# PROTOTYPE OF A COHERENT TRACKING AND DETECTION RECEIVER WITH WIDE BAND VIBRATION COMPENSATION FOR FREE-SPACE LASER COMMUNICATIONS

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## ABSTRACT

The Optical Communications Group of the German Aerospace Research Establishment (DLR) has investigated the feasibility of a fiberless receiver telescope for high sensitive coherent optical space communication, resulting in an elegant Pointing, Acquisition and Tracking (PAT) concept.

To demonstrate the feasibility of this new concept, an optical receiver terminal that coherently obtains both the spatial error signal for tracking and the data signal with only one set of detectors has been built. The result is a very simple and compact setup with few optical surfaces. It does not require fibers for superpositionning and is capable to compensate for microaccelerations up to about one kilohertz.

**Keywords:** free-space optical communication, coherent optical receiver terminal, satellite vibration compensation, fiber-free heterodyning, Pointing, Acquisition and Tracking

## 1. INTRODUCTION

To the same extend that personal communication systems and earth observation satellites need to carry an increasing information rate, the use of high data rate intersatellite links (ISL) becomes more important. Since no atmospheric effects are to be taken into account, the carrier frequency for ISLs should be chosen as high as possible in order to obtain high antenna gain and small terminals. For this reason, optical communication systems are considered to be useful for space applications. However, their small beam divergence requires precise acquisition and tracking in the microradian range. As a drawback, the angular vibrations of a satellite need to be compensated by the acquisition and tracking subsystem, as they are in the order of magnitude of the beam divergence [1, 2].

For many space applications, heterodyne reception is advantageous compared to direct detection because of higher receiver sensitivity and smaller degradation due to background illumination [3]. Most concepts for heterodyne receivers use optical fiber cross couplers to superposition the local oscillator light with the received signal. This requires very accurate alignment between acquisition sensor and data detector. Other problems are the dust sensitivity of the fiber tip and the need for additional nutation elements for beam tracking. Besides, the sensitivity of optical fibers to space radiation is very questionable as strong degradation effects are expected.

In this paper we describe a new approach to an optical receiver terminal without fibers that coherently obtains both the spatial error signal for tracking and the data signal with only one set of detectors. The result is a very simple, small and robust design with only a few optical surfaces. Its tilt-mechanics for beam-steering combines a high bandwidth with a wide dynamic range (5.8 mrad field of view). The front-end and the electronics were designed to allow both heterodyne and homodyne detection. Both direct detection (used to support acquisition) and coherent detection reception are possible with the same detectors. There is no systematic loss caused by obtaining the tracking signal.

## 2. EXPERIMENTAL SETUP

Fig. 1 shows the design of the realized experimental telescope. It contains an achromat with 48mm diameter as field lens (antenna) and a small concave lens (6.25mm) in order to achieve the desired Fresnel-Number (f#) of 58. The received signal is combined with the local oscillator light by means of a symmetrical beam splitter cube and then fed to two perpendicular mounted bi-cell InGaAs photo detectors with a diameter of 150µm. The data signal as well as the two spatial error signals are obtained by combining the four signals out of these photo detectors. Vibration compensation as well as beam acquisition is performed by two piezo-driven tilt mirrors in the beam path. The typical power density spectrum of the mechanical noise on a satellite platform can approximately be described according to [2] with

$$S(f) = \frac{160 \frac{\mu rad^2}{Hz}}{1 + \left( \frac{f}{1Hz} \right)^2} \quad . \tag{1}$$

As this spectral distribution behaves like white noise filtered by a low-pass with 1Hz cut-off frequency, the compensation movements can spectrally be split into slow motions with relatively high amplitude which are covered by the large mirror and fast but small angular movements which are compensated by the small mirror.

