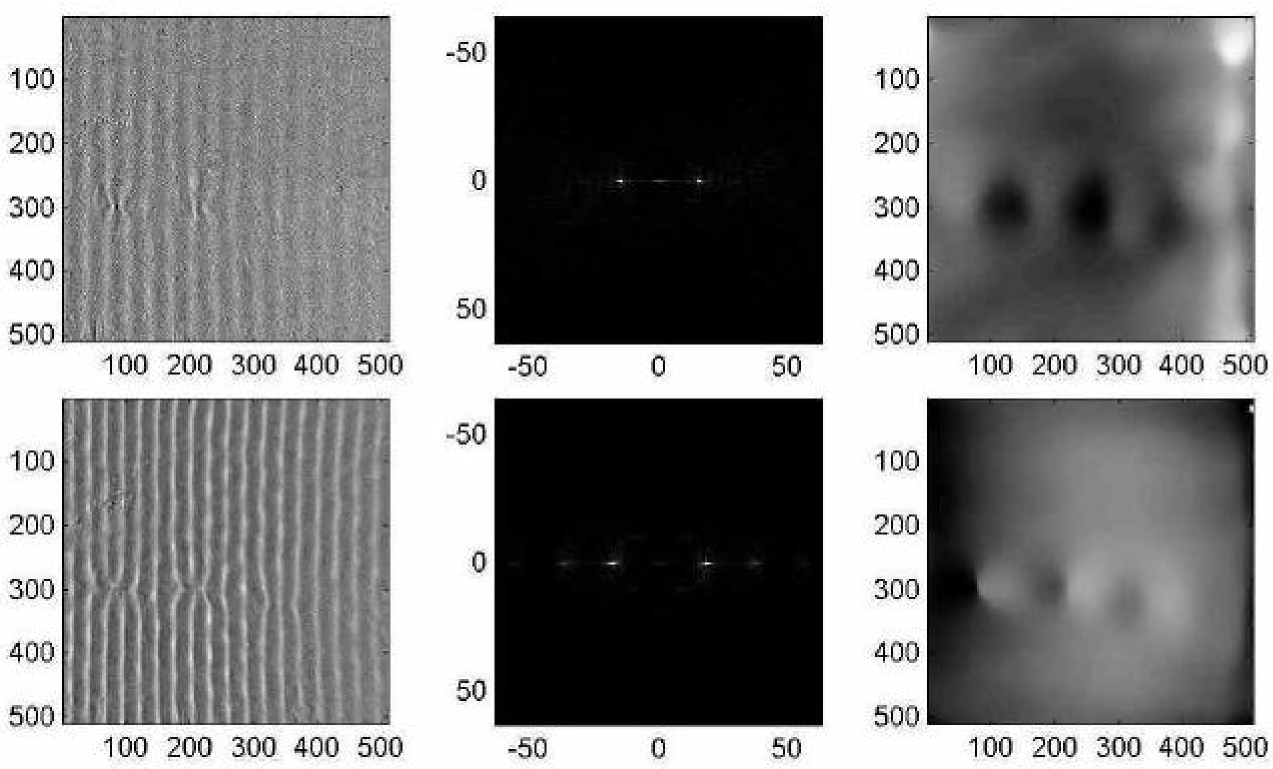
100
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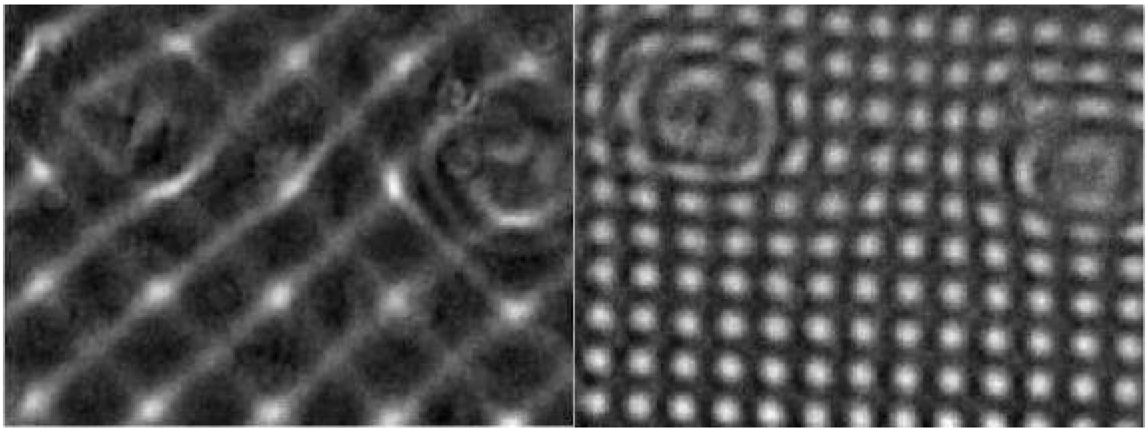

