Evaluations and Progress in the Development of an Adaptive Optics System for Ground Object Observation

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ABSTRACT

Hereby we present the idea of a new passive sensor intended to compensate atmospheric turbulence distortions of object images. It is based on the applications of the already successful concept of adaptive optics. The main application of this sensor will be the compensation of the trajectory jitter of flaring objects in the far distance which will allow quicker identification and better tracking. The system consists of a wavefront sensor and a deformable correcting mirror, both commercially available, keeping the overall costs and size in reasonable limits. The research is divided into two main topics: the first is the characterization of the influence of the atmospheric turbulence on the object image when the observer’s line of sight is parallel to the ground. The second is the development of the components and the software to achieve the required performances. First progress have been made on determining the shape of the deformable mirror with good accuracy by means of a modal reconstruction as well as in measuring the wave front distortions of a point-like source due to atmospheric turbulence.

Keywords: Adaptive optics, Atmospheric turbulence, Close Loop

1. INTRODUCTION

The interest in adaptive optics sensors capable of removing image distortions of objects on the ground or low flying, is a recent aspect in adaptive optics which was until now confined to astronomical image correction or to focusing ultra powerful lasers. The growth in interest is mainly due to the spectacular success reported from observatories in resolving detailed images of celestial bodies.

However, there are several crucial differences between astronomical conditions and the scenarios where our adaptive sensor is to be employed.

The aim of the project presented here is the development of a sensor which is intended to be used to track and resolve flaring point-like objects like airplane plumes in the far distance, or lights.

The basic idea we rely on is a correction of the first Zernike modes until the radial order \( n = 6 \), thus avoiding a complete high resolution correction of the image of the object. Simulations developed at FOM give us hope to achieve a significant improvement of the image by more than 55%.

The characterization and analysis of atmospheric turbulence statistics and of the structure constant \( C_n^2 \), the Fried radius \( r_0 \) and the Greenwood frequency \( f_G \) in particular is an indispensable part of the project. Therefore will be presented a device able to measure these parameters.

2. THEORETICAL INTRODUCTION TO THE PROBLEM

2.1. Analogies and differences with the classical AO problem

The statistical atmospheric model of Kolmogorov is here assumed in consideration of the good results achieved in the description of the turbulence in astronomical observations and its intrinsic generality.

The first thing to understand for achieving a compensation of the turbulence effects are the characteristics of what we want to compensate. Namely, our system should be fast enough and have a sufficient range in order to reach the desired performances. From classical turbulence theory there are mainly three parameters which describe these performances:
- $C_n^2(z)$ the so-called \textit{structure constant} which describes the power spectral density of the turbulence in function of the distance $z$ from the observation point. The higher its value, the stronger the turbulence.

- the \textit{Fried radius} $r_0$ defined as:

$$r_0 = 0.185 \left( \frac{4\pi^2}{k^2 C_n^2 \Delta z} \right)^{3/5}$$

(1)

where $k$ is the wave number and $\Delta z$ is the turbulent layer thickness. The factor $(8/3)^{3/5}$ follows from the spherical form of the wavefront. This parameter defines the maximum size of a pupil which can give us diffraction limited images in a turbulent medium characterized from a uniform $C_n^2$ structure constant, therefore it gives us the maximum size of our system sub-pupils (the size of one of the Shack-Hartmann lenslet in our case).

- the \textit{Greenwood frequency} $f_G$ defined as:

$$f_G = 0.427 \frac{|v_\perp|}{r_0}$$

(2)

where $v_\perp$ is the wind velocity orthogonal to the line of view commonly named \textit{transversal velocity}. This parameter gives us the bandwidth which has to be reached to have a mean square error of 1 radian on the corrected wavefront in presence of wind.\textsuperscript{5}

Once these parameters are known, we can calibrate and optimize an adaptive optics servo loop. It has to be said, however, that equations (1) and (2) are valid only when a uniformly turbulent layer is placed between source and observer, otherwise an integration should be done taking into account that $C_n^2$ is a function of $z$. The problem we have to face also differs in several other aspects from the problem of astronomical observation.