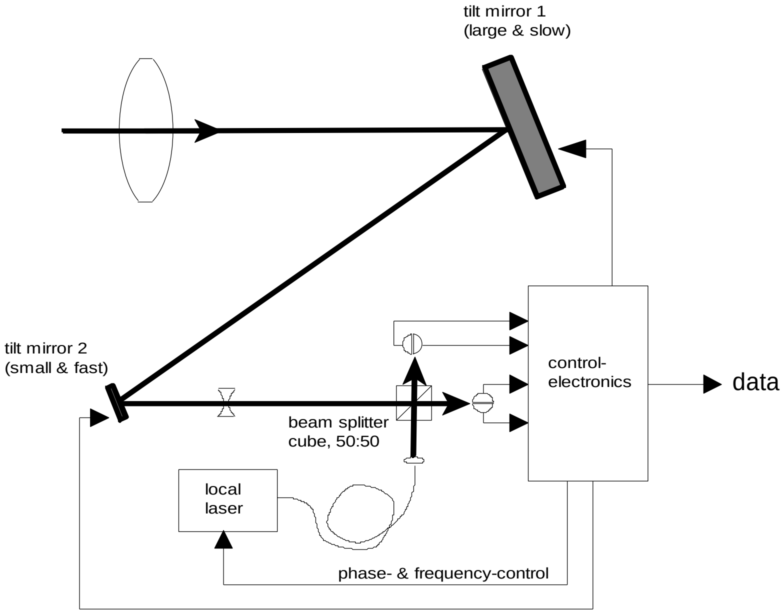

**Fig.1:** Experimental setup of the telescope

This two-mirror design perfectly meets the demands of the mechanical noise spectrum as well as it enables self-alignment of the optical axis. Another advantage of this design is that the beam path is folded with the result of a small telescope size. The front-end and electronics were designed to allow both heterodyne detection - e.g. with differential phase shift keying (DPSK), and homodyne detection with binary phase shift keying (BPSK) which then provides highest sensitivity. An optical fiber is still needed to feed the local oscillator (LO) light to the detectors. But this is not essential for functionality and will be replaced in the next design revision.

Fig. 2 shows the coherent generation of the two spatial error signals by superposition of the received signal (Airy distribution) and the local oscillator (Gaussian distribution). Subtracting the two sum signals of the bi-cell detectors results in the data signal, simultaneously cancelling local oscillator amplitude noise (balanced receiver principal).

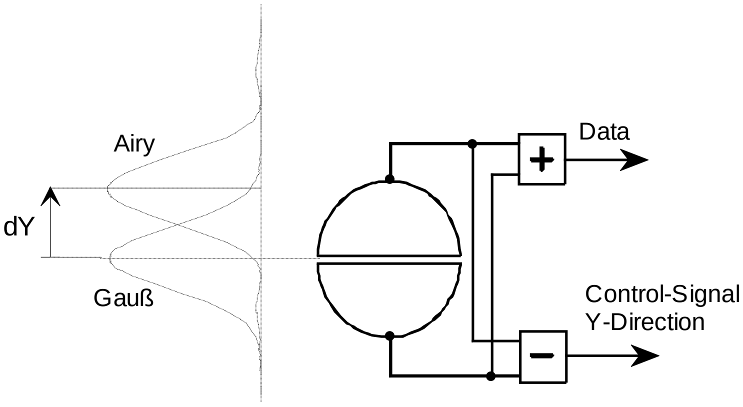

**Fig.2:** Coherently combining received- and LO-light on the bi-cell chips delivers error and data signals.

The amount of heterodyne current generated on one half-cell can be calculated according to

$$i_{half-cell} = R \cdot \sqrt{P_R \cdot P_{LO}} \cdot \eta_i(\delta x, \delta y)\,. \qquad (2)$$

with:

| | |
|---|---|
| $P_R$ | received signal power on detector plane |
| $P_{LO}$ | local oscillator power on detector plane |
| R | detector-sensitivity in A/W |
| η | heterodyneing efficiency |

The heterodyning efficiency η(δx, δy) of the IF-current, regarding the spatial focus-spot deviation δx and δy of the received light on a detector with its gap oriented horizontally, results from formula 3 (see also [4]).

$$\eta_i(\delta x, \delta y) = \frac{\iint\limits_{A_{half-cell}} (Gauss(x,y)\cdot Somb(x-\delta x, y-\delta y)dx,dy}{\sqrt{\iint\limits_{\infty} Gauss^2(x,y)dxdy \cdot \iint\limits_{\infty} Somb^2(x,y)dxdy}} \qquad (3)$$

For the optimization of the LO and received light spot ratio, regarding also the influence of shot noise, see [5].

The error signal is then calculated as i(upper half-cell) - i(lower half-cell) and figure 3 shows the distribution of the error-signal with the deviation parallel to the gap as parameter.

