# BROADBAND COMMUNICATIONS FOR AERONAUTICAL NETWORKS: THE ATENAA OUTER OPTICAL LINK VALIDATION

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## Abstract

The ATENAA-Project[4] aims on the development and validation of several technologies that are able to offer broadband communication services to civil aircraft passengers. The proposed Mobile-Ad-Hoc-Network (MANET) in conjunction with broadband data links would allow high data rate services, like In-Flight-Entertainment such as Video-On-Demand or High-Speed Internet Connections. Besides that, flight-relevant information with high amounts of data, e.g. high-resolution weather maps, could be made available for airplane-captains and -crews.

This paper is intended to give an overview about the optical data link system that has been investigated in the scope of ATENAA. It provides a broadband communication link to enable the mentioned services. The developed validation platform consists of a Fixed Terminal (FT) as well as a Mobile Terminal (MT) mounted on top of an airplane simulator. A reliable Fast-Ethernet service has successfully been demonstrated. Furthermore, the results of a measurement campaign, which was performed in Oberpfaffenhofen near Munich at the End of January 2007, are presented and an outlook to the follow-up project MINERVAA is given.

## 1 OVERVIEW [a]

The topics that are discussed in the scope of this paper relate to the EU-funded project ATENAA[4]. ATENAA aims on the development of services that enable broadband communications for commercial aviation.

Communication systems that are utilized on today's commercial aircraft are based on radio frequency (RF) links with typical data rates in the kbit/s range. This permits the delivery of broadband data services, like Video-On-Demand or High-Speed-Internet, to airplane passengers. To allow such services, data links with higher data rates need to be deployed on aircrafts.

Aeronautical Free Space Optical (AFSO) Communication links in conjunction with a Mobile Ad-Hoc Network (MANET) consisting of many planes (i.e. each plane is one network node, planes are e.g. en route on north atlantic flight corridor) offer a solution for the problem of limited bandwidth. (A)FSO links outperform RF links in terms of data rate, terminal size and weight, and also power consumption. Data rates in the order of several 100 Mbit/s up to many GBit/s are feasible, and realistically only achievable with optical communication technologies. The maturity of FSO links has recently been demonstrated in a number of projects, e.g. in the experimental FASOLT link[5] or the CAPANINA HAP (high altitude platform) downlink[6]. Further satellite downlinks were demonstrated, e.g. DLR carried out the KIODO-experiment (Kirari Optical Downlink to Oberpfaffenhofen) together with the Japan Aerospace eXploration Agency[7]. The experiment LOLA - a link between an aircraft and ESA's geostationary telecom test satellite ARTEMIS - was performed by Astrium, Toulouse, with several successful trials in December 2006. The technology used is similar to the one of KIODO.

This paper deals with the ATENAA Outer Optical Link (OOL) Validation Platform which consists of a Fixed Terminal (FT) and a Mobile Terminal (MT). A simplex Fast-Ethernet link from the FT to the MT has been implemented. In order to overcome link outages due to strong fading or Line-Of-Sight-Obscurations, a packet-layer based Forward Error Correction (FEC) scheme was applied to the link. A video stream was encoded on the transmitter's side and – after decoding – displayed on the receiver's side. Furthermore, the transmission of a synchronous Pseudo Random Binary Sequence (PRBS) was made possible. This allowed the characterization of the optical channel conditions by measuring the bit errors rates (BER). Terminal acquisition was done by means of GNSS-position data, which was transmitted via an omnidirectional RF signalling link. This paper mainly describes the setup and results of the validation platform. A more general investigation and discussion on terminal design aspects can be found in [8].

## 2 SYSTEM DESCRIPTION AND SPECIFICATIONS

### 2.1 Scenario [a]

Although the aim of the ATENAA-Project was to develop technologies that are suitable for Inter-Aircraft-Communications, only the essential parts for showing the feasibility of these objectives were implemented. The ATENAA OOL validation platform consists of an Optical Ground Station (OGS) that serves as FT. The MT was mounted on top of an airplane simulator. This allowed the cost-effective evaluation of the technologies that are necessary to implement an actual aeronautical optical data link system.

