IAC–24–B2,IP,24,x83965

# Towards the Smallest Inter-Satellite Terminal

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## Abstract

The demand for higher data rates is on the rise in inter-satellite space communication. With the increased development of sub-cubesat systems, a pressing need for the development of innovative optical communication solutions is growing. This paper aims to derive the top-level requirements and constraints for the development of a miniaturised laser inter-satellite link (L-ISL) terminal for commercial and military applications. Recently, optical laser-based communication systems have been implemented and demonstrated in orbit and in inter-satellite applications. These systems have superior performance metrics compared to the capabilities of radio frequency (RF) and microwave systems. As the number of small- and nanosatellites is exponentially increasing, future spacecraft networks will require L-ISL terminals operating under more stringent size, weight, and power (SWaP) budgets compliant with the spacecraft and mission use cases. This research builds upon a comprehensive literature survey on the state-of-the-art L-ISL systems, focusing on the critical aspects of the terminal SWaP requirements. The aim is to develop classes of miniaturised L-ISL that bring value to identified spacecraft missions. First, a survey that encompasses a thorough analysis of existing research and developments in space laser communication technologies is presented, highlighting key advancements, challenges, and emerging trends. Additionally, a feasibility study of implementing L-ISL systems in picosatellite missions is shown, highlighting the trade-offs made for performance in view of miniaturisation for typical operation scenarios. In the pursuit of optimising SWaP for picosatellite deployments, this work explores technological innovations and performance trade-offs associated with miniaturising L-ISL terminals. Emphasis is placed on identifying scalable solutions that balance SWaP constraints with the need for reliable, high-throughput communication capabilities. This study aims to provide an overview of the current landscape and analyse the viability of miniaturising a L-ISL for picosatellite applications. The findings of this literature and feasibility research are expected to provide a system model for the future design and implementation of laser communication system for small satellites. As the demand for efficient and secure L-ISL communication grows, optimising LCT SWaP for picosatellites becomes crucial for exploring the potential applications of these miniature platforms.

**Keywords:** Laser Intersatellite Link, Space System Engineering, Optical Communication, Nanosatellites, Picosatellites

**Acronyms/Abbreviations**

Acquisition, Tracking, and Pointing (ATP)

Bit Error Rate (BER)

Consultative Committee for Space Data Systems (CCSDS)

Fast Steering Mirror (FSM)

Free Space Optics (FSO)

Geostationary Earth Orbit (GEO)

German Aerospace Center (DLR)

Inter-Satellite Link (ISL)

Laser Communication Terminal (LCT)

Laser inter-Satellite Link (L-ISL)

Low Earth Orbit (LEO)

Medio Earth Orbit (MEO)

Micro-Electro-Mechanical Systems (MEMS)

National Aeronautics and Space Administration (NASA)

National Institute of Information and Communications Technology (NICT)

On-Off Keying (OOK)

Optical Communication and Sensor Demonstration (OCSD)

Quadrature Phase Shift Keying (QPSK)

Radio Frequency (RF)

Size Weight and Power (SWaP)

Small Optical Transporder (SOTA)

Technology Readiness Levels (TRL)

Very Small Optical Transponder (VSOTA)

## 1. Introduction

The rapid evolution of satellite technology, such as higher efficiency and compact sensors and detectors allow for higher data production in space [1]. Consequently there is an increasing demand for higher data rates and lower latency which has positioned optical communication as a cornerstone for future inter-satellite communication [2]. An example of the growing data rate trend is shown in Figure 1.

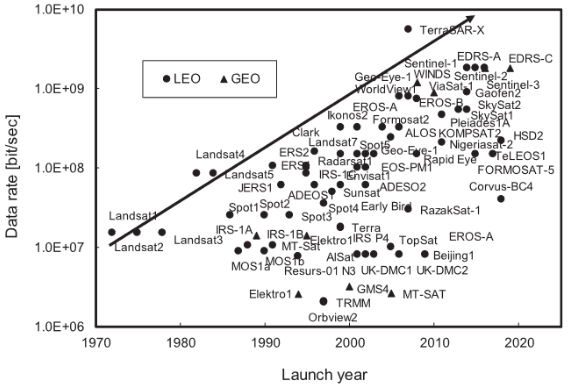
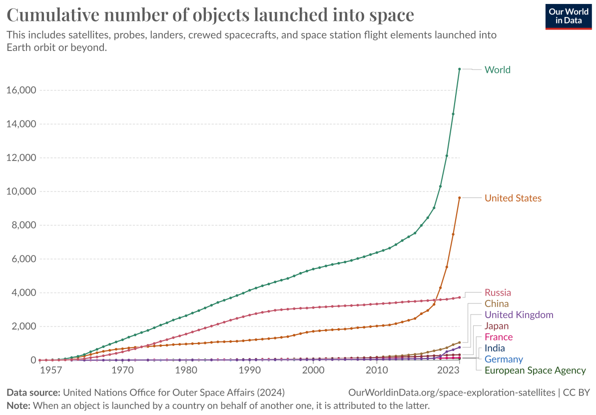


Fig. 1. Trends in Earth observation satellites with respect to their data rate (Credits: Toyoshima, 2021) [3].



Data source: United Nations Office for Outer Space Affairs (2024) OurWorldinData.org/space-exploration-satellites | CC BY
Note: When an object is launched by a country on behalf of another one, it is attributed to the latter.

Fig. 2. Cumulative number of objects launched into outer space [4].

