

Laboratory assessment of SDA and CCSDS non coherent standards for GEO Optical Links

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ABSTRACT

To improve terrestrial high-rate communication coverage, an optical network is currently under development in space, where satellites act as nodes. This network is distributed across three orbital regimes: LEO, MEO, GEO. Projects such as Hydron [1] demonstration aim to interconnect all nodes of this multi-orbit optical network to deliver high availability, very high data rate communication services worldwide.

Currently, two standards of synchronization and coding layer exist and have demonstrated their capability to deliver data between satellites and Earth: CCSDS non coherent [2] and SDA OCT [3] standards. In [4], both standards are assessed in a laboratory environment in the case of a difficult turbulent LEO downlink channel at low elevation angles.

In this paper, this laboratory assessment is extended to the GEO case, considering both uplink and downlink channels, while considering the state-of-the-art adaptive optics developed for the FrOGS [5] optical ground station (OGS) within the framework of the TELEO in-orbit demonstration.

This paper presents the laboratory setup and the simulation workflow. Then, the performance of both standards is evaluated under different simulated turbulent channel conditions.

The second part of this paper briefly describes the in-orbit demonstration setup used to capture received optical power (ROP) time series on both uplink and downlink during the second TELEO measurement campaign. Finally, the assessment of both standards is carried out on the captured uplink channel time series as the uplink is the more challenging link.

Keywords: GEO DTE optical communications, TELEO, optical ground stations, adaptive optics, CCSDS, SDA

1. INTRODUCTION

Radiofrequency spectrum congestion, SWaP, link security, OISL technological maturity and geopolitical uncertainties are strong incentives for development of fiber in the space technologies and free space optical communications. This future space optical network will link the three space orbits LEO, MEO, GEO and standard such as ESTOL [6] aims at interconnecting the three orbits and the ground. In this framework one use-case of the GEO is data relay or point to point interconnection between mobile terminals. For these use-cases two standards already exist: SDA and CCSDS non coherent. This paper will assess both standards in the frame of communications with a GEO satellite. In section 2 both standards are succinctly presented. In section 3, turbulent channels simulations used to assess both standards are described for both direct focal APD and pre-amplified detector. Both cases are considered in this paper, as APD is a cost effective and compact solution for mobile applications. Section 4 provides performances of both standards on simulated channels and finishes with assessment of CCSDS on channel captured on satellite and ground OCT in the frame of the TELEO [9] In Orbit Demonstration (IOD). Finally, section 5 presents ground and satellite acquisition systems used to capture the IOD channel.

2. CODING AND SYNCHRONIZATION LAYER STANDARDS

A. CCSDS non coherent

This standard primarily addresses interoperability in the use-case of Earth Observation. This standard uses a time diversity scheme to mitigate the turbulence based on long interleaving. The required interleaver depth and consequently the latency induced by the physical layer is independent from the orbit. This is the reason why this standard is used for communications with the GEO orbit OCT TELEO [9].

CCSDS physical layer described in [2] in its LDPC flavor consists of 30,720-bit blocks of LDPC-encoded data that are interleaved to mitigate turbulence-induced fading and concatenated into major code frames. Each major code frame is delimited by a 4096-bit Sync Layer Frame Marker (SLFM) concatenating a 2048-bit Frame Sync Marker (FSM) followed by a 2048-bit in-band signaling field that identifies the coding parameters (code rate, repeat factor, spacing, and interleaving size). These major frames are subdivided into subframes delimited by Secondary Sync Layer Frame Markers (SSLFMs), each consisting of an FSM and an Interleaver Frame Signaling (IFS) field to distinguish the first subframe from subsequent ones. This subdivision facilitates re-indexing of coded blocks within the long interleaver if Clock Data Recovery (CDR) synchronization is lost due to deep turbulence-induced fading

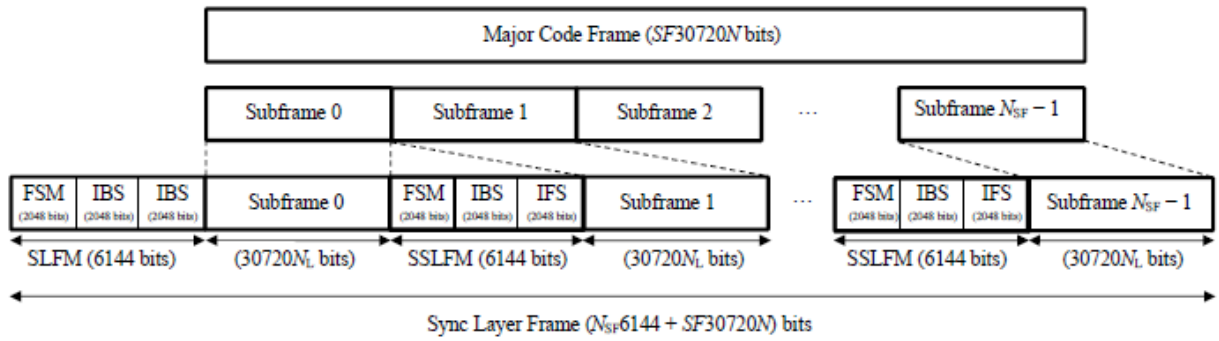


Fig. 1. CCSDS Physical Layer Framing

B. SDA V3.X / ESTOL “low rate”

This standard primarily addressed interoperability in the use-case of low-rate full duplex data link for LEO constellation. Instead of interleaving SDA relies on Automatic Repeat Request (ARQ) mechanism to mitigate turbulent Direct To Earth (DTE) channel. This time diversity scheme offers very low latency as far as retransmission probability remains low. The latency induced by this time diversity scheme is dependent on the orbit, as retransmission requires a two-ways round trip time.

