Applications of Astronomical Adaptive Optics Techniques to Reducing the Effects of Acoustic fluctuations

Applications des techniques optiques adaptatives à la réduction des effets des fluctuations acoustiques

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Abstract

Acoustic fluctuations due to turbulence and internal waves known to limit the bearing resolution and detection capabilities of a sonar. Similar problems exist in astronomy, and techniques have been developed by astronomers (the « guide star ») with which to sense the errors. Such an approach is obviously not relevant to sonars, but more recent approaches use artificial beacons generated by ground–based lasers. It seems likely that an active sonar could use sound scattered from within the volume of the ocean to generate an underwater artificial beacon analogous to the astronomical laser guide–star, thus making it possible to sense and compensate for medium induced fluctuations. This paper discusses such a scheme.

Key words : Atmospheric Optics, Fluctuations, Imaging, Resolution, Scintillation, Sonar, Telescopes, Underwater Acoustics.

Résumé

Les fluctuations acoustiques dues aux turbulences et aux ondes internes sont connues pour limiter les capacités de définition et de détection de relèvement d'un sonar. Des problèmes similaires existent en astronomie et les astronomes ont développé des techniques pour contrebalancer les turbulences atmosphériques en utilisant une étoile brillante comme balise, « l'étoile–guide » grâce à laquelle ils détectent les erreurs. Cette approche ne s'applique bien entendu pas aux sonars, mais les méthodes plus récentes développées pour aborder ce problème utilisent des balises artificielles produites par des lasers basés sur terre. Il semble probable qu'un sonar actif pourrait utiliser le son dispersé dans le volume de l'océan pour produire une balise artificielle sous–marine analogue à l'étoile–guide laser utilisée en astronomie, ce qui permettrait de détecter et de contrebalancer les fluctuations créées par le milieu. Cet article discute de ce projet.

***Mots clés :** Optiques atmosphériques, Fluctuations, Prise d'Images, Définition, Scintillation, Sonar, Télescope, Acoustiques sous–marine.*

1. Introduction

In underwater acoustics, fluctuations are caused by internal waves, turbulence, and other oceanographic phenomena, and they impose a limit on sonar and other underwater systems. The amplitude fluctuations bring about signal fading and the failure to detect targets well within the theoretical range of the sonar, whilst phase fluctuations cause a loss of directivity or angular resolution of receiving arrays, spreading of transmitted beams, variations in the apparent arrival direction of signals and fluctuations in their arrival time.

The causes of fluctuations and their effects on wave propagation have been the subject of much research in the fields of sonar, radar, astronomy and laser propagation. In underwater acoustics the existence of fluctuation phenomena has been demonstrated experimentally for a variety of causes [1]. The resulting degradation of system performance, however, and means of overcoming it, have received much less attention. Probably the most significant problem is loss of angular resolution [2]. Fluctuations limit the directivity of an array, which means that there is a maximum useful size for an array in any particular environment — generally about 50–100 wavelengths [2], giving 0.5–1.0° angular resolution. No increase in gain or angular discrimination can be obtained by making the array larger.