The last decade, the number of satellites and spacecrafts launched is increasing. Figure 2 depicts the overall number of objects launched into space since the second half of the $20^{th}$ century. Similarly for the systems within the nanosatellite, CubeSat and sub-CubeSat classes, their number continues to grow [5]. These smaller classes of satellites have become a pivotal element in the development of low Earth orbit satellite information networks, as well as in space exploration, technical validation, and scientific research [6]. The benefits revolve around their high performance, cost efficiency, rapid responsiveness, and other advantageous properties. Researchers in Europe, the United States, and Japan have undertaken comprehensive and in-depth studies of the essential technologies for laser communication terminals (LCT) on CubeSats, achieving significant on-orbit validations [7]. As such, nanosatellites are often proposed for satellite networks of hundreds or thousands of satellites with intersatellite communication capabilities [8] [9].

At the same time, the need for global satellite communication services has resulted in a variety of satellite networks and mega-constellations to be launched or planned for the future by many countries [10], [11], [12]. It is expected that from 2020 to 2030, 85% of all satellites launched will be part of satellite constellations [13].

As the miniaturisation of satellites continues, there is an urgent need to develop communication systems that can deliver high performance while operating within the stringent size, weight, and power (SWaP) constraints typical of smaller platforms such as picosatellites [14] [15]. However, the miniaturisation of L-ISL terminals to suit these SWaP budgets poses a significant engineering challenge given the power and thermal management and the precise pointing required.

This paper aims to address this challenge by identifying and analysing the requirements and constraints necessary for the development of such miniaturised L-ISL terminals. In section 2, a literature survey of the current state-of-the-art in miniaturised space laser communication is presented. Previous research has presented miniaturised LCTs but mainly focused on satellite-to-ground links and CubeSat or larger spacecrafts [16]. This research highlights key technological advancements, emerging trends, and the different considerations for miniaturisation. This study evaluates the SWaP necessary to achieve a viable communication solution, considering typical operational scenarios and mission requirements. In section 3, a simplified analysis of a potential picosatellite L-ISL is shown. The research not only identifies the challenges of scaling down L-ISL systems but also suggests potential future solutions that could enable these systems to meet the rigorous demands of modern space missions.

## 2. State of the Art

In this section the current lasercom systems employed for L-ISL are discussed. First an overview of the characteristics of the LCTs is given. In subsection 2.3, the different applications of LCTs are then discussed and design considerations and limitations are presented.

### *2.1 RF and Optical Communication Systems*

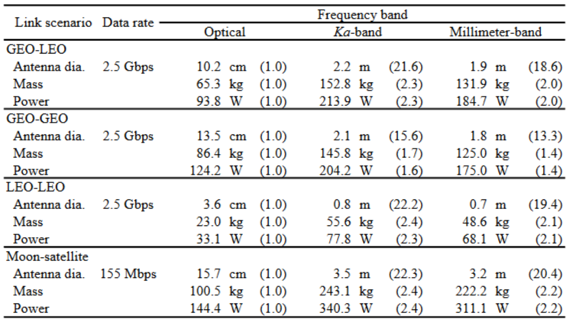
Communication systems perform three primary functions: receiving commands from Earth (uplink), sending data back to Earth (downlink), and exchanging information with other satellites (crosslink or inter-satellite link). There are two main types of communication systems: radio frequency (RF) and free space optical (FSO), the latter also known as laser communications or lasercom. The majority of spacecraft communication systems utilise RF technology, typically operating within the radio bands ranging from 300 MHz to 40 GHz [16].

Traditional RF and microwave systems, which have long been used for satellite communication, are facing limitations in terms of bandwidth, data rates, and susceptibility to interference [17]. Today, nanosatellites exploit telecommunication subsystems based on UHF, S, or X band to transmit data, with bit rates bounded from few kbps to some tens of Mbps. Ka–band is an emerging technology which is not a standard in the nanosatellite community yet [18]. With regards to the intersatellite links (ISLs) between nanosatellites, there have been some recent developments using S–band systems, but the in-flight performance in terms of bit rate are not useful for commercial purposes, achieving just $1\,\mathrm{kbit\,s^{-1}}$ over few hundred km [19].

In contrast to RF systems, laser communication systems improve SWaP efficiencies while reducing costs [20]. Features such as wide spectral ranges and narrow beam widths enhance link security, reducing risks such as mutual interference, jamming, and signal interception from other systems. This advancement enables applications across the commercial and defence sector [21]. These systems have already been successfully implemented and demonstrated in various space missions, proving their viability for intersatellite communication [2][22].

### *2.2 Existing Systems*

Various organisations, including NASA, DLR, MIT and others, have developed L-ISL systems, each tailored to specific mission requirements. These systems exhibit considerable variation in terms of terminal size, weight, power consumption, data rates, and modulation schemes. Please refer to Figure 5 for further characteristics of the reviewed terminals. The LCTs summarised in Figure 5 have published planned or demonstrated L-ISL communication hitherto. The missions are listed with respect to their terminal size.