Frame detection is made possible thanks to a much short preamble of 64 bits, which can be ultimately confirmed by Header CRC.

Field	# of bits	Comments
Preamble	64	Preamble: 64'53225b1d0d73df03. The MSB (64 th) bit is transmitted first followed in order down to the LSB (1 st).
Header	960	See Section 3.4.2.1.
Payload - Data	8448	Information payload. Fixed size (8160 bits) for all modem frame configurations.
Payload - CRC	32	Cyclic redundancy check covering payload bits.
Payload - Parity	variable	Number of parity bits depends on the configured payload FEC codec and code rate.

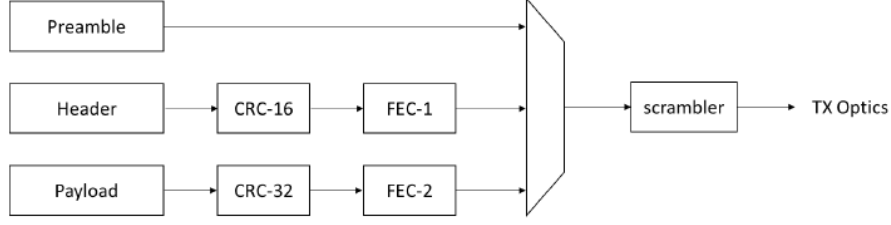


Fig. 2. SDA Physical Layer Framing

Contrarily to CCSDS standard, SDA header encodes free running fields such as time and thus making direct correlation on complete encoded header not possible. All tests performed in following sections will be thus performed on 64 bits preamble.

Parameter	Valid Range	Number of bits	Description
ARQ_HOLDOFF_NFRAMES	0,16,32,...4096 N x 16, N=0...2 ⁸	8	Window size of ARQ shall be a multiple of 16. The maximum value is 16 times 2 ⁸ =4096. The value of ARQ_HOLDOFF_NFRAMES determines the hold off time: e.g. 256 × 80 μs = 20 ms for 312.5 Mbps. Window size and hold-off time are not set independently.
ARQ_MAX_RETX	0-5	3	Maximum number of retransmission attempts.
ARQ_HOLDOFF_TIME	0-2500ms	12	Hold-off time between re-transmissions

Fig. 3. SDA ARQ parameters

3. TRANSMISSION CHANNELS AND LABORATORY SET-UP

To compare the performance of the non-coherent physical layers of the two standards, SDA [3] and non-coherent CCSDS O3K[2], laboratory measurements were conducted. As ESTOL standard [6] relies on SDA for 2.5 Gbps OOK links, results given in this paper applies as well. The baseline performance was initially assessed in a static environment, without turbulence emulation. Subsequently, fading vectors were applied to the signal using High Speed Variable Optical Attenuators (HSVOAs). This process has been applied for both uplink and downlink channel, in three different cases of turbulence based on probability of occurrence on the site of the FrOGS OGS.

For the downlink channel, tests have been conducted with a pre-amplified detector, and with avalanche photodetectors (APD), to evaluate the performance of transportable terminals against multi-mission terminals equipped with adaptive optics. For the uplink channel tests have been conducted considering only the pre-amplified model with SMF injection.

A. Propagation Channels

The simulation parameters selected to assess downlink channel performance corresponds to three probabilities of turbulent conditions occurrence.

The selected elevation angle is 30°, the wind speed at ground level is 10 m/s.

For the downlink the three profiles are the following:

Parameter	1% DL profile	10% DL profile	30% DL profile
r_0	2.8 cm	7.09 cm	9.79 cm
θ_0	6.5 μrad	3.97 μrad	5.91 μrad
σ_χ^2	0.3	0.17	0,09

For the uplink the three profiles considered are:

Parameter	1% UL profile	10% UL profile	30% UL profile
r_0	5.11 cm	7.08 cm	9.79 cm
θ_0	3.75 μ rad	5 μ rad	7.47 μ rad
σ_χ^2	0.2	0.12	0,07

The selected parameters were employed to generate turbulence and wind profiles, which were then input into the Turandot turbulence simulator [7], developed by ONERA. This simulator was used to produce far-field patterns (FFP) at the entrance pupil of a ground station with characteristics like those of FrOGS with a 50 cm aperture.

APD transmission Channel

APD detection is modeled by the power collected at the pupil plane within a disk whose diameter equals that of the aperture. The FFP are produced by Turandot and the power encircled within the aperture is then collected.

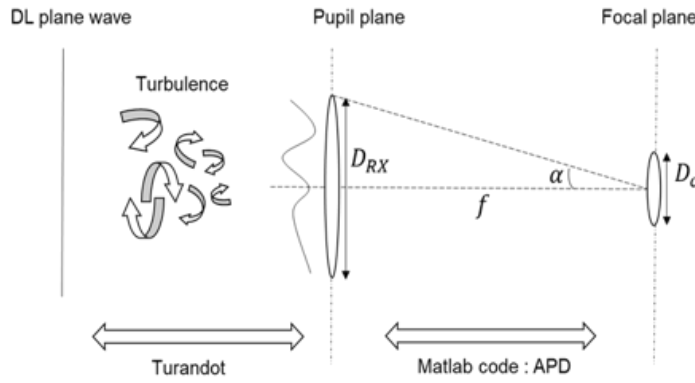


Fig 4: modeling of collection by OGT pupil of turbulent field

AO transmission channel

To obtain time series of the signal injected into a single-mode fiber, the same Turandot's FFP as the ones used for APD channel are processed using AO simulator. The AO model that is used is the one provided by Bertin Alpao state-of-the-art system composed of one deformable mirror and one wavefront sensor with additional tip-tilt, representative of the FrOGS adaptive optics system.

