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German Roadmap on Optical Communication in Space

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***Abstract*— Germany identifies optical communication as a strategic space-technology. Past and present in-orbit achievements and future goals on the German Roadmap towards optical communication in space are discussed. Inter-satellite and Ground link results are covered.**

OCIS codes: (060.4510) Optical communications; (060.2605) Free-space optical communication;

I. Introduction

Optical communications is recognized as a strategic technology in the Space Strategy of the German Federal Government published in November 2010 [1]. For more than a decade optical communication occupies an important place in strategic research and development of the German Space Agency (DLR). Optical space communication systems have the potential for substantially higher data rates than RF-based solutions with similar onboard mass, volume and power consumption. Optical communication is identified as a key technology, which will be capable to meet future requirements for the transmission of high resolution images and video either in near earth or for deep space missions. Moreover, optical communication does not require frequency regulation and provides inherently secure data links by means of a high beam directivity. DLR targets mainly three scenarios where optical communications can be applied:

1. Inter-satellite links: Satellite links (LEO-LEO/ LEO-GEO) without atmospheric propagation are predestined to optical communications. Inter-satellite (LEO-LEO) or relays applications (LEO-GEO, high altitude unmanned aerial vehicles (UAV)-GEO), profit greatly from the superior availability and higher timeliness of the link than optical links to ground which is impeded by clouds.
2. Atmospheric links – Satellite to Ground Links (GEO/LEO-up and downlink): Earth-observation satellites and UAV are anticipated to show an increasing demand for large data rates in the down-link. The DLR-Space Administration is running an extensive test campaign for LEO to Ground links in order to probe the atmosphere at 1064 nm, studies optical links to mobile platforms flying above the clouds and will start to test duplex satellite to ground links (SGL) from GEO-Satellite in 2014.
3. Remote-space downlinks (beyond GEO orbit): Remote space missions are mainly exploration missions where high data rates are required in order to retrieve scientific data or to support human flights (e.g. with video transmission). Alternatively, providing the same data rate as a RF terminal, a laser terminal may save mass and volume.

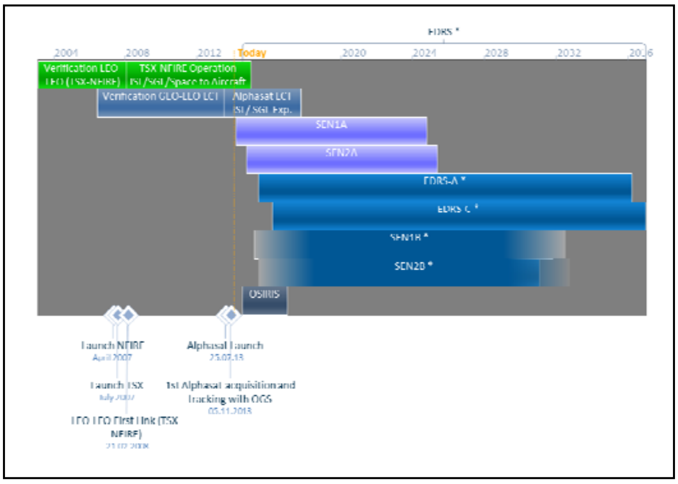

Fig. 1. Timeline optical communcation in space. DLR contributes to the LCTs on EDRS-A/C and Sentinel 1B/2B via the ESA program EDRS and Copernicus (formerly GMES) respectively. Activities performed in the ESA programm are marked with a star (*).

DLR currently implements optical communication missions at two wavelengths: 1064nm homodyne BPSK and 1550nm PPM. The overall timeline of the activities is shown in Fig. 1. The scope of the activities at 1064nm is the development of an industrialized Laser Communication Terminal (LCT) for operational use in space application. This paper mainly scopes the DLR activity at 1064nm. DLR has contracted the developments of the industrialized terminal at 1064nm to TESAT-Spacecom GmbH & Co. KG (TESAT), Backnang. Please refer to section II for an introduction and comparison of the different developments. Shown in green is the early

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development phase of the first generation LEO to LEO inter-satellite terminal. Results of this phase are detailed in section III of this contribution. The follow up generation of Laser Communication Terminal is designed for a GEO-Relay application. The timeline of related developments (Alphasat, Sentinel satellites, and EDRS) are shown in purple and blue in the figure and are described in section IV. In general only the planned in orbit time is shown. Only the development and verification phase of the TerraSAR-X and Alphasat terminals is shown. This paper concludes with remarks on the standardization of optical links recently initiated in section V and a summary and outlook in the following section VI. The activities of the DLR institute of communication and navigation scope a research driven development of a small experimental terminal called OSIRIS at 1550nm (PPM). OSIRIS is planned for embarkation on cube sats built by the University of Stuttgart and DLR. Information on the scientific driven DLR activity can for example be found in [2].

II. Coherent Laser Communication Terminal for Inter-satellite and GEO Relay Application

The DLR-Space Administration has supported the development of a coherent Laser Communication Terminal (LCT) built by TESAT. The communication and beacon wavelength is 1064 nm. The modulation is BPSK with homodyne detection. The coherent LCT can be deployed for any point-to-point near-Earth links. A 5.6 Gbit/s bidirectional link between two LEO satellites (TerraSAR-X and NFIRE) was demonstrated in 2008 and inter satellite link experiments are ongoing for more than five years [3][4]. While the main purpose of this effort was to demonstrate maturity of inter-satellite links, space-to-ground links were a second focus of investigation. Meanwhile the scope of these activities has been further extended to space to aircraft links. On the DLR roadmap to establish a European Data Relay Satellite System (EDRS) based on an optical service the development of laser terminals suited for LEO-to-GEO application was the logic next step. In cooperation with TESAT, DLR Space Administration initiated the development of a second generation LCT in 2006. The qualification of the LCTs for EDRS is based on this development.

