Abstract:
In order to design reliable inter platform-, platform to satellite-, and optical downlink terminals, stratospheric tests are necessary. The Capanina Stratospheric Optical Payload Experiment (STROPEX) is one step in this direction in terms of gaining system performance experience and gathering atmospheric index-of-refraction turbulence data. The experiment is focused on experimental verification of the chosen acquisition, pointing, and tracking systems, measurement of atmospheric impacts (turbulence) and successful verification of a broadband downlink from a stratospheric testbed (HAP/balloon/aircraft).
In the first part, this document introduces the Freespace Experiment Laser Terminal (FELT) which was built for the CAPANINA STROPEX. Subsystems are explained briefly. The second part describes the results of the fully successful stratospheric experiment with the first known optical 1.25 Gbit/s downlink form the stratosphere.

Keyword list: free space optics, stratospheric optical payload experiment, optical terminal, refractive index effects
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EXECUTIVE SUMMARY

Laser free-space communications technology has a major potential to complement RF and microwave technology for the backhaul traffic. In order to design reliable inter-platform, platform to satellite, and optical downlink terminals, stratospheric tests are necessary. The Capanina Stratospheric Optical Payload Experiment (STROPEX) is one step in this direction in terms of gaining system performance experience and gathering atmospheric index-of-refraction turbulence data. It is not within the scope and budget of the project to design a commercial optical terminal for future high altitude platform (HAP) links. The program is focused on experimental verification of the chosen acquisition, pointing, and tracking systems, measurement of atmospheric impacts (turbulence) and successful verification of a broadband downlink from a stratospheric testbed (HAP/balloon/aircraft).

The STROPEX development and hardware constructions were based on previous free space optical experiments, theoretical calculations, technical literature searches, broad market analysis, and program constraints. Proven hardware and concepts were incorporated into the design whenever possible. When proven hardware and concepts were not available or feasible, research and studies were accomplished to reduce the risk of the chosen concept or hardware design as much as possible. Due to budget and time constraints, it was essential to design STROPEX using commercial off the shelf components whenever possible or where custom made parts would not have a clear advantage. Due to environmental conditions and other constraints (pointing requirements, weight boundaries, size, specific needs...) it was necessary to manufacture numerous other parts. The main design constraints were the stratospheric environmental conditions with temperatures down to –70°C and near-vacuum; high balloon rotation speeds of up to 9 rotations per minute; lightweight and streamlined design for a possible trial with an aerodynamic HAP; and ability of an autonomous and robust ground station acquisition in the presence of strong background light (sun reflections in lakes).

Within a design, implementation and test phase of less than one year, prototype subsystems were developed and tested, numerous thermal vacuum chamber tests were carried out, and several thousand lines of program code were implemented into the two onboard computers of the terminal. The final STROPEX design which can be seen in the picture below was able to meet all Trial 2 objectives.

The stratospheric experiment was launched on the night of 30.08.2005 with a 12000 m³ altitude controlled balloon. Immediately after the takeoff, the optical ground station tracked the balloon via open loop GPS-tracking. The GPS position of the FELT was down linked via the mm-wave telemetry service link. After 70 minutes, the balloon reached the targeted altitude of 23 km. The laser beacons of the ground station were switched on. Then the optical terminal on the balloon received initial nadir angle information from the ground station control computer in order to shorten the scan time during acquisition.

With a selected scan speed of 10º/s, the acquisition process lasted 20 seconds when the FELT tracking system was locked. The FELT-beacons were switched on and illuminated the ground station (see picture below, left). Then the ground station changed form GPS tracking to the closed loop optical tracking and kept the balloon beacon within the field of view (FOV) of the ground station's communication receiver, which was 100µrad. Finally, the 1550 nm communication system of the terminal was activated via the telemetry link and the data transmission tests started.

The high signal to noise ratio enabled a bit error rate (BER) of less than 10⁻⁹ within an unlimited measurement interval at a bit rate of 622 Mbit/s. Frequently, the BER went down to 10⁻¹⁰ for several
minutes. This high quality signal was received up to a maximum distance of 64.15 km from the ground station (see lower middle picture). This was the distance at which the pilot succeeded in manoeuvering the balloon to a stratospheric layer with a wind direction that brought the balloon back nearer to the launch site. The minimum elevation angle at 64.15 km was about 21 degrees. The 622 Mbit/s eye pattern can be seen in the picture below (middle).

The 1.25 Gbit/s transmission was also successful. Due to the limited bandwidth of the bit error rate test receiver, no direct BER measurements could be performed at 1.25 Gbit/s. The eye pattern of the received 1.25 Gbit/s can be seen in the picture below (right).

Ground station tracking camera picture of the stratospheric test-bed after successful acquisition (left) and received 622 Mbit/s data signal with bit error rate (middle) and received 1.25 Gbit/s data signal. The range is approximately 60 km.

During the major part of the 8.5 hour trial the communication link between the FELT and the ground station was activated and worked perfectly. During the rest of the time several acquisition experiments have been performed.

With special instruments at the ground station, the atmospheric turbulence effects have been investigated. The turbulence profiler measured the fluctuations of the received intensity as well as the mean size of the intensity speckles which was around 3.5cm during the whole trial. By means of the scintillation theory, the turbulence profile along the 60-km path was recovered from the intensity spatial covariance function (see left figure below). Turbulence is represented with the refractive-index structure constant $C_n^2$ along the link path, which is a measure of the strength of turbulence or energy within the turbulence.

The coherence length $r_0$ was derived from the spatial statistics of phase fluctuations within the pupil plane of the receiver. This was done by evaluating the differential image motion of two spots. The estimation of the $r_0$ parameter from the DIMM over the daytime is shown in the right graph below. Around 8:00, we note that the coherence length was larger (i.e., better) than earlier or later in the morning. In parallel we observe a drop of the scintillation index near 8:00. This decrease of the atmospheric turbulence level around 8:00 corresponds approximately to the sunrise which is known to provide a turbulence minimum in the lower atmosphere.