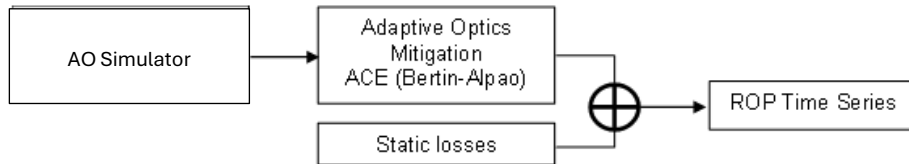


Fig 5: modeling of received optical power injected in the OCT SMF

The generated time series are then normalized by the non-turbulent gain. In this paper two other parameters are considered to enable a fair comparison between direct APD detection and pre-amplified detector with AO wavefront correction. The first parameter is the Single Mode Fiber (SMF) coupling loss, set at 3.18 dB. This coupling loss is detailed in section 4.A.

B. Laboratory set-up

The normalized time series are loaded on an arbitrary generator that drives the HSVOA to emulate the turbulence as shown on figure 6.

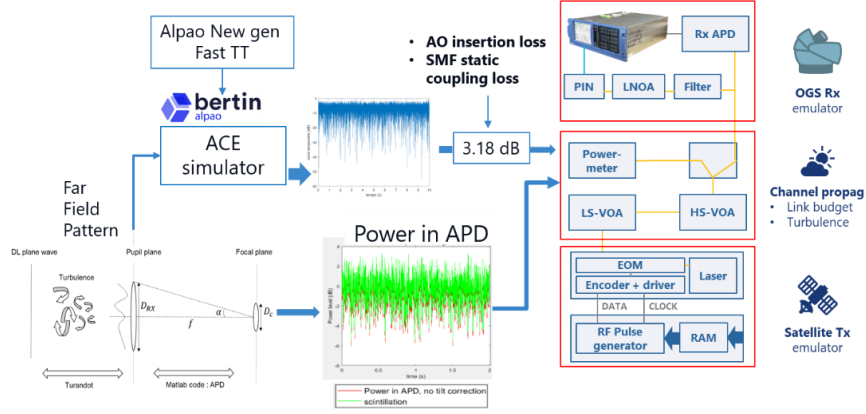


Fig. 6. Downlink fibered optical test bench

Then depending on the standard tested, Cortex Lasercom on figure herebelow is then loaded with SDA or CCSDS non coherent LDPC configuration at 2.5 Gbps or 10 Gbps.

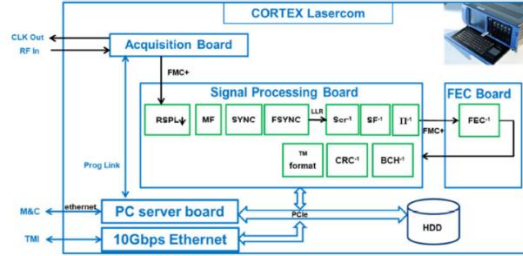


Fig. 7. Digital Processing Unit of Cortex Lasercom optical modem

4. LABORATORY PERFORMANCES ON SIMULATED CHANNELS

A. FIXED POWER

All further sections in this paper will consider a FEC code rate of 1/2 (PL4 for SDA), and a hard decision decoding for SDA. The SDA frame synchronization strategy is set to 3 errors in the preamble to consider it as valid and to cope with long fades, tracking strategy is set to a maximum of 254 bad preamble detections in a window of 255. Such a time window is well adapted to strong turbulence as 255 frames time window enables to survive to a 1,8 ms fading below the detection threshold. The CCSDS frame synchronization strategy is set according to the rationale developed in [8] to minimize the probability of false detection of the preamble to minimize the occurrences of bad reindexing in the deinterleaver. The CCSDS frame synchronization strategy is thus set to 1200 for cold detection, 900 for hot detection, with a maximum of 200 consecutive preambles undetected before unlocking. The CDR loop bandwidth is set to 0,002% of the symbol rate, and the acquisition range is set to 300 kHz for 10 Gbps and 100 kHz for 2.5 Gbps. The considered symbol rate is the line rate.

We first measure performances of both standard implementations in the absence of turbulence with pre-amplified detectors and an ASE filter with a ± 28 GHz 1 dB bandwidth.

Results are gathered in the following table. The first line gives the received optical power (ROP) at the input of the detector required to reach a quasi-error free link. Quasi-error free link is considered reached for a bit error rate less than $1e-9$. The second line gives the received optical power at the input of the detector required to maintain the lock of the frame

synchronizer (FS). The last line gives the received optical power required to maintain the lock state of the CDR. The measurements made in this contribution are given in the three first columns, the two last columns are measurements performed in [4] with the same test bench, to be able to compare the performance of pre-amplified detector and direct focal APD detector. To compare APD and pre-amplified detector performances, ROP must be considered before SMF injection to take into account the optical power lost in the static coupling. In this paper, all performances for the pre-amplified scheme are given with the static coupling loss included. As the static coupling loss in the SMF is 3.18dB, as detailed in section 5, to get the required ROP coupled in the fiber 3.18 dB must be subtracted from the figures given in the three first columns. This enables a direct comparison of the performance of the two kinds of detection.