TABLE I. Comparison Key Parameters of the Coherent LCT for LEO-LEO (First Generation) and GEO-LEO Links (Second Generation)

Link	First Generation LCT (LEO-to-LEO) (Terra-SAR-X and NFIRE)	Second Generation (LEO-GEO) (Alphasat, Sentinel 1A and 2A and EDRS)
Data Rate	5.625 Gbps (duplex communication)	1.8 Gbps (duplex communication)
Link Distance	1,000 – 8,000 km	> 45,000 km
Optical Transmit Power	0.7 W	2.2 W
Telescope Diameter	125 mm	135 mm
Bit Error Rate	10^{-11}	10^{-8}
Mass	35 kg	53 kg
Power Consumption	120 W	160 W
Volume	0.5 x 0.5 x 0.6 m^3	0.6 x 0.6 x 0.7 m^3

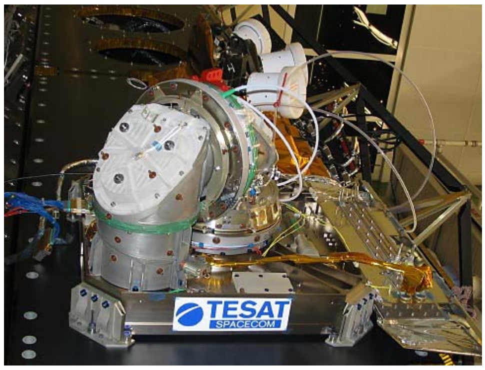

Fig. 2. First generation LCT embarked on TerraSAR-X

DLR has launched an LCT as a technical demonstrator payload on the geostationary ESA satellite Alphasat owned and operated by Inmarsat to serve as the precursor mission for EDRS [5]. The GEO-to-LEO link is planned to be tested between the Alphasat LCT in GEO orbit and LCTs embarked on the Copernicus earth observation satellites Sentinel 1A and Sentinel 2A in LEO orbit. In TABLE I. the key performance parameters of the first and second generation TESAT LCTs are compared.

III. First Generation Coherent Laser Communication Terminal for LEO to LEO Application

The development of the first generation LCT dedicated for LEO to LEO optical inter-satellite communication was contracted to TESAT in 2002. LCTs of the first LCT generation have been launched to LEO orbit aboard the German radar satellite TerraSAR-X and the US satellite NFIRE in 2007. The LCT embarked on TerraSAR-X is shown in Fig. 2. Main objective of the mission was the verification of the beaconless spatial acquisition scheme and to test feasibility and performance of the homodyne BPSK communication scheme. The beaconless acquisition scheme, which uses the communication optics during the acquisition phase and the communication signal itself for tracking, was chosen, because it allows for significantly reduced mass and operating power compared to technical solutions with a separate beacon laser aboard the space craft [6]. Homodyne BPSK was selected as modulation scheme due to the 3dB advantage of coherent detection methods in terms of link budget and because solid state lasers at 1064nm are robust and have been proven as space qualified technologies. The initial optical link between TerraSAR-X and NFIRE at a data rate of 5.6 Gbps was recorded on February 21st 2008. [3]. The link trajectory of this first link is shown in Fig. 3

A. *Status and Results of the LEO to LEO inter-satellite links*

Following the first link repeatedly inter-satellite link campaigns have been performed to explore the capabilities of the first generation LEO-LEO LCTs [3], [4], [7]-[9]. Due to the orbit configuration of both LEO space crafts the dynamics of the links is demanding. The maximum link distance between the two space craft observed in the specific orbit configuration is 5500 km and maximum relative velocities of 25,000 km/h are observed.

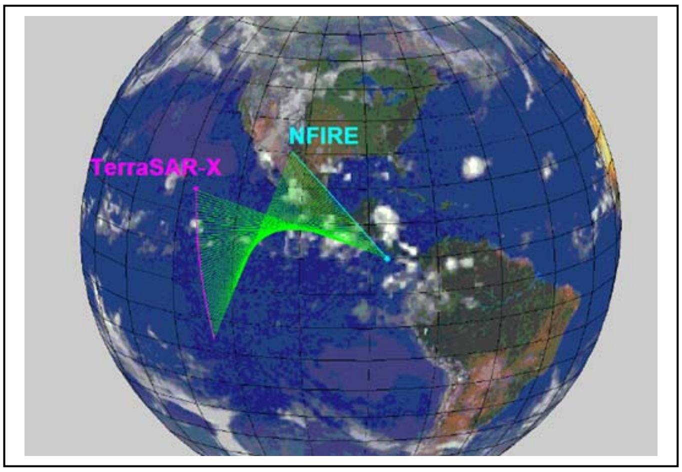

Fig. 3. Trajectory of the first optical link between TerraSAR-X and NFIRE recorderd on 21.01.2008. (picture courtesy of TESAT)

A typical inter-satellite link sequence is shown in Fig. 4 at hand of the bit error rate during an exemplary LEO to LEO link at grazing altitudes [9]. The link sequence consists of the following phases: the initial link acquisition phase, a communication phase which usually is bit error free, and a link termination phase, when the link passes the atmosphere and the counter space craft descents below the horizon. The link scenario remains the same in principle if the link takes place at nominal, non-grazing altitudes. The bit error rate (BER) in these cases is, however much lower, as the BER remains below 10^{-8} in nominal links cases. The maximum duration of the acquisition phase is parameter preset during link planning. Acquisition includes spatial acquisition and frequency acquisition to close the phase locking loop of both counter terminals. The in-orbit experiments have verified that the link can be successfully acquired in acquisition durations smaller than 10 s, if the quality of the orbit information is sufficiently high. The Fig. 4 shows an example with a communication sequence of 450 s at 5.6 Gbps without any bit error. During this communication sequence 16.2 Tbit have been transmitted without error in a single communication link. In its final phase the line of sight of the link passes increasingly through turbulent regions of the higher atmosphere thus causing an onset of bit errors. Beyond line of sight the link is then finally terminated. To date more than 400 links have been performed after more than 5 years of optical inter-satellite link campaigns. A degradation of the link performance has not been observed yet.

