Frequency dissemination with free-space optical links

Ramon Mata Calvo(1), Florian Moll(1), Dirk Giggenbach(1)

(1)*DLR - Deutsches Zentrum fuer Luft- und Raumfahrt*
German Aerospace Center, Institute of Communications and Navigation
Muenchner Straße. 20, 82234 Wessling, GERMANY
Email: Ramon.MataCalvo@dlr.de, Florian.Moll@dlr.de,
Dirk.Giggenbach@dlr.de

ABSTRACT

Optical clock technology is very certain to be integrated in the next high precision time standards. The demand for higher accuracy in time synchronization makes the use of free-space optical links necessary for frequency dissemination, especially if mobile partners are involved. These links are the most suitable solution in order to disseminate high frequencies in between satellites, ground stations, aircrafts, and any other mobile vehicles.

However, setting up an optical link requires good knowledge of the atmospheric channel as well as sophisticated engineering technology. The available facilities at DLR Institute of Communications and Navigation, Optical Communications Group, offer the opportunity of performing frequency dissemination measurements by using its aeronautic terminals and optical ground station. These facilities were already successfully used for measurements of the atmospheric channel, investigation of modulation formats and data communication applying optical downlinks from satellite, aircraft, and high-altitude platforms.

For free-space optical links, atmospheric turbulence is one of the main impairments to deal with since it causes degradation of spatial and temporal coherence of the propagating wave. The application of adaptive optics is proposed here to correct for these impairments and thus to achieve stable frequency transfer.

In this paper, based on the former and current field trials of free-space optical communication links, we present possible link scenarios in which the channel behavior for frequency transfer can be investigated and name the main challenges to overcome.

INTRODUCTION

Optical frequency standards operating at hundreds of THz have higher stability and accuracy performance than the micro-wave ones [1]. The dissemination of such frequencies through the fiber [2] and by means of free-space optical (FSO) links [3] [19] is currently being investigated.

In order to extend the application of optical clock references to satellite to ground frequency dissemination it is necessary to evaluate the optical carrier frequency accuracy after propagation of the optical wave through atmospheric turbulence. A frequency comb can be used to directly phase-control the frequency of a light wave and measure its stability. By the use of an acousto-optic modulator as frequency shifter it is possible to compensate the phase drifts. With a frequency comb the optical frequency can be directly compared to a reference either in the optical domain or RF domain.

The atmospheric turbulence is one of the main impairments of free-space optical links. It degrades signal integrity, i.e. temporal and spatial coherence, dependent on link distance and turbulence strength. The wave-front is distorted as it propagates through the atmosphere due to small refractive index fluctuations. Such fluctuations are random and depend on the atmospheric conditions [17] [18]. Eventually, they may cause heavy wave-front distortions and intensity fluctuations, scintillations at the receiver, and fading, i.e. loss of communication.

The Optical Communications Group (OCG) at the DLR Institute of Communications and Navigation is developing an adaptive optics system in order to correct the wave-front distortions introduced by the atmosphere. These systems are important in free-space optical links when restoration of spatial coherence is a matter, as it is the case for coherent detection techniques.

Fig. 1 DLR Optical Ground Station, OGS-OP (left), and illustration of the KIODO downlink scenario (right)

FREE-SPACE OPTICAL LINKS THROUGH THE ATMOSPHERE

The FSO frequency dissemination is affected by the atmospheric turbulence. In satellite to ground links, the beam crosses the atmosphere and as the elevation angle decreases the disturbing effects of the turbulence increase because of a longer propagation path through denser atmospheric layers.

LEO-to-ground laser downlinks were demonstrated by the experimental link between the DLR Optical Ground Station and JAXA's OICETS (Fig. 1), called KIODO (Kirari Optical Downlinks to Oberpfaffenhofen). The left figure depicts an astronomical all-sky dome hosting a two axes gimbal mount which is located at the institute roof. The transmitter optical power was 100mW at a wavelength of 847nm and 50Mbps data-rate with a PRBS pattern. At link distances between 840km and 2540km, a BER down to $2{\cdot}10^{-6}$ could be achieved [4] [5].

By means of signal reception, the optical ground station comprises a 40cm Cassegrain receiver telescope and co-aligned beacon telescopes for various wavelengths in the near infrared (820, 1064, 1550, 1590nm) to illuminate the counter-terminals and to enable closed-loop optical tracking.

