# 5.6 Gbps optical intersatellite communication link

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## ABSTRACT

A 5.6 Gbps optical communication link has been verified in-orbit. The intersatellite link uses homodyne BPSK (binary phase shift keying) and allows to transmit data with a duplex data rate of 5.6 Gbps and a bit error rate better than $10^{-9}$ between two LEO satellites, NFIRE (U.S.) and TerraSAR-X (Germany). We report on the terminal design and the link performance during the measurement campaign. As an outlook we report on the flight units adapted to LEO-to-GEO intersatellite links that TESAT currently builds and on plans to study GEO-to-ground links.

**Keywords:** LCT, optical communication, laser, homodyne BPSK, optical intersatellite links, TerraSAR-X, NFIRE

## 1. INTRODUCTION

Compared to conventional RF communication systems laser communication terminals (LCT) offer the advantage of higher data rate and larger link distance at lower size, weight and power. The major factor is the four orders of magnitude shorter carrier wavelength translating into higher antenna gain. As additional benefits laser communication links are free of interference problems, they provide safe transmission and the user is not limited by ITU regulations. Of the available optical technologies homodyne BPSK (binary phase shift keying) is superior due to the merits of:

- spatial filtering by the homodyne detection cone (the narrowest possible for a given aperture)
- frequency filtering by phase locking loop (far more selective than available optical coatings)
- leveraging the signal amplitude (superposition with the orders of magnitude larger local oscillator amplitude)

As a result homodyne BPSK very effectively discards unwanted noise power and even allows to maintain a communication link if the Sun is within the receivers field-of-view. Commercial programs like CELESTRI and TELEDESIC prerequisited immunity against Sun and selected therefore this technology and TESAT as supplier for laser communication terminals.

TESATs LCTs for intersatellite links are the result of more than two decades of development expertise in the field of free-space optical communications in combination with a broad heritage of commercial space equipment production. Tesat was responsible for the communication subsystem of the SILEX optical communication terminal which is successfully operating in orbit since 2001. TESAT verified in 2005 homodyne BPSK as a robust ground communication modulation scheme by a 142 km free-space measurement campaign between two Canary Islands [1]. Satellite based beacon-less acquisition and the hand-over to coherent tracking of laser communication terminals was verified in 2007 [2]. For in orbit verification of duplex 5.6 Gbps communication two TESAT LCTs based on homodyne BPSK have been accommodated on LEO satellites. One LCT is on board the German satellite TerraSAR-X and the other on board the U.S. satellite NFIRE.

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# 2. LASER COMMUNICATION TERMINAL

The purpose of the LCT is to operate a duplex communication link for binary digital data between two satellite S/Cs via a single optical carrier. The carrier wavelength is 1.064 μm. A common optical I/F to space is used for transmit and receive.

As shown in the figure below (Fig. 1) the coherent laser communication terminal is a one-unit design. Interfaces to the satellite are limited to standard electrical harness and mechanical / thermal interfaces. Without an optical S/C interface harness the accommodation and test of the LCT on a satellite has been demonstrated to take shorter than a week.

The one-unit design consists of a central rectangular base structure, a coarse pointer (gimbal) mounted on space side and the optics unit reaching through this structure on the S/C side. The frame unit structure houses the entire laser communication terminals electronics and active optics. The optics unit comprises the receive/transmit optics, fine steering mechanisms and the receiver. The coarse pointer is designed for hemispherical tracking of the counter terminal. In park position (shown in Fig. 1) the optics are protected during non-operational modes against contamination and a launch lock secures the coarse pointer during launch.