B. Satellite to Ground Links

Despite the fact that the main objective of the first generation LCT was demonstration of inter-satellite optical communication in LEO orbit, also an optical ground station was built. This optical ground station is based on already existing equipment. Either qualification models or bread boards are reused, which have been manufactured during the development phase of the TerraSAR-X – NFIRE flight models. The main purpose of the ground station is to check out the LCT in orbit before a second LCT has been launched and to calibrate the pointing of the laser terminal in orbit after exposure to environmental loads during launch.

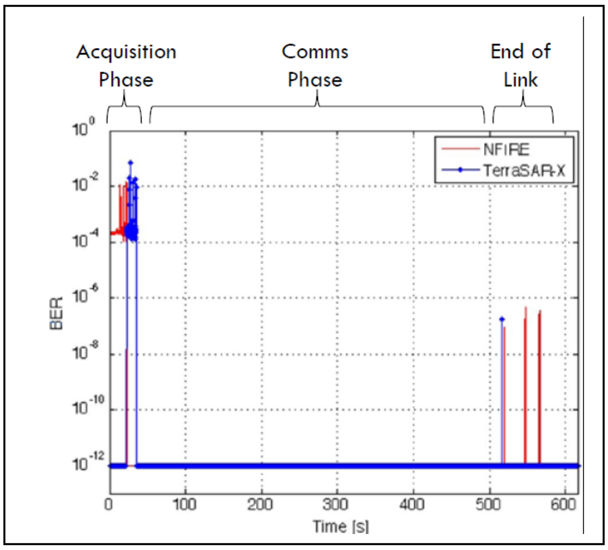

Fig. 4. Typical optical inter-satellite link sequence LEO to LEO space craft. (picture courtesy of TESAT)

Due to the reuse of equipment and the above mentioned main objectives, this ground station is not optimized for space to ground links and the ground station is more or less identical with the first generation LCTs in space. A set of LEO to ground link campaigns has been performed from different sites. A significant learning curve was achieved between the first link campaigns from Maui (2009) to Tenerife (2010/2011) where excellent results have been recorded [10]. In order to counter the atmospheric turbulence in the ground link scenario the aperture of the optical ground station was reduced from 125 mm to a diameter of 65 mm. As a telescope aperture diameter, which is smaller than the Fried parameter r_o, is required for the receive path. Analysis shows that the chosen diameter is sufficient for different sites at high altitudes as e.g. in Maui and Tenerife.

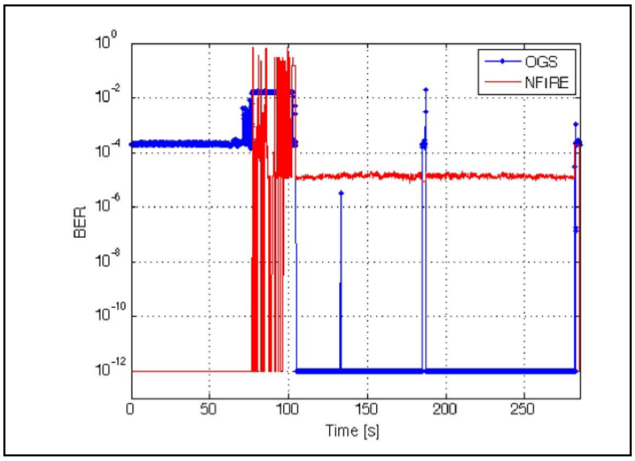

Fig. 5. Bit error rate of LEO – optical ground station bidirectional communication link scenario (picture courtesy of TESAT)

Even though the experiments at Maui were challenged by head winds to which the ground stations coarse pointing mechanism and the optical aperture was exposed, several successful coherent tracking and communication downlink sessions have been achieved even in this disadvantageous condition. The influence of head wind and turbulence directly in front of the telescope aperture was significantly reduced by placing the ground station inside the ESA OGS dome during the following Tenerife ground link campaigns. The atmospheric conditions at the sites in Maui and Tenerife are comparable. The possibility to install the LCT optical ground station inside the ESA OGS instead of operating the LCT from the top of an externally installed container improved the communication situation such that now also bidirectional up and downlinks were successfully established. Bidirectional communication links of duration up to 177 s have been established. The bit error rate of an exemplary optical up and downlink from Tenerife to the US satellite NFIRE is depicted inFig. 5. Due to the asymmetric shower curtain effect the bit error rate is increased in the up-link with respect to the down-link and i.e. the received BER at the LEO space craft. The shower curtain effect makes the link performance through the atmosphere asymmetric, because the optical wave passes through turbulent atmosphere first and the wave front disturbance is broadened more strongly during the following free space propagation than in the reverse direction.

