Adaptable adaptive optics and image processing at Fraunhofer IOSB

S Gladysz, P Marin Palomo, A Zepp and K Stein
Fraunhofer Institute of Optronics, System Technologies and Image Exploitation IOSB
Gutleuthausstraße 1, 76275 Ettlingen, Germany

Abstract. Research activities in the Adaptive Optics Group at the Fraunhofer Institute of Optronics, System Technologies and Image Exploitation (IOSB) in Ettlingen, Germany, revolve around imaging and laser propagation through strong turbulence, especially along horizontal paths. We are developing simulations, theoretical models, image processing software and adaptive optics systems. This paper gives an overview of two application areas bound by the same deficiency: both image processing and laser correction systems often require information about average turbulence strength at the time of their operation in order to function properly or to maximize their effectiveness.

1. Introduction
Performance of electro-optical systems is always affected by environmental factors. One of such factors is atmospheric turbulence which limits the attainable resolution delivered by ground-based [1] or space-based [2] telescopes. Similarly affected are the directed-energy [3], or horizontal-path imaging and laser communications systems [4].

Measurements of optical turbulence at Fraunhofer IOSB in Ettlingen have a long tradition [5-7]. More specifically, the research group Optics of the Atmosphere carries out vertical and horizontal turbulence measurements in various climates around the World in order to predict the performance of imaging and laser systems when deployed in less-than-perfect conditions. On the other hand, the Adaptive Optics group focuses on turbulence correction, in software and in hardware. The overlap between the research themes of both groups is therefore significant. This overlap forms the topic of this paper. Specifically: how information about average turbulence strength at the time of the observations can be used to maximize the performance of adaptive optics (AO) and image processing systems. This premise will be demonstrated by two examples: digital holographic wavefront sensor (DHWS) and estimation of turbulence strength directly from target images.

2. Digital holographic wavefront sensor
The most widely applied wavefront sensor for the measurement of turbulence-induced phase errors is the Shack-Hartmann sensor. This sensor has several advantages, the most significant being its clear principle of operation. On the other hand it has some limitations, namely the sensor relies on a time consuming matrix-vector multiply algorithm to reconstruct the wavefront, and secondly the error rate of the wavefront reconstruction algorithm becomes significant with the onset of strong scintillation which causes obscuration or saturation of sections of the detector [8].
An interesting alternative is the holographic wavefront sensor [9-11] which directly measures the strengths of the Zernike modes, hence avoiding extra processing time. Several approaches have been proposed with regard to the core of this sensor, i.e. the diffractive optical element (DOE) which contains the holograms of one or several Zernike (or actuator) modes. The two main categories of these approaches are concerned with the type and generation method of the hologram, i.e. analogue, using a holographic plate, or digital, using a multiplexed computer generated hologram (CGH). The former approach has the advantage of low cost and high spatial resolution, while the latter offers more flexibility. It is this flexibility (or adaptability) which is the focus of the current communication. Other properties of the DHWS which we have tested, e.g. its insensitivity to scintillation, are described in detail elsewhere [11].

The implementation of holographic wavefront sensor for one wavefront aberration is as follows: with one DOE, two holograms are recorded one after another. The object beams are symmetrically arranged converging beams – they form two foci (called here \(A^+\) and \(A^-\)) behind the hologram plate where the detector(s) will subsequently be positioned (figure 1). The reference beams are collimated and have conjugated wavefronts (with phases \(2\pi a Z_i(x,y)\) and \(-2\pi a Z_i(x,y)\)) corresponding to a specific Zernike mode \(Z_i\). For the first hologram, the amplitude of the chosen aberration is \(+a\), where \(a\) is the maximum amplitude of the chosen mode that the sensor will be able to measure. For the second hologram, the amplitude is \(-a\). After recording, this setup consisting of DOE and two detectors per mode can be used as wavefront sensor. The incoming light will be diffracted into positions \(A^+\) and \(A^-\). The normalized difference of intensities \((I_{A^+} - I_{A^-}) / (I_{A^+} + I_{A^-})\), integrated over a small area on the detector, is proportional, within a certain range, to the amount of the aberration mode contained in the input wavefront.

![Figure 1](image.png)

**Figure 1.** Recording scheme of one aberration mode in the holographic wavefront sensor, from [11].

There are two properties of holographic wavefront sensor which were just alluded to in the above paragraph: (1) its operation is bound to a range \(\pm a\), unless one can change \(a\) after hologram recording, and (2) the operational characteristics of the sensor such as sensitivity or linearity are connected to integration area on the detector, in case of a CCD or CMOS array, or to pinhole/light-sensitive area in case of avalanche photodiodes. Both of these properties have been extensively tested in [11] and we only give a summary here.