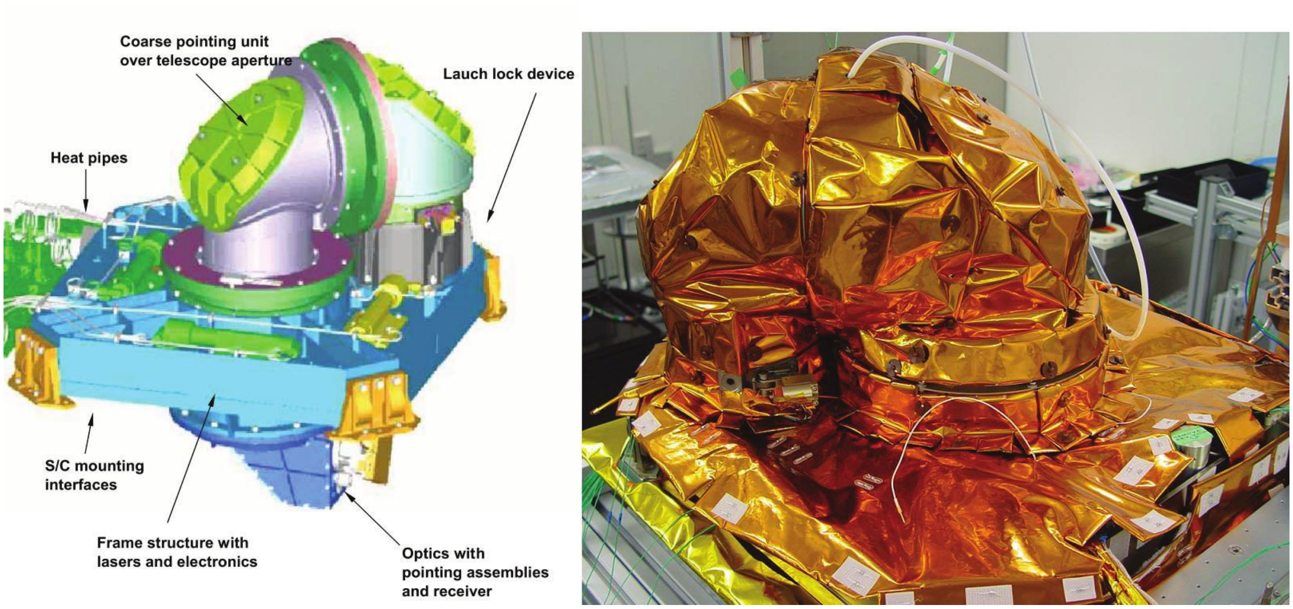


Fig. 1. LCT drawing highlighting major functional elements (left side)

Key parameters of the LCTs accommodated on the TerraSAR-X and NFIRE satellites and now verified on orbit are:

- optical transmit power 0.7 W
- telescope diameter 124 mm
- data rate 5.625 Gbps (chosen to fit TerraSAR-X data interface)

All I/Fs are optimized for easy integration of LCT to S/C. Mechanical alignment of LCT on S/C level is not necessary. On S/C level the LCT alignment cube is to be measured and this known misalignment then compensated in orbit by propagator processing software. Four quasi isostatic feet serve as mechanical I/F and compensate any thermomechanically induced stresses between LCT and S/C. The feet are thermally isolating and their stiffness is sufficiently high to cope with launch loads.

The LCT is isolated via MLI against ambient or space environment (shown in Fig. 1). LCT internal heatpipes transport the dissipated power via a flexible thermal I/F to a S/C radiator.

As electrical I/Fs are foreseen:

- Transmit Data / Receive Data
- Main Bus
- TM/TC, Discrete + Analog + MIL 1533B Data
- Launch Lock Release
- Heater and Thermal Sensors

Spatial acquisition is performed using the collimated communication beam instead of an additional highly divergent beacon laser. The beacon-less acquisition procedure is shown in Fig. 2.

Both LCTs need to know the direction of their counter LCT with S/C AOCS typical accuracy (2,500 µrad), the so-called uncertainty cone. After initial pointing the acquisition sequence is initiated.

Coarse Acquisition phase 1 starts in a master-slave mode. The master LCT-a scans and hits the counter (slave) LCT-b (at least) once per scan spiral. While LCT-a continues scan spiraling, the counter LCT-b iteratively adjusts itself to the wave front of LCT-a beam flashes ending up with a remaining small angular deviation.

In Coarse Acquisition phase 2 the roles are switched. Now LCT-a passively adjusts itself to the wavefront of LCT-b scan spiral flashes. Since LCT-b is already quite well aligned from Phase 1, the scans and alignment of LCT-a can be performed quickly.

During the subsequent Fine Acquisition phase both LCTs scan while also adjusting themselves further in parallel. The scan spirals and the remaining misalignments are progressively reduced until coherent tracking locks in.