C. *Space to Aircraft Links*

In order to test the influence of atmospheric distortion on laser com links, a dedicated test campaign using the DLR-TESAT optical ground station installed in a DLR owned “Falcon” aircraft is performed. The DLR Falcon aircraft is shown in Fig. 6. The LCT ground terminal coarse pointer is installed in front of a window at the side of the aircraft for the experiments. These experiments are seen as a minimal effort study to explore the feasibility of aircraft to space links and to estimate and identify the parameters essential for the design of an airborne LCT. The pilot is required to follow a flight path of the plane such that the window of the plane is oriented in field of view of the LEO space craft passing overhead. Initial feasibility experiments showed that for this purposes the pilot needs additional support to be able to follow an optimised flight path. A second campaign is planned for later this year. The experiments are expected to show the influence of atmospheric (scintillation, phase front disturbances) and platform induced distortions (e.g. micro vibrations, flight trajectory errors) on the optical links depending on flight levels and weather conditions. The results gained in this experimental feasibility study will contribute towards the development of an optical communication terminal for aerial vehicles. TESAT of Germany and General Atomics of the US have started a development of a Laser Communication Terminal for General Atomics UAV platforms. The development will use the 1064nm homodyne BPSK TESAT communication standard and it will profit from General Atomics equipment, which is already approved for flight on aircraft. Results may be expected in the 2016 time frame. Thus, reliable and near real time high data relays services could be provided to aircrafts flying above the clouds in the near future.

Fig. 6. DLR Falcon. A space to aircraft link feasibility study has been performed by placing a LCT infront of a side window.

IV. SECOND GENERATION COHERENT LASER COMMUNICATION TERMINAL FOR GEO RELAY APPLICATION

On the DLR roadmap to establish a European Data Relay Satellite System (EDRS) based on an optical service the development of laser terminals suited for LEO-to-GEO application was the next step after the successful development of the TerraSAR-X LEO to LEO optical terminal. In cooperation with TESAT, DLR Space Administration initiated the development of the second generation LCT dedicated for the LEO-to-GEO link in 2006. At the same time, Germany concluded a bilateral agreement with Switzerland on the development and production of several key components of the second generation LCT. The coarse pointer, the main telescope and small optical components have been developed and are manufactured by industrial partners from Switzerland. A comparison of key parameters of the first generation terminal with the second generation terminal can be found in TABLE I. The main driver for the difference in the key-parameters is the distance requirement of GEO to LEO links. The larger distance between the space crafts (up to 45,000 km) requires an increased level of optical power and a larger telescope aperture. Based on the link budget calculation and an assessment of the midterm user requirements on the bit rate, it was decided to reduce the user data rate from 5.6Gbps to 1.8Gbps. Despite the already existing capability of the technology to communicate at 5.6 Gbps and the potential for an upgrade of the data rate to 10 Gbps and beyond for future evolution of the LCT 1064nm technology, it must be noted that potential users are not (yet) prepared to significantly increase their data rate. Optical communication is yet seen as an operational add on and the communication payloads are designed according to requirements based on the assumption that RF-technology is mandatory, if not as main communication payload at least as back-up. Furthermore, space qualified technology is yet lacking, which allows fast and power efficient memory read out aboard the space craft. Therefore, the bottleneck for multi-10-gigabit per second data streams in space, as promoted by some developers for optical space communication technologies, is not primarily the optical communication technology itself, but the lacking of sufficiently fast enough data sources on the space craft side.

A. *Status optical communication payload on Alphasat I-XL*

A second generation LCT embarked on Alphasat I-XL as a technological demonstration payload serves as an early validation platform towards EDRS [11][12]. The Alphasat LCT will be used for optical inter-satellite link tests with the Copernicus satellites Sentinel 1A and Sentinel 2A and for further optical link experiments to the ground. The Inmarsat Satellite Alphasat I-XL was successfully launched from Kourou on July 25th 2013. In addition to Inmarsat's commercial payload, Alphasat I-XL offered space for innovative technologies that are tested for the first time under the special conditions prevailing in space. Two of the four payloads that fly on Alphasat for demonstration purposes originate from Germany: an innovative star sensor developed by Jena Optronic supplies ultra-precise information about the satellite's orbit and attitude, thus supporting the precise alignment of the laser communication terminals, the other demonstration payload from Germany. The technology demonstration program 1 (TDP1) laser communication payload aboard Alphasat consists of the laser communication terminal itself and a Ka-Band downlink. Images of laser communication terminal embarked on Alphasat are shown in Fig. 7. The data relay concept followed here provides a high data rate downlink for LEO space craft users. Apart from the feasibility of extremely high data rates feasible with optical links, the high availability of the link and the timely access to the data are main arguments to make the relay scenario favorable in comparison to direct downlink. If data is downlinked directly from a LEO space craft the availability of the link is limited to approximately 10min per flighover. The GEO relay link is available for 45min of a typical 90min on every orbit. As optical downlinks are currently not considered to mature enough due to the restriction of cloud free line of sight a conventional RF-downlink is chosen for the Alphasat and EDRS implementation. The data of the LEO space craft is transmitted optically to the GEO stationary relay node at the LCT user data rate of 1.8Gbps. The Alphasat I-XL demonstration payload then provides a Ka-band downlink at two optional data rates 300 Mbps and the Copernicus user data rate of 600 Mbps. The Ka-Band downlink frequency of the optical Alphasat payload is centered at 26.5 GHz. The service area of the beam is centered in Southern Germany and covers the main parts of Germany. The Ka-Band feeder ground station is situated in Oberpfaffenhofen at the DLR earth observation center (DFD). For EDRS a similar concept is implemented, but EDRS will provide a user service at the full optical bandwidth of 1.8 Gbps also in the Ka-band downlink

Meanwhile, the Alphasat I-XL commercial Inmarsat payload was checked out at 8°E in the first phase of commissioning after launch. The satellite was then relocated to its final operational orbit slot at the end of August 2013. The technological demonstration payloads including the optical communication payload were checked out at the final location. All parts of the Alphasat optical communication payload successfully passed the commissioning tests and both the LCT and the Ka-Band downlink showed functional performance in nominal parameters. LCT self-tests have been performed using a retro-reflecting mirror installed in the parking position of the LCT during commissioning. The 600MBps Ka-band downlink allows analyzing in more detail the up to now excellent LCT performance at a high resolution telemetry data rate. Just in time before the onset of bad weather winter season at the optical ground station site in Tenerife, the commissioning of the Alphasat LCT was concluded by ground link pointing and tracking tests with the ESA OGS at Tenerife. Main objective of these tests is to determine the in orbit alignment of the LCT with respect to the space craft coordinates. This is an important task because the environmental loads experienced during launch are able to induce minor changes in attitude of the LCT aboard the space craft.

