VERIFICATION OF GROUND STATION DIVERSITY FOR DIRECT OPTICAL TTC-DOWNLINKS FROM LEO SATELLITES BY MEANS OF AN EXPERIMENTAL LASER-SOURCE

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INTRODUCTION

Most of today's satellites make use of microwave data-links for their TTC-downlinks. However, these data-links are limited in terms of achievable data-rate and spectrum availability. Free-space optical communication links might play an important role in the future, as they outperform microwave links in many relevant parameters, namely terminal-size and -mass, power consumption, and data-rate. A solution taking advantage of these attributes might be the usage of direct optical downlinks from a LEO satellite to an Optical Ground Station (OGS).

The challenge of limited availability due to cloud coverage can be overcome by using Ground Station Diversity with several Optical Ground Stations placed at suitable locations around the globe. With this approach, high link availabilities can be achieved.

The Optical Communication Group of DLR's Institute of Communications and Navigation is currently developing an experimental laser source for compact LEO satellites. The pointing will be accomplished by utilizing the attitude control system of the satellite bus, aligning the source towards an Optical Ground Station during a satellite pass. As no Coarse Pointing Assembly (CPA) is necessary, a system with a low mass (<1kg) and volume can be built. Thus, this concept might be a cost-effective solution for small and compact satellites with the need for a downlink with a high data-rate.

At first, this paper will describe the experimental payload, a directly modulated laser diode with a relatively low data-rate, which is intended to be used on a compact-satellite.

The feasibility of the CPA-less pointing concept will be shown. Data-rates 1Gbit/s are achievable with this approach and relatively small OGS-apertures 60cm, depending on the attitude accuracy of the satellite bus.

Then we will give an overview about the Ground Station Diversity concept. Based on cloud coverage data, it will be pointed out that the concept results in link availabilities close to 100%.

A Transportable Optical Ground Station (TOGS) with an aperture of 60cm, which is currently under development, will be also presented. Due to its low mass and easy transportability it can be used to carry out a global validation campaign.

I. Satellite Hardware

On small satellites, the power and space available for a downlink payload is limited. So there is a need for power-saving and lightweight downlink terminals. This can be achieved by using directly modulated semiconductor laser diodes. A fibre-coupled laser diode is driven by an electronic circuit, which connects to the satellite bus and receives TTC data from it, which then is transformed into a current modulating the laser diode. The emitted light is guided in a single-mode fibre and emitted from a collimator with a defined divergence angle. The wavelength used is 1550nm, which allows the use of standard fibre-optic components and ensures eye-safety.

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Figure 1: Space-qualified directly modulated laser diode

This technology allows data rates up to 200Mbit per second and a mean optical output power of approximately 20dBm. The power consumption is typically 8Watt at an operating Voltage of 5V. The mass of such a device can be as low as 0.2kg.

A prototype of a directly modulated laser diode has been built and space qualification tests have been carried out successfully. These tests included thermal/vacuum cycling as well as vibration and pyroshock tests.

For applications demanding even higher data rates or transmit powers, a different approach can be targeted. The use of optical amplifiers (EDFAs), as used in commercial fibre optic transmission systems, allows data rates up to 2,5Gbit/s and optical output powers up to 5W. In this concept, a low-power modulated laser source is used as a transmitter, whose output signal is then amplified by the EDFA and transmitted as described above.

Figure 2: Laser Source using an optical amplifier

Optical downlinks need to be aligned accurately to the receiving ground station as the achievable data rate depends on the light intensity at the receiving aperture. Therefore, choosing a smaller divergence angle allows for higher data rates, but makes the alignment of the satellite more challenging.

In this concept, the alignment of the collimator towards the ground station is done by the attitude and orbit control system (AOCS) by rotating the body of the satellite. Most modern satellites have the capability to do these “target-pointing” maneuvers. The system can easily adapted to satellites with worse target-pointing capability to the disadvantage of data rate.

To overcome the drawbacks due to the limitations in the satellite’s target pointing accuracy, which are mainly governed by the accuracy of the satellite’s star sensors, a Four-Quadrant Pointing device can be installed onboard the satellite. If the Optical Ground Station further illuminates the satellite and thus the Four-Quadrant Device by open-loop pointing based on orbit data with a Beacon Laser, a closed control loop can be realized and a very good positioning accuracy can be achieved. Tracking accuracies of several micro radians become feasible with such an approach, in case the satellite's AOCS supports such accurate movements. A possible implementation of such a device is depicted in Figure 3.

