Optical inter-satellite link demonstration on CubeSats – Update on the CubeISL-IOD mission

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ABSTRACT

Free-space optical communication has become a mature technology to extend and replace classical radio channels for data transmission from satellites to the Earth. The advantages of high data throughputs, resilience against electromagnetic disturbances and its robustness against jamming spoofing and eavesdropping makes laser communication attractive for governmental, defense authorities and commercial users. To enable global connectivity and interoperability beyond the line of sight, inter-satellite links are required and therefore terminals with high data rates are necessary to avoid communication bottlenecks. Size weight and power limitations on spacecraft demand highly efficient and miniaturized payloads, especially for use cases on smallest satellites.

The German Aerospace Center (DLR) developed laser communication terminals especially designed for CubeSats. The next step is to transfer this technology from direct-to-Earth into the inter-satellite domain. Thus, DLR developed the CubeISL terminal to establish an optical connection between two identical terminals to exchange information with a data rate of 100 Mbps over distances of up to 1,500 km. The standardized formfactor of just 1U allows easy and simple integration into standard CubeSat busses and the separation of the receiver and transmitter signal by wavelength allows building up constellations containing multiple satellites.

The capabilities of the CubeISL terminals will be demonstrated in a relevant, operational scenario on two 6U CubeSats built by the Spanish company Alén Space. The mission is led by Responsive Space Cluster Competence Center and the satellites will be operated by the German Space Operations Center, both as parts of DLR.

This paper gives an update on the latest state of the project. It depicts the status of the terminal development as the key component of the in-orbit demonstration mission. The two carrier platforms are described briefly and their concept is explained. Laser communication is highly dependent on the pointing performance and a stable orbit control. In addition, the capabilities of the optical connection will be demonstrated and evaluated in different distances. All this

leads to strict requirements for the satellites, especially for the attitude and orbit control system. The concept to achieve this precision and accuracy is briefly discussed.

Furthermore, the paper describes the mission architecture and the operations concept. Different communication standards used in the terminal, the satellite and the ground segment require an aligned coordination of the protocols and standards. Alén Space will take care of the satellites during the launch and early orbit phase and hand over the satellite to DLR afterwards. This transition and the following operations concept of the laser experiments are briefly discussed as well.

INTRODUCTION

Global connectivity is the key to linking distant areas with each other. Satellite communication is therefore a widely used tool to transfer information over large distances.[1] Beside the research and commercial sector, also critical infrastructure like governmental or defensive entities use satellite networks to coordinate and communicate.[2] Modern challenges like regional conflicts or hybrid threads can harm these critical infrastructures. Furthermore, it is necessary to react responsively on disruption events to ensure a reliable communication without any outages.

Free-space optical communications (FSOC) provides solutions to face these challenges of secure global connectivity.[3] FSOC provides communication channels which are inherently resilient against external attacks such as jamming, spoofing or eavesdropping and is therefore the method of choice. The German Aerospace Center (DLR) developed in the optical space infrared downlink (OSIRIS) program several laser communication terminals (LCT) for small satellites and CubeSats.[4,5] All of these terminals established an optical connection between a satellite and an optical ground station (OGS), i.e. they are operating solely in direct-to-Earth (DTE). The goal in the CubeISL project is to transfer this technology into the optical inter-satellite link (OISL) domain. Thus, DLR evolved the world's smallest LCT OSIRIS4CubeSat towards OISL.[6]

The terminal development is followed by an in-orbit demonstration (IOD) mission lead by the Responsive Space Cluster Competence Center (RSC³). RSC³ coordinates the satellite procurement, integration and launch as well as the operation of the IOD mission. The operation will be executed by the German Space Operation Center (GSOC) of DLR.

The satellites will be provided by the Spanish company Alén Space who will develop two 6U CubeSats, especially designed for this mission. The crucial part for laser communication is the precise and accurate orientation of the laser beams. Even though the LCTs contain a fine pointing assembly (FPA), the coarse pointing has to be performed by the satellites itself.[7] Thus, the focus of the development lies in the attitude and orbit control system (AOCS) which is developed by the Spanish company GMV.

