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Cube Laser Communication Terminal state of the Art

[a]Patricia Martín Pimentel*, [b]Benjamin Rödiger [b]Christopher Schmidt, [b]Christian Fuchs, [a]Christoph Rochow, [a]T. Hiemstra, [a]Andreas Zager, [a]Philipp Wertz, [c]Marcus Knopp, [c]Marc Lehmann, [d]Falk Mrowka.

[a] *TESAT Spacecom, Gerberstrasse 49, 71522 Backnang*
[b] *German Aerospace Center (DLR), Institute of Communications and Navigation, Muenchner Straße 20, 82234 Wessling*
[c] *Responsive Space Cluster Competence Center (RSC³), Eugen-Sänger-Str. 50, 29328 Faßberg*
[d] *German Space Operation Center (GSOC), Muenchner Straße 20, 82234 Wessling*

* Corresponding Author

Abstract

Based on the increasing need for higher data rates in CubeSat missions primarily for Earth observation and communication missions mainly focused on Direct-to-Earth (DTE) applications, DLR started the development of a highly compact laser communication payload for CubeSats.
In parallel TESAT has used its experience for preparing and developing this technology for volume production.
At the same time to ensure the compatibility with the ground stations, DLR started and lead the CCSDS working group for Optical On-Off-Keying (O3K) to further extend the commercial use of CubeLCT terminals
This cooperation between industry and research center has been very successful. The PIXL-1 mission was accomplished in a very agile new space approach, developing and demonstrating the technology in record time.
Moreover, in order to enable the potential customers to deploy a complete end-to-end system, TESAT in cooperation with GSOC has specified the interface requirements for developing the first demonstrator for DTE optical system mission planning, mainly focused on the link planning challenges. This concept can be applied to current missions, and allows identifying the needs also for further applications.
In addition to DTE links, the increasing demand for higher data rates and low latency communication in upcoming constellations of CubeSats also drives the need to extend the CubeLCT terminal with Inter-Satellite-Link-functionality. In continuation to the first development, IKN, RSC³ and TESAT, are currently developing a CubeLCT for intra-plane communication capable of transferring 100 Mbps over 1800 km.
The upcoming challenges in operation of inter-satellite-links on CubeSats combined with the possibilities of enabling DTE are also covered in this paper.

Keywords: CubeSat, Direct-to-Earth (DTE), FSO Communication, O3K, OISL, PIXL-1

Nomenclature

This section is not numbered. A nomenclature section could be provided when there are mathematical symbols in your paper. Superscripts and subscripts must be listed separately. Nomenclature definitions should not appear again in the text.

Acronyms/Abbreviations

DTE: Direct to Earth
FM: Flight Model
FPA: Fine Pointing Assembly
FSM: Fine Steering Mirror
4QD: 4-Quadrant Diode
GlobeON: Global Optical Ground Station Network
LCT: Laser Communication Terminal
LCE: Laser Communication Experiment
O3K: On-Off-Keying
O4C: OSIRIS4CubeSat
PINTA: Program for Interactive Timeline Analysis
QKD: Quantum Key Distribution

1. Introduction

The evolution of laser communication technology has been dizzying in recent years. The efforts made by institutions, agencies and companies have paid off. Programmes such as EST-VI, ARTEMIS, TerraSAR-X, NFIRE or TDP1 have guided this development.

The Communications Research Laboratory (CRL) in Japan successfully demonstrated the Laser Communication Experiment (LCE) on the Japanese Engineering Test Satellite-VI (ETS-VI) satellite in 1994 with the first purpose-built lasercom satellite for demonstrating space-to-ground laser communications [1].

The ARTEMIS (Advanced Relay and Technology Mission Satellite) program, was ESA's first GEO data relay communication satellite with the objective to demonstrate new communication technologies, principally for data relay and mobile services. This incorporated narrower beam divergences than the LCE mission, which allowed higher data rates and enabled a better understanding of atmospheric impairments, particularly at low zenith angles. On Nov. 21, 2001, ARTEMIS made a world premiere by establishing a inter satellite laser link with the French Earth Observation satellite SPOT-4: imaging data was sent by SPOT-4 (in LEO) using a laser beam as signal carrier to Artemis and from there by radio waves to the ground [2].