The consequences of scintillation on the imaging process are another issue to consider. The scintillation produced by a turbulent medium with $C_n^2(z)$ varying with the distance $z$ from the source, is given by:\textsuperscript{6}

$$\sigma^2_x(L) = 0.56 k^{7/6} \int_0^L C_n^2(z) \left( \frac{z}{L} \right)^{5/6} (L - z)^{5/6} dz$$

(3)

for a spherical wave. $L$ is the distance between source and detector, $k$ the wave number and $\sigma^2_x$ is the so called log-variance, defined as:

$$\sigma^2_x = \frac{\log(\sigma_I^2 + 1)}{4}$$

(4)

where $\sigma_I^2$ denotes the variance of the intensity in a point of the detector. The amount of variation of the intensity in a point depends strongly on $C_n^2(z)$. Comparing studies of the values of $C_n^2$ for vertical layers\textsuperscript{4} with recent measurements for layers near to the ground\textsuperscript{7} becomes evident that the latter is on an average two orders of magnitude larger. So a larger scintillation is to be expected when observing in a direction nearly parallel to the ground. This negatively affects the performances of the wavefront sensor as will be shown (section 4.2).

The presence of background represents another challenging problem. It is not always possible to avoid the presence of other light sources around the object of interest to influence the measurement and correction of the wavefront. This is particularly true in the daytime and with objects flying close to the ground. The presence of such light also influences negatively the performance of the wavefront sensor, for example changing the centroid of the spot on the Shack-Hartmann sensor. Avoiding the background is possible only if we succeed to separate its influence somehow from the signal we are looking for. This could be done in some cases via a filtering of optical parameters, like spectrum, polarization, intensity or via an electronic filtering like frequency filtering.
Finally, since we want to develop a passive sensor, the correction philosophy must avoid any kind of energy beacon for creating artificial wavefronts sources and the overall correction has to be done in real time, therefore a posteriori evaluations and calculations, like speckle imaging, cannot be considered for our purposes.

With regard to all these difficulties in using conventional adaptive optics, some ideas and studies using compensation techniques based on the evaluation of image quality metrics like the point spread function or the modulated transfer function have been recently started. Part of the research in our group concerns also this aspect.

2.2. Evaluation of the atmospheric parameters through wavefront sensing

As it was said in the previous section, the knowledge of $C_n^2$, $r_0$ and $f_G$ is essential in order to have an idea of the performance we have to reach. Hence it is our intention to conduct some atmospheric measurements to determine these parameters. Our first simple attempt we rely on the measurement of the wavefront statistic of a point source when it is distorted by the turbulence.

Let $\phi(x, y, t)$ denote the incoming wavefront measured at time $t$ in the point of the pupil of coordinates $x, y$. Then it is easy to extract the correlation function $\Gamma_\phi(r)$ and the structure function $D_\phi(r)$ of the wavefront, with $r = \sqrt{x^2 + y^2}$. Making the hypothesis of approximately uniform turbulence over the path between source and sensor, we apply the formulas for a single turbulent layer and a spherical wavefront. It is possible then to write:

$$D_\phi(r) = 6.88 \left( \frac{r}{r_0} \right)^{5/3}$$  \hspace{1cm} (5)

so that we can derive from a fit a reasonable value for $r_0$ and then from equation (1) an estimation of $C_n^2$. The Greenwood frequency to be calculated from the formula (2) needs a measurement of the transverse wind velocity. It will be possible to estimate the frequency of change of the different Zernike modes of the turbulence anyway just by using a fast acquisition wavefront sensor in order to "freeze" the turbulence and then to explore its dynamics. Our intention however, after these first preliminary measurements and determinations, is to extend our method to a SLODAR measurement, which will allow us to estimate the structure of $C_n^2$ in function of the distance from the sensor and also of the wind profile. The idea is similar to the SCIDAR technique, vastly used in astronomy to probe $C_n^2$ at different altitudes. Finally making a time cross-correlation measurement, under the Taylor hypothesis of the frozen flow, it is possible to measure the wind velocity of the different layers in a similar way.

