FROM DEFORMABLE MIRROR POINTING AT SKY TO UNDERWATER ACOUSTICS

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Due to air density variations, turbulence, eddies, and cross winds in the atmosphere, ground-based telescopes record temporal and spatial fluctuations of phase and amplitude of received stellar light. For astronomical imaging, the effects of the atmosphere result in aberrations of received light leading to blurring and other undesired affects. Using a complex optical system called adaptive optics, aberrations can be effectively reversed resulting in improved imaging quality. Similarities between the atmosphere and ocean are apparent when considered as a propagation medium for light or sound, respectively; both media are turbulent and governed by similar dynamic processes involving temperature gradients, pressure differentials, and other factors. Similarities also exist in the distortions that the changing medium produces on each wavefront. In presenting the adaptive optics solution that has improved ground-based astronomical imaging, this paper will propose that similar strategies could be utilized in underwater acoustics.

INTRODUCTION

In the recent past, the detrimental effects of the atmosphere severely limited the resolution of ground-based telescopes, with space-based telescopes the only alternative to overcome this problem. Although the Hubble Space Telescope has met this challenge with success, the expense of such an instrument is very large. In the past two decades, advances in various fields have enabled the feasibility of a technique known to be theoretically possible for 60 years, but, due to technological limitations at that time, impossible to implement. This technique is known as *adaptive optics*. Telescopes equipped with an adaptive optics system can compensate for the effects of the atmosphere, providing vastly improved imaging.

Prior to the advent of adaptive optics, the effects of the atmosphere resulted in wavefront aberrations leading to blurring and reduced image quality. The atmosphere imposes temporal and spatial fluctuations of phase and amplitude on stellar light as perceived by ground-based-telescopes. These fluctuations are caused by random fluctuations of the refractive index of the atmosphere resulting from air density variations, turbulence, eddies, and cross winds. Although atmospheric distortions still occur when using an adaptive optics system, distortions are sensed and corrected prior to final imaging. Using a corrective element called a deformable mirror, adaptive optic systems effectively realign the wavefront to one closely resembling that prior to incidence on the atmosphere.

In the field of underwater acoustics, a similar scenario exists, in which a turbulent medium causes undesired distortions on a wavefront travelling through water. Similarities between the atmosphere and ocean are apparent when considered as a propagation medium for light or sound travel, respectively; both media contain turbulence and are governed by the same dynamic processes involving temperature gradients, pressure differentials, and other factors. Therefore, similarities also exist in the distortions that the media cause. By examining the adaptive optics solution implemented by astronomers to solve this problem, this paper will recommend similar strategies drawn from adaptive optics could find valuable usage in underwater acoustics.

1. ORIGIN OF ADAPTIVE OPTICS

Adaptive optics originated in a prior concept called *active optics*. As early telescopes grew in size, their primary mirrors became increasingly thick and heavy, to minimize the gravity sag bending the parabolic mirror surface as the telescope rotated, conventional methods of telescope construction to provide sufficient structural rigidity became infeasible and too costly, giving rise to active optics. With this new concept a relatively thin mirror would keep its surface curvature by continuous action of multiple actuators pushing and pulling on the back of the mirror to counteract the gravity sag and keep the prescribed parabolic or hyperbolic shape. Active optics was a very useful technology; however, the distorting effects of the atmosphere remained uncorrected.

Following the concept of active optics, Babcock [1] proposed in 1953 that real-time compensation for both telescope alignment errors and atmospheric fluctuations could be accomplished using fast active optics continuously correcting for the effects of the atmosphere with adjustable optical components. This concept, known as adaptive optics, requires a system bandwidth up to 1000 Hz, compared to the active optics system bandwidth of less than 1 Hz [2]. Although Babcock was able to detail how an adaptive optics system would operate, due to the limitations of computer and other technologies of the time the concept became feasible only decades later.

The United States military was the first to use adaptive optics to image Soviet satellites and for this reason the research was kept classified. Upon de-classification of military research in the early 1990s, in conjunction with advances in computer power and optical technologies, adaptive optics found new use in the field of astronomy as a means to obtain improved image quality. As a result, adaptive optics has become a widely studied area of research and applied to nearly all modern telescopes.

The possibility also exists of applying similar strategies to large underwater acoustic arrays. Since only a finite precision of acoustic transducer alignment is attainable, a concept similar to that used in active optics can implement transducer position correction. Following this, a higher system bandwidth may also provide correction for fluctuating underwater channel effects.

