terms of higher bandwidth and data rates [4,27].

Similar to previous works, this paper presents a comparative analysis of all FSO links deployed in space both historically, considering commercial and non-commercial missions, and in the context of future missions specifically addressing LEO-to-LEO challenges. We also produced a comparative analysis in terms of latency reliability, data rate, and power consumption. The work emphasizes the development of compact and power-efficient laser communication terminals that are suitable for small satellite platforms and CubeSats and demonstrates how the emerging trend towards mega-constellations of small, interacting satellites, a topic that has not been extensively covered in earlier surveys. Included in the discussion about increased interest and future LEO missions, we will present a brief overview of our planned mission Autonomous Laser Inter-satellite Gigabit NetWork (ALIGN) and the Free-space Optical Communications Unit for Satellites (FOCUS) payload.

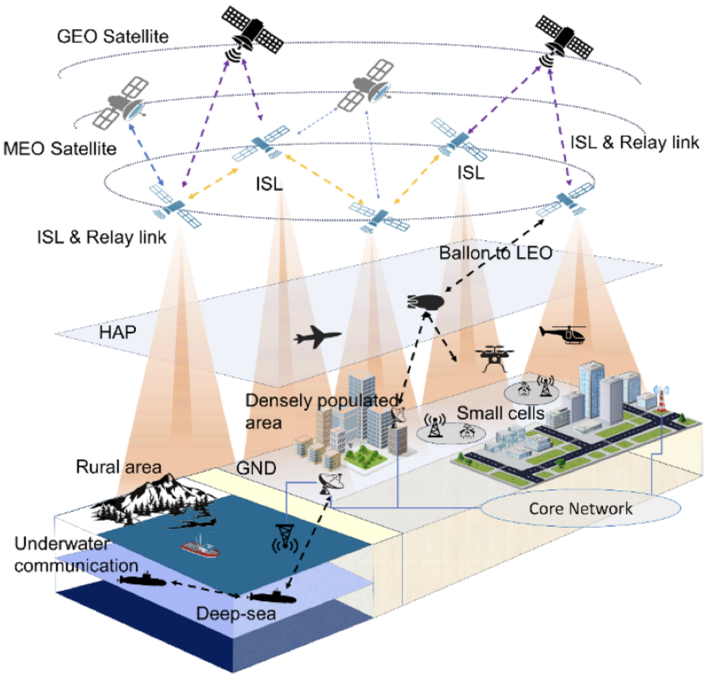

Figure 1. Architecture of satellite communication systems via different communication link types.

Table 1. An example of optical space communication across various platforms.

Platform	Project/Experiment	Maximum Link Span (km)	Maximum Data Rates
LEO to Ground Station	LUCE [13], OPALS, Tesat LCT links [12]	5000	1.8 Gbps
LEO to GEO Satellite	SILEX [14], EDRS [15]	45,000	50 Mbps to 1.8 Gbps
LEO to Aircraft	OCSD [9]	200	100 Mbps
Aircraft to Ground Station	[21]	50–79	1.25 Gbps
Balloon to LEO Satellite	STROPEX [23], CAPANINA [24]	200	2.5 Gbps
GEO to Ground Station	LCE aboard ETS-VI [8,9]	-	1 Mbps
HAP to Ground	Stratobus [2,29]	20 km above earth surface	-
Ground to Deep Space	LLCD, LCRD [7,18,19]	380,000–400,000	620 Mbps to 20 Gbps
Deep Sea	JAMSTEC [26]	0.9	1 Gbps
Inter-satellite Link	OICETS, SILEX [16], LCRD [17]	45,000	50 Mbps

The remainder of the paper is organized as follows. Section 2 describes all previous space-based laser communication missions. CubeSats and inter-satellite links are covered in Section 3. Finally, Section 4 presents the conclusions and future work.

2. Previous Space-Based Laser Communication Missions

In recent decades, a variety of space missions utilizing optical terminals have been launched for diverse purposes. For instance, the National Aeronautics and Space Administration (NASA) of the United States demonstrated a laser transmission link to the Galileo probe in outer space in 1992, as a part of Galileo Optical Experiment (GOPEX). The communication link used Earth-emitted pulses with megawatt power at a 532 nm wavelength, captured by a camera onboard the Galileo probe around 6 million kilometers away [30]. The first space-to-ground (i.e., GEO to the optical GNS) bi-directional laser communications link was demonstrated by LCE aboard the Japanese Engineering Test

Satellite-VI (ETS-VI) satellite in 1994, with a data rate of 1 Mbps, weight of 22 kg, and power consumption of 60 W [8,9].

