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From SILEX/LOLA to High data rate optical telemetry for LEO satellite

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BIOGRAPHY

The authors are from the Optical Instrument Division of EADS Astrium Satellites in Toulouse and were involved in the Optical Image Telemetry (OIT) study for CNES in 2011/2012.

M. Planche and M. Vaillon were previously involved in the LOLA programme, respectively as System Engineer and responsible of Pointing, Acquisition & Tracking (PAT) system.

INTRODUCTION

The continuous improvement of performances of Earth Observation satellites results in dramatic increase of image volume, asking for Payload Telemetry with higher downlink capability. Thanks to the intrinsic high operating frequency (hundreds of THz) leading to very high optical antenna gain, free-space optical communications offer the technology breakthrough required by future Earth Exploration Satellites for their High Rate Payload Telemetry. LOLA programme has demonstrated the maturity of this technology with an atmospheric propagation channel (robustness to fading). However, as communication performances require clear sky propagation conditions, it is necessary to implement ground stations site diversity with meteo decorrelation to reach operational system availability.

This paper presents the architecture and performances of LEO-to-ground optical telemetry system operating at 1.55 µm laser wavelength, as investigated in the frame of the study conducted for CNES. The choice of 1.55 µm technology is justified by the analysis of eye safety constraints, but also by the growth capability offered by wavelength multiplexing (several laser wavelengths in the same optical beam). The optical link sizing is derived from the link budget consolidated on the basis of SILEX & LOLA flight results. The maturity level of the key technologies required for the space segment are analysed in order to derive technology pre-developments required prior to an operational system.

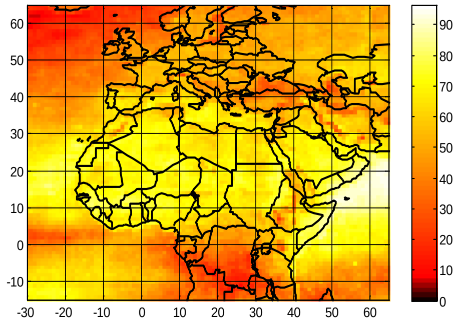
1. WHY AN OPTICAL TELEMETRY LINK?

The interest for optical link to download payload data from LEO satellites is pushed by three factors: the congestion of the X-Band (8025-8400 MHz) used today for such links, the rapid increase of payload telemetry needs and the demonstration with LOLA that optical links are possible through the atmosphere.

The X-Band congestion is first due to bandwidth limitation (375 MHz), providing today a data rate of about 500 Mbps, expected to reach 2 Gbps with more sophisticated modulation schemes. The other factor of congestion is that X-band Earth stations are concentrated around the North Pole, to have frequent visibility with remote sensing satellites, generally set on near-polar helio-synchronous orbits. Moreover, most orbits have similar local hour to benefit from adequate illumination conditions, so the satellites fly over the same earth stations at about the same time. Interferences between simultaneous RF links are therefore an additional limiting factor, which also reduce the interest of moving to higher frequency RF bands to solve the bandwidth limitation;

Both issues are solved by optical communications, with the tremendous increase of the available bandwidth at optical frequencies (THz, i.e. 10^{12} Hz!) and the total immunity to interferences of the narrow optical beam. The latter feature also presents the advantage to avoid any frequency coordination.

The major limitation of an optical telemetry link are clouds which are thick enough to stop the laser signal (in practice all clouds but high altitude ones like cirrus). The operational availability relies therefore on "site diversity", i.e. several ground stations with de-correlated meteo conditions. Preliminary investigations show that 4 ground stations adequately located in Southern Europe and North Africa provide good availability. This has been confirmed by more detailed analyses conducted by CNES & Meteo France (see for instance [8]).



