Optical Free-Space Communications Downlinks from Stratospheric Platforms - Overview on STROPEX, the Optical Communications Experiment of CAPANINA

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Abstract - **This paper describes the current (April 2005) status of the STRatospheric OPtical Downlink EXperiment (STROPEX) which is part of the European Union funded research project "CAPANINA" (Communications from Aerial Platform Networks delivering Broadband Communications for All). CAPANINA is one of Europe's initiatives to develop the promising technology of HAPs (High Altitude Platforms) which can one day complement - and where economically reasonable replace - terrestrial or satellite based wireless services. The aim of STROPEX is to perform measurements to characterize the propagation channel for high-speed optical free-space communication. In addition, a downlink from a stratospheric carrier (alt. 22km) will be researched. Therefore both, the optical flight terminal and the optical tracking-receiver ground station had to be developed from scratch.**

Index Terms - **Optical Inter Platform Link, High Altitude Platform, Optical Ground Station, Atmospheric Optical Downlink, Index of Refraction Turbulence**

I. INTRODUCTION

A. The CAPANINA Project

The CAPANINA project is a 3-year European Framework 6 project, commenced on 1st November 2003. The project consortium involves 13 partners, representing a mixture of large industry, SMEs, and academia/research organisations. All partners are European with the exception of the National Institute of Information and Communications Technology (NiCT) from Japan, which have a similar national project.

CAPANINA focuses on the development of low-cost broadband services from HAPs aimed at providing efficient ubiquitous coverage to users who may be marginalised by geography, distant from infrastructure, or those travelling inside high-speed public transport vehicles (e.g. trains) [1]. The aim will be to exploit this future third wireless technology (besides terrestrial and satellite wireless communications) to deliver burst data rates to users of up to 120Mbit/s anywhere within a 60km coverage area. Both mm-wave band and free space optic communications technologies will be used. Free space optic communications have the potential to deliver very high data rates in clear air conditions, and can be used for interplatform links and to supplement mm-wave band communications for backhaul traffic. The CAPANINA scenario is illustrated in Fig. 1.

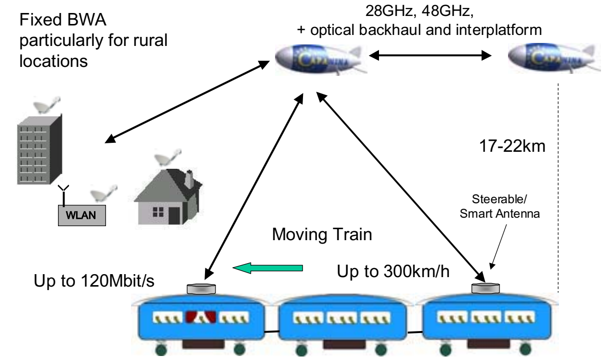

Fig. 1. Application scenario of CAPANINA. High speed connections for fixed users in mostly rural areas as well mobile connections to e.g. high-speed trains. Optical backbone links shall interconnect the HAPs network.

The CAPANINA project foresees two trials, one has already taken place in autumn 2004 at Pershore, UK and the next will be performed in summer 2005 at Kiruna, Sweden. The technical possibility of a third trial, envisaged in summer 2006 using the stratospheric aerodynamic platform "Pathfinder-Plus" of NASA, is currently investigated by the National Institute of Communication Technology (Japan) and CAPANINA partners.

B. Why Optical free-space communications

Optical free-space point-to-point communication links are favourable for certain applications involving HAPs. One characteristic of HAPs is their location in a cloud-free atmospheric altitude, enabling reliable line-of-sight links between different HAPS (up to a certain distance of typically 700km) [2], between HAPs and aircrafts in cruise-altitude, and between HAPs and any kind of communications satellites. Furthermore, when thinking of a meshed interconnected HAP network e.g. over Europe, even optical downlinks for connection of the stratospheric network to the terrestrial network would be feasible using site-diversity. This means that those HAPs without cloud-blockage over their underlying optical ground station would serve as hubs for the whole

network. Whenever the HAP network is much larger than the cloud-coverage correlation length, site-diversity can be used at a high and calculable reliability [3]. Direct user connectivity by dedicated optical links from HAPs are but not realistic because of their high risk of outage through cloud coverage in mid-latitude Europe.
Technical benefits of optical free-space over RF-links are their low weight- and power-impact and their high realisable data rates of several Gbps. Also, because optical links do not interfere with RF-transmission, no spectrum limitations apply.

