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IN-ORBIT VERIFICATION OF

HIGH DATA RATE LASER COMMUNICATION LINKS

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Abstract

For the first time inter-satellite laser communication links with a data rate higher than 1 Gbps have been verified in-orbit. The links have been established between two satellites on low earth orbits. 5.625 Gbps have been transmitted with a bit error rate better than 10^{-9}. Today, the laser communication terminals are applied in programs to investigate the propagation of coherent beams through the atmosphere.

1. INTRODUCTION

Compared to RF communication laser communication offers the advantage to transmit data at a higher data rate across larger ranges with terminals of lower mass, lower power consumption and smaller size. March 1998 the first laser communication terminal was launched on SPOT-4, a satellite on a low earth orbit (LEO) [1]. November 2001 the European Space Agency (ESA) performed SILEX, the world-first laser inter-satellite communication link [2]. The link with a data rate of 50 Mbps (bps: bits per second) was established between SPOT-4 and ARTEMIS, a satellite on a geostationary orbit (GEO). SILEX proved that the demanding pointing, acquisition and tracking requirements, which are due to the highly collimated optical transmit beam, reliably were mastered. August 2005 the Japanese Space Exploration Agency (JAXA) launched LUCE, a SILEX compatible Japanese laser communication terminal [3] on OICETS, a LEO satellite, to establish communication links to ARTEMIS.

ESA [4] and the Japanese National Institute of Information and Communications Technology (NICT) [5] also developed SILEX compatible ground stations for optical satellite-to-ground links. 2006 the French experiment LOLA established an optical link between an aircraft and ARTEMIS [6] and demonstrated communication in strongly turbulent and dynamic environment. In this way the performance of an optical GEO-relay was demonstrated in successive steps with links from aircraft to GEO, LEO to GEO and GEO to ground.

More than 10 years ago data rates in the order of 100 Mbps seemed to be sufficient for inter-satellite links. Today, there is a clear demand for data rates in the order of Gbps [7]. The SILEX laser communication terminal is based on on-off keying (OOK), i.e. amplitude modulation of semiconductor laser diodes and direct detection of the transmitted signal. OOK cannot cope with the demand of an increased data rate, since it is limited to a few 100 Mpbs. For that reason the German Aerospace Center (DLR) developed laser communication terminals based on homodyne binary phase shift keying (BPSK), i.e. phase modulation of a frequency-stable laser and homodyne detection.

In case of homodyne detection the received signal is superposed to the beam of a so-called local oscillator. The local oscillator runs on the same frequency as the signal's carrier and its optical phase is locked to the signal. Homodyne detection ensures highest detection sensitivity and suppression of any kind of false light, especially sun light. Homodyne BPSK – combined with coherent tracking (tracking with a control signal generated by homodyne detection) – is the only modulation scheme that maintains an optical communication link even with the counter terminal in front of the sun.

Today, an optical 5.625 Gbps homodyne BPSK communication link is operational in-orbit for more than two years [8]. Established between two LEO satellites the link demonstrates robust and reliable link quality under realistic environmental conditions. The LEO-LEO constellation allows to characterize the link quality under more demanding constraints than is the case for LEO-to-GEO links, because the angular tracking velocity is larger, the link distance strongly varies, larger Doppler shifts have to be compensated and larger point-ahead angles need to be adjusted.

The homodyne BPSK laser communication terminals are also applied in LEO-to-ground links to investigate the propagation of coherent beams through the atmosphere. Beside scientific objectives this is of interest for the design of optical ground stations being developed by ESA [9] and DLR [10].

2. LASER COMMUNICATION TERMINAL

Fig. 1 shows a functional block diagram of the homodyne BPSK laser communication terminal (LCT). The frequency-stable (seed) laser is a Nd:YAG laser with a wavelength of 1,064 nm. After phase modulation the beam is amplified to the power level required.

