Results from the DOLCE (Deep Space Optical Link Communications Experiment) Project

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ABSTRACT

Oerlikon Space AG has since 1995 been developing the OPTEL family of optical communications terminals. The optical terminals within the OPTEL family have been designed so as to be able to position Oerlikon Space for future opportunities open to this technology. These opportunities range from commercial optical satellite crosslinks between geostationary (GEO) satellites, deep space optical links between planetary probes and the Earth, as well as optical links between airborne platforms (either between the airborne platforms or between a platform and GEO satellite).

The OPTEL terminal for deep space applications has been designed as an integrated RF-optical terminal for telemetry links between the science probe and Earth. The integrated architecture provides increased TM link capacities through the use of an optical link, while spacecraft navigation and telecommand are ensured by the classical RF link. The optical TM link employs pulsed laser communications operating at 1058nm to transmit data using PPM modulation to achieve a robust link to atmospheric degradation at the optical ground station. For deep space links from Lagrange (L1 / L2) data rates of 10 - 20 Mbps can be achieved for the same spacecraft budgets (mass and power) as an RF high gain antenna.

Results of an inter-island test campaign to demonstrate the performance of the pulsed laser communications subsystem employing 32-PPM for links through the atmosphere over a distance of 142 km are presented. The transmitter of the communications subsystem is a master oscillator power amplifier (MOPA) employing a 1 W (average power) amplifier and the receiver a Si APD with a measured sensitivity of –70.9 dBm for 32-PPM modulation format at a user data rate of 10 Mbps and a bit error rate (BER) of 10^{-6}.

Keywords: Optical Inter-Satellite Links, Deep Space Optical Links, Atmospheric Optical Links

1. INTRODUCTION

Laser communications technology (LCT) has been identified as a key technology for a wide range of future applications. Within Europe a number of developments have been realized to develop the technology and verify the feasibility of LCT. The ESA SILEX project was the first to successfully demonstrate LCT links between two satellites (ARTEMIS and SPOT4) over distances of up to 40’000km [1] as well as between a geostationary satellite and ground [2]. Optical link services are performed by ARTEMIS each day, as a routine operation, with link distances in the order of 40’000 km and data rates of 50 Mbps. In addition, the Japanese OICETS satellite has achieved an optical communications link with the ARTEMIS satellite [3] using a common interface definition between the two satellites. In addition to these demonstrations using LEO satellites a successful link from an aircraft to ARTEMIS was performed by EADS Astrium within the LOLA project to transmit data at a rate of 50 Mbps from an aircraft using the SILEX technology and communications protocol [4]. Finally, Tesat has recently performed a successful in-orbit LEO-LEO demonstration of an optical link at a data rate of 5.625 Gbps between the NFIRE and TerraSAR satellites [5].

Following on from the success of these LCT demonstrations a number of new and interesting applications can now be considered. One such application is to apply the LCT technology demonstrated for near Earth communications for use in deep space links [6]. The concept developed by Oerlikon Space is a hybrid RF – optical TT&C terminal [7]. Within this concept the LCT is not intended to replace radio communication, but both technologies can complement each other very efficiently. Due to low data rates and thus reduced (or sometimes non-existing) satellite attitude requirements commanding and controlling spacecraft (TM/TC) will remain a domain of radio communication (e.g. S-band). On the

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other hand, the transmission of large amounts of scientific data back to Earth can be much more efficiently performed via optical communication.

A number of ESA studies have been performed to assess the capability of LCT for deep space links to the Lagrange points (L1 / L2), to Mars [7] and to the Moon [8] in which it has been shown that LCT can achieve an order of magnitude increase in data rate that can be transmitted back to Earth for the same mass, power and volume as a high gain antenna. The data rates that can be achieved using today's state of the art LCT are summarized below in Table 1.

