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# LASIN optical link on-board CO3D constellation

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## ABSTRACT

Earth Observation missions generate an increasing volume of data as their spatial resolution and swath have constantly increased over the last years. Downloading to ground such amounts of data with limited end-user latency is quite challenging. In this context, optical links offer an effective solution for such image downlink.

To demonstrate the feasibility and the relevance of using direct optical links from LEO satellites to ground, to download large volume of data, Airbus DS and CNES have joined to develop LASIN.

LASIN, which stands for LASer through the INstrument, is flown onboard the CO3D constellation and will provide a 10 Gbps optical link dedicated to image data downlink. This is achieved thanks to a laser system which transmits directly through the CO3D instrument. LASIN requires only few equipment to turn the instrument into a laser terminal. No pointing mechanisms are required as the beam pointing is achieved thanks to the satellite attitude control capability.

LASIN also benefits from the implementation of a new family of high-efficiency LDPC codes recently adopted by the CCSDS and optimized by Airbus DS.

In the frame of this demonstration, the optical ground station is developed by CNES and located at the Observatoire de la Côte d'Azur in south of France. The first optical links will take place in 2024.

Beyond this demonstration, the goal is to propose a fully operational downlink capability for future EO missions. The system is designed to be compatible with low cost optical ground stations in order to offer innovative and competitive solution for image downlink for the EO export market.

**Keywords:** optical communications, Direct to Earth link, LEO satellite, in-orbit demonstration

## 1. INTRODUCTION

Optical communication is a promising solution for earth observation data downlink, compared to radiofrequency. It provides a much larger bandwidth (up to multi-gigabit per second), more compact dimension, lower power consumption, greater security against eavesdropping and protection against interference. However, the signal is more sensitive to the atmosphere (clouds, turbulences) and it requires a precise pointing and tracking.

LASIN is a joint ADS/CNES optical link demonstration, that aims to demonstrate the feasibility and the relevance of using direct optical links from LEO satellites to ground, to download large volume of data. LASIN will fly on one of the CO3D satellites. CO3D is an earth observation constellation of 4 small satellites that are set to map the globe in three dimensions from low Earth orbit.

The specificities of LASIN lies in the full integration of the terminal to the satellite and the instrument unlike classical optical terminals. The accurate pointing is ensured by the satellite itself in open loop after a first calibration on the ground station. LASIN will fly on one of the CO3D satellites. The ground station is developed by the CNES and will be installed in the plateau de Calern (Observatoire de la Côte d'Azur).

LASIN is the first step of system enabling to significantly improve the download capability of the acquired images by EO satellites to data centers. This aims to reduce the latency between the acquisition and the availability of the image by the users. This system is designed to be cost efficient with a minimum impact on the overall satellite architecture and operations.

Targeted data rate is 10Gbps while ensuring a $10^{-1}2$ Bit Error Rate (BER).

## 2. ON-BOARD ARCHITECTURE AND CONCEPT OF OPERATIONS

The specificity of LASIN (*LASer through the Instrument*) lies in its integration to the satellite. Indeed, this system differs from existing optical terminals as it is embedded in the satellite and instrument.

It is constituted of 3 components:

- the LCE-Tx: Laser Control Electronics transmitter
- the HPOA: High Power Optical Amplifier
- the ORA: Optical Relay Assembly