The airport at the DLR premises in Oberpfaffenhofen, southwest of Munich, has been chosen as test site for the

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demonstration. An aerial map of the test site can be seen in Fig. 1.

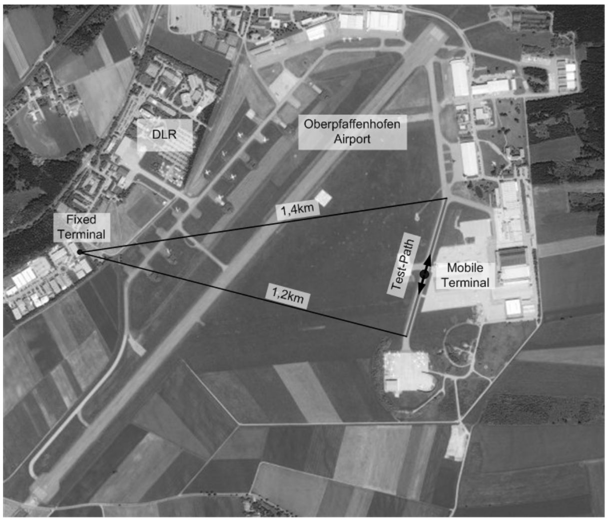


**Fig. 1: Aerial View of the test site that was chosen for the Outer Optical Link validation tests**

The intended test-path for the airplane simulator was Taxiway E. The distance between FT and MT can thus be found to be in the range between 1.2km and 1.4km. The Line-of-Sight (LOS) between the two terminals was sometimes blocked by poles or bushes in front of the FT.

## 2.2 Fixed Terminal [a]

### 2.2.1 Overview

In the ATENAA scenario the FT serves as transmission terminal. It has been implemented on base of an azimuth-elevation mount and carries the Tx-laser. For ease of use for the human operator a tracking camera has been added to the system so the operator can verify the tracking quality of the terminal. The tracking camera could also have been used for implementing closed-loop tracking using an optical feedback from the MT, but this has not been done. The following figure displays the FT.

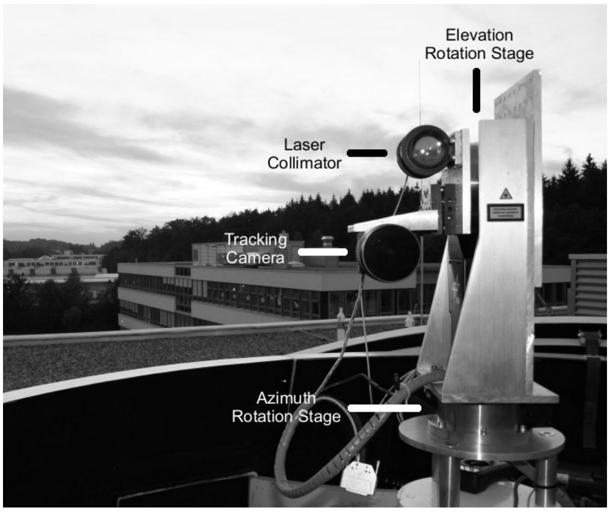


**Fig. 2: The demonstrator fixed terminal in the dome of DLR's ground station in Oberpfaffenhofen**

### 2.2.2 Pointing the Fixed Terminal

For pointing the terminal towards a target, three sets of information have to be known. These are the GPS coordinates of the fixed and mobile terminal as well as the fixed terminal orientation.

Because the terminal is fixed at its place its orientation and global position had only to be determined once. The position was already known from previous calibrations and the orientation could be determined using objects on the DLR premises of which the positions were also well known. The position of the MT has been transmitted from a GPS-Receiver on the MT via an RS232-RF-bridge to the FT. The used GPS-Receiver has been measured to produce a spherical error of less than 13 meters in 95% of the measurements. The update rate of the GPS-receiver is limited to 5 Hz which introduces an additional error due to the age of the received data at the MT. Based on the available information, the terminal calculates the pointing vector towards the partner terminal and targets the transmission beam at the MT. Additionally to this open-loop pointing of the terminal the operator has the possibility to add correction values to the system or to do the tracking by hand to be able to react on unforeseen situations or in cases where the RF-connection gets jammed. The design of the implemented automatic open-loop pointing system is shown in Fig. 3.