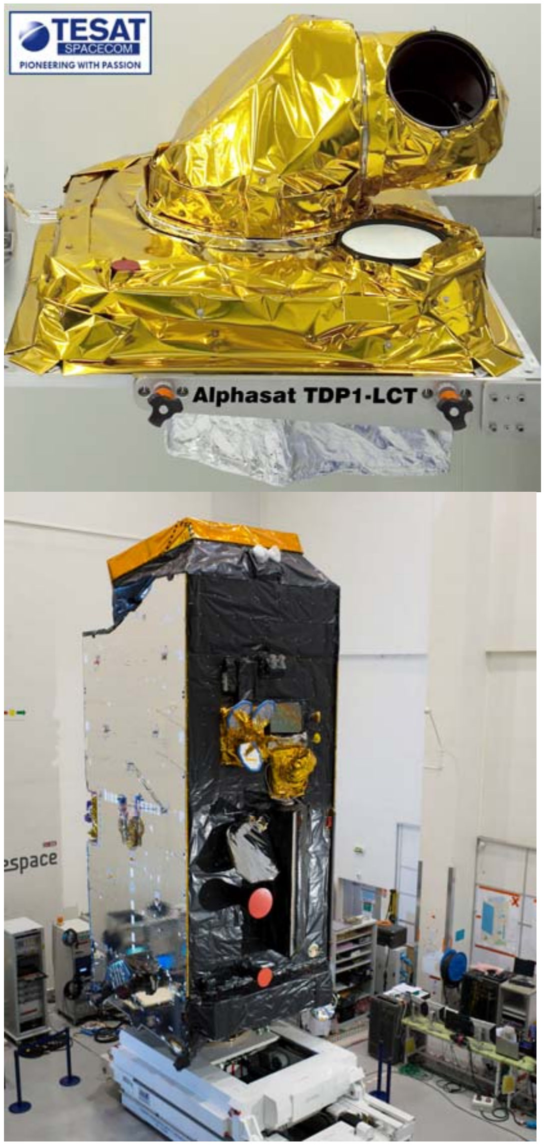

Fig. 7. Top: Alphasat LCT before delivery to space craft. (Picture courtesy TESAT) Bottom: LCT embarked on Alphasat as TDP1 (picture courtesy ESA).

Meanwhile the alignment of the LCT with respect to the space craft was successfully calibrated. As add on to the original plan also coherent tracking was achieved with the ESA optical ground station in November 2013. Power levels received and the achievement of coherent tracking confirm that the link budget calculations have been appropriate. Since all relevant performance parameters have successful been verified, everything has been prepared for a real end to end test with a counter terminal aboard a LEO space craft.

A three years phase of verification and experimental optical links to the Alphasat LCT with the contractual option of an extension is planned after the commissioning phase. The experimental phase will scope inter-satellite link experiments, space to ground links and space to aircraft links. The success story of European developments of optical communication in space which started with the heritage of the Silex terminal aboard the Artemis satellite [6] can therefore now to be continued with the optical terminal aboard Alphasat. Regarding its main mission objective the Alphasat Laser communication terminal now awaits the in orbit arrival of its LEO counter terminals.

B. Status LCTs on the Copernicus Satellites

The anchor customer for the space data highway service provided by the European Data Relay System will be the Copernicus earth observation satellites of ESA. The Laser Communication Terminals are embarked on the Sentinel 1A and Sentinel 2A satellites as customer furnished items by DLR. The terminals aboard these two satellites will serve DLR as counter terminals for the testing of optical inter-satellite links with the TDP1 optical communication payload of Alphasat I-XL. The launch of the first Sentinel satellite is rapidly approaching. The launch campaign of the Sentinel 1A satellite is in full swing. Both environmental test campaign on optical communication payload level and space craft level have successfully been completed. The functional performance of the LCT on Sentinel 1A is nominal according specification. The Sentinel 1A LCT is equipped with a coarse pointing mechanism from a second source supplier of Switzerland. Fig. 8 depicts the embarkation situation of the LCT aboard the Sentinel 1A space craft. The LCT and the thermal radiator sit directly in the center of the launch adaptor ring. The launch of the space craft is planned for the beginning of April time frame. Since in this situation the LCT is literally hard mounted to the launch vehicle, we are looking forward to maybe the hardest ride to space a LCT flight model has yet seen. Early results on the verification of the first optical inter-satellite link may be expected for late summer 2014. The second LEO terminal to follow will be the LCT flight model aboard Sentinel 2A. The Sentinel 2A LCT flight model assembly is complete and environmental test campaign of the Sentinel 2A LCT is ongoing. The launch of Sentinel 2A is planned for 2015.