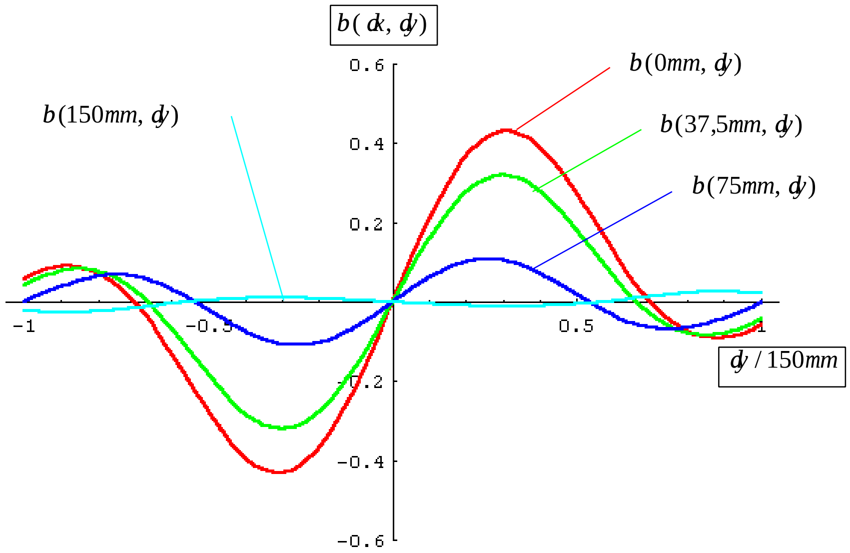

**Fig. 3:** Error signal distribution orthogonal to the gap with the deviation parallel to the gap as parameter

$$b = h_{i1}(dx, dy) - h_{i2}(dx, dy)$$

The receiver head combines the functionality of generating the data- and error signals and additionally features a direct detection front-end which can support the acquisition process.

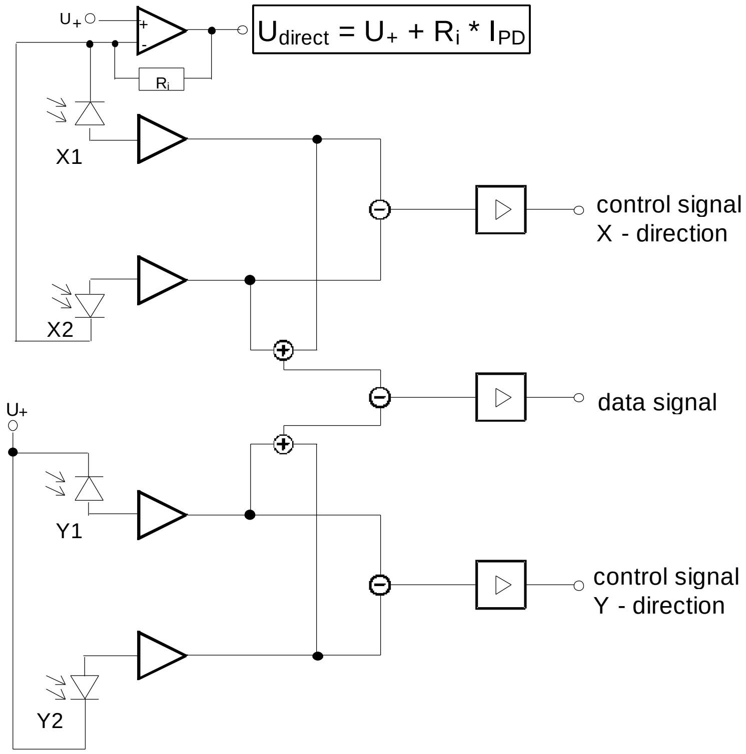

**Fig. 4:** Scheme of the receiver head electronics

All optical components together with the receiver head are assembled on a platform sized 35cm*22cm. Additional components like demodulator, clock recovery, frequency acquisition and µ-controller for system control are placed separately.

## ESTIMATED SYSTEM PERFORMANCE

Since only 5 optical elements resulting in 10 optical surfaces are needed, the optical losses are less than 1dB. The beam control is distributed to the two mirrors, so that slow movements with large amplitude are performed by the large mirror and small but fast movements by the small one.

The resulting tracking control loop bandwidth (including signal processing) is more than 1kHz, the max. angular range is ±2.9mrad.

The diameter of the active area of a bi-cell photodiode has been chosen to 150µm, which is a compromise between electrical capacity (which limits the bandwidth) on the one hand and small influences of misalignment, dust particles and the aberrations of the optical system on the other.