Similarly, another milestone in creating the world's first inter-satellite laser communication link was developed, named the Advanced Relay and Technology Mission Satellite (ARTEMIS) by the European Space Agency (ESA). The communication link provided mobile services with a data transfer rate of 50 Mbps and a data relay from French Earth Observation satellite SPOT-4, positioned in LEO, through an optical channel to the geostationary ARTEMIS satellite. Then, the ARTEMIS satellite transmitted the information between the LEO and the GND via radio waves [14,31]. Likewise, the Optical Inter-orbit Communication Engineering Test Satellite (OICETS) demonstrated LEO to GND inter-orbit laser communication experiments in conjunction with ESA's ARTEMIS, known as "Kirari", and was a product of the collaborative efforts of the Japan Aerospace Exploration Agency (JAXA) [32]. It showcased an advanced on-orbit pointing, acquisition, and tracking methodologies. Structurally, Kirari was designed with a three-axis stabilization mechanism, weighing ~570 kg and having a power consumption of 1200 W, which was measured at the end of the satellite's operational life. The optical link can achieve a downlink data rate of 50 Mbps and uplink rates of 2 Mbps at a wavelength of 800 nm. The Kirari's orbital path is sun-synchronous, characterized by an inclination of 97.8° that occurs due to its altitude variations, ranging from 550 km at its operational end to 610 km at its commencement [13]. Alternatively, a HAP inter-connected with optical links was initiated by EADS Astrium (currently known as Airbus Group) in collaboration with the French Ministry of Defense's arms procurement division (DGA), in which a seamless laser communication link was established between an optical terminal on-board an aircraft flying at 9 km and the SILEX terminal on the ARTEMIS geostationary satellite. The link characteristics are dictated by the SILEX system, in terms of data rate, which is recorded as 50 and 2 Mbps for downlink and uplink channel, respectively, laser wavelength of ~800 nm and OOK (On–Off Keying) modulation [33].

The primary challenges encompassed: (i) ensuring quasi-error-free (bit error rate $< 10^{-9}$) data transmission, especially given the fast signal fading caused by laser propagation in the atmosphere; (ii) technical demands of instruments with μrad pointing requirements needed highly stable structures; (iii) optical communications introduce further complexities, particularly in optical design and detection; (iv) robust isolation between emission and reception, considering the significant power disparity of a factor of ~109 in laser power levels that range from 150 mW down to 20 to 200 pW; and (v) efficient stray light protection, especially during communication between satellites, with the Sun at angles nearing 5 degrees from the field of view, coupled with the need for exact alignment between emission and reception paths [20].

Furthermore, a coherent optical inter-satellite link in LEO was demonstrated in collaborative efforts between the German TerraSAR-X radar satellite and the U.S. Missile Defense Agency's NFIRE satellite [34]. The Laser-Communication-Terminal-on-TerraSAR-X (LCTSX) was established using a space-borne Nd:YAG laser with a wavelength of 1064 nm and two redundant 808 nm laser diode pump modules to attain higher reliability [35]. A mass of less than 30 kg and data rate of up to 5.6 Gbps was achieved over a distance of up to 80,000 km and a binary phase shift keying (BPSK) modulation scheme. The link provides sun exposure capability with a radiation tolerance greater than 80 Krad and a power consumption of less than 130 W [36]. In addition, China developed another LEO-GND communication terminal named the Haiyang-2 HY-2 satellite. The satellite was equipped with on-orbit micro-vibration measurement unit to assist in laser beam pointing prediction and correction. A data rate of 504 Mbps was achieved using a laser wavelength of 1.5 μm and an Intensity Modulation/Direct Detection (IM/DD) scheme [37,38].

In addition, the Onboard Terminal of a Laser Communication System (BTLS) on the Russian Segment demonstrated data rates of up to 1.8 Gbps between GEO-LEO and GEO-GND [39]. In addition, the USA continued its endeavours with LLCD (NASA GSFC) in 2013, which focused on Lunar-GND communication and demonstrated a 622 Mbps [40]. Table 2 summarizes the collective global effort to push the boundaries of space communication technology, each contributing unique capabilities and insights.

Table 2. Collective programs of space-based laser communication.