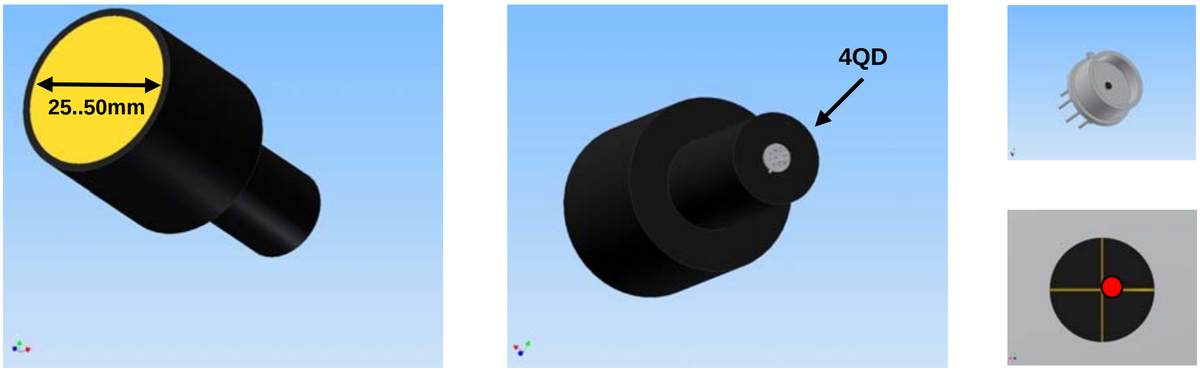

Figure 3: Four-Quadrant Pointing Device to be installed onboard satellite
Left: Front View, Middle: Rear View, Right: Four Quadrant Detector (4QD)

Furthermore, the Beacon Laser can be modulated. This allows the suppression of background light [2] and the transmission of data with a low rate, using the Tracking DSP/FPGA as data receiver. Thus an uplink channel can be implemented without any additional components. This system concept is shown in Figure 4. It allows a broad variety of additional functionalities, as e.g.

- A Back-Channel for FEC-Coding in downlink direction to implement ARQ Functionality
- A Backup Channel for TT&C, i.e. the commandment of the satellite over the optical link alone
- The Transmission of real-time cloud coverage data during a satellite pass to react with appropriate coding on the tx-data stream regarding the current cloud situation

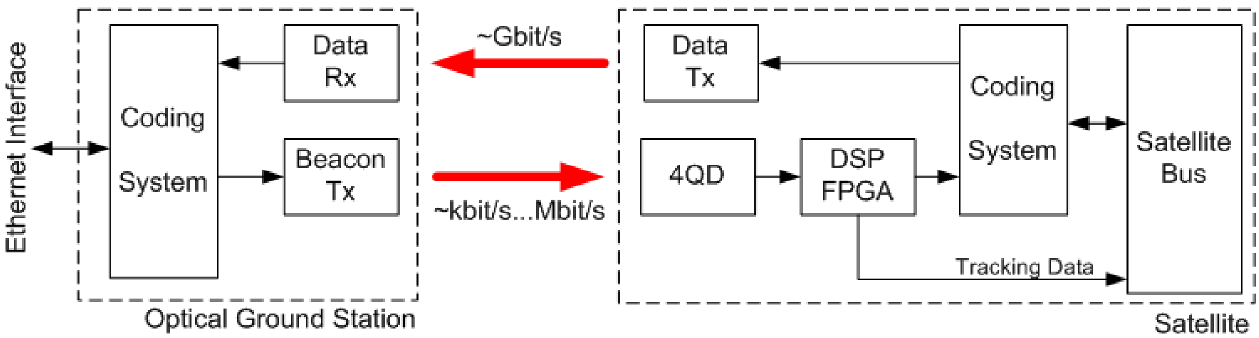

Figure 4: Block-Diagram of communication system with Optical Uplink

DLR has several flight opportunities with the systems mentioned above onboard of several satellites. This will allow for the verification of simple optical sources, consisting of a single high-power laser-diode, as well as the verification of a more accurate system with an optical amplifier and tracking detector. The flight opportunities typically have earth observation instruments as primary payload and operate in polar orbits with a height between 500km and 700km.

II. Feasibility

As already mentioned in the previous section, the beam-divergence of the laser beam emitted by the satellite is mainly determined by the Pointing Accuracy of the satellite. In other words, the Pointing Accuracy of the satellite defines the power budget in downlink direction and thus the possible data-rate.