A central part of OGS-OP is the Atmospheric Turbulence Monitor (ATM) which combines several optical measurement instruments to characterize the atmospheric turbulence, i.e. a differential image motion monitor, a pupil camera, a focus camera, and a Shack-Hartmann wave-front sensor. From these instruments, the important atmospheric parameters for turbulence characterization are derived. This helps to understand the influences of the atmosphere on the optical link during various atmospheric conditions [6].

An illustrative example of signal fluctuation is given in Fig. 2. It shows the received power during one of the downlink trials. The power level increases while the variance gets lower because the link distance through the atmosphere decreases for higher elevation angles. That results in a less turbulent communication channel and a higher power due to the shorter link distance. The visible signal breaks are due to characteristics of the laser terminal onboard OICETS [7].

The effect of the elevation angle on the bit error rate (BER) is also shown in Fig. 2. At higher elevation angles, the BER improves because of increased received power and decrease of scintillation.

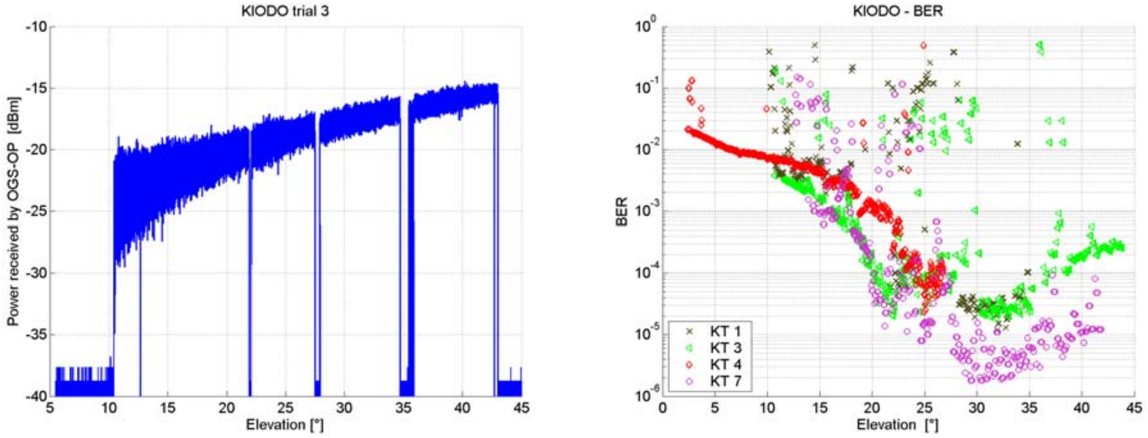

Fig. 2 Received Power in dBm (left) and Bit Error Rate (right) during KIODO trials [5]

SCENARIO PROPOSAL FOR FREQUENCY STABILITY MEASUREMENTS IN FREE-SPACE LINKS

In order to evaluate the turbulence impact on frequency dissemination, we propose possible scenarios for experiments with the available DLR facilities. A slant path between an air terminal and a ground station is the best option from our point-of-view in order to emulate a satellite communication in terms of atmospheric impact and pointing accuracy. Both can be analyzed under several conditions, choosing the elevation angle and the distance between the optical terminals.

For example, downlink path lengths between 30km and 100km with flight heights below 3000m result in small elevation angles which means moderate to strong turbulence is present. This scenario can represent a worst case reference because low elevation angles produce more cumulated turbulence along the path, as the atmosphere is denser near ground.

There are many options for the air terminal that can be taken into consideration: an aircraft, a high-altitude platform (HAP), a zeppelin, an unmanned aerial vehicle, etc. Each one has its advantages and disadvantages. For example, the vibration of an aircraft is more demanding compared to those of satellites and can produce longitudinal phase fluctuations, called piston. It produces phase noise and an OPLL is necessary in order to track it. Whereas these vibrations are less bothering using a HAP, here, system engineering is challenged by the meteorological conditions in the stratosphere.

The pointing error between terminals has a great influence on the link budged design. The transmitted beam must be divergent enough in order to guarantee that the receiver is illuminated even in the case of pointing errors. The beam foot print area in the receiver plane increases with the square of the beam divergence. Since the aperture of the receiving telescope is of finite extent, e.g. 40cm aperture of the OGS-OP, it only collects a fraction of the transmitted power.