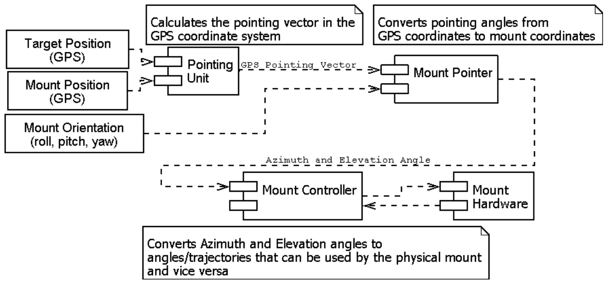


**Fig. 3: Structure diagram of the FT's open-loop pointing system**

For ensuring the correct pointing of the transmission beam the system has to be calibrated. This is done by pointing the terminal at a known location, e.g. a radar reflector, and to measure the received power at the target. Then the alignment of the transmission laser has to be adjusted to increase the power at the target to a maximum. To ensure a good alignment the target should be as far away as possible.

### 2.2.3 Pointing Accuracy and Divergence Angle of Transmitted Laser Beam

For a successful communication the Tx-beam has to illuminate the target despite the errors contained in the terminal pointing. This means that the full divergence angle of the Tx-beam has to be twice the angular error of the pointing. In the given scenario this angular error can be calculated from the error contained in the target's position information and the minimum link distance. For a link distance of 1500m, an update rate of 5Hz, a maximum velocity of the target of 20km/h and a spherical error in the position information of 13m the minimum divergence angle is 18.8mrad. Note that the response and command processing time of the tracking system (including mount hardware) has been neglected since it is in the range of only a few ms. To reduce the pointing error and also the needed divergence angle a prediction filter has been implemented that predicts the target position based on its position history. With this filter, the open-loop pointing accuracy has been measured to be better than 10mrad at the maximum distance of about 1400m. Accordingly, the divergence angle of the Tx-beam has been set to 15mrad to include some margin. To further reduce the pointing error it would be possible to change the tracking paradigm from position mode, i.e. adjusting the mount angles only when new target position information arrives, to velocity mode which means that a filter is used to guess the target's velocity and adjust the mount axes' velocities according to it. The following figure illustrates the problem when operating the transmitting terminal in position mode. It shows the spectral density of the measured received power at the MT. The peak at 5Hz caused by the update rate of the GPS receiver can clearly be seen.

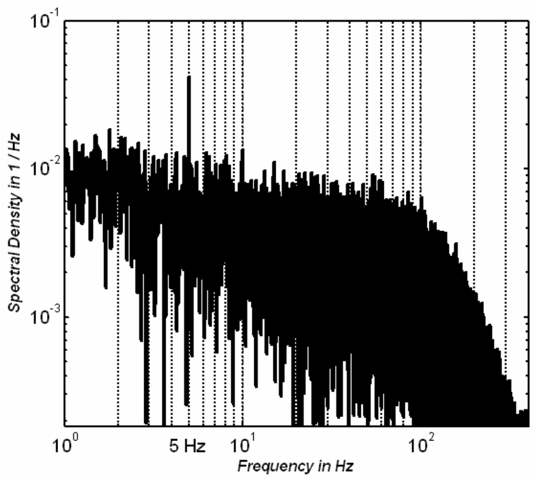


**Fig. 4: Spectral Density of the received power at the receiver. The peak at 5Hz is caused by the update rate of the GPS-receiver (The target position has a random error. Therefore the multimode-speckle transmit beam is moved with the update rate of the pointing around the target value. This produces a spectral line at 5Hz.).**

## 2.3 Mobile terminal [b,c]

### 2.3.1 Overview

The Mobile Terminal (as seen in Fig. 5) is composed of different functional assemblies responsible for acquiring and tracking the data laser and receiving and recovering the data transmitted from the Fixed Terminal.