For a good illumination probability of the Optical Ground Station, the satellite's tx-divergence must be matched to the tracking capabilities of the satellite. The Full-Width-Half-Maximum (FWHM) divergence angle of the satellite should be remarkably higher than its pointing accuracy. To achieve a probability of nearly 100%, it has to be chosen as 6 times the 1δ tracking accuracy of the satellite, considering a pointing error with Gaussian distribution.

An elevation angle of 2° will be considered as design point in the following explanations, as the line-of-sight towards the horizon is obscured for lower elevations at Optical Ground Station Oberpfaffenhofen (OGS-OP). For the design of operational communication links, Optical Ground Stations at e.g. mountain-tops might be considered, allowing lower elevation angles and thus larger link durations.

Figure 5 shows a link-budget for 3 different FWHM-beam divergences (ρ_{FWHM}), considering the Optical Ground Station Oberpfaffenhofen (OGS-OP) as downlink site. A beam divergence of 1mrad allows data rates in the order of only several Mbit/s. To achieve this, the satellite must be capable of pointing towards a ground-station with an accuracy of some 100microradians. For smaller divergence angles, as e.g. 30µrad, data rates up to several Gbit/s become easily possible. However, this requires a very good Tracking Accuracy of the satellite.

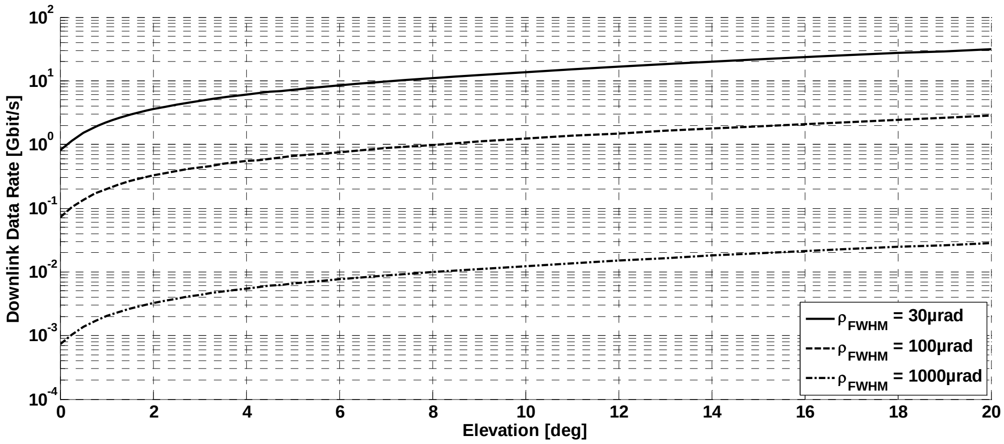

Figure 5: Link-Budget in Downlink-Direction for a LEO with 545km orbit height.
Parameters: Wavelength: 1550nm, OGS-Telescope: 40cm, OGS-Sensitivity: 1000Photons/bit, Sat.-Power: 1W, Optical Losses: 3dB, Pointing Loss: 3dB, Atmospheric Absorption: High Volcanic Activity, Fade Margin: 6dB

It is unlikely, that a satellite can achieve such accuracies in Open-Loop Pointing Mode. With a Four Quadrant Tracking Device, as described in the last section, greatly increased pointing accuracies can be achieved. Lambert and Casey [1] have calculated estimates for the tracking accuracies which are achievable with a 4QD-system. State-of-the art beacon lasers (10W, 1mrad divergence) enable thus pointing accuracies in the order of some micro radians up to tens of micro radians with comparably small Receiver-Apertures onboard the satellite. Estimated Tracking Accuracies are shown in Figure 6 for two different aperture diameters.