Threshold	SDA HD [dBm]	CCSDS HD [dBm]	CCSDS SD [dBm]	APD SDA HD[dBm] [4]	APD CCSD SD [dBm] [4]
QEF < 1e-9	-45,82	-47,07	-48,92	-44,2	-45,8
FS	-48,52	-57,37	-57,37	-45,3	< -57,5
CDR	-60,02	-60,02	-60,02	-57,5	-57,5

Table 1. Thresholds of SDA and CCSDS on non-turbulent channel.

The first conclusion is that CCSDS standard implementation provides in the absence of turbulence a gain of more than 1 dB on the quasi-error free threshold over SDA . This is mainly the consequence of the FEC error floor shown in [4]. These measurements show that the CCSDS standard gives an extra margin of 8.85 dB on the frame synchronizing threshold, which is an expected results as the SDA preamble is 64 bits long against 6144 bits for the CCSDS. The measurement performed with soft detection in CCSDS shows an extra gain of 1.85 dB against hard decision, which is less than the 2.5dB shown in [4] with the APD detector. The last outcome of these measurements is that pre-amplified detector in the absence of turbulence outperforms the direct focal APD detector by 1.5dB. The main explanation is that the APD detector at 2.5 Gbps as a wide equivalent surface enabling to collect all the light with a tip-tilt mirror, and pre-amplified detector even in absence of turbulence suffers from a 3.18 dB penalty.

B. WITH SIMULATED TURBULENCE IMPACT WITHOUT TIME DIVERSITY MITIGATION

In a second step, we measured the performances of both standards without any time diversity mitigation. The first three lines give the results for downlink channels with a probability of occurrence of respectively 30%, 10% and 1%, the three last lines give the results for uplink channels with the same respective probabilities of occurrence. This gives performance for the minimum latency case.

Channel	SDA [dBm]	CCSDS NO ILV HD [dBm]	CCSDS NO ILV SD[dBm]
SIMU DL 30%	-42,72	-44,17	-45,62
SIMU DL 10%	-40,75	-42,3	-43,55
SIMU DL 1%	-39,49	-40,99	-42,34
SIMU UL 30%	NOK	NOK	NOK
SIMU UL 10%	NOK	NOK	NOK
SIMU UL 1%	NOK	NOK	NOK

Table 2. Performances of SDA and CCSDS on GEO turbulent channels at 2.5 Gbps with no time diversity

Whatever the downlink channel the extra margin provided by the CCSDS implementation is in the order of 1.5 dB. The implementation of the soft decision in CCSDS with no time diversity improves the link margin in the order of 1.5 dB. Whatever the standards without time diversity scheme, the budget link cannot be closed for the uplink.

C. WITH SIMULATED TURBULENCE IMPACT WITH TIME DIVERSITY MITIGATION

Then we measured the performance with a 67 ms interleaver for the CCSDS. Our target is 50 ms, however, to perform the test we used PRBS sequence, this constrains the interleaver size that must be a multiple of the length of the PRBS sequence.

The measured has not been performed with ARQ for SDA, the ARQ_HOLD OFF_NFRAMES is indeed specified at a maximum value of 4096 frames which gives a maximum round-trip time (RTT) of 30,6 ms far below the RTT imposed by the geostationary orbit. This point is noteworthy, CCSDS standard has a latency which is mostly imposed by the interleaver, which is independent from the RTT imposed by the orbit, SDA latency jitter is imposed by the RTT of the orbit. For LEO the ARQ may be an asset, for GEO it is a drawback. The measurements are shown in the following table. The first three lines give the results for downlink channels with a probability of occurrence of respectively 30%, 10% and 1%, the three last lines give the results for uplink channels with the same respective probabilities of occurrence.

Channel	CCSDS ILV HD [dBm]	CCSDS ILV SD[dBm]
SIMU DL 30%	-45,52	-47,12
SIMU DL 10%	-44,55	-46
SIMU DL 1%	-42,92	-44,39
SIMU UL 30%	-38,92	-41,54
SIMU UL 10%	NOK	NOK
SIMU UL 1%	NOK	NOK

Table 3. Performances CCSDS on GEO turbulent channels at 2.5 Gbps with time diversity

A 67 ms interleaver with soft decision improves the link margin in the order of 1.4 dB for 30% scenario, 2.5 dB for the 10% scenario and 2 dB for the 1% scenario.

With CCSDS standard the budget can be closed only in the 30% scenario with an extra margin of 2.62 dB provided by the soft decision. On 10% and 1% scenarios deep fadings require to increase the input power at the input of the detector, which leads to a power level at the input of the PIN detector too high. These measurements will have to be made with a new set-up.

In the 30% scenario several fadings attenuate the ROP of more than 20 dB, which means that the ROP drops below the CDR threshold of -60 dBm. This is the reason why bit slips were detected by the DSP during the measurements. Thanks to the reindexing DSP process detailed in [8], it was however possible to reach a quasi-error free link.

Then measurements were performed for downlink on the same channels with APD detectors to compare performance with pre-amplified detectors on the ground segment. As APD does not require single mode fiber injection, this detector largely simplifies the OGS focal plane. This is an advantage especially for small transportable terminals. On uplink the measurements were not performed as on-board detector is pre-amplified.