Mission	Moon	Lagrange	Mars	Jupiter
Link distance	386 000 km	1.5 Mio km	≤ 400 Mio km	av 780 Mio km
TX aperture	100 mm	135 mm	135 mm	135 mm
TX power	1 W	1 W	6 W	6 W
TX architecture	MOPA	MOPA	Q-switched, 40 kHz	Q-switched, 20 kHz
OGS RX aperture	1 m	1 m	10 m	10 m
Data rate	100 Mbit/s	20 Mbit/s	300 kbit/s	100 kbit/s

Table 1: Optical Telemetry Data Rates as a Function of Link Distance

One key difference in the technology proposed for deep space communications is to use pulse position modulation (PPM) as the format for the communications link. PPM uses short duration, high peak power pulses as a communication protocol selected due to the high receiver sensitivity that can be achieved when detecting optical pulse information within a direct detection system (such as the case with optical links through the atmosphere). The DOLCE project was an ESA contract awarded to Oerlikon Space to design and breadboard a deep space optical link communications end-to-end (DOLCE) demonstrator to verify the feasibility of the data return link examples from the first and the second Lagrange orbit (L1 and L2) back to Earth. ESA's optical ground station (OGS) with its 1-meter diameter telescope was to be used as the receiving station. The baseline requirements for the DOLCE demonstration were a user data rate of 10 Mbps at a bit error rate (BER) of 10^{-6} using 32-PPM modulation.

The design and simulated performance of the DOLCE communications subsystem has been reported previously [9] – in this paper we present the results of the DOLCE test campaign.

The structure of this paper is as follows:

- Section 2 summarises the principles of the PPM communications format and presents the required signal to noise ratio and receiver sensitivities for the DOLCE communications subsystem.
- Section 3 presents a description of the DOLCE communications subsystem design together with the breadboard implementations of the DOLCE transmitter and DOLCE receiver.
- Section 4 provides a summary of the tests performed to verify the feasibility of the links from the Lagrange points (L1 / L2). These tests were performed both in the lab at Oerlikon Space premises and between two islands over a distance of 142km.
- Section 5 summarises the results achieved and conclusions arrived at from the DOLCE project.

2. PULSE POSITION MODULATION (PPM) FORMAT

Pulse-position-modulation (PPM) uses short duration, high peak power pulses as a communication protocol selected due to the high receiver sensitivity that can be achieved when detecting optical pulse information within a direct detection system (as is the case within optical links through the atmosphere). Figure 1 depicts important timing parameters that define the PPM symbols s_i. The slot time T_{SLOT} is the shortest time instance at which the laser diode is switched "on" or "off". Using PPM, a single pulse is transmitted per symbol s_i representing a symbol period T_{SYMB} consisting of M time slots plus the blank time T_{BLANK} in which no pulse is located, i.e., the symbol period is equal to $T_{BLANK}+M\cdot T_{SLOT}$. The raw data rate is $\log_2(M)/T_{SYMB}$ bps and the peak-to-average power ratio of the transmitted laser pulses is T_{SYMB}/T_{SLOT}.

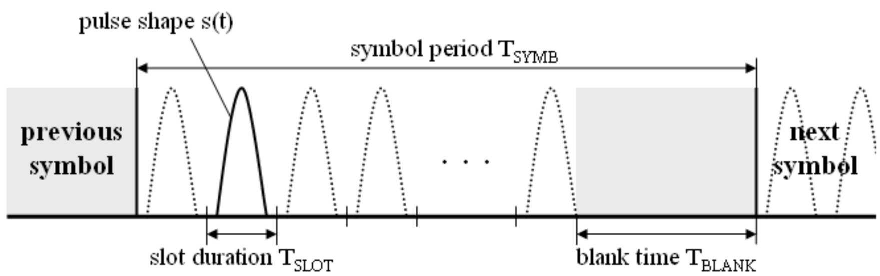


Figure 1: PPM Symbol Definition

The PPM communications protocol uses a single pulse per symbol period to encode a defined bit sequence. Since the receiver on the ground station has a (small) tendency to produce symbol errors next to the correct symbol position, a Gray mapping has been employed, such that symbol errors cause only a small number of bit errors [10, 11].

Figure 2 shows the results of bit-error-rate (BER) simulations of the communication link as function of the receiver signal-to-noise ratio (SNR) $P_{RXE}/P_{noise,off}$ (electrical peak Rx power versus electrical detector noise power without input signal) with and without forward error correction coding. For the expected signal and noise power settings the SNR is given by

- Detector temperature -10°C: $P_{RXE}/P_{noise,off} = 164pW/5.6pW = 14.7$ dB.
- Detector temperature 20°C: $P_{RXE}/P_{noise,off} = 164pW/25pW = 8.2$ dB.