| Link scenario | Data rate | Frequency band | | |
|---|---|---|---|---|
| | | Optical | *Ka*-band | Millimeter-band |
| GEO-LEO | | | | |
| Antenna dia. | 2.5 Gbps | 10.2 cm (1.0) | 2.2 m (21.6) | 1.9 m (18.6) |
| Mass | | 65.3 kg (1.0) | 152.8 kg (2.3) | 131.9 kg (2.0) |
| Power | | 93.8 W (1.0) | 213.9 W (2.3) | 184.7 W (2.0) |
| GEO-GEO | | | | |
| Antenna dia. | 2.5 Gbps | 13.5 cm (1.0) | 2.1 m (15.6) | 1.8 m (13.3) |
| Mass | | 86.4 kg (1.0) | 145.8 kg (1.7) | 125.0 kg (1.4) |
| Power | | 124.2 W (1.0) | 204.2 W (1.6) | 175.0 W (1.4) |
| LEO-LEO | | | | |
| Antenna dia. | 2.5 Gbps | 3.6 cm (1.0) | 0.8 m (22.2) | 0.7 m (19.4) |
| Mass | | 23.0 kg (1.0) | 55.6 kg (2.4) | 48.6 kg (2.1) |
| Power | | 33.1 W (1.0) | 77.8 W (2.3) | 68.1 W (2.1) |
| Moon-satellite | | | | |
| Antenna dia. | 155 Mbps | 15.7 cm (1.0) | 3.5 m (22.3) | 3.2 m (20.4) |
| Mass | | 100.5 kg (1.0) | 243.1 kg (2.4) | 222.2 kg (2.2) |
| Power | | 144.4 W (1.0) | 340.3 W (2.4) | 311.1 W (2.2) |

Fig. 3. Comparison between Optical and RF Communications Systems with Transmit Power of 10, 50, and 20 W for Optical and RF Systems, respectively (Credits: Toyoshima, 2005) [2].

The first demonstration of optical communication from a CubeSat platform was executed by the Aerospace Corporation and NASA's Optical Communication and Sensor Demonstration (OCSD) mission [23]. Although this was a downlink and not a L-ISL, it was an important stepping stone for laser communication in these smaller platforms. Integrated into a 1.5U CubeSat, these communication terminals relied solely on the spacecraft's body-pointing mechanisms. This approach was made feasible by using high-power optical amplifiers that increased beam divergence. Without employing a beacon for pointing reference, the terminals successfully reached a downlink data rate of $200\,\mathrm{Mbit\,s^{-1}}$ [24].

The National Institute of Information and Communications Technology (NICT) has developed two LCTs. The Very Small Optical Transporder (VSOTA) and its predecessor Small Optical Transpoder (SOTA) show capabilities of up to $10\,\mathrm{Mbit\,s^{-1}}$ [25] [26]. The evolution of these LCTs is the CubeSOTA opting for a LEO to GEO ISL. This mission is a 6U CubeSat with a 3U bidirectional laser terminal of $10\,\mathrm{Gbit\,s^{-1}}$ and $1550\,\mathrm{nm}$ laser of differential phase-shift keying (DPSK) modulation [27].

Another example, MIT's TBIRD system uses Quadrature Phase Shift Keying (QPSK) modulation and achieves data rates suitable for distances up to $20\,000\,\mathrm{km}$ [28]. MIT additionally has developed the CLICK-A and later CLICK-B/C [29] [30]. These LCTs have a size of approximately 1.2U and achieve about $20\,\mathrm{Mbit\,s^{-1}}$ in distances ranging from $25\,\mathrm{km}$ to $580\,\mathrm{km}$. CLICK-B and -C will be deployed from the ISS and fly in a trailing configuration, with an expected precision ranging up to a precision of $50\,\mathrm{cm}$ relative to each other [31].

In contrast, DLR's OSIRIS [32] systems are optimised for shorter distances and utilise On-Off Keying (OOK) modulation, reflecting the diversity in design approaches based on the specific operational environment and mission objectives [33]. OSIRISv1, the initial LCT of the series, launched in 2017, is capable of downlink data rates of $200\,\mathrm{Mbit\,s^{-1}}$. This LCT employs a body-pointing-only methodology for optical communication. In contrast, OSIRISv2, launched in 2016, offers enhanced capabilities with downlink speeds of up to $1\,\mathrm{Gbit\,s^{-1}}$. This LCT utilises a closed-loop body-pointing system enhanced by a beacon reference for improved pointing accuracy. The OSIRISv2 terminal is presently undergoing its commissioning process [16]. DLR has developed the OSIRIS4CubeSat transmitter, or later commercialised by TESAT CubeLCT [34]. This optical communication terminal designed to demonstrate optical downlink capabilities within the smallest form factor of 0.3U. This transmitter incorporates a Micro-Electro-Mechanical Systems (MEMS) Fast Steering Mirror (FSM) for fine pointing control. Like its predecessor a beacon system is employed for precise fine-pointing reference [35]. An adaptation of OSIRIS4CubeSat is being developed for bidirectional L-ISL, while another version of it is planned to demonstrate a Moon-Earth data link [36][37]. The next generation of the OSIRIS series, OSIRIS v3 is also under development.

The choice of operating wavelength plays a significant role in L-ISL performance. The majority of systems reviewed employ wavelengths around $1550\,\mathrm{nm}$, which is optimal for minimising atmospheric absorption and maximising data transmission efficiency. Some systems also operate at $1064\,\mathrm{nm}$, particularly for higher-power applications or specific use cases [3].

Although there are various LCTs for space to ground communication, not a lot of them are bidirectional L-ISL capable. A novel space-to-space LCT suggested by Yonsei University is VISION. The mission aims to enable formation flying between two 6U nanosatellites while maintaining a L-ISL. The bidirectional LCT hosts a deployable space telescope that enhances the optical power gain of the system, targeting $1\,\mathrm{Gbit\,s^{-1}}$ [21].

Another terminal developed by Stellar Product is LASERCUBE. This LCT has a size of 2U with aperture diameter of $40\,\mathrm{mm}$ and on-ground tested data rate of up to $100\,\mathrm{Mbit\,s^{-1}}$ [19]. Other companies like QUUB space have announced the development of LCTs that are adoptable to picosatellites (Pocketqube 1P = $5\mathrm{x}5\mathrm{x}5\,\mathrm{cm}^3$) with a communication link distance of $1000\,\mathrm{km}$ [38].