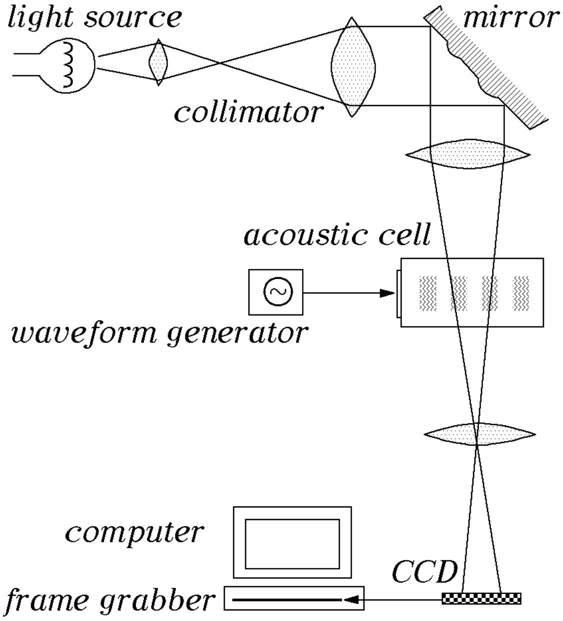
light source
mirror
collimator
acoustic cell
waveform generator
computer
CCD
frame grabber

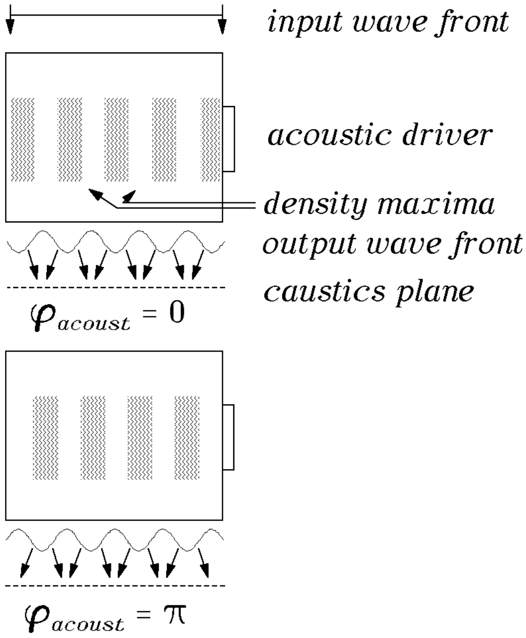
input wave front
acoustic driver
density maxima
output wave front
caustics plane
$\varphi_{acoust} = 0$
$\varphi_{acoust} = \pi$

FIGURE CAPTIONS

Figure 1: When a wave front passes through an acoustic wave, it suffers from periodic delays. At some distance away from the cell, caustic lines are created, switching between the two phases where the sound wave spends most of the time.

Figure 2: An image of the mirror is formed on the detector after passing through the acousto-optics cell. In another arrangement, the two last lenses form a telescope. The cell can be before, after, or between the lenses.