2. ATMOSPHERIC EFFECTS AND ADAPTIVE OPTICS

The wavefront of light emitted from a star or other distant point-like object can be considered planar prior to reaching the atmosphere. As this wavefront travels through our atmosphere, spatial- and time-dependant refractive index variations, resulting from local fluctuations in atmospheric temperatures, pressure, and humidity, cause the light to bend. Local fluctuations are affected by wind speed, which is also random in time and space [3]. As a result, the initially plane wavefront becomes distorted, as shown in Figure 1. The distorted wavefront arriving at the telescope will create a blurred, time-varying image.

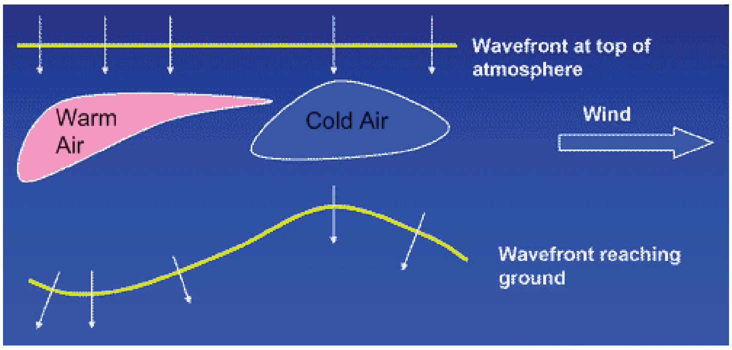


Fig. 1. Atmospheric effect on a wavefront [4]

The distorted wavefront contains spatial variations in both phase and amplitude. Phase variations are of most importance in image formation since image quality is largely determined by the extent to which phase distortions are present in the wavefront. Amplitude or intensity variations (also called scintillation) contribute much less to image quality degradation than do phase variations; as a result, adaptive optics systems do not yet correct for wavefront amplitude variations [2].

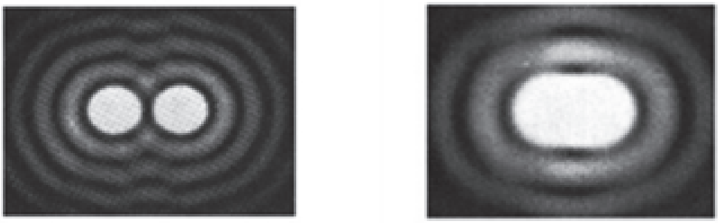
The extent to which atmospheric distortion degrades a telescope's ability to image clearly can be measured by its angular resolution, a figure that describes the ability to distinguish between two closely positioned objects. The angular resolution is typically given in arcseconds (or arcsecs). A typical telescope on earth subjected to atmospheric blurring can achieve an angular resolution of no more than 0.5 arcseconds at best [4]. The angular resolution without any atmospheric degradation or telescope flaws is still limited to the so-called diffraction limit, θ, related to the geometry of the telescope and the wavelength of the light observed. The angular resolution limit is due to the diffractive nature of light, which cannot be avoided.

$$\theta[rad] = 1.22 * \frac{\lambda}{D}[rad]$$

$$\theta[arcsec] = \theta[rad] * \frac{180}{\pi} * 60 * 60$$

where λ is the wavelength of the light observed and D is the diameter of the telescope's main lens (aperture).

Unfortunately, all ground-based telescopes suffer from atmospheric effects, leading to an angular resolution less than the diffraction limit, such as in Figure 2. For a 4-meter telescope, atmospheric distortion degrades the resolution by more than one order of magnitude from the diffraction limit [5]. However, telescopes utilizing an adaptive optics system are able to recover this loss of resolution leading to operation at the diffraction limit. These telescopes, therefore, achieve the best possible resolution for their given aperture.

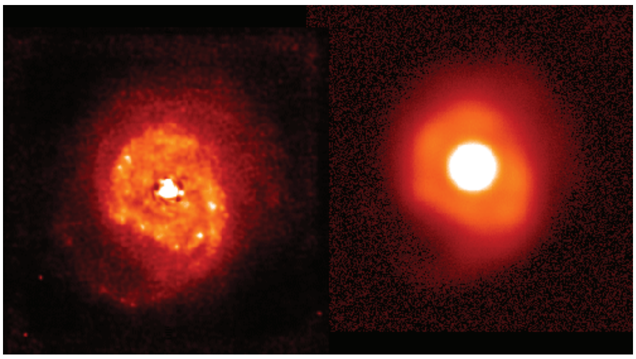


a) Good resolution b) Poor resolution

Fig. 2. Imaging a double star with various resolutions [6]

Since nearly all modern telescope designs now incorporate adaptive optics, resulting in operation at the diffraction limit, the current trend is to build very large aperture telescopes as this is the final means of improving the angular resolution further. This gives rise to the new class of extremely large telescopes such as the Thirty Meter Telescope (TMT) currently in design. Using a combination of adaptive optics and extremely large apertures, these telescopes will be able to achieve image resolutions vastly superior to that of previous instruments.