Channel	APD CCSDS ILV SD	PREAMP CCSDS ILV SD
SIMU_DL_30%	-47,07	-47,12
SIMU_DL_10%	-46,58	-46
SIMU_DL_1%	-46,6	-44,39

Table 4. Comparison of performances of APD and pre-amplified detectors at 2.5 Gbps

If in the absence of turbulence pre-amplified detection provides a 1.5 dB extra margin against direct focal detection, measurements show that the more turbulent the channel is the more direct focal detection provides extra margin.

To complete the lab assessment, measurements were performed at 10 Gbps. Measurements were only performed with CCSDS standard because at that time 10 Gbps extension of SDA specified in ESTOL standard is not completed yet. However, as 5G-NR FEC at 10 Gbps is replaced by a Reed-Solomon FEC, the extra margin provided by CCSDS is expected to be measured higher than the one presented in this paper at 2.5 Gbps. Indeed 5G-NR FEC has a coding gain greater than Reed-Solomon.

In the absence of turbulence and considering the 3.18 dB coupling loss, the following thresholds were measured.

Threshold	CCSDS HD [dBm]	CCSDS SD [dBm]	APD CCSDS HD [dBm]	APD CCSDS SD [dBm]
QEF < 1e-9	-41,87	-45,42	-36,85	-39,5
FS	-54,52	-54,7	< -47,5	< -47,5
CDR	-55,22	-55,4	-47,5	-47,5

Table 6. Thresholds of detection on non-turbulent channel with CCSDS physical layer at 10 Gbps

At 10 Gbps the loss on the link margin with pre-amplified detector and soft decision against 2.5 Gbps is 3.5 dB. As the loss is not 6 dB, the receiver is thus not limited by signal-ASE beat noise. With APD focal mode, using an adapted TIA for each rate, the loss is measured at 6,3 dB which looks consistent for a receiver operating at an approximately constant number of photons per bit. At 10 Gbps the pre-amplified detection provides an extra margin of almost 6 dB over APD detectors. Soft decision gives an extra gain of 3.5 dB for the pre-amplified detection scheme, 2.65 dB for the APD scheme. This is 1.5dB above the extra margin measured at 2.5 Gbps. The reason why remains to be explored. Then the measurements were performed on the same turbulent channels as per 2.5 Gbps with 47 ms interleaver and 94 ms to check if time diversity is enough to reach ergodic capacity.

Channel	CCSDS ILV 15360 HD	CCSDS ILV 15360 SD	CCSDS ILV 32640 HD	CCSDS ILV 32640 SD
SIMU_DL_30%	-41,07	-43,72		
SIMU_DL_10%	-40,2	-42,9	-40,2	-43,1
SIMU_DL_1%	-38,34	-41,19	-38,34	-41,34
SIMU_UL_30%	-35,34	-37,24	-36,84	-39,22
SIMU_UL_10%	NOK	NOK	-25,98	-27,62
SIMU_UL_1%	NOK	NOK	NOK	NOK

Table 7. Quasi error free thresholds in CCSDS on turbulent channels at 10 Gbps

Measurement shows that 47 ms interleaver depth reach the same performance as 94 ms depth up to 10% scenario. For 1% scenario doubling the interleaver depth and consequently the latency provides in soft decision an extra margin of 2 dB. As for 2.5 Gbps, CCSDS standard enables to uplink data with a quasi-error free link at the expense of an extra power of almost 14 dB and a latency of 94 ms.

And finally, both detectors were compared on turbulent channels. As for 2.5 Gbps the extra gain provided by the pre-amplified detectors decreased with the strongness of the turbulence. However, at 10 Gbps the pre-amplified detector outperforms in all scenarios the direct focal APD detector, contrary to the LEO case as shown in [4].

Channel	APD CCSDS ILV SD [dBm]	PREAMP CCSDS ILV SD [dBm]
SIMU_DL_30%	-38,52	-43,72
SIMU_DL_10%	-37,9	-42,9
SIMU_DL_1%	-37,9	-41,19

Table 8. Comparison of performances of APD and pre-amplified detectors at 10 Gbps

D. LABORATORY MEASUREMENTS ON CHANNEL MEASURED IN ORBIT

In this section we present laboratory measurements performed on real channel captured by the TELEO OCT and FrOGS. The channel time series in this section are run on the test bench to compare the standards.

Parameter	IOD profile	30% UL profile	30% DL profile
r_0	9,5 cm	9.79 cm	9.79 cm
θ_0	13 μ rad	7.47 μ rad	5.91 μ rad
σ_χ^2	0.04	0,07	0,09

Table 9. Turbulence integrated parameters measured on FrOGS

The IOD turbulent channel is close from 30% profile regarding Fried parameter. In the absence of time diversity once again CCSDS outperforms SDA by 1 dB on the uplink and by 1.3 dB on the downlink.

Channel	CCSDS NO ILV HD	CCSDS NO ILV SD	CCSDS ILV HD	CCSDS ILV SD	SDA
IOD DL	-37,62	-39,07	-41,32	-42,72	-36,32
IOD UL	-33,52	-35,32	-38,32	-39,97	-32,57

Table 10. CCSDS and SDA performances on IOD channel at 2.5 Gbps

At 10 Gbps uplink measurements on the IOD profile are close to the one measured with simulated channels. However, comparison is not valuable as the anisoplanetism angle of the IOD channel is twice the one of the simulated channel and scintillation half the one of the simulated channel.

