# ADAPTIVE TELESCOPE ARRAYS FOR LASER COMMUNICATIONS AND ASTRONOMY

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## 1 Introduction

In the near future, space communication systems will use laser beams as carrier. Due to the small wavelengths involved, the associated optical antennas have very high directivities. Therefore the terminals have to be pointed with high accuracy. In present system designs, antenna tracking is accomplished by electro-mechanical means, for instance by moving a small mirror.

For coherent optical communications, multi-aperture telescopes provide non-mechanical, adaptive fine steering of the main lobe direction, thus compensating sattelite attitude jitter and reducing the requirements on mechanical pointing [1]. Further benefits of a telescope array over a single, large telescope are modularity, ease of fabrication, and implicit redundancy.

Recently the implementation of optical space-ground communication links has been proposed [2]. In this case, i.e. the propagation through the turbulent atmosphere, the original wavefront can be restored by using deformable mirrors or phased telescope arrays. Both coherent [3] and incoherent modulation schemes benefit from wavefront correction.

For imaging, adaptive receive telescope arrays (RTAs) offer a large collecting area and a high angular resolution, while diminishing the influence of atmospheric turbulence. By intentionally steering the RTA's main lobe in the vincinity of a reference axis and by recording the array's output power, the image of an object can be acquired. The reference axis is determined by a point source, i.e. a source that cannot be resolved by the array. The RTA's angular resolution is given by the diffraction angle associated with the overall array diameter. The angular range that can be scanned by the RTA is equal to the diffraction-limited divergence of a single subtelescope.

In addition, phased telescope arrays operating in receive mode allow to implement wide field-of-view imaging systems [4], and — using long baselines — to obtain images with extremely high angular resolution [5].

## 2 Coherent optical communications

We are investigating RTAs for coherent optical space communications. Within a study conducted for the European Space Agency (ESA) we developed several implementation concepts and performed a proof-of-principle experiment. Currently we are building an engineering demonstrator with dimensions that are realistic for the use on a geostationary laser communication terminal.

### 2.1 Beam-combining telescope array

Figure 1 shows the basic block diagram of a phased four-aperture RTA. Subtelescopes couple the incident optical wave into four polarization-maintaining single-mode fibers. Piston actuators set the relative phases (pistons) of the four optical subfields propagating to the beam combiner.