The improvement in resolution when utilizing adaptive optics is illustrated in Figure 3. This image is from the 3.6 meter Canada France Hawaii Telescope (CFHT) of the starburst galaxy NGC7469. Figure 3a, utilizing adaptive optics, demonstrates an angular resolution of 0.13 arcseconds; Figure 3b, on the other hand, shows the result possible with good ground-based telescope without adaptive optics and an angular resolution of 0.7 arcseconds. Clearly adaptive optics provides a large improvement in image resolution.

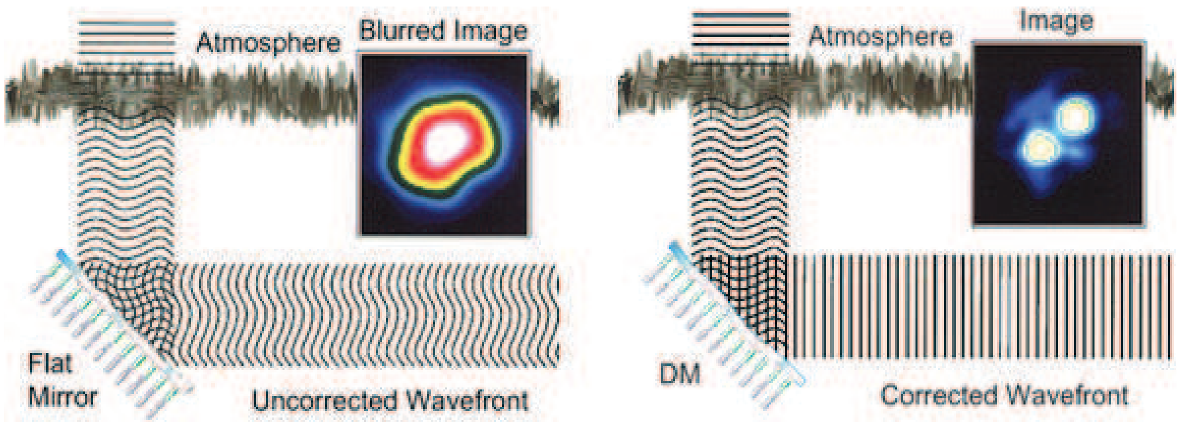


a) Adaptive optics image b) Image without adaptive optics

Fig. 3. Adaptive optics image enhancement in a CFHT image of starburst galaxy [7]

3. SYSTEM OVERVIEW OF ADAPTIVE OPTICS

A closed-loop control system is at the foundation of the adaptive optics concept, the essential components of which are a wavefront sensor, a deformable mirror (DM), and a controller. The deformable mirror has the task of cancelling phase distortions. The DM does this by applying small deviations spatially to its surface, as shown in Figure 4b. Physically, the surface of a DM is deformed by an array of piezoelectric actuators.



a) Uncorrected wavefront using flat mirror b) Corrected wavefront using DM

Fig. 4. Wavefront correction via a deformed reflecting surface [8]

Driving the DM is a control system that calculates the corrective action required by the DM using the information gathered from a wavefront sensor. The wavefront sensor measures any phase aberrations in a sample of light diverted from the primary light path using a beamsplitter. A typical adaptive optics system diagram is shown in Figure 5, with the control system loop indicated with a dashed line.

