ON THE IMPORTANCE OF ACTIVE IMAGE STABILISATION

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Abstract:

The performance of an optical telescope can be improved considerably by opening the shutter only at moments of good seeing. The resulting instantaneous high-resolution images must be corrected for shift before adding them all together. The optimum aperture diameter for which this technique works well is 1 meter or less, depending on atmospheric conditions. Image stabilisation not only improves the resolution and thus the point-source sensitivity, but it is also expected to improve the performance of speckle interferometry and optical aperture synthesis. This makes its implementation on large telescopes desirable. While it is certainly possible to do this by treating a large filled aperture like a set of independent subapertures, a much more logical approach would be to build an array of 1-meter telescopes, preferably mounted in a single large frame so that it can be pointed in all directions without extensive pathlength compensation. Such a "Many Mirror Telescope" has many advantages, and is feasible because image stabilisation helps to solve the beam-combining problem.

1. Introduction.

For all practical purposes, the spatial resolution of groundbased optical telescopes has been limited to about 1 arcsec ever since its invention, 300 years ago. The reason for this is atmospheric turbulence, or "seeing", which spreads the image and makes it wander around. The resulting time-averaged seeing disk of about 1 arcsec is much bigger than the theoretical diffraction-limited resolution of a large telescope, which is 0.1 arcsec*meter at a wavelength of 5000 A.

Over the last decade, an improvement by a factor of two has been achieved by paying special attention to the temperature distribution around the telescope, which is influenced by the site, the airflow in the dome, the telescope structure, and the heat generated by instruments. Especially the group at the Multi Mirror Telescope (MMT) in Arizona has made significant contributions here. It should be noted, however, that 0.5 arcsec seeing is only possible under exceptional conditions.

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Fully diffraction-limited resolution with large telescopes has been achieved by post-detection image processing called "speckle interferometry", invented by Labeyrie (1970). Unfortunately, this technique has until now only been successful for objects that have a simple structure, like a double or triple source. The reason for this, and a possible cure, will be discussed below.

Diffraction-limited resolution can also be achieved by correcting atmospheric wavefront distortions in real time by means of "active" or "adaptive" optics. The telescope aperture is subdivided into independent subapertures which are so small (10-20 cm), that the phase error across each of them can be considered to be approximately "constant" (i.e. within 1 radian) at a given instant. A bright reference source is then used to estimate these errors. Only the brightest objects in the sky provide enough (>100) photons for each subaperture in the short time (10-100 msec) that the atmosphere is approximately stationary. Moreover, the observed object and the reference must share the same "isoplanatic patch" which is only a few arcseconds across. For large apertures the problem is aggravated by the difficulty to separate the effects from the many subapertures.

It has now been realised, that the seeing cells are actually much bigger than the 10-20 cm cited above, if the wavefront is first corrected for linear phase-gradients, or tilts. Most of the power in the Kolmogorov spectrum of atmospheric turbulence is stored in low-frequency large-scale variations (Fried 1978). This means that, whereas the phase-error may vary quite rapidly across the aperture, the average error gradient is more or less constant over a much larger distance (see fig 1).

This paper seeks to emphasize the importance of exploiting this fortunate property of atmospheric seeing. If it really works (!?), it can help groundbased optical and infrared observations in the following ways:

(a) A spatial resolution of a few tenths of an arcsec can be routinely achieved for a limited (but a-select) part of the sky.

(b) The conditions for post-detection image reconstruction techniques like speckle interferometry will be improved so that they work better for a wider range of objects.

(c) The use of phase-closure techniques in multi-element aperture synthesis arrays will be helped, because the element telescopes can be larger and their light can be made to interfere more effectively.

(d) The feasability of very attractive "Many Mirror Telescopes" is increased because the beam-combining problem is solved.

These advantages will outweigh the disadvantage that parts of the sky are inaccessible for want of a bright enough reference source, and a certain loss in efficiency because the shutter is closed during moments of bad seeing.