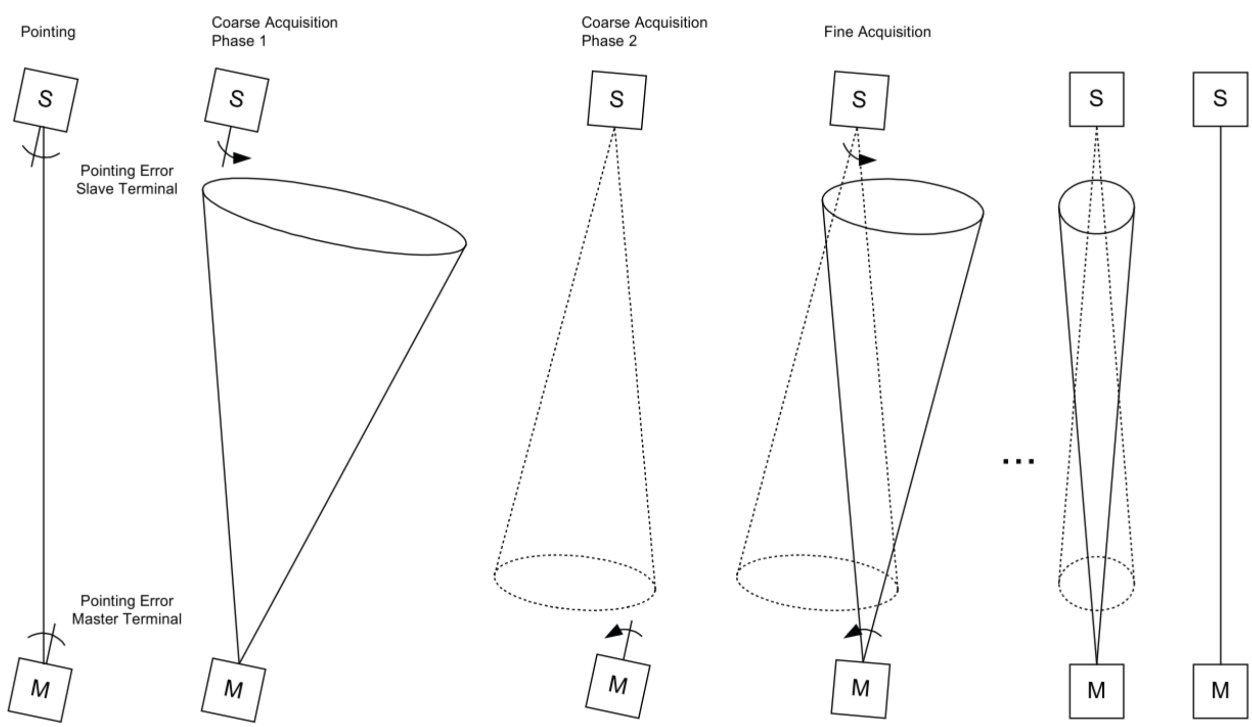


Fig. 2. Sequence of beacon-less acquisition modes according to a master(M/a)-slave(S/b) approach

## 3. IN-ORBIT VERIFICATION

Fig. 3 shows the LCT accommodated on the TerraSAR-X satellite. On the right hand the LCT is shown with its frame unit structure and the coarse pointer moved out of the park position. The corresponding LCT on NFIRE is also mounted in a way to allow both intersatellite links and satellite-to-ground links.


Fig. 3. LCTSX LCT flight unit:
Left hand picture: Ready to go on TerraSAR-X. Right hand picture: During integration test on TerraSAR-X.

Since February 2008 the two TESAT LCTs on TerraSAR-X and NFIRE perform optical intersatellite links within an extended test campaign. The LCTs algorithm parameters for pointing, acquisition and tracking can be modified in between link runs allowing the on orbit system to perform a learning curve. Initially unknown biases from launch settlement or geometrical limits to ground triangulation resolution can now be calibrated using the precise angle measurements over several thousand kilometers. As a consequence full data communication is now routinely achieved within less than 20 s, while the initial acuqisitions described below took 40 s to 50 s.

The heritage gained here allows TESAT to choose the right set of parameters for reliably and efficiently operating the LCT link in scenarios ranging from a fully optimized standard service situation to the initial commissioning. A description of the link parameters leading to TESATs first two intersatellite links is detailed later in this section.