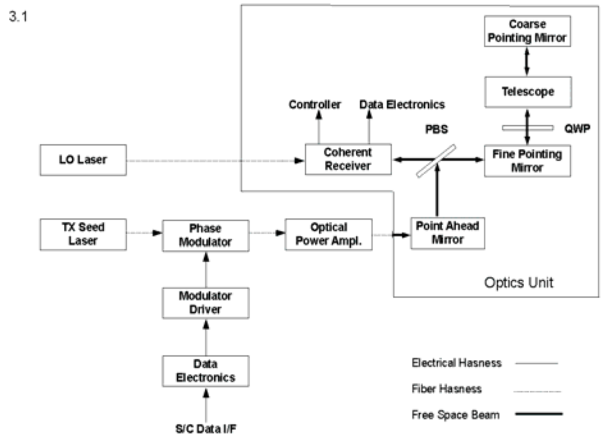

Fig. 1: Functional block diagram of the LCT

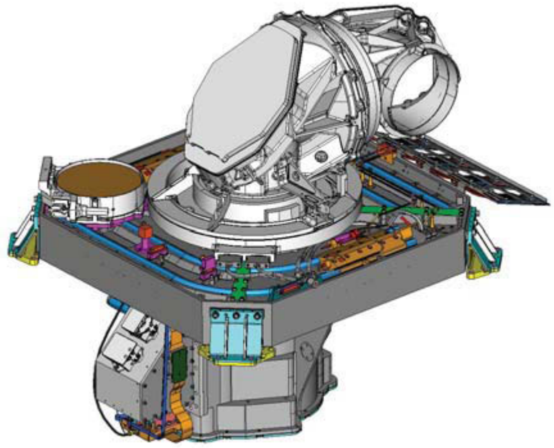

Fig. 2: Laser communication terminal (LCT)

The point ahead mirror aligns the receive axis to the transmit axis with an angular deviation of the point ahead angle. The polarization dependant beam splitter (PBS) reflects the (linear polarized) beam to the fine pointing mirror which compensates the satellite's vibrations in a closed loop to keep the transmitted beam aligned in space coordinates. A quarter wave plate (QWP) transforms the polarization from linear to circular. This makes the link robust against rotation of the LCT (around the transmit axis, around the other axis' the LCT is robust by tracking). The telescope adjusts the beam's diameter and – by diffraction at the telescope aperture – its divergence. The coarse pointing mirror directs the beam to the counter LCT.

The counter LCT transmits light of different circular polarization. The light received by the telescope is transformed to a linear polarization perpendicular to the one of the transmitted beam and the light beam is transmitted at the polarization dependent beam splitter (PBS) to be detected in the homodyne receiver by superposition with the local oscillator laser beam. The fine pointing mirror compensating the satellite's vibrations keeps the received beam on the coherent receiver's optical axis (by the control loop mentioned above). The tracking control signal is generated in the coherent receiver.

As shown in Fig. 2 the LCT consists of a rectangular frame structure. The coarse pointer is mounted on the space side and allows to track the counter LCT across a full hemisphere. The optics unit (Fig. 1) reaches through the frame structure into the satellite. The frame structure houses the entire electronics and active optics. Fig. 3 shows a photograph of the LCT accommodated on the TerraSAR-X satellite.

To build up a communication link the LCTs run through a so-called pointing, acquisition and tracking (PAT) sequence summarized in Fig. 4.

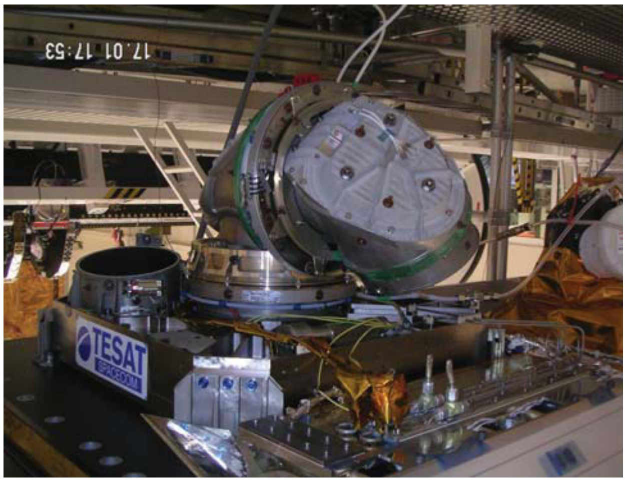

Fig. 3: LCT accommodated on the TerraSAR-X satellite

During “pointing” the LCTs align their coarse pointer towards the counter LCT following its calculated trajectory in an open loop. This alignment is performed with some uncertainty since the satellite's attitude and the counter satellite's trajectory are not accurately known.

During “spatial acquisition” the alignment uncertainty is reduced to a fraction of the beam's divergence. For the homodyne BPSK LCTs verified in space the spatial acquisition is beacon-less, i.e. it is performed with the highly collimated transmit beam used for communication later. The transmit beams scan the cone of the alignment uncertainty until both LCTs detect light. The LCTs align their receive axis perpendicular to the detected wavefront and by this the LCTs align themselves exactly towards their counter LCT.