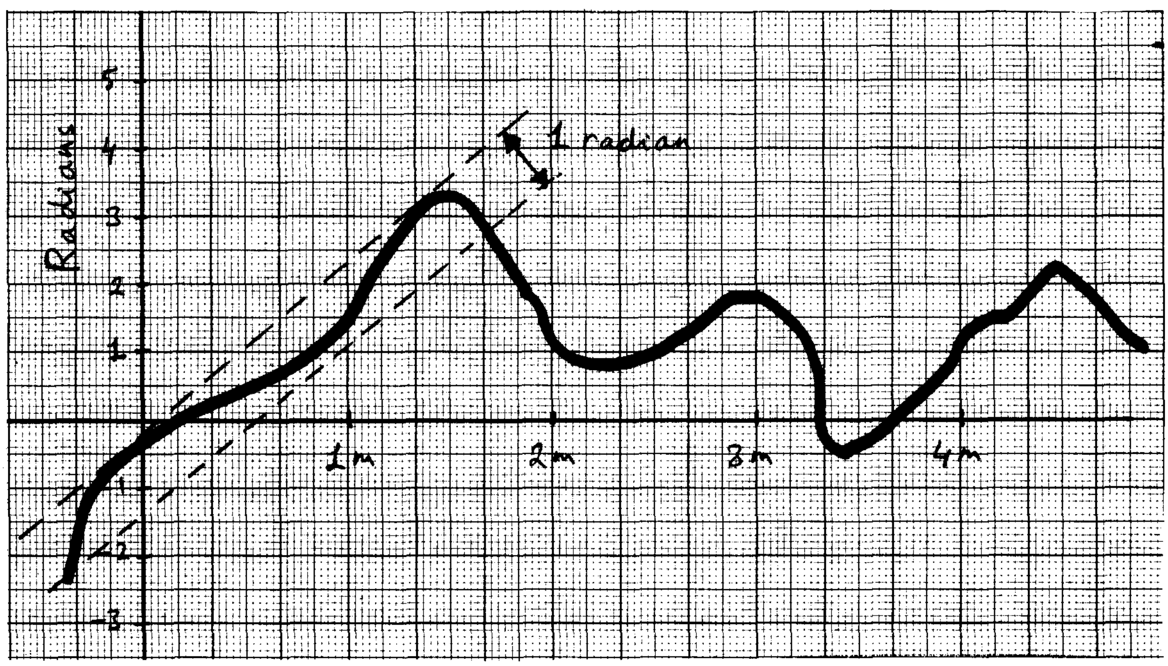

Fig. 1 Example of an atmospheric phase error distribution across the telescope aperture. Note the seeing cell size, which is 30 cm for the convential definition, and 200 cm if linear gradients are ignored.

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2. Image Stabilisation. The image produced by an optical telescope represents the observed object, convolved by some point-spread function (PSF). For a circular aperture and under perfect conditions, this PSF is the familiar Airy pattern, with a central peak and some circular sidelobes around it. Image degradation can be described by means of a phase error function across the aperture. If this function is a linear gradient, the only result is a shift of the perfect image. Higher order terms cause distortion of the PSF, and multiple peaks of comparable size appear when these non-linear phase errors are greater than about 1 radian. The resolution is then no longer diffraction-limited.

The phase error function is continuous, and one can define "seeing cells" over which the error does not depart more than a radian from a straight line (which may be tilted, see fig 1). This definition differs slightly from the conventional one in that it separates image distortion and image shift. The seeing cells thus defined are much larger, because large-scale components dominate the phase error function (Fried 1976). This intuitively simple property of atmospheric turbulence is very fortunate, and its exploitation can have a revolutionary impact on groundbased optical and infrared observations.

Each cell then produces a moderately distorted but still diffraction-limited image, with a resolution inversely proportional to its size, and which is shifted by an arbitrary amount. If there are many cells of varying size across the aperture of a telescope, any short exposure will be a chaotic mixture of images, each with its own resolution and shift. (Interference effects will be ignored for the moment). Studied through a large telescope, a star will look much like a "can of worms", with many sub-images of varying resolution wriggling around independently. If on the other hand the telescope aperture is smaller than the average cell size, a single star image will be seen "dancing about", and occasionally flaring out when the cells get particularly small. This was demonstrated very clearly by the video pictures shown by Dr Labeyrie on this conference, taken with a 25 cm telescope.