*2.3 Applications*

L-ISL systems have diverse applications, including Earth observation, data relay networks, and deep-space communication. Emerging use cases include Low Earth Orbit (LEO) to Geostationary Earth Orbit (GEO) links and LEO to lunar communication [39]. Additionally, there is growing interest in swarm configurations where a master satellite controls several slave satellites through optical links, a configuration that enhances the scalability of communication networks in space [40]. Similarly, nanosatellites have been studied for satellite formations, where optical communication can facilitate the communication and data exchange between the formation nodes [41]. The use case for LCTs highly correlates to the configuration of the satellites. L-ISLs can take place between satellites in the same orbital plane (intra-orbital plane, same velocity) or between satellites in two different orbital planes (inter-orbital plane) [11]. A summary of L-ISL communication applications is depicted in Figure 4.

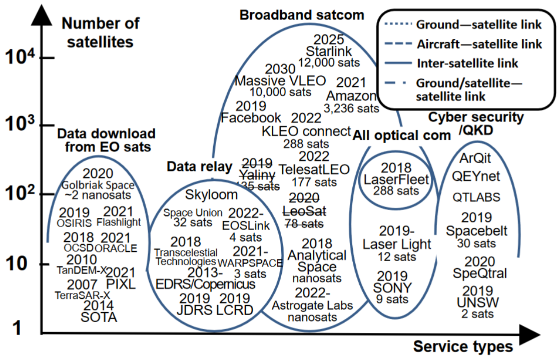


Fig. 4. Applications and link types for space laser communication (Credits: Toyoshima, 2023) [42].

The LCT-equipped systems then can achieve ISLs that are beneficial for [43]:

1. Earth Observation Constellations: Smaller satellites equipped with imaging payloads can form constellations to provide frequent and high-resolution Earth observation data. L-ISLs allow these satellites to communicate and synchronise their observations, enabling continuous monitoring of specific regions with rapid data collection and transmission.
2. Disaster Monitoring and Response: During natural disasters such as earthquakes, hurricanes, or wildfires, picosatellite constellations with L-ISLs can provide real-time imagery and data to aid in disaster assessment and response efforts. This information helps emergency responders prioritise and coordi-

nate their actions.

3. Climate Monitoring: Satellites equipped with sensors for measuring atmospheric parameters like temperature, humidity, and greenhouse gas concentrations can form constellations for global climate monitoring. L-ISLs enable these satellites to exchange data and collaborate in studying climate patterns and predicting weather events with higher accuracy.

4. Navigation and Positioning: L-ISLs can be used in satellite constellations to improve global navigation and positioning systems. By exchanging precise timing and positioning data between satellites, they enhance the accuracy and reliability of satellite-based navigation services, particularly in areas with limited ground infrastructure or challenging terrain.

5. Interplanetary Exploration: Smaller spacecrafts deployed in interplanetary missions can use L-ISLs for communication and coordination with larger spacecraft or orbiters. They can relay scientific data, images, and telemetry back to the main spacecraft or Earth, enabling extended mission capabilities and facilitating collaborative exploration of celestial bodies.

6. Space Traffic Management: With the increasing congestion in space and the growing number of satellites, L-ISL-enabled satellites can play a role in space traffic management. They can exchange information about their orbits, velocities, and maneuvers to avoid collisions and maintain safe distances between satellites, contributing to the sustainability of space activities.

### *2.4 Current Limitations*

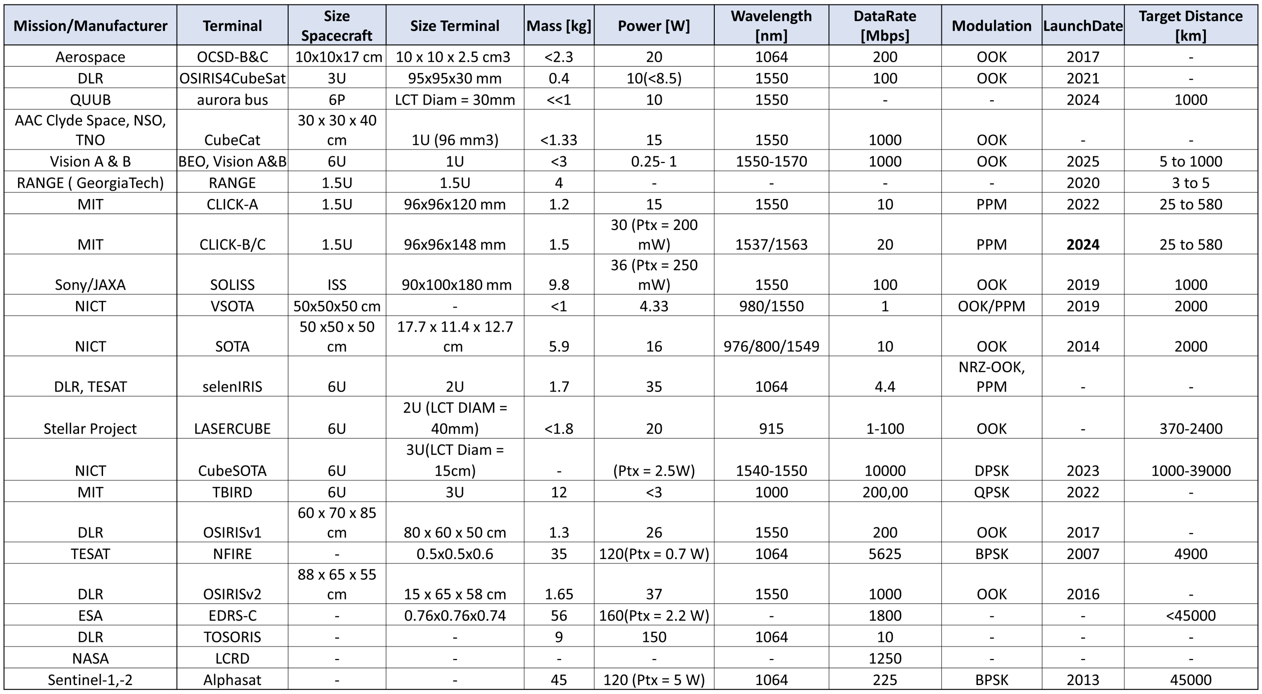
L-ISL are becoming an integral component of modern satellite communication systems due to their potential for high data rates and resistance to interference compared to traditional RF communications [1]. However, current implementations face several technical challenges that hinder widespread adoption.