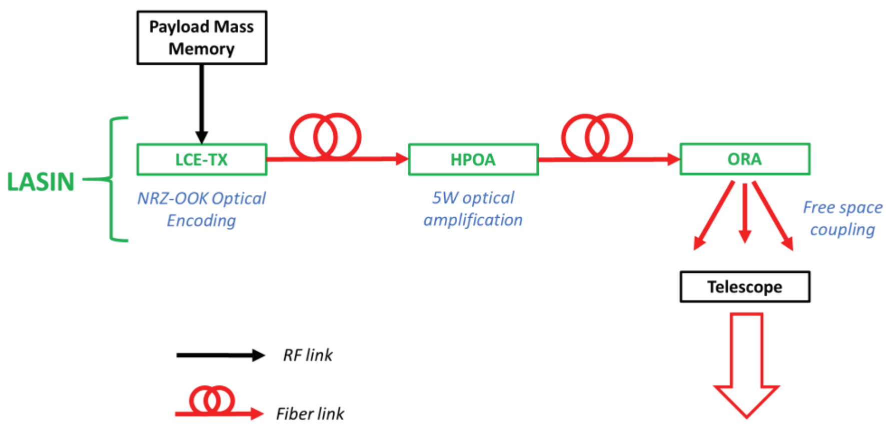


*Figure 1 : overview of LASIN on-board architecture*

The LCE-Tx optically encodes the data coming from the satellite Memory Module. The used modulation is NRZ-OOK (Non Return to Zero - ON OFF keying) at 10Gbauds. The generated optical signal is then routed to the HPOA via optical fiber. The HPOA amplifies the incoming signal up to 5 W optical. For more details on the amplifier refer to [3]. The optical flux is then routed to the ORA to inject the beam at its instrument focal plane level. From there on the signal is transmitted via the telescope toward the Earth.

LCE-Tx and HPOA are based on the Laser Communication Board and Booster developed in the frame of FOLC and FOLC2 project (ESA ARTES Program). A System Test Bed was used in various configurations of data rates (10Gbps/25Gbps) and modulations (OOK/DPSK) and optimum product baseline were selected in the product development phase.

The overall mass of this optical communication system is 2kg. The impact in terms of mass and more widely resources on the satellite is considered small with respect to more classical terminals for such performances.

The operating wavelength is in the 1550 nm domain (C band) allowing to go through the atmosphere.

The signal incoming from the mass memory module is encoded via the Forward Error Code (FEC) and implementing an interleaver to minimize the sensitivity of the signal to optical fading through the atmosphere. These aspects play a central role in the link performance [4].

LASIN benefits from developments led in the frame of the TELEO program [1]. If LASIN and TELEO are meant for distinct applications they share core technologies as the optical amplifier and encoding approaches.

In addition to transmit images stored in the Memory Module, LASIN can also transmit PRBS (pseudorandom binary sequence). PRBS will be used in depth to estimate the downlink performance estimation as well as to investigate on the propagation channel properties.

## 3. POINTING

High performance optical links use directive beams requiring accurate pointing to maintain the link budget. In the frame of LASIN the pointing performances is directly ensured by the satellite AOCS capability. In the frame of this demonstration, the accurate initial localization of the ground station is performed using a beacon emitted by the OGS. The beacon is imaged using the instrument sensor. This image is processed via a dedicated on-board algorithm. Its output enables to locate with extreme accuracy the OGS position and ensures the required pointing accuracy by the satellite. After this initial acquisition, the system directly transmits data to the ground. It is then operated in open loop.

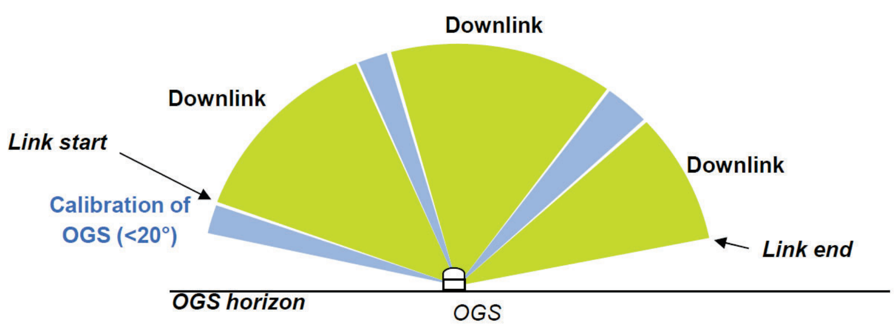


*Figure 2 : downlink sessions include periodic OGS calibration phases before and between downlink phases.*

Additional calibrations with the OGS beacon remain possible during the link after the initial one. The need for extra calibration depends both on the overall duration of the visibility and the pointing stability performance achieved in orbit. The outage associated to a calibration lasts 5 seconds. The impact on the link duty cycle is small as the links last several minutes and remains below 10%.

Regarding the eye safety regulation, operating at 1550nm is favorable. The received optical power from the satellite at ground level or even at altitude of airplanes is negligible (pW) and is compliant with the regulation.

## 4. GROUND STATION

The FrOGS consortium (CNES, and the companies, Safran Data System, OGS Technologies, ALPAO, and Airbus Defence and Space) is currently developing an optical ground station (OGS) for demonstrating optical communications in free space and, more particularly adapted to the cases of GEO feeder links and TMI-LEO downlinks. This development is supported by CNES and co-financed by the aforementioned manufacturers.