Channel	CCSDS ILV 15360 HD	CCSDS ILV 15360 SD	CCSDS ILV 32640 HD	CCSDS ILV 32640 SD
IOD DL	-37,17	-39,17	-37,62	-39,62
IOD UL	-33,82	-35,92	-35,32	-37,47

Table 11. CCSDS and SDA performances on IOD channel at 10 Gbps

5. TELEO IN ORBIT DEMONSTRATION

A. THE FRENCH OPTICAL GROUND STATION

The French Optical Ground Station (FrOGS) is a versatile optical ground station, commissioned by CNES to support various Free Space Optical (FSO) missions. These missions include LEO Direct To Earth (DTE) data repatriation, SatCom GEO feeder links, Satellite Laser Ranging and quantum communications. Developed at the French Riviera observatory near Grasse, FrOGS is the result of a collaborative effort among industry partners, including OGS Technologies, Safran Data Systems, and Bertin Alpao, with contributions of Airbus Defence as a provider of space LaserCom systems.

The architecture of the FrOGS dedicated to TELEO campaigns and experimental results are provided in [10].

FrOGS can utilize a bi-static optical configuration comprising two identical telescopes, each equipped with a 50 cm primary mirror and a 34% central obstruction. One telescope is designated for the receiving channel (Rx), while the other is dedicated to the transmitting channel (Tx).

On the transmit focal plane assembly (FPA) adaptive optics (AO) system provided by Bertin Alpao, is composed of a tip-tilt mirror, a deformable mirror (DM277), a tip-tilt sensor and Shack-Hartmann wavefront sensor paired with a SWIR camera (SH-InGaAs-fast), and a real-time controller system (ACE-RTC) that supports operation at frequencies of up to 4.6 kHz. A dedicated fine-pointing camera to allow the tip-tilt loop to operate independently of the loop designated for high-order modes, with a control frequency reaching as high as 14 kHz. This setup is referred to as double single-input single-output (2-SISO) and corresponds exactly to the design defined in CO-OP).

The RX AO system integrated into the Rx Cassegrain focal plane shares the same 2-SISO configuration as the TX AO system, with a few key differences: the deformable mirror features 308 actuators (DM308) and has a significantly higher resonance frequency compared to the DM277, enhancing its effectiveness in compensating for downlink signals. The DM loop functions at frequencies of up to 3.7 kHz.

A simplified schematic of the two benches is provided in *Figure 8*

FrOGS is the main OGS involved in the TELEO in-orbit demonstration. Measurements of the turbulence integrated parameters and downlink time series presented in section 4.D have been made with FrOGS. Measurements of the uplink time series performed by the TELEO OCT are done on the FrOGS pre-compensated uplink emitted by the Tx tube shown herebelow.

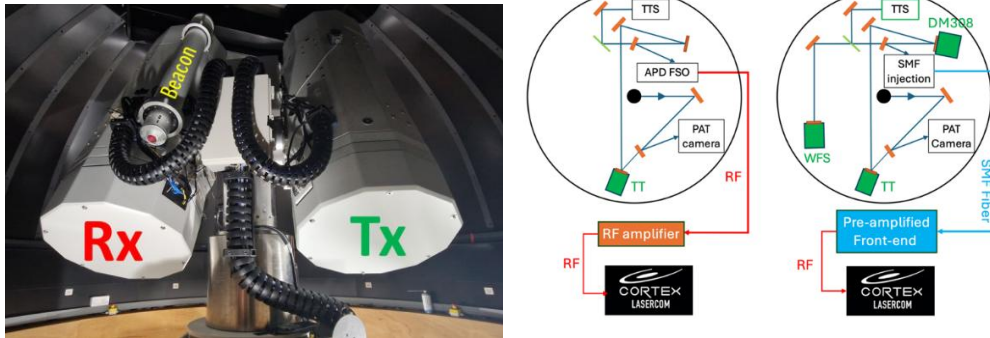


Figure 8 : FrOGS bistatic architecture with the beacon affixed atop of the Rx telescope (left) and the schematics of the two Rx Cassegrain focal plane assemblies (right)

FrOGS has two versions of the receiving focal plane assembly (Rx FPA): one with a direct free space coupling to APD detector, for direct detection of amplitude modulation; and a second one with a pre-amplified detector that uses the signal coupled in a single mode fiber by the adaptive optics. The TELEO mission is supported by the pre-amplified detector. The received optical power (ROP) is the power received by the LNOA and modem. The ROP is measured with a powermeter attached to a 95/5 optical fiber coupler and depends on the power received at the telescope entry, total optical

transmission from the telescope to the SMF, and the AO coupling efficiency (the ratio between the ROP and the power received at the fiber entry. This coupling efficiency characterized the instrument performance and can be evaluated with

$$T_{\text{fibre_th}} = \rho_{\text{PSFfib}} \cdot \rho_{\text{Rfib}} \cdot \rho_{\text{BS5}}$$

where ρ_{PSFfib} is the coupling efficiency, ρ_{Rfib} accounts for the reflection losses at fiber interfaces (Fresnel losses), and ρ_{BS} the transmission of the fiber coupler for ROP measurement (95%).