The size of the final time-averaged seeing disk is determined by the movement of the sub-images, and will be the same for any telescope with an aperture that is larger than the average atmospheric cell. It is clear, that the seeing disk of a small telescope can be reduced by compensating for the image motion and only opening the shutter when there is a single cell across the aperture (i.e. when the image of a guide star is diffraction-limited). Larger telescopes must be split up in subapertures of less than about 1 meter, each with its own shutter and shift-compensation.

The shutter becomes increasingly important if the aperture gets larger than the average cell size, because then it must remain closed for an ever greater percentage of the time. There is clearly a trade-off between resolution and efficiency. On some nights the seeing will be worse than 0.5 arcsec for 99 percent of the time, but on other nights it may well be possible to reach 0.1 arcsec for 10 percent of the time, especially if the same kind of environmental temperature control is exercised as with the MMT. The loss of efficiency will at least partly be made up by the increased sensitivity for unresolved objects, which is inversely proportional to the square of the seeing disk. In any case some provision should be made to match the size of the subapertures to the prevalent seeing conditions.

3. How to do it. There are several ways to stabilise an image, all of which require a bright enough (15th magnitude?) star close enough (2 arcmin?) to the observed object. It is important to subdivide the aperture into subapertures with a size comparable to the average seeing cell size, and to provide an independent tilt-correction/shutter system for each.

A very simple (but effective) method, devised by Thompson et al. makes use of a pinhole mask. The telescope shutter is opened only if the light intensity through the hole exceeds a certain value, indicating that the guide star is in the right position and that it is not too much spread out. The efficiency is low because all images that are displaced but of good quality, are ignored. This may be improved by tilting a flat mirror or using the deflection coils in an image tube to keep the image within (say) 0.1 arcsec. At the same time its variable size can be used to decide when to open the shutter. A third method records the positions of incoming photons, and selects and shifts them in software. This technique will be tested in late 1984 at the new anglo-dutch observatory at La Palma, using the Imaging Photon Counting System (Boksenberg 1972) as a detector.

It should be noted, that these techniques may be used for observations in the infrared as soon as good CCD/CID detector-arrays become available. The seeing cells are much larger at this wavelength (Mariotti 1983).

Image stabilisation is so promising and so conceptually simple, that many people will try their hand at it, especially if it turns out to work for a wide range of conditions. In that case one might expect a comparatively cheap system to emerge in the next few years, that can be mounted on any telescope. (Since each subaperture is treated independently, a large telescope does not require a different system, but only more of them). The cheapest variety would presumably

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consist of a beamsplitter to take off part of the light, an uncooled CCD or CID detector, and a microprocessor to control a tiltable mirror and a shutter.

4. Problems and Limitations. The best possible introduction to my talk are the very impressive 0.1 arcsec pictures that Dr Racine showed us at this conference. They were taken with the 3.5 meter CFHT on Hawaii and prove without any doubt that there are conditions under with image stabilisation works very well. We must now try to determine under what range of conditions it will also work, and what the ultimate limitations are.