This station is a first prototype designed to meet the future needs for experimentation and to test new architectural concepts. The LASIN demonstration is part of the first application of FrOGS. However this station is developed to answer multipurpose optical missions:

- Data repatriation, Optical TMI (scope of LASIN IOD)
- Optical telecommunication (scope of the TELEO IOD)
- Laser ranging and telemetry
- Time transfer.

The OGS will be designed in a modular way to be able to meet the requirements of these different missions.
FrOGS is located in the Observatoire de la Côte d'Azur (OCA), on the Calern site and developed by a consortium of French companies: SAFRAN Data System, OGS Technologie and ALPAO, with the support of CNES and ADS. It will be operated by CNES via a dedicated mission center.

## 5. MODEM

ADS with support of CNES has developed a cost-efficient and flexible modem technology for multi-gigabit optical communication downlinks. To tackle this challenge, the synchronization and channel coding sublayer of the optical waveform has been designed to achieve best signal performances by taking into account hardware constraints of state-of-the-art on-board and ground hardware data processing technologies. The short technical specification of the communication link applicable is summarized in the following table.

*Table 1: Short technical specification of the communication link*

| Air interface throughput | Link adaptation | Modulation | Data Processing Technology | Coding gain | BER | Upper Layer Interface |
|---|---|---|---|---|---|---|
| Up to 10 Gbit/s | YES (VCM) | NRZ-OOK | FPGA (on-board and ground) | Comparable to DVB-S2 codes | $< 10^{-12}$ | Transfer frames compatible with CCSDS 131.0 |

One of the most challenging part to consider is the CODEC (coder/decoder) used to deliver reliable information transmitted over the optical downlink channel. For that purpose, a new forward error correction (FEC) technology has been proposed to the CCSDS optical working group (SLS-OPT) as a competitive alternative to current standardized solutions for RF telemetry downlinks such as DVB-S2, SCCC, and ARJA/C2 LDPC codes. The goal is to achieve best signal processing performances at a lower cost, in particular for the on-board side in which embedded constraints compatible with a space environment are very demanding.

ADS has designed a new family of LDPC codes based on accumulate-repeat-accumulate (ARA) construction with a low rate extension (Raptor-like) [5]. The obtained family provides a flexibility in the choice of the code rate to enable efficient link adaptation (VCM), while guarantying code floors below a BER $< 10^{-12}$ and thresholds close to the Shannon limit. The quasi-cycle structure of proposed LDPC codes with additional implementation constraints (codeword size, lifting factor size, etc.) make them very suitable for FPGA implementations running at few hundred of MHz, assuming state-of-art LDPC partial-parallel architectures for encoders and decoders.

BER decoding performances for a QPSK modulation over an AWGN channel are given in Figure 3. There were obtained using an acceleration framework based on FPGA acceleration cards with fixed-point quantized IP cores. The LDPC decoder uses the standard Offset Min Sum (OMS) algorithm with 6 bits for the channel LLRs. Random generation of payloads, channel sample generation, and error rate measurements are achieved in software using a floating-point arithmetic for random numbers and Gaussian distributions.

