Optical Inter-Satellite Communication Operational

F. Heine, H. Kämpfner, R. Lange
Tesat Spacecom
Backnang, Germany

R. Czichy
Synopta
Eggersriet, Switzerland

R. Meyer, M. Lutzer
DLR
Bonn, Germany

Abstract: **Optical inter-satellite communication based on TESAT Laser Communication Terminals (LCT's) is operational by now on LEO satellites for more than two years. The LCT's demonstrate their performance in LEO-LEO inter-satellite links (ISL) and they are used also for LEO-to-ground links to investigate beam propagation through the atmosphere. Based on homodyne BPSK, a highly robust and sun light immune modulation scheme, the LCT's offer a full duplex data rate of 5.625 Gbps at a bit error rate lower than 10^{-9} for ISL. The LCT operations in the dynamic LEO scenario has shown that spatial and frequency acquisition can reliably be achieved within a few seconds. Due to its demonstrated performance, TESAT LCT's were selected for the European Data Relay Satellite (EDRS) Program of the European Space Agency. Their performance features makes them well suited also for commercial GEO data relay applications and government system requiring high data rates for LEO-to-GEO and UAV-to-GEO links.**

Keywords: optical inter-satellite communication

I. INTRODUCTION

LEO-to-GEO laser communication links have already been demonstrated in the SILEX program by ESA [1] and JAXA [2]. They have proven that the demanding pointing, acquisition and tracking requirements of optical communications can be mastered reliably. Ground stations have been developed for optical space-to-ground links to investigate data transmission through the atmosphere [3, 4]. An optical link between an aircraft and a GEO satellite was established (the French LOLA program) and used to demonstrate a communication link in strongly turbulent and dynamic environment [5]. These programs - all performed with SILEX-compatible laser communication terminals - verified basic performance features of an optical GEO relay.

The SILEX laser communication terminals transmit data at a data rate of 50 Mbps. They are based on amplitude modulation of semiconductor laser diodes and direct detection of the received signal, which limits the data rate capability of to a few 100 Mbps.

Today, there is a strong demand for data rates higher than 1 Gbps [6]. Homodyne binary phase shift keying (BPSK), phase modulation of a frequency stable laser and homodyne detection, is the best suited modulation scheme for that purpose. In this concept, the received signal is superposed to the beam of a so-called local oscillator running on the same frequency as the signal's carrier with the phase locked to the signal. Homodyne detection suppresses any kind of false light, especially sun light. Homodyne BPSK combined with coherent tracking (tracking with a control signal generated by the homodyne receiver) is the only modulation scheme that maintains an optical communication link even with the counter terminal in front of the sun. Furthermore, this concept provides also excellent security features that make it immune to jamming and interception.

II. SATELLITE-BORNE LCT

The homodyne BPSK laser communication terminal (LCT) uses a frequency stable Nd:YAG laser on a wavelength of 1,064 nm which guarantees robust and reliable operation with scalable output power.

Beside high reliability and low mass, size and power consumption the LCT is also designed for easy handling, integration and test in order to simplify the LCT's integration on its host spacecraft. Therefore, the LCT consists of one single unit only, as shown in Fig. 1 and 2.

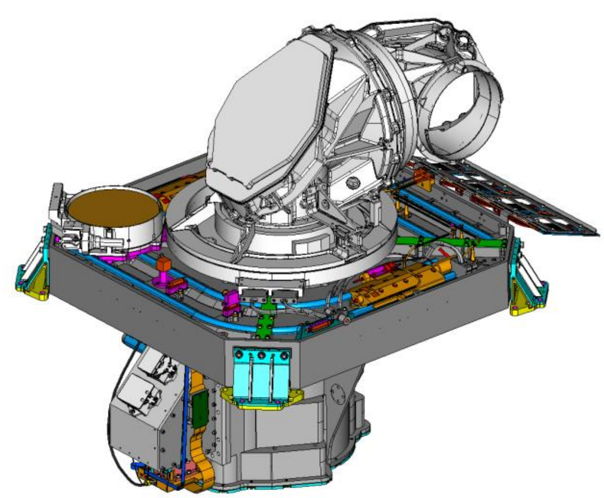

Fig. 1: Laser communication terminal

The LCT consists of a rectangular frame structure with the coarse pointer mounted on the space side and the telescope with the receiver front end reaching through this structure into the satellite. The frame structure houses the entire electronics and active optics. The coarse pointer allows to track the counter LCT across a full hemisphere.