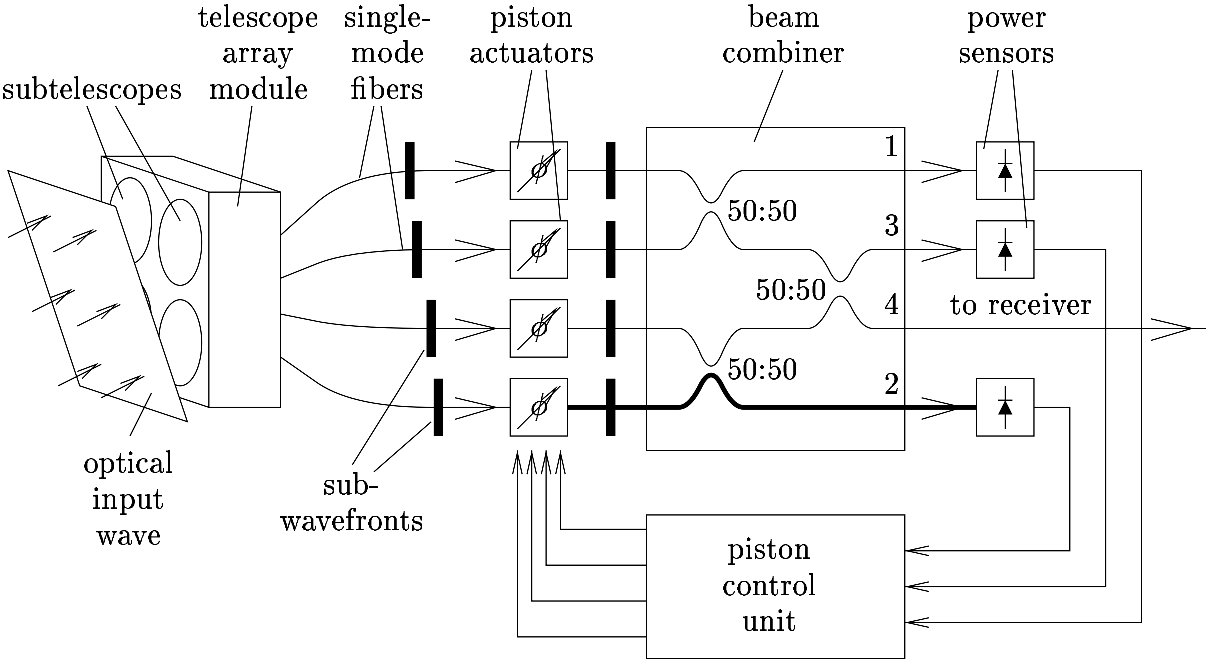

Figure 1: Block diagram of a phased receive telescope array

The beam combiner is realized by a tree of symmetric directional couplers. If the correct phase relationships are set, the incident optical radiation is coherently collected and directed to fiber 4 which can be attached to a coherent optical receiver. In this case fibers 1, 2, and 3 carry no optical power. Hence the optical power sensors attached to these fibers indicate whether the proper piston values are set. By driving the piston actuators, the control unit automatically adapts the phases of the optical subwaves so that the optical powers in fibers 1, 2, and 3 are minimized. For monochromatic radiation this status is achieved if the subtelescope path lengths differ only by multiples of the wavelength. Hence, within a single subtelescope's field of view, the antenna output power available for the subsequent receiver is automatically maximized, independent of the direction and the shape of the incident wavefront.

Figure 2 visualizes the principle of piston control. Two subtelescopes couple the incident optical wave into two polarization-maintaining single-mode fibers. The relative phase $\phi_1 - \phi_2$ between the optical subfields propagating towards the polarization-maintaining directional coupler is set by a piston actuator. The directional coupler superimposes both subfields which are assumed to carry identical optical power ($P$). At one output port, an optical power sensor detects the power $P_B$, which is proportional to $1 - \cos(\phi_1 - \phi_2)$. The desired phase difference is $\phi_1 - \phi_2 = 0$, implying $P_B = 0$ and $P_A = 2P$ at the second output. Periodical dithering around the operating point causes the power sensor to detect a signal at the dither frequency $f_d$. The power sensor output is synchronously demodulated into the baseband, resulting in a phase detector voltage $V_{PD}$ proportional to $\sin(\phi_1 - \phi_2)$. In combination with a loop filter and an integrator $V_{PD}$ is used to close an optical phase-locked loop (OPLL). The dither frequency $f_d$ must be higher than the bandwidth of the phase-locked loop, and the dither amplitude must be very small compared to $2\pi$. The OPLL locks at $\phi_1 - \phi_2 = 0$ and directs the total optical input

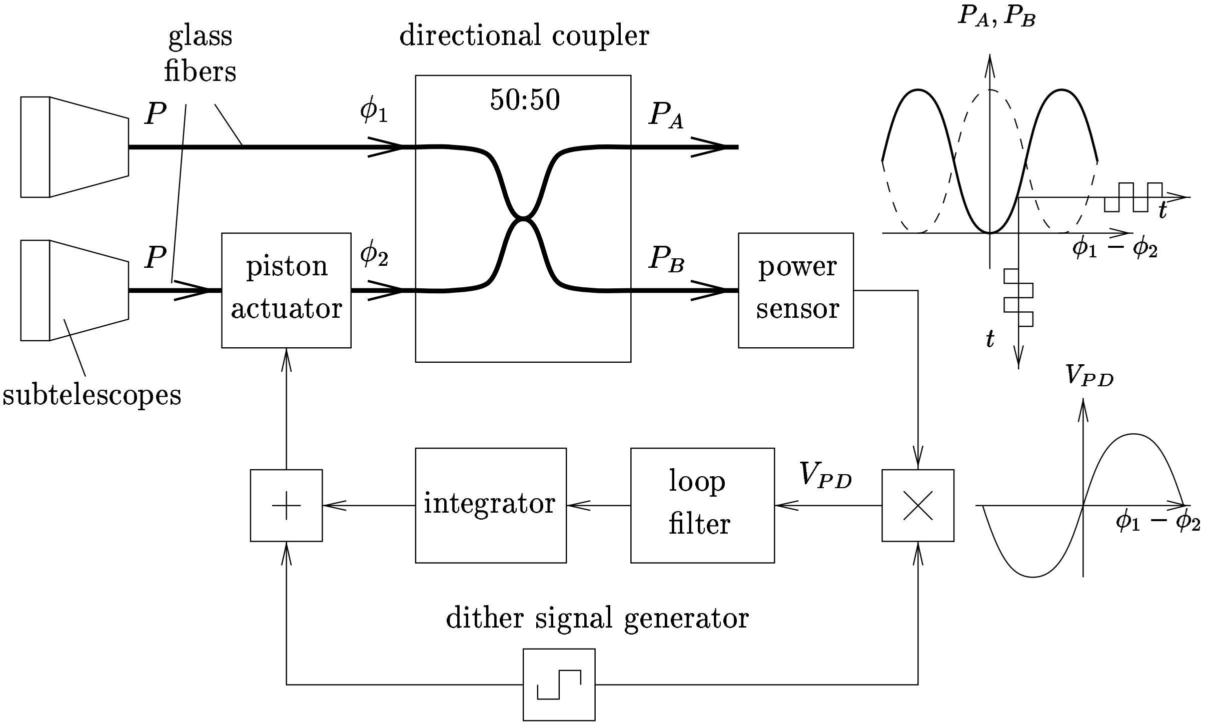

Figure 2: The dither method used for piston control

power to output port A.