Among the main projects carried out by DLR in the free-space optical communications field, there are the HAP downlinks (Fig. 3 left). HAPs can be used as data-relays for optical downlinks from satellites. In this European project CAPANINA, the viability of integrating isolated areas into the broadband network using different forms of aerial platforms is investigated [8].

The stratospheric optical payload experiment (STROPEX) is a part of the CAPANINA project and used a broadband downlink at 1550nm wavelength from the concerned HAP. A downlink between a HAP and ground station crosses the most turbulent part of the atmosphere.

DLR has also developed a flight terminal for downlink transmissions between an airplane and a ground station (Fig. 3 right). The aircraft is the Do228, a short take-off and landing type aircraft with twin turboprop engines. By flying below the clouds, the link can be established till distances of 100km with low elevation angles. The transmitted power is 1W at 1550nm through an aperture diameter of 30mm with a pointing error below 1mrad [9].

However, the development of the optical terminal is still ongoing. Possible further improvements include the implementation of a Fine Pointing Assembly, consisting of a fast steering mirror and a fast tracking sensor. With this new subsystem, a very fast tracking of the impinging beacon light would be possible, resulting in a more stable tracking during agile flight maneuvers. Furthermore, the system can compensate the vibrations of the aircraft that are transferred to the terminal hardware.

The aircraft and HAP downlink scenarios are two good options to investigate behavior of free-space optical frequency dissemination with mobile links, i.e. under dynamic atmospheric conditions and varying propagation paths. In general, it is important to determine the influence of the atmosphere on frequency stability for many future optical clock applications.

Fig. 3 The STROPEX before launch (left) and advanced Optical Terminal mounted on an aircraft (right)

While the aforementioned trials demonstrate feasibility and status quo of mobile links, several studies and experiments concentrate on investigation of coherent transmission for both, communications and frequency comparison.

In 2005, the German company TESAT together with DLR established a coherent free-space optical link of 142km between two of the Canary Islands, La Palma and Tenerife. It was based on homodyne BPSK (binary phase shift keying) with a data-rate of 5.625 Gpbs. For this experiment mainly proved feasibility of free-space optical coherent communication, it also shows the possibility of phase tracking over long atmospheric paths [20].

More recently, two near ground free-space optical links were set up by Max-Planck Research Group and LNE-SYRTE to study the advantage of optical frequencies over microwaves [3] and the influence of atmospheric turbulence on clock comparison [19]. Both conclude in using optical frequencies for future highly accurate clock comparison. However, big efforts still have to be done for practical applications, especially in long distance scenarios.

Since single-mode fibers (SMF) are nowadays used in optical clock comparison systems [2], it is straightforward to apply it also in free-space scenarios. This means that sophisticated fiber coupling techniques are needed that can cope with strong wave-front distortions due to atmospheric turbulence. Here, application of adaptive optics is unrivalled to correct the incident distorted wave-fronts.

ADAPTIVE OPTICS IN FREE-SPACE COMMUNICATIONS

Nowadays, adaptive optics is widely used in astronomical telescopes to boost imaging performance towards the diffraction limit. While in that case, Strehl ratio for a large field of view has to be optimized, the conditions for optical links are somewhat different. Because tracking is used to keep the partners on-axis, only correction of small fields of view are important. However, since turbulence is stronger in typical scenarios than in astronomy, e.g. LEO satellite downlinks, aircraft downlinks, etc, requirements on the adaptive optics are more demanding.

As turbulence impact increases intensity speckles in the beam transverse plane appear, creating irradiance fluctuations in space and time, called scintillation. This produces coupling losses because the fiber is not able to collect all the power, especially, when single-mode fibers shall be used at the receiver. Therefore, an adaptive optics system is required in order to improve the system performance and obtain an efficient fiber coupling.

The main four elements that constitute an adaptive optics system are the tip-tilt mirror, the wave-front sensor, the deformable mirror (DM) and the control computer. They are shown in Fig. 4. The tip-tilt mirror is used to compensate the angle-of-arrival fluctuations due to the atmosphere and the tracking errors. These angle fluctuations cause spot shifts in the focal plane, degrading the fibre coupling efficiency. The wave-front sensor collects information of the received wave-front and the control computer generates the signals to pilot the DM. The DM surface shape is formed by a set of actuators and is adapted to the received beam in order to conjugate its distortion. Here, conjugate stands for compensating and comes out from the fact that the deformable mirror performs the conjugate beam wave-front phase in order to correct the aberrations. The operations performed by the control computer in order to estimate the incoming phase are called reconstruction. For the concerned scenarios, the atmosphere can reach frequencies in the order of kHz which causes very strong requirements on the AO system closed-loop speed [10].