On Feb. 21, 2008, a government-to-government cooperation between the United States and Germany to establish a laser link between two operational satellites in Low Earth Orbit (LEO) started a new chapter in the history of space. The German radar satellite TerraSAR-X and the U.S. Missile Defense Agency satellite NFIRE, both equipped with Laser Communication Terminals (LCT) manufactured by Tesat-Spacecom, established the first successful and stable orbital laser link [3][4].

DTE capabilities were also verified using TerraSAR-X towards DLR (Deutsches Zentrum für Luft- und Raumfahrt) optical ground station located @ Oberpfaffenhofen [5].

At the present, programs like TDP1 [6,7,8] (footprint for ISL optical communication commercial services EDRS [9]) are providing unique testing facilities for pushing the boundaries of the new optical communication development.

With the same aim and for enabling the commercial applications in the DTE range, DLR's Institute for Communication and Navigation (IKN) and TESAT have done another step forward. Missions like PIXL-1, are a proof of success where research institutions and industry have worked side by side bringing together the advantages of both infrastructures [10].

In the following sections the present and the future of the smallest LCT for Cube Satellites applications is presented.

2. CubeLCT

With the upcoming New Space move, the demand for high data rate communication terminals increased tremendously also for small satellites. To fill the needs of compact designed terminals with high data throughputs, DLR worked on the miniaturization of their OSIRIS (Optical Space Infrared Downlink System) terminals. The idea is to refine established technologies in a small form factor especially designed to fit in a standard CubeSat. With this idea DLR and Tesat started a collaboration to develop the "OSIRIS4CubeSat" (O4C) terminal (later known as "CubeLCT"), the world's smallest Laser Communication Terminal. The CubeLCT provides an optical data link with 100 Mbps with a size of only 1/3 U. Tesat funded the O4C project which includes the development of the terminal and a demonstrator mission on a 3U CubeSat, the mission "PIXL-1". Therefore, Tesat got from DLR all required documents and was included during the development of the terminal to prepare their industrialization.

2.1. Terminal Development

The maximum achievable data rates are directly related to the received optical power. The higher the power density on ground, the higher data rates can be achieved. The highest power density can be generated with a refraction limited optical system inside the transmitter. This is the physical limitation of the divergence, means the absolute minimum of the widening angle of the transmission laser beam. Because of the small form factor a 20 mm lens is the maximum feasible aperture in the design of the CubeLCT. Thus, the divergence of the terminal is limited to 193 µrad ($1/e^2$, full angle).

Common CubeSat busses can achieve a pointing accuracy in target pointing of better than ±1°. This remaining uncertainty cone is larger than the divergence of the CubeLCT (193 µrad ≈ 0.011°). To compensate this inaccuracy the CubeLCT is equipped with a Fine Pointing Assembly (FPA) which is shown in Figure 1.

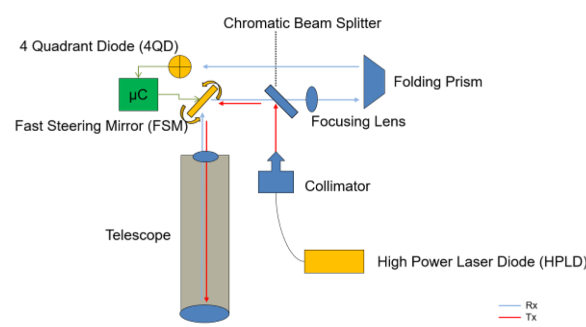

Figure 1: Block diagram FPA CubeLCT

The FPA consists of a 4-Quadrant Diode (4QD) and a Fine Steering Mirror (FSM). The 4QD measures the angular offset to a beacon sent by the Optical Ground Station (OGS), an onboard microcontroller (µC) calculates the angular error and steers the FSM in the opposite direction to compensate measured error. The transmission beam is coupled into the exact same optical path as the receiving beam. With this closed loop tracking it is guaranteed that the terminal transmits in the same direction where the beacon comes from to hit the OGS.

Transmission (Tx) and receiving (Rx) beam are separated by wavelength. The CubeLCT follows the O3K standard described by the Consultative Committee for Space Data Systems (CCSDS). The Tx-wavelength of the terminal's laser operates in the C-Band (1550 nm), while the beacon of the OGS operates in the L-Band (1590 nm).