Figure 2 shows that to achieve the target BER of 10^{-6}, the following SNRs are required:

- Detector temperature -10°C: $P_{RXE}/P_{noise,off} = 12.0$ dB.
- Detector temperature 20°C: $P_{RXE}/P_{noise,off} = 8.5$ dB.

Detector temperature: 20°C

Detector temperature: -10°C

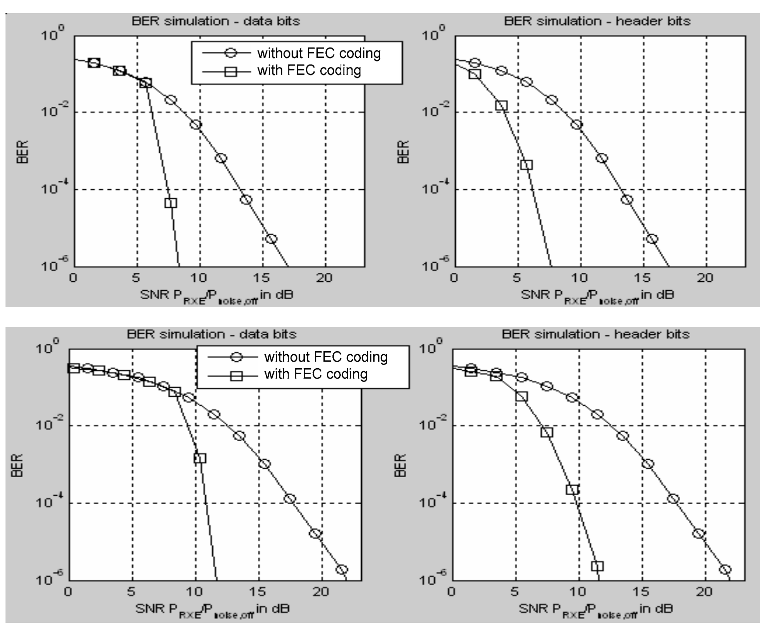


Figure 2: Bit Error Rate of the DOLCE Receiver as a Function of the SNR

At first it seems to be a contradiction that a higher SNR is required for the cooled detector. It can be explained from the fact, that signal-dependent noise (i.e. signal shot noise amplified by the APD during reception of the desired pulse) has been excluded from the above definition of the SNR. The net performance of the communications system of course increases when the detector is cooled (+2.7dB vs. -0.3dB margin).

3. DOLCE BREADBOARD DESCRIPTION

The DOLCE breadboard is a point-to-point communications link comprising a transmitter that is to be accommodated on a deep space satellite located at either L1 / L2 Lagrange points, whilst the DOLCE receiver is representative of that to be integrated onto the Coudé bench of the ESA optical ground station (OGS).

A block diagram for the DOLCE transmitter is shown in Figure 3 and comprises the following:

- Communications Transmit Electronics (CTE) – the CTE contains an FPGA that implements all the control and signal processing functions of the DOLCE transmitter. This is done via an embedded computer inside the FPGA that receives and interprets the user data from the satellite payload. From the user data the CTE generates the pulsed serial PPM data stream that is then processed by the Laser Modulator Electronics (LME).
- Laser Modulator Electronics (LME) – the LME generates the laser drive signal for modulating the seed laser diode of the MOPA transmitter.
- Laser Diode Module (LDM) – the LDM contains the laser diodes to be modulated with the pulsed electrical signal from the LME to generate the PPM optical pulse train.
- Optical Fibre Amplifier (OFA) and associated pump module – the OFA boosts the optical signal at the output of the LDM to the required multi-Watt peak power levels need to meet the link requirements.