The gap between the two cells is less than 7µm, so the loss is very small. The photodiodes are antireflection coated, 90% quantum efficiency have been achieved. A gaussian distributed LO source is used which together with the gap implies a heterodyne current efficiency of 65%. This telescope was practically designed to demonstrate the feasibility of an ISL between two geostationary satellites 70,000km apart, at a data rate of 625Mbit/s.

## 3. TECHNICAL DATA SUMMARY

| | | |
|---|---|---|
| Mechanics and Optics: | tracking control closed-loop bandwidth | > 1kHz |
| | maximum angle compensation | ± 2.9mrad |
| | reception-lens diameter | 48mm |
| Electronics: | direct-detection bandwidth | 20 kHz |
| | IF band-width | 1GHz |
| | InGaAs detector quantum efficiency | 90% |
| | detector sensitivity (R) | 0.75 A/W |
| | power consumption (with tilt-piezos) | approx. 20W |
| LO-Power: | | > 1mW |
| Losses: | through optical elements | 1dB |
| | bi-cell gap and heterodyning efficiency | 1.8dB |
| | through distance to absolute shot noise limit | approx. 1dB |
| Telescope- | Size: | 35cm * 22cm * 10cm |
| | Weight: | 5.5kg |

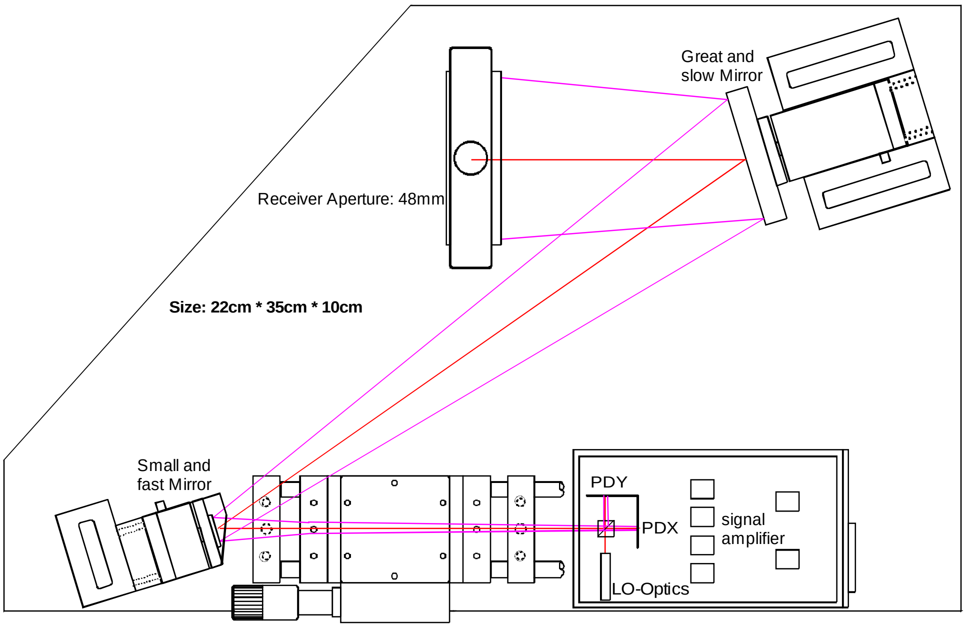

**Fig. 5:** Setup of the whole receiver telescope

## 4. CONCLUSIONS

This prototype shows a promising attachment to introduce optical ISLs in future satellite and spacecraft technology. It comes with a beam control mechanism fast enough to meet the requirements on satellite platforms, and provides a small and rugged design with little complexity and the ability of realignment after shock impacts. The fiberless design avoids typical problems like dust-sensitivity of the fiber tip or degradation due to space radiation and it allows diffraction limited performance of the optical system which is more difficult to achieve for the small focal spot on a fiber tip.

Further improvements of this hardware shall be to integrate the LO, which is now fiber-coupled, on the receiver head with its beam directly faced towards the heterodyning beam splitter cube. The great mirror shall be placed in front of the reception lens. Combined with a tilt mechanism, a greater field of view could be achieved without decreasing the optical performance. This could extend the pointing angle towards the range of coarse-pointing.

The next step shall be the development of an optical transceiver terminal with combined beam-steering for the outgoing and the incoming beam, a slow speed (up to 20Hz) closed control loop for transmitter pointing and an even smaller size.

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