The coupling efficiency is derived from the overlap integral between the complex field of the fiber's fundamental mode and the complex field of the incident beam. Assuming no optical aberration and a central obstruction of 34% (FrOGS Rx telescope), the coupling efficiency is 0.545. Fig. 9 illustrates the Airy amplitude for an incident beam without aberration and the SMF fundamental mode. Assuming 7% reflection (Fresnel) losses and fiber interfaces and 5% losses for the ROP measurement coupler, we derive a maximum possible coupling rate for the FrOGS configuration of 48%. This is the coupling loss considered in this paper. In real world situations, we should also account for slight misalignment between the beam and the SMF, as well as some residual aberration. A realized coupling rate of 40% to 45% may therefore be viewed as excellent. Compared to the -10 dB loss commonly assumed for SMF injection, this implies that a reduction of about 6 dB reduction may be considered.

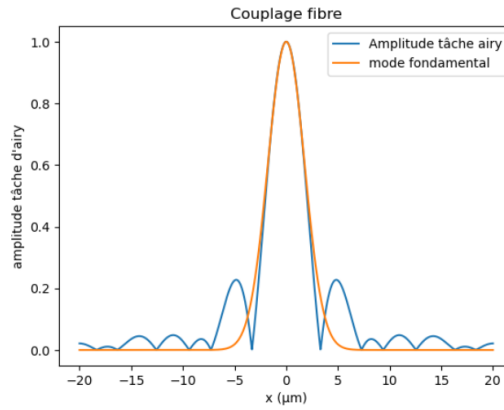


Figure 9: SMF fundamental mode and Airy amplitudes

The measurement of the turbulence integrated parameters is performed with the WaveFront Sensor (WFS) of the adaptive optics

B. TELEO OCT

The Acquisition and Tracking Sensor (ATS) of TELEO OCT is based on a fully qualified Component Of The Shelf (COTS) matrix. After acquisition of the optical link, the ATS works in windowing mode at few kilohertz. The detection software retrieves from the ATS data the spot power received from the partner terminal (beacon or part of the Rx com beam). The high frequency time series of spot power is encapsulated in a dedicated protocol which is then encapsulated into the CCSDS L1 physical layer by the on-board optical modulator and send to the ground. On ground, the optical signal is demodulated and send to TELEO mission control centre over a VPN. The high frequency time series of received irradiance on board is computed from the spot power.

High frequency time series of injected power into the LNOA and modem can be derived from TELEO IOD received irradiances for OCT of different size.

6. STANDARD PERFORMANCES WITH DIVERSITY TECHNIQUES TO COMPENSATE TURBULENCE IMPACT

In section 4.A, it has been demonstrated that CCSDS recommendations lead to better performances than SDA standards at fixed power for QEF threshold and especially for frame synchronization threshold with an extra margin of 8.85 dB.

In section 4.B, it has been demonstrated that that CCSDS recommendation leads to about 3dB better performances than SDA standards without time diversity technique, no ARQ for SDA, no interleaver for CCSDS.

In this section, we introduce by simulation ARQ for SDA and interleaver for CCSDS.

The 10Gbaud CCSDS performances is derived from mathematical model whose results are compliant with hardware performances used in TELEO with an accuracy better than 1 dB [9].

The 2.5G SDA performance with ARQ is derived from an Airbus simulator fed with hardware performance provided in

Table 6. Thresholds of detection on non-turbulent channel with CCSDS physical layer at 10 Gbps . The maximum number of retransmissions is set to 5 as per [3].

The performances estimated by the simulator are:

- The useful L1 data rate includes the impact of retransmission.
- The packet arrival time which corresponds to the duration needed by a packet to be correctly received at the receiver side. Such metric is a contributor of the latency and jitter of the overall connection.

Figure 10 depict the useful data rate achieve for both standard functions of the injected optical power available at the LNOA and modem on board the satellite.

The CCSDS is simulated for two arbitrary interleaver durations of 100ms and 30ms. In the laboratory, only the 100ms interleaver with FEC $\frac{1}{2}$ has been tested, it is reported has the red box on the figure.

The blue box on the figure corresponds to laboratory result of 2.5G SDA without ARQ, which is error free without retransmission for a ROP of -35.75dBm.

The figure illustrates the wide range of channel condition that the modem can cover by adjusting it FEC rate.

The figure illustrates also the greater, useful data rate accessible thanks to CCSDS implementation and said differently the lower SWaP optical terminal that is authorized.