After both LCTs are aligned to each other, the received light is used for tracking the counter LCT in a closed loop. Since the received signal and the local oscillator run on different frequencies, tracking is based on heterodyne detection.

A frequency search ("frequency acquisition") starts to adjust the local oscillator frequency to the frequency of the (Doppler shifted) signal. After the frequencies are adjusted the phase of the local oscillator can be locked to the phase of the signal in a closed loop. Tracking then is homodyne and communication can start.

The phase modulation frequency is much higher than the one of the phase locking loop. A "logical 1", no phase shift, results in constructive interference, while a "logical 0", a phase shift of 180° leads to destructive interference. By this way the phase signal is demodulated.

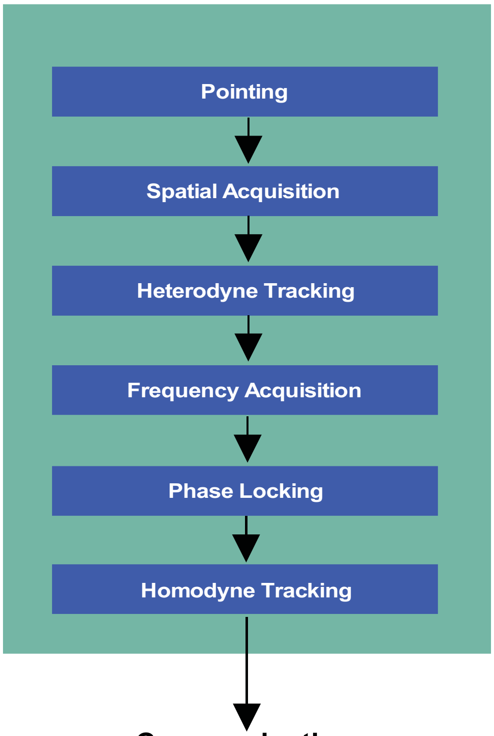

Fig. 4: PAT sequence

The following numbers may illustrate some pointing and tracking requirements. In case of a Nd:YAG wavelength a telescope with an aperture of 100 mm diameter leads to a beam divergence of about 10 µrad. Then, the optical axis' of the transmitter and the receiver shall be aligned (in the closed tracking loop) better than 0.5 µrad (in space). Otherwise, burst errors might occur in case of strong satellite vibrations.

3. INTER-SATELLITE VERIFICATION

The inter-satellite verification has been performed in close cooperation between the United States and Germany.

- April 23rd 2007, the first homodyne BPSK LCT was launched on NFIRE, a U.S. LEO satellite.
- June 14th 2007, a second LCT was launched on TerraSAR-X, a German LEO satellite.
- February 21st 2008, the first homodyne BPSK laser communication link was established.

Established between two LEO satellites the inter-satellite link shall demonstrate robust and reliable link quality (bit error rates, burst errors, sensitivity) and acquisition (reliability, duration) under realistic environmental conditions over years.

The key design features of the NFIRE-TerraSAR-X communication link are summarized in Tab. 1.

Link	LEO – LEO duplex communication
Data Rate	5.625Gbps
Link Distance	1,000 – 5,100 km
Bit Error Rate	< 10^{-9}
Optical Transmit Power	0.7 W
Telescope Diameter	125 mm
Mass	35 kg
Power Consumption	120 W
Volume	0.5 x 0,5 x 0,6 m^3

Tab. 1: Key design features for the LCT verified in-orbit

Fig. 5. shows the location of the first laser communication link. The NFIRE trajectory is depicted in blue. NFIRE runs over Mexico to the United States. The TerraSAR-X trajectory is depicted in pink. TerraSAR-X runs in opposite direction across the Pacific Ocean. The link is depicted in green. Ranges in this constellation vary between 3,700 km and 4,700 km.