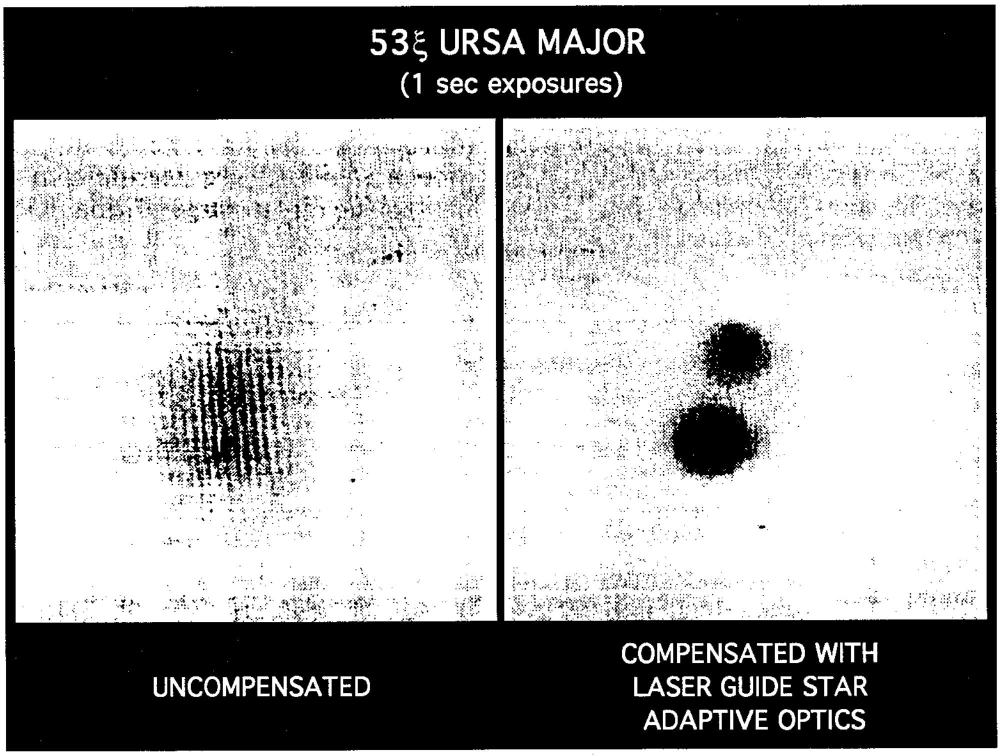

Figure 1. – Compensated and uncompensated images of a binary star (after [5]).

Loss of resolution caused by wavefront fluctuations is also a problem in astronomy. Turbulence in the atmosphere limits the effective aperture of a telescope to 5–10 cm (1–2 arcsec angular resolution) at visible wavelengths. Telescopes with larger apertures are only useful for their light gathering properties. Techniques were developed by astronomers some time ago to compensate for atmospheric turbulence by using a bright star as a reference beacon, or guide star, to sense the wavefront distortion [3]. Such an approach is obviously not directly applicable to sonar — a suitable reference source is not likely to be available. More recently, however, new astronomical systems have been developed and these use artificial beacons generated by scattering ground–based laser beams from the upper atmosphere [4]. It is feasible that an active sonar could use sound scattered from within the volume of the ocean to generate an underwater artificial beacon analogous to the laser guide star. It should, in principle, be possible to sense and compensate for medium induced signal fluctuations.

2. Artificial Beacons

The principle behind the laser guide star technique is to measure optical wavefront distortion caused by atmospheric turbulence, by taking « snapshots » of an artificial guide star formed by light scattered from a laser beam focused in the upper atmosphere. The principle has been demonstrated experimentally and Figure 1 shows an example of compensated and uncompensated images of the binary star 53 ξ Ursa Major (two objects with an angular separation of 1.3 arcsec) obtained when atmospheric conditions limited uncompensated visible wavelength resolution to worse than 2 arcsec [5]. Clearly, the compensation mechanism separates the two objects, which were previously unresolved.

The essential features of the system are show in Figure 2. The optical system is a conventional telescope with the addition of the laser and the deformable mirror. The laser beam is focused in the upper atmosphere where it generates an artificial beacon, either by Rayleigh backscatter at low altitudes, or by resonant scattering from the sodium layer at higher altitudes. The backscattered light is collected by the telescope mirror and sent to the wavefront sensor. The control system switches on the sensor at a time after the pulse was transmitted corresponding to the focusing altitude and for a period corresponding to a beacon length of about 1 km in the sky. The sensor measures a frame of wavefront phase, which is sent to the controller which computes the necessary compensation and controls the deformable mirror. The incident light from the star being observed is recorded by the star imager, via the adjusted deformable mirror, and then the process is repeated.

Astronomical systems operate under a number of constraints. The first of these is the time scale of atmospheric fluctuations. This is determined by the spatial scale of the turbulence and the wind speed and its typically of the order of a few milliseconds. The second is referred to as focal anisoplanatism. This relates to the concept of the far field in acoustics and means that propagation