Experience with exploiting the acquisition optimization potential is an important requirement for developing realistic link analyses together with civil and military customers. The progress and results demonstrated in 2008 have for example recently convinced ESA to select TESAT LCTs as the baseline for GMES / Copernicus satellites and the planned GEO-stationary EDRS (European Data Relay Satellite) system.  The benefit for ESAs Earth observation satellites will be on demand and broadband connectivity via GEO relay without the need to have an X-band or Ka-band ground station directly underneath.

The first intersatellite link was performed above the Pacific Ocean and Central America (see Fig. 4). The link distance varied between 3,700 km and 4,700 km, with a maximum range rate of 8,500 m/s (shown in Fig. 5).  Spatial acquisition started with uncertainty cones of 530 µrad and 1,000 µrad, respectively,  and was completed after 13 s (phase 1 in 10 s, phase 2 in 3 s). After that it took 28 s to phase lock the two laser systems for homodyne BPSK. Communication and data transfer with a bit error rate better than $10^{-9}$ lasted for 134 s until the counter LCT was no longer visible. The link trajectory started out with about 200 km minimum height above Earth (Fig. 6) and was kept stable until about 30 km, meaning a large part of the link trajectory ran through rather dense atmosphere at this point.

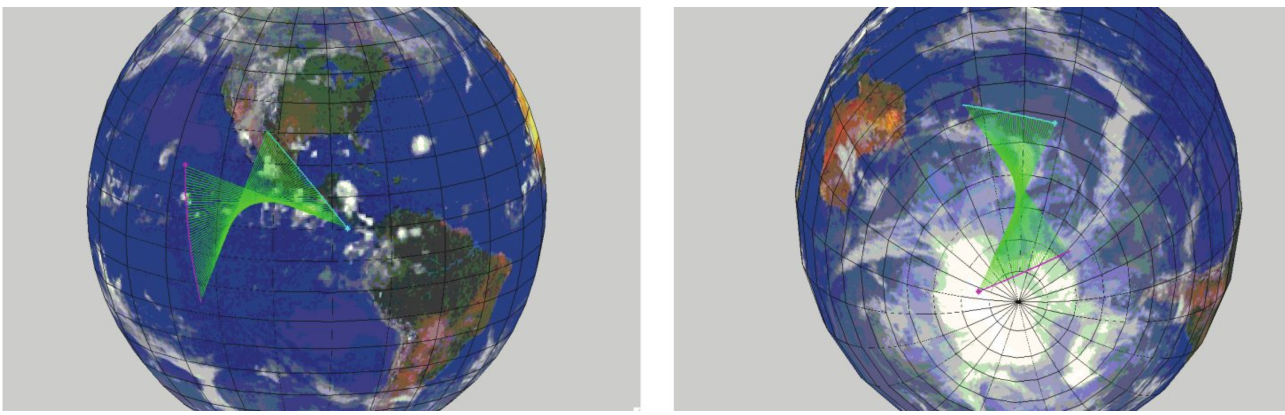

Fig. 4.  Localization of the first two optical intersatellite links between TerraSAR-X and NFIRE in February 2008