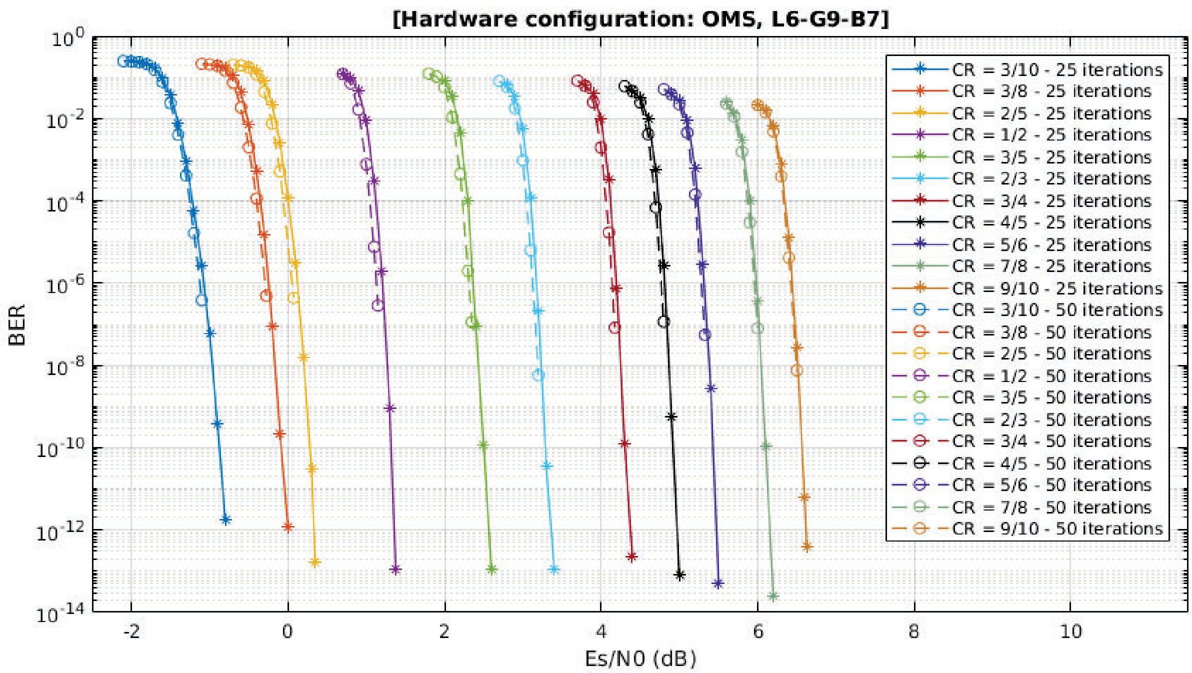


*Figure 3: BER decoding performances with 6-bit soft inputs over an AWGN channel for a QPSK modulation*

The atmospheric turbulence is also a fundamental aspect to consider for optical downlinks. A classical FEC is inadequate to overcome the slow fading process generated by this phenomenon. The common solution is to pair the FEC with a long channel interleaver that aims to introduce a temporal diversity. It operates across multiple codewords with depths of up to several seconds. When considering gigabit data rates, fast and dense memories such as DRAM devices are required for a practical implementation. Because DRAM devices are designed to efficiently operate using sequential and burst read/write accesses, a flexible block row/column algorithm has been proposed for the interleaving process. It requires a useful and cumulated bandwidth requirement up to 20 Gbit/s to enable simultaneous read and write operations on external memories.

By relying on the DVB-S2 philosophy, a new waveform framing has been proposed with in-band signalling to enable robust detection and synchronization in the presence of optical fading. Variable coding and modulation (VCM) adaptation is natively supported at this layer thanks to the use of a dedicated in-band signalling field that defines the used ModCod. It allows the spectral efficiency of the downlink to be adapted on-the-fly according to the elevation of the satellite.

Thanks to these design choices, the digital baseband modulator developed by ADS is of very low complexity and requires less than of 10% of a space-grade FPGA resources. It eases its integration with other functions such as mass memory unit (MMU) management and upper layer encapsulation with optional ciphering.

A partnership with Safran Data Systems has been implemented for the ground demodulator.

## 6. PERFORMANCES

The overall system for the LASIN demonstration is designed to achieve a 10 Gbauds Direct-to-Earth link quasi error free (BER $10^{-12}$) after encoding. The Bit Error Rate performance has been modelled. This considers the demonstration configuration including the characteristics and performances of each contributor: the satellite, the OGS, the modem and the propagation channel.

The propagation channel contribution include the turbulence, the cloud and aerosols presence, the atmospheric refraction…etc. The impact of the turbulence is included in the simulations via the times series. They have been defined based on the associated link availability. We consider series covering 99% of turbulence cases; in other words the turbulence impact will be stronger in 1% of the occurrences and the link can be degraded in such cases. These figures rely on measurements performed at the future OGS site –by night – and kindly provided by the Observatoire de la Côte d'Azur. In addition to the turbulence, the propagation model includes the presence of clouds (moderate), the impact of the molecular absorption (both with transmission loss depending on the elevation) as well as the polarization loss. The considered cases are associated to a future operational system for which availability (and therefore the robustness to turbulence) is a driving aspect.

In the frame of the demonstration, we currently consider to initiate links above 20° elevation above the horizon from the ground station. The first links will be performed in night conditions as they are expected to be more favorable; the turbulence is often weaker at night and the solar background by day is also less favorable. Nevertheless, day links will be attempted as well.