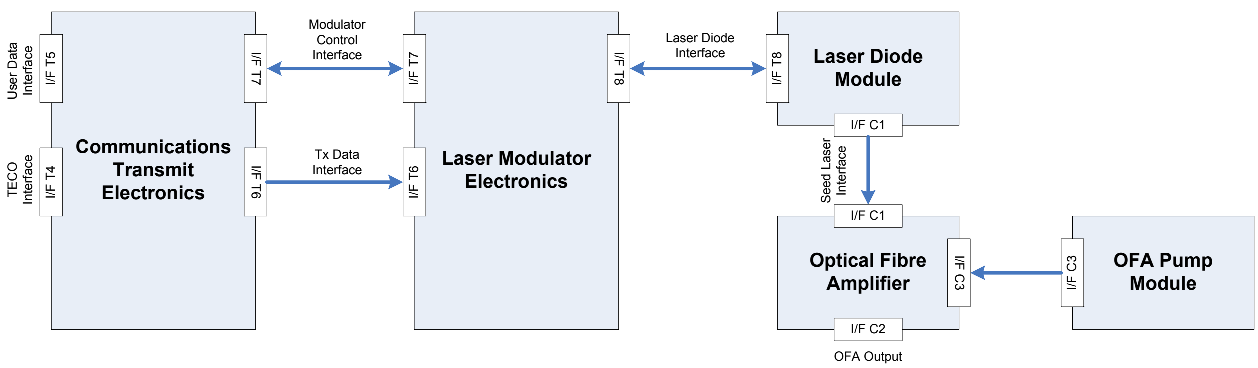


Figure 3: Block Diagram for the DOLCE Transmitter

The components used for the breadboard are commercial devices but selected such as to have an alternative that is either available as a space approved component or the technology is compatible with space qualification. The critical components are:

- FPGA which for the breadboard was the Virtex-IIPro-FF1152. A suitable space compatible FPGA would be the radiation tolerant RT-AX2000.
- The laser diode module which in the DOLCE breadboard is located in the CTE rack unit. The laser diode used was a 1058nm Fabry-Perot device with an emitted optical output power of 150 mW.

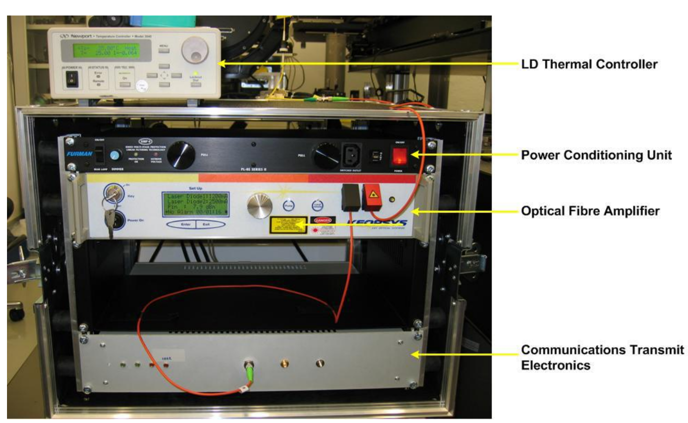


Figure 4: Photograph of the DOLCE Transmitter Breadboard

- The optical fibre amplifier (OFA) used in the DOLCE transmitter breadboard is a commercial 19” rack unit from Keopsys. Alternative space qualified amplifiers operating at around 1060nm have been developed and are available. The OFA is a single frequency polarization maintaining OFA with an output power of between 1 W (average) which when operated in pulsed mode can generate 40 W pulses with a pulse duration of 10 ns.

The DOLCE receiver is a direct detection receiver using an avalanche photodiode (APD) to detect the pulsed optical signal received from the L1/L2 satellite/probe followed by demodulation and signal processing to recover the original telemetry data. A block diagram for the DOLCE receiver is shown in Figure 5 and comprises the following:

- APD Module – the laser pulses emitted by the OFA propagate over the free-space optical path from L1/L2 to Earth and are received at the OGS by an avalanche photo diode (APD) mounted on the Receive Detector Electronics.
- Receive Detector Electronics – the Receive Detector Electronics consists of all the required analog circuitry to control the APD and to amplify the received laser pulses. The received pulses are fed into the Receive Electronics.
- Receive Electronics – the Receive Electronics amplifies and samples the received laser pulses with a high-speed analog-to-digital converter (ADC).
- Receive Digital Electronics (RDE) – the pulse samples from the Receive Electronics are fed into the RDE where the digital signal processing is implemented in a second Virtex-IIPro FPGA to convert the pulse samples back to the original user data.