Ref.	Year	Mission	Link Type	Wavelength	Modulation	Data Rate
[9]	1994 1995 2000 2001	ETS-VI (NICT, Japan) GOLD (NASA JPL, USA) STRV-2 (BMDO, USA)-fail GOLITE (NRO, USA)	GEO-GND GEO-GND LEO-GND GEO-GND	0.8/0.5 µm 0.8/0.5 µm 0.8 -	IMDD IMDD IMDD -	1 Mbps 1 Mbps 1.2 Gbps -
[14]	2001	SILEX (ESA)	GEO-LEO, GEO-GND, GEO-Air	0.8 µm	IMDD	50 Mbps
[13]	2005	OICETS (JAXA/NICT)	GEO-LEO, LEO-GND	0.8 µm	IMDD	50 Mbps
[36]	2003	NFIRE (MDA, USA)	LEO-LEO	1.06 µm	BPSK	5.6 Gbps
[34,41]	2008	TerraSAR-X (DLR)	LEO-LEO, LEO-GND	1.06 µm	BPSK	5.6 Gbps
[37,38]	2011	HY-2 (China)	LEO-GND	1.5 µm	IMDD	504 Mbps
[39]	2011	BTLS (Russia)	LEO-GND	1.55/0.85 µm	IMDD	125 Mbps
[40]	2013	LLCD (NASA GSFC)	Lunar-GND	1.5 µm	PPM	622 Mbps
[42]	2013	EDRS/Copernics (ESA)	GEO-LEO, GEO-GND	1.06 µm	BPSK	1.8 Gbps
[43,44]	2014	SOCRATES/SOTA (NICT)	LEO-GND	0.98/1.5 µm	IMDD	10 Mbps
[45]	2014	OPALS (NASA JPL)	LEO-GND	1.5 µm	IMDD	30–50 Mbps
[46]	2015	OCSD-A (Aero. Corp., USA)-fail	LEO-GND	1.5 µm	IMDD	5–50 Mbps
[47]	2016	OSIRISv1-2 (DLR)	LEO-GND	1.5 µm	IMDD	20–100 Mbps
	2016	CAS SIOM (China)	LEO-GND	1.5 µm	DPSK	5.12 Gbps
[48]	2017	Micius (China)	LEO-GND	0.85/0.532/0.671 µm	-	-
	2018	OCSD-B/ AeroCube-7B (Aero. Corp.)	LEO-GND	1.064 µm	IMDD	50/100 Mbps
[49]	2019	Starlink/Space-X (USA)	-	-	-	1 Gbps
[50]	2019	RISESAT/VSOTA (NICT)	LEO-GND	0.98/1.5 µm	IMDD	~1 kbps
[51]	2019	SOLISS (Sony)	LEO-GND	1.5 µm	IMDD	100 Mbps
[52]	2019	EDRS-C (ESA)	GEO-LEO	1.06 µm	BPSK	~1.8 Gbps
[53]	2019	OPS-SAT (TU Graz)	LEO-GND	-	PPM	2 kbps (uplink)
[13]	2020	JDRS (JAXA)	GEO-GND	1.5 µm	DPSK	1.8 Gbps
[54]	2020	ALOS-3 (JAXA)	GEO-LEO	1.5 µm	DPSK	1.8 Gbps
[47]	2020	OSIRIS v3, v4 (DLR)	LEO-GND	1.5 µm	IMDD	10 Gbps
[55]	2021	ALOS-4 (JAXA)	GEO-LEO	1.5 µm	DPSK	1.8 Gbps
[56]	2021	LCRD (NASA GSFC, USA)	GEO-LEO, GEO-GND	1.5 µm	DPSK/PPM	2.8 Gbps/622 Mbps
[57]	2021	DSOC (NASA JPL, USA)	Deep space-GND	-	PPM	264 Mbps
[58]	2022	ETS-9/HICALI (NICT)	-	1.5 µm	DPSK	10 Gbps
	2022	LEMNOS (NASA GSFC)	Lunar-GND	-	PPM	311 Mbps

3. CubeSats and Inter-Satellite Links (ISLs)

While ISLs play a crucial role in satellite communication, enabling direct and efficient data exchange in space, their deployment in LEO constellations is less common compared to LEO-GND or GEO-LEO links, as shown in Figure 2 and Table 2. This scarcity is primarily due to the technical and operational challenges associated with implementing ISLs in LEO satellites, which are often smaller and have limited resources compared to satellites in other orbital regimes [59].

The advent of the miniature satellites with a standardized dimension, known as Cubesat's, have paved the way for the space-based laser communication system (lasercom) to be deployed for ISLs [60]. Compared to their larger, traditionally designed counterparts, Cubesat's offer significant advantages in cost, development time, and launch opportunities. Their compact size and modular design enable faster development cycles and lower production costs, making them particularly suitable for technology demonstration, scientific discovery, and educational purposes. Additionally, their compatibility with secondary launch opportunities allows for more frequent access to space, further accelerating the pace of exploration and innovation. However, CubeSat's are currently limited by their size and weight constraints, impacting their power generation, processing capabilities, and payload capacity. Thus, this has imposed a strict requirement in terms of the size, weight, and power (SWaP) when it comes to design of laser communication systems for space.