With the coarse pointer at the so-called park position the optics is protected against contamination during non-operational modes, especially during launch. A mirror mounted in the park position unit allows functional end-to-end tests of the entire data transmit and receive chain (including the telescope and the coarse pointer). This so-called self test of the LCT running in an optically closed position can be performed on ground, e.g. during satellite tests, and in-orbit, e.g. during commissioning to verify the LCT's performance after launch. During launch the LCT is secured by a launch lock.

All interfaces are optimized for easy LCT integration on the satellite; four quasi isostatic mechanical mounts connect the LCT to the satellite panel. This mechanical interface compensates thermo-mechanically induced stresses at the interface. The mounts are thermally isolating and their stiffness is sufficiently high to cope with the launch loads. LCT internal heatpipes transport the dissipated power via a flexible thermal interface to a radiator.

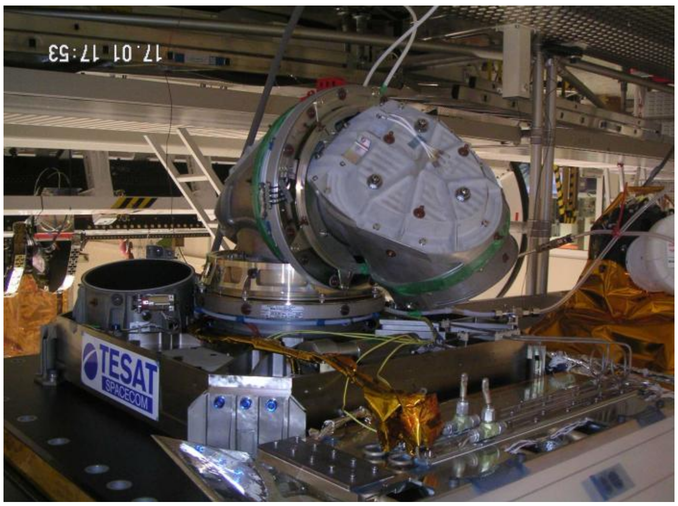

Fig. 2: LCT accommodated on the TerraSAR-X satellite

On satellite level an alignment of the LCT is not necessary. The alignment is measured using an internal reference and any misalignment will be compensated in-orbit by software. The LCT is integrated on the satellite panel simply by mounting the mechanical and the thermal interface to the satellite and by connecting the electrical interfaces. LCT integration and performance self-test are usually completed within a few days. The single unit design guarantees that the LCT's performance verified during its acceptance testing is reliably maintained also after integration.

III. Operational Modes

To establish a communication link the LCTs first run through a so-called pointing, acquisition and tracking sequence (PAT).

They align themselves – initially via the coarse pointer – with some uncertainty towards the direction of their counter LCT following its trajectory in an open loop.

Then, the uncertainty is reduced by spatial acquisition. Acquisition is done beacon-less with the highly collimated transmit beam that is later-on used for communications. This beam scans the cone of pointing uncertainty until both LCTs detect light from the respective counter LCT. The communication signal is also used for closed loop tracking. Both LCTs start a frequency search to adjust the frequency of their local oscillator to the received (Doppler shifted) signal and to lock the phase for homodyne BPSK. This sequence is called frequency acquisition. It is, finally, followed by the start of communication with coherent tracking

Fig. 3: LCT during integration on the NFIRE satellite

IV. In-Orbit Verification

The inter-satellite verification has been performed in close cooperation between the United States of America and Germany. April 23rd 2007, the first LCT was launched on NFIRE, a U.S. LEO satellite. June 14th 2007, the second LCT was launched on TerraSAR-X, a German LEO satellite. February 21st 2008, the first communication link between both LCTs was established. Today, the optical communication link experiment is in operation on routine basis for more than two years.

A. *Inter-satellite Links*

Compared to LEO-GEO scenario the LEO-LEO constellation allows to verify the performance under more demanding dynamic constraints: larger tracking angles, varying link distance, Doppler shifts to be compensated, and - last but not least - larger point-ahead angles to be adjusted.