To achieve the ambitious goals of Size Weight and Power (SWaP) DLR patented a new design where the Printed Circuit Board (PCB) is used as an optical bench. Usually electronics, optics and mechanics are separated from each other. With this new design idea, the optical elements could directly be placed on the electronics mainboard to achieve the highest possible compactness of the terminal.

This led to the world's smallest Optical Laser Terminal CubeLCT with the following parameters:

Size	1/3 U
Weight	395 g
Peak Power Consumption	8.5 W
Data rate	100 Mbps
FPA Field of Regard	±1°

Table 1. SWaP Parameters CubeLCT

Even though the CubeLCT is highly compact it still follows a modular design approach. Every subsystem can be distinguished. The terminal mainly consists of the following subsystems:

- Mechanical System
- Optical System
- Electronical System
- Software
- Control Loop
- Interfaces

This modular design allows to easily adept, change or extend the single subsystems without a major redesign of the terminal. Thus, the CubeLCT is the base development for future DLR developments in the CubeSat sector, like inter-satellite links or Quantum Key Distribution (QKD). Figure 2 shows the Flight Model (FM) of the first CubeLCT built by DLR.

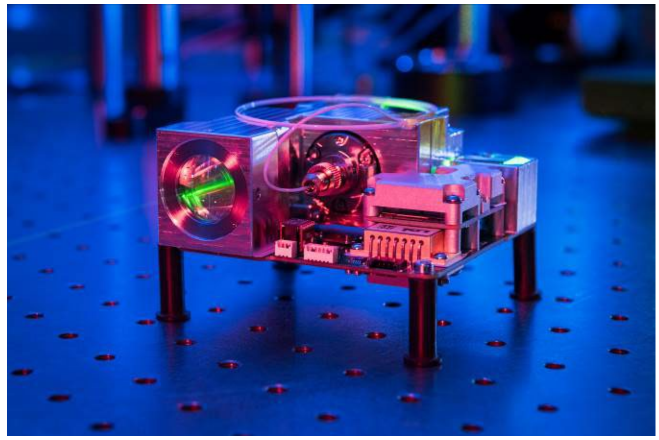

Figure 2: CubeLCT Flight Model

2.2. Industrialization

The industrialization process starts in an early stage of the design development. Therefore, TESAT has defined which work packages are necessary during the different project phases.

2.2.1 Industrialization Concept

The concept is built in two main blocks.
The first block covers the concept development and its configuration, the flow starts with the project specification, the project boundary conditions were clarified:

-Determination of the target production costs and allocation to material and personnel
-Definition of target number of units and ramp-up
-Develop qualification philosophy and agree with customers.

During the system design and definition of the detailed process steps the preconditions for manufacturability shall be fulfilled:

-Communication of the design requirements from manufacturing
-Design concept review (system design iteration)
-Determine qualification requirements
-Carry out design FMEA (iteration detailed design)
-Develop production concept and a rough time planning
-Identify equipment and tooling requirements and needs.

The second block covers the hardware, which is representative for the later manufacturing process. It starts with the development and provision of the required processes / infrastructures:

-Provision and procurement of equipment
-Provision and procurement of devices and aids
-Implementation of the production concept
-Carry out qualifications
-Create manufacturing specifications
-Adapt / develop business processes

Then it is necessary to have evidences of the implementation into the manufacturability:

-Successfully completed all qualifications
-Verify compliance with work and time schedules
-Verify suitability of (business) processes

After the verification of the complete process shall be done, in order to the manufacturing:

-Provide the resources (specialist, machine) required for the target number of pieces.
-Adapt time planning, work planning to series production.

For the PIXL-1 mission IKN and TESAT ensured that for each program milestone the necessary inputs were available.

2.2.2 Milestones delivery items

This section contains the information delivered by each partner during the industrialization process for the major program milestone.

1.PDR
Delivered by IKN:
Preliminary Design; Sufficient information for initial cost calculation: Bill of materials, GSE concept, Process *list.*
Delivered by TESAT:
Preliminary cost calculation and comparison to target costs; Qualification requirements (materials, processes); Preliminary Tesat manufacturing concept; Make or buy decision templates; Preliminary definition of required equipment and tools for Tesat manufacturing concept; Adaptation requirements in business processes.