Wave-front sensor evaluation

A wave-front sensor analysis is mandatory to find the optimal one that fits the scenario requirements. The most common type is the Shack-Hartmann sensor, widely used in astronomical applications. Its biggest advantage is its simplicity and robustness. But, computational charge is high which limits its speed and accuracy in practice.

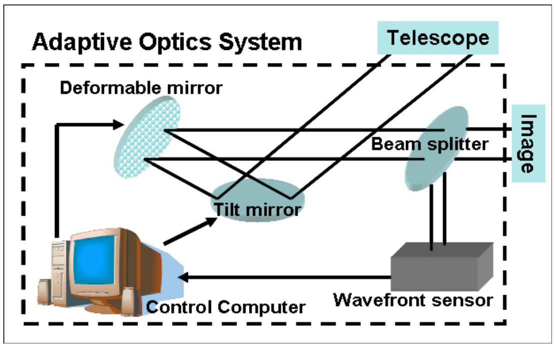

Fig. 4 Adaptive Optics System Components

The Shack-Hartmann sensor comprises a lenslet array, a CCD camera and the electronics needed to compute the calculus. It retrieves the wave-front phase by measuring the slope of the incoming beam wave-front on each sub-aperture. There are several geometries that define the relationship between the discrete wave-front points and the measured slopes. The choice of the geometry also affects the reconstruction effectiveness. There are several algorithms to reconstruct the wave-front phase. Among them, the least-squares algorithm is the most popular due to its simplicity. But its performance drops in strong turbulence conditions [12].

As turbulence increases, phase singularities, forming optical vortices, appear. The least squares algorithm is not able to detect correctly the phase near these points [13] [14]. Other algorithms like the complex exponential reconstruction [12] or the potential method [11] are more effective, however, demand more computational power.

Optical Test-Bed in Laboratory

To evaluate the performance of the Shack-Hartmann wave-front sensor and correction of phase distortions, an adaptive optics test-bed was set up that is shown in Fig. 5. The beam is sent be a telescope and passes through the turbulence generator, placed on a support about three meters away. This turbulence generator is constituted by a box with two fans. One injects cold air and the other hot air. By mixing the two air flows, Kolmogorov-like turbulence is generated. A mirror placed behind the box reflects the incoming beam back towards the optical table. An iris placed at the receiver controls the amount of power the system receives. A pellicle beam splitter takes some power in order to measure the focal spot. The pupil is imaged onto the tip-tilt mirror that corrects the angle-of-arrival fluctuations. The DM, located in conjugation to the aperture, corrects the phase distortion. Then another beam splitter guides the beam to the Shack-Hartmann sensor and the fiber coupler. The control computer performs the reconstruction of the phase and calculates the actuators position of the DM, closing the adaptive optics loop.

The actual system performs the reconstruction at 160fps and closed-loop correction at 100fps, which is sufficient to correct low frequency atmospheric turbulence. The images have 640x512 pixels with a 24x24 lenslet grid, where each of these sub-apertures contains a matrix of 15x15 pixels. This kind of wave-front sensor needs a lot of data for the reconstruction, 15x15 pixels for each phase-point, with a respective number of mathematical operations that limits its performance. However, this system in its current implementation is not yet optimized and thus, the experiments will be continued and permanently improved.