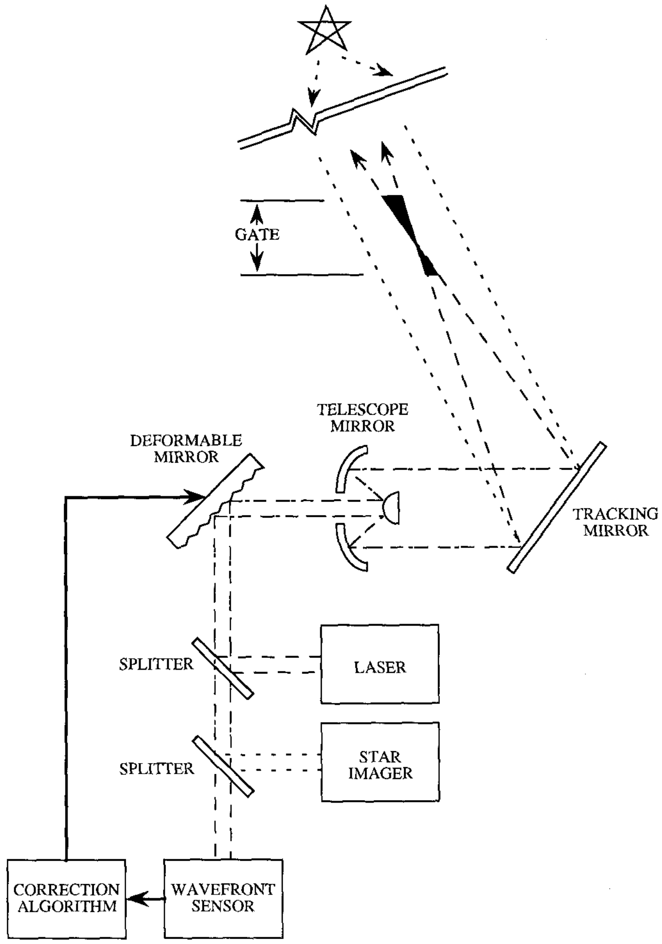

Figure 2. – Essential features of the laser guide star system.

distances from various points on the object being observed to the observation point should not deviate by more than a small fraction of a wavelength. It has been found that for optical systems this variation should not exceed $\lambda/25$.

3. Underwater application

In principle, the artificial guide star concept is applicable to active sonars using scattering from the water volume to create the artificial beacon. Figure 3 shows a sonar implementation that is a direct analogue of astronomical system, although architectures more appropriate to sonar technology are possible. Such systems would be subject to similar constraints to the optical case. Because the mechanisms that cause underwater acoustic fluctuations are much slower than atmospheric turbulence, the operating speed of the system is not likely to present problems, although the slow propagation velocity of sound in water may be significant. Other areas also require investigation to prove the feasibility of the technique, and the maximum allowable size of the artificial beacon and appropriate signal processing are discussed below.

3.1. BEACON SIZE

The artificial beacon must be small enough to look like a point source; any increase in angular size leads to a decrease in the level of fluctuations at the receiver. The main reason for this is that signals from different points on the beacon travel over slightly different paths to the receiver. The receiver then effectively averages these different components, smoothing the fluctuations to an extent that depends on the correlation between the different paths, and hence on the size of the artificial source.

Because the effect of acoustic fluctuations depends upon the spatial distribution of phase and amplitude variations across the array [2], a useful indicator is the spatial correlation function $\rho(r)$. This gives the cross–correlation between the fluctuations at two points in the plane of the array separated by a distance r. The scale size of the fluctuations at the receiver, r_s, is defined as that separation for which $\rho(r)$ falls to $1/e$ of its value at $r = 0$, and for the case of fluctuations caused by a thin scattering layer, this is given by $r_s = r_0(1 + h^2 + bF)^{\frac{1}{2}}$ [6], where $F = \frac{4z}{r_0^2 k}$, $h = \sqrt{2}\left(\frac{z\phi_0}{2r_0}\right)$, r_0 is the mean scale size of the sound speed variations in the medium, k is the wavenumber ($= \frac{2\pi}{\lambda}$), b is the fractional bandwidth of the signal, z is range and ϕ_0 is the angle subtented by the artificial beacon at the receiver. This result is valid for any form of wave propagation in a random medium. However, because the ocean is not a thin scattering layer, but an extended scattering medium, the effects of fluctuations require integration over the entire propagation path to obtain a precise value for r_s. Nevertheless, the formula may be used to obtain approximate values for the scale size of the fluctuation pattern across the array, and this is r_0 for a point source and monochromatic radiation. A finite beacon size and finite bandwidth increase the scale size by a factor $(1 + h^2 + bF)^{\frac{1}{2}}$.