C. Why an Optical Downlink Experiment

Optical inter-platform-links (OIPL) and HAP-satellite links are seen as the high-peed backbone for a future European HAP-network. Though - as stated above - also HAP-downlinks can be of a great value for such a network, the initial intention of STROPEX was the development and test of OIPL-technology. As there are not two different stratospheric platforms available at the same time during CAPANINA, a downlink experiment was the reasonable scenario for development, test, and evaluation of this technology. In hopefully further development steps, two airships might be available to directly test an OIPL-like scenario.

II. TEST SCENARIOS

A. Tethered Balloon Trial

In a first trial in autumn 2004 an optical downlink from a tethered balloon at 400m altitude was tested at Pershore, UK [4]. Transmitted data was digitised live video from the balloon down to a tracking-receiver ground station below. Data rate was 270MBps with BER<10^{-6} and transmission wavelength was 808nm with 500mW mean source power. The transmitter terminal did not track the ground station and thus had to send its signal down in a fairly broad angle of 16° while the ground station was tracking the source actively with an accuracy of approx. 120µrad. This first optical ground station setup comprised a 20cm diameter telescope with a silicon imaging tracking sensor and a fiber-coupled high-sensitive silicon APD receiver frontend.

This setup was used to test tracking capabilities of the optical ground station in a similar configuration as it will be used for the final tests in 2005 and 2006.

B. Stratospheric Trials

The situation in the following stratospheric trials is close to a typical future commercial HAP scenario. In summer 2005, the FELT (Free-Space Experimental Laser Terminal) and further RF-communications equipment will be flown on board a weather balloon which will be launched in Kiruna, Sweden, ascending in approx. 2 hours to an altitude of 22km, staying there for about 8 hours while it drifts of horizontally to max. 60km, imposing a link distance of up to 64km. Finally the payload is parachuted and hopefully recovered undamaged.
The balloon can pick up a rotary speed of up to 6 rounds per minute. While a stationary aerostatic HAP would not rotate at all due to active station keeping, this rotation of the weather balloon imposes a strong impact on the PAT of FELT and optical ground station (OGS). Because no attitude sensors are available for the FELT, it can not point directly towards the ground station but rather has to scan for the OGS' beacon along a ring of uncertainty. The identification of the signal from the ground station is further complicated by background light reflections from water surfaces and windows on the ground. After having identified the beacon, the FELT PAT-processor can identify the rate of rotation of the balloon to be able to keep tracking the ground station with an accuracy of max. 500µrad. Only then the narrow data beam can be pointed sufficiently towards the OGS.

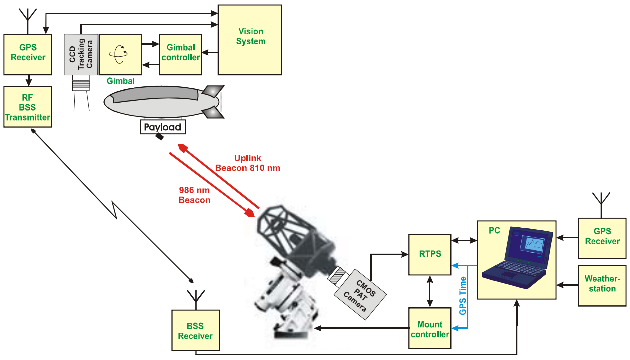

Fig. 2. Optical communication scenario of CAPANINA trials 2 and 3.

C. Atmospheric Attenuation and Index-of-Refraction Turbulence

The attenuation due to atmospheric absorption and scattering along the link path can be assessed with the help of data bases [5]. Fig. 3 shows the results for the CAPANINA trial 2 scenario (downlink from 22km under different elevation angles). By choosing the right wavelength, atmospheric attenuation can be kept below 2dB, while at the wrong wavelengths, attenuation can reach values of over 50dB. This effect is mostly due to molecular absorption lines of water vapour.

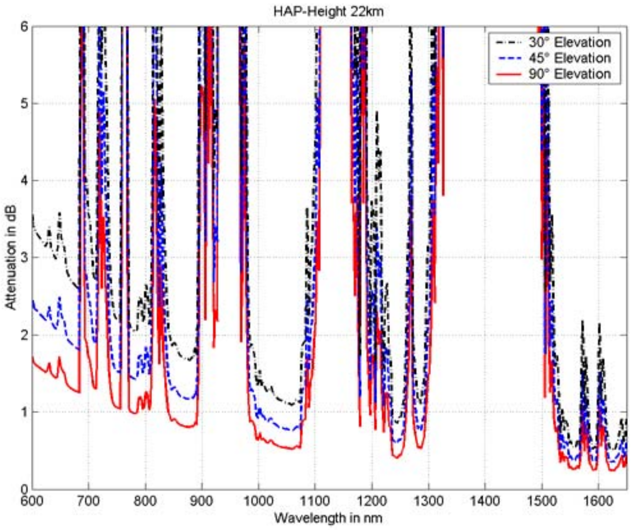

Fig. 3. Total atmospheric attenuation in a HAP-downlink scenario for wavelengths between 600nm and 1650nm