**Fig. 5: Mobile Terminal**

The assemblies are (Fig. 6) the *Receiving Optical Assembly*, the *Optical Tracking Assembly*, the *Moving Platform*, the *Controller Assembly*, the *Position/Attitude Sensors*, the *Communications Subsystem* and the *Position Signaling RF Link*. Furthermore, the MT was equipped with a *Visual Acquisition Unit*.

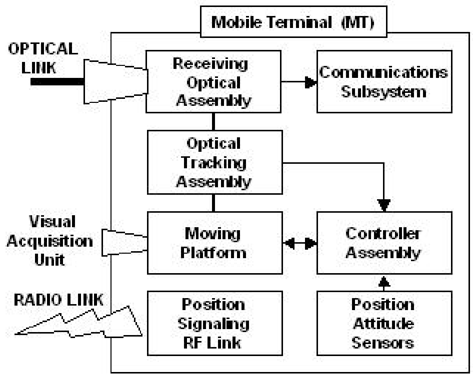


**Fig. 6: Block Diagram of Mobile Terminal (MT)**

In order to ensure a proper pointing in the direction of the FT during the initial acquisition phase, position and attitude sensors are used. Once the data signal of the FT is acquired, an optical closed loop tracking is enabled. In case of long communication losses, the position and attitude sensors are used for re-acquisition purposes. Short communication breaks, such as link outages due to LOS obscurations, are recovered by the Optical Tracking Assembly.

The Receiver Optical Assembly collects, splits and focuses the incoming laser radiation onto a CCD camera and onto an avalanche photodiode (APD), which is embedded in the Receiver Front End (RFE).

The focusing telescope (aperture 85 mm) has two different optical paths integrated in the same mechanical system. The incoming light is divided by a purposely designed beam splitter: 80% are available for the APD (data channel) while the remaining 20% are guided to the CCD camera's focal plane (PAT channel). Both optical paths are equipped with interferential filters centred on the operating wavelength (808nm).

The Optical Tracking Assembly processes and analyzes the video signal of the CCD sensor. It supplies the current tracking offset to the Controller Assembly of the Moving Platform. In order to keep the received light on the RFE's APD, an optical closed loop tracking has been implemented.

The Moving Platform is a mechanical mount based on two axes (elevation over azimuth). It is used to point the Receiving Optical Assembly (i.e. the telescope) in the commanded direction. A co-aligned video camera (part of the Visual Acquisition Subsystem) helped for manual pointing, excluding calculations based on the Attitude and Position Sensors.

The Moving Platform is controlled by the Controller Assembly, consisting of an Electronic Control Unit, including controller and drive modules for the servo and stabilization control of the Electro Mechanical Assembly. Furthermore, a PC capable of handling MT status information and managing all the operational roles is used.

A block diagram of the Mobile Terminal's controller can be seen in Fig. **7**.

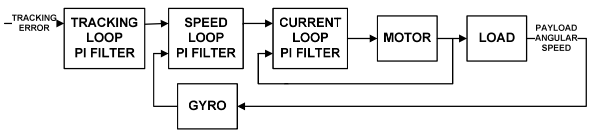


**Fig. 7: MT Controller Block Diagram**

During the tracking phase, the Mobile Terminal is controlled by a triple closed loop:

- The internal loop is a current loop - the current in the motor is controlled by an analogue PI type filter. The closed loop bandwidth of the current loop is about 500Hz. The power driver for the motor is a PWM controlled H bridge.
- The medium loop is a speed loop. This loop reads the gyro feedback and performs the stabilization of the platform. Again, an analogue PI type filter has been used. The output of the filter is the current required for the electrical motor
- The external loop is the tracking loop: it receives the output provided by the Optical Tracking Assembly (the tracking error) and calculates, by means of a digital PI type filter, the command to the platform

The two inner loops are performed inside the Electronic Control Unit, while the outer loop is performed on the PC.