CAPANINA STROPEX, the first known optical downlink from the stratosphere, was a complete success!
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<td>BER</td>
<td>Bit Error Rate</td>
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<tr>
<td>BSC</td>
<td>Beam Splitter Cube</td>
</tr>
<tr>
<td>BSS</td>
<td>Balloon Service System</td>
</tr>
<tr>
<td>PA</td>
<td>Pointing Assembly</td>
</tr>
<tr>
<td>CVS</td>
<td>Compact Vision System</td>
</tr>
<tr>
<td>CW</td>
<td>Continuous Wave</td>
</tr>
<tr>
<td>DD</td>
<td>Direct Detection</td>
</tr>
<tr>
<td>DIMM</td>
<td>Differential Image Motion Monitor</td>
</tr>
<tr>
<td>EDFA</td>
<td>Erbium Doped Fibre Amplifier</td>
</tr>
<tr>
<td>EIRP</td>
<td>Equivalent Isotropic Radiated Power</td>
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<td>FELT</td>
<td>Free-space Experimental Laser Terminal</td>
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<td>Field of View</td>
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<td>Free-space Optics</td>
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<td>Global Positioning System</td>
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<td>High Altitude Platform</td>
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<td>HAP Control Software Package</td>
</tr>
<tr>
<td>HAPPRO</td>
<td>HAP Processing System</td>
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<tr>
<td>IM</td>
<td>Intensity Modulation</td>
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<tr>
<td>LAN</td>
<td>Local Area Network</td>
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<tr>
<td>NEP</td>
<td>Noise-equivalent power</td>
</tr>
<tr>
<td>PAT</td>
<td>Pointing, Acquisition, and Tracking System</td>
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<tr>
<td>RFE</td>
<td>Receiver Front End</td>
</tr>
<tr>
<td>ROI</td>
<td>Region of Interest</td>
</tr>
<tr>
<td>Rx</td>
<td>Receiver</td>
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<td>Transportable Optical Ground Station</td>
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</tr>
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1. Introduction

1.1 The CAPANINA goal

Communication from High Altitude Platforms (HAPs) has the potential to fill the gap between terrestrial and satellite communication. Aerodynamic aircraft or aerostatic platforms hovering quasi-geostationary at an altitude of 18 to 25 km could combine the advantages of both established infrastructures. Some advantages include short deployment time and easy equipment upgrade, flexible capacity increase through spot-beam re-sizing and additional platforms, ability of substantial indoor coverage, and a geographical coverage of hundreds of kilometers. The European CAPANINA project is developing communications technologies for use with aerial platforms with the aim of delivering “broadband for all.” The emphasis is on hard-to-reach users and those disadvantaged by geography [i], [ii].

1.2 Application of Free-Space Optics

Services like fixed broadband wireless access up to 120 Mbit/s to an end user or to users traveling at high speeds (e.g. in a train) require a broadband backhaul network [iii]. Free-space optical (FSO) communication technology has a major potential to complement microwave technology for the backhaul traffic. High attenuation due to clouds for communication wavelengths used today is not a limiting factor for inter-platform and platform to satellite links. These links are the main application of HAP-FSO. Due to a maximum cloud ceiling of 13 km for mid-latitude locations, inter platform link distances of up to 900 km are possible with 100% availability [iv]. For the optical downlink, large scale cloud cover diversity techniques can be used to supplement the microwave downlink and save platform power during FSO terminal operation. Beside the high data rate and low power consumption, the system parameters of the optical downlink beneficial for HAP systems include also the small aperture size and the modest terminal weight.

In order to design reliable inter platform-, platform to satellite-, and optical downlink terminals, stratospheric tests have to be performed. The Capanina Stratospheric Optical Payload Experiment (STROPEX) is one step in this direction in terms of system performance experience and measurement data.

1.3 STROPEX objectives

In order to design reliable future optical terminals, stratospheric tests are necessary. It is not within the scope and budget of the project to design a commercial optical terminal for future HAP links which is optimised for serial production already. The scope of STROPEX is focused on experimental verification of acquisition pointing and tracking systems and algorithms and verification of a broadband downlink from a stratospheric testbed (balloon/HAP). Several design trade-offs are possible, adapted to the needs of the downlink experiment.

The overall program objective is to evaluate/test the free space optics technology for the delivery of broadband backhaul links on aerial platforms.

The stratospheric trial 2 primary objectives include:

- Measurement on the optical downlink channel. Index-of-refraction effects are one of the main interests. Detailed knowledge of these effects and spatial redistribution of irradiance is important for assessing the atmospheric impact on free-space optical communication systems. These parameters will be measured with turbulence instruments.
- Data transmission on the optical downlink channel. This will be established in parallel to the channel measurements.

This document is divided into 2 main sections:

- Setup of the experiment and description of the Free-space Experimental Laser Terminal (FELT) subsystems
- Results of STROPEX (CAPANINA stratospheric campaign, T2)
2. SYSTEM DESCRIPTION

The overall system concept for STROPEX was to mount a free-space optical terminal (FELT) on a stratospheric balloon that would fly to an altitude of approximately 22 km. A downlink would then take place between the FELT and a Transportable Optical Ground Station (TOGS) as depicted in Figure 1.