2.CDR
Delivered by IKN:
Coordinated design for release; Procurement-ready specification of all required parts and materials, parts list; Process list, Proof of addressing design risks (design FMEA); Proof of addressing process risks during the integration phase (process FMEA).
Delivery by TESAT:
Tesat manufacturing concept, make or buy allocation; Work plans, cost calculation with proof of compliance with target costs; Definition of required equipment and tools for Tesat manufacturing concept; Proof of successful qualifications (materials, processes); Proof of availability of new/changed business processes.

3.EQM
Delivered by IKN:
EQM integrated according to Tesat work plans; Logging of deviations from Tesat work plans (integration).
Delivered by TESAT:
Evaluation of the effects on the industrialisation concept; Derived measures (design, processes, manufacturing concept, work plans).

4.PFM
Delivered by IKN:
PFM integrated according to Tesat work plans; Logging of deviations from Tesat work plans (integration).
Delivered by TESAT:
Evaluation of the effects on the industrialisation concept; Derived measures (design, processes, manufacturing concept, work plans).

5.FRR
Delivered by IKN
Results of the flight hardware tests; Logging of deviations from Tesat work plans (commissioning, alignment, test).
Delivered by TESAT
Evaluation of the effects on the industrialisation concept; Derived measures (design, processes, manufacturing concept, work plans).

2.3. **PIXL-1 Mission**

The capabilities of the CubeLCT are demonstrated in the “PIXL-1” (Photo Images Cross Laser) mission. The goal of the mission is to transmit a high-resolution picture from a CubeSat via a CubeLCT to an OGS. Transmitting a picture including the required de- and encoding demonstrates a quasi-operational scenario on the way to a commercial product. Therefore, the first CubeLCT flight model, shown in Figure 2 is flying on the 3U CubeSat “CubeL” built by GomSpace. CubeL is illustrated in a downlink scenario in Figure 3.

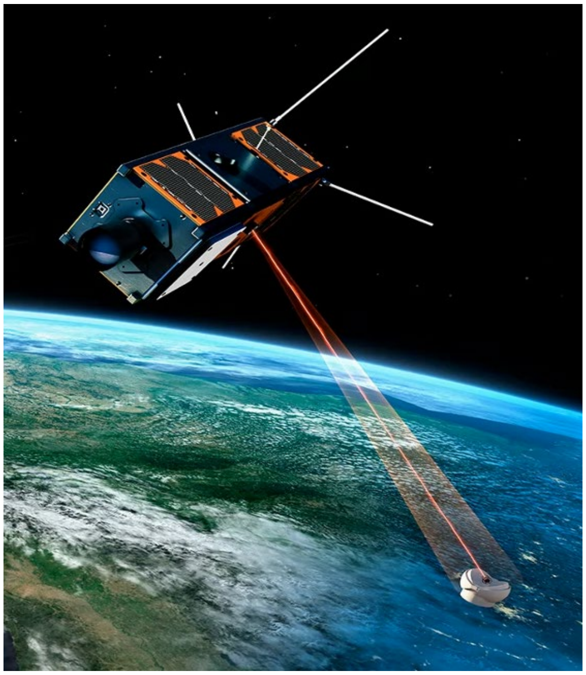

Figure 3: Artists illustration of CubeL in a laser downlink scenario

CubeL was launched on the 24th of January 2021 into a Sun-synchronous orbit. After the Launch and Early Orbit Phase (LEOP) DLR started with laser experiments to check out the CubeLCT. Thus, DLR's Transportable Optical Ground Station (TOGS) was used. The TOGS is especially designed for operational scenarios like data reception of laser transmitted data.

First signals of the CubeLCT could be observed beginning of August 2021. Afterwards the tracking loop of the FPA was activated onboard. In the beginning of September 2021, a first tracking lock could be achieved. During the bad weather period afterwards in Germany DLR, GomSpace and German Space Operation Center (GSOC) concentrated on stabilizing the Attitude Orientation Control System (AOCS) and the integration of CubeL into the ground segment of GSOC (the latter will be discussed in chapter 4 in detail). Together with colleagues from Flight Dynamics department of GSOC, DLR and GomSpace work together on stabilizing the attitude control system and improving the target pointing accuracy. These measures are required to make the last step to demonstrate a successful data transmission.