2.3. Wavefront correction theory

The implementation of a servo loop to correct the wavefront is the other research problem we have to face. Our idea relies on the use of a Shack-Hartmann sensor for the wavefront sensing part of the loop and on a membrane deformable mirror for the turbulence compensation part. To achieve the wavefront correction we must be able to reconstruct on the mirror a precise shape which is calculated starting from the wavefront sensor data. The reconstruction philosophy which will be used is the modal reconstruction. We have chosen to follow this way because our interest is limited to the first order Zernike modes. Compared with the zonal approach, the modal reconstruction is a faster way to achieve the result in our case. Since we are using a continuous membrane mirror with 37 actuators, the position of each should be calculated using a zonal reconstructor. Using the modal reconstruction until the radial order 6 the number of modes to be corrected are still under the number of actuators, not considering the radial mode orders 0 and 1 which are not influencing the image quality or are corrected separately. More over because the mirror is a continuous membrane one and not a segmented, the usual advantage to use zonal instead of modal reconstructor is here limited from the actuators correlations.

Figure 1 shows a very simple schematic of the closed loop. The wavefront slopes are measured directly by the sensor and from these it is possible to extract the Zernike coefficients immediately without passing through a reconstruction of the phase before. Once the coefficients are extracted the mirror surface has to be changed so that the wavefront will be corrected from the reflection. Here comes the question what means corrected wavefront in our case. Since we want to concentrate on the observation of distant point objects, we assume that the corrected wavefront is a plane wavefront, at least as far as the first Zernike modes are concerned.
The tip-tilt modes are corrected separately using a tip tilt mirror. The residual phase $\xi(x, y)$, that is the difference between the incoming wavefront and a plane wave, is corrected using the deformable mirror. For small deviations from a plane wavefront the shape $\epsilon(x, y)$ which the mirror has to assume to correct the residual wavefront is:

$$\epsilon(x, y) = -\frac{\xi(x, y)}{2}$$

This results in the Zernike decomposition:

$$\sum_{i=1}^{\infty} b_i Z_i(x, y) = -\frac{1}{2} \sum_{i=0}^{\infty} a_i Z_i(x, y)$$

So the Zernike coefficients of $\epsilon(x, y)$ are $-\frac{1}{2}$ the measured Zernike coefficients of $\xi(x, y)$. The problem to achieve the desired form of the mirror remains however and will be discussed in section 4.1 where also the results achieved will be presented.

### 2.4. Quality metrics method

The following idea originates from recent studies of the IOL group at university of Maryland. Since there are many difficulties to be dealt with regarding wavefronts of light from extended sources, it seems reasonable to try other methods to achieve a good image quality through turbulence. A schematic of the concept is shown in Figure 2. Here it is important to specify what kind of quality metrics we want to use. In fact, some metrics are calculated faster than others but give worst results if the image is not appropriate. For example, the point spread function is easy and fast to calculate if the object is a distant light spot but will give worse results than the modulated transfer function if the object is a complex image.

Once the most appropriate metric is determined the problem to relate it to the deformation of the mirror remains. An intuitive approach could be based on an iterative algorithm which changes for example the Zernike coefficient of the surface one by one by calibrated small steps until the metric is maximized. Understandably this approach is very slow. The stochastic gradient descent method described in\(^9\) represents a faster and well tried approach. The principle is similar to the well known steepest descent technique. Let us assume we have a certain shape of our deformable mirror and let us denote the Zernike coefficients of the mirror surface as $a_1, \ldots, a_M$. The quality $Q$ of the reflected image will be a function of the $a_1, \ldots, a_M$. We start by measuring the initial image quality $Q(a_1^0, \ldots, a_M^0)$ of the image, then we assign random values to the coefficients $a_1^1, \ldots, a_M^1$ and we measure the new value $Q(a_1^1, \ldots, a_M^1)$. It is then possible to calculate the gradient as follows:

$$\left(\frac{\partial Q}{\partial a_i}\right)^{(1)} = \frac{Q(a_1^1, \ldots, a_M^1) - Q(a_1^0, \ldots, a_M^0)}{a_i^1 - a_i^0}$$