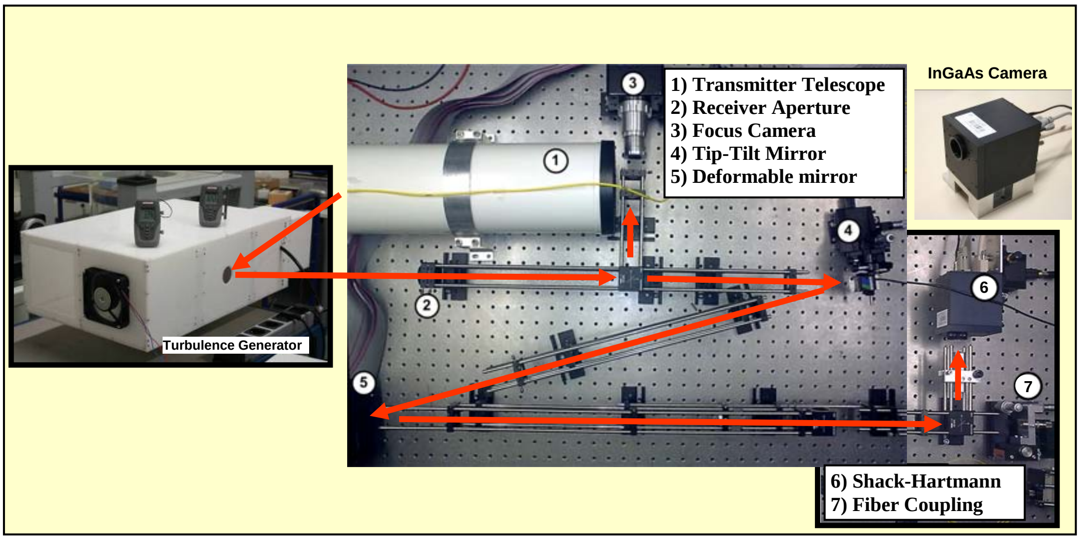

Fig. 5 Adaptive Optics test-bed in the laboratory

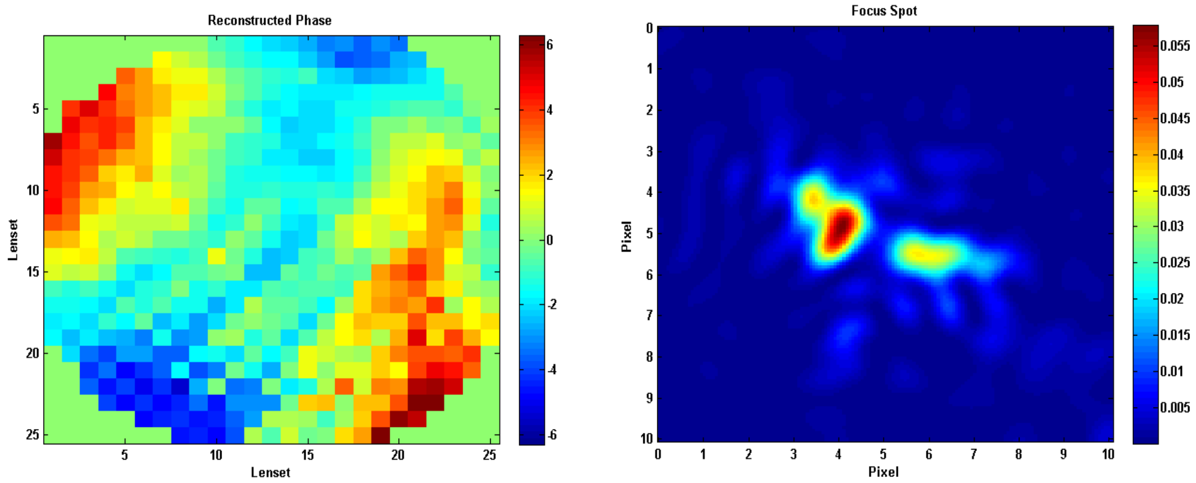

Fig. 6 Reconstructed aperture phase (left) and focus spot (right) of an uncorrected beam

Experiments using a non-homogeneous distortion plate that “statically” warps the optical phase were performed and are shown in Fig. 6. The effects of the wave-front distortion to the focus spot can clearly be seen. The left image is the reconstructed phase, the right one is the focus spot calculated from the Shack-Hartmann measurement. Thus, such distortion can produce high losses when coupling to a single-mode fiber because of the speckles in the focal plane. In Fig. 7, the effects of the closed-loop correction applied by the DM are illustrated. The correction is in real-time and maintains its performance for low-rate shifts of the plastic-plate. The focus spot shows a substantial improvement: the power is more concentrated and the phase distortions are reduced. The enhancement of the focus spot is clearly visible but the residual phase error after the correction is still quite high. This is mainly due to the quality of the Shack-Hartmann image used for the phase reconstruction which indicates a limitation of the Shack-Hartmann sensor type. Because of scintillation, some spots have not enough power and thus the reconstruction algorithm in these areas is not able to calculate the correct phase.