One of the main challenges in L-ISL systems is the effect of satellite platform jitter and tracking on link stability. The delicate nature of laser communication requires precise pointing and alignment, which are disrupted by even minor vibrations, resulting in beam misalignment of the two spacecrafts. These disturbances include noises originating either from the LCT sub-assembly itself or by the satellite. The noises range from thermal and dark current shot noise to micro vibrations created by the platform such as by mechanically moving parts and gimbals jitters [44]. Additionally, the harsh space environment, which includes temperature fluctuations, radiation, and micrometeoroid impacts, further complicates maintaining a stable optical link [45]. Compared to space-to-ground communication, L-ISL do not have to accommodate for atmospheric attenuation [46]. Nonetheless, an important consideration on the receiver of an L-ISL is the background noise sources that need to be accommodate for. These include the detector dark current, as well as scattering of stray light and the stellar or celestial radiant fluxes. Another issue for L-ISL resides in the relative motion of the two communication nodes. In order for the transmitting LCT to be able to reach the receiving one, the return signal transmitted need to be an offset from the apparent location of the beacon. This is called Point Ahead Angle. Furthermore, the relative motion results in Doppler shift, which leads to frequency variations that affect signal acquisition and tracking [47]. Background noise sources, such as solar radiation and cosmic rays, also degrade signal quality. The satellite must maintain communication with angular precision better than a few microradians, even when the host satellite is subjected to vibrational disturbances.These factors necessitate the optimisation of Acquisition, Tracking, and Pointing (ATP) mechanisms, which are critical for establishing and maintaining stable L-ISL connections [48].

### *2.5 Size, Weight, and Power (SWaP) Considerations*

A critical factor in the design of L-ISL systems is the minimisation of SWaP, particularly for small satellite applications. For the design of LCTs for nanosatellite platforms, the tight volume restrictions is often a major hindrance. Furthermore, an additional challenge for L-ISLs stems from the fact that both communication terminals are resource-constrained when deployed onboard spacecrafts. LCT systems rely predominantly on the satellite's body pointing to direct the LCT toward the target. The requirement for beam pointing with microradian precision poses major challenges, in particular in smaller platforms. The available stabilisation control in sub-CubeSat platforms is not thoroughly developed for these accuracy levels. Potentially the utilisation of an internal fine-pointing mechanism could attain the required pointing precision [22]. The limited volume and compact packaging inherent to small satellite platforms present significant challenges in designing low-SWaP LCTs. Thermal management during operation is also problematic, as the minimal surface area available for radiators hampers effective heat dissipation. Power limitations arise due to the restricted space for solar arrays and secondary battery systems.

Further design constraints and requirements are discussed in [49] and relative literature. The main classification of