The Sentinel B series, which is planned for successive launch after the Sentinel A satellites, will also be equipped with optical communication payloads. The recurring terminals for Sentinel 1B and Sentinel 2B are contracted by ESA. The production of both terminals is ongoing. The procurement of the next batch of Sentinel satellites i.e. the Sentinel C and Sentinel D series is currently in planning as recurrent satellites. The procurement is subject to a decision of the European Commission and the procurement is planned to be managed by ESA. At least four further Sentinel satellites: Sentinel 1 C and D and Sentinel 2 C and D are planned to be equipped with recurrent optical communication TESAT LCT payloads in the years to come.

Fig. 8. Laser Communication terminal embarked on Sentinel 1A (courtesy of TAS-I).

C. Transportable Adaptive Optical Ground Station

When the LEO to GEO inter-satellite terminal development was defined, DLR has made a tradeoff between all optical downlink and the RF-downlink. The result of this tradeoff is that optical ground links will in the midterm be not acceptable for a broader range of users, because the requirement of a cloud free line of sight imposes a much too high burden on the operations concept and the ground infrastructure. Highly complex link planning and the extensive site diversity (in the order of 10 ground stations) are required to reach availability figures acceptable for users. Even the all optical GEO relay up or downlink would appear the more favorable than the direct downlink from LEO, because at already demanding operations and site diversity constraints, the LEO downlink case adds additional complexity. The restricted visibility of a ground station from LEO orbit in combination with the need of fast weather induced switch of operation will cause severe additional effort compared to a stationary GEO scenario, which already is difficult to implement. The willingness to embark on such highly complex concepts of operation required for all optical ground links either to LEO or GEO may, however, change in the long run when the demand for high data rates increases while the available RF bandwidth reduces.

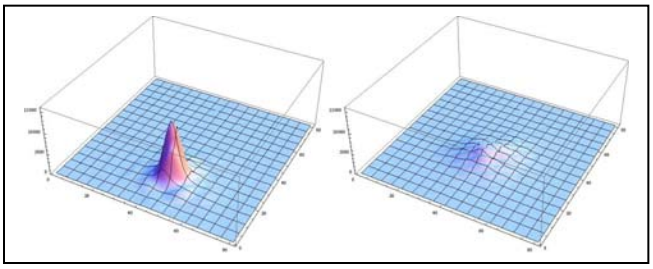

Fig. 9. Influence of adaptive optics on the signal. Right hand side: without adaptive optics. Left hand side: with adaptive optics the signal to noise ration is significantly increased (picture courtesy of TESAT)

Despite of the tradeoff, which results in a restricted suitability for operational optical ground links for the time being, nonetheless a second main objective of the experiments with Alphasat LCT is defined as performance of ground link communication experiments. During commissioning phase one part of this objective – i.e. the demonstration of mutual coherent acquisition and tracking both of the GEO and ground station terminals – has already been successfully achieved. The ground link experiments will be resumed from spring 2014 using the ESA OGS. In context of the TerraSAR-X and NFIRE campaign with the above mentioned basic LEO-LCT ground station a study on the influence of adaptive optics on the bidirectional ground link has been performed in combination with the ESA OGS at Tenerife, as a preparation for the upcoming ground link experiment campaign with Alphasat. Implementation of adaptive optics within an optical ground station allows to reducing scintillation effects significantly [13]. Thus, telescopes with larger apertures can be implemented, and the link budget for optical ground links may significantly be improved for coherent optical communication.

A major result of this study is shown in Fig. 9. On the right hand side of the figure the CCD image communication signal is shown when the adaptive optics was switched off. The atmospheric turbulence i.e. scintillation causes a large broadening of the beam and the originally Gaussian shaped beam becomes speckled. The signal to noise ratio of the communication beam, however significantly improves when the adaptive optics is active. Please refer to the left hand side of Fig. 9. Based on these findings DLR concluded a contract on the development of a transportable adaptive optical ground station (T-AOGS). The T-AOGS is designed such that all equipment fits into the envelope of a standard 20 foot shipping container. The T-AOGS consists of two parts: the optical container and the operating container. The optical container comprises all optical elements including the adaptive optics, the transmitter and the receiver. The T-AOGS is operated and controlled from the operating container, which comprises all supply and control equipment. Thus, providing immediate access is provided to operator. The optical container can be placed inside a segment of the operating container during transport. For operation the optical container is installed at a distance of several meters from the operation container to decouple the optical parts from micro-vibration and to operate the optics at thermal equilibrium with the environment. The aperture of the T-AOGS receive telescope is 265 mm and therefore significantly enlarged in comparison with the previous 65 mm ground station aperture. Higher order phase distortions are corrected by a deformable mirror and the phase distortions of the receive path are measured by a classical Shack-Hartmann sensor. The T-AOGS is designed to communicate both with the first generation LEO-LCT and with the second generation LCTs installed in GEO and up to now to be embarked on the Sentinel satellites. The communication link experiments using adaptive optics are planned to be started when the T-AOGS will have been installed next to the ESA OGS in Tenerife later this year.

D. The European Data Relay Satellite System

The Member states of ESA decided at the ESA Ministerial Council 2008 in Den Haag to start the development of the European Data Relay Satellite System (EDRS) in ESA’s Advanced Research in Telecommunications Systems Programme (ARTES-7). This decision roots in a German initiative and the advance in the German roadmap on the development for optical communication reached at that time. The EDRS is implemented as a private public partnership between the public partner ESA and the private partner Astrium Services, now being part of the Airbus Defense & Space Group. EDRS will be an operational constellation of GEO satellites intended to relay user data between satellites on one hand (as well as unmanned aerial vehicles (UAV) in the future), and ground stations on the other hand. EDRS will allow almost full-time communication with satellites in LEO orbit, which often have a very reduced visibility from any ground station. EDRS is envisaged to significantly improve the stringent timeliness requirements of demanding Earth observation missions (i.e., time critical services).