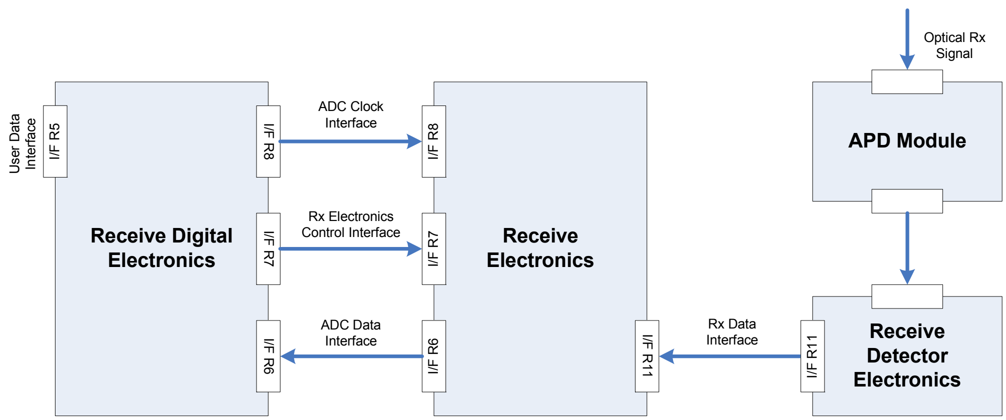
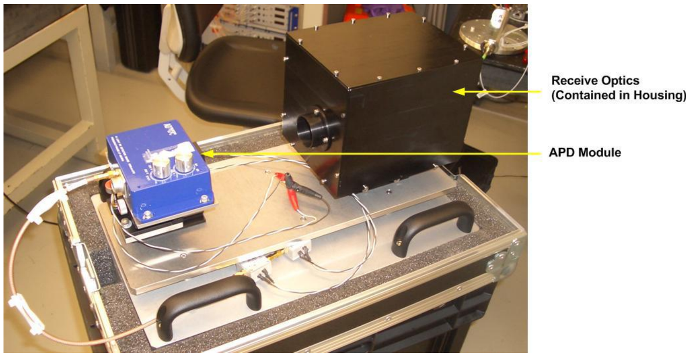


Figure 5: Block Diagram for the DOLCE Receiver

The DOLCE receiver comprises two modules. The transmitted laser pulses are received at an avalanche photo diode (APD) mounted with the receive detector electronics within the receiver detector package (RDP). The RDP consists of the receive optics to interface to the OGS Coudé optical bench (consisting of an optical bandpass filter and focussing lens) and the APD. The second module is the Communications Receive Electronics which is a 19” rack unit housing the Receive Electronics and Receive Digital Electronics boards. Photographs of the Receive Detector Package and Communications Receive Electronics are shown in Figure 6 and Figure 7 respectively. Figure 7 also shows the DOLCE laptop used to control, operate and measure the performance of the DOLCE breadboard.



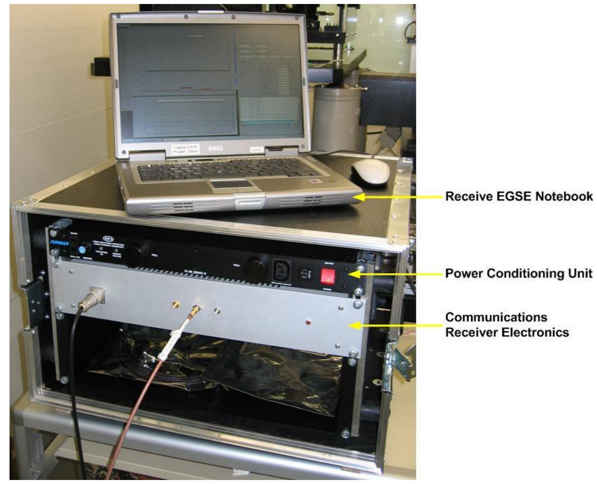


Figure 6: Receive Detector Package (RDP)

Figure 7: Photograph of the DOLCE Receiver

Characterisation of the DOLCE breadboard has been performed at Oerlikon Space to confirm the correct functional operation. The tests performed have verified that:

- Pulse generation for a 32-PPM modulation format generating 10ns pulses synchronised to the correct slot position in the PPM symbol. The selected symbol period for the PPM slot was 390ns with a blank time of 70ns.
- Implementation of the forward error correction code (FEC) and bit interleaving on the payload of the PPM frame. The FEC used has rate 0.79 which applied to the user data rate of 10 Mbps leads to a raw data rate for the optical link of 12.8 Mbps.
- Characterisation of the emitted laser pulses. For pulsed operation the power emitted by the OFA of each pulse is determined by both the ratio of the symbol period to the PPM slot duration (for a raw data rate of 12.8 Mbps and using 32-PPM with 10ns pulses then the optical peak to average power ratio is 39) and also to the physical limitations for the OFA (which for the device used in the DOLCE breadboard was shown to have an optical peak to average power ratio of 31 ± 3).
- APD sensitivity characterisation to determine the required received optical power to achieve the target bit error rate (BER) of 10^{-6} with and without FEC using 32-PPM. The achieved performance is shown in Figure 8 in which a receiver sensitivity of -68.8 dBm (BER < 10^{-6}) without FEC was achieved (this corresponds to 56 photons/bit). With FEC applied a coding gain of 2.1 dB was achieved resulting in a receiver sensitivity of -70.9 dBm (BER < 10^{-6}) which corresponds to 35 photons/bit.

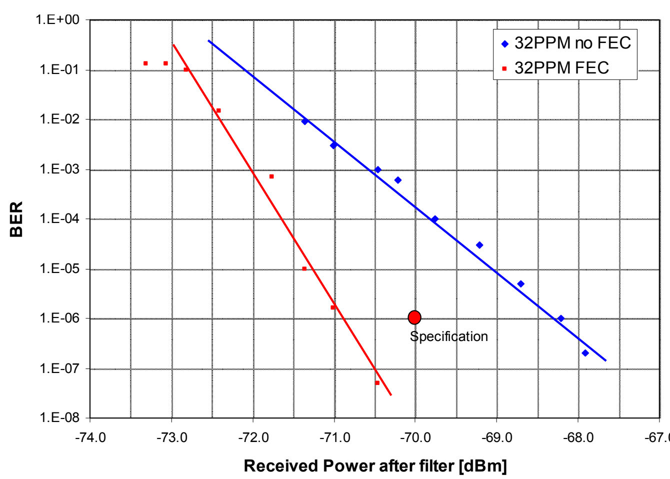
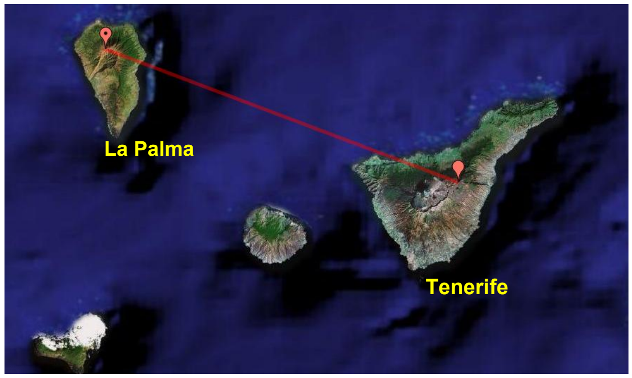


Figure 8: DOLCE Receiver Sensitivity

4. RESULTS OF THE DOLCE INTER-ISLAND COMMUNICATIONS LINK EXPERIMENT

In order to demonstrate the robustness of the pulsed communications subsystem developed within the DOLCE project within the atmospheric channel a communications link experiment was performed between the Canary Islands of La Palma and Tenerife over a distance of 142 km. Note that such a link to the ESA OGS represents a worst case compared to a link from space as both the transmitter and receiver are located in the atmospheric channel. The DOLCE inter-island communications link (I2CL) is illustrated in Figure 9.

Nordic Optical Telescope on La Palma



ESA Optical Ground Station at Tenerife

Figure 9: DOLCE I2CL Experiment

For the I2CL to be representative of a communications link from L1 / L2 the following considerations were taken into account when design the I2CL experiment:

- The ESA OGS located on Tenerife was used as the receive ground station and the DOLCE receiver was accommodated in the Coudé room. This is shown in Figure 10 where the DOLCE RDP is shown integrated on the ESA OGS optical bench. Shown are the RDP, a dichroic beamsplitter (DBS) to separate the receive wavelength (1058nm) from the beacon wavelength (in the 800nm band) and to direct the receive beam to the RDP and an electrical amplifier used to boost the electrical signal level before transmitting it via a coax cable to the receive electronics rack.