	February	May	August	November
Nice	**50%**	**60%**	**70%**	**60%**
Djibouti	**60%**	**80%**	**50%**	**70%**
Calar Alto (Spain)	**70%**	**80%**	**80%**	**70%**
Canary Islands	**70%**	**90%**	**90%**	**80%**
1 station over 4	**98.2%**	**99.8%**	**99.7%**	**99.3%**

Figure 1: Clear sky probability in February (top) and link availability for de-correlated stations

2. LOLA PROGRAMME EXPERIENCE

LOLA stands for Liaison Optique Laser Aéroportée (Airborne Atmospheric Laser Link). The main objective of this prospective program was to characterize the performance of an optical link between a demonstrator of an airborne optical terminal and the SILEX terminal flying on-board the Artemis geostationary spacecraft (cf. Figure 2). Optical links from the ground have also been successfully performed. A demonstrator for a future airborne optical terminal demonstrator has been developed and flown during the 6-month test campaign on a Falcon 20 from the CEV (Centre d'Essais en Vol), the French aeronautical test centre. Despite the numerous functional & technology innovations introduced to simplify the terminal design, the overall development took less than 2.5 years, from go-ahead early 2004 to the world first optical communication between an aircraft and a GEO satellite in November 2006.

The data link characteristics were imposed by the SILEX system, both in terms of data rate (2 Mbit/s uplink and 50 Mbits/s downlink), laser wavelength (0.8 µm) and OOK (On-Off Keying) modulation. Higher data rates, up to 360 Mbit/s per channel, are however possible with the same flight-proven 0.8 µm laser technology. In order to ensure the quasi error-free (bit error rate < 10-9) data transmission despite large & fast signal fading introduced by laser propagation in the atmosphere, specific coding of the data stream was implemented.

Figure 2: LOLA bi-directional optical data link between an aircraft and Artemis GEO satellite

The LOLA program has allowed the development and the validation of a detailed link model of the optical link, including:

- Link parameters such as altitude, elevation angle, turbulence level, cloud coverage;
- Design parameters of the optical terminals (pupil diameter, source power, optical transmissions…);
- Statistical parameters such as terminal pointing error and atmospheric scintillation.

The distorted irradiance profile received by each terminal is computed by propagating the laser beam in the various atmospheric layers (Figure 3). The model was correlated with flight test results and used for extrapolation to other flight conditions. This extensive simulation activity demonstrated an excellent worldwide and seasonal availability of optical UAV-to-space communications (detailed results are classified).

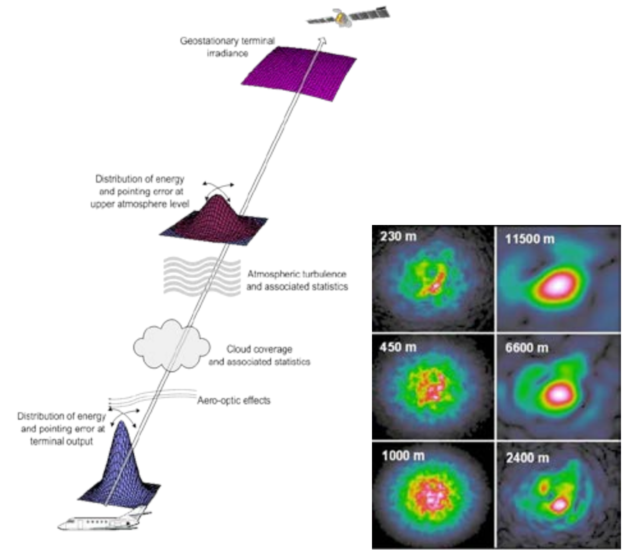


Figure 3: The link model (uplink in this case) and distribution of energy at various altitudes

Acquisition performances

A key issue in optical communication is the capability to point each terminal towards the other before the incoming laser signal is detected (so-called "a priori pointing"). The pointing reference of the LOLA terminal is computed from the ephemerides of the Artemis satellite and the attitude & position measurements of the inertial measurement unit (IMU).

Figure 4 shows the position in the terminal FoV (Field of View) of the detected beacon spot for more than 50 acquisitions. The position of the detected spot measures the a priori open-loop steering error (up to 2 mrad), showing the good sizing of the ±2.5 mrad FoV. Figure 4 also illustrates the thermal sensitivity, with an average pointing error different for day (X = -0.7 mrad, Y = -0.45 mrad) and night (X = 0.1 mrad, Y = -1.3mrad) flights, where the terminal temperature is significantly lower. These effects justify the use of Silicon Carbide (SiC) high performance material for telescope & focal plane opto-mechanical parts to minimise terminal thermo-elastic deformation.