The inter-satellite verification will demonstrate the LCT performance under realistic environmental conditions over several years with regard to

- Link quality: bit error rates, burst errors and sensitivity
- Acquisition: duration and reliability.

The results will allow the evaluation of link budgets and the models used – for e.g. tracking errors, atmospheric channel – to verify basis link budget assumptions with measured empirical data.

The key design features of the LEO-LEO communication link are summarized in Tab.1.

Link	LEO – LEO Full duplex communication
Data Rate	5.625 Gbps
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. 4 shows the location of the first inter-satellite link which is depicted in green between the satellites' trajectories. Ranges in this constellation vary between 3,700 km and 4,700 km.

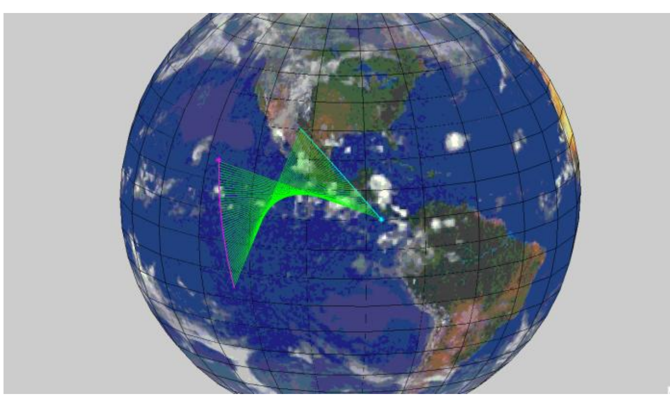

Fig. 4: Location of the first inter-satellite link

In summary, the in-orbit verification demonstrates robust and reliable inter-satellite communication with bit error rates (much) better than 10^{-9}. Burst errors do not occur. The spatial and frequency acquisition modes lead to successful hand-over to homodyne tracking and are closed within seconds. Spatial acquisition takes 2 s, depending on the initial uncertainty of pointing, frequency acquisition takes less than 8 s.

As an example, Fig. 5 shows bit errors for a typical duplex communication link.

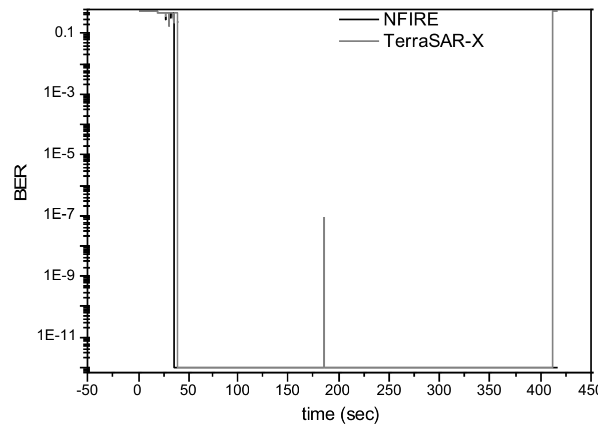

Fig. 4: Bit error detected during a duplex communication link by NFIRE and TerraSAR-X

Communication starts at 35 s and is closed after 350 s when the counter LCT disappears behind the Earth horizon. Bit errors are detected in a 225 Mbps data channel, which is representative for the overall data channel. A bit error rate of 10^{-7} corresponds to a single bit error. Thus, in only one of two 225 Mbps channels one bit error occurs within 350 s. The bit error rate derived from that is analyzed to be about10^{-11}.

B. LEO-to-ground links

Communication links based on homodyne BPSK have been established from NFIRE to Hawai (mount Halaekala) with a receive telescope of 60 mm diameter in the optical ground station (OGS). Fig. 6 shows the first realization of the 5.625 Gbps link.