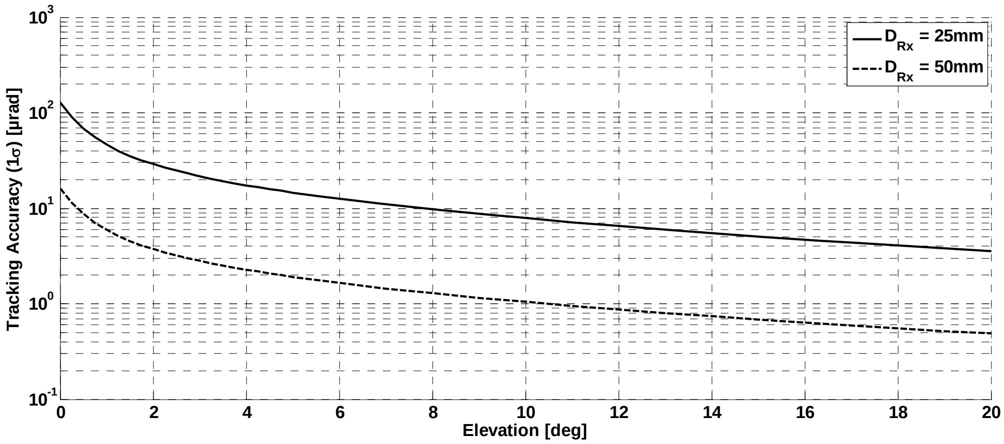

Figure 6: RMS Tracking Accuracy of Four-Quadrant Device on Satellite for different Four-Quadrant Tracker Apertures
Parameters: Wavelength: 1550nm, Beacon-Power: 10W, Beacon-Divergence: 1mrad, Optical Losses: 3dB, Pointing Loss: 3dB, Atmospheric Absorption: High Volcanic Activity, Fade Margin: 6dB

If the above results are combined, downlink data rates can be calculated by matching the beam divergence with the tracking accuracy. Figure 7 shows such a combined result with a beam divergence of $6 \cdot \rho_{RMS}$, resulting in an illumination probability at the ground station of nearly 100%. Downlink data rates in the order of some Gbit/s can be achieved with a 50mm tracking aperture onboard the satellite, assuming that the satellite bus is able to point with such accuracies.

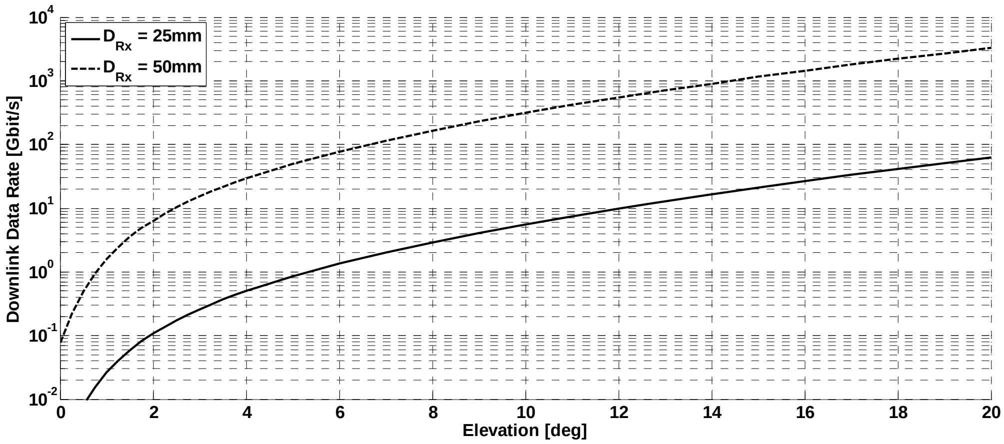

Figure 7: Downlink data rate considering the Tracking Accuracies from Figure 6. FWHM Beam Divergences have been matched to 6 times the Tracking Accuracy.
Parameters: Wavelength: 1550nm, OGS-Telescope: 40cm, OGS-Sensitivity: 1000Photons/bit, Sat.-Power: 1W, Beacon-Power: 10W, Beacon-Divergence: 1mrad, Optical Losses: 3dB, Pointing Loss: 3dB, Atmospheric Absorption: High Volcanic Activity, Fade Margin: 6dB

Figure 8 finally shows the estimated data rates in uplink direction. Several 100kbit/s are possible with aperture diameters in the order of 25mm to 50mm. Compared to typical data rates for optical links, which are in the Gbit/s range, the achievable rates for such an uplink seem very low. However, such an uplink can be implemented with only little hardware effort, and might thus be a good and cost-effective solution as back channel for ARQ or other applications.