### 2.3.2 Tracking Accuracy

In order to proof the function of the Validation Platform and to evaluate the tracking accuracy, the calculated position of the spot on the CCD Camera was logged. By comparing the deviations with the intended position (which is the center of the RFE), the performance of the system could be found.

The tests carried out involved in detail the CCD Camera, the Optical Tracking Assembly (i.e. the elaboration of the spot recognition algorithm and values of displacements as an output) and the Moving Platform Control Unit (effective displacements).

The misalignment between CCD and RFE has been identified with a detailed analysis of the Optical Tracking Assembly's output data in conjunction with the signal level at the RFE's output. The control system was designed to accomplish an optimum stabilization performance considering a van speed of 20 km/h.

An ideal system should automatically guarantee that the output of the RFE is maximal, if the laser spot is tracked to the center of the CCD's FoV. The experimental realization of such devices should instead consider eventual misalignment problems, e.g. due to the incorrect mounting of the photodiode on the Receiver's electronic board. A flexible system, such as this validation platform, includes the possibility to have an adjustment parameter for the possible offset between the center of CCD and RFE. A scanning pattern has been followed in order to identify the spatial offset between CCD and RFE. After the identification of this offset, the obtained coordinates were inserted in the Software of the Optical Tracking Assembly. This allowed tracking the received light onto the RFE.

A straight path trajectory has been used to test the OOL Validation Platform. The Mobile Terminal showed a good performance with driving speeds up to 40km/h.

Furthermore, the tracking performance has been evaluated by analyzing the output data of the Tracking Unit. Fig. 8 represents the laser spot's trace on the CCD's focal plane area.

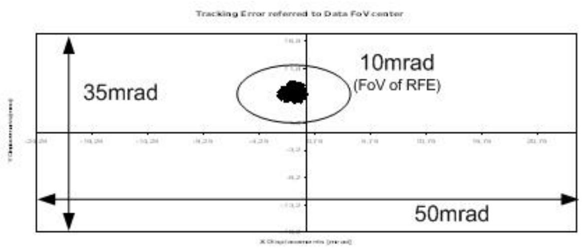


**Fig. 8: Tracking Error. This plot shows a scatter diagram of the measured spot positions on the CCD during tracking. The offset between the center of gravity and the center of the diagram can be justified by the misalignment between RFE and CCD. The whole Field of View of the CCD is shown.**

As shown in Fig. 9 and Fig. 10, the spot is well stabilized in a fixed position. The peaks in the histograms refer to the center of the RFE.

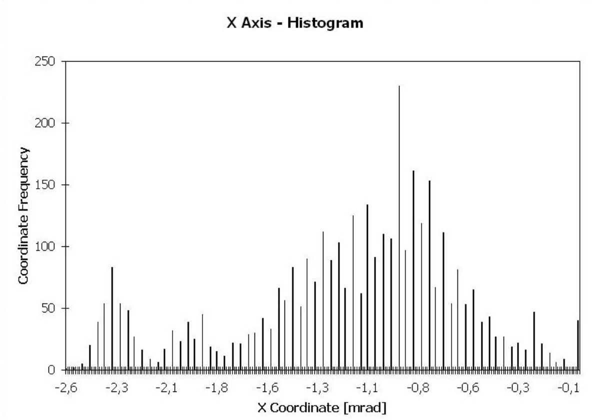


**Fig. 9: Histogram of X coordinate (azimuth). The plot represents the frequency of spot presence in a determined position. It can be seen that the stability is around -1mrad. Other significant data are: range (2.6mrad) and standard deviation (0.56mrad). The errors are less then 3mrad, what is around 3 times smaller than the Receiver's Field of View. The observed offset can be justified by the disalignment between RFE and CCD camera**