IN-ORBIT DEMONSTRATION MISSION

The CubeISL-IOD project aims to demonstrate bidirectional optical communication between two satellites in orbit, as well as an optical DTE data link. To this end, two CubeSats are being developed, and each will be equipped with equally capable CubeISL-LCT terminals, and placed in a low-Earth orbit (LEO). The two CubeSats will demonstrate optical data transmission in space over distances of up to 1500 km with data transmission rates of up to 100 Mbit/s in formation flight. At the same time, a significantly improved downlink data rate of up to 1 Gbit/s between the CubeSat and the OGS will be demonstrated.

Modern space assets rely more and more on distributed functionalities than on monolithic solutions. Satellite constellations are on the rise as they are scalable systems and provide shorter revisit times when compared to a service on a single spacecraft. In addition, constellations are less sensitive to external influences, as individual spacecraft can be replaced after an outage or designed redundantly at the start of the mission. Thus, the CubeISL LCTs are explicitly designed with extension capabilities so that in the future several satellites can be connected in a daisy chain configuration with this technology. The CubeISL-IOD mission marks the base for future CubeSat (mega)constellations connected by OISL.

An IOD mission is a critical step for any transformative space technology, as is the case for FSOC. By proving the technology works in precursor missions in orbit, IODs lower the risk for larger, more expensive missions that depend on the system. This is especially vital for critical applications like national security. Moreover, early IODs allow engineers to identify flaws and refine designs before scaling up the systems. Without such demonstrations, even the most promising innovations remain unproven and unusable for operational systems.

Demonstrating the pointing precision and accuracy, in the order of milliradians, that is the base for stable links between fast-moving satellites or ground stations, will constitute the main challenge of the CubeISL-IOD mission. Also, ensuring compact, low-power and thermally stable optical terminals that work reliably on small satellites will also be a problem tackled during the development of the project. Additionally, mitigation strategies to reduce the weather dependency for DTE links affected by clouds will be addressed from the operational standpoint.

Beyond the well-known benefits of high-speed data rates and unprecedented data throughputs, FSOC also enable secure, resilient and responsive space operations. The narrow laser beams are harder to intercept or jam than radio signals, even when compared to state-of-the-art beam-forming radio communications, enhancing mission assurance. Even in the case of interception, such an event would be hardly pass unnoticed since the laser beam would need to be disturbed. Additionally, the use of laser communications frees the operators from the use of congested RF bands, mitigating interference and regulatory obstacles.

Despite the challenges presented with the miniaturization of the systems, CubeSats present themselves as ideal platforms for the development of IOD missions due to the large offer of commercial-off-the-shelf components (COTS) and their inter-compatibility[8]. In particular, CubeSat platforms are really cost effective, simpler, faster to develop and more flexible to put into orbit when compared to their larger counterparts[9]. These beneficial properties also enhance their use for Responsive Space missions.

LASER COMMUNICATION TERMINAL

DLR showed the advantages of precursor IOD during the PIXL-1 mission as part of the OSIRIS4CubeSat project.[10] The Institute of Communications and Navigation (IKN) had to build up the entire knowledge of a satellite mission, including satellite procurement, launch and operation during the project. In CubeISL, it was intended for IKN to focus on their core competence of developing LCTs. Thus, the project was split into two parts, the terminal development and the IOD mission, carried out by RSC³.

The built-up know-how and lessons learned could directly be transferred from OSIRIS4CubeSat to CubeISL. IKN supported RSC³ and GSOC during the mission design phase and will support during the mission's execution. Especially the requirements and specialties which are very specific for laser communication could be brought into the project with the project coordinator (RSC³), the operator (GSOC) and the satellite manufacturer (Alén Space).

The entire CubeISL project including the terminal development and the IOD mission is a New Space project which demonstrates the benefits of short development times and low development effort. For the LCT, this could be achieved by using the modular approach of re-using as many subsystems as possible and relying on already standardized processes. Thus, the optical terminal of the CubeISL LCT was based on the OSIRIS4CubeSat LCT. To transfer FSOC into the ISL domain, OSIRIS4CubeSat was extended by an optical amplifier to overcome the lack of optical power over large distances, an additional receiver for bidirectional communication and a data handling unit (DHU) for satellite independent data processing. Especially the reuse of the optical system allowed a very fast development. The tracking capabilities of CubeISL could already be demonstrated in an inter-island campaign in February 2023.[11] Especially the identical design of the FPA, taken over from the previous project, enabled this fast achievement in a very early phase of the project. Nevertheless, the link establishment in CubeISL is comparably more complex than in a DTE scenario. Therefore, IKN developed a procedure for beaconless acquisition between the two LCTs in an ISL use case.[7, 12] These processes require a high pointing precision and accuracy of the carrier platform. Thus, the development of the satellites and the AOCS (which are described in the following chapters) were done in close collaboration with IKN.