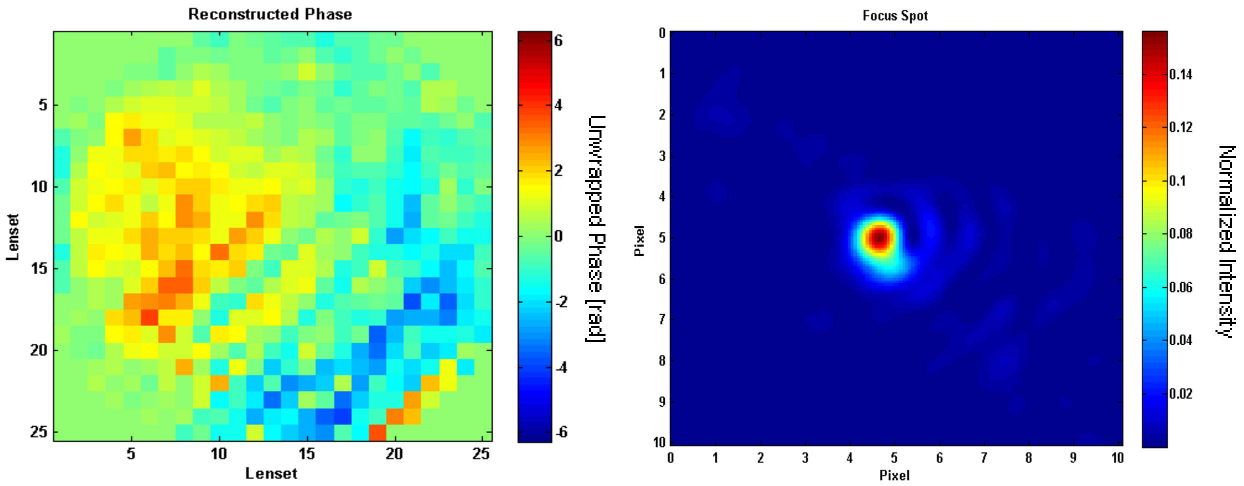

Fig. 7 Reconstructed phase (left) and focus spot (right) of the corrected beam

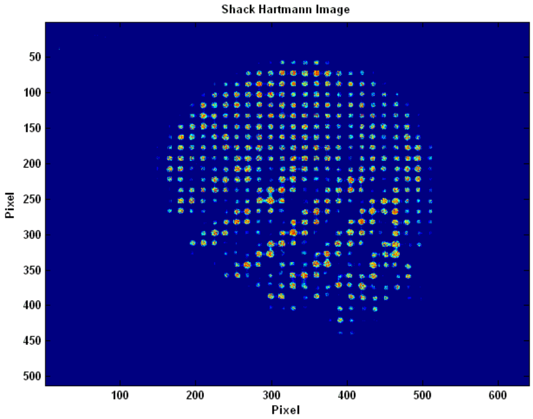

Fig. 8 Shack-Hartmann image used for the reconstruction

Fig. 8 shows the Shack-Hartmann image used in the previous reconstruction. The dark areas in this image are correlated with the higher residual error areas in the corrected phase in Fig. 7. In fact, the distortion in this Shack-Hartmann image does not look like a typical one produced by atmospheric turbulence, but it is very descriptive to explain the problematic of this sensor type.
Obviously, the speed of the Shack-Hartmann sensor can be improved but we think it will always remain limited in speed and accuracy compared to interferometric techniques. Several interferometer configurations exist that are applicable as a wave-front sensor. Amongst others, worth mentioning are the low coherence phase-shifting interferometer that consists of a Polarising Michelson Interferometer and a four-channel polarization stepper that allows the direct phase reconstruction with only one CCD camera [15]. Both are self-referencing interferometers and much less sensitive to the presence of optical vortices and scintillation. The last one was already used successfully in [16] under weak and strong turbulence conditions but at low frame rate.

CONCLUSIONS

The time dissemination by means of free-space optical links is necessary for future optical clock links from space to ground and vice versa. Here we propose to perform an optical link between an aircraft and ground station as a precursor to test the stability of frequency transmission under atmospheric turbulence. For this purpose, the adaptive optics system is of great importance to achieve single-mode fiber coupling and thus allowing connectivity to the fiber network. However, further development of the system for application in this kind of signal transmission is necessary. These downlink scenarios, often having low elevation angles, need application of wave-front sensor configurations that can face higher turbulence impacts. The use of interferometer techniques is proposed as an alternative to Shack-Hartmann sensors for its higher turbulence resistance and speed.