3. CubeISL

The CubeLCT is a pure transmitter in the DTE scenario. Due to (mega-)constellations the number of small satellites and therewith the number of communication channels increases tremendously also in this field of Inter-Satellite Link (ISL). Thus, DLR decided to transfer the technology of the CubeLCT into the ISL domain and started the project "CubeISL".

The goal of CubeISL is to develop an ISL terminal for CubeSats which can establish a bidirectional data transmission with 100 Mbps over a distance of up to 1,500 km. Beside the ISL, CubeISL will improve the DTE capabilities to 1 Gbps. The payload itself will have the following parameters:

Size	1 U
Weight	1.000 g
Peak Power Consumption	30 W
Data rate (ISL, bidirectional)	100 Mbps
Data rate (DTE)	1 Gbps
FPA Field of Regard	±1°

Table 2. SWaP Parameters CubeISL

To establish a bidirectional communication between two CubeISL terminals and still being compatible to the O3K standard, a new wavelength concept had to be implemented. CubeISL is still able to receive the beacon from an OGS in the L-band (1590 nm). For ISL transmission and receiving beam are also separated by wavelength. The ISL wavelengths are still operating in the C-band (1536 nm and 1553 nm). That means that there are two types of terminals, A and B where the transmission wavelength of terminal A is the receiving wavelength of terminal B and vice versa.

Chapter 2.1 already described the modular approach of the CubeLCT. CubeISL benefits from this as the necessary adaptions and with this the effort for new developments can be reduced to a minimum. Reusing and transferring technology allows very short development and qualification times. The payload itself consists of three major subterminals:

- Optical Terminal
- Transmitter System
- Data Handling Unit (DHU)

The Optical Terminal is based on the CubeLCT. To establish a bidirectional connection a receiver is required. Thus, the Optical Terminal was extended by an Avalanche Photo Diode (APD) as an optical receiver. Slight adaptions in the optics where necessary to adapt the terminal to the new wavelengths. Beside that the optomechanic development could completely be reused from the CubeLCT.

In ISL the receiving aperture is the aperture of the partner terminal (20 mm), which is a lot smaller than the aperture of an OGS in the DTE (600 mm – 800 mm). To overcome the resulting lack of optical power the transmission power has to be increased. CubeLCT is equipped with a High-Power Laser Diode (HPLD) operating at 100 mW peak power. CubeISL uses an Erbium Doped Fiber Amplifier (EDFA) to generate an optical output power of 1 W. Comparable EDFA's are already known from previous missions like "OSIRISv1" and OSIRISv2". Based on this the Transmitter System of CubeISL can be built up based on the large heritage of DLR.

The CubeLCT outsources high processing tasks like channel coding to the satellite bus. To be more independent from the satellite platform CubeISL has an own Data Handling Unit (DHU) to prepare and analyse the transmitted and received data. This includes the operation of the whole payload as well as the channel de- and encoding of the data. The DHU is based on Commercial Off The Shelf (COTS) CubeSat components.

Figure 4 shows the design of the CubeISL Laser Communication Terminal.

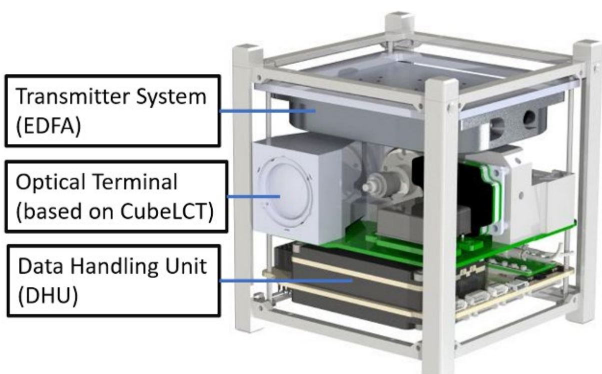

Figure 4: CubeISL Terminal Design

3.1. CubeISL Mission

To validate the CubeISL LCT IKN and the Responsive Space Cluster Competence Center (RSC³) are executing the CubeISL mission. The mission is comprised of two 6-unit CubeSats to validate the LCT and demonstrate use cases of a formation of small satellites capable of laser communication.