If more than two subtelescope signals have to be combined, the simple structure shown in Figure 2 can be cascaded, still using a single dither frequency [6].

## 2.2 Proof-of-principle experiment

To demonstrate the feasibility and the capabilities of such a receive telescope array, we implemented a proof-of-principle laboratory experiment [7]. As optical input source we use a fiber-coupled Nd:YAG laser ($\lambda = 1064nm$, linear polarization, $P = 1nW$ per subaperture). The output beam is collimated by a lens, reflected off a tilt mirror, and directed to the telescope array unit. The telescope array consists of four lenses ($3mm$ diameter each) which couple the incident wave into four polarization-maintaining single-mode fibers. The piston actuators are realized by piezo-electric tubes wrapped by the fibers. By applying voltage to the tubes the fibers are stretched, effectively changing the optical path lengths. The beam combiner consists of three symmetric, polarization-maintaining fiber directional couplers. Optical power sensors based on InGaAs photodiodes detect the error signals and feed the piston control unit. The control loops are completely realized with analog circuits.

Using a dither frequency of $f_d = 10kHz$, the control unit phases all four subtelescope waves. As a result, the total optical input power is coherently combined into a single output fiber. Within the field of view of a single subtelescope, the RTA adapts itself to the direction of the incident wave, maxmizing the optical output power. The $3dB$ cut-off frequency of the control loops amounts to some $400Hz$. For a step-like change of the input wavefront, we measured a response time of $0.8 ms$.

### 2.3 Engineering demonstrator

After the successful completion of the proof-of-principle experiment we designed a technologically mature demonstrator.

The system consists of 16 fiber-coupled refractive subtelescopes. Each subtelescope has a diameter of $25 mm$ and is equipped with automatic tilt control, which is achieved by laterally shifting the fiber end within the focal plane of the lens. Piston actuators, beam combiner, and optical power sensors will be implemented basically in the same technology as it was used for the proof-of-principle experiment. Their performance values will be significantly increased, though.

The control unit which simultaneously sets the proper pistons and tilts of 16 subtelescopes will be implemented using a single ADSP-21020 digital signal processor (DSP). The dither frequency of the piston control loops will amount to $20 kHz$, resulting in a $2 kHz$ $3 dB$-cutoff frequency of the antenna's steering response.

## 3 Imaging

### 3.1 Overview

Phased telescope arrays can also be used for optical imaging through the turbulent atmosphere. Several approaches can be found in the literature.

For example, the Multipurpose Multiple Telescope Testbed (MMTT) consists of four $20 cm$-apertures phased together within a $\pm 1.2 mrad$ field of view (FOV) [4]. The disadvantage of such wide FOV telescope array imaging systems is that subtelescope pistons, subtelescope tilts, and pupil geometry have to be actively controlled with extremely tight mechanical tolerances.

Another approach is to measure amplitude and phase in the pupil plane of the telescope array and to obtain the image by a two-dimensional Fourier Transform [8].

We propose a method similar to that developed for space communications, i.e. to use a beam-combining telescope array.

### 3.2 Beam-combining telescope array

The beam-combining telescope array shown in Figure 1 automatically adapts its subtelescope path lengths for maximum output power, even in the presence of atmospheric turbulence. After adaption to a single, bright point source which is dominant within the subtelescopes' FOV the array's receive characteristic consists of a main lobe and several weak sidelobes (see Figure 3). By intentionally changing the adapted piston values of the subtelescopes it is possible to shift the receive characteristic and to record the received optical power pertinent to the angular position of the main lobe (see Figure 3). Scanning the main lobe within the total FOV and proper signal processing results in the desired image.