| Mission/Manufacturer | Terminal | Size Spacecraft | Size Terminal | Mass [kg] | Power [W] | Wavelength [nm] | DataRate [Mbps] | Modulation | LaunchDate | Target Distance [km] |
|---|---|---|---|---|---|---|---|---|---|---|
| Aerospace | OCSD-B&C | 10x10x17 cm | 10 x 10 x 2.5 cm3 | <2.3 | 20 | 1064 | 200 | OOK | 2017 | - |
| DLR | OSIRIS4CubeSat | 3U | 95x95x30 mm | 0.4 | 10(<8.5) | 1550 | 100 | OOK | 2021 | - |
| QUUB | aurora bus | 6P | LCT Diam = 30mm | <<1 | 10 | 1550 | - | - | 2024 | 1000 |
| AAC Clyde Space, NSO, TNO | CubeCat | 30 x 30 x 40 cm | 1U (96 mm3) | <1.33 | 15 | 1550 | 1000 | OOK | - | - |
| Vision A & B | BEO, Vision A&B | 6U | 1U | <3 | 0.25- 1 | 1550-1570 | 1000 | OOK | 2025 | 5 to 1000 |
| RANGE ( GeorgiaTech) | RANGE | 1.5U | 1.5U | 4 | - | - | - | - | 2020 | 3 to 5 |
| MIT | CLICK-A | 1.5U | 96x96x120 mm | 1.2 | 15 | 1550 | 10 | PPM | 2022 | 25 to 580 |
| MIT | CLICK-B/C | 1.5U | 96x96x148 mm | 1.5 | 30 (Ptx = 200 mW) | 1537/1563 | 20 | PPM | **2024** | 25 to 580 |
| Sony/JAXA | SOLISS | ISS | 90x100x180 mm | 9.8 | 36 (Ptx = 250 mW) | 1550 | 100 | OOK | 2019 | 1000 |
| NICT | VSOTA | 50x50x50 cm | - | <1 | 4.33 | 980/1550 | 1 | OOK/PPM | 2019 | 2000 |
| NICT | SOTA | 50 x50 x 50 cm | 17.7 x 11.4 x 12.7 cm | 5.9 | 16 | 976/800/1549 | 10 | OOK | 2014 | 2000 |
| DLR, TESAT | selenIRIS | 6U | 2U | 1.7 | 35 | 1064 | 4.4 | NRZ-OOK, PPM | - | - |
| Stellar Project | LASERCUBE | 6U | 2U (LCT DIAM = 40mm) | <1.8 | 20 | 915 | 1-100 | OOK | - | 370-2400 |
| NICT | CubeSOTA | 6U | 3U(LCT Diam = 15cm) | - | (Ptx = 2.5W) | 1540-1550 | 10000 | DPSK | 2023 | 1000-39000 |
| MIT | TBIRD | 6U | 3U | 12 | <3 | 1000 | 200,00 | QPSK | 2022 | - |
| DLR | OSIRISv1 | 60 x 70 x 85 cm | 80 x 60 x 50 cm | 1.3 | 26 | 1550 | 200 | OOK | 2017 | - |
| TESAT | NFIRE | - | 0.5x0.5x0.6 | 35 | 120(Ptx = 0.7 W) | 1064 | 5625 | BPSK | 2007 | 4900 |
| DLR | OSIRISv2 | 88 x 65 x 55 cm | 15 x 65 x 58 cm | 1.65 | 37 | 1550 | 1000 | OOK | 2016 | - |
| ESA | EDRS-C | - | 0.76x0.76x0.74 | 56 | 160(Ptx = 2.2 W) | - | 1800 | - | - | <45000 |
| DLR | TOSORIS | - | - | 9 | 150 | 1064 | 10 | - | - | - |
| NASA | LCRD | - | - | - | - | - | 1250 | - | - | - |
| Sentinel-1,-2 | Alphasat | - | - | 45 | 120 (Ptx = 5 W) | 1064 | 225 | BPSK | 2013 | 45000 |

Fig. 5. LCTs planned or reported to be used for L-ISL in nanosatellites.

the design considerations are split in mission constraints, specifications imposed by the platform and imposed by communications. Mission constraints include space environment and cost . The platform specifications focus on the mass, aperture size, power and attitude control accuracy. The communication or sub-system specification revolve around details of the ISL such as low loss requirement and range of the communicating spacecrafts.

Several studies, such as [50], have outlined the SWaP requirements for small satellite communication systems, focusing on 3U CubeSats and smaller platforms. These platforms typically operate with power constraints below 15 W, necessitating the optimisation of all subsystems, including the LCTs. The trade-offs between power consumption, data rate, and terminal size are key considerations in the development of L-ISL systems for both commercial and defence applications [50]. The main considerations for small satellites and sub-CubeSat platforms lie on the attitude control capabilities. Additionally, the available power on board is limited, meaning that L-ISL would only be possible for smaller distances.

## 3. Basic Analysis and Feasibility

In [22] a flow down of requirements is shown for the development of a transceiver. This procedure includes definition of subsystem characteristics, identification of technology readiness levels (TRL) and identification of assumptions and constraints needed for the mission. However, in order to assess the feasibility of LCTs for sub-CubeSats, the definition of the link geometries that will be supported need to be evaluated [51]. The smaller spacecraft subclass following CubeSats is PocketQubes [14]. As such, the volume restrictions of such a platform need to be respected as well as their power restrictions.

Based on the trends seen in section 2, various LCT characteristics were assumed to simplify the analysis. These assumptions include:

- **Optical Antenna Efficiency**: $0.8$
- **Antenna Aperture Diameter**: $0.005\,\mathrm{m}$ (same for transmitting and receiver)
- **Pointing Error**: $80 \times 10^{-6}$ radians
- **Data Rate**: $100\,\mathrm{Mbit\,s^{-1}}$
- **Wavelength**: $1550\,\mathrm{nm}$
- **Required Signal Power**: $-110$ dBm
- **Transmitted Power**: $26$ dBm
- **Beam Divergence**: $41\,\mu\mathrm{rad}$

The analysis approach that was applied is very similar to

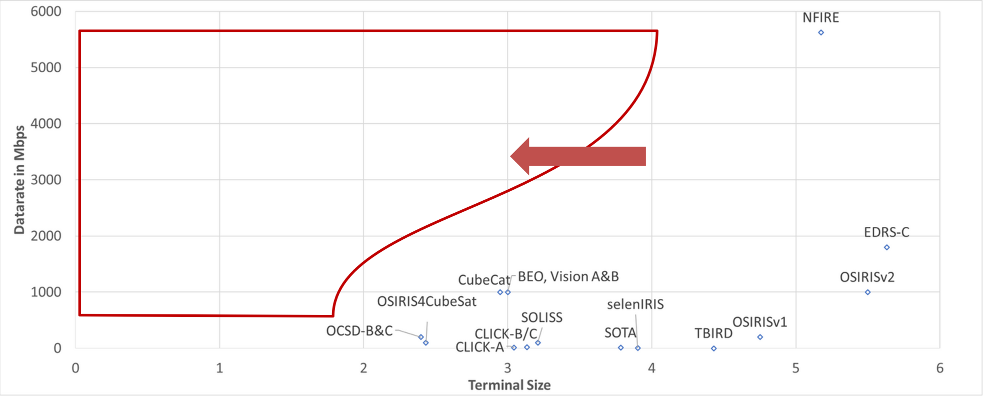


Fig. 6. Graphical representation of miniaturised L-ISL LCTs and their data rate with respect to the terminal volume, showing the technological gap for smaller terminals.

that of a conventional communication link budget. The performance of an optical communication system is commonly evaluated in terms of link margin [52]. A positive link margin indicates that the link has enough power to overcome the total attenuation in the receiver's end. A negative link margin indicates that the received signal is too weak for communication to function properly.