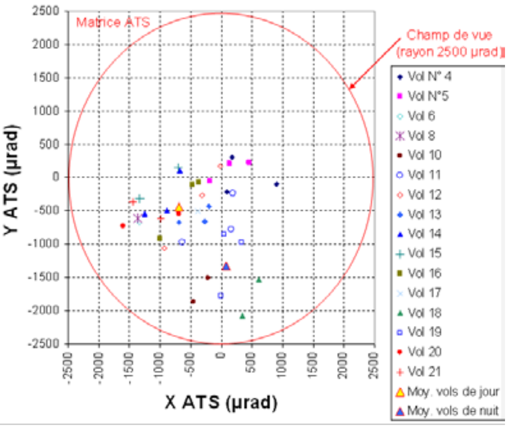


Figure 4: A priori pointing error measured over more than 50 link acquisitions

Tracking performances

After a convergence process, the tracking of the beacon signal is initialised. The average received beacon signal is weak and depends on the attenuation due to cirrus clouds. The communication phase starts when the communication signal is received from the GEO terminal after a similar convergence phase. The average received signal is higher (< 100 to 200 pW depending on cirrus cover). Nevertheless, with an integration time reduced from 500 µsec for beacon to 85 µsec (12 kHz sampling) to allow higher tracking bandwidth, the signal-to-noise ratio on the detector is often similar.

The signal is highly variable due to scintillation caused by propagation in the atmosphere, with standard deviation increasing at low altitude, around 10% at FL300 (9,000 m) and 20% at FL210 (6,000 m), but also largely depending on the turbulence level (the worst case standard deviation of 33% was measured at 9,000 m).

Any pointing error (due to terminal or tilt during propagation on the atmosphere) induces a loss in the signal intensity emitted towards the other terminal. These losses are contributors in the link budget, which allocates at most 3 dB to this parameter. The terminal pointing error is not directly measurable in flight since the resulting attenuation of the signal received by the GEO relay cannot be separated from atmospheric propagation effects (attenuation & scintillation).

The terminal pointing error is better than 3 µrad and measured in flight as the dynamic tracking error is on the ATS (difference between measured spot centre and tracking reference, with zero mean due to closed-loop control). This tracking error also includes the residual atmospheric tilt of the received signal not compensated by the tracking loop. The measured performance is excellent, about a factor of two better than required, mainly because the tracking bandwidth (300 to 700 Hz depending on flights) was larger than assumed in the analyses that supported budget allocation. The tracking performance is better in communication (because of the increased bandwidth) and at higher altitude because the atmospheric tilt is reduced.

Communication performance

The communication performance is measured in both directions by computing the bit error rate (BER), the ratio of the number of false bits to the total number of bits in the same duration. The BER is computed on the raw data and after decoding the data with the error correction code introduced at emission to handle dynamic fading of the signal due to scintillation. The following discussion is focused on the uplink (user to relay) which features the largest bit rate (50 Mbit/s).

The BER before decoding (see Figure 5) is highly un-stationary depending on dynamic fading introduced by the atmosphere. It tends to increase at the end of communication sessions when the aircraft is flying over the Alps, where the atmosphere is more turbulent. The error correction code is very efficient, since after decoding the data is error free (BER < 10^{-10}, i.e. less than one error every 200 sec.

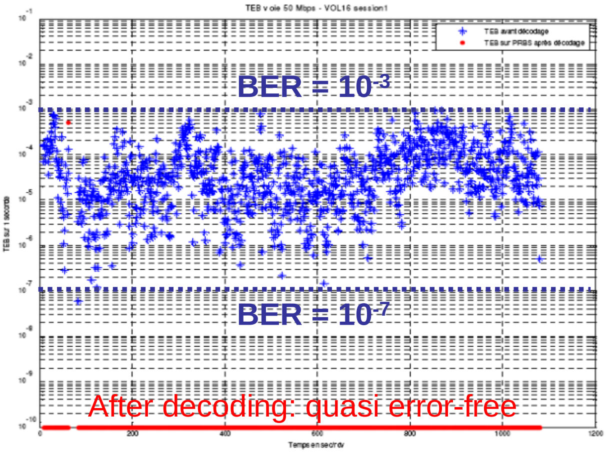


Figure 5: Bit error rate over 18 min communication

The measurement of the power on the communication receiver also allowed correlating the propagation models supporting the computation of the link budgets. The correlation is excellent on the downlink budget, with a difference between prediction & measurements lower than 5%. It is still very good on the uplink budget (error < 20%) despite the much more complex propagation model due to the proximity of the emission and of the disturbed atmospheric layers.