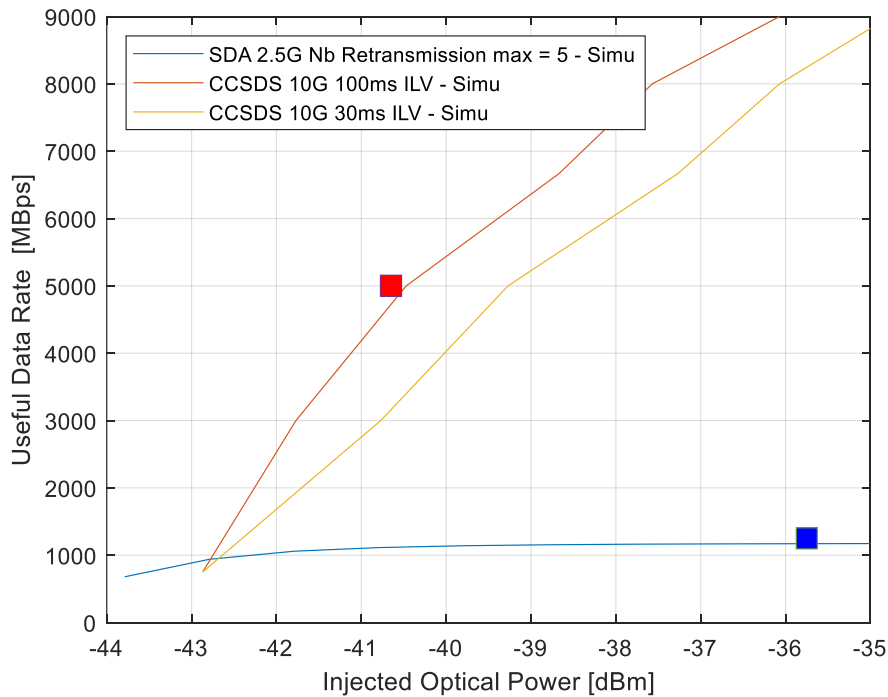


Figure 10: Useful data rate function of injected optical power for both standard [dBm]

The figure below corresponds to the simulated duration needed for a packet to reach the receiver with no error; it includes 125ms of flight between ground to GEO. For CCSDS, it is computed by two times the interleaver duration plus the flight duration, it corresponds to a probability of 100% as it is deterministic. For SDA, it includes the impact of retransmission, and the arrival time of packet follows a distribution. In the figure, we provide the longest duration taken at 99,9% probability.

We retrieve that for 35,75dBm no retransmission is needed for SDA for a useful data rate of 1250Mbit/s. But as soon as we lower the power, retransmission is needed and the longest arrival duration increases. It worst noticing that as soon as one retransmission is needed, SDA latency exceeds the CCSDS one with an additional cost of jitter.

In the range between -40dBm and -36dBm, SDA offers about 1.2Gbps useful bit with worst case duration about 380ms while CCSDS with an interleaver of 30ms offers between 4 to 8Gbps with a deterministic latency of 185ms.

At -43dBm, CCSDS and SDA provide similar useful bit rate, but worst-case duration is above 1s for SDA while it is 185ms for CCSDS.

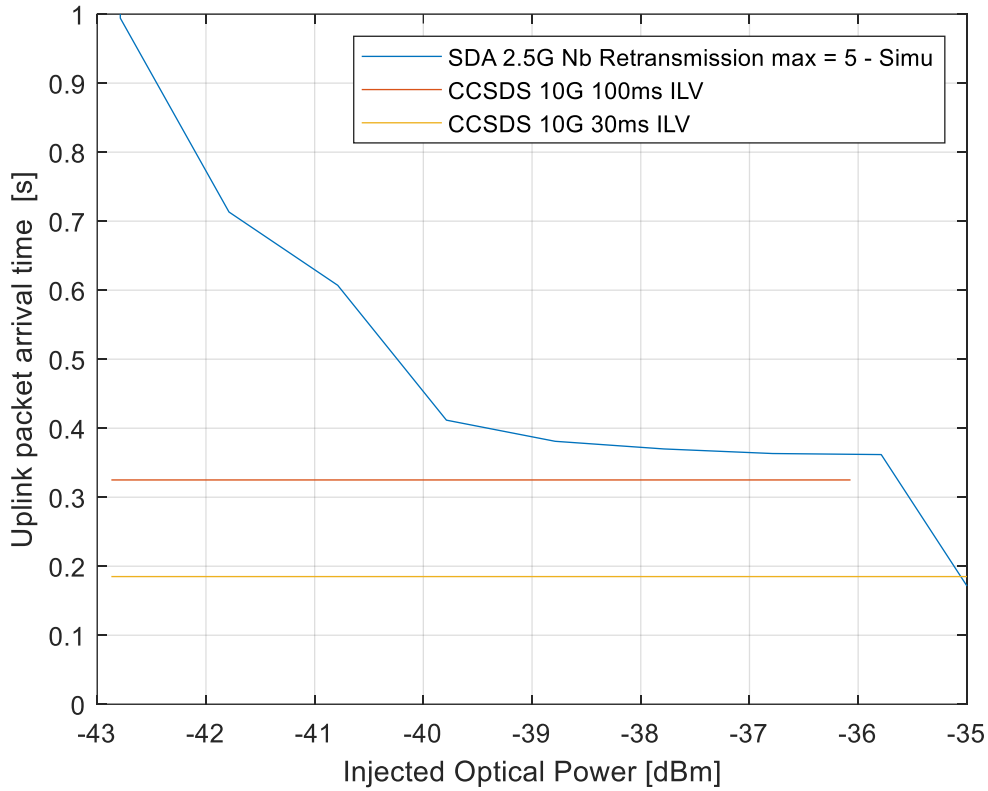


Figure 11: uplink error free packet arrival time function of on-board injected power [dBm]

7. CONCLUSION AND PERSPECTIVES

This work offers quantitative comparison of standard performances for cross-atmospheric GEO optical link.

The comparison has been performed with hardware implementation for CCSDS and SDA without ARQ and with simulator for SDA with ARQ. The next step will be to compare with hardware implementation of SDA with ARQ.

Already, CCSDS is the best candidate for cross-atmospheric GEO optical link.

This work has also demonstrated a gain of 2.5 dB typical on medium GEO turbulent channel by using soft decision FEC decoding.

Finally, this work also shows that direct APD focal detection on the ground segment can outperform pre-amplified detection at 2.5 Gbps on turbulent channel, making it a valuable scheme for small transportable OGS.

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