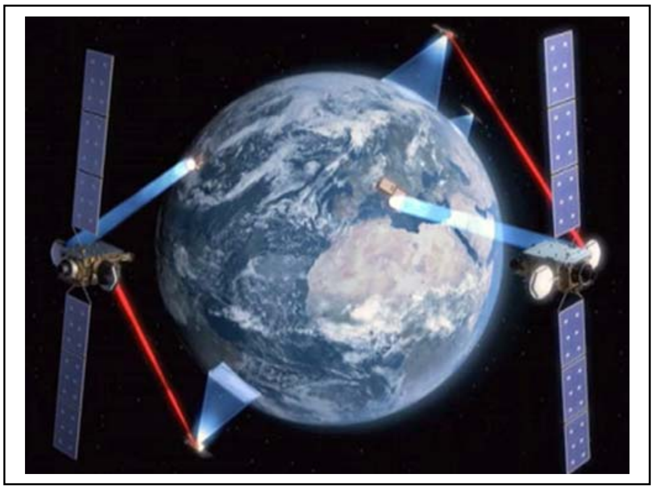

Fig. 10. Sketch of the EDRS System (courtesy of ESA).

The EDRS space segment is composed of two elements:

- The EDRS-A payload contains a LCT and a Ka-Band inter-satellite terminal. The data will be linked to ground by Ka-Band at a maximum user data rate of 1.8Gbps. The EDRS-A payload will be placed as a piggyback payload on-board Eutelsat 9B commercial telecommunication GEO satellite manufactured by the Airbus Defense & Space Group, formerly Astrium Satellites (France). The Eutelsat 9B satellite will be launched in 2015 and will be positioned at 9°E.
- EDRS-C is a dedicated satellite, which is built by OHB (Germany). The platform is based on the OHB SmallGEO platform. The EDRS-C payload includes an LCT for Optical inter-satellite link and a Ka-Band downlink at a maximum user data rate of 1.8Gbps. The satellite additionally carries Avanti's HYLAS3 as a hosted payload. The EDRS-C satellite is planned to be launched in 2016.

Furthermore, the German Space Operation Center (GSOC) of DLR will contribute and operate major parts of the EDRS ground network. The ground infrastructure of EDRS will comprehend four ground stations: two data ground stations for the EDRS-A satellite in Weilheim (Germany) and in Harwell (United Kingdom) respectively, and the feeder link ground stations for EDRS-C in Weilheim (Germany), and its back-up in Redu (Belgium). As part of the agreement DLR will also implement and operate the payload control center for EDRS-A and the satellite control center for EDRS-C in Oberpfaffenhofen (Germany).

The core operational service of EDRS will rely on the optical inter-satellite link, which will be realized by the second generation LCT of TESAT. A frame contract was concluded between the space agencies ESA and DLR and the industrial partner TESAT in 2009, in order to secure the terms and conditions of the LCT procurement for all partners both from a technical and a commercial point of view in the long run. As part of this agreement DLR took the responsibility to perform the qualification of the LCT for EDRS on behalf of ESA. The qualification of the LCT for EDRS is based on the LCT development contract developments of DLR's national program i.e. the qualification performed for the above mentioned Alphasat, Sentinel 1A and Sentinel 2A flight missions. The qualification of the LCT for EDRS is based on an extensive verification program at subunit level and is additionally based on the verification of all DLR LCT flight models to proto-flight loads. Environmental requirements for the LCT development were derived in a generic matter to cover many space craft platforms and launch environments for GEO and LEO orbits. The environmental requirements have been traced to subunit level and have been tested with appropriate margin. The approach of verification at subunit level has the clear advantage that it is possible to build up second source suppliers for units with a reduced risk on the re-qualification effort necessary. In the future this approach will be beneficial to LCT customers since it allows for continued evolution of the industrialized product. The EDRS program according to DLR point of view is well on track and the project makes good progress. DLR looks forward to see the EDRS service becoming operational in 2015 [14].

V. STANDARDIZATION OF OPTICAL LINKS FOR INTEROPERABILITY

DLR has participated to discussions in context of the optical links study group (OLSG) setup in context of Consultative Committee for Space Data Systems (CCSDS) to prepare the standardization of optical links. One main topic treaded in context of the OLSG work has been the feasibility of eye safe optical links in the atmosphere. Optical up and down links have been analyzed at the example of several link scenarios in a near earth and deep space environment based on the evaluation of the maximum permissible exposure levels. As a result of the OLSG investigation regarding these link scenarios it can be stated: 1) All down link scenarios studied can be considered eye-safe in the down link independently of the wavelength. 2) None of the up-link scenarios is eye-safe according to the internationally applicable standard of the international civil aviation organization (ICAO) independently of the wavelength, even though 1550nm nominally shows some higher allowable maximum exposure levels. 3) The Optel-μ Terminal development of Switzerland demonstrates that a 1064nm up-link beacon got eye-safety approval of the national Swiss flight traffic authority. If at all possible, OLSG recommends seeking adaptation of the ICAO standards in order to extend the permissible power for optical link. In the current situation therefore the main focus for developing optical communication systems for space and related standardization should, in DLR point of view, be the communication related performance aspects and the verification of optical communication systems for space and not the laser safety aspect in the first.