Communications sessions were also performed from the ground in clear sky conditions (light cirrus clouds only). The link was successfully established and data were transmitted, but the power margin was not as good as during flight test because of the large scintillation introduced by the first atmospheric layers above the ground, which feature a high level of turbulence.

3. LEO OPTICAL TELEMETRY LINK DESIGN

Wavelength selection

Different laser wavelengths are candidate for free space optical communications, 0.8 µm, 1.06 µm and 1.55 µm. The 0.8 µm and 1.06 µm technologies have been validated in orbit, respectively on SILEX/LOLA and on TESAT LCT (LEO-LEO links). Nevertheless, evolution to the 1.55 µm technology is mandatory for optical telemetry with the ground to comply with eye safety regulations, not offered by the two other wavelengths. Indeed, the threats that 1.55 µm and 1.06 µm lasers represent for the human eye have been analysed in detail in order to derive the constraints on the system (e.g. in terms of emitted power) and limit distance from the laser path to avoid eye damage.

The comparison between the two wavelengths has been performed for the following worst case scenarios:

- Observer close to the Ground Station (for downlink only)
- Observer with binocular close to the Ground Station (for downlink only)
- Aircraft crossing the laser beams. For downlink, a maximum aircraft altitude (10 km) is considered. For uplink, the flight altitude is varied from 100 m (approach) up to 10 km (cruise), together with aircraft velocity.

- Spationaute eying the laser source with telescope: in this case, a spationaute on board a LEO orbit vehicle (e.g. Space Station) is considered.

In all cases, 10 sec and 0.1 sec exposure times are considered to respectively cover continuous exposure to the average laser flux and transient amplification due to scintillation in the atmospheric path (if any).

The study was done assuming a 10W laser emitter which is coherent with the 20 Gbps TMCU data rate dimensioning.

The following conclusions have been drawn:

- 1.55 μm wavelength is eye safe with good margins in all cases.
- 1.06 μm wavelength presents eye safety risk : a wide aircraft exclusion area around the ground station and coordination with manned space missions would be necessary for the uplink, while the downlink is not safe for the spationaute observer, so coordination with manned space missions is needed.

1.55 μm has also the advantage of a large heritage from ground fibred telecom systems, with in particular high power stable laser sources. DFB (Distributed Feed-Back) laser provides very narrow line width (10 MHz) allowing frequency multiplexing (hundreds of channels multiplexed in a single fibre demonstrated on ground). For each channel, very high data rate is accessible with external modulation, typically 20 Gbps per channel. High emission power is obtained by amplification of the modulated signal by fibre amplifiers. With Erbium-doped fibre amplifier (EDFA), an optical power of 2 W can be reached, with a power conversion efficiency of about 4%. Co-doped Erbium/Ytterbium fibre amplifier (YbEDFA) offer high optical power (up to 10 W) and improved power efficiency (~6%), but such fibres are sensitive to radiations, requiring pre-development activities prior to space use.

Link architecture

The main specificity of the optical link in the OIT application is the data rate dissymmetry between the upwards link (from ground to LEO) that requires only of few kbps for TC transmission purpose and the downward link (from LEO to ground) where tens Gbps are necessary.

Based on LOLA validated models, a LEO to ground link preliminary definition and sizing have been performed including beacon & telecom signals acquisition & tracking budgets, telecom link budgets, and sensitivity to elevation angle, telescope size, adaptive coding & modulation.