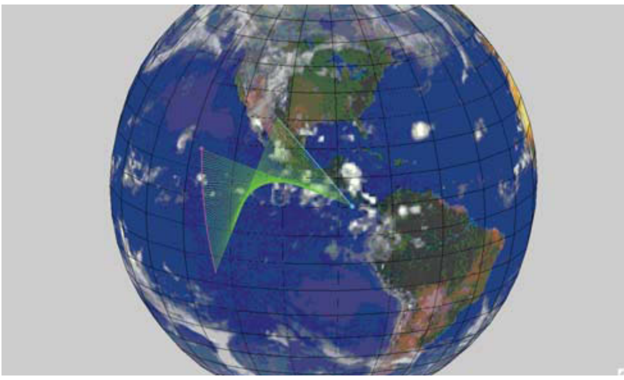

Fig. 5: Location of the first homodyne BPSK laser communication link

In summary, the in-orbit verification now running for two years verifies a bit error rate (much) better than 10^{-9}. Burst errors do not occur. The PAT sequence is verified as very reliable. PAT successfully leads to hand-over from spatial acquisition to heterodyne tracking and from frequency acquisition over phase locking to homodyne tracking. Spatial acquisition is closed within 2 s. Frequency acquisition and phase locking are closed within 8 s. This extraordinary good spatial acquisition performance, of course, depends on the stability knowledge of the satellite's platforms, i.e. on the high pointing precision. Indicated by the burst error rate and read from the tracking telemetry the alignment (in the closed tracking loop) is much better than required and very robust.

Measurements with lowered transmit power yield the LCT's sensitivity. The sensitivity and the measured tracking alignment allow to verify the link budget and its models.

As an example Fig. 6 shows bit errors for the first inter-satellite homodyne BPSK communication link. Communication starts at 35 s and is closed after 350 s because the counter LCT declines behind the horizon. Bit errors are detected in a 225 Mbps data channel. A bit error rate of 10^{-7} corresponds to a single bit error.

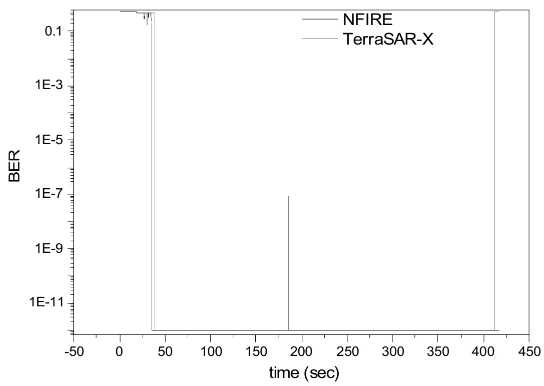

Fig. 6: Bit errors detected during an inter-satellite link

Fig. 6 shows the bit error rate (in the 225 Mbps channel) for both communication links, one from NFIRE to TerraSAR-X the other from TerraSAR-X to NFIRE. While no bit error occurs in the TerraSAR-X-to-NFIRE communication link (during the entire duration of 350 s) there is one single bit error in the other one. With a channel data rate of 225 Mbps and a link duration of 350 s the bit error rate is estimated to 10^{-11}.

4. SPACE-TO-GROUND LINKS

5.625 Gbps homodyne BPSK communication links have been established from NFIRE to a ground station in Hawai (mount Halaekala). The ground station is equipped with a receive telescope of 60 mm aperture, small enough to ensure high efficiency for homodyne detection.

Fig. 7 shows the first realization of a NFIRE-to-ground link. Burst errors occur separated by time intervals of error-free communication. Due to the system's stability – verified by the inter-satellite link – these burst errors are assigned to distortions of the coherent beam after propagating through the atmosphere. With the burst errors as a measure of the optical channel's quality the LEO-to-ground link is a well suited tool to investigate the atmosphere and its impact on coherent beam propagation by relating bit errors with e.g. the LEO LCT's elevation and tracking velocity. A measurement campaign on this topic is ongoing.

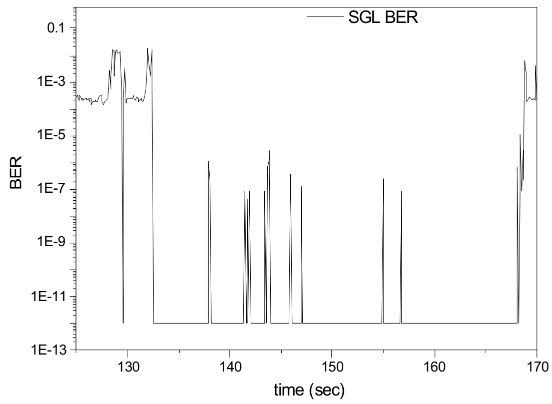

Fig. 7: Bit errors detected during a LEO-to-ground link

5. APPLICATION IN GEO-RELAY SYSTEMS

In terms of short term service realization the most imminent market applications are relay services (LEO-to-GEO-to-ground links) to make the large data amount of LEO earth observation satellites immediately available. For EDRS, the European data relay system, LCTs will be accommodated on two LEO satellites, Sentinel 1a and Sentinel 2a. A further LCT will be accommodated on Alphabus, a European GEO satellite. Links will be established from the LEO satellites to Alphasat or other EDRS GEO satellites equipped with an LCT.