As an example, a minehunting sonar operating at 100 kHz and having a transmitting beamwidth of 1° is considered. The system bandwidth is taken as 2%, although this can be increased up to 20% without significantly affecting the results. The effect of ocean inhomogeneities on acoustic propagation depends upon the frequency, the range and the particular environment [2], but it may be assumed that for a high frequency short range system the main contributor is turbulence with a 1 m mean scale size.

The effect of a finite beacon size is shown in Figure 4, where the relative increase in scale size is plotted against angular beacon width (or transmitting beamwidth) at ranges of 50, 100 and 200 m. If a relative increase in scale size of say 1.5 is allowable, it is seen that a width of 1° is acceptable at ranges up to about 100 m. Thus, the nominal beamwidth of this system would form a small enough artificial beacon out to moderate ranges. For greater ranges a smaller beacon would be needed — reducing the beamwidth by a

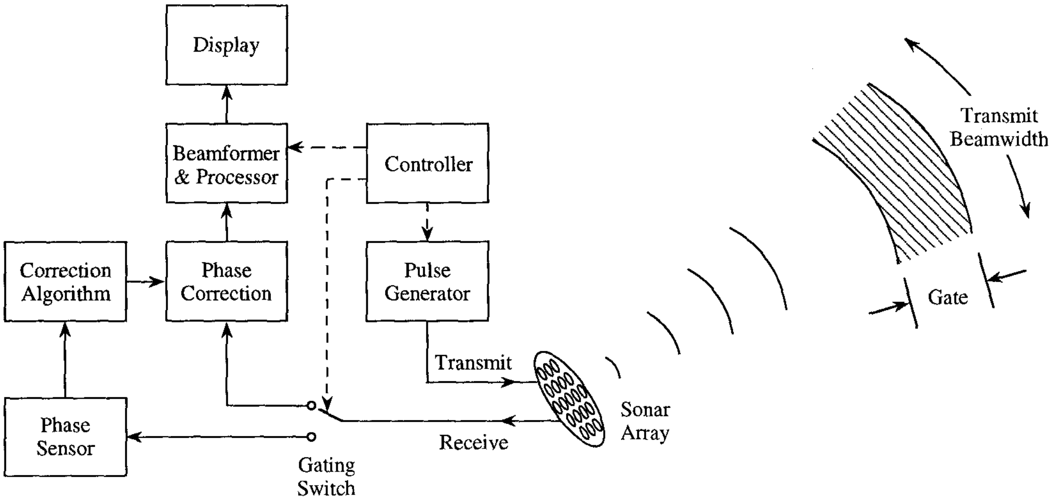

Figure 3. – Sonar analogue of astronomical laser guide star system.

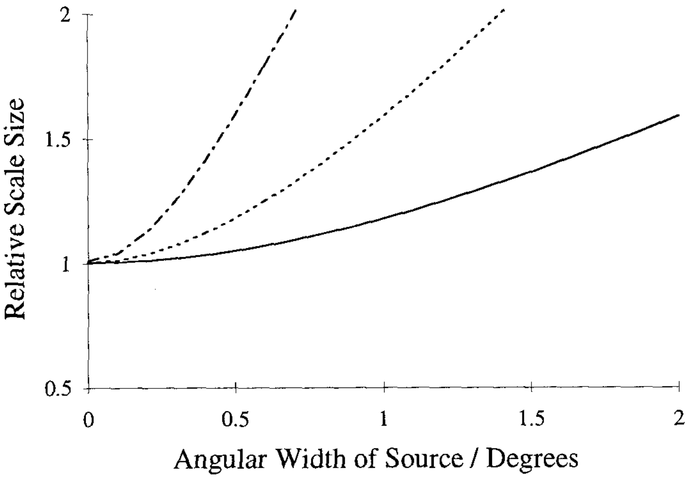

Figure 4. – Increase in fluctuation scale size plotted against angle subtended at the receiver by a finite width source for the minehunting sonar, at ranges of 50 m (solid line), 100 m (dashes) and 200 m (dash-dot).

factor of two would double the range, and this seems quite feasible in an operational system. For further improvement a more drastic reduction in beamwidth is required, and the astronomical system uses focusing.