![Figure 1. Close servo loop schematic to compensate aberration of the wavefront via wavefront sensor and deformable mirror](image_url)
Figure 2. Closed servo loop schematic to compensate wavefront aberration using a quality metric algorithm and a deformable mirror

Here the superscript \(^{(1)}\) indicates the iteration number. The next step is to change the Zernike coefficient to:

\[
a_{n+1}^i = a_n^i + \gamma \left( \frac{\partial Q}{\partial a_i} \right)^{(n)}
\]  

(9)

with \(\gamma\) a weighting coefficient which has to be chosen properly. The iteration procedure will converge to the closest maximum. While this method is clearly much slower than wavefront sensing techniques, it still offers solutions to large part of the problems affecting the first method when applied to extended objects. Which method is to be chosen is therefore a question which depends on several parameters of our requirements. Also hybrid techniques involving both at the same time might be evaluated in the future.

3. DESCRIPTION OF THE EXPERIMENTAL SETUP

3.1. Closed loop test bed

To develop the necessary experimental knowledge and to check the several aspects of the closed servo loop under controlled conditions, a test-bed concept has been developed. The setup is illustrated in Figure 3. Before describing the setup in detail few words have to be spent on the two main devices of the loop namely the deformable mirror and the wavefront sensor.

The deformable mirror is a product from OKO technologies. It consists of a thin metallic membrane of 15 mm diameter which is attached to the boundary circle of the support. Underneath, at about 1 mm distance, 37 electrodes disposed in a honeycomb pattern can be charged positively from 0 to 200 Volts independently from each other. The membrane can be then only pulled from the electrostatic forces. In order to allow the compensation of both negative and positive gradient wavefront distortion, a voltage offset of about 180 V is applied to the actuators, which causes the mirror shape to curve inwards. This shape is the "rest" shape of the mirror. The reflected light will be then affected by a constant defocus aberration which has to be taken in account.

The wavefront sensor we use is a HASO 16 Shack-Hartmann from Imagine Optics. The device is able of a frame rate acquisition virtually up to 3000 Hz and has a resolution of 260x256 pixels. The lenslet array is a square pattern of 16x16 lenslets the dimensions of each 153x153 \(\mu m^2\), the pupil has 2.45 mm diameter.

The main characteristic of this device is the software included which follows the spots on the CCD sensor and associates them with the corresponding lenslet even when they lie outside the area directly beneath the lenslet. This results in a capability of the device to measure tilts up to 3\(^o\), thus eliminating the need of an additional tip-tilt sensor and an additional beam splitter in the setup.

A focused Helium-Neon laser provides a point source as reference. The light is then collimated with the help of a
Figure 3. Test setup for a closed loop. The focal length of the lenses are \( L_1 = 10 \text{ mm}, \ L_2 = -20 \text{ mm}, \ L_3 = 100 \text{ mm}, \ L_4 = L_5 = 75 \text{ mm}, \ L_6 = 200 \text{ mm}, \ L_7 = 40 \text{ mm} \)

divergent and a convergent lens (\( L_2, L_3 \)). The divergent lens is used to expand the central part of the diffracted Airy spot exiting from the spatial filter as much as possible to get a beam as homogeneous as possible. The beam section is then reduced by mean of an iris and then the light travels to a spatial light modulator. The spatial light modulator has the charge to produce aberrations in the incoming plane wave.

This device has the advantage of producing calibrated aberrations, also dynamically, and it allows us to study the behavior of the system under controlled disturbances. It has however the disadvantage of reaching a maximum frequency change at 200 Hz. The aberrated beam is then reflected from BS1 towards the relay of lenses \( L_4 \) and \( L_5 \), which is slightly defocused so that a small divergence is added to the beam. The motivation of this is to correct the defocus of the deformable mirror which has been explained before. The rays then reach the deformable mirror through beam splitters BS2 and BS3. The role of BS3 is to allow a calibration of the mirror (see section 4.1) directly in place, without moving either the mirror nor the Twyman-Green interferometer, because of the sensitivity of the alignment. It can be ignored in the close loop description.