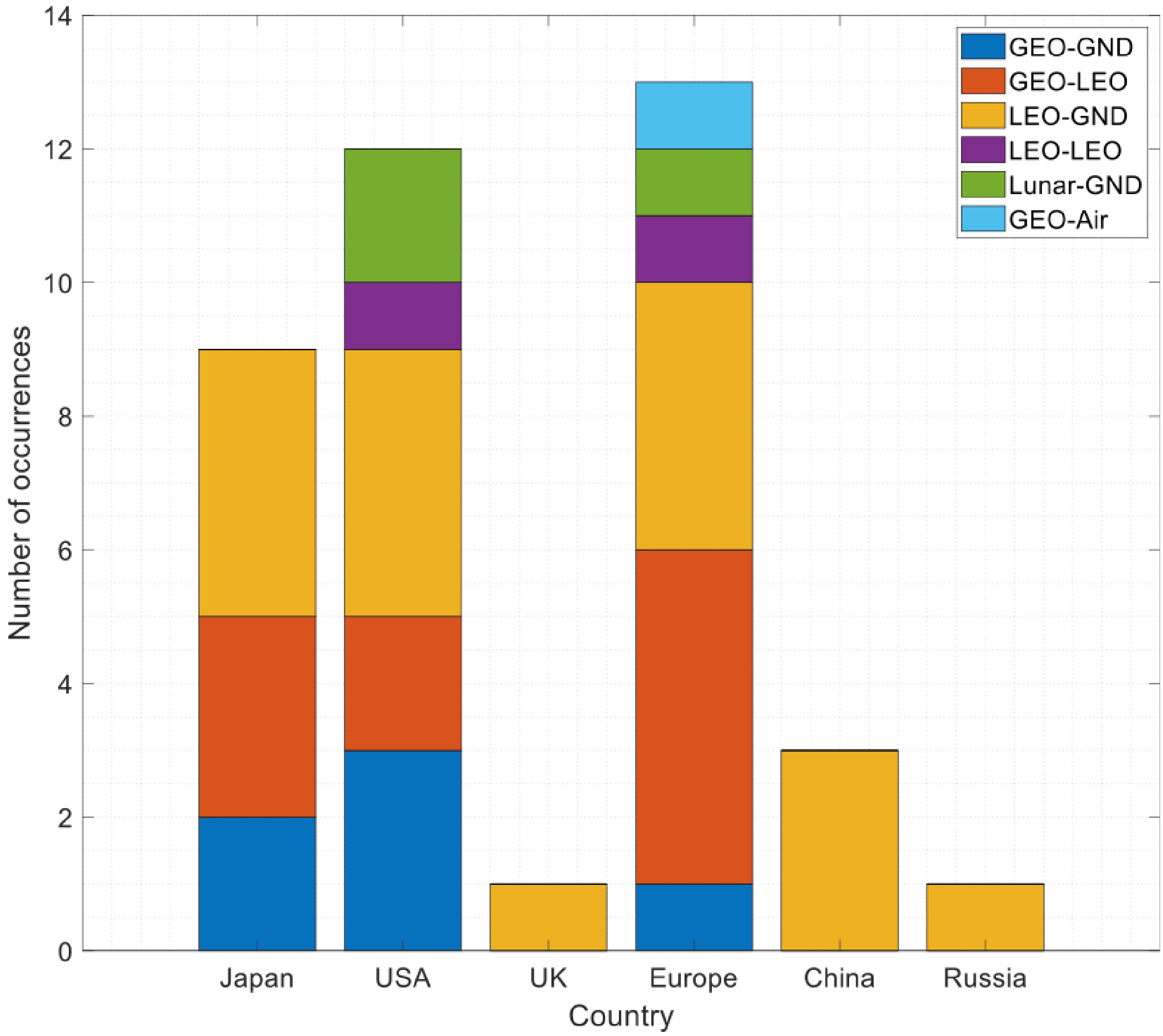

Figure 2. Distribution of link types in satellite communication systems by country.

3.1. Lasercom Terminals Payload Capacity

The analysis of commercially available and custom-designed laser communication (lasercom) systems suitable for CubeSats reveals a diverse landscape of technological capabilities, catering to the increasing demand for global satellite constellations. This paper surveyed leading corporations and research institutions involved in the development and deployment of CubeSat-compatible lasercom terminals, presenting a comprehensive overview of their characteristics and parameters.

In Table 3, a variety of commercial lasercom terminals from notable entities, such as TESAT, Mynaric, Thales Alenia Space, and Hyperion Technology, among others, are listed. These terminals exhibit a wide range of features including data rates, link types, size, power consumption, and release times. For instance, TESAT's TOSIRIS offers data rates ranging from 1.25 to 10 Gbps with a compact volume of 28.0 × 20.0 × 15.0 cm^3 and a power consumption of 40 W. Similarly, Mynaric's CONDOR Mk2 and Mk3 support data rates from 0.1 to 1.25 Gbps and 0.1 to 10 Gbps, respectively, showcasing the flexibility in bandwidth options.

Table 3. Commercial lasercoms terminals suitable for CubeSat or MicroSats.