The resulting link architecture shown in Figure 6 has the following features:

- the link initialisation principle is a fast beacon acquisition type (see Figure 7), the beacon being implemented in the ground terminal where power consumption in not an issue
- the upwards link requiring only a very low data rate, the communication is performed by the beacon signal modulation, therefore no telecom channel is necessary in the ground terminal
- the chosen wavelengths are 1.55 μm for the downlink communication channel and 0.8 μm or 1.55 μm for the beacon. 1.55 μm beacon is the reference for consistency with downlink, but 0.8 μm should be further investigated in the future, since it offers some advantages: availability of high power laser diode bars, simplified ATS design on LEO satellite relying on qualified CMOS technology. Eye safety is not a selection criterion because the power density of the diverging beacon beam is very low (a factor of ~10^6 smaller than the telecom beam).
- The LEO terminal is simplified with only a single stage pointing mechanism to perform the steering, the fine pointing and point ahead functions.
- Fine pointing mechanisms are implemented in the ground terminal to perform the PAT fine pointing and fibre injection of the received telecom signal
- Adaptive Coding & Modulation (ACM) is used to adjust the useful data rate to link conditions, driven by LEO elevation during a visibility period. The principle of ACM is to vary the coding level as a function of the link conditions. Based on LOLA experience, the DVB-S2 coding level can be changed during transmission without prior notice to the receiver. The simplest strategy consists in deterministic change of the coding level vs. the link elevation. For instance, Figure 8 shows a typical case where three DVB-S2 coding levels are used, 1/2 for elevation between 20 & 30 deg, 2/3 between 30 & 40 deg and 4/5 above 40 deg. The average useful data rate over a zenital pass and 20 Gbps channel data rate is 13.2 Gbps, i.e. 55% improvement vs. the constant data rate sized to worst case elevation (8.5 Gbps). The interest of ACM is therefore quite significant with only minor impact on the communication chain.

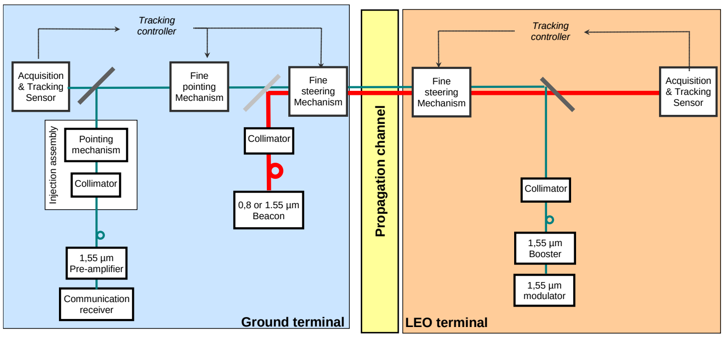


Figure 6 : Overall link architecture

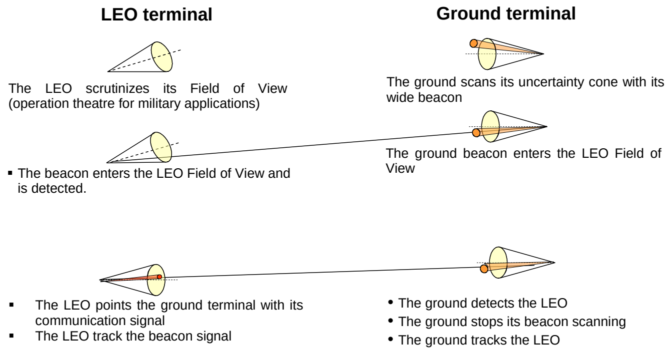


Figure 7: Fast beacon acquisition strategy principles

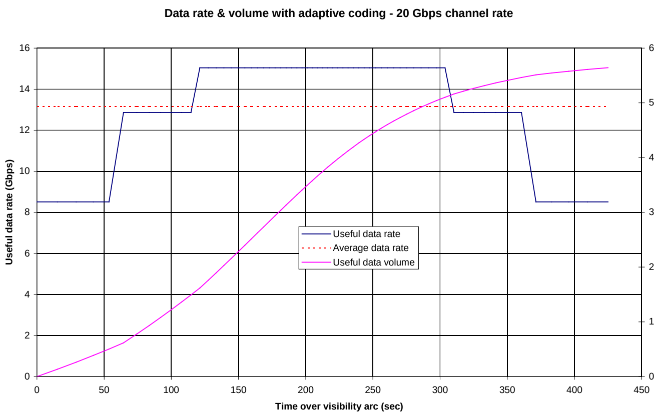


Figure 8: ACM efficiency example

Reference parameters summary

The following table summarises the parameters of the link resulting from the preliminary sizing studies:

LEO Terminal	Pupil size	80 mm	Can be optimised with OGS diameter
	Telecom optical power	2 W	Erbium fibre amplifier
	Uncertainty cone (radius)	2.5 mrad	
	ATS size	610 x 610 pixels	
	Mechanism	Fine steering only	
	Data rate	20 Gbps @ 20° elevation	Growth potential thanks to wavelength multiplexing
Ground terminal	Pupil size	250 mm	
	Beacon optical power	30 W +/-5 mrad beam	To cover uncertainty cone to avoid beacon scanning
	Uncertainty cone (radius)	5.7 mrad (zenith) 3.8 mrad typical case	
	ATS size	1000 x 1000 pixels	
	Mechanisms	Fine steering Fibre injection Fine pointing (TBC)	Fine pointing needed only if uplink telecom beam

Communication chain architecture

The architecture of the emitting (on LEO) and receiving (on ground) communication chains is based on a split data stream between several optical carriers using wavelength division & multiplexing (WDM). This provides growth capacity for the link and allows more flexibility in data rate adaptation to link conditions.

The selected modulation scheme is RZ-DPSK (Return to Zero, Differential Phase Shift Keying) because it offers about 5 dB improvement of the sensitivity despite a more complex communication chain. Moreover, since the phase information is derived by differentiation at symbol rate (i.e. over a fraction of nsec), it is not affected by msec-scale signal variations due to atmospheric scintillation.

The optical detection sensitivities derived from experimental and theoretical is -44.6 dBm for RZ-DPSK at 20 Gbps data rate and 10^{-3} BER.

The link conditions are highly variable during the LEO to ground visibility period since both link distance and atmospheric loss depend strongly on the LEO elevation angle as seen from ground. For 20 deg elevation (minimum assumed value), 12 dB additional loss compared to typical link conditions at 40 deg elevation need to be handled by the coding system or by over-sizing of the link.

DVB-S2 LDPC (Low Density Parity Code) with soft decision is preferred to conventional RS (Reed Solomon) associated to hard decision since it offers 3.7 dB improvements at similar coding efficiency (90% for LDPC 9/10 and 94% for RS). For low elevations, LDPC offers flexibility on the coding level, down to 1/4, with 5.8 dB coding gain.

Implementation of interleaving is necessary to withstand fading due to scintillation. Based on available data from links between ESA OGS in Canaries Islands and Silex and from OICETS data, the worst case fading duration is evaluated to 10 msec. To ensure coding convergence, interleaving over 20 msec is considered.

4. LEO TERMINAL PRELIMINARY DEFINITION

The LEO terminal is composed of two main parts: the aerial part and the back end electronics located inside the bus at a distance of a few meters from the aerial part.

The **aerial part** includes:

- The Telescope: this optical antenna is an afocal on-axis Cassegrain telescope.
- The Fine Steering Mechanism: this 2-axis mechanism is composed of the azimuth and elevation articulations, a U bracket and optical relays to transfer the output pupil of the telescope to the focal plane. The pointing angle is hemispherical to allow for direct transmission (fresh information needs) over a wide Earth coverage
- The Focal plane: Core of the terminal, the focal plane provides highly stable environment to key units located either on transmit or receive optical paths. On the receive path, the optical beam is directed towards the Acquisition and Tracking sensor. On the transmit path, the focal plane forwards the communication signals from Power booster amplifiers towards the telescope. The focal plane includes beam splitters and filtering optics and optical collimators. These units are mounted on a stable silicon carbide bench. Redundancy of the communication channels is ensured thanks to optical multiplexing
- The satellite interface assembly: it provides the aerial interface structure with host spacecraft and, therefore,

depends of the selected accommodation. It aims at rejecting the singular point outside the area of interest. An interface structure supports the Fine Steering Mechanism, the focal plane and its proximity electronics and the power booster amplifiers.

- The back end electronics include:
    - The Terminal Control Electronics that manages the interfaces with the platform and the terminal units, delivers the electrical power to the terminal units, and performs the terminal control (high level modes, thermal control, open loop pointing, partner detection, closed loop high frequency tracking and pointing).
    - The Laser & Communication Electronics that receives the communication signal and delivers the modulated optical signal to the power booster amplifier using a mono-mode optical fibre. It interfaces with the Terminal Control Electronics for the data management.