The beam reflected from the deformable mirror is sent from BS2 in the relay \( L_6, L_7 \) to reduce the size of the collimated beam from 13 mm diameter to 2.5 mm that is the size of the Shack-Hartmann pupil. The tip-tilt of the beam is corrected near the entrance pupil of the Shack-Hartmann by a tip-tilt mirror. The position of the tip-tilt mirror close to the wavefront sensor is chosen to prevent the beam from missing the pupil if large tilts occur. The final beam splitter BS4 provides the signal for a CCD camera to evaluate the beam quality. As previously said both the deformable mirror and the tip-tilt mirror will be controlled by signals of the Shack-Hartmann sensor.

3.2. Adaptive optics sensor prototype: atmospheric measurement setup

In view of future atmospheric applications and studies a customizable frame for an adaptive optics sensor has been realized recently. The frame as depicted in Figure 4 consists essentially of a mobile aluminium board apt to serve as construction base for standard opto-mechanical items, an upper plate where a motorized pivoted mirror is mounted and a Cassegrain telescope underneath the mirror fixed in vertical position so as to form with this latter a magnifying periscope.

In order to measure the atmospheric characteristics, a setup has been realized on the optical board as shown in Figure 5. The image of the pupil is initially re-imaged from a \( f/\# = 1.5 \) lens to have a fast system. The light is then divided between the camera and the Shack-Hartmann. The lens \( L_2 \) is placed at the exit of the beam.
Figure 4. Mobile frame for adaptive optics studies. The optical periscope gives a magnified view of the objects to track. The optical construction on the board can be changed and adapted to different purposes.

Figure 5. Setup for atmospheric measurements. The focal lengths of the lenses are: L1=75 mm, L2=100 mm, L3=10 mm, L4=5 mm, L5=75 mm, L6=200 mm.

splitter to reduce the divergence of the exiting beam, the relay formed by lenses L3 and L4, both with short focal lengths, form a system able to shrink the image to the dimensions of 2.5 mm, that is the Shack-Hartmann pupil diameter, and to correct the defocus. The relay formed by L5 and L6 instead is useful to image the pupil or the object onto the CCD camera. The measurements are performed placing a 100 W halogen lamp with a 4° reflector behind at a distance of 2.5 Km. Assuming the source as point-like, we can study the residual wavefront and the scintillation in the pupil. It is possible then to calculate the different parameters analyzed in section 2.2.

To perform a SLODAR measurement two sources have to be arranged with an angular separation large enough to distinguish the single lenslet images of both sources in order to make a simultaneous measurement of their wavefront slopes. In this case it won’t be possible to rely on the internal program of the wavefront sensor and an a posteriori analysis will be made directly on the recorded image of the CCD sensor.

3.3. Atmospheric turbulence compensation setup

The concept of this setup has been already illustrated in. Here some changes in the setup are illustrated (see Figure 6).

The idea is to reduce the usage of beam splitters to a minimum in order to lose as little intensity as possible and
Figure 6. Setup for adaptive correction of atmospheric blurring of images. The focal lengths of the lenses are: L1=75 mm, L2=100 mm, L3=10 mm, L4=5 mm, L5=75 mm, L6=200 mm.

also to reduce the intrinsic aberrations of the optical system. The light from the telescope will be focused from L1 in the point F1. This point coincides with the focus of the off axis parabolic mirror M1. Parabolic mirrors allow us to avoid both spherical and chromatic aberrations. The collimated light is sent to the deformable mirror which is placed at an angle between 10 and 15 degrees. This positioning permits to avoid the use of beam splitters to collect the reflected light from the deformable mirror as it is done in the setup of section 3.1. Another off-axis parabolic mirror M2 is placed in the beam path to focus the light in a point F2.