Corporation	Name	Data Rate (D:Down; U:Up)	Link Type	Volume (cm^3)	Power Consumption (W)	Mass (kg)	Release (Year)
TESAT [12]	TOSIRIS	D: 1.25–10 Gbps, U: 1 Mbps	LEO-GND	20.0 × 20.0 × 15.0	40	8	2019
	SmartLCT	1.8 Gbps	GEO-GEO, GEO-LEO	<35.0 × 35.0 × 20.0	150	30	2020
	CubeLCT	D: 100 Mbps, U: 1 Mbps	LEO-GND	9.0 × 9.5 × 3.5	10	0.397	2021
	SCOT80	10 Gbps	LEO-LEO	2U	60–86	15	2023
	ConLCT	10 Gbps	GEO-LEO	OU:50.0 × 18.0 × 26.0, EU:26.0 × 11.0 × 17.5	80	15	2021
	LCT-135	1.8 Gbps	GEO-LEO	60.0 × 60.0 × 70.0	150	53	-
Mynaric	CONDOR Mk2	0.1–1.25 Gbps	GEO-LEO	OU:57.3 × 27.1 × 23.0, EU:34.0 × 25.9 × 16.3	-	-	2014
	CONDOR Mk3	0.1–2.5 Gbps	GEO-LEO	OU:35.1 × 21.1 × 17.0, EU:16.1 × 33.6× 25.5	-	-	2017
Thales Alenia Space	OPTEL-μ	2 Gbps	LEO-GND	8 U	43	8	2015
MOSTCOM	SOT-90	10 Gbps	GEO-LEO	45.0 × 30.0 × 38.0	60	16	2020
	SOT-150	1.25 Gbps	GEO-GND	60.0 × 40.0 × 48.0	100	50	2020
NICT [61]	SOTA [62]	1 Mbps–10 Mbps	LEO-GND	11.7 × 17.7 × 27.8	40	5.9	2014
	SOLISS [63]	80 Mbps	LEO-GND	All:29.5 × 35.6 × 43.6, OU:9.0 × 10.0 × 18.0	36	1.2	2019
	VSOTA	1 kbps–1 Mbps	LEO-GND	-	4.33	<1	2018
	HICALI	10 Gbps	GEO-GND	-	340	6	2021
	CubeSOTA [64]	10 Gbps	GEO-LEO	3 U	-	<14	2024
Hyperion Tech. & TNO [65]	CubeCat	D:100 M/300 M/1 G-bps, U:200 kbps	LEO-GND	1 U	15	1.33	2022
Aerospace Corporation [46]	AeroCube-7a	-	LEO-GEO	-	-	-	2015
	AeroCube-7b/7c	100 Mbps	-	1.5 U	-	3	2018
Astrogate Labs	ASTRO-LINK	1 Gbps	GEO-GND, LEO-GND	1 U	-	3	2022
HENSOLDT	Lasercom	U: 1.8 Gbps	Air-GEO	-	-	20–100	2015
CACI	CrossBeam-ST0	1.25 Gbps	LEO-LEO	-	50	10	2021
	CrossBeam-ST1	2.5 Gbps	LEO-LEO	-	75	10	2021
SONY [63]	SOLISS	80 Mbps	-	-	-	1.2	2019

Moreover, Table 4 presents customized (R&D) lasercom systems developed for CubeSats by research and development institutions like TESAT, NEC/JAXA, NASA/MIT/University of Florida, and DLR/University of Stuttgart. These systems offer unique transmission rates and link types tailored to specific mission requirements. For instance, TESAT's EDRS-A LCT provides a transmission rate of 1.8 Gbps for GEO-GND links, whereas NASA/MIT/University of Florida's CLICK-A focuses on LEO-LEO communication at a modest 10 Mbps.

The significant progress and innovation in CubeSat laser communication technology has offered a spectrum of solutions, encompassing varying data rates, link types, and spectral wavelengths. These advancements not only meet the increasing demand for global satellite constellations but also drive the miniaturization and efficiency enhancement of CubeSat payloads, ushering in a new era of space-based communication and exploration. However, despite these technological advancements, significant challenges remain. The earlier generation of terminals accentuates the pressing need for continued efforts towards miniaturization and decreased power consumption. Furthermore, factors including reliability, security, and the impact of atmospheric conditions necessitate careful consideration to ensure the dependable operation of laser communication systems within LEO constellations.

Table 4. R&D customized lasercom systems developed for CubeSats.

Corporation	Name	Data Rate (D:Down; U:Up)	Link Type	Volume (cm^3)	Power Consumption (W)	Mass (kg)	Release (Year)
NEC/JAXA	LUCAS	1.8 Gbps	LEO-GEO, LEO-LEO	-	-	-	2020
NASA, MIT, Uni. of Florida [67]	CLICK-A	10 Mbps	LEO-LEO	1.2 U	-	1.2	2018
	TBIRD [66]	D:200 Gbps, U:5 kbps	LEO-GND	1.8 U	-	2.25	2022
DLR Uni. of Stuttgart	OSIRISv1	200 Mbps	LEO-GND	-	26	1.3	2017
	OSIRISv2 [68]	1 Gbps	LEO-GND	-	37	1.65	2016
	OSIRISv3	10 Gbps	LEO-GND	-	150	9	2021
	OSIRIS 4 PIXL-1 [69]	100 Mbps	LEO-GND	0.3 U	10	0.39	2021
ESA (ARTES) Spire	OCT	-	LEO-LEO	-	-	-	2023

In conclusion, the evaluation of laser communication terminals presents a promising trajectory for their integration within LEO constellations. The escalating data rates, optimization of SWaP, diverse link options, and the advancing maturity of technology collectively position laser communication as a viable solution for future high-performance satellite networks.

3.2. LEO Exploration

Historically, LEO constellations have not utilized frequent LEO-to-LEO laser communication links due to the combined effect of several factors. LEO satellites, with their lower altitudes and higher orbital velocities (7–11 km/s) compared to MEO or GEO satellites, experience shorter communication windows and require more frequent handovers between satellites to maintain a connection. This handover process introduces complexity and increases the risk of disruption [70]. Additionally, atmospheric drag necessitates frequent orbital corrections for LEO satellites, further complicating link maintenance [71]. Finally, achieving comprehensive global coverage with LEO constellations demands a large number of satellites, and the challenge of maintaining continuous links between these rapidly moving spacecraft has historically favored communication link implementation in MEO and GEO constellations with fewer and slower-moving satellites [72].