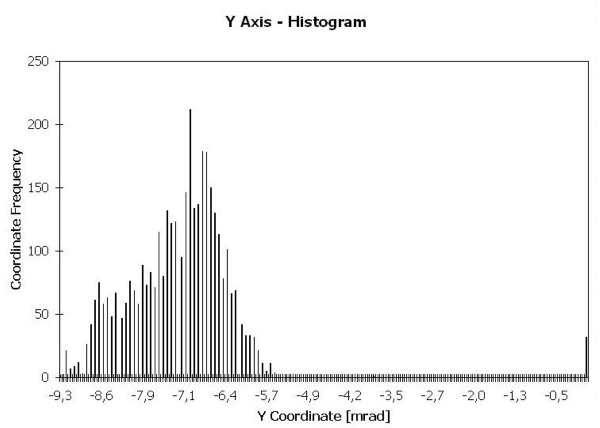


**Fig. 10: Histogram of Y coordinate (elevation). The plot represents the frequency of spot presence in a determined position. It can be seen that the stability is around -7mrad. Other significant data are: range (4mrad) and standard deviation (1.02mrad). The errors are less then 4mrad, what is smaller the the Receiver's Field of View. The observed offset can be justified by the disalignment between RFE and CCD Camera**

As a conclusion, the synergy of Tracking Unit and Moving Platform allowed to establish a stable optical link over a range of 1.2km to 1.4km. The Tracking and Stabilization accuracy has been shown to be in the range of 1mrad.

## 2.4 Optical Communication System [a]

### 2.4.1 System Overview

The optical communication system can be divided into transmitter and receiver. Block Diagrams for both parts are provided in Fig. 11 and Fig. 12.

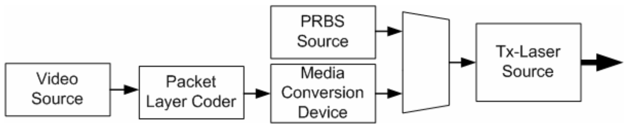


**Fig. 11: Tx Block Diagram**

The Transmitter consists of a Video Source, whose data is fed into the Packet Layer Coder that applies a transport layer forward error correction scheme to the data. Afterwards the data is guided to a Media Conversion Device, which performs the conversion from asynchronous Ethernet Data to a synchronous signal that is sent via the optical link. Optionally, a Pseudo Random Bit Sequence (PRBS) can be sent over the optical link.

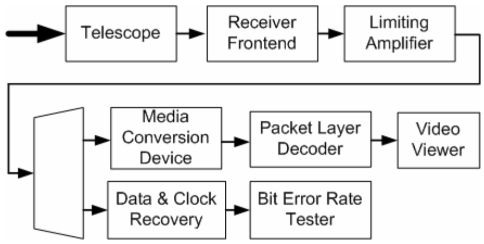


**Fig. 12: Rx Block Diagram**

The Telescope on the receiver's side gathers the light that has been sent by the Tx-laser, while the receiver front end (RFE) performs an electro-optical conversion. The limiting amplifier acts as data slicer. Subsequently, a Media Conversion Device accomplishes the conversion between the received synchronous data stream to an asynchronous Ethernet data stream. Finally, the Packet Layer Decoder extracts the user data from the stream and the signal of the video source can be seen on the viewer. The Data and Clock Recovery together with the Bit Error Rate Tester (BERT) allows to measure bit errors rates (BERs) whenever a PRBS is sent. This is helpful to evaluate the current conditions of the optical channel.

### 2.4.2 Transmission Performance

Mobile FSO mainly suffers from relatively long link outages, produced by temporary obscured laser-beams, pointing- and tracking-errors or deep signal-fades caused by index of refraction turbulence effects [1,2]. It is well known that the correlation time of the signal variations in FSO can be shown to be on the order of a few milliseconds [1]. The received power coupled in the receiver has been sampled (10kS/s) during the ATENAA trials and one example is given in Fig. 13. The figure shows one second of a received power vector. The power vector is showing signal fading and signal surges caused by index of refraction turbulence superposed with tracking errors. Further total link-blockings produced by lantern masts can be observed. The vector was measured while the MT was moving with 20 km/h on a straight trajectory.