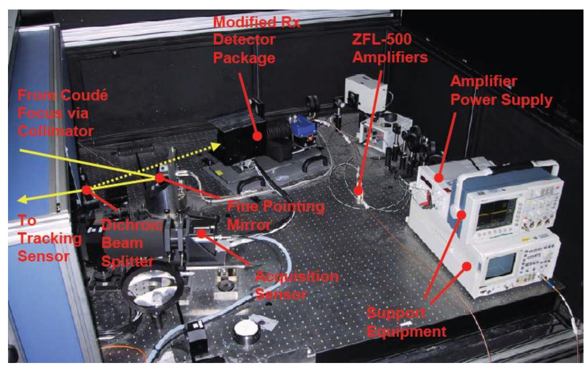


Figure 10: RDP at the OGS Optical Bench

- The link distance from L1 / L2 to the ESA OGS is 1’500’000 km whereas the link distance for the I2CL is 142 km. To ensure that the I2CL is representative of a link from L1 / L2 the reduction in link distance by a factor of ~10^4 is compensated for by reducing the effective emitted irradiance of the transmitter by a factor of ~10^8 such that the light collected by the 1m telescope at the OGS and therefore incident on the APD receiver is at the same power level as measured at Oerlikon Space. For the DOLCE I2CL the transmitter was then not an optical terminal with a 13.5cm telescope but an optical fibre with a small collimating optics. The DOLCE transmitter was accommodated in a portacabin next to the Nordic Optical Telescope on La Palma.

After alignment of the DOLCE transmitter with the ESA OGS the communications link was acquired and a number of measurements were performed to characterise the performance of the DOLCE communications subsystem in the atmospheric channel. Specifically the following tests and measurements were performed:

- Experiments performed to determine the excess loss of the link during day-time conditions (19.3 dB) and night-time conditions (15.2 dB).
- Long term BER measurements during day-time conditions (blue sky) and night-time.

During the day-time BER measurements it was observed that the FEC did not give the expected coding gain and improvement from a BER of 2 x 10^{-3} to better than 10^{-6} due to the strong atmospheric fades observed on the recoded SNR at the APD. These atmospheric fades were stronger than expected due to the transmitter being located in the atmosphere and not in space as would be the case for a link from L1 / L2. To overcome this and enable the FEC to be effective would require the bit interleaver depth to be increased by adding additional memory to the DOLCE transmitter.

For the inter-island communications link (I2CL) experiment measurements the target BER to be achieved was therefore 2 x 10^{-3} (i.e. the uncoded performance as shown in Figure 8). The received optical power on the APD to achieve this BER was measured at the ESA OGS to be -68.8 dBm. If we compare this performance with that measured during the tests at OSZ premises then the night-time receiver sensitivity degradation due to scintillation is estimated at -2.1dB.

In addition to perform the I2CL at 10 Mbps with 32-PPM format a number of other links were performed to assess the DOLCE breadboard performance (specifically the flexibility of subsystem design to adapt to different link conditions thereby being able to increase data rate when the atmospheric channel is more benign). A summary of the links achieved is provided in Table 3 from which it can be seen that the breadboard can adapt to vary the modulation format, blank time, peak-to-average power ratio, frame structure and data rate.

Tx Power (mW)	Modulation Format	Blank Time (slots)	Peak to Average Ratio	Words per Frame	Data Rate (Mbps)
22	64-PPM	56	120	512	4.6
32	64-PPM	16	80	1024	7.0
43	32-PPM	28	80	1024	7.7
65	32-PPM	5	37	2048	12.7
100	16-PPM	4	20	4096	19.0
230	8-PPM	2	10	8192	28.9

Table 3: Summary of the Performed DOLCE I2CL Experiments

5. SUMMARY AND CONCLUSIONS

The objectives of the DOLCE project have been met in that the design, implementation and verification of a pulsed laser communications subsystem for 10 Mbps optical telemetry links from L1 / L2 has been achieved with the breadboard developed during the course of the project.

A comparison of the link budgets for the deep space link from L1 / L2 with that of the DOLCE inter-island communication link experiment is shown in Table 4.