3.3. Future Constellations

In Table 5, a list of known planned mega-constellations of small satellites that indicate an ambition to incorporate optical communication links in LEO (i.e., catering for LEO-LEO or LEO-ground or both), are presented (NB This list may not be complete and subject to modification). The emergence of low-cost, fast turnaround launch capability to LEO is heralding a significant growth in the development of optical communication terminals for small satellites such as CubeSats and nanosats. The mass, power, and volume envelope restrictions now force manufacturers of optical communications terminals to adapt their payloads, applying novel approaches to optical design, while maintaining competitive data rates that greatly outstrip RF communications systems.

Table 5. (Known) planned future constellations of small satellites in mesh networks.

Company	Origin	Constellation Type	Objective	Achievements
Amazon (Kuiper Systems)	USA	LEO	Provides broadband internet services with low latency	Plans to launch 3236 LEO satellites as part of the Kuiper Systems project. Intends to employ laser communication technology for enhanced connectivity.
Facebook (Athena)	USA	E-Band (71–86 GHz)	Conducts a satellite communication experiment focused on high-speed data.	Filed an application for E-band frequency usage with the Federal Communications Commission (FCC) and aims to deliver data 10 times faster than Space-X's Starlink internet satellites using laser communications.
Laser Light Communications	USA	MEO	Create sa 12-MEO satellite constellation with high capacity and data rates.	Collaborated with Australian telescommunications company Optus to prepare satellites and ground stations. Aims to establish a global network connecting terrestrial fiber systems with satellite systems.
ILLUMA-T	USA	LEO	Laser Communication Terminals for use in the ISS and Orion manned space vehicle utilizing the LCRD data relay with a data rate of 1.2 Gbps	-
BridgeCom (formerly BridgeSat)	USA	LEO	Create a 10-Gbps LEO constellation with laser communication services.	Plans to distribute 50 optical ground stations with software-defined modems worldwide to provide laser communication services, including support for small satellites and unmanned aerial vehicles. Also invested in governmental and 5G network communication needs.
Kaskilo (KLEO Connect GmbH)	Germany	LEO	Build a 288-satellite LEO constellation primarily for IoT services under Germany's Industry 4.0.	Will utilize laser communication for inter-satellite links to support IoT connectivity.
Huawei (Massive VLEO)	China	LEO	Construct a 10,000-satellite LEO constellation (Massive VLEO) for beyond-5G.	Plans to use low satellite altitudes of 300 km for ultra-reliable, low-latency communications, covering massive machine-type communications. Broadband communication will be achieved using terahertz and laser communications.

Table 5. *Cont.*

Company	Origin	Constellation Type	Objective	Achievements
Transcelestial Technologies	China	Various	Provide space laser communication.	Planning to offer space laser communication services using CubeSats and micro-satellites.
Golbriak Space	Estonia	Various	Provide space laser communication.	Intending to provide space laser communication services with CubeSats and micro-satellites.
Starlink/Space-X [49]	USA	LEO	-	-
Analytical Space Fast Pixel Network	USA	LEO	Six CubeSats, a constellation of 36 satellites across three orbital planes	Hybrid RF-laser to relay data for satellite operators and customers based on the technologies capability for data increases through RF.
CONDOR Mk3 Optical Communication Terminal	Germany	-	Optical Communication Terminal is capable of high-performance, high-bandwidth, and secure and reliable satellite communications.	It supports link distances greater than 10,000 km with a flexible data rate coverage of up to 100 Gbps, fast acquisition time, configurable Laser Ethernet Terminals (LETs), and seamless link configuration and interoperability across various optical communication terminals. It has a highly modularized design, and an option for Dual or Quad configuration for reduced power consumption and reduced mass.
Telesat's Lightspeed	USA	LEO	+300 satellites	

3.4. Future OISL Payloads

In Table 6, a list of known planned payloads for small satellites that indicate an ambition to provide optical communication links in LEO, are presented (NB: this list may not be complete and subject to modification). The next generation of optical communication terminals that will emerge over the next few years will push the limits of optical communications technology, not only to lower mass, power, and volume requirements, but also to more adaptable designs that allow for scalability at cost and can address the most challenging problem for LEO-to-LEO communications, which is PAT (Pointing, Acquisition, and Tracking). Table 6 is ordered in terms of mass from high to low. As can be shown, one of the most competitive products to emerge over the next few years is the FOCUS (Free Space Optical Communications Unit for Satellites) terminal being built by Northumbria University (UK) and partners and funded by the UK Space Agency. The FOCUS terminal is the most competitive because it will adequately address the growing requirement for lower mass, lower power consumption, and smaller volume envelope, while still achieving greater than 1 Gbps data transfer rates for LEO-to-LEO communications. It is only one of two (together with the Spire OCT) that is UK sourced that will address the LEO-to-LEO challenges that are agency funded (rather than commercially funded).