Both satellites will be launched into a trailing formation on a high inclination low-Earth orbit. To enable experiments with the LCT over different distances, up to the LCT's designed maximum distance of 1,500 km, the satellites are equipped with thrusters. The satellites need an attitude control system with very fine accuracy of ± 0.1 deg attitude error to achieve laser lock in reasonable time. Besides pointing accuracy, this maximum tolerable error must also include the deviances in known versus actual position of both satellites. Thus, both are fitted with GNSS sensors to update the orbit models regularly so that each satellite can calculate the others position for correct orientation. For DTE experiments, the satellites need to be able to perform target-pointing maneuvers with a more relaxed pointing accuracy of ± 1 deg.

To be compatible with DLR GSOC's ground stations the satellites will use S-band transceivers for TM/TC instead of an UHF solution, which is becoming rarer but still popular in the CubeSat community. An overview of the key elements of the satellites can be seen in Figure 5 which shows a drawing of both satellites linked by the communication laser.

Beside the validation of the CubeISL LCT DLR is pursuing the goal to close the gap of communication standards between the highly innovative CubeSat industry and DLR GSOC's multi mission and multi manufacturer infrastructure. GSOC will be tasked with the operations of both satellites using their own infrastructure and processes. Thus, TM/TC will be communicated via a set of PUS services. This step will enable GSOC to stay competitive and offer their experience in high reliable operations for CubeISL and other upcoming CubeSat Missions.

The mission itself is divided into different phases: Phase one is focused on the validation of the CubeISL LCT. Here IKN will take the lead in scheduling operations. After the successful LEOP both satellites will first execute DTE experiments which will aid an on-orbit calibration of the alignment between ADCS sensor suite and the LCT. After that the ISL experiments can be started at small distance. The distance will then be increased successively up to 1,500 km with ISL experiments to acquire performance data on different distances.
After the successful validation RSC³ will take over scheduling of the satellites to demonstrate use-case focused operations. This includes using the network of optical ground stations that DLR is creating in Almeria, Spain and Trauen, Germany additionally to the one in Oberpfaffenhofen.

Another interesting use case for CubeSats with laser communication are clusters of these small satellites as federated sensors with a bigger main satellite. The main satellite can gather the CubeSat's data via laser ISL and use it for tasks that aren't feasible for the CubeSats' power budget like heavy on-board processing or forwarding the data over a LEO relay.
Both phases shall be completed after 2 years of operations.

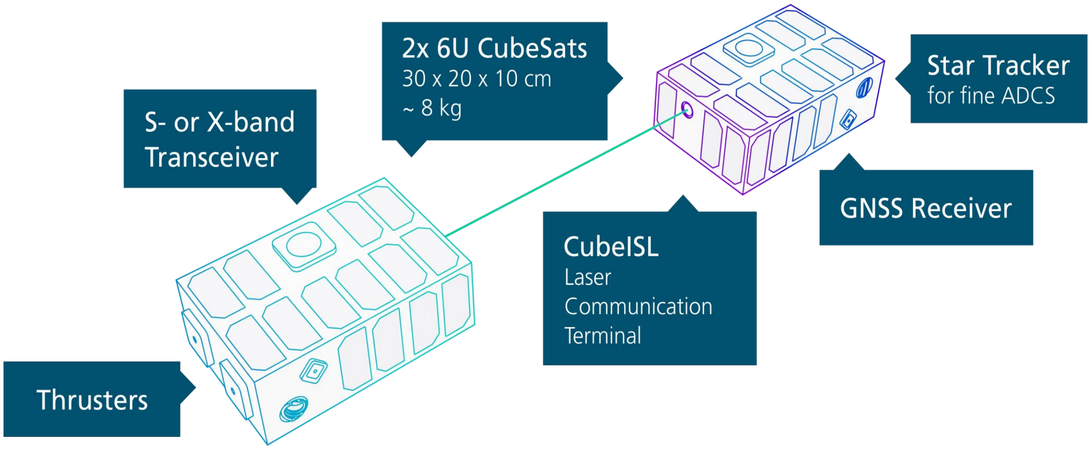

Figure 5: Key elements of the CubeISL satellites [15]

4. Operational Concept

Nowadays, there are nine TESAT laser communication terminals (LCTs) in orbit. They support inter-satellite links between LEO-GEO. Six of them belong to commercial data relay systems. The link planning and commanding used for operating these terminals started with the first generation of TESAT LCTs (where also LEO-LEO was feasible) and continues with the support of the second LCT generation where a high degree of automatism is achieved. Currently the commercial system uses a fully automated planning system which is based on weekly inputs.