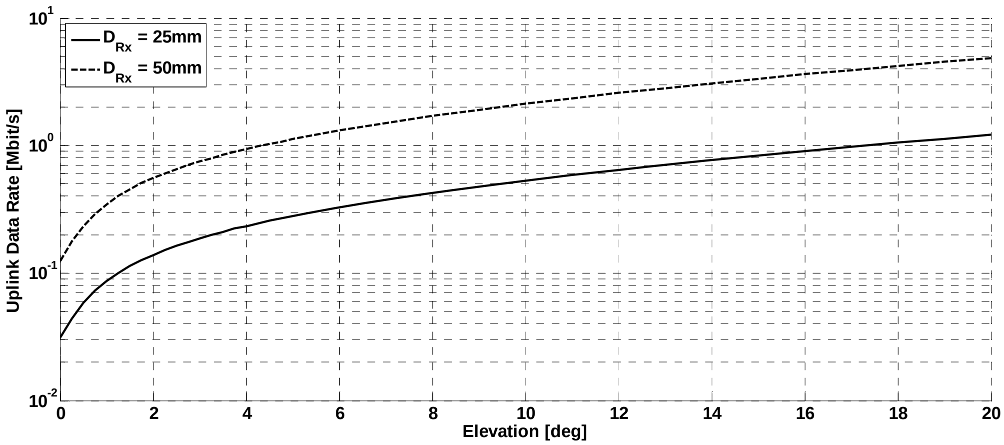

Figure 8: Possible data rate in Uplink-Direction with using a Four Quadrant Detector as receiver
Parameters: Wavelength: 1550nm, Sat.-Sensitivity: 1000Photons/bit, Beacon-Power: 10W, Beacon-Divergence: 1mrad, Optical Losses: 3dB, Pointing Loss: 3dB, Atmospheric Absorption: High Volcanic Activity, Fade Margin: 6dB

III. Ground Station Networks and Diversity performance

The blockage of ground stations by cloud cover is the central availability-limiting factor. While there exist places on earth with annual mean cloud blockage probability well below 20%, these unfortunately are in remote or political unstable areas. To make use of optical downlinks to arbitrary ground station sites, several optical ground stations should be placed at least as far apart as the meteorological correlation length of large cloud cover structures. This implies a distance of typical 300km or more. In practice, reusing astronomical observation sites for this purpose seems most promising. However, adding more de-correlated ground stations will always be beneficial, especially when sites on both sides of the equator can be used due to the negative correlation of their cloud statistics with the seasonable effect.

Ground Station Diversity inside limited national territory (example Germany)

Assuming that the LEO flies high enough during a satellite pass to contact any of four potential ground stations inside Germany (spaced as far apart as possible, see Figure 9) we can calculate a combined availability (meaning that at least one OGS will be visible to the satellite) of 91% in the summer half year and 73% in the winter half year. This availability is calculated based on European Cloud Climatology (ECC) data between 1990 and 2005.

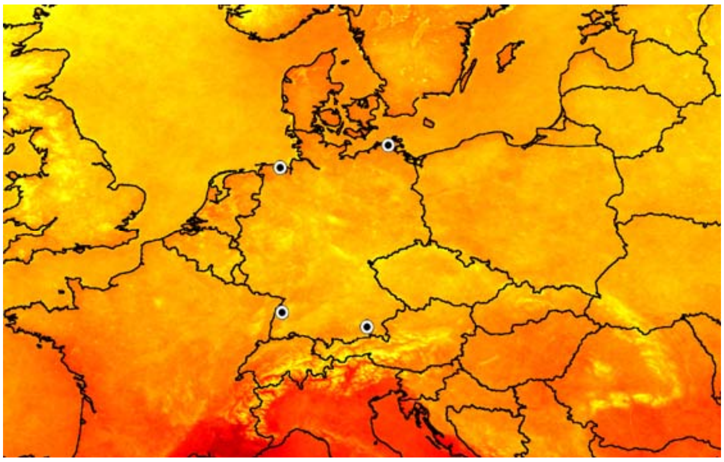

Figure 9: Suggested German national ground station network with OGSs at Rügen, Bremerhaven, Freiburg, and in the foothills of the Alps.

European Ground Station Network

When installing an OGS-network inside Europe one would prefer sites around the Mediterranean due to the lower cloud probability. Combining this requirement with existing astronomical sites and a large distance for weather de-correlation, the following locations can be identified:

- Izana on Tenerife / Spain
- Calar Alto near Almeria / Spain
- Marseille / France
- Catania on Sicily / Italy
- Skinaka on Crete / Greece

With such a network, and annual availability of 98% can be reached. With only three stations (Skinakas, Marseille, and Catania) still 96% can be achieved.

Note however that the availability numbers are for sole visibility of at least one OGS, no specific satellite orbit has been taken into account here (the OGS are so far apart that only one at a time could be seen from a typical LEO orbit, in contrast to the situation in Figure 9 above).

Global Network of Optical Ground Stations (GLONOS)
A concept for integrating global partners on a non-profit basis into a worldwide ground station network has been developed by DLR. This shall enable experimental optical satellite downlinks to various OGSs disposed by their partners on a mutual (non-compulsory) usage. Currently coordination with Japanese and Australian partners is ongoing. We expect that after the launch and testing of the first experimental laser sources an increased global interest in this technology might trigger more partners to get involved in this initiative.
A simulation example for the throughput of a global OGS network with an inclined LEO orbiting satellite is given in [3].