As we already know, the deformable mirror produces a defocus aberration in the reflected beam. To correct it the relay L2, L3 is used in a similar way as the relay L4, L5 in the setup of Figure 3. The final stage of the system includes the tip-tilt compensation and the division of the beam for imaging and wavefront sensing purposes. To calibrate the deformable mirror directly in place as before, a movable plane mirror M3 can be introduced in the beam path so that the surface of the deformable mirror can be measured by the Twyman-Green interferometer without moving the deformable mirror or the interferometer.

As stated previously the tip-tilt mirror and the deformable mirror will be controlled only via data coming from the HASO 16 wavefront sensor without need of additional tip-tilt sensor. The final setup includes, as can be seen, only one beam splitter.

4. EXPERIMENTAL RESULTS

4.1. Modal control of the mirror surface

In this section, as mentioned before, we will deal with the problem of controlling the mirror surface and the related results. The method used is based on the linear least square approximation of the function relating the voltages of the actuators and the surface.

For controlling the mirror a preliminary calibration is necessary, once the calibration is done and the alignment is not changed, the surface of the mirror can be controlled quite accurately without any other necessity of
The calibration is done using a Twyman-Green interferometer from Fisba to measure the shape of the mirror surface. The interferometer allows us also to subtract an offset surface from the measurements. For this reason it proves ideal, since the OKO mirror presents a defocused shape in the "rest" position (see section 3.1). Supposing that the surface of the mirror is described by the function 

\[ S(x, y, v_1, ..., v_p) \]

where \( x, y \) are the coordinates of the surface of the mirror and \( v_1, ..., v_p \) are the actuator’s voltages (\( p = 37 \) for the OKO mirror). At "rest" settings the surface is described by:

\[ S_0(x, y) = S(x, y, v_0, ..., v_0) \quad (10) \]

where \( v_0 \) is 180 volts in our case. Let us call \( \delta S(x, y, v_1, ..., v_p) \) the difference:

\[ \delta S(x, y, v_1, ..., v_p) = S(x, y, v_1, ..., v_p) - S_0(x, y) \quad (11) \]

This is what the interferometer actually measures. Decomposing into Zernike yields:

\[ \delta S(x, y, v_1, ..., v_p) = \sum_{k=0}^{s} a_k(v_1, ..., v_p)Z_k(x, y) \quad (12) \]

Here \( Z_k(x, y) \) denote the Zernike modes. As we can see now, the dependence on the actuator’s voltages is contained only within the coefficients.

First of all we recognize, from previous studies, that the dependence of the membrane deformation due to a single actuator is quadratic respect to the voltage applied.

Then we assume a linear approximation of the dependence of the Zernike coefficients on the squared voltages:

\[ a_k(v_1, ..., v_p) = \alpha_k v_1^2 + ... + \alpha_p v_p^2 \quad (13) \]

Subsequently we collect a number \( m \) of surface measurements, generating \( m \) random configurations of the actuators voltages \( v_1, ..., v_p \) such that:

\[ \delta S^1 = \sum_{k=0}^{s} a_k^1(v_1^1, ..., v_p^1)Z_k(x, y) \quad (14) \]

\[ \vdots \]

\[ \delta S^m = \sum_{k=0}^{s} a_k^m(v_1^m, ..., v_p^m)Z_k(x, y) \]

Here the superscript indicates the number of the measurement. Let’s simplify the notation substituting \( v_i^2 \) with \( \nu_i \). From the equation (13) follows the matrix equation:

\[
\begin{pmatrix}
  a_1^1 & \ldots & a_s^1 \\
  \vdots & \ddots & \vdots \\
  a_1^m & \ldots & a_s^m
\end{pmatrix}
\begin{pmatrix}
  \nu_1^1 & \ldots & \nu_p^1 \\
  \vdots & \ddots & \vdots \\
  \nu_1^m & \ldots & \nu_p^m
\end{pmatrix}
= \begin{pmatrix}
  \alpha_1^1 & \ldots & \alpha_s^1 \\
  \vdots & \ddots & \vdots \\
  \alpha_1^p & \ldots & \alpha_s^p
\end{pmatrix}
\quad (15)
\]