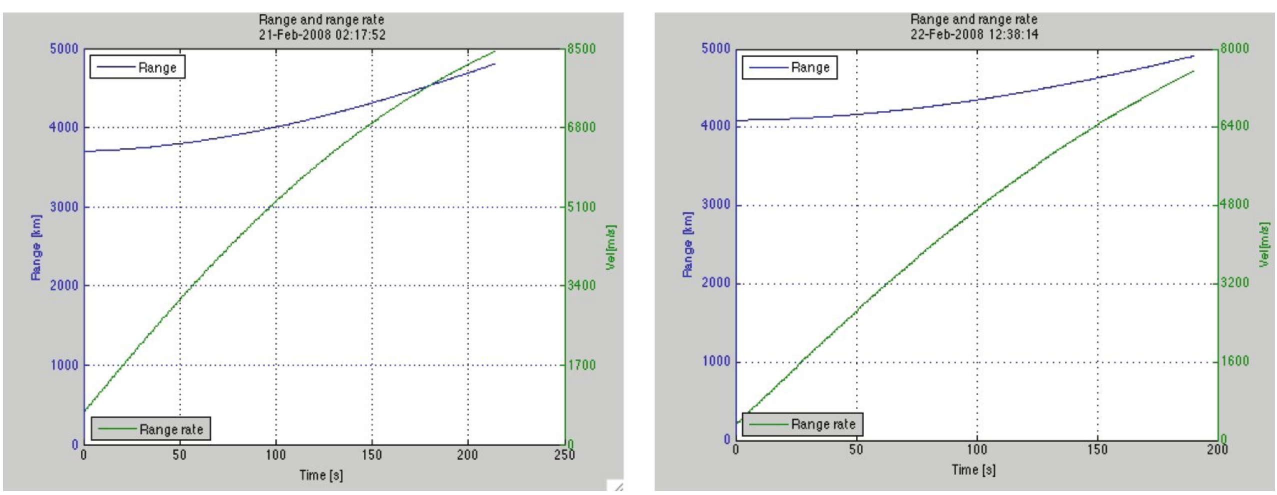


Fig. 5.  Distance/Range and rates of change  for the first two optical intersatellite links

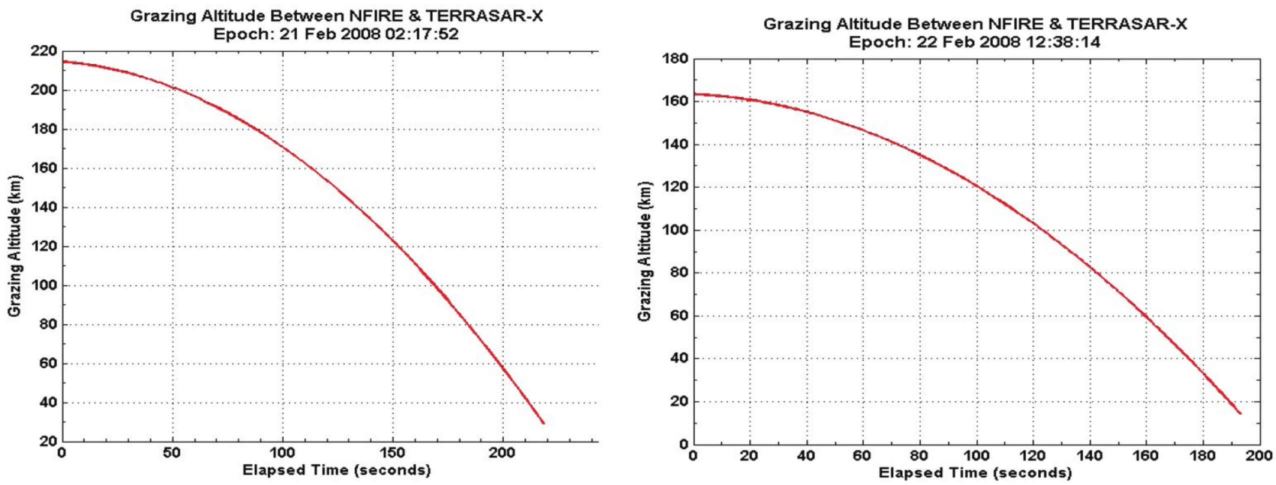


Fig. 6. Link trajectory minimum beam height above Earth for the first two optical intersatellite links

The second intersatellite link was established near the South Pole (Fig. 4). The link distance in this case varied between 3,700 km and 4,875 km with a maximum range rate of 7,200 m/s (Fig. 5). The counter LCT was visible for 190 s. Spatial acquisition started after 10 s with uncertainty cones of 745 µrad and 1,000 µrad, respectively, and was completed after 23 s (phase 1 in 20 s, phase 2 in 3 s). The two laser systems were phase locked within 29 s for homodyne BPSK detection. Communication and date transfer with a bit error rate better than $10^{-9}$ lasted for 128 s until the counter LCT was no longer visible. The link trajectory for this second link cut even deeper into the atmosphere with a minimum height below 20 km (Fig. 6). The azimuth and elevation time traces of the TerraSAR-X LCT gimbal for both links are shown in Fig. 7.