The CubeISL-IOD mission is a precursor mission to demonstrate a technology to de-risk a potential operational scenario and gain knowledge in the final environment far before the final functionality will be established in space. The goal of global interoperability – which is considered for a defensive use case – requires constellations or networks. Hence, the transmission and receive concept of the CubeISL LCT was designed that the channels are separated by wavelength. This leads to two types of terminals (A and B) where the transmission channel is the receiving channel of the partner terminal and vice versa. This enables bidirectional communication and, with two terminals (version A and B) per satellite, the establishment of a future potential constellation. Figure 1 illustrates the daisy-chain concept how to build up constellations with CubeISL LCTs.

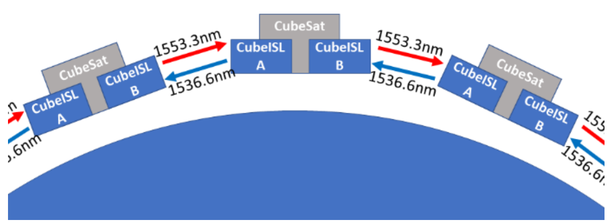

Figure 1: Constellation concept with CubeISL LCTs

Besides the technical properties of the LCT, also the processes during the development could be standardized. Tailored qualification processes were used in OSIRIS4CubeSat and could directly be transferred to CubeISL.[13] This allowed to qualify the CubeISL LCT with a very low effort and a short timeframe. Furthermore, failures during the qualification process could be avoided as most of the subsystems were already qualified or the critical parts were identified previously. To this day, the engineering qualification model (EQM) of the LCT was fully qualified and the two flight models (FM) are about to be assembled. Optical characterization and fine tuning of the pointing, acquisition and tracking principle will follow. Figure 2 shows the EQM of CubeISL integrated in a CubeSat structure during optical characterization.

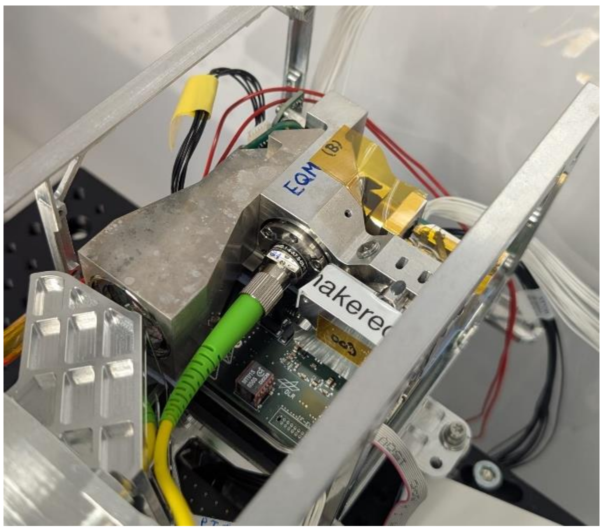

Figure 2: CubeISL EQM during optical characterization

CUBESAT PLATFORMS

The LCTs are hosted in two almost-identical 6U Platforms, which enable the IOD of these payloads. The platforms are tailored to support the operations of the payload. The main features of its subsystems are described in the following subsections. Given the importance of the development of the AOCS for this mission, it is described in its own section.

Platform Summary

The main characteristics of the mission are shown in Table 1:

Table 1: Platform Characteristics

Parameter	Value
Mass	10.2 kg
Maximum Power Generation	23 W
Maximum Power Capacity	172 W·h
Expected Orbit	510 km SSO LTAN 10:30
Delta-V capacity	260 m/s
Communication Capabilities	S-band TM/TC GNSS positioning

while a render of the current design of the platform is shown below:

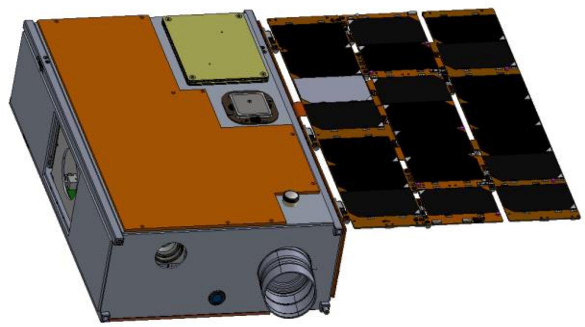

Figure 3: Platform Render

Mechanical Interface

The structure has been customized to integrate the payload directly in the main structure, with an equivalent volume of 1U.

