Low-order adaptive optics: a possible use in underwater imaging?

M. L. HOLOHAN, J. C. DAINTY

The possibility of applying adaptive optical technology to underwater imaging is discussed. An introduction to the history and problems associated with imaging through turbulence is outlined. Trends in low-cost adaptive optical technology and results from a system applied to the correction of water generated turbulence are presented. The aim of this paper is to demonstrate the current solutions used in the correction of atmospheric turbulence in the hope of applying these same techniques to underwater imaging and communications. Copyright © 1996 Elsevier Science Ltd.

KEYWORDS: adaptive optics, underwater imaging, turbulence

Introduction

Adaptive optics (AO) is the name given to optical systems which continually measure and monitor incident wavefronts and apply real time compensation in order to compensate for the effects of a turbulent transmission medium and maintain beam or image quality¹-². As one can see from Fig. 1 an adaptive optical system consists of three components, namely:

- a wavefront sensor—a Shack–Hartmann and a curvature sensor are the two most commonly used in astronomical imaging. These sensors measure the derivative or Laplacian of the incident wavefront phase;
- a wavefront modifier—this is usually a deformable mirror which will try to compensate for the perturbations in the wavefront which were caused by its passage through the atmosphere. It does this by taking the shape of the conjugate of the perturbed wavefront which gives the original wavefront upon reflection;
- a control system—this converts the signals from the wavefront sensor into mirror commands to correct the turbulence in an intelligent fashion.

The Shack–Hartmann wavefront sensor is shown schematically in Fig. 2. An array of lenslets focus a plane wavefront into an array of spots with each spot along the optical axis of a lenslet. Any deviation from normal incidence in the lenslet sub-aperture (local tilt) will cause a spot to be focused at an off-axis point whose position is proportional to the magnitude of the local tilt at the sub-aperture. From this information the wavefront can be reconstructed and the appropriate signals sent to the wavefront modifier.

The problem of astronomical imaging

Since the earliest days of astronomical imaging with large telescopes, astronomers noticed that the long-exposure of a science object-of-interest was blurred. From diffraction theory, when one considers a plane wavefront passing through a circular aperture then one would expect to see the familiar Airy pattern as shown in Fig. 3. The angular resolution associated with this Airy pattern using the Rayleigh criterion gives the equation

\[ \Omega_a = \frac{1.22\lambda}{D} \]

where \( \Omega_a \) is the minimum angular separation between two points which are said to be resolved, \( \lambda \) is the wavelength at which one is observing and \( D \) is the diameter of the telescope. This is the theoretical limit at which perfect optics operate and if this is achieved then the system is said to be diffraction-limited. Unfortunately this is rarely the case. From Fig. 3 it is evident that the image can be highly degraded. The Airy pattern becomes a speckle pattern and the parameter, which is now used to determine the resolution of a telescope, is called Fried's parameter, \( r_0 \). It is defined as the diameter of a telescope at which atmospheric turbulence rather than diffraction effects limit the resolution of an imaging system. The resolution criterion now becomes \( \Omega_a = 1.22\lambda/r_0 \) and at optical wavelengths (~ 0.5 μm), \( r_0 \) has a value of the order of tens of centimetres in good night-time observing conditions.
Atmospheric turbulence

The atmosphere, just like water, is a fluid and has an associated Reynolds number, \( R_e = \frac{V_0 L_0}{\nu_0} \), where \( V_0 \) is the characteristic velocity of the fluid flow, \( L_0 \) is the flow’s characteristic size and \( \nu_0 \) is the kinematic viscosity of the air. When \( R_e \) exceeds a critical value the flow turns from laminar to turbulent. In normal atmospheric conditions the air is in a state of fully developed turbulence. Kolmogorov\(^4\)\(^5\) postulated that when the air is in a turbulent state, kinetic energy is transferred into smaller and smaller motions. Eventually, on a very small scale this energy transfer mechanism is replaced by viscous friction. \( V_0 \) is driven by local temperature variations in the atmosphere which leads to an associated change in refractive index. In fact, the atmosphere’s refractive index is considered to have a mean value together with a randomly fluctuating component. This gives random phase variations in an incident wavefront making atmospheric turbulence characterization a statistical problem. The Kolmogorov model compares the mean square velocity between two points separated by a vector \( r \). If one assumes that \( r \) is small, the air is locally isotropic and incompressible then these velocities can be related to the refractive index via a refractive index structure function, \( D_n \). Tatarskii\(^6\), deduced the equation