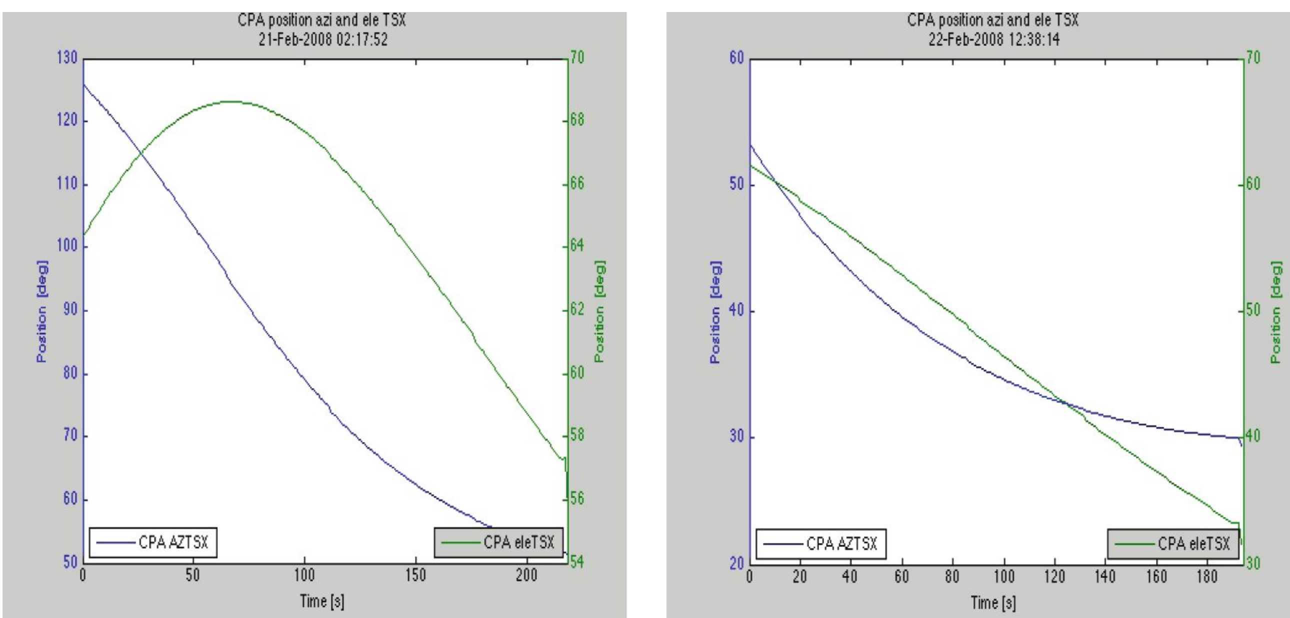


Fig. 7. Link trajectory movement of the CPA gimbal on TerraSAR-X for the first two optical intersatellite links

## 4. OUTLOOK ON NEXT STEPS OF LASER COMMUNICATION

With a data rate of 5.6 Gbps the laser communication links reported here have been a milestone in the introduction of laser communication terminals to the space market. For the first time the major advantage of laser communication terminals compared to RF payloads - data rates larger than 1 Gbps - has been demonstrated on orbit. In terms of short-term service realization the most imminent market applications are relay services (LEO-to-GEO-to-ground) to make the large data amount of LEO Earth observation satellites immediately available. DLR plans to utilize the laser communication capabilities for the TanDEM-X mission and took TESAT under contract to adapt the now successfully proven LEO-LEO laser communication terminals to LEO-to-GEO, GEO-GEO, and GEO-to-ground links. This GEO-class LCT is designed for up to 45,000 km distance at a maximum user data rate of 1.8 Gbps.

The next figure (Fig. 8) shows the application for which TESAT has developed and currently builds laser communication terminals and a 600 Mbps Ka-band subsystem.