Thermal Management

The platform includes a radiator dedicated to the thermal dissipation of the heat generated by the payload operation. For this purpose, a thermal strap is included in the design.

Power Handling

The system includes an electrical power subsystem (EPS), hosting two batteries, a power conditioning and distribution assembly and a triple deployable solar panel. This configuration ensures the survivability during critical early phases and enables a sustainability of the duty cycle required for the mission alternating pointing modes for maximum generation.

Propulsion

The platforms carry an electric propulsion system based in the gridded ion propulsion technology, which enables both the IOD of the OISL communication between both platforms at different distances, as well as an active approach to fulfill the debris policy set by the European Space Agency (ESA)[14].

Communications and data handling

For ground communication means, each platform carries two S-band patch antennas hosted on opposite facets, which enable quasi-omnidirectional coverage even in attitude-uncontrolled cases.

For internal communication means, each platform uses CAN, I2C buses, UART differential signals and Ethernet. The platform carries on board an array of internal sensors (temperature, voltage) which define the actuations of a fault-detection, isolation and recovery (FDIR) software.

ATTITUDE AND ORBIT CONTROL SYSTEM

Laser communications is highly depending on precise and accurate beam steering. As in the CubeISL-IOD, the satellites themselves will be used as a coarse pointing assembly (CPA), the attitude control of both is crucial for the mission. Thus, a lot of effort was put into the design and development of the system which is described in this chapter.

Pointing performance challenges

The main challenge for the attitude and orbit control system (AOCS) is the stringent requirements for attitude pointing. The two values used for sizing the system are:

- 0.1° for OISL experiments
- 1° for DTE experiments

These values are determined by the capability of the LCT to search for the target terminal inside its field of regard (FOR). The contribution of all possible sources of misalignment shall be equal or lower than the values presented to ensure a successful link acquisition within a reasonable time frame. The following contributors to the pointing error, and mitigation actions, have been considered in the design:

- **Misalignment between LCT and AOCS frame**, which is divided into:
    - **Mounting and internal bias**: To minimize its impact, the possibility of calibration between AOCS and LCT on ground is currently being explored. However, launch loads will settle some components, causing additional biases. Additional calibration procedures on-board can be analyzed to minimize the misalignment, such as cross-calibration of the AOCS and LCT gyroscopes to estimate their relative orientations.
    - **Thermoelastic effects**: To mitigate this effect, the platform has been designed with the star tracker (STR) and LCT as close as possible to each other to minimize the impact of thermal deformations.
- **Attitude knowledge error**: This contributor corresponds to the knowledge of the attitude state of the vehicle, and it usually has the lowest impact but its accuracy depends on the available sensor suite: During DTE, the STR will not be available because of the high angular rates required and the intrusion of the Earth in the instrument field of view (FOV). However, the fine sun sensor (FSS) and earth horizon sensor (EHS) can provide the desired knowledge accuracy. Additionally, mission design considers ISL experiments only when the Sun is not inside the exclusion angle of the STR and the LCT, which is described later in this paper.
- **Attitude control error**: For a mission in a low attitude disturbance and well-known dynamics as in this case, this contributor is negligible.
- **Relative position knowledge error:** This contributor has the highest potential impact. It is necessary to separate between:
    - **DTE:** The satellite needs to know its own position and the position of the target station. It is equipped with a GNSS receiver to estimate its own position with an accuracy of the order of 1-2 meters.
    - **OISL:** The vehicles need to know each other's positions to determine the relative state. At 500 km, the 0.1° roughly translates into 800 m of error in the direction perpendicular to the satellite's line of sight. Usual orbit determination and propagation using IGS Ultra-Rapid products can provide accuracies of a few tens of meters in cross-track and radial components for an interval of 48 hours or more, which is enough for the desired application.