The advantage of the DHWS is that its properties can be changed on the fly (“adaptable adaptive optics”). These include: the number of Zernike modes sent to the spatial light modulator (SLM), and the range of operation \((a)\). One may want to decrease the former if turbulence gets stronger, while the former could be made smaller after the AO loop is closed in order to increase both linearity and sensitivity of the sensor to AO residual aberrations.

Defocus-only DHWS is shown in figure 2. It consists of a beam expander, a defocus generation system, CGH displayed on the SLM and the CCD. The two images on the camera corresponding to the defocus channel are separated by 16 mm and the plane of the camera is placed 800 mm from the SLM. In this experiment, \(1.4\lambda\) has been chosen for \(a\) to be encoded in the CGH. Previous measurements of
the atmospheric conditions in Ettlingen, Germany, showed that this amplitude range is sufficient to cover the defocus variability over our paths of interest but the range can be very easily changed by sending new holograms to SLM when turbulence gets stronger.

Figure 2. Top: Setup used for DHWS calibration and defocus measurement. Bottom: diagram of the same setup. Insets: (A) Multiplexed CGH after the mod $2\pi$ operation is applied; (B) Three-dimensional representation of the CGH and therefore of the optical wavefront after being diffracted by the SLM. From [11].

3. Self-calibrating turbulence mitigation in software

Image restoration methods such as speckle imaging [12,13], Richardson-Lucy deconvolution [14,15], Wiener-filter deconvolution [16] and others rely on the availability of a PSF, or in general, a transfer function. This transfer function combines the effects of: diffraction by the sensor’s aperture, turbulence, and static aberrations of the imaging system.

The turbulent PSF is completely specified by known optical parameters, such as observing wavelength and the aperture of the sensor, and one unknown describing the integrated effect of the atmospheric turbulence between the source and the observer. This unknown is usually the Fried’s parameter $r_0$.

In night-time astronomy usually an unresolved reference star is observed simultaneously with, or after the target to naturally provide an estimate of the PSF. Solar observations unfortunately do not provide reference point sources. Same is true for surveillance applications. In ground-to-ground scenarios, methods based on image motion are most commonly used [17] but their accuracy is limited by non-atmospheric sources of image jitter (such as platform vibration, movement).

Object-cancelling transformation, as a way of removing object being observed from the image formation equation, was first proposed by von der Lühe [18]. We proposed an original transformation, which we call “Fourier contrast” method [19]. This transformation is more accurate than the original spectral ratio [18] and additionally it is insensitive to image motion.
Image formation equation, expressed in the Fourier domain, is:

\[ I(\mathbf{u}) = O(\mathbf{u})H(\mathbf{u}) \]  \hspace{1cm} (1)

where \( \mathbf{u} \) is a spatial frequency vector in the Fourier plane and \( I(\mathbf{u}) \), \( O(\mathbf{u}) \) and \( H(\mathbf{u}) \) stand for Fourier transforms of the (instantaneous) image, object, and speckle PSF, respectively. For each frequency we calculate the mean values and standard deviations of the power spectra:

\[ C_j(\mathbf{u}) = \frac{\text{var}([I(\mathbf{u})]^2)^{1/2}}{\langle [I(\mathbf{u})]^2 \rangle} = \frac{\text{var}([O(\mathbf{u})]^2)^{1/2}}{\langle [O(\mathbf{u})]^2 \rangle} = \frac{\text{var}([H(\mathbf{u})]^2)^{1/2}}{\langle [H(\mathbf{u})]^2 \rangle} \]  \hspace{1cm} (2)

where \( \langle \cdot \rangle \) denotes average and \( \text{var} (\cdot) \) denotes variance. We use the term “contrast”, and denote it with letter \( C \) as is customary in research pertaining to speckle. The object’s information gets cancelled and one only needs to have models of the quantities on the right-hand side of equation (2) which involve a set of known parameters like telescope aperture or observation wavelength and one unknown, that is \( r_0 \).

We used this approach to estimate turbulence strength from observations of quasi-point sources (figure 3) where the estimation could be done globally, on the whole image, and extended, anisoplanatic scenes, where local estimation on isoplanatic fragments of the scene was necessary (figure 4). Subsequently, we used bispectrum image restoration technique to recover sharp representations of the objects. The whole process was therefore automated, and no parameter had to be tweaked to obtain these results.

**Figure 3.** Left to right: 1-, 2.5- and 5-cm source. Top to bottom: long exposures, short exposures, and bispectrum reconstructions. Data taken over 2.5 km horizontal path. The sources are white-light lamps.
4. Conclusions and outlook
We demonstrated the utility of knowledge of average turbulence strength, even for adaptive optics systems which should be able to correct turbulence in real time. Also for turbulence correction software it is extremely useful to know $r_0$ or $C_n^2$ at the time of the observations. Work is underway to build demonstrators utilizing the ideas described in this paper.

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