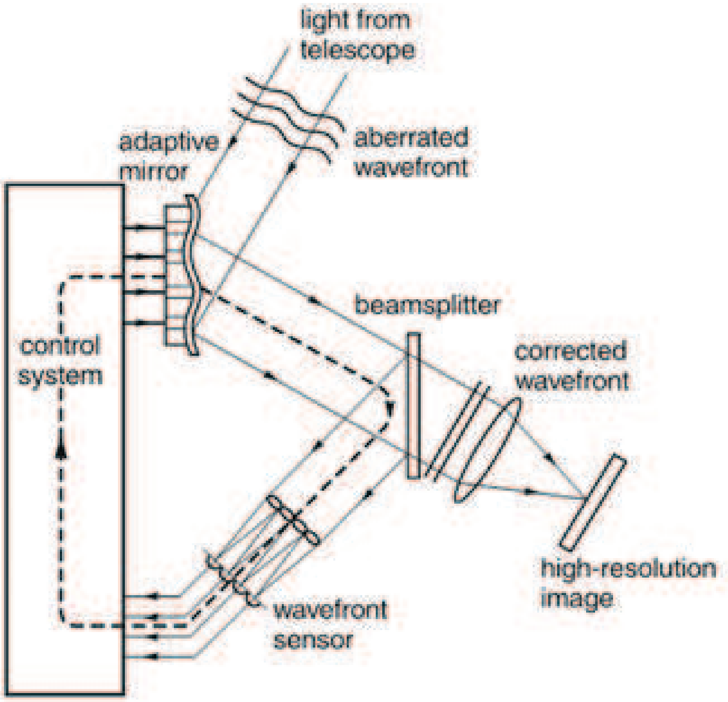


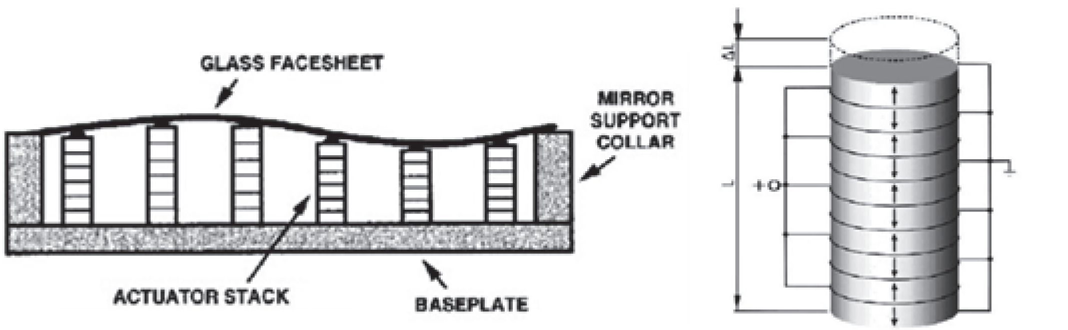
Fig. 5. Adaptive optic system diagram [9]

To operate the DM continuously, wavefront sensing is performed using a sufficiently bright reference light source called a guide star near a fainter or more diffuse target object . If no sufficiently bright natural guide star is available near the target object, an artificial guide star can be created using the backscatter of laser light from sodium atoms present in the high mesosphere [10]. This artificial reference is called a laser guide star or laser beacon.

4. DEFORMABLE MIRROR

The DM is the wavefront correcting component in an adaptive optics system and is the adaptive element of the system. Spatial variations of the surface of the mirror cancel phase differences by modifying the optical path length. Since an initially plane wavefront travelling 20 km through the turbulent atmosphere accumulates phase errors corresponding to a few micrometers of optical path, these have to be sensed and corrected to a fraction of a micrometer [5]. The stroke of the reflective surface of the DM is required to be on the same order, that is, between 3 and 10 micrometers, and achieve a displacement resolution of a fraction of a micrometer. For illustration, the width of a human hair is around 100 micrometers; the DM is capable of adjusting surface displacement by one-thousandth of this width. Advances in DM technology were a major contributor to the advancement of adaptive optics since DM performance is essential to the performance of the system as a whole.

Continuous face-sheet DMs driven by a 2-dimensional array of discrete actuators are most commonly used in astronomy; although other types of DMs exist, including micro-electromechanical systems (MEMS), bimorph and segmented DMs. The actuators are typically stacks of piezoelectric or electrostrictive materials coupled to the back surface of the mirrors face-sheet, as illustrated in Figure 6. Each actuator is mounted on a thick, common base plate, which is much stiffer than the mirror face-sheet, and which is usually made of a stable, low expansion material such as quartz.



a) DM cross-section [11] b) PZT actuator construction [12]