\[
D_n(r) = C_n^2(r) r^{2/3}
\]

where \( C_n^2 \) is the refractive index structure constant.

The integral \( \int_0^H C_n^2(h) dh \) determines the strength of the turbulence. \( C_n^2 \) varies with height, location and time. Fried\(^5\)\(^7\)\(^8\), assuming Kolmogorov turbulence, defined the parameter \( r_0 \) mentioned above to be

\[
r_0 = \left[ 0.432 k^2 \sec(\beta) \int_0^H C_n^2(h) dh \right]^{-3/5}
\]

where \( H \) is the depth of the atmosphere, \( k = 2\pi/\lambda \), and \( \beta \) is the zenith angle of the observed science object. From the definition of \( r_0 \) it can be shown that

\[
\lambda 0 \propto \lambda^{6/5}
\]

This implies that infrared astronomical images are degraded less than visible ones under the same turbulence conditions using a given telescope diameter.

Overcoming turbulence

In the astronomical community there are currently three methods of retrieving diffraction-limited images from wavefronts which have traversed a turbulent medium. These are as follows.

- Going outside the atmosphere altogether, as is the case with the Hubble Space Telescope. This is an expensive procedure and there is no analogue for underwater imaging.
- The method of post-processing. This involves taking a large number of short exposure images and applying image processing techniques such as speckle interferometry\(^5\)\(^9\) or using high order statistics such as bispectral imaging\(^10\)\(^11\). The problem with these methods is that although near diffraction-limited images have been obtained, these cannot be done in real time and they work best on point-like sources.
- Adaptive optical systems, which have been described above. These try and give real-time corrected images. However, the systems used in astronomy are generally highly complex and the cost of achieving full correction in real time is prohibitive. Low-order adaptive optical systems are less ambitious systems which give real-time correction of low frequency and low-order aberrations while allowing the possibility of further post-processing at a later time. In the atmosphere, as most of the energy is in the low-order aberrations\(^12\), it is hoped that these systems will be adequate for some non-astronomical applications such as line-of-sight communications, laser beam correction and shaping, or underwater imaging.
A low-order AO system

The current system being developed in our laboratory has its emphasis stressed on simplicity and low cost. It is controlled by a standard personal computer with a Pentium processor. The program to control the system was written such that it can be used in the Microsoft Windows environment. The active elements are two piezoelectric mirrors which were manufactured at the International Laser Centre (ICL), Moscow State University, Moscow, Russia. The first mirror compensates for tip/tilt only while the second, a 17 electrode bimorph deformable mirror (BDM), corrects other low-order aberrations. Each mirror is operated in the voltage range ±150 V.

The preliminary system set out to correct laboratory generated turbulence in the form of a heated water tank and is shown in Fig. 4. The water tank consists of two plates separated by a distance of 5 cm. The top plate is cooled while the lower plate is heated. A collimated laser beam is passed between these plates and then into the system. The system attempts to maintain the focal spot at a pinhole thereby maximizing the recorded intensity. A simple hill-cllimbing algorithm is used to maximize the energy through a pinhole. There are a total of 19 electrodes to be manipulated. For each electrode a random voltage direction is chosen and the signal is evaluated. If the signal has improved then this direction of application is chosen, otherwise the opposite voltage direction is applied. This is repeated for all electrodes.
Initial results

Results from this low-order adaptive optical system in correcting static aberrations are shown in Fig. 5 while the performance at correction turbulence is shown in Fig. 6. For the correction of static aberrations as shown in Fig. 5 an absolute maximum was found by careful manual adjustment of the beam. This corresponded to a diffraction limited spot passing through the pinhole producing a normalized intensity value of 1. From there the beam was aberrated by the addition of some tip-tilt and defocus. This reduced the intensity of the beam to a normalized value of 0.34. The AO system was then switched on and operated on this aberrated beam. The results show that a much higher intensity was found with complete correction giving a value of 0.73. To a first approximation these values correspond to Strehl ratios. At this value the electrodes were operating at their maximum swing implying that the original diffraction limited beam was beyond the range of the mirrors working from the aberrated reference.