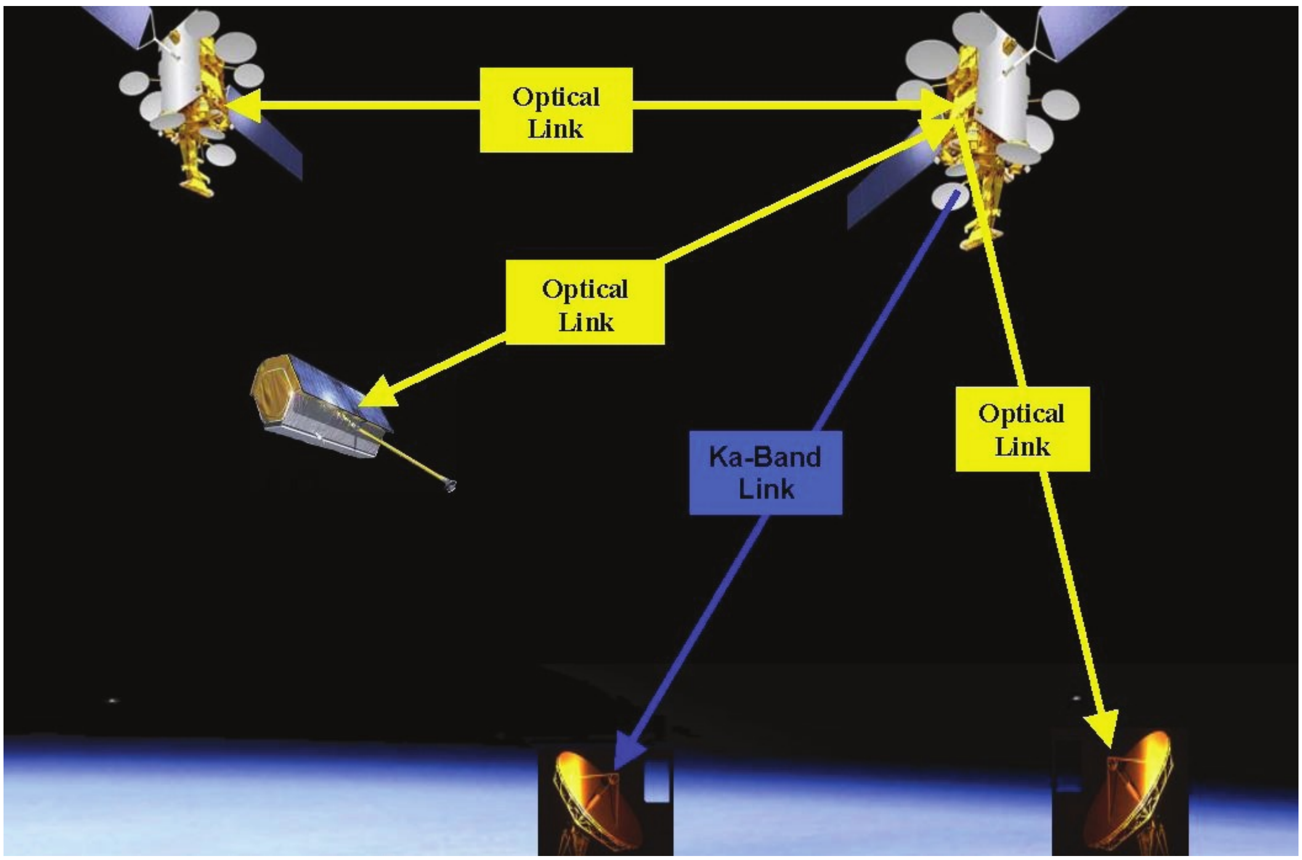


Fig. 8. LEO-GEO-ground relay configuration. Under contract from DLR a link shall be established between the LEO TanDEM-X satellite by optical intersatellite link up to a GEO relay station (AlphaSAT) and by Ka-band RF downlink to Oberpfaffenhofen, Germany.

The short term mission goal is the realization of a LEO-to-GEO laser communication link completed by a GEO-to-ground RF link. The strategic goal of a purely optical high data rate GEO-network will be pursued by employing the GEO LCT for GEO-GEO and GEO-to-ground links. For these experiments an optical ground station near Backnang, Germany (Fig. 9) is being set up by TESAT with funding support from DLR . The ground station will initially participate in a LEO-to-ground experimental campaign (from NFIRE and TerraSAR-X) but it will also field-test an adaptive optics system similar to the one used by ESA on Tenerife.


Fig. 9. Optical ground station Allmersbach near Backnang, Germany.

## 5. SUMMARY

With service-like availability the two TESAT LCTs on TerraSAR-X and NFIRE perform on demand optical intersatellite links based on homodyne BPSK. The links transmit duplex data streams of 5.6 Gbps across nearly 5,000 km with with a bit error rate below $10^{-9}$. Links are established and full communication entered within typically less than 20 s including spatial acquisition and laser phase locking. The design of the LCT is optimised for a short delivery time of about 24 months after receipt of order, satellite integration time of less than one week and for fully autonomous operation. Therefore the TESAT LCTs are well suited for use in satellite networks with mandatory short integration time and automated operations.

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