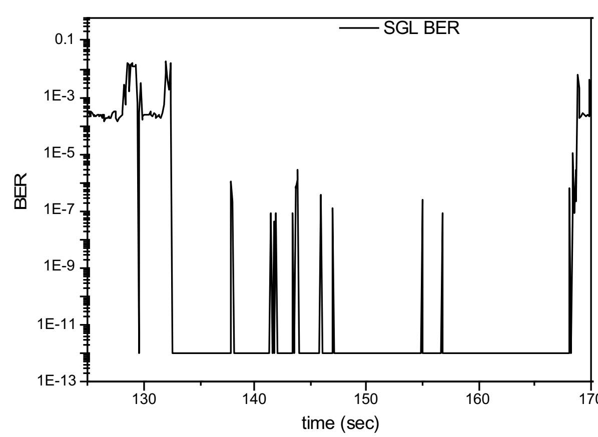

Fig. 6: Bit error of the first LEO-to-ground homodyne BPSK communication link

The result is to be interpreted like the one in Fig. 5. In the space-to-ground link burst errors occur but are separated by time intervals of error-free communication. Due to the system's performance as verified in the inter-satellite link these burst errors have to be assigned to atmospheric beam distortion resulting in scintillation. They serve as a measure to evaluate the performance of an optical space-to-ground communication channel and to optimize the design of advanced optical ground stations (AOGS) equipped with adaptive optics (see also Chapter V.B). End of April 2010 also uplinks were established with rather similar performance.

V. GEO-RELAYS

In terms of short-term service demand the most imminent applications are relay services: a LEO-to-GEO link followed by a GEO-to-ground link. Homodyne BPSK LCTs are in production for the European Data Relay System (EDRS) consisting in a constellation of GEO satellites. Data shall be transmitted from Sentinel 1a and Sentinel 2a, two LEO satellites, to an EDRS GEO satellite and for the time being via Ka-band to the ground. Future developments will include also optical downlinks from GEO with route diversity.

A. *LEO-to-GEO links*

The key design features of the LEO-to-GEO communication link are summarized in Tab.2. The link budget of the LEO-LEO link with its parameters and margins tested in-orbit verifies the feasibility of this approach also on an empirical basis.

Link	LEO – GEO Full 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

B. *GEO-to-ground links*

The development and optimization of optical GEO-to-ground links require to consider in more detail the influence of the Earth's atmosphere due to the more constrained link budget. Optical downlinks are influenced by various atmospheric effects: most important are absorption, scattering, refraction and the dynamic refractive index fluctuations of the air mass.

Absorption as well as scattering depends on the optical path length in atmosphere and the optical properties of the air mass within the optical path. The effect on the link is basically an attenuation of the received power. Refraction due to the large-scale refractive index variation of the atmospheric layers along the beam path causes an elevation-dependent mispointing, the same as known from astronomy. The dynamic, small-scale refractive index variations in the atmosphere above the telescope aperture (also called "seeing") cause scintillation, beam wander and blurring of the image Airy disk at the OGS (most of the time a combination of all effects can be observed).

Scintillation can be explained by a strong defocus effect of an air lens; the light is spread into a larger cone resulting in a steep drop of the power received at the OGS telescope aperture. Beam wander is cause by an air "wedge" causing a lateral shift of the image (of cause, the same effect can also be caused by instrumental instabilities at the OGS). Blurring can be explained by a slight defocus due to an air bubble; the image sharpness is degraded.

The seeing quality of the atmosphere is usually described by the dimension of the air turbulence cells, expressed in terms of the Fried parameter r_0, the diameter of the turbulence cells, and their speed of travel which is correlated with the wind speed.

Due to the fact that the disturbance layer are rather close to the OGS aperture its effect is quite different for the case of the uplink; any slight beam deflection or defocus causes power loss at the LCT receiver in space. Therefore, all of those atmospheric disturbances manifest mainly as scintillation at the space-borne LCT.

The influence of seeing on the image quality depends also strongly on the telescope aperture: if the telescope diameter is comparable to the diameter of the turbulence cell the dominating seeing effect will be scintillation, with an increasing telescope aperture also the other effects (beam wander, blurring) play an increasing role.

The beam wander and blurring effects can be compensated by adaptive optics (AO); the quality of the received wavefront is measured by a wavefront sensor and an adaptive optical element, usually a deformable mirror, is used for closed loop correction of the degraded wavefront. The potential for improvement of an optical satellite-to-ground link by use of an OGS with adaptive has already been proposed by ESA [7].