The same procedure was repeated a number of times with the water tank switched on and the results are shown in Fig. 6. The normalization procedure described above was repeated on the results. From Fig. 6 one can see that the system was capable of improving the intensity (Strehl) of the aberrated reference beam up to a temperature difference of 10 K between the plates. Above 10 K the AO system performance decreases rapidly, implying that the focal spot was breaking up into a large speckle pattern from which the AO system could not operate.

Possible application to underwater optics

Light propagation in the sea has many similarities to propagation in the atmosphere. However, unlike atmospheric imaging there is the problem of beam attenuation through the mechanisms of scattering and absorption. Scattering is due to small suspended biological organisms whose refractive index is close to that of water. Attenuation at visible wavelengths exhibits a minimum absorption centred at 478 nm. In such conditions, attenuation lengths of less than 10 m are not uncommon.

Clear sea water which is free of these suspended particles exists in many places, particularly in the Caribbean. This type of water is still inhomogeneous due to random
temperature and salinity variations and Yura\textsuperscript{17} stated that, in this type of underwater environment, turbulence may be a major factor in loss of resolution of imaging systems. No data are readily available on saline variations so only temperature variations are considered. Changes of the order of tenths of a degree with a scale size, $a$, of tens of centimetres are not uncommon. These effect the modulation transfer function (MTF) by cutting out higher spatial frequencies. Considering a spherical wave, the MTF, $M(p, R)$, of clear water can be expressed as

$$M(p, R) = \exp(-k^2p^2(\Delta n^2)/4a)$$

where $p$ is the transverse distance in the pupil at a propagation distance $R$, $k$ is the optical wave number, $k = 2\pi n/\lambda$. From this equation a Gaussian beam profile can be examined in the Fresnel regime and Yura also found that

$$\theta_0^2 = (\Delta n^2)R/6a$$

where $\theta_0$ is the angle corresponding to a standard deviation of the Gaussian beam. For typical values of $a = 50$ cm, $\langle \Delta n^2 \rangle = 10^{-5}$ and $R = 20$ m; this angle has a magnitude of a few tenths of a milli-radian. In the absence of this turbulence the angular resolution, $\lambda/D$ has a magnitude of a few hundredths of a milli-radian ($\lambda = 500$ nm, $D \approx 50$ cm). So underwater turbulence reduces the attainable resolution by an order of magnitude. From this one can estimate underwater turbulence to have an equivalent $R$ of some millimetres. This means that any underwater optical system with an entrance pupil greater than a few millimetres and imaging objects a few metres away will be severely affected by underwater turbulence as well as scattering and attenuation.

Underwater turbulence is driven by convection currents in the sea rather than winds, as is the case with the atmosphere, so it is thought that the degradation of the image will be mainly low-frequency low-order aberrations and image motion. These could be corrected by low-order systems, as mentioned above, in particular optical underwater 'line-of-sight' links or systems that image the sea bed or illuminated structures. This illustrates a possible need for using AO in the underwater environment. Nevertheless, before any underwater AO system can be realized, problem scattering and signal attenuation should be addressed. One possible solution to the problem of scattering is to include a range-gated feature in the system while attenuation could be overcome by using an intensified CCD as the final detector.

References

10. Rddler, F. Triple correlations as a phase closure technique, Optic Comms, 60 (1986) 305–322
17. Yura, H.T. Imaging in clear water, Appl Opt, 12 (1973) 1061–1066