2.1 System Concept

An overview of the overall system can be seen in Figure 2. It shows a block diagram highlighting the components included.
The optical communication transmission occurred only on the downlink (i.e. from the FELT to the TOGS) whereas a RF RS422 link was used to communicate with and operate the FELT. The left box in the Figure shows the optical free-space experimental laser terminal (FELT). The beacon and communication wavelengths are transmitted from a single-mode fibre by use of a collimating lens. An optical periscope is used for mechanical beam steering. The ground station in the right box consists of a 40cm Cassegrain telescope and attached optical system, the front end for communication, the pointing, acquisition, and tracking system (PAT), and two instruments to monitor the atmospheric turbulence (DIMM and turbulence profiler).

2.2 Modulation Scheme for CAPANINA STROPEX

Intensity modulation (IM, on/off-keying) with direct detection (DD), which is widely used in terrestrial fibre-optical transmission and was already successfully tested in Trial 1, has the advantage of using a range of components with proven reliability (e.g. laser diodes, fibre amplifiers and detectors). Theoretically, 10 incoming photons per bit (mean) are sufficient for an un-coded bit-error-rate (BER) of $10^{-9}$. However, in practical systems using standard APD-detectors (avalanche photodiode), the receiver sensitivity is usually not better than 500 Photons per bit. This is due to thermal receiver noise and other degrading electronic effects. Another disadvantage is the susceptibility to background radiation from celestial bodies or clouds that are located in the line-of-sight behind the transmitter, which causes additional shot-noise on the detector. This can be reduced by lossy optical filters and narrow field of views of detectors.

Coherent transmission systems (e.g. BPSK homodyne) for HAPs in the stratosphere are feasible with sophisticated techniques and would provide an extra margin of 10 dB compared to IM/DD. The effect of background radiation can also be neglected due to the extremely small noise bandwidth of the homodyne receiver which is in the order of the data-bandwidth. Due to the complex system architecture, BPSK was not the primary candidate for STROPEX.

In principle, pulse-position-modulation (PPM) would be the most efficient optical transmission scheme. However, constraints in laser technology (limited repetition time of consecutive pulses) and the susceptibility to background radiation prevent its implementation for high bit rate systems.

Intensity modulation (IM, on/off-keying) with direct detection (DD), common in terrestrial fiber-optical transmission, was the chosen transmission scheme. An IM/DD scheme is advantageous because there are a range of available components with proven reliability e.g. laser diodes, fiber amplifiers, detectors and receiver electronics. According to theory, 10 incoming photons per bit (mean) are sufficient for an un-coded bit-error-rate (BER) of $10^{-9}$. However, in practical systems using standard APD-detectors (avalanche photodiode), the receiver sensitivity is usually not better than 500 Photons per bit due to thermal receiver noise and other degrading electronic effects. The actual sensitivity of the front end developed for STROPEX was measured at 168 Photons per bit at a data transmission rate of 1.25 Gbit/s and a bit error rate of $3 \times 10^{-7}$.

2.3 Atmospheric attenuation effects and selected wavelength

The analysis and simulation of atmospheric attenuation was essential for the selection of communication and beacon wavelengths. The spatiotemporal change of atmospheric attenuation along an optical path is very slow. Therefore, the attenuation, especially in higher altitudes over 13 km, is predictable very accurately. At such altitudes, the atmospheric attenuation is mainly caused by volcanic ash.

Figure 3 shows the total attenuation for the STROPEX experiment, containing molecular, Rayleigh-, aerosol- and water-vapour-continuum-absorption. The spectral graphs were produced using the height profile of atmospheric constituents in the data base after AFGL vi,vii assuming moderate background volcanic activity. The wavelength span between 1545 nm and 1565 nm is not affected by the dominant molecular absorption lines. Therefore the STROPEX communication wavelength of 1550 nm is very suitable for broadband communication in the atmosphere. The background absorption for this wavelength is about 0.3 to 0.6 dB for the downlink. This spectral window around 1550 nm is also suitable for future
wavelength division multiplexed systems. A system with 100 GHz channel spacing (0.8 nm) for instance, would allow 25 channels.

Care had to be taken in selecting of the downlink beacon laser wavelength. On one hand, the radiation of the beacon has to meet the requirements for being guided in the coupler’s fiber as a single mode. Therefore the wavelength could not be decreased below the cutoff wavelength of the fiber. On the other hand, the beacon wavelength should be as close as possible to the most sensitive wavelength of the ground station tracking camera. This is around 800 nm. A beacon wavelength of 986 nm would meet both requirements; we note that this would have been also the common wavelength for pump diodes of optical amplifiers.

![Figure 3: Total attenuation for stratospheric optical downlink. Both diagrams show the primary interesting wavelength region between 600 and 1650 nm for atmospheric optical communication. The left diagram shows the overview plot with a dynamic range of 100 dB. The atmospheric spectral windows outside the broadened absorption lines can be easily seen for three different elevation angles of the stratospheric downlink. The transmitter altitude is 22 km. The right diagram shows the same spectral plot with other scaling (6 dB). The decrease of background attenuation with increasing wavelength is caused by Rayleigh scattering.](image-url)
By investigating the lower edge of the 980 to 1200 nm atmospheric spectral window more precisely (see Figure 4), we found out that the wavelength of 986 nm would be a good compromise without high water vapor attenuation but with a moderate absorption value. This value would have caused an attenuation of 4 dB for a downlink from 22 km with a 90 degree elevation.

In order to use the most perfect wavelength, a design of stabilized beacon diodes with spliced fiber Bragg gratings operating at wavelengths of 977.8 nm and 978.6 nm has been commissioned and used (see 2.4.3).

Finally the TOGS used beacon lasers at 810 nm to illuminate the FELT. The FELT used a communications laser at 1550 nm.