Unfortunately, focusing is only effective in the near field of an aperture, which reaches only a few metres for a typical sonar projector. Possible alternatives are reverse shading and superdirectivity [7], or the use of a parametric array [8]. In a superdirective array, the elements are spaced less than $\frac{\lambda}{4}$ apart with the polarities of adjacent elements reversed, and in reverse shading the outer elements are driven at a higher level than those near the centre. These techniques can give a reduction in beamwidth by a factor of two, but at the expense of high sidelobes and reduced efficiency. A reduction factor of 10 or more, with very low sidelobes, could be achieved with a parametric array, which operates by the non–linear mixing of two higher frequency signals, but again with low efficiency. However, it has been shown that the coherence of a parametric source is not significantly degraded by fluctuations [8], so a sufficiently narrow artificial beacon could be generated out to reasonable ranges.

3.2. SIGNAL PROCESSING

Finally, suitable processing techniques to compute and apply the required compensation must be considered. Compared with astronomical systems the speed requirement is reduced by about three orders of magnitude, but computing loads in sonar systems are already great and an efficient approach must be sought. A technique operating on the post–processing display image rather than the raw sensor signals would be less complex and a method that can be implemented using Fast Fourier Transforms (FFT's) or other « standard » algorithms would be advantageous.

In the astronomical system, the phase distortion of the wavefront from the guide star is detected optically and the conjugate distortion is applied to a deformable mirror. Such an approach is not ideally suited to sonar. Although the phase (and amplitude) of the signals at each array element could be measured and the results used to apply corrections, more efficient techniques are availalble. One likely candidate is known as Point Spread Function (PSF) Deconvolution [9]. Conceptually, the method operates as follows :

An ideal imaging system would produce a point image from a point source but, in reality, the image will be distorted or spread in some way. This spread may be due to the finite aperture of the sensor, to errors in the system, or to medium–induced fluctuations. This distorted image of a point source is the point spread function of the system, analogous to the impulse response in the time domain. In the same way that the output of a linear system is the convolution of the input signal and the impulse response, the image of an object observed with a real imaging system is by definition the convolution of the error-free image and the point spread function, and the effects of distortion and fluctuations may be removed by deconvolving the degraded image with the point spread function.

A sonar system, without fluctuations, would have a point spread function given by the array directivity pattern, perhaps convolved with some function representing the signal processing and imaging process. The image may be a range-bearing display, a true map in geographic coordinates, or any of the many other displays found in sonar systems, but it is always possible to relate a point in the image to a point in the field of view. In a real medium with fluctuations, the beampattern of the array is convolved with the angular spectrum of the incident wavefront to give a degraded directivity function [2], so the effective point spread function is the convolution of the angular spectrum of the wavefront, the array directivity and the imaging system. Thus, it is possible to remove the effects of fluctuations by PSF deconvolution, and this may be carried out in practice by applying classical Fourier deconvolution [10].

4. Conclusions

In this paper, an approach to overcoming the degrading effects fo inhomogeneities and fluctuations in the ocean on sonar systems has been suggested. The basic concept — the use of an artificial beacon as a reference point source — has been proven in the field of astronomy, where the problems caused by fluctuating wavefronts are very similar to those found in underwater acoustics. It has been shown for a « typical » active sonar system that an acoustical beacon, small enough to look like a point source, could be obtained from volume reverberation at reasonable ranges, albeit with some modification of the transmitting array. An image processing technique — point spread function deconvolution — has been suggested which would compensate the displayed image for the effects of fluctuations more efficiently than acting on the raw receiving array signals directly. Although there are a number of problems to be overcome before such a system could be put into practice, this concept obviously merits further investigation.

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L'AUTEUR

Peter DOBBINS had his first professional contact with underwater acoustics at Ultra Electronics where he worked on the development of transducer arrays for sonobuoys. He joined Sperry Gyroscope in 1976 to work on electronics design, but moved into underwater acoustics in 1981, and at that time he gained a first class honours degree in applied mathematics from the Open University. Following this, he was involved in research into the degrading effects of sea water inhomogeneities on sonar performance until 1991. He has published a number of papers on this topic and was awarded a PhD by the University of Bath in 1989 for the work. Peter now works for BAeSEMA, and his primary interest is in modelling transducers and arrays.