Fig. 6. Continuous face-sheet DM structure

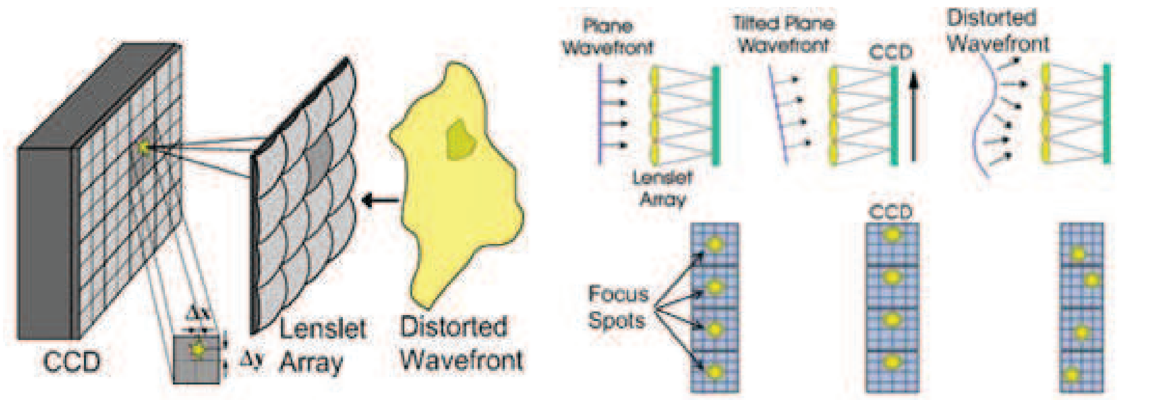
Typically, the piezoelectric actuator is comprised of PZT material. A complication of PZT actuators is the large voltage required to obtain a useful stroke. To increase stroke, the actuator is made in the form of disks stacked with alternating polarity and connected electrically in parallel so that the same voltage is applied across each disk, as shown in Figure 6b. Commonly used stack actuators achieve a relative displacement of up to 0.2% of its length [14]. Monolithic stacks formed of 100 or more layers with integral electrodes have been produced, each layer about 150 μm thick. This increases the electric field for a given applied voltage, producing a stroke of 15 μm for an applied voltage of 150 V. Typical devices are 20 mm long and 6 mm in diameter [13].

The scientific goals of the system determine the parameters of the array of actuators. For example, perfect correction for an observation done in visible light with an 8-meter telescope would require an array of 6400 actuators, whereas perfect correction in the near infrared would require 250 actuators [5]. The TMT uses two DMs based upon a 3125 and 4548 element array of actuators; these DMs will employ over twice as many actuators as any other mirror attempted to date [15]. A compromise in the number of actuators may be considered if the scientific goals are achievable while reducing system cost. Since an increased actuator count will necessitate a wavefront sensor with an increased resolution, the cost and complexity of separate components are interdependent on each other.

5. WAVEFRONT SENSOR

The wavefront sensor measures the distortion induced by the atmosphere by analyzing the light from a guide star. Astronomical wavefront sensors analyze stellar white light emissions therefore have to operate over a broad optical spectrum [2]. Since it is impossible to compare a wavefront incident on the atmosphere directly with that reaching a telescope, measurements which assess the (spatially) differential wavefront distortions within the telescope pupil are used [2].

Most commonly, wavefront sensors measure wavefront gradients (slope) to reconstruct wavefront distortions; this is the case for the Shack-Hartmann type of wavefront sensor which is most commonly used in astronomy. The sensor uses an array of lenses (lenslet array) in front of an charge-coupled device (CCD); see Figure 7a. A small sample of the light is diverted to the lenslets using a beamsplitter as illustrated in Figure 5. Each lenslet then focuses a segment of the light onto the CCD.



a) Shack-Hartmann wavefront sensor structure [8] b) Detection of wavefront tip/tilt distortions [16]

Fig. 7. Shack-Hartmann wavefront sensor

The converging beams of lenslets form a regularly spaced matrix of focused spots on the CCD, as shown in Figure 7b. Any local wavefront curvature will yield displacements (Δx, Δy) of the focused spots on the CCD relative to their expected centred locations, as illustrated in Figure 7a. Based on the spot displacement measurements the distorted wavefront shape can be derived mathematically.

A common displacement vector detected on every focused spot indicates that the incoming wavefront is not parallel to the desired plane of incidence and requires correction; see Figure 7b. Tipping and tilting a gimbal mounted mirror will correct this distortion. The remaining displacement errors will not have any commonality and will require independent local corrective action. Local shape manipulations on the surface of the DM will make these corrections.

The structure of a wavefront sensor does not translate well into an acoustic system since it operates strictly on optical properties; however, other means of determining phase variations of acoustic signals exist. Since acoustic signals are of a lower frequency than light, direct phase measurement by signal processing methods could determine relative phase differences between signals from each element of an acoustic transducer array.