### 2.4 Free Space Experimental Laser Terminal (FELT) design

The Free-space Experimental Laser Terminal (FELT) is an optical transmission terminal developed mainly for the CAPANINA stratospheric experiments. The following were the primary design constraints for the FELT:

- Stratospheric environmental conditions (temperatures down to $-70^\circ$C and near vacuum conditions)
- High balloon rotation speeds (9 rotations per minute, see 2.4.1)
- Lightweight and streamlined design for future trials with an aerodynamic HAP
- Autonomous and robust acquisition capability in the presence of strong background light

In under a year, the FELT was designed, built, tested, and flown. This included numerous subsystem prototype developments, thermal vacuum chamber tests, and the development of several thousand lines of program code that was implemented into the two onboard computers of the terminal\(^1\). Before flight, the overall system was tested for a month at a 28 km test range in the Bavarian Alps.

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\(^1\) FELT software description is not part of this document. TMTC control software screen shots are explained in 2.4.8
Figure 5: Assembly Photo of FELT with opened carbon fibre housing (left) and the ready to fly terminal (right) before payload integration.

The final FELT design is shown in Figure 5 with a side access panel removed (left picture). The structural subsystem consisted of an aluminium base plate which was also used for passive thermal control. The objective design weight was 25 kg and the final terminal weight was 17.54 kg thanks in part to the payload housing developed by project partner Carlo Gavazzi Space SpA. The housing consisted of a carbon fiber sandwich structure that reduced weight and maximized thermal insulation properties. Additionally, the housing was designed to easily interface with an aerodynamic HAP (i.e. a stratospheric airplane).

Figure 6: CAD sketch of FELT – Bottom side.

Figure 6 shows the bottom side of the mounting plate, where the electrical power subsystem along with the beacon laser diodes and their supporting electronics (diode drivers and thermal control) were mounted. For redundancy, the FELT used two independent co-aligned beacon systems at 977.53 nm and 977.8 nm, each with 200 mW output power. One of the beacons was coupled with the 1550 nm signal light and used the same transmission optics. The pointing assembly consisted of a 2-axis optical periscope along with the supporting encoders, DC motors, and motor drivers. Five DC-DC converters were also mounted on the bottom side of the plate. The balloon power system provided a 28 V and 24 V power source for the FELT which was converted to ±3.3V, 5V and 12V.
The components mounted on top of the plate can be seen in Figure 7. An onboard Telemetry and Tele-Command (TMTC) subsystem (see 2.4.4) enabled control of the terminal via RS422 connection and included the monitoring of 16 temperature probes. The signal electronics generated a pseudo random binary sequence (PRBS) with a sequence length of $10^{23} - 1$ and an adjustable data rate of up to 1.25 Gbit/s. This data source drove a laser diode module with 1 mW output power which was optically amplified to a transmission power of 100mW. The beam was routed into the pointing assembly via the optical assembly, which consisted of the laser collimators, optical components, and the fast CMOS tracking camera with a 4° FOV [viii]. The pointing assembly was controlled by the FELT Pointing Acquisition and Tracking (PAT) computer. The PAT computer took inputs from on-board gyroscopes, the tracking camera, and the periscope encoders and controlled the motion of the pointing assembly.

The FELT characteristics are summarized in Table I.

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<tr>
<td>Mass</td>
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<tr>
<td>Power Consumption</td>
<td>&lt; 75 Watts</td>
</tr>
<tr>
<td>Communication Rate</td>
<td>Up to 1.25 Gbit/second</td>
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<tr>
<td>Pointing Resolution</td>
<td>8.72 µrad</td>
</tr>
<tr>
<td>Laser wavelengths</td>
<td>9xx nm (beacon)</td>
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<tr>
<td></td>
<td>1550 nm (communication)</td>
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<tr>
<td>Power busses</td>
<td>±3.3V, 5V and 12V</td>
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**Table I: FELT Characteristics**

### 2.4.1 Pointing assembly subsystem

Due to the narrow beam divergence angles typical in FSO systems active pointing and tracking is very essential. The requirements for the pointing assembly are mainly depending on the attitude behaviour and base motion disturbance (vibration) of the optical terminal carrier. In our case the stratospheric carrier or testbed is a stratospheric balloon (see 3.2). The payload platform on the balloon has two basic movements, a rotation (spinning balloon) in yaw, and pendulous movements in roll and pitch. Requirements for the pointing assembly have been derived from the balloon experiments MIPAS [ix] and are shown in Table 2 and Table 3.
Max. angular velocity of flight platform in yaw 54 deg/s
Max. rotation of flight platform per minute 9 1/min.

| Table 2: Assumed Movement of Flight Platform for pointing assembly design |
|---|---|
| Peak at ~0.75Hz with max. Angles | ±2 Deg |
| Peak at ~0.05Hz with max. Angles | ±2 Deg |

| Table 3: Pendulous Movement in Roll & Pitch |
|---|---|
| Resolution | 8.72 µrad |
| Velocity | 240 and 120°/sec |
| Acceleration | > 250°/sec² |
| Rotation limits | No rotation limits for both axes |

Several approaches were investigated for the pointing assembly, including gimbals, voice coil actuators or galvanometers, and turret-type systems. Analysis and market research has shown that the unexpectedly high balloon yaw rotation of 9 rpm is a very difficult design criterion for precise gimbaled systems. All systems within the price range considered are limited in either the achievable resolution or the maximum speed. Also, the required angular range of at least ±70 deg due to the expected balloon drift and pendulous motion is not possible for most systems. Conversely, most off-the-shelf systems which achieve the specified requirements can’t cope with the stratospheric conditions and high performance systems which meet all requirements (military turret systems) exceed the budget and weight boundaries and have a too high counter torque because of the moved mass in relation to the lightweight CAPANINA payload. Considering all the facts, it has been concluded that no off-the-shelf system meets the requirements for the pointing assembly. Therefore, a proprietary development is necessary.

Acquisition of the ground station must be possible at the worst-case spin rate of the balloon. Together with the necessary angular system resolution for accurate tracking, the balloon spin rate was the main driving factor of the pointing assembly design which resulted in a two-axis optical periscope. The CAD design of the pointing assembly is shown in Figure 8. The final parameters are shown in Table 4.