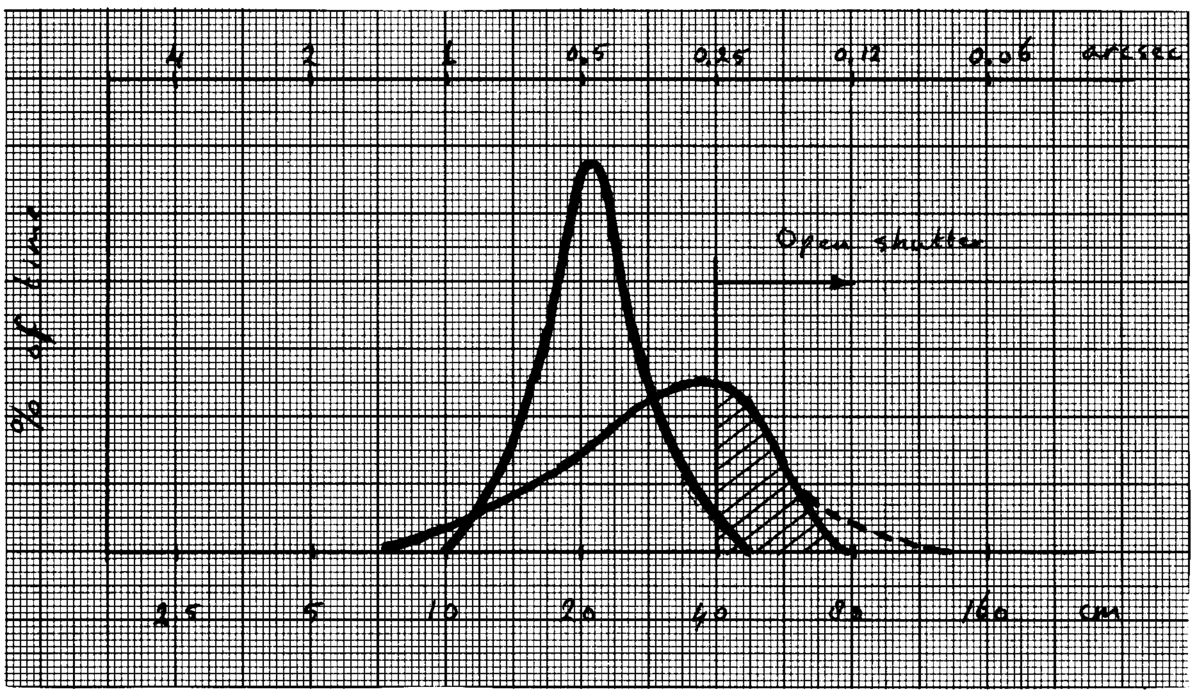

Fig. 2: Two possible cell size frequency distributions that would both result in 0.5 arcsec passive seeing.

The foundation upon the whole technique rests is the distribution of atmospheric seeing cell size as a percentage of time. This graph determines the usable subaperture size, and hence the achievable resolution, usable reference stars and possibly the field-of-view. Since most authors until now have concentrated on the average size in order to predict the performance of a passive telescope, very

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little is known about this. Fig 2 shows two such distributions, that will both give the 0.5 arcsec passive seeing conditions that are known to occur from time to time at the MMT and on Hawaii. We are particularly interested in the shape of the tail at the right-hand side of the graph, because this indicates the percentage of time that the cells are big enough to open the shutter.

It is very encouraging to note, that the results on Hawaii have been obtained with a 3.5 meter telescope, apparently without subdividing the aperture. This suggests that an (optical) seeing cell size of more than 1 meter should be not at all rare. Similar indications can be found in the work of Woolf (1983).

A clear limitation of image stabilisation is the requirement of a guide star. Again, experiments will soon tell us how bright it has to be, and how close it must be to the observed object. It is possible that the optical universe can only be studied at high resolution from the ground through a large number of "windows" around bright stars. Fortunately, selection-effects are diminished by the fairly random distribution of such stars. And we will be able to study many objects that have up till now been "wiped out" by the close presence of a bright star.

Finally, there is the problem of time constants. In some schemes one has to be able to predict the quality and position of the subimages, in order to operate the shutter and to compensate for shifts. This will be very difficult if they move rapidly and erratically.

5. Speckle Interferometry. Until now we have concentrated on the "classical" effects of selecting good images from subapertures and making then coincide. Speckle interferometry clearly relies on interference between them. The diffraction-limited images from each subaperture can be seen as probability-distributions for photons to strike a particular spot on the detector. If the number of photons is limited, interference effects between two or more subapertures will only be seen if their
probability peaks coincide, since the peak on an Airy function is much higher than its sidelobes. This means, that the point-spread function (PSF) at each point in a short-exposure speckle image will mainly be determined by the set of subapertures whose images happen to coincide at that point. Thus, if there are many subimages spread over a large area, the PSF varies wildly in shape and resolution across the speckle image. This effect causes the socalled "seeing envelope" in the auto-correlation of a speckle image. This seeing envelope is so

dominant, that only very simple brightness distributions (like a double or a triple source, with components of roughly equal strength) have a clear enough signature to be distinguised from it. Another problem is, that only the visibility amplitude is measured, in which case a fully sampled UV-plane is a prerequisite for reconstruction of complicated images (see next section). This latter condition may no longer be fullfilled if not most subimages coincide.