To maintain the link after a successful acquisition, the AOCS uses information of the LCT command angles to improve its pointing performance. This increases the robustness of the system by ensuring that it can correct misalignments and becomes less sensitive to sensor failures.

AOCS subsystem description

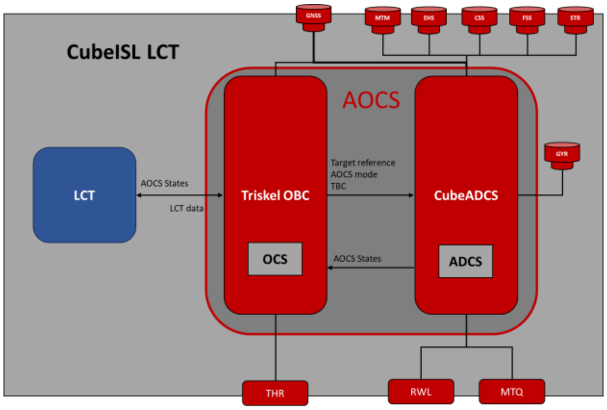

Figure 4: AOCS-LCT interface

Figure 4 shows the AOCS system architecture. The system uses a combination of Alén Space's Triskel computer as the main onboard computer (OBC), and CubeSpace's CubeADCS Gen 2 solution adapted to the specific needs of the project as attitude determination and control system (ADCS) computer. Triskel is in charge of managing the internal and external communications of the system, operator command execution, mode handling and overseeing the FDIR process, while CubeADCS oversees sensor handling, and attitude determination and control.

The sensor suite contains:

- GNSS RX for accurate position and velocity estimation
- 3-axis magnetometers for robust attitude estimation
- EHS for coarse and robust attitude estimation.
- Coarse and Fine Sun Sensors for coarse and robust attitude estimation
- STR with a baffle to provide fine attitude estimation with an exclusion angle with respect to the Sun that allows continuous experiments
- Gyroscope to support the angular rate estimation

The actuator suite contains:

- One thruster for orbit control
- Magnetorquers for detumbling, safe control and desaturation of wheels
- Reaction wheel assembly, four wheels in pyramidal configuration with vibration dampeners to minimize the vibrations imparted to the payload

The ADCS by CubeSpace contains a series of functionalities that are particularly helpful for the mission:

- Pointing to a ground station and to a target satellite, with the possibility of adding feedback from the LCT angles to improve pointing (as described previously)
- Payload protection against the Sun for contingency situations, to ensure that the Sun does not enter a cone centered around the instrument boresight

Orbit and mission analysis

The satellites' orbit has been studied to ensure that it fulfils the mission needs. The proposed orbit is a sun-synchronous orbit (SSO) with 15+1/6 and a local time of ascending node (LTAN) of 10:30 h. This leads to an orbit with a mean altitude of 510 km. The satellites are placed in two orbits with the same geometry but slightly different true anomalies to ensure a relative distance between satellites to perform OISL. This distance is changed with correction maneuvers, varying between 500 km and 1500 km in intervals of 100 km.

The available windows for OISL have been studied, as well. During the OISL experiments, the two satellites' payloads need to point towards each other to establish a link, with a direction approximately tangent to the orbit. Because of the orbital geometry and this attitude constraint, there are situations in which the experiments cannot be performed because the Sun would enter the exclusion angle of the payload and the star tracker. A rough schematic of these constraints is presented in Figure 5. Considering a sun exclusion angle of 30° for the payload, and 35° for the STR, it leads to a worst-case available time, per orbit of 63 minutes, in two symmetric windows of ~31 minutes each. These two available windows would happen during the ascending and descending nodes of the orbit, while the zones of violation appear close to the poles.

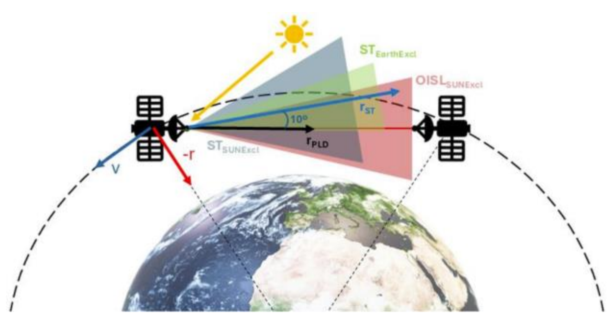

Figure 5: OISL Sun interference conditions

The contact windows for DTE have also been analyzed, as seen in the "visibility circles" in Figure 6 considering a minimum elevation of 5° for the optical ground stations of Oberpfaffenhofen (DE), Trauen (DE), Almeria (ES) and Tenerife (ES).