![Figure 8: Back view of pointing assembly with 50 mm aperture duct (left) and side view with cover](image)

Resolution | 8,72 µrad |
Velocity | 240 and 120°/sec |
Acceleration | > 250°/sec² |
Rotation limits | No rotation limits for both axes |
2.4.2 Optical Assembly

The FELT optical system consists of the tracking camera aperture for the incoming ground station beacon and the fibre-coupled transmission system. A sketch can be seen in the left part of Figure 9. Compared to the initial design with a chromatic beam splitter cube, this design features a relatively simple system layout. The challenge in the design was that the optical axis of the transmission systems and tracking system keep their precise co-alignment with a maximum tolerable deviation of 100 µrad (0.0057 deg) within a temperature range of 120°C (-70 to +50°C)! A tempered aluminium alloy has been used to mill the optical assembly part. Numerous tests with different glues for the fibre collimators were necessary to solve the co-alignment problem. One of the prototype systems during the assembly process can be seen in Figure 9 (right).

![Figure 9: schematic sketch of optical assembly (left) and the machined part during assembly of fibres (right)](image)

2.4.3 Beacon System

The FELT uses two beacon systems for tracking purposes. One system is for redundancy. A photo of a beacon system can be seen in Figure 10. The laser diode in a cooled 14-pin butterfly package is mounted in the diode holder. The holder is built in such a way that one part of the power dissipation is radiated and the other part is conducted into the base plate.

The diode holder is connected with the temperature control electronics and the diode power control unit.
2.4.4 Telemetry & Telecommand (TMTC) / Onboard Ethernet

In principle, the FELT is designed for autonomous and automatic acquisition and tracking of the ground station. A TMTC system has been implemented into the design for the following purposes:

- To establish a feedback channel to the ground station in order to know what is going on in the stratosphere (rotation speed of the stratospheric carrier, status of the FELT…).
- The enable subsystem temperature feedback
- To activate and switch off the FELT subsystems (saving of energy for a possibly long mission)
- To gear up the acquisition process (shorter acquisition phase when ground station elevation angle is available for the FELT)
- To enable at least a few software control possibilities from the ground (restart acquisition, upload a few tracking parameters, reboot the FELT computer systems in case of unforeseen software behaviour…)
- …

For these purposes, the FELT is equipped with a 10 Mb/s onboard Ethernet which connects all interface devices, the mechanical pointing assembly, and the tracking computer system CVS. An Ethernet to Rx-422 Bridge connects the onboard Ethernet Hub with the Balloon/HAP service system (BSS) which provides the transparent radio link to the ground station (Note: The BSS is provided by CGS. A block diagram of the total system can be seen in Figure 11. The Ethernet I/O modules are small microcomputers which are used to control the communication system by use of digital output ports. This allows the data rates and the data source to be selected. The laser module as well as the optical amplifier can be switched on and off. Several input ports of the I/O modules enable temperature control as well as the control of basic parameters of the communication system

By using the Ethernet protocol, we ensured that no additional error correction for the ground station RF link is necessary. This error correction is implemented in the Ethernet protocol. This error correction guaranteed error free communication with the ground station via the transparent RS 422 Bridge. However, this error correction scheme is not as effective in terms of data rate throughput as physical layer error correction techniques and can lead to a decreased bit rate. Since the FELT was programmed to operate autonomously and the TMTC Link was just to monitor and occasionally control the terminal, this was not a problem at all.

Figure 10: Photo of a single beacon system with the Laser-diode/holder (top) and TEC/diode electronics (bottom).
Figure 12 shows a photo of the hardware built. The printed circuit boards (PCB) are mounted to aluminium plates with heat conduction material. The size of the three aluminium plates is matched to the power dissipation needs of the TMTC system.

Conclusions on the TMTC system

- Communication between the TOGS and the FELT occurred via the Balloon/HAP Service System (BSS).
- The Onboard Ethernet interfaces with the BSS via an Ethernet to RS-422 bridge.
- The Onboard Ethernet will operate at 10 Mb/s.
- The following FELT subsystems interface with the Onboard Ethernet:
  - Pointing and Tracking System
  - PAT Computer
  - Thermal monitor and control system
  - Electrical power
  - Communication system
  - Optical subsystem
2.4.5 Electrical power System (EPS)

The Felt is powered from the nacelle power system. The system provides a standard aircraft power bus voltage of 28V. The FELT EPS DC-DC converters power four FELT main power busses: ±3.3V, 5V and 12V. The CPA was powered from a separate nacelle power supply (24V). The power buses are controlled by the FELT EPS switching board. The switching board can be controlled via the TMTC link. A schematic sketch is shown in Figure 13. Most systems are powered via the FELT EPS switching board. The EDFA and beacon diode electronics are permanently powered and have internal beacon diode power-up and power-down electronic which is activated via TTL-disable from the FELT EPS switching board.

![Schematic sketch of FELT EPS](image)

Figure 13: FELT Electrical Power System

2.4.6 Data electronics

The FELT Communication system comprises the data sources and data switches. Figure 14 shows an overview block diagram of the system including the optical transmitter modules and the EDFA from the optical subsystem. Data sources, switches and optical modules are shown in yellow. The control circuits (blue) are connected to the onboard Ethernet (see section 2.4.4).

The maximum data rate of 1.244GBps was chosen on the grounds of availability of a commercial laser transmitter module. A special kind of module which can cover the entire range between the maximum data rate and the low rate of a few Mbps was required. This demand could not be fulfilled by commercial 2.5 Gbit/s modules. Table 5 summarises the parameters for the transmitter of the communication system.
Figure 14: Block diagram of FELT Data electronics and photo of the system already integrated into the FELT.