Local index-of-refraction turbulence (IRT) is caused by the inhomogeneous distribution of the temperature in a given atmospheric volume. The free air is constituted of a continuum of cells with different temperatures and thus different index-of-refraction. Cell sizes are between millimetres and meters close to the ground and tend to get larger in higher altitudes. When an optical wave travels through such an IRT-medium, its wavefront gets distorted due to the slight variance of the propagation speed inside the different cells - a phenomenon well understood from optical astronomy (where it lead to the development of *adaptive-optics* technologies for mitigation of IRT-effects on imaging). In the further process of propagation, this leads also to amplitude variations due to interference. Thus, after travelling through some kilometres of the atmosphere, the coherence of an optical field has dropped dramatically, imposing severe problems in terms of fading and heterodyning quality for a data receiver.

III. DESCRIPTION OF FELT

The Free-Space Experimental Laser Terminal (FELT) consists of a motorised periscope for beam steering, an optical beam-path with Tx-sources and the tracking sensor, the PAT-processor, telemetry and environmental sensor electronics, DC-DC-converters and the data-sources electronics. The total setup without housing has a mass of 18kg and a size of 250mm x 700mm x 420mm (Fig. 4). The periscope's clear aperture is 50mm but only 22mm are used for the tracking sensor due to the coallignment of the Tx-optics (Fig. 5). Direction of transmission is from the stratospheric terminal down to the OGS.

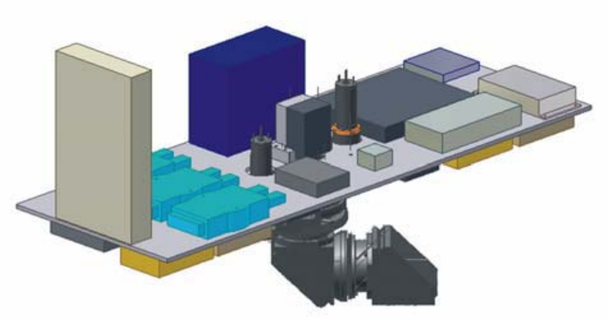

Fig. 4. View of the FELT terminal including the periscope at the bottom and the electronics-bench, without housing and fairing.

A. Optical Layout

Wavelengths used in STROPEX are 808nm as beacon from the optical ground station, 9xxnm as beacons from the FELT, and 1550nm as carrier frequency for the IM/DD binary data stream. 1550nm and 986nm are combined in a fibre cross coupler and radiated with a divergence of approx. 1mrad. Additional and partly redundant 97xnm beacon sources are also placed in the Tx-path of the terminal. The incoming 808nm beacon signal from the OGS is passed through the same beam path (Fig. 5). Then this OGS-beacon is detected and tracked by the tracking sensor.

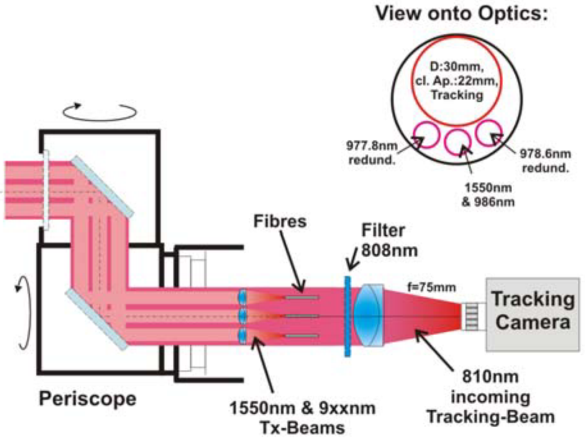

Fig. 5. Optical Layout of the FELT

B. PAT-Processor

FELT's PAT (Pointing, Acquisition, and Tracking) is based on a CMOS imaging sensor with area-of-interest ability for the acquisition and tracking of the ground station's beacon at 808nm wavelength. The video signal from the sensor is processed by an integrated vision system, which allows high speed implementation of control algorithms.