Space ground optical links (SGL) add an extra challenge to the already existing conventional link planning tool, which is the capability for regulating the ground station availability depending on the on-site weather conditions. TESAT has six years heritage operating optical ground stations and has identified the needs of each interface (I/F) involved in the SGL. As a result, TESAT has developed a DTE link planning concept, which combines the current commercial inter-satellite planning concepts with the complexity of the atmosphere/weather and different ground stations (site diversity).

4.1. *Link planning*

The task of link planning is the processing of all data exchanged over all considered interfaces like e.g. data requested by user and information about the LCTs and OGSs, followed by the generation/coordination of the link time line. This enables the optical terminals to initialize their systems and point towards the counter terminal on scheduled time.

A schematic drawing of the system´s interfaces, main functionality and stakeholders are shown in Figure 6.

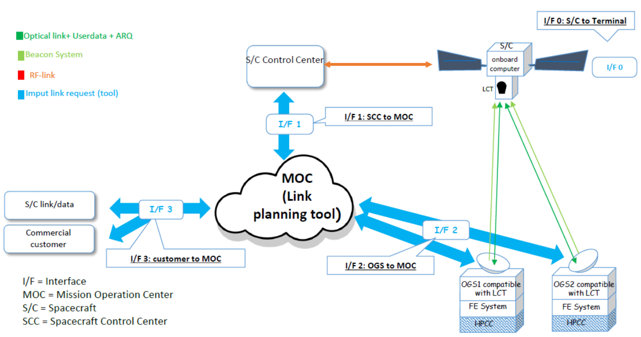

Figure 6: Schematic structure of the interfaces. Currently the Osiris terminal and compatible optical ground station are named but the concept is applicable to any kind of optical terminals

In this chapter, we will briefly describe ideas for a mission planning system plan and schedule optical links. In contrast to earlier Mission Planning Systems to plan optical links such as for TDP-1 or EDRS, the new system now builds upon generic interfaces as far as possible.
For example, the Flight Dynamics System now provides the planning system with link visibilities using a new message-based interface, which receives all relevant parameters (e.g. the orbit) together with the request; not

holding any configuration, this microservice is fully generic.

The interfaces to the Optical Ground Stations will be based on the CCSDS Service Management Utilization Request Formats (SMURF), such as Planning Information Formats and Service Package Data Formats. As these specifications are based on the experience of decades of classical RF communications, we will have the chance to extend this specification with the special needs of optical communications (e.g. exchange of atmospheric condition information).
Last but not least the interface to the S/C control center will be generic. It will be based on the CCSDS Mission Planning & Scheduling Service Specification.

The link planning prototype is based on PINTA [11], a generic planning tool developed by DLR/GSOC. The prototype will be used to demonstrate the link planning concept between the users of the PIXL-1/CubeL mission, its CubeLCT terminal and the Global Optical Ground Station Network GlobeON. It is important to emphasize that the demo scenario considers the space craft control center of PIXL-1/Cubel as an external SCC, even though it is located at GSOC, thus this demo can easily be adopted to any other CubeLCT mission.
The architecture of the prototype for the link planning system for GlobeON is shown in Figure 7.

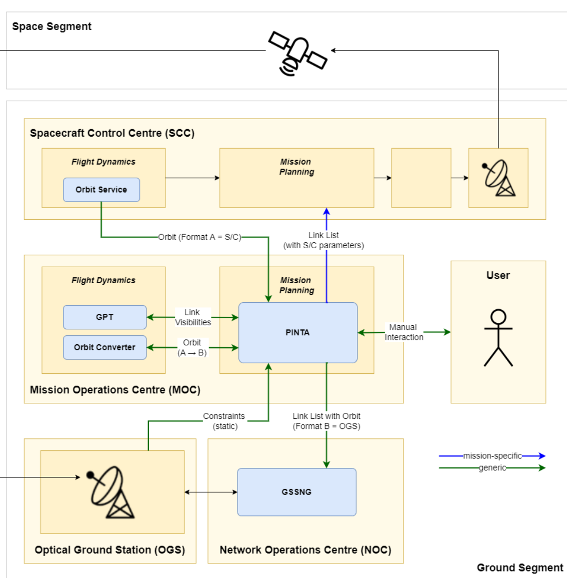

Figure 7: Detailed Architecture for the Link Planning Prototype for GlobeON using PINTA.