Laser-transmitter operating datarates: 1 - 1300 Mbit/s
Centre wavelength: 1550 nm
Transmitted output power, (guaranteed minimum @1550nm): 100 mW

Table 5: FELT Optical/Communication Subsystem – transmitter specifications

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laser-transmitter operating datarates</td>
<td>1 - 1300 Mbit/s</td>
</tr>
<tr>
<td>Centre wavelength</td>
<td>1550 nm</td>
</tr>
</tbody>
</table>
| Transmitted output power, (guaranteed minimum @1550nm) | 100 mW  

2.4.7 Thermal Measurements

One overall program objective was to gain experience designing optical communication systems that can operate successfully in the harsh stratospheric conditions. Thermal modelling and testing were accomplished during the system design to account for temperatures down to -70°C. During the design phase, several prototype subsystems such as the pointing assembly were tested in a small thermal chamber to optimize and validate the design. The FELT was tested in a thermal vacuum chamber prior to the balloon flight in order to validate the passive thermal control approach and the system design. Figure 15 shows a picture of the FELT setup in the thermal vacuum chamber prior to testing.

Figure 15: FELT in thermal vacuum chamber

The FELT performed well during the thermal vacuum test with no anomalous behaviour. Figure 16 shows the temperature measurements from selected thermocouples on the FELT during the thermal vacuum test. The effective minimum temperature of the chamber was about -65°C (thermocouple placed on the inside surface of the chamber). The air temperature inside the chamber was approximately -45°C.
(thermocouple hanging free in the chamber). However, the air temperature reading from the thermocouple can not be completely relied upon due to the near vacuum conditions (50 milibar). The carbon fiber housing provided good thermal insulation, which can be seen by comparing the temperature readings on the inside and outside surface of the pod; the inside surface was approximately 30°C warmer than the outside surface. In addition, the passive thermal control approach was validated. Most of the components mounted on the plate stabilized between 20-30°C during testing at a chamber temperature of -65°C.

![Figure 16: Selected FELT thermocouple data from the thermal vacuum chamber test](image)

### 2.4.8 TMTC Software

The TMTC Software was the user interface for FELT operations during the trial. Tree different systems provided mainly data feedback and some control abilities in case some parameters of the autonomous tracking system needed to be adjusted. No direct tracking camera feedback was possible because of the limited bandwidth of the TMTC Channel (RS 422: 9600kbit/s).
On the first payload support computer, the temperatures have been monitored. 16 temperature probes have been monitored and recorded. The programmed surface can be seen in Figure 17, left.

The second system was the terminal control system (TCS) which interfaced with the EPS System (section 2.4.5). Each system of the FELT could be switched on and off as shown on the programmed surface (Figure 17, right). This included the tracking computer the tracking support interface computer, the two TEC systems for the beacon diodes and the beacon diodes. The TCS also controlled the optical amplifier and received several status signals from the terminal (amplifier temperature alarm, amplifier pump temperature alarm, loss of optical input signal alarm, loss of optical output alarm and pump bias alarm). Additionally, the TCS gave an overview of the remaining energy of the nacelle power supply system.

The third system is the FELT tracking commander. This system recorded the status of the tracking system and indicated all parameters. In case the tracking sensor automatic control would not have worked, the parameters like gain Threshold etc. could be uploaded into the terminal tracking computer. Also, the main tracking control loop parameters could be changed and optimised with the FELT tracking commander during a locked tracking system status. The programmed surface can be seen in Figure 18.
2.5 Transportable Optical Ground Station (TOGS)

The FELT was designed to transmit to the Transportable Optical Ground Station (TOGS), which is pictured in Figure 20. The TOGS is not part of this document but is mentioned briefly for completeness. The central component of the ground station was a 40 cm Cassegrain telescope. The optical communications receiver and the atmospheric measurement devices were integrated into the ground station as well. A full description of the TOGS can be found in [xi].

![Transportable Optical Ground Station (TOGS) during pre-tests at DLR](image)

3. MEASUREMENT CAMPAIGN

3.1 Payload Integration

The measurement campaign took place at the ESRANGE facilities in northern Sweden near Kiruna. A picture which was taken from the adjacent radar hill can be seen in Figure 21.
Figure 21: ESRANGE facilities in northern Sweden with the 332280 m$^2$ balloon launch pad and the optical ground station tent on the pad as a white dot in front of the assembly hangars.

Prior to balloon launch, the FELT was integrated into the nacelle of the stratospheric balloon carrier system along with the millimeter-wave CAPANINA payload (Figure 22). The solar radiation protection cover and retro reflectors can be seen on top of the nacelle. These reflectors were added as a contingency plan in case the FELT malfunctioned. They could reflect the ground station beacons and minimal TOGS experiments/measurements could have been performed.

Figure 22: Integrated CAPANINA payload. Millimetre-wave and optical payload (FELT) integrated into the nacelle. Bottom view of the launch vehicle (left) and front view (right). Retro reflectors are attached at the top of the payload which is also covered with solar radiation protection foil.

### 3.2 Launch and Operations

A 12000 m$^3$ piloted balloon carrying the FELT was launched at 3:54 a.m. on 30.08.2005 and flew for approximately 8.5 hours before parachuting to the ground. During the mission, data transmission tests and atmospheric measurements were carried out. Figure 23 shows two pictures of the balloon at launch. The long flight train can be seen hanging from the bottom of the balloon. The nacelle which housed the FELT was located at the bottom of the flight train.
Figure 23: Picture of balloon before launch with payload at the launch vehicle (left) and flight train at launch (right). The nacelle is located at the bottom of the flight train.