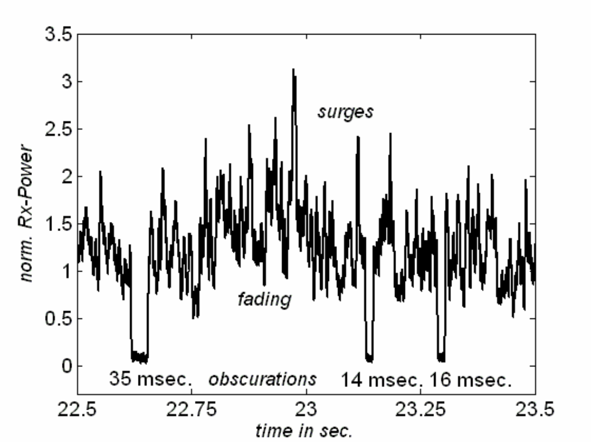


**Fig. 13: Power vector of received power on MT during movement of MT with 20 km/h. Power vector shows fading, surges and link obscurations produced by PAT and index of refraction turbulence. The power spectrum of the whole measurement can be seen in Fig. 4.**

During the first trials the bit error rate was measured when the MT was standing still about 1400m away from the FT and tracking was running automatically on both sides. With 500mW (mean) transmit power the transmission of the 125Mbit/s signal was error free (no error observed within the measurement interval of 1second). The weather conditions on the test day were: overcast, partly sunny, wind 2kt SW, RH 81%, temperature 5°C, area was partly covered by snow, some light rain showers. Visibility was reported by the airport tower to be greater than 10km. It can be assumed that only weak atmospheric fading is produced at such stable air temperature conditions.

Further tests were made under operational conditions. The van carrying the MT was driving on a taxiway continuously forward and backward on a non predictable trajectory with speeds up to 25km/h. Weak fading of 3 to 4dB was observed (compare Fig. 13).

The Fading resulted from:

- Index of Refraction Turbulence (little influence, as mentioned above)
- A multimode-speckled beam is sent by the FT (up to 3dB fading because of moving speckles over the receiver aperture)
- Receiver Tracking Accuracy (medium influence)

Long term bit error rate measurements were made. When the PAT system was working stable and no link blockings were present a bit error rate of $10^{-6}$ was observed. With link blockings the long term bit error rate was measured to be $10^{-2}...10^{-3}$ depending on the frequency and duration of link-blockings.

It has to be pointed out that synchronous transmission strongly suffers from link-blocking because the resynchronization times make the link outages longer than the physical obscuration time is. Frequent link blockings with the needed resynchronization demand asynchronous transmission schemes with inherent synchronization before each transmitted packet or frame.

### 2.4.3 Error Protection System

Large differences between channel coherence time and bit duration in the (A)FSO channel causes problems if working with physical-layer coding to mitigate link blockings and fades. Interleaving over some milliseconds to seconds is needed in order to avoid erasure of whole codewords during fades. For high data-rates these interleavers are technically not feasible. Packet-layer coding, e.g. on transport layer, makes it possible to generate codewords that are longer than fades. Depending on the datarate the code-symbol length will be in the same order as fade-duration [1,2].

Fig. 14 shows the implemented packet-layer (transport-layer) coding system setup. A DVD-video was streamed via Fast-Ethernet (IP and UDP) over an FSO-bridge to a special destination. The FSO-bridge uses UDP-packet based packet-layer coding. Further the bridge implements media-conversion devices (MCD) which are interfacing Ethernet and the simplex on-off-keying (OOK) optical communication system [3]. Thanks to the error protection during transmission lost packets can be recovered. The receiver side of the bridge sends the video stream to a streaming monitor computer.