A first set of ModCod has been tested on ground with the representative Modem. This set can be expanded if required for the in-orbit demonstration. It will be possible to change the ModCod on the fly over on visibility without interrupting the link. Using a VCM approach enables to optimize the datarate with the satellite elevation over the ground station. At low elevation, the turbulence is stronger and the range to the ground station is higher than for larger elevations above the ground station. The link budget is therefore less favorable at lower than at higher elevations. The ModCods for low elevation are required to be more robust than at higher elevations. Robust codes are used at the beginning and the end of the links and highly efficient ModCods are used anywhere else; that is in the central part of the visibility slots. For a given propagation channel model one can derive the minimum elevation over which a given ModCod can be used while keeping a 3dB margin on the link budget. The useful data rate improves highly with elevation.

Based on the pass durations and its geometry (maximum elevation with respect to the OGS) on one side and on the minimum elevation associated to each ModCod, it is possible to derive the volume of data that can be transmitted to ground during the links.

Figure 4 shows the tracks offering a visibility of the satellite above 20° elevation above the horizon from the FrOGS ground station. Night visibilities are presented over a month. In addition Figure 4 presents the instantaneous useful data rate along the tracks. The color scale associates low useful data rates to dark colors and high useful data rates to bright colors (up to 9 Gbps).

Both ends of visibility slots, as well as tracks away from Nadir (most East and West of the OGS), remain in low elevation ranges leading to the lower useful data rates range. The most central tracks culminating to high elevations offer the highest data rates. The durations of the visibilities range from circa 2.5 minutes for the most outer tracks up to 5 minutes for the most central ones. In terms of transmitted volume, the combination of the rates and link duration results in transmitted data figure from 150 Gb (~2 minutes far outer tracks) up to 2300 Gb (~5minutes central tracks). These figures are based on conservative assumptions on the propagation channel and on tests on representative hardware.

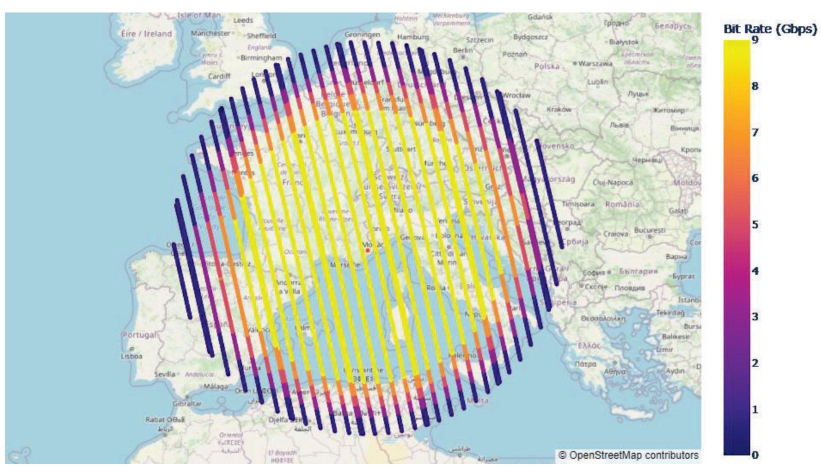


*Figure 4 : Night visibilities map for elevation above 20° with the effective bit rate over the tracks. Central visibilities have higher maximum elevations therefore longer durations and higher code rates.*

## 7. CONCLUSION

LASIN is a joint ADS/CNES optical link demonstration preparing an operational system to perform Direct-to-Earth image downlink for Earth observation satellite at high data rate. Fully integrated to the satellite, LASIN has a low mass impact on the platform. Its dedicated equipments are embedded in the platform and benefit both its functions and its agility. Such agility enable to achieve the accurate pointing required for optical links. Besides the hardware parts the implemented modulator largely contribute to achieve error free transmission at high throughput.

The partner ground station FrOGS is developed by the CNES and will be located on Calern site (Observatoire de la Côte d'Azur).

LASIN is the first step of system enabling to significantly improve the download capability of the acquired images by EO satellites to ground. This aims to reduce the latency between the acquisition and the availability of the image by the users. This system is designed to be cost efficient with a minimum impact on the overall satellite architecture and operations

This system is able to deliver over 2Tb during a visibility slot in operational conditions. Such volume is large with respect to common RF links capability and compatible with future demanding EO missions.

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