Figure 24 shows a map of the region surrounding ESRANGE as well as a ground track of the balloon over the duration of the mission. Winds caused the balloon to drift away from the TOGS until the balloon pilot was able to manoeuvre the balloon into a stratospheric layer with a wind direction that brought the balloon back toward the launch site.

Figure 24: Map of the region surrounding ESRANGE and a ground track of the stratospheric experiment.

The maximum range during the mission was 64.15 km and occurred at 07:03 a.m. local time. Although the communication system had been designed for a maximum range of 60 km, optical transmission tests were still successful at the range of 64.15 km. At this maximum range, the elevation angle from the TOGS to the FELT was about 21 degrees. Figure 25 shows the range from the TOGS to the balloon during the mission.
Figure 25: Plot showing the range from the TOGS to the balloon

Figure 26 shows a plot of the balloon altitude. The balloon pilot was able to keep balloon near the 22 km target altitude for the duration of the mission.

Figure 26: Plot showing the balloon height during the mission

3.3 Acquisition and Tracking

Immediately after takeoff, the TOGS tracked the balloon via open-loop GPS tracking. The GPS position of the balloon was downlinked via the telemetry service link. Seventy minutes after launch, the balloon reached the targeted altitude at a horizontal distance of 48.4 km from the ground station (Figure 25, Figure 26). At this point the TOGS laser beacons were switched on. Based on the GPS positions of the balloon and the TOGS, the TOGS calculated the initial elevation pointing angle for the FELT and sent this data to the FELT via the telemetry link. Using this elevation angle and the nacelle rotation speed, the FELT PAT computer directed the pointing assembly to scan a circular pattern at a predetermined rotation rate. A scan was necessary for acquisition because the FELT had no way to determine the absolute heading angle. The scan rate was chosen in order to minimize the acquisition time.
Once the FELT began scanning for the ground beacon, the establishment of the optical communications link occurred as follows. When the FELT tracking camera detected any bright objects, the size and circumference of the object was measured and compared to expected ground station spot sizes. With this information, it was possible to distinguish between the ground station beacons and spurious background light (e.g. sun reflections on water or glass). If any object passed this test, the system switched from acquisition to tracking mode. In the tracking mode, the two periscope axes were driven by a PID position (or rate) controller. The periscope axes were positioned in order to hold the detected object in the center of the tracking camera image. Since the tracking camera and the FELT lasers were co-aligned \( x \), the FELT lasers could be pointed very precisely using this tracking method. When the FELT started tracking the ground beacon successfully, the FELT beacon lasers were turned on as seen in Figure 27.

At this point, the TOGS switched from GPS tracking to closed-loop optical tracking and kept the balloon beacon within the 100\( \mu \)rad field of view (FOV) of the ground station's communication receiver. Finally the 1550 nm communication system on the FELT was activated via the telemetry link and the data transmission tests were performed.

Coincidentally with the data transmission tests, atmospheric measurements were also carried out. These measurement instruments took advantage of the 986 nm beacon lasers, which allow the use of off the shelf silicon detector cameras. A detailed description of the instruments and the measurement results can be found in \([x]\).

At the end of the successful mission, the flight termination system was armed and the nacelle was cut away from the balloon (12:18 pm) and parachuted to the ground. To protect the payloads from ground impact, the nacelle was capsized and crash pads were installed on the top side of the nacelle. After 37 minutes of decent from the stratosphere the payload touched down at 12:55 pm as seen in Figure 28. The payload was recovered without damage.

**Figure 28: Payload after touchdown**

## 4. Measurement Results

### 4.1 Data Transmission Results

The FELT was capable of data transmission at three different rates: 270 Mbit/sec, 622 Mbit/s, and 1.25 Gbit/s. Bit error rates (BER) were measured for the 270 and 622 Mbit/s links; however, due to the limited bandwidth of the bit error rate test receiver, no direct BER measurements could be performed at 1.25 Gbit/s.
At 622 Mbit/s, the high signal to noise ratio enabled a BER of less than $10^{-9}$ within an unlimited measurement interval. Frequently, the BER went down to $10^{-10}$ for several minutes. This high quality signal could be received up to a maximum distance of 64.15 km from the ground station. The 622 Mbit/s eye pattern can be seen in Figure 29.

![Figure 29: Received PRBS signal eye pattern at 622 Mbit/s with bit error rate measurement receiver](image)

The data transmission at 1.25 Gbit/s was also successful. The eye pattern of the received 1.25 Gbit/s signal can be seen in Figure 30.

![Figure 30: Received PRBS signal eye pattern at 1.25 Gbit/s](image)

During the transmission tests, several thick clouds disturbed testing from time to time. Several very thick black clouds totally prevented communication. Thin white clouds did not severely affect the transmission, but did lead to a slight closing of the eye pattern and an increased BER.

Late in the mornings, most of the clouds disappeared resulting in near clear sky conditions. During that time, the angular separation between the sun and the balloon was very small at about 5°. Despite an increase of background radiation which could have affected the signal reception, no impairment of link quality was observed. This positive effect was achieved by the narrow filtering (10nm) of the incoming
1550 nm signal and the reduced sun-radiance at this mid-IR wavelength. This highlights a clear advantage of the 1550 nm technology over common NIR wavelengths like 850 nm.

4.2 Acquisition and Tracking Results

FELT acquisition of the ground station worked very reliably during night and day conditions. The acquisition time depended on the pointing assembly scan speed, but even with a slow scan speed of 10°/sec, the maximal acquisition time was 30 seconds.

![Figure 31: Cumulative Density Function of FELT tracking deviation](image)

The FELT exhibited very precise tracking capability in stratospheric conditions. Figure 31 shows a cumulative density function of the FELT tracking deviation over the 8 hours of data collection during the trial. 75% of the time, the FELT tracking deviation was less than 142 μrad (0.0081 deg) which corresponded to 1 pixel on the FELT tracking sensor. During the other 25% of the time, the system was either in acquisition mode or could not track the ground station due to stratospheric wind shear that caused a large pendulous motion of the nacelle. Compared to the high beam divergence of 1 mrad, the margin of the tracking system was very high and did not lead to a significant decrease of the communication system performance.