REFERENCES

[1] M. M. Boyd, A. D. Ludlow, S. Blatt, S. M. Foreman, T. Ido, et al., ^{87}Sr Lattice Clock with Inaccuracy below 10^{-15}. *PRL* 98, 083002, 2007.
[2] G. Grosche, O. Terra, K. Predehl, R. Holzwarth, B. Lipphardt, et al., *Optical frequency transfer via 146 km fiber link with* 10^{-19} *relative accuracy*, Optics Letters, Vol. 34, 2270-2272, 2009.
[3] B. Sprenger, J. Zhang, Z. H. Lu, and L. J. Wang, *Atmospheric transfer of optical and radio frequency clock signals*, Optic Letters, Vol. 34, No. 7, 2009.
[4] T. Jono, Y. Takayama, K. Shiratama, I. Mase, B. Demelenne, et al., *Overview of the inter-orbit and orbit-to-ground laser communication demonstration by OICETS*, Proceedings of SPIE, Vol. 6457, 2007.
[5] N. Perlot, M. Knapek, D. Giggenbach, J. Horwath, M. Brechtelsbauer, et al., *Results of the Optical Downlink Experiment KIODO from OICETS Satellite to Optical Ground Station Oberpfaffenhofen (OGS-OP)*, Proceedings of SPIE, Vol. 6457, 2007.
[6] M. Knapek, J. Horwath, N. Perlot, and B. Wilkerson, *The DLR Ground Station in the Optical Payload Experiment (STROPEX) - Results of the Atmospheric Measurement Instruments*, Proceedings of SPIE, Vol. 6304, 2006.

[7] Y. Takayama, T. Jono, M. Toyoshima, H. Kunimori, D. Giggenbach, et al., *Tracking and pointing characteristics of OICETS optical terminal in communication demonstrations with ground stations*. Proceedings of the SPIE 6547, 2007.

[8] J. Horwath, N. Perlot, M. Knapek, and F. Moll, *Experimental verification of optical backhaul links for high altitude platform networks: Atmospheric turbulence and downlink availability*, Int. J. Satell. Commun. Network. 2007; 25:501–528.

[9] J. Horwath and C. Fuchs, *Aircraft to Ground Unidirectional Laser-Comm. Terminal for High Resolution Sensors*, Proceedings of SPIE, Vol. 7199-8, 2009.

[10] R. K. Tyson, *Adaptive Optics Engineering Handbook*, Marcel Dekker, USA, 2000.

[11] K. Murphy, R. Mackey, and C. Dainty, *Branch point detection and correction using the branch point potential method*, Proceedings of SPIE, Vol. 6951, 2008.

[12] J. D. Barchers, D. L. Fried, and D. J. Link, *Evaluation of the performance of Hartmann sensors in strong scintillation*, Applied Optics 41, 1012-1021, 2002.

[13] D. L. Fried, *Branch point problem in adaptive optics*, J. Opt. Soc. Am. A 15, 2759-2768, 1998.

[14] M. Vasnetsov, *Optical Vortices*, Nova Science Publishers, USA, 1999.

[15] C. Dunsby, Y. Gu, and P. French, *Single-shot phase-stepped wide-field coherence-gated imaging*, Optics Express, Vol. 11, No. 2, 2003.

[16] J. Notaras and C. Paterson, *Demonstration of closed-loop adaptive optics with a point-diffraction interferometer in strong scintillation with optical vortices*, Optics Express, Vol. 15, No. 21, 2007.

[17] L. C. Andrews and R. L. Phillips, *Laser Beam Propagation through Random Media*, SPIE Press, USA, 2005.

[18] H. Hemmati, *Deep Space Optical Communications*, John Wiley & Sons, USA, 2006.

[19] K. Djerroud, O. Acef, A. Clairon, P. Lemonde, C. N. Man, et al., *A coherent optical link through the turbulent atmosphere*, Nov 2009.

[20] R. Lange, B. Smutny, B. Wandernoth, R. Czichy, and D. Giggenbach, *142 km, 5.625 Gbps Free - Space Optical Link based on homodyne BPSK modulation*, Proceedings of SPIE, Vol. 6105, 2006.