To compute the link margin in dB, use this equation:

$$LM = P_{rx} - P_{req}$$

where: $P_{rx}$ is the received signal power in dBm and $P_{req}$ is the required signal power to achieve a specific bit error rate (BER) at a given data rate in dBm.

Ultimately, the link margin is a critical metric that indicates whether the received signal power is sufficient to meet the BER requirements of the system. The basic analysis described here models the satellite properties, optical link characteristics, and computes critical parameters such as gain, pointing loss, and path loss. The link margin is solely determined based on these calculations for varying distances between satellites. The distances are determined based on the trajectories given to two spacecrafts acting as communication nodes. The modelled trajectories of the spacecrafts include LEO, GEO and Medium Earth Orbit (MEO) orbits. The ISL simulated include LEO to LEO, in trailing and different orbit configuration, LEO to GEO, GEO to MEO and MEO to LEO. The timespan of the simulation was set to 3 years. The orbital altitudes given to the satellites are:

- LEO 1: 479 km
- LEO 2: 479.01 km
- LEO Diff: 600 km
- GEO: 35 793 km
- MEO: 5629 km

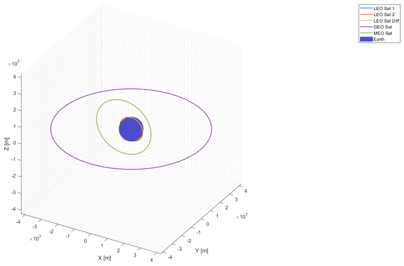


Fig. 7. Modelled trajectories of the communicating satellites over 3 years. Note: 'LEO Sat 1' and 'LEO Sat 2' are in trailing configuration while 'LEO Diff' is in a different LEO orbit.

### *3.1 Satellite and Link Characteristics*

Each satellite in the system is characterised by its physical properties, such as aperture diameter and pointing accuracy. These parameters are assumed to be the same for both spacecrafts. The link characteristics are also provided, including parameters such as the wavelength of the optical signal, the distance between the satellites.

### *3.2 Gain and Pointing Loss Calculations*

The transmitter and receiver gains are computed based on the satellite aperture diameter and the wavelength of the optical signal. These gains, represented in decibels (dB), are critical in determining the overall system performance. Additionally, the pointing loss is calculated for both the transmitting and receiving satellite. Pointing loss accounts for the degradation in signal strength caused by misalignment between the transmitter and receiver. This loss is directly proportional to the pointing error and gain.

*3.3 Path Loss and Link Margin Calculation*

For varying satellite distances, the free-space path loss ($L_{\text{fspl}}$) is calculated as shown 3.3.

$$L_{\text{fspl}} = \frac{\lambda}{4 \cdot \pi \cdot z}^{2} \qquad [1]$$

where:

- $\lambda$ is the transmission wavelength,
- z is the distance between the communicating satellites.

Path loss is a significant factor in long-distance satellite communications and is determined by the satellite distance and wavelength of the optical signal. Using these values, the function computes the link margin for each distance between the two satellites. The link margin is computed as follows:

$$LM = P_{\text{tx}} + G_{\text{tx}} + G_{\text{rx}} + \eta_{\text{tx}} + \eta_{\text{rx}} - L_{\text{path}} - L_{\text{pointing}} - P_{\text{req}} \qquad [2]$$

where:

- $P_{\text{tx}}$ is the transmitted power,
- $G_{\text{tx}}$ and $G_{\text{rx}}$ are the transmitter and receiver gains,
- $\eta_{\text{tx}}$ and $\eta_{\text{rx}}$ are the optical efficiencies of the transmitter and receiver,
- $L_{\text{path}}$ is the free-space path loss,
- $L_{\text{pointing}}$ accounts for the pointing losses at both the transmitter and receiver,
- $P_{\text{req}}$ is the required received power.

*3.4 Results*

The graphs of the calculated link margins for the different mission configurations are shown in Figures 8.