DLR recommends continuing a technical discussion on results of currently emerging in orbit verifications of optical communication to advance interoperability of optical ground station for interagency cooperation. Only the Silex terminal on the ESA satellite ARTEMIS at 820-850nm[5], which will not be further pursued, the pulse position LADEE mission of NASA from the moon [15], and the GEO and LEO ground link at 1640nm, show in orbit heritage today. Thus further in orbit verification is needed to demonstrate that the technologies can be qualified for reliable operation in space. Successful in orbit verification of the technology and related link-budgets should be the baseline for standardization in order to standardize useful solutions. The decision to establish a working group of the CCSDS on optical communication in space was taken at the autumn 2013 CCSDS meeting. DLR and TESAT in co-operation with ESA have in this context decided to make available the LCT communication standard available for interoperability and interagency cross support. Originally, it was agreed to make available this information to ESA by end of 2018. DLR and ESA recommend the TESAT LCT standard for standardization, because it will be the first operational optical communication system in space from 2015 onwards. ESA and DLR will have brought valuable assets of three geostationary nodes and of four to eight LEO users into space for operational lifetime of the satellites. EDRS itself, due to the private partner, is set up as an open system, which welcomes third party users on a commercial basis to benefit from this infrastructure. Based on the launch of Alphasat and the advent of EDRS, Europe, as J. Dordain, Director General of ESA, put it during a press conference: ", will be able to impose the Laser Communication Terminal as a world standard for high data rate communication".

VI. Conclusions and Outlook

This contribution gives an overview on the German activities related to optical communication in space since 2007. Major results of inter-satellite optical communication links between the LEO space craft TerraSAR-X and NFIRE as well as results of ground link campaigns from these space crafts are reported. As major achievements of these experiments the demonstration of fast and efficient position acquisition and tracking in highly dynamic LEO-LEO link environment, the virtually BER free inter-satellite communication at 5.6Gbps and the establishing of bidirectional ground links with a coherent detection scheme must be noted. The following development of GEO-LEO second generation LCT has matured to a technology readiness level of 9, since the successful launch of the optical communication payload aboard Alphasat. The status of the optical communication payloads aboard the Sentinel 1A and Sentinel 2A space crafts is reported. DLR is looking forward to the successful launch, in orbit commissioning and operation of these future users of EDRS in 2014 and 2015. Step by step EDRS is becoming a reality and start of in orbit service can be expected for 2015. Major milestones on the road to bring these optical payloads therefore have been achieved and the exciting time to test and explore the results of this disruptive technology in space has just begun. DLR hopes that these activities create a momentum, which convinces a broader community of users that the maturity of the technology has sufficiently advanced to now also utilize it. DLR welcomes any activity of international partners, which helps to underline the advantages of laser communication for space craft users. The upcoming exemplary activities related to the SOTA terminal of NICT [16], and the LCRD technology verification mission of NASA [17] are acknowledged as great contributions in this direction. The development of unmanned aerial vehicle optical communication terminals for communication with a GEO-relay may open the door for a much broader field of applications. It is currently discussed to develop the EDRS service for the benefit of global users. The EDRS partners consider to add one additional EDRS relay payload(s) to better serve either the pacific and/ or the Northern Atlantic region. This Globenet proposal is also considered as a platform to implement several technological improvements, which however will not question the fundamental design of the EDRS LCT. Based on the experience gained from the in-orbit verification, the operational experience of EDRS and user requirements an evolutionary technology development is planned, when results of the Alphasat experiments will have been analyzed.

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References

[1] Federal Ministry of Economics and Technology, "Making Germany's space sector fit for the future. The space strategy of the German Federal Government", Federal Ministry of Economics and Technology (BMWi), Berlin, 2010

[2] D. Giggenbach. "Lasercomm Activities at the German Aerospace Center's Institute of Communications and Navigation" " Proc. ICSOS 2012, 4-1 (2012)

[3] B. Smutny, "5.625 Gbps optical inter-satellite communication link verified in-orbit", Proc. of the Ka and Broadband Communications Conference (2008).

[4] R. Fields, "5.625 Gbps bidirectional laser communications measurements between the NFIRE satellite and an Optical Ground Station," Proc. of ICSOS,44–53 (May 2011).

[5] M. Witting," Status of the European Data Relay Satellite System" Proc. of ICSOS (2012)

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

[7] M. Gregory, "TESAT laser communication terminal performance results in 5.6 Gbit coherent inter-satellite and satellite-to-ground links," Proc. of ICSOS,(2010).

[8] M. Gregory, "Coherent inter-satellite and satellite-ground laser links," Proc. SPIE, 7923, 792303–1 792303–8 (2011).

[9] M. Gregory, "Commercial optical inter-satellite communication at high data rates", Optical Engineering 51 (2012).

[10] M. Gregory, "3 Years Coherent Space to Ground Links: performance results and outlook for the optical ground station equipped with adaptive optics", Proc SPIE 03/2013; DOI:10.1117/12.2022253.

[11] K. Boehmer, "Laser Communication Terminals for the European Data Relay System", Proc. of SPIE 8246 (2012).

[12] G. Mühlnickel, "The Alphasat GEO Laser Communication Terminal flight acceptance tests", Proc.ICSOS, 13-1, (2012).

[13] Z. Sodnik, "Adaptive optics and ESA's optical ground station", Proc. SPIE 7464 (2009).

[14] H. Hauschildt, "European Data Relay System - One Year to Go", Proc. ICSOS 2014, S1-3, unpublished.

[15] D. Boroson, "Overview and Status of The Lunar Laser Communication Demonstration" Proc. ICSOS 2012, 1-3 (2012)

[16] Y. Takayama, Y. Koyama, H. Takenaka, H. Kunimori and M. Toyoshima, "Studies on candidate approaches for satellite-ground laser communications" Proc. ICSOS 2012, 5-3,(2012)

[17] B. Edwards, D. Israel, K. Wilson J. Moores and A. Fletcher "The Laser Communications Relay Demonstration"Proc. ICSOS 2012, 1-1, (2012)