Table 6. Planned future payloads that provide laser communications capability in LEO, ordered by mass (kg) from high to low.

Corporation	Payload Name	Max. Data Rate (Gbps)	Link Type	Volume (cm^3)	Power Consumption (W)	Mass (kg)	Release (O:Operational, D:Development)
TESAT	LCT 135	1.8	GEO	252,000	~150	~53	O
Mynaric	CONDOR Mk3	2.5	LEO	32,422.5	-	-	O
TESAT	SCOT-80	10	LEO	54,109	60–86	~12.5	O
OneWeb [73]	Gen 2 Terminal	20	LEO	3750	70	25	D
UKSA, Northumbria Uni.	FOCUS	>1	LEO	3 U	40	3.6	D
NASA, MIT, Uni. of Florida	CLICK B/C	>0.02	LEO	1.3 U	-	-	D
TESAT [12]	SCOT20	2.5, 0.1	LEO	1135 (1U)	<35	<1.6	D

3.5. Autonomous Laser Inter-Satellite Gigabit Network (ALIGN) and the FOCUS (Free-Space Optical Communications Unit for Satellites) Solution for LEO-to-LEO Platforms

The ALIGN mission is designed to carry out an in-orbit demonstration of a novel laser communication system in LEO using two 6U CubeSats. We refer to the lasercom system herein as the Free-space Optical Communications Unit for Satellites (FOCUS) as the primary payload for each CubeSat. The aim of the mission is to establish Gbps full-duplex communication links autonomously, with a ranging capability of up to 1000 km and with SWaP requirements that are suitable for small- to nano-satellites in data-intensive constellations in LEO. The novel aspect of the FOCUS design includes (i) incorporation of a PAT approach that adheres to the Space Development Agency (SDA) standards; (ii) a powerful System-on-chip (SoC) communication device control board; and (iii) compact telescope integration. The proposed system offers efficient scalability, allowing for potential applications involving LEO-LEO, LEO-GEO, and LEO-ground resilient communications capable of networking mega-constellations.

Figure 3 represents the CAD design of FOCUS payload. The payload contains three main sections: (i) the top section contains the transmitter and receiver telescopes supported by a chassis (red structure); (ii) the middle section contains the amplifiers of the laser and the controller for the fast-steering mirror, held together by a cradle (grey structure); and (iii) the bottom section is where the Optical Interface Assembly (OIA) PCB stack is located. The primary function of this section is to manage the payload electronics, which include important components such as power management modules, data processing boards, and control electronics. The stack also controls the telescope actuation in addition to driving the high-speed communications. The actuators provides line-of-sight stabilization, micro-scanning, tracking, and fine pointing, essential for the PAT process.

3.5.1. Key Operational Features of ALIGN

Figure 4 depicts the concept of operation for the link acquisition process of ALIGN in LEO. The PAT process is highly challenging when considering two moving satellites with the relatively large uncertainties in real time, which progressively worsen due to minor variations in atmospheric drag. The uncertainties are represented by yellow circles along the orbital path (black dash line) with respect to transmitter Tx and receiver Rx satellite. As shown in Figure 4, the transmitter satellite must spiral the laser beam to search for the receiver and at the same time the receiver must be correctly orientated such that the transmitter is within the field of view (FoV) of the receiver’s detector (green and blue cones).

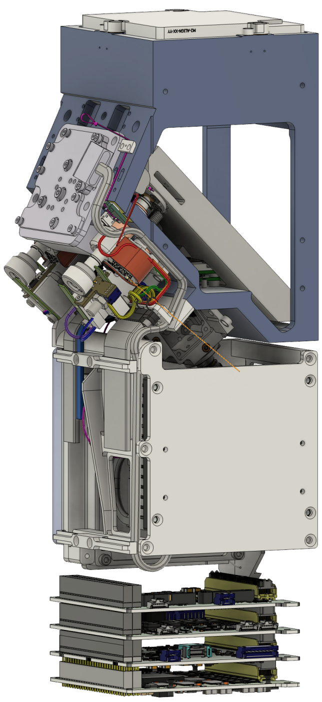

Figure 3. Current design of FOCUS.

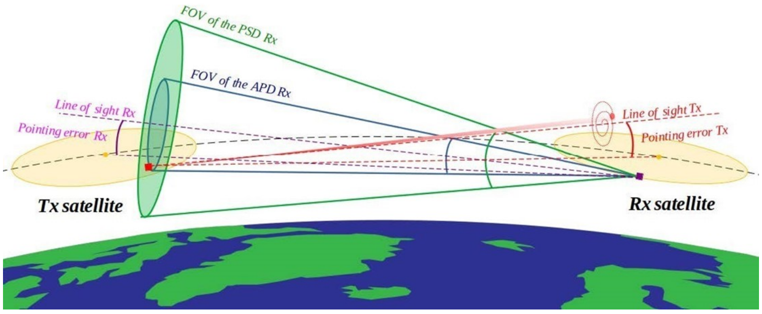

Figure 4. Mission concept in space, showing positional uncertainties (yellow circles) along the dashed path, with Tx and Rx alignment in green and blue cones.