IV. TOGS – Transportable Optical Ground Station

Current Optical Ground Stations, as e.g. the Optical Ground Station Oberpfaffenhofen, are typically stationary. Thus the place of the ground-station is fixed and demonstration campaigns are bound to one location. A Transportable Optical Ground Station can be used for optical downlinks around the globe with little effort, resulting in a much higher flexibility regarding the location of operation.

Figure 10: Transportable Optical Ground Station (TOGS)

DLR's transportable optical ground station, TOGS, consists of an integrated platform, containing a foldable mast as well as transmitter, receiver and control electronics. The mast is used to deploy a 60 cm Ritchey-Chrétien telescope to a height of 3 m. The telescope mirrors are milled from aluminium and optimized for optical free space communications. Due to the automatic unfolding mechanism, the station can be set up for operation in very short time.

To be able to point to a target precisely, the ground station needs to know its position and attitude. Therefore, GPS and attitude sensors have been implemented to determine the position as well as heading, pitch and roll angles.

By the usage of modern composite materials, a low weight could be achieved, allowing the station to be transported to literally any place in the world in a very short time by means of standard airfreight. It can be operated on both AC and DC power networks supporting common line voltages and frequencies. Autonomous power supply by a generator included in the transport vehicle is also possible.

Optical Ground Stations like DLR's TOGS might be used for future demonstrations or of optical link technology. Furthermore, DLR intends to use the TOGS for Optical Downlinks from LEO satellites and other carriers, as e.g. UAVs.

V. Concepts for Validation Campaigns

The described concepts as well as the developed hardware are subject to verification during experimental downlink campaigns. The principal operability will be shown with optical downlinks to DLR's Optical Ground-Station Oberpfaffenhofen (OGS-OP). It has already been used for several optical satellite downlink campaigns [4] and can be set up with little efforts for further optical downlinks.

For the purpose of showing the capabilities of ground station diversity, more advanced verification concepts need to be followed. As the satellites, which are available as flight opportunities, typically operate on polar orbits, the principal proof of the diversity concept requires one or more additional ground stations on a North-South-Line originating from Oberpfaffenhofen. This can be done by placing DLR's TOGS e.g. at the DLR premises in Neustrelitz close to Berlin, or at other locations e.g. in southern Italy.

Depending on the current weather conditions, the satellite can be commanded to downlink its operational data to either one of the two stations. Thus it can be shown, that optical data downlinks with high availabilities are possible.

VI. Conclusions

This paper described the concept of optical satellite-ground links (OSGL) and showed possible implementations for the purpose of proving the functionality of such systems. Further the feasibility of direct optical satellite downlinks was pointed out by means of link-budget calculations. Data Rates in the order of several Gbit/s are possible with reasonable efforts on hardware side. A tracking device based on a Four Quadrant Detector might further increase the satellite's tracking accuracy and thus also the data rate. Furthermore, an Optical Uplink can be implemented easily, allowing advanced coding concepts or other novel applications.

It has been described, that optical link systems incorporating ground station diversity can reach availabilities up to 91%, in case 4 ground stations are placed at suitable locations inside Germany. With 5 stations placed throughout Europe, downlink availabilities become as high as 98%.

Furthermore, DLR's Transportable Optical Ground Station was introduced. Due to its easy transportability, it will greatly help to carry out validation campaigns with more than a single Optical Ground Station. Finally, a validation concept for showing the operability of the ground station diversity concept was explained. It will allow proofing the concept of direct optical data downlinks to earth.

REFERENCES

[1] S. Lambert and W. Casey, *Laser Communications in Space*. Artech House, Inc., 1995. ISBN 0-89006-722-8.

[2] Christian Fuchs, *Fine Tracking System for Aeronautical FSO Links*. Proceedings of Ka & Broadband Conference, Cagliari, Italy, 2009.

[3] Dirk Giggenbach et. al., *Direct Optical High Speed Downlinks and Ground Station Networks for Small LEO Missions*. Proceedings of Ka & Broadband Conference, Milano, Italy, 2010.

[4] Nicolas Perlot et. al., *Results of the Optical Downlink Experiment KIODO from OICETS Satellite to Optical Ground Station Oberpfaffenhofen (OGS-OP)*. Proceedings of the SPIE, Vol. 6457A, 2007.