Figure 3: Standing acoustic waves emanate from transducers at 45^0 and 135^0 to create a cross pattern of bright spots. At 1.256 MHz (left) the caustics are weak because of low power or short distance, but at 3.388 MHz (right) they are clear. Two protrusions on the mirror are visible which bend the grids. They are 1.2 m m high and 1 mm across. Other artifacts are due to spots on the optics.

Figure 4: One-dimensional caustics from sound waves at 0.97 MHz (top) and 1.20 MHz (bottom). Left: Images, background subtracted. Center: Fourier transforms. The sidelobes slide outside with the sound frequency. Demodulation means shifting only one sidelobe to the center and transforming back. Right: Phase of the inverse transform, representing the horizontal gradient of the wave front. Apart from the angle of the sound wave and the larger field, conditions were like Figure 3. The results are very close except for a small multiplicative factor.

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In adaptive optics, the lenslets are to match a specific deformable mirror. Obviously, for a mirror with cartesian components, the realisation above is preferred. In other cases, the mirror actuators are organised in an hexagonal pattern. Hence the sound waves also need to be sent in these directions. Even a centrosymmetric lenslet array[7,8] can be excited, although in this case Fourier analysis methods will not be very useful.

the long light-sound interaction range (20 mm) lead to non-linear effects[3]. Finally, there was spreading of the colours at high frequencies, and the caustics were not so sharp (Figure 3). The colour spreading could be mitigated by imaging a closer caustics plane onto the CCD, extending the frequency range to 8MHz.

In traditional Hartmann-Shack sensing, the location of the foci is found by centroiding each one of them, and comparing the locations to a reference pattern. This is difficult if the pitch is variable, so a simple Fourier demodulation scheme supplied the wave front gradients. In the past, we found that lateral resolution can be traded for depth resolution[6]; here the CCD was sampled at a resolution of 500,000 pixels, so there was ample resolution in all directions.

First the image was transformed into the Fourier domain. Since the spot array is a sum of two perpendicular caustic lines, they have distinct sidelobes. The distance of the sidelobes from the origin is the number of waves visible in the acoustic cell window. When changing the temporal frequency of the sound wave, all sidelobes shift simultaneously and linearly with that frequency along a radial line. Two orthogonal sidelobes were isolated, downshifted to zero frequency, and transformed back (only two are necessary, because the opposite two contain the same information). The phases of the two transforms yielded the two gradient components of the wave front. It is also possible to alternate between the orthogonal waves, and to detect separately the same two gradient components from two separate images. This is shown in Figure 4 for one sidelobe.

When there is a need for a flexible wave front sensor, an acousto-optics cell performs the function of a Hartmann-Shack sensor array, and the spatial frequency is set by the sound frequency. In white light, the permitted frequency range is limited by the bandwidth of light and mechanical resonances. In wave front measurements, the flexibility of the sampling frequency helps remove aliasing effects. This is achieved by measuring in at least two distinct sound wave lengths, and combining the results to yield long and short spatial frequencies (somewhat like two-colour interferometry).

and sound beams is not so strict. On the other hand, at higher frequencies colour effects begin to govern, and the polychromatic caustic spots begin to smear. In another method of acousto-optic wave front sensing, a single acoustic pulse sweeps across the monochromatic beam and measures its gradient sequentially at different spatial frequencies[4,5].

A simple cell was built to check the performance of the flexible wave front sensor. The acousto-optical medium chosen was water – other media like glycerol or lucite (perspex) were also tested but had weaker response. Aluminium was machined to create a nearly cubic box whose side is 50 mm and whose walls are 2 mm thick, and anodised to reduce corrosion. Two transparent windows were attached to two opposite sides of the box, and two piezoelectric discs attached to the two orthogonal sides as drivers. A cosine waveform, of up to 20 V and 0.1 A (p-v), was applied to either or both discs. By tuning the frequency, many standing wave resonances were immediately visible between 300kHz and 8 MHz. Because the box was not perfectly square, not all resonances appeared at both directions simultaneously. Above 4 MHz, the caustics diminished due to spectral spreading.