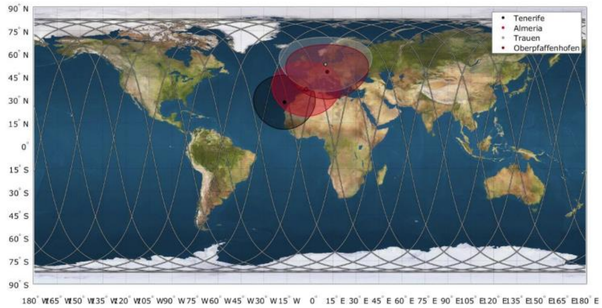

Figure 6: DTE Ground Station Network

The maximum contact duration per station is approximately ~9 minutes with the selected orbit.

Finally, the mission ΔV is, in the worst case, 64 m/s considering:

- Error injection corrections
- Separation maneuvers of 100 km (each satellite performs half) with a transfer duration of 5.6 days
- In-plane station keeping with a ground-track accuracy of 10 km
- Collision Avoidance Maneuvers
- Deorbiting with a worst-case surface area

OPERATION CONCEPT

GSOC, will take over the satellite from the manufacturer after the launch and early orbit phase (LEOP). The main goal of GSOC is to integrate the CubeSat mission into its multi-mission operating environment using already existing tools. Further, operations team will support IKN and RSC[3] in FSOC experiments both intersatellite links and to the ground.

The operations team is already working in close cooperating with the satellite manufacturer to tailor the onboard software to suit the requirements of the GSOC multi-mission tools.

A new mission planning tool, called as Pinta-on-Web will be introduced to support payload operations via a website including automatic conflict management between various activities on board the spacecraft. This tool will prepare the list of commands to be uploaded at routine intervals and will also consider the user requested payload activities.

The command and control operations will be performed using GECCOS (SCOS-2000 based tool). After handover from Alén Space, operations will be performed manually. After gaining sufficient experience, the operations will be fully automated. The Weilheim ground station belonging to DLR will serve as the primary telemetry and telecommand (TM/TC) transmitting station for communication via S-Band.

The flight dynamics group of GSOC will provide the necessary orbit and position information to the mission planning system to be plan and prepare the list of commands for both S-Band and payload operations. They will also support in collision avoidance and in maintaining the separation between the two spacecraft.

CONCLUSION AND OUTLOOK

With the current design of the spacecraft – especially the AOCS – the LCTs and the operations concept, the IOD mission is on a very good way to demonstrate OISL on CubeSats in orbit. The high effort put into the mission analysis and the design of the AOCS fulfils the crucial requirements to establish an optical link between the satellites. The CubeISL-IOD mission already passed the preliminary design review (PDR) and is ready to be integrated after the upcoming critical design review (CDR) later this year. The CubeISL LCT is already under testing and characterization. As this subsystem which is newly developed, intensive testing and characterization will be required to ensure the success of the mission.

The successful deployment of a laser communication mission marks a transformative leap in space technology, offering unprecedented data transmission speeds, enhanced security, and reduced latency. By leveraging optical systems, such missions ensure resilient, high-bandwidth connectivity, critical for real-time decision-making in dynamic environments. Collaborative efforts between governments, industry, and international partners will be pivotal to standardize protocols and scale infrastructure. As laser systems mature, they will become more relevant by supporting a new era of responsive and secure space capabilities, ensuring humanity's sustained presence in increasingly congested and contested orbital domains.

Precursor missions like CubeISL-IOD enable fast and responsive technology demonstrations in the final environment. CubeISL-IOD is therefore a great example of how CubeSats can be used in science and research to de-risk larger services and demonstrate the key-technologies before an operational mission is set up. In this case, the demonstration of a peer-to-peer OISL will show that laser communication can support large (mega)constellations in the future.

Acknowledgments

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