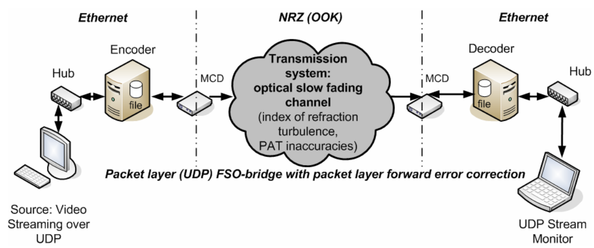


**Fig. 14: Overview over the coding system (MCD: media conversion device)**

### 2.5 Collection of technical data [b,c]

| | |
|---|---|
| Position Attitude Sensors | |
| DGPS Garmin, 18Hz (accuracy better than 15m)<br>AHRS: MTi-DK Xsens (static accuracy better than 0.5°) | |
| Receiver Optical Assembly | |
| Aperture | 85mm |
| Data Channel FoV | 10mrad |
| Background Light Filter Bandwidth | 20nm |
| Optical Tracking Assembly | |
| Update rate | 5 Hz; 25fps (PAL input) |
| Tracking Accuracy | 1-3 pixels in both directions (1σ) |
| Resolution | 720x576 pixel |
| PAT FoV | 48mrad |
| Overall PAT Accuracy | 1.5mrad (1σ) |
| Moving Platform (Mass Stabilization) | |
| Two axes, elevation over azimuth | |
| Angular Coverage | 300° azimuth<br>5° elevation |
| Angular Velocity | Azimuth ≥ 100mrad/s<br>Elevation ≥ 100mrad/s |
| Angular Acceleration | Azimuth: ≥ 200mrad/$s^2$<br>Elevation: ≥ 200mrad/$s^2$ |
| Stabilization Accuracy | Stabilization error better than 0.8mrad |
| Tracking accuracy | Tracking error better than 1.5mrad (1σ) |
| Communication Subsystem | |
| Laser Transmitter, fiber coupled | Operational wavelength: 808 nm |
| | Power: 1W (CW) |
| | Divergence: 15mrad |
| Receiver Front End (RFE) | APD and TIA based |
| | Sensitivity: ~6000ph/bit; 125Mbit/s |
| | Dynamic: 20dB;<br>Vout: min 50$mV_{pp}$; max 3.5$V_{pp}$ |
| | APD: Diameter: 0.5mm<br>Responsivity: 128A/W @ 900nm |
| Data Recovery Unit | Input Sensitivity: 9$mV_{pp}$ |
| | Catch Range: 82-162Mbit/s |

## 3 OUTLOOK TO MINERVAA [a]

The objective of the ATENAA-Project was to prove the feasibility of several emerging technologies that are required for future airborne optical link systems. As described in this paper, the readiness of this technology has been successfully shown by the completion of the OOL validation tests.

However, the researched technologies need to be improved in order to become a commercial product. This enhancements will be accomplished during the follow-up project MINERVAA[9].

MINERVAA will aim on the development of a real airborne communication terminal and complete with a flight-test campaign in 2009.

## 4 CONCLUSIONS [a]

A technology validation platform for optical free space communication applications in the aeronautical environment has been developed. This included the construction of hardware that served as fixed and mobile terminal, as well as the utilization of packet layer forward error correction schemes to overcome some inherent restrictions of optical links. The development process was finalized with a test campaign that proved the principal operability of the system.

## 5 LIST OF ACRONYMS AND ABBREVIATIONS

| | |
|---|---|
| AFSO | Aeronautical Free Space Optical |
| AHRS | Attitude Heading Reference System |
| APD | Avalanche Photodiode |
| BER | Bit Error Rate |
| CCD | Charge Coupled Device |
| DVD | Digital Versatile Disc |
| FEC | Forward Error Correction |
| FoV | Field of View |
| FT | Fixed Terminal |
| GNSS | Global Navigation Satellite System |
| GPS | Global Positioning System |
| HAP | High Altitude Platform |
| IP | Internet Protocol |
| LOS | Line Of Sight |
| MANET | Mobile Ad-Hoc Network |
| MCD | Media Conversion Device |
| MT | Mobile Terminal |
| OGS | Optical Ground Station |
| OOK | On-Off Keying |
| OOL | Outer Optical Link |
| PAT | Pointing, Acquisition and Tracking |
| PRBS | Pseudo Random Binary Sequence |
| PWM | Pulse-Width Modulation |
| RF | Radio Frequency |
| RFE | Receiver Front end |
| UDP | User Datagram Protocol |

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