In exactly the same way, sophisticated techniques to retrieve the visibility phase from speckle images usually assume a badly distorted but constant PSF over the whole image (Walker 1982, Knox-Thompson), and a fully sampled UV-plane. This explains why these techniques perform so well in computer simulations, but so poorly with real speckle data.

Thus it may be expected that speckle interferometry and related techniques will perform dramatically better if the equally-sized images from a selected set of subapertures are made to coincide by means of image stabilisation. No amount of post-detection processing will be able to emulate these conditions. A peripheral advantage is that processing time will drop sharply since speckle images will be so much smaller. It is not clear whether image stabilisation will increase the socalled "isoplanatic patch", but the possibility is mentioned here for completeness.

6. Aperture Synthesis. Image stabilisation alone is not enough for aperture synthesis, because it only corrects for wavefront tilts (and selects against moments of bad seeing), but does not correct any path-length differences between subapertures. These become vitally important if images are to be obtained with a multi-element system, rather than just source-parameters with a two-element intermerometer.

Experience with Very Long Baseline Interferometry (VLBI) has taught us that, if the UV-plane is sparsely sampled, it is impossible in general to reconstruct an image unambiguously from the visibility amplitudes alone. All the successes of Fienup, Knox-Thompson, Walker etc had the benefit of a UV-plane that was fully sampled. The situation in radio (and optical) aperture synthesis, with a small number of widely spaced elements, is much less favourable and some famous errors have been made in the interpretation of early VLBI results. The great success and reliability of VLBI dates from the introduction of phase closure techniques which require the simultaneous interference of at least three (and preferably six or more) telescopes. It should be mentioned here, that optical and infrared multi-element interferometry cannot be done in the same way as its radio counterpart since the light from each subaperture cannot easily be amplified and then split to be correlated with all the others separately. It is possible however, to determine the visibility-function by Fourier transforming a short-exposure image back to the UV-plane while taking care that the contributions from redundant interferometers are kept separated (Greenaway, Brown).

Anybody who has seen a two-element optical interferometer in operation knows, that very often the two images are moving about independently, and "fringes" can only be seen during the moments that they happen to coincide. In a multi-element interferometer, the probability that all images coincide at the same time rapidly decreases with the number of element telescopes, especially if the baselines are long. In this sense, image stabilisation is absolutely essential for groundbased optical (or IR) aperture synthesis.

Another very important aspect of image stabilisation is, that it allows subaperture diameters that are much larger than the 10-20 cm commonly thought to be maximum. This allows weaker guide stars and/or shorter integration times to be used. It should be noted however, that unless the element apertures are very small, the shutter of each telescope will be closed for a certain percentage of the time. Thus it may still be relatively rare that all elements participate at the same time. This will cause problems if the array configuration is important, like in exploiting the redundant baselines for internal calibration. (Noordam 1982). For this reason, and also because of the infinite size of seeing cells and isoplanatic patch, the real potential for optical aperture synthesis lies in space, away from the boiling atmosphere.

7. A "Many-Mirror Telescope. It must be clear, that if a next-generation large telescope is to enjoy a better resolution than 1 arcsec, some sort of image stabilisation will have to be implemented. Since this involves treating the aperture as a set of more or less independent subapertures, it is a logical step to consider an array of physically separated mirrors. Arrays have many advantages over single big monolithic telescopes: With the same collecting-area and diffraction-limit, they are lighter, cheaper, easier to maintain, easier to upgrade and easier to extend. Some of the mirrors can even be of a different design than the others, for instance during the process of gradually replacing them all, or to do aperture synthesis experiments without disrupting the normal observations.

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If each individual telescope in an array has its own selective guiding system, the position of its image is accurately known at all times. And since each telescope only opens its shutter when it can contribute a "good" image, the combined result should have the same enhanced resolution, on top of the benefit of all collected photons. Thus another important aspect of image stabilisation is, that it helps to solve the beam-combining problem and makes arrays of cooperating telescopes possible.