The experience gained with exploiting the in-orbit verification results is important for developing realistic link scenarios for LEO-GEO, GEO-GEO and GEO-to-ground data transmission systems. The design features of the LEO-GEO communication link summarized in Tab. 2 are based on the empirically verified LEO-LEO link budget.

Link	LEO – GEO duplex communication
Data Rate	1.8 Gbps
Link Distance	> 45,000 km
Bit Error Rate	10^{-8}
Optical Transmit Power	2.2 W
Telescope Diameter	135 mm
Mass	50 kg
Power Consumption	160 W
Volume	0.6 x 0,6 x 0,7 m^3

Tab. 2: Key design features for GEO relay LCT

Compared to the LCTs accommodated on NFIRE and TerraSAR-X the performance of the LEO-to-GEO link will be met by adaptation of the data rate, bit error rate, telescope and transmit power. The adaptation is state of the art. Fig. 8 shows the LEO-to-GEO LCT which today is under qualification.

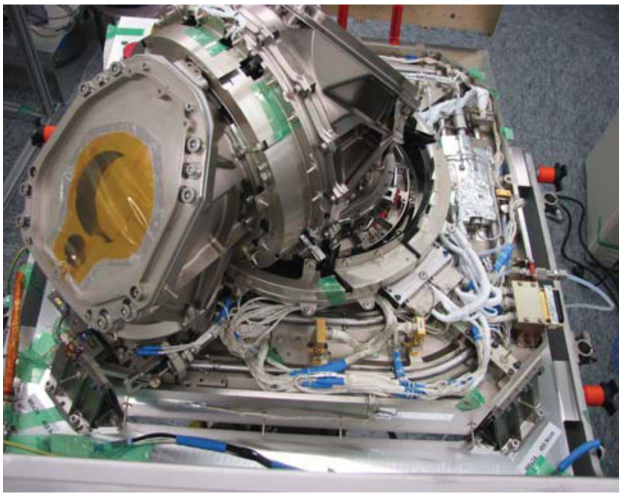

Fig. 8: GEO-relay LCT under qualification

6. SUMMARY

Laser communication at high data rates no longer is a scientific specialty, but is verified as a well manageable robust and reliable technology ready for commercial space applications, e.g. in data relay systems. Links between LEO satellites verify data transmission at a rate of 5.625 Gbps and a bit error rates far below 10^{-9}. Burst errors do not occur, demonstrating the robustness of the alignment. Spatial acquisition is closed within seconds. On the basis of an in-orbit proven link budget the feasibility of LEO-to-GEO links is verified.

Acknowledgments

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References

[1] Oppenhäuser G., “SILEX program status – a major milestone is reached”, Proc. SPIE 2990 (1997)

[2] Nielsen T. and Oppenhäuser G., “In-Orbit Test Result of an Operational Inter-Satellite Link between ARTEMIS and SPOT-4, SILEX”, Proc. SPIE 4635 (2002)

[3] Toyoshima M. et al., “Ground-to-satellite optical link tests between the Japanese laser communication terminal and the Eurpean geostationary satellite ARTEMIS”, Proc. SPIE 5338 (2004)

[4] Reyes M. et al, “Preliminary results of the in-orbit tests of ARTEMIS with the optical ground station” Proc. SPIE 4635 (2002)

[5] Toyoshima M.et al, “Results from Phase-1. Phase-2 and Phase-3 Kirari Optical Communication Demonstration Experiments with the NICT optical ground station (KODEN)”, AIAA ICSSC AIAA-007-3228 (2007)

[6] Cazaubiel V. et al. “LOLA: A 40.000 km optical link between an aircraft and a geostationary satellite”, Proc. ICSO (2006)

[7] Iida T., “Satellite Communications: How High Speed We Should Pursue”, Proc. ICSOS (2009

[8] Smutny B. et al., “5.625 Gbps optical inter-satellite communication link verified in-orbit”, Proc. Of the Ka and Broadband Communications Conference (2008)

[9] Sodnik Z. et al., “Adaptive Optics and ESA's Optical Ground Station”, Proc. SPIE vol. 7464 (2009)

[10] Smutny B. et al., “High Data Rate Optical Inter-Satellite Links”, Proc. ICSOS (2009)