*3.5 Discussion*

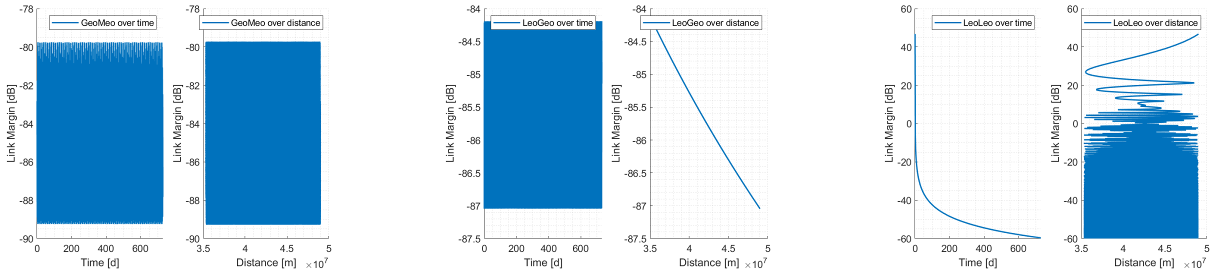
The link margin for the GEO-MEO communication link, as illustrated in Figure 8a, remains relatively stable over time, fluctuating around $-80$ dB. According to the definition of link margin, this value indicates that the received signal is below the threshold required for reliable communication. In the case of the LEO-GEO communication link (Figure 8b), the link margin stays approximately $-84$ dB over time. The negative link margin in this scenario indicates that, without corrective measures like an increase in transmitted power or enhanced receiver sensitivity, the LEO-GEO link in these platforms is impossible. Similarly, as shown in Figure 8e, the LEO-MEO communication link maintains a link margin of approximately $-68$ dB over both time and distance. For LEO-LEO communication between satellites in different orbits (Figure 8d), the link margin oscillates between $-40$ dB and $-50$ dB. The sustained negative link margin suggests that the communication link consistently suffers from inadequate signal strength. The periodic oscillations likely result from changes in relative positioning between the satellites in different orbits, which affect the path loss and, consequently, the link margin. Potentially the signal losses can be mitigated by adjusting the communication parameters or using more efficient modulation techniques.

The link margin for LEO-LEO communication, depicted in Figure 8c, shows a dramatic decline from 60 dB to approximately $-60$ dB within the first 100 days. This rapid drop implies that the communication link starts with significant excess power, but experiences severe degradation over time, likely due to dynamic changes in relative motion and line-of-sight between the satellites. As distance increases, the link margin exhibits considerable fluctuations, varying between $-60$ dB and $40$ dB. The periodicity of the fluctuations suggests that the LEO satellites' fast motion relative to one another causes frequent changes in the link quality. However, this suggests that an L-ISL might be possible for PocketQubes in trailing configuration. This is highly correlated with the possible attitude control that these platforms can offer as well as the power and thermal management.

## 4. Future Work

In this paper the L-ISL communication for nanosatellite and sub-CubeSat platforms has been addressed. The State of the Art review done reveals that various systems exist for smaller platform which have demonstrated or planned L-ISLs. An in-depth analysis of the requirements and constraints is presented which is necessary for the development of miniaturised L-ISL terminals, particularly for picosatellite platforms. The study highlights the technological advances and challenges associated with designing L-ISL systems that operate within stringent SWaP limitations, which are critical for small satellites and CubeSats. The analysis of current systems shows that while optical communication offers significant benefits in terms of data rates, security, and performance compared to RF systems, the miniaturisation of L-ISL terminals still faces substantial challenges. The key issues include ensuring stable communication under platform vibrations, thermal management, and power efficiency.

The applications of these systems extend in various fields



(a) Calculated link margin for GEO to MEO link.

(b) Calculated link margin for GEO to LEO link.

(c) Calculated link margin for LEO to LEO link in trailing configuration.

(d) Calculated link margin for LEO to LEO inter orbital plane link.

(e) Calculated link margin for LEO to MEO link.

Fig. 8

with the main trend being the usage of L-ISL in mega constellations. As such, the potential applications for these miniaturised L-ISL systems make them an essential area of research for the future of space communication networks.

The link margin analysis across different orbital configurations of picosatellites reveals that GEO-MEO and LEO-MEO links, with the current system configuration, is insufficient for reliable communication. The LEO-LEO links are the most variable, particularly in the same orbit, where rapid changes in relative position lead to significant fluctuations in the link margin. Periods of positive link margin in the LEO-LEO scenario highlight moments of reliable communication, while the negative margins indicate frequent outages. These results underline the importance of optimising both transmission power and receiver sensitivity to achieve consistent and reliable communication across different orbital configurations.

Although several aspects of L-ISL have been covered, further work is needed to increase the depth of investigation at various levels. The analysis presented in the paper had various assumptions that would need to be optimised. Previous research has given guidelines for link analysis optimisation, visibility and key design drivers that need to be taken into account for L-ISL [10] [53] [22]. An analytical model would need to be constructed that would investigate further the correlation between the optical parameters of the system, such as wavelength, range, aperture diameter and power to achieve feasible beam divergence and pointing accuracy requirements. For example, the assumed communication wavelength in this analysis was 1550 nm while other systems have previously used laser of 847 nm or 1064 nm [54]. Since L-ISL are not affected by the atmospheric attenuation, other possible wavelength outside the previously used ones would need to be assessed. At the same time, the BER of such a communication needs to be acceptable and comparable over that offered from current RF systems for these platforms. The Consultative Committee for Space Data Systems (CCSDS) has various recommended standards for the design of LCTs [55]. These include various modulation schemes commonly used in L-ISLs such as OOK and Pulse Position Modulation (PPM). These modulations would also need to be assessed for the link optimisation of picosatellites. The theoretical results of the critical design drivers would then need to be confirmed with the availability of hardware components that can satisfy their requirements [56]. Future research should benefit from the low costs and time to market of these smaller platforms. Practical demonstrations of these terminals in real satellite missions, focusing on communication stability, link margins, and data throughput have to be occur. By addressing these areas, miniaturised L-ISL systems could become a critical enabler for the next generation of satellite communication networks, transforming both commercial and scientific missions.

## Acknowledgements

This research was funded in whole, or in part, by the Luxembourg National Research Fund (FNR), grant reference [FNR17791622]. For the purpose of open access, and in fulfilment of the obligations arising from the grant agreement, the author has applied a Creative Commons Attribution 4.0 International (CC BY 4.0) license to any Author Accepted Manuscript version arising from this submission.

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