	DOLCE I2CL			Liberation Point L2		
Parameter	**Value**	**Unit**	**Remark**	**Value**	**Unit**	**Remark**
Tx power	14.0	dBm	25mW	30.0	dBm	1W
Tx antenna gain	45.6	dB	$G = \frac{8}{\theta^2}$ θ = 14.8mrad	116.5	dB	$G = 0.8145 \frac{\pi^2 D^2}{\lambda^2}$ D = 0.25m
Free-space loss	-244.5	dB	$\left(\frac{\lambda}{4\pi z}\right)^2$, z = 142km	-325.0	dB	$\left(\frac{\lambda}{4\pi z}\right)^2$, z = 1'500'000km
Rx antenna gain	129.1	dB	$G = \frac{\pi^2 D^2}{\lambda^2}$, $(D/m)^2 = 1.016^2 - 0.33^2$	129.1	dB	$G = \frac{\pi^2 D^2}{\lambda^2}$ $(D/m)^2 = 1.016^2 - 0.33^2$
Power on Rx aperture	-55.8	dBm		-49.4	dBm	

Table 4: Comparison of DOLCE I2CL and L2 link budgets (λ=1058nm)

In deriving the link budgets it has been assumed that the aggregate excess loss, due to atmospheric propagation and technical implementation, remain the same in both cases. In our opinion this assumption is valid since the OGS implementation could remain as it is and the transmitter would be located in space thereby leading to reduced atmospheric loss and scintillation (due to a shorter path length though the atmosphere) and no atmospheric turbulence close to transmitter.

Main points to note from this link budget are:

- The transmit power and the transmit antenna gain are the as used values for the inter-island communications link. The transmit power was set so as to achieve a stable link at the OGS at a data rate of 10 Mbps with 32-PPM. The measured receiver sensitivity was -68.8 dBm (without FEC) at the DOLCE APD.
- For the above conditions the extrapolated receive power at the entrance aperture of the ESA OGS is -55.8 dBm. If we calculate the extrapolated receive power at the OGS aperture from the Lagrange points (L1 / L2) then the receive power is -49.4 dBm.
- The downlink from the Lagrange points (L1 / L2) therefore has a link margin of 6.4dB with respect to the sensitivity limit demonstrated during the DOLCE inter-island communications link experiment.

6. ACKNOWLEDGMENTS

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7. REFERENCES

1. T.T. Nielsen and G. Oppenhauser, “In-Orbit Test Result of an Operational optical intersatellite link between ARTEMIS and SPOT-4, SILEX”, Proc. SPIE Vol. 4635, Free-Space Laser Comm. Technologies XIV, 2002.
2. M. Garcia Talavera, S. Chueca, A. Alonso, T. Viera and Z. Sodnik, “Analysis of the Preliminary Optical Links between ARTEMIS and the Optical Ground Station”, Proc. SPIE Vol. 4821, Free-Space Laser Comm. And Laser Imaging III, 2002.
3. T. Jono, et al, “Overview of the Inter-Orbit and the orbit-to-ground lasercom demonstration by OICETS”, Proc. SPIE Vol. 6457, Free-Space Laser Comm. Technologies XIX, 2007.
4. LOLA project web site : http://www.space.eads.net/families/a-safer-world/futuredefnce/lola
5. B. Smutny, R. Lange, H. Kämpfner, D. Dallmann, G. Mühlnikel, M. Reinhardt, K. Saucke, U. Sterr, B. Wandernoth and R. Czichy, “5.625 Gbps Optical Inter-Satellite Communication Link Verified in Orbit”, 14th Ka- and Broadband Communications Conference, Paper No. 16B-3, Sept. 2008.
6. H. Hemmati, “Deep Space Optical Communications”, Wiley Interscience, 2006.
7. T. Dreischer, K. Kudielka, G. Baister and T. Weigel, “Integrated RF-Optical TT&C Subsystems for Missions to Mars and to Libration Points”, 23rd AIAA International Communication Satellite Systems Conference, Sept. 2005.
8. T. Dreischer, M. Tüchler, K. Kudielka and G. Baister: “Enhanced Data Return from Lunar Farside using RF-Optical TT&C”, DGLR International Symposium, Sept 2008.
9. G. Baister. T. Dreischer, M. Tüchler and E. Fischer, “OPTEL Terminal for Deep Telemetry Links”, Proceedings of the SPIE Vol. 6457, Free-Space Laser Comm. Technologies XIX, 2007.
10. T. Rappaport, Wireless Communication, Prentice Hall, 2002, 2nd Ed.
11. J. Proakis and D. Manolakis, Digital Signal Processing, Prentice Hall, 1996.