When comparing the beam-combining telescope array with an adaptive optics system using deformable mirrors, the following advantages come to mind:

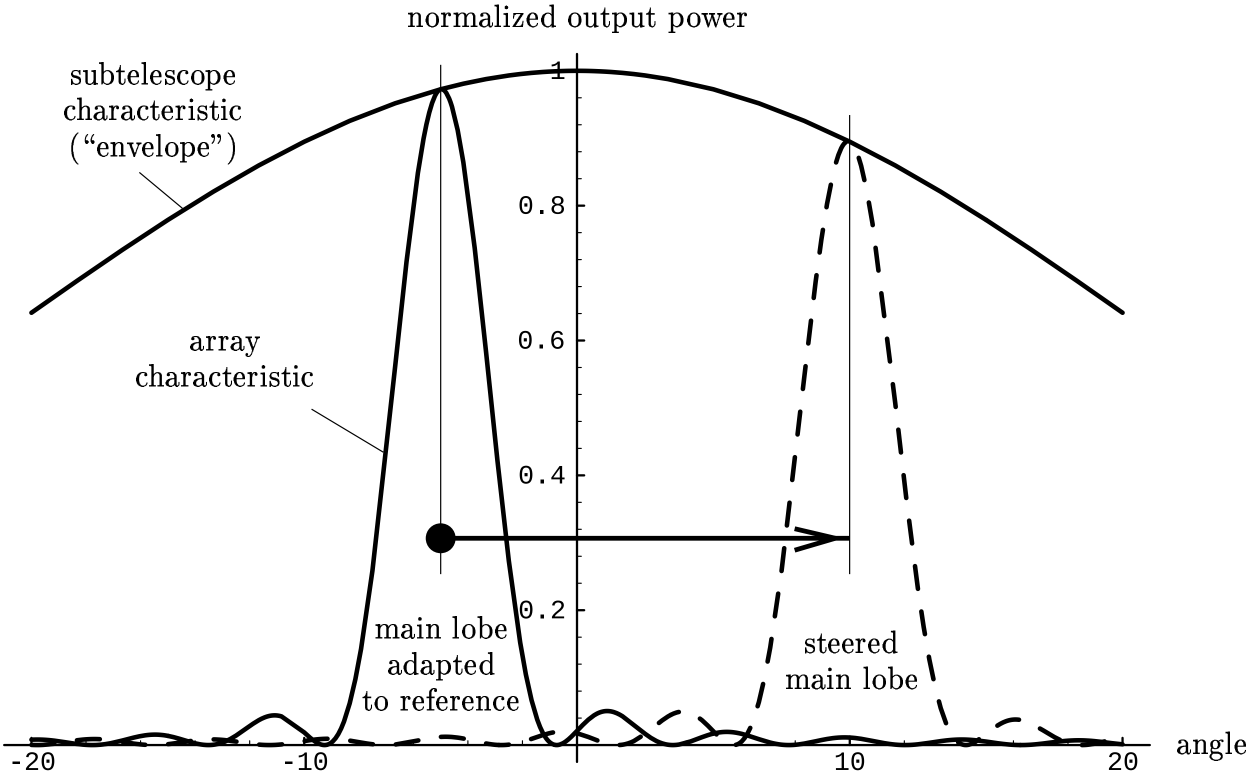

Figure 3: Receive characteristics of a phased telescope array

First, the highly modular optical setup of a telescope array is much easier to fabricate and to maintain than a large, monolithic telescope. Second, the use of fiber optics and integrated optics for piston actuators, beam combiner, and power sensors may eventually allow the implementation of large arrays at a reasonable expense. All this may result in a reduction of system complexity and cost.

However, several problem areas exist when using the imaging method described above:

First, the scanning process itself appears as an additional wavefront disturbance. Hence it has to be performed very quickly so that the piston control loops do not compensate the intentional change of the receive characteristic. Sufficient sensitivity may then be achieved by averaging many scans. Second, in order to obtain interference from wideband point sources (e.g. stars), it is necessary to absolutely equalize the subtelescope path lengths — it is not sufficient to control the path length differences to multiples of the wavelength. A method to achieve this goal was experimentally demonstrated and is presented in [9]. Finally, to compensate for wavefront distortions due to atmospheric turbulence, a bright point source has to be present in the vicinity of the object to be observed. Preliminary simulations have shown that the reference source should be about a factor of 10 brighter than any object within the subtelescopes' FOV, so that the piston control unit is not irritated and a well-defined main lobe can be attained.

# 4 Conclusion

We have shown that adaptive receive telescope arrays can be used for optical intersatellite communications, optical space-to-ground communications, and optical imaging. For intersatellite communications, we have experimentally verified the feasibility of the chosen system concept and are now developing an engineering demonstrator showing performance values typical for an operational system. For imaging purposes the concept has the advantage of modularity of hardware, but requires a point-like reference source, e.g. a bright guide star.

# 5 Acknowledgment

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