The 1.55 µm laser source is connected by optical fibres to the optics of the focal plane, allowing moving this dissipating unit away from the stable optical bench.
The mass of the terminal is 19 kg (including control and communication electronics) and the power consumption during communication is 95 W.

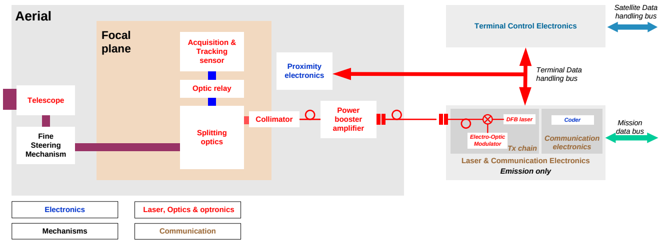


Figure 9 : LEO terminal architecture

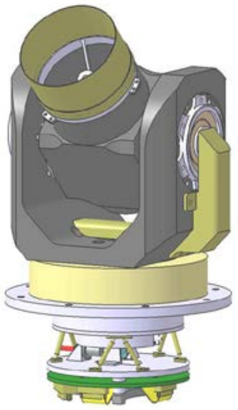


Figure 10: LEO optical telemetry terminal

5. TECHNOLOGY MATURITY ASSESSMENT

Based on the LEO terminal definition, a technological state of the art detailed review has been performed for every component in order to assess its level of maturity (TRL) for a space application. The synthesis of these reviews is provided in Table 1
It appears that the unit requiring risks mitigation activities to increase its TRL level is clearly the laser booster amplifier:

- Er/Yb Power Booster Amplifier, mainly Fibre radiation darkening robustness, isolator, sealed Fibre / optics interfaces with alignment capability, optical filters (especially in multiplexing scenario)
- Resonantly pumped Er doped fiber amplifier

Other areas where some technology monitoring and investigation are to be pursued and risks mitigation actions can be envisaged are:

- Fine steering mechanism (optimization, especially elevation axis)
- Adaptive optics (implementation and isoplanatic issue)
- Beacon laser sources
- Optical filtering (complexity vs. required filtering)
- Acquisition and Tracking Sensor, mainly InGaAs radiation behaviour
- Laser transmitter with DPSK modulation

Function	TRL
Structure & thermal	>7
Mechanism	> 5 to 7
Optical & optronic	> 3 to 7
Electronics	> 5 to 6
Laser power	> 2 to 5
Laser communication (transmission)	> 4 to 6
Laser communication (reception)	> 4 to 6

Table 1 : LEO terminal technologies maturity level

6. CONCLUSION & PERSPECTIVES

The LOLA program was the opportunity to demonstrate that high data rate optical communications between satellites and airborne or ground users are not only feasible with attractive performance, but also that the overall system can be made robust to signal fading due to propagation in the atmosphere, guarantying a good system availability. The flight test campaign also allowed detailed correlation of the atmospheric propagation model.

The validated model was then used in the frame of the Optical Image Telemetry study for CNES to assess the performances and the definition of a LEO to ground optical telemetry system, as well as a LEO terminal preliminary design.

The proposed LEO terminal is based mostly on mature technologies suitable for space application, thanks to LOLA experience. Indeed, LOLA was also the opportunity to introduce and test some major technology & functional innovations providing a good maturity level for some key element of a LEO terminal : SiC material and associated integration techniques to realize stable telescope & focal plane assemblies; fast & accurate wide angle pointing mechanism able to perform signal acquisition; CMOS detector which flexible windowing capability allows to combine acquisition & tracking detection and point ahead angle compensation in a single device.

Nevertheless, the technological maturity assessment of the terminal definition has identified some technological areas that require further action for validation and risk mitigation prior to their use on a space borne terminal. In particular, all the technologies related to the laser booster amplifier need to be further studied and validated.

A study and predevelopment work plan has been built suitable with the objective of a terminal space demonstrator available in 2018.

ACKNOWLEDGEMENTS

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