The planning problem for the link planning for DTE optical communication differs significantly from 'classic' satellite-to-ground links in one detail, this is the predictability of the planned link's reliability. As already mentioned due to the strong influence of the atmospheric conditions, such as clouds, the user cannot get exact times about the availability of its data downlinked and processed, he can get only probabilities for certain time frames. Therefore, the user sends to the planning system only the desired and the maximum acceptable time that is allowed to elapse between data acquisition and data availability. Additionally, within the planning system a global maximum dwell time is defined for balancing data downlink completeness and data throughput.

The scheduling flexibility on ground also depends strongly on the capabilities of the CubeLCTs, for example, the ability to automatically switch to the next ground station in the case of a failed link setup, the ability to change the tele command buffer, and the ability to modify the data memory on board.
With the prototype the different capabilities will be demonstrated.

When the impact of atmospheric conditions, especially clouds, is considered in the planning process, one has the possibility of using different horizons of weather forecast. First, for long-term-plans (weeks or even months), global statistical data is used. For mid-term-plans (for the next days) the weather for cast for the region of the ground station location is used, more preferable is the availability of on-site weather information. If on-site weather information is available a short-term update of the plan is possible, but always depending on the ability to synchronize the on-ground plan with the on-board telecommand buffer of the CubeLCT on short notice.

After the planned execution of the link it is necessary to incorporate the actual link execution status information from both, the ground station and the CubeLCT. Thus, the link planning system can update its internal information model and is able to give a better prediction of the upcoming links.

Since this planning problem domain is just starting, we hope to use the prototype to gather initial results with the PIXL-1/CubeL mission. With subsequent missions and the better availability of local ground station weather information, we should be able to provide a reliable link planning service that best meets user needs.
In Figure 8 a typical classical schedule of RF links is shown.

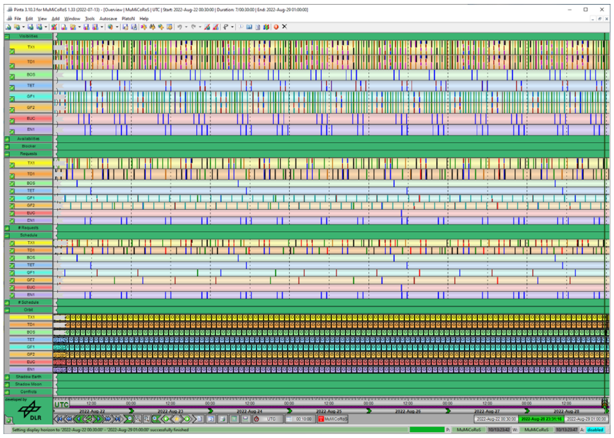

Figure 8: A typical classical one-week schedule of RF links for 8 LEO-satellites and 12 ground stations generated and displayed using PINTA.

Along with the challenging planning aspects for successful execution of DTE optical communication links, the flight dynamics input is an essential pillar for the overall process. With the embedded flight dynamics service in the link planning, as shown in Figure 6, different types of links can be computed based on well proven and its methods and algorithms [12]. In addition to the already mentioned DTE, or satellite to ground links, this service is able to calculate inter satellite links or between any other vehicle with a given trajectory.

The methods and algorithms of this service have been continuously improved since the first successful intersatellite link between NFIRE and TerraSAR-X in 2008 [12]. And with successful operation of TDP-1 since 2012 [13,14], with all three different types of links in routine operation, this service is able to provide reliable input for any use case we can imagine for CubeLCTs.

5. Conclusions

In this paper we have presented a consolidated overview of the PIXL-1 mission status. The transition to the industrialization and commercialization marked has been also present.

The CubeISL characteristics and development status has been introduced and together with the corresponding mission concept.

Regarding the operations and link planning for DTE missions, an inside view of the additional challenges for scheduling of DTE optical communication links has been given.

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