6. ADAPTIVE OPTICS TEMPORAL CONSIDERATIONS

Wind velocities at various heights in the atmosphere determine the minimum update rate of an adaptive optics system, since turbulent elements passing through the line-of-sight of the telescope generally live longer than the time it takes for them to move across their own diameter [2]. A minimum system update rate can, therefore, be determined by the radius of these atmospheric fluctuations, $r_{0,}$ known as the Fried parameter (or atmospheric coherence radius) and the wind velocity, shown in Figure 8.

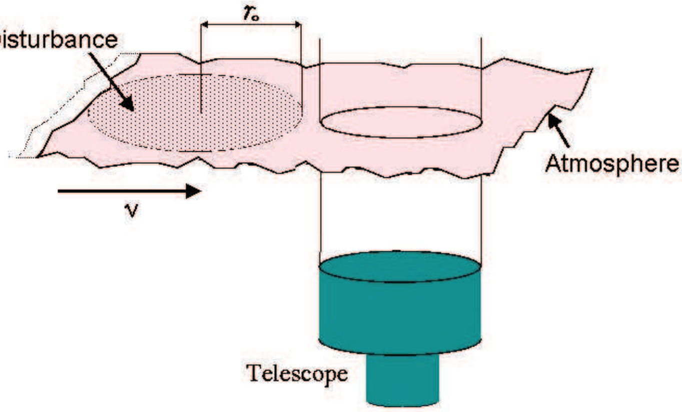


Fig. 8. Atmospheric fluctuations experienced by telescope [18]

Since the wind directions and velocities vary with height, the temporal behaviour of the wavefront is complex and hard to characterize [2]. However, it is often described by an average velocity, ν, which is typically considered 10m/s [17]. From these two parameters, the typical expected atmospheric coherence time, $\tau_{0,}$ can be found as:

$$\tau_0 \cong 0.31 * \frac{r_0}{v}$$

The distortions are considered to remain unchanged for the duration of the coherence time. On an average night at an astronomical observatory, typical coherence times are expected to be around 30 ms at visible wavelengths. To monitor and then remove distortions, the electro-optic control system must operate at least 10 times faster than the atmospheric changes [19]. Typically, an adaptive optic system will operate up to around 1000 Hz.

Increasing the system bandwidth further will provide improved phase correction; practically, however, performance trade-offs must be considered since a higher system update rate would require a faster wavefront sensor read-out rate, resulting in a reduced integration time yielding fewer photons collected per cycle. As a consequence, the wavefront sensor noise increases [11], requiring a more sensitive and expensive wavefront sensor.

7. ACOUSTIC APPLICATION

Development of an *adaptive acoustic* system employing techniques similar to those used in adaptive optics may be possible considering the apparent similarity between the DM and an acoustic piezoelectric transducer array, as well as the similarities between the propagation phenomenon. The implementation of two types of acoustic systems is possible; the difference between the two is analogous to the differentiation between active and adaptive optics systems.

An *active acoustic* system could serve to align individual transducer elements that may be misaligned due to assembly inaccuracies or environmental effects. This type of system would be most useful when applied to a large array of acoustic transducers with alignment deviation between elements of the array and where, due to the number of elements, manual adjustment would be time consuming. Implementation of an adaptive acoustic system would require a bandwidth greater than that of the active system, as well as a means of wavefront sensing. Such a system should accomplish acoustically what the adaptive optics system achieves optically; that is, to provide images free of distortion due to underwater currents, turbulence, and temperature variations. In the case of adaptive optics, the piezoelectric actuator modifies the optical path length, which directly affects the electrical signal at the detector. Considering the acoustic equivalent, the piezoelectric element itself directly converts the incoming acoustic wave into an electrical signal, essentially acting as both the DM reflecting surface and the image detector.

Phase re-alignment would occur in a manner identical to that of adaptive optics, by displacing the transducer itself to adjust the acoustic path length. Displacement adjustments of the transducer could be achieved either by a separate stacked PZT actuator upon which the piezoelectric acoustic transducer is mounted, or by applying a bias voltage to the transducer itself to expand and contract the piezoelectric material of which the transducer is composed. However, these possibilities are limited by the stroke achievable using a PZT structure which is required to be a fraction of a wavelength. Acoustic signals have a much larger wavelength than light; as a result, an alternative actuator capable of larger stroke is required. Although specific applications of an adaptive acoustic system remain for discussion, uses in sonar imaging or flow and turbulence measuring, among other possibilities, are plausible.

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