To view the caustics, a collimated beam of white light was reflected off an aluminised mirror, on which three small hillocks were evaporated, 1.2 m m tall and 1mm wide. Two lenses imaged the mirror onto a commercial CCD, in order to minimise the curvature effect and have the intensity as constant as possible (Figure 2). The acoustic cell could be placed before, between or after the lenses. In the first cases, it was possible to change the effective focal length of the caustics to maximise their contrast. In the latter case, the focal length of the effective lenslets was governed by the strength and the length of the acoustic wave. The spatial frequency of the array, linear with the temporal frequency of the standing sound waves, was 0.3-3 mm.

The contrast in the focal plane was limited because of few reasons. First, the foci alternated between two positions half a wave apart during each cycle, and two patterns added up in the slow CCD. The switching was not instantaneous, but following a sine (rather than square) wave. Second, Similar problems arise in ocular adaptive optics, where turbulence is replaced by variable aberrations in the cornea and inside the eye. Another very important field, in which photons are more plentiful, is measurement of optical surfaces and components. The wave fronts can have very large aberrations, which need to be measured on a very fine lateral scale. Segmented optics, such as in large telescopes, is an extreme case of ill-behaved wave fronts.

Mild scintillations, caused by remote aberrations in the wave front, were shown to add information about these aberrations[1]. Going to the extreme, it is possible to induce very strong scintillations, or caustics, to provide all the necessary information about the aberration.

Instead of changing the magnification of the wave front sensor, it is proposed here to change the sampling frequency of the sensor itself. The sensor can be thought of as a Hartmann-Shack sensor where the lenslets are variable in space and time. The flexibility is achieved by passing the wave front though an acousto-optic cell. If a standing wave is excited in such a cell, the wave front passing through it will suffer from a periodic delay[2] and will become corrugated (Figure 1). At some distance down the light beam, the rays (normal to the wave front) cross each other - this is the caustics region. An array of linear caustic lines appears, moving at the speed of sound. If the sound wave resonates in the cell (a standing wave), the array of lines vibrates between the end positions of the wave.

A simple lenslet array can be created from two crossed lenticular cylindrical lens arrays. In this flexible realisation, two standing waves are being launched perpendicular to the investigated beam and to each other. Again, at some distance down the optical beam, each sound wave creates a comb of caustics. The two orthogonal combs add up to an array of caustic spots, just like spots behind a lenslet array. Since at each half cycle the location of maxima shifts by half the acoustic wave length, the slower CCD detects both sets of spots.

The description of wave fronts is not the only one: the light can be thought of as being Bragg diffracted from the acoustic sound beam[3]. Hence the condition of orthogonality between the light

Harnessing Caustics for Wave Front Sensing

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Abstract

Scintillation in measured wave fronts adds spurious dislocations and deformations to their reconstruction. The source of the problem is caustics formed by aberrations in intermediate planes. I propose to use intentional caustics to measure wave fronts under severe conditions such as low light level, fast scale variations, large aberrations and discontinuities in the wave front. A simple realization is based on the Hartmann-Shack sensor, which samples the wave front with a lenslet array. Movement of the lenslets' foci is linear with slope changes. Here the lenslets are effectively formed in an acousto-optic device: two standing waves are launched perpendicular to the light beam and to each other. At some distance down the beam, each wave creates a comb of caustics, and the two orthogonal combs add up to an array of caustic spots. The spatial frequency of the array is linear with the temporal frequency of the standing sound waves. A simple Fourier demodulation scheme supplies the two wave front gradients.

Keywords: Adaptive Optics, Caustics, Wavefront Sensing.

Most astronomical adaptive optics systems use either a Hartmann-Shack wave front sensor or a curvature sensor. There are many cases when the spatial and temporal parameters of the turbulence change with time. These cases are difficult to deal with, since the geometry of the sensors is not flexible. With few photons, one tries to minimize the number of pixels in the detectors, and use the best detectors, currently single avalanche photodiodes. If one uses instead continuous cameras such as CCDs, it might be possible to measure the wave front at different spacings. This is achieved by zooming (changing the magnification) of the relayed aperture onto the wave front sensor.