The Tesat OGS currently operating in field trials with NFIRE and TerraSAR-X was designed for LEO downlinks. It has a telescope aperture of 60 mm telescope. This is comparable or smaller than the r_0 to be expected in many sites and, therefore, this OGS was not equipped with AO. However, the next generation of Tesat OGS types will have larger telescopes (mobile OGS with 25 cm telescope aperture, stationary OGS with a 40 cm telescope) to cope also with higher data rates and longer link ranges (up to 42000 km for GEO) and, therefore, those OGS types will be equipped with a high-performance AO correcting the incoming disturbed wavefront at high bandwidth to become quasi diffraction limited.

The AO used for those Adaptive Optical Ground Stations (AOGS) consists of a high-speed Shack-Hartmann-type wavefront sensor (WFS) with a special InGaAs matrix array camera (640 x 512 pixels, pixel size 20 µm x 20 µm) and a deformable mirror (DM) with continuous surface in MEMS technology (12 x 12 elements, element size 0.45mm x 0.45mm). The WFS uses only a 100 x 100 pixel subframe of the overall detector array, therefore, it is possible to operate at rather high read-out frequencies (> 5 kHz).

A parallel processing technique is used for calculation of the aberration coefficients and the correction functions that are provided to the DM drive electronics. The software operates with a quite flexible adaptive correction approach that allows to cope with various site-specific seeing conditions. It is possible to set a number of operating parameters that optimize the AO operations. Depending on the incoming signal level the control-loop bandwidth can be increased to several kHz.

A particular feature of this AO design is the field correction capability; if needed, the system can be tuned to correct also a slightly wider field-of-view. This offers significant advantages for fast acquisition-tracking transition needed for the initial operational modes during link build-up.

The control bandwidth of the AO system is high enough to cope with the conditions at all potential site types that could be envisaged for laser communication ground stations. The quality of the corrected image is sufficient for coherent receivers requiring diffraction limited beam quality (Strehl better 0.8).

This AO concept allows the mobile and stationary AOGS to operate full-duplex uplink/downlinks with LEO and GEO with data rates of up to 5.525 Gbps.

VI. UAV-TO-GEO LINKS

The feasibility of homodyne BPSK based UAV-to-GEO links has been verified by analysis. The turbulent flow around a HALE has no impact on the homodyne BPSK link, in case of a MALE the impact can be compensated. With sufficient beam divergence, i.e. with sufficiently small optical apertures – which should also be choosen to minimize the size of the instrument – the respective pointing and tracking errors do not induce burst errors. Corresponding system design are in progress.

VII. SUMMARY

Homodyne BPSK based laser communication links from LEO-to-LEO/GEO, LEO/GEO-to-ground and even UAV-to-LEO/GEO are no longer scientific visions but have been verified by in-orbit demonstrations to be a well manageable and reliable technology ready for operational commercial and military applications.

ACKNOWLEDGMENTS

The LCT development and the in-orbit-verification is sponsored by the German Space Agency DLR/BMWi under 50YH0202 and 50YH063.

We gratefully acknowledge the support of the German MoD/BWB and the U.S. DoD/MDA for execution of the in-orbit verification program. Furthermore, we are indebted to the Aerospace Corporation and General Dynamics (now Orbital) for the excellent cooperation in accommodation of the LCT on NFIRE and for the close dialog during the in-orbit verification program.

REFERENCES

[1] T. Nielsen and G. Oppenhäuser, "In-orbit test result of an operational nter-satellite link between ARTEMIS and SPOT-4, SILEX", Proc. SIE 4635, 2002

[2] M. Toyoshima et al., "Ground-to-satellite optical link tests between the Japanese laser communication terminal and the European geostationary satellite ARTEMIS", Proc. SPIE 5338, 2004

[3] M. Reyes et al., "Preliminary results of the in-orbit tests of ARTEMS with the optical ground station", proc. SPIE 4635, 2002

[4] M. Toyoshima 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

[5] V. Cazaubiel, "LOLA: A 40000 km optical link between an aircraft and a geostationary satellite", Proc. ICSO (2006)

[6] T. Iida, "Satellite communications how high speed we should pursue", Proc. ICSOS, 2009

[7] Z. Sodnik et. al, "Adaptive optics and ESA's optical ground station", Proc. SPIE vol. 7464, 2009