Or in simpler notation:

\[ (a) = (\nu) (\alpha) \quad (16) \]

The matrices \( (a) \) and \( (\nu) \) are already known, the first decomposing the measured surfaces in Zernike modes and the second is directly generated by the computer. The matrix \( (\alpha) \) is called characteristic matrix of the mirror and is what we want to extract. The least square solution of the (16) is then given from:

\[ [(\nu^t \nu)^{-1} \nu^t] (a) = (\alpha) \quad (17) \]

The characteristic matrix is the link between the Zernike decomposition of the mirror surface and the actuator’s voltage configuration.
Figure 7. Zernike modes calculated (left) and reproduced on the mirror surface (right). The modes are labeled in radial order, azimuthal order and azimuthal parity (sine or cosine). The graph below represents the precision of the reproduction of the modes in terms of Peak-to-Valley and Root Mean Square of the difference of the corresponding surfaces. 

If we want to reproduce a precise surface \( \delta S(x, y) = \sum_{k=0}^{s} a_k Z_k(x, y) \) on the mirror it is only necessary to multiply the row vector containing the Zernike coefficients \( a_k \) by the pseudoinverse of \( (\alpha) \). As can be easily seen from the equation (16) the resulting row vector will give us the actuator’s voltages necessary to get the desired surface. The experimental results are shown in Figure 7.

The best reproduced modes are the ones which have smaller radial frequency. This can be attributed mainly to the fact that the mirror membrane is bound at the border, a condition that is not satisfied by most of the Zernike modes. Therefore a better performance could be obtained using only the central part of the mirror for compensation purposes, leaving the actuators at the border free to be used to gain the necessary degrees of freedom.

4.2. Atmospheric measurements

Another result that can be cited here is the successful measurement of the wavefront of a point source after propagating through atmospheric turbulence using the design depicted in Figure 5. A small halogen lamp of 100 Watt has been set at 2.5 km distance. The measurements were done overnight to avoid disturbances by background illumination. Simultaneous records of lamp images and incoming wavefront were made.
Since the ideal wavefront of the lamp is known, it is possible to extract statistical information on the atmospheric turbulence through the residual wavefront as already explained (section 2.2). The previous attempts to measure turbulence on a distance of about 5 km have demonstrated that the light intensity necessary to get images at a frame rate of 700 Hz has to be much greater than 100 Watt with the HASO 16 wavefront sensor in the setup of Figure 5. Additionally, the scintillation creates much stronger disturbances as can be seen from Figure 8. In consequence, large parts of the wavefront sensor pupil were not illuminated causing a loss of information from the wavefront and therefore the inability to reconstruct it. An enhanced sensitivity of the CCD sensor behind the lenslet could solve both problems, since the dark points of the wavefront sensor pupil could become sensitive enough to receive a signal anyway, without missing information.

The first results of the measurements are visualized exemplarily in Figure 9. As can be seen, the lower the radial order is, the lower is the frequency of change of the mode and the greater is the influence on the wavefront distortion. Hence with a moderate bandwidth a loop ought to be able to correct the main part of the atmospheric turbulence effects.

5. CONCLUSIONS

The development of an adaptive optics sensor for the observation of terrestrial objects or low-flying has been evaluated and analyzed. Several theoretical considerations have brought us to the conclusion that the development should concern at first the turbulence compensation of flaring point-like sources. Following this concept
two steps have been done. The first is the development of a method to successfully control a deformable mirror in a fast and reliable mode, therefore avoiding iterative procedures. The second is the construction of a setup which has demonstrated the ability to measure the wavefront of a point source in the atmospheric turbulent environment when the line of sight lies parallel to ground. Future steps concern the completion of an on the table closed loop setup as well as a more complete analysis of the atmospheric turbulence using a SLODAR technique.

REFERENCES