5. Turbulence measurement results

One goal of the trial was to evaluate the impact of the refractive index turbulence. Air volumes with different temperatures and therefore different refractive indices along the propagation path act like small lenses which focus and defocus the beam. The received field at the receiving telescope ends up in a speckle pattern (Figure 32, left). This speckle pattern or spatial intensity distribution at the receiver changes in time due to wind shear and the turbulent mixing process. Depending on the modulation format, this effect results to a greater or smaller extent in a characteristic channel fading. On one hand, for IM/DD the speckle size and integrated signal energy over the aperture size is important [xii]. On the other hand, the phase distortions or atmospheric coherence length in relation to the aperture size is an important factor for coherent (e.g. BPSK) receivers.

Therefore, two turbulence instruments were implemented in the optical ground station setup in order to sense the optical field: the Differential Image Motion Monitor (DIMM) to measure the atmospheric coherence length; and the turbulence profiler, in order to derive the spatial irradiance statistic and the turbulence profile along the propagation path.
The DIMM measured the variance of the differential angle of arrival of two spots. These spots (Figure 32, right) were the result of a focused image due to a telescope pupil mask. The coherence length $r_0$ was derived from the spatial statistic of phase fluctuations within the pupil plane of the receiver. This was done by evaluating the differential image motion of the two spots. The advantage of this instrument is that the measurement procedure is not influenced by the tracking motion of the telescope.

Figure 32: Example of gathered turbulence raw-data. Recorded turbulence profiler pupil intensity snapshot of the 40 cm Cassegrain telescope aperture with central obscuration (left). Recorded DIMM sample picture (right).

The estimation of the $r_0$ parameter from the DIMM over the daytime is shown in Figure 33. Around 8:00, we note that the coherence length was larger (i.e., better) than earlier or later in the morning. In parallel, we observe a drop of the scintillation index (the normalized intensity variance scaled by the mean intensity) near 8:00. The scintillation index was around 0.7 at the beginning of the trial (6:30 a.m.). It went down to 0.2 at (8:00) and increased slowly till the end of the trial (11:30 a.m.) where it was evaluated around 0.6.

This decrease of the atmospheric turbulence level around 8:00 corresponds approximately to the sunrise which is known to provide a turbulence minimum in the lower atmosphere. At that time, the air and the ground have the same temperature and no heat transfer occurs.

Figure 33: Atmospheric coherence length $r_0$ between 6:00 and 11:00 o’clock.

The turbulence profiler measured the fluctuations of the received intensity as well as the mean size of the intensity speckles which was around 3.5cm during the whole trial.

Using scintillation theory, the turbulence profile along the 60-km path was recovered from the intensity spatial covariance function. Turbulence is represented with the refractive-index structure constant $C_n^2$. 


which is a measure of the strength of turbulence or energy within the turbulence. One way of calculating
the turbulence profile is to solve the so-called inverse problem [xiii]. However, this approach provides
unstable solutions. Instead, we generate a large number of candidate discrete turbulence profiles and
look at which profile best fits the measured intensity covariance function. To obtain candidate discrete
$C_n^2$ profiles, the path and the $C_n^2$ were sampled at sensible values.

Figure 34 shows a 3D plot of 7 selected turbulence profiles measured during the trial. The first profile
measured at 6:30 shows two turbulence peaks of $2 \times 10^{-15} \text{ m}^{-2/3}$ and $2 \times 10^{-17} \text{ m}^{-2/3}$ at 2.5 and 50 km away from
the receiver. In the second curve, measured 64 minutes later, the turbulence peaks disappeared and the
strength of turbulence was constant between 10 and 40 km ($C_n^2=10^{-17} \text{ m}^{-2/3}$). At 7:59, a significant
turbulence layer at a distance of 5 km from the receiver with a $C_n^2$ of $2 \times 10^{-16} \text{ m}^{-2/3}$ could again be
observed. The profile measured at 8:54 shows two turbulence minima, again at 10 and 40 km. At the
end of the trial, the stratospheric balloon approached the ground station again and the maximum
distance of 64.14 km at 7:00 decreased to 47 km at 11:30. Because of that, the last three turbulence
profiles stop at 40 km. In general, the turbulence near the transmitter and the ground was more
influenced by the boundary layer conditions and changed with changing irradiation from the sun.

![3D Plot of 7 selected $C_n^2$ turbulence profiles measured during the trial between 6:12 and 11:11 o’clock.](image)

### 6. Outlook

Knowledge gained in this program will be applied to future optical communication terminal designs.
Additionally, with the turbulence data gathered, the numerical turbulence simulation tool PiLab will be
optimized [xiv],[xv]. Optical system parameters such as aperture sizes can be defined appropriately,
according to turbulence conditions and modulation scheme. Furthermore, turbulence mitigation
techniques can be designed [xvi]. The next logical major step for a trial would be an optical inter-platform
crosslink.
7. Conclusions

CAPANINA STROPEX, the first known stratospheric optical high bit rate downlink, was a success. A nearly error free signal was received by the optical ground station at a maximal bit rate of 1,25 Gbit/s at a link distance of 64 km. The FELT demonstrated good pointing accuracy and tracking performance in the harsh stratospheric conditions. The FELT tracking camera’s field of view could be decreased from 4° for a future system. With a correspondingly decreased divergence angle of the communication laser, the system margin could be increased dramatically with the same transmission power. The measured turbulence effects did not affect the communication performance because of the system margin. A future system can easily rely on passive thermal control with nominal thermal insulation.

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