The elements of the array may be scattered over a large area to achieve a very high resolution. The problem with such an approach is, that the individual telescopes will in general not be pointed parallel to the (vertical) array axis. This causes nasty complications like an extra two reflecting surfaces per telescope, vieuw-obstruction and the necessity of extensive path-length compensation in the case of coherent combination (aperture synthesis). It is much more attractive to mount all telescopes in a single large frame that can be pointed in all directions. Since the elements have a diameter of less than 1 meter, the result would be a "Many Mirror Telescope", rather than a Multi Mirror Telescope. Apart from being a very powerful (and cheap) astronomical instrument, such an MMT could be the focus of all kinds of innovative thinking about telescopes, just like its namesake in Arizona.

REFERENCES

L.A.Thompson and H.R.Ryerson, "An active mirror image stabilisation instrument system (ISIS) for use on Mauna Kea". SPIE conference 444 London (1983) pp 560-568

A.Labeyrie "Attainment of diffraction-limited resolution in large telescopes by Fourier analysing speckle patterns in star images". A+A, vol 6, (1970) pp 85-

N.J.Woolf, D.W.McCarthy, J.R.P.Angel, "Performance of the MMT: Image shrinking in sub-arcsec seeing at the MMT and 2.4m telescopes". SPIE conference 332 Tucson (1982) pp 50-56

J.H.Hardy, "Active Optics: Don't build a telescope without it". SPIE conference 332 Tucson (1982) pp 252-259

A.Boksenberg, "Auxiliary Instrumentation for large telescopes". Proc of ESO/CERN conference Geneva (1972) pp 205-

J.R.Fienup, "Reconstruction of an object from the modulus of its Fourier transform". Opt.Lett. No 3 (1978) pp 27-29

K.T.Knox and B.J.Thompson, "Recovery of images from atmospherically degraded short-exposure photographs", Ap.J. vol 193 (1974) pp 145-

https://doi.org/10.1017/S0252921100108516 Published online by Cambridge University Press

D.L.Fried, "Probability of getting a lucky short-exposure image through turbulence", J.Opt.Soc.Am vol 68 (1978) pp 1651-

A.T.Young, "Seeing, its cause and cure", Ap.J. vol 189 (1974) pp 587

J.M.Mariotti, "Experimental results on atmospheric turbulence obtained with an infrared speckle-interferometer" Optica Acta vol 30 (1983) pp 831-

A.H.Greenaway, "Diffraction-limited pictures from single turbulence-degraded images in astronomy". Optcics Comm Vol 42 No 3 (1982) pp 157-161

T.M.Brown, "Reconstruction of turbulence-degraded images using non-redundant aperture arrays". J.Opt.Soc.Am Vol 68 No 7 (1978) pp 883-889

J.E.Noordam and A.G.de Bruyn, "High dynamic range mapping of strong radio sources, with application to 3C84". Nature Vol 299 No 5884 (1982) pp 597-600

DISCUSSION

D. Enard: The limit that is possible to obtain with image selection or stabilization techniques is ultimately limited by the quality of the telescope which is usually of the order of 0.5 arcsec if we take also into account a possible residual misalignment. The gain that can be expected is therefore limited. For future telescopes it might be necessary to increase the specifications by a factor of 2 or more. This can probably be only achieved with active optics and image analysis feed-back.

J.E. Noordam: Some residual misalignments are undistinguishable from atmospheric "tilts" and would then be corrected by "image stabilisation" per subaperture of about 1m. It may be easier to maintain good mirror-quality by using separate 1m mirrors.

R. Racine to J.E. Noordam: Much emphasis has been placed in the last few papers on how difficult it would be to approach difraction limits with centering and sampling techniques. I would like to stress that from an astronomer's point of view a "modest" gain in resolution by a factor of two, say from 0".8 to 0".4, would be a tremendous step indeed! And this seems achievable, even at visible wavelenghts.

A. Labeyrie: It is true that image selection improves planet exposures in large telescopes. It is only a slight improvement, owing to the random-