The PAT system of ALIGN adopt spiral scans to ensure optimal coverage of search areas, which reduces the link acquisition time. Attitude Determination and Control System (ADCS) errors, which can cause pointing inaccuracies due to satellite movement, are mitigated by the system's adaptability, improving PAT precision. This adaptability is crucial for maintaining stable links between fast-moving satellites, even in environments with fluctuating signal-to-noise ratios or external interferences.

3.5.2. Link Budget

Table 7 presents a performance comparison between the proposed FOCUS link budget and other laser communication systems used on application scenarios [13,74]. The results indicate that FOCUS is comparable in terms of size, mass, data rates, pointing accuracy, and optical power requirements. Also, the FOCUS link-budget analysis confirms that by adjusting two fundamental parameters, i.e., the beam divergence and the transmit power, the same terminal design could also be adapted to serve a variety of communication scenarios, as also demonstrated by the different models of [13]. The market trend for next-generation laser communication terminals shows a shift toward smaller with extended link acquisition capabilities. However, the key factor for any commercially viable product will be its adaptability to various communication scenarios. The primary distinction between FOCUS and the other models discussed is that FOCUS is specifically designed for inter-satellite communication, which involves a significantly more complex PAT process. FOCUS's ability to autonomously establish a link between two fast-moving satellites is a groundbreaking technological advancement, critical for large satellite constellations that support high-speed global communication networks.

Table 7. Link budgets of the application scenarios.

Parameter	HAPS → OGS	LEO → GEO	LEO → OGS	Drone → OGS	LEO → LEO
	Referenced in [13]				ALIGN
Tx Power (W)	3	2	2	0.1	0.75
Transm. aperture (cm)	9	9	9	3	1.5
Pointing accuracy (µrad)	5	5	5	5	5
Beam divergence (µrad)	200	30	30	500	150
Distance (km)	100	37,000	1200	10	900
Footprint (m)	20	1110	36	5	112.5
Atmospheric attenuation (dB)	6	-	6	6	-
Pointing loss (dB)	1	2.2	2.2	1	<1
Tx loss (dB)	3	3	3	3	1.690
Rx aperture (cm)	9	15	30	9	9.57
Rx loss (dB)	10	6	12	10	1.690
Rx power (dBm)	−32	−55.6	−31.8	−34.9	−35.895
Bit rate (Gbps)	10	0.1	10	10	1.25
Required power (dBm)	−38.9	−58.9	−38.9	−38.9	−35.895
Margin (dB)	6.8	3.3	7.1	4	-

4. Conclusions

Space-based FSO systems have emerged as a viable solution for high-speed, long-distance, and secure communication compared to traditional RF communication systems used on satellites. While longer-distance links such as GEO-GND and GEO-to-LEO have been preferred in previous missions due to their less demanding pointing requirements, the deployment of FSO-based LEO-to-LEO communication systems is gaining traction. These systems offer reduced signal latency thanks to their proximity to Earth compared to GEO satellites. Hence, they provide high-speed, secure, and reliable data transmission, addressing the limitations of current communication technologies and meeting the future demands of global connectivity and space exploration.

This paper summarized the global effort in terms of current and future missions and payloads associated with FSO links deployed in space from commercial and non-commercial perspectives. In addition, a comparative analysis in terms of latency reliability, data rate, and power consumption was introduced. The work emphasized on the development of compact and power-efficient laser communication terminals that are suitable for small satellite platforms and CubeSats and demonstrates how the emerging trend towards mega-constellations of small, interacting satellites, a topic that has not been extensively covered in earlier surveys.

As part of the discussion on the growing interest in future LEO missions, we provided a brief overview of our ALIGN planned mission, along with a brief overview on the main key operational features in terms of PAT and link budget analysis.

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Abbreviations

The following abbreviations are used in this manuscript:

FSO	Free-Space Optical
GEO	Geostationary orbit
GOPEX	Galileo Optical Experiment
HAP	High Altitude Platform
IMDD	Intensity Modulation with Direct Detection
JAXA	Japan Aerospace Exploration Agency
LCE	Laser Communication Equipment
LEO	Low Earth Orbit
LUCE	Laser Utilizing Communication Equipment
MEO	Medium Earth Orbit
NASA	National Aeronautics and Space Administration
NFIRE	U.S. Missile Defense Agency satellite
OCSD	Optical Communications and Sensor Demonstration
OGS	Optical Ground Station
OICETS	Optical Inter-orbit Communication Engineering Test Satellite
OOK	On-Off Keying
OPALS	Optical Payload for Lasercomm Science
OIA	optical interface assembly
PAT	Pointing Acquisition and Tracking
PCB	Printed Circuit Board
PSD	Position-sensitive detector
SDA	Space Development Agency
SILEX	Semiconductor-laser Intersatellite Link Experiment
SoC	System-on-chip
SOTA	Small Optical Transponder
SSM	Slow Steering Mirror
STROPEX	Stratospheric Optical Payload Experiment
SWaP	Size, Weight, and Power

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