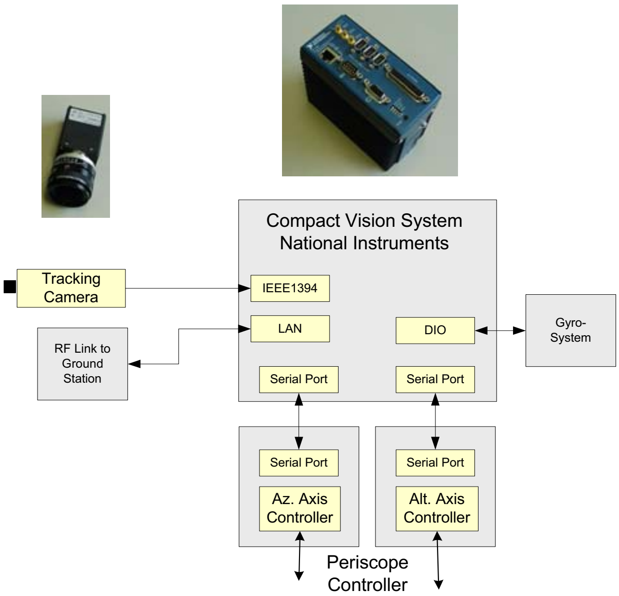

Fig. 6. Structure of FELT's PAT subsystem

C. Communication Sub-System

Three different data-sources at different data rates (1.25Gbps, 270Mbps, and 10Mbps) are available for modulation onto the 1550nm data signal laser diode. The modulated optical signal is boosted by a fibre amplifier to 21dBm output power. The different data rates shall enable the adoption to changing weather situations with higher atmospheric attenuation during the test flight. PRBS are transmitted at 1.25Gbps and 10Mbps and a live digital video stream is transmitted at 270Mbps. The selection of the different data sources is done by RF telemetry commands from ground.

IV GROUND STATION AND CHANNEL MEASUREMENT DEVICES

A. Ground Station Setup and Data Path

For the stratospheric trials a receiver system with 40cm aperture diameter is developed. It consists of a classical Cassegrain telescope and a sophisticated optical bench which is depicted in Fig. 7. From the incoming light firstly the 1550nm part is separated by a chromatic beam splitter plate (BSP), focused, and detected by a high sensitive InGaAs-APD RFE. The optical data signal is detected, filtered, digitised and synchronised. Finally, the different types of data (PRBS, video) are evaluated resp. visualized.

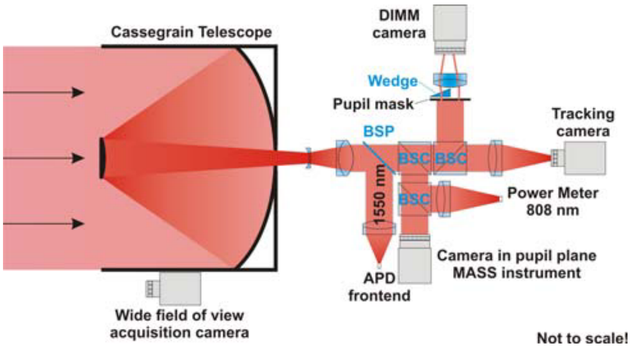

Fig. 7. Optical layout of STROPEX' optical ground station telescope. Separated by beam splitter plate (BSP) resp. beam splitter cubes (BSC), the 1550nm-RFE, the MASS and DIMM, the tracking sensor and a power sensor are integrated into one optical bench behind the telescope's back plane.

B. Channel Measurement Devices

The optical free-space channel can be characterised by statistical parameters describing field-perturbations. Usually the disturbances of the intensity distribution (size and strength of variations of the speckle patterns) and optical wavefront distortions are measured. In STROPEX we will furthermore analyse the profile of the index-of-refraction turbulence along the link path. This can be done with an imaging turbulence profiler based on an advanced MASS-profiler (MASS: Multi-Aperture Scintillation Sensor). Another measurement instrument is a DIMM (Differential Image Motion Monitor). This device monitors the dancing of the focal spot produced by two apertures. The differential motion of these spots can be converted into an angular error of the optical wavefront and thus allows the calculation of spatial phase statistics, which are crucial for coherent (heterodyning) receiver performances.

V. OUTLOOK

With the gathered measurement data of the atmospheric transmission channel optimized transmission schemes can be developed to overcome the impacts of the atmosphere [6]. With the optical downlink experiment being only the first step in investigating the optical free space technology for HAP applications, as a next step it is required to perform inter platform link tests.

ACKNOWLEDGMENT

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ABBREVIATIONS

APD	Avalanche Photo Diode
FELT	Free-Space Experimental Laser Terminal
HAP	High Altitude Platform
IM/DD	Intensity Modulation / Direct Detection
IRT	Index-of-Refraction Turbulence
OIPL	Optical Inter Platform Links
OGS	Optical Ground Station
PAT	Pointing, Acquisition, and Tracking
PRBS	Pseudo Random Binary Sequence
RFE	Receiver Frontend
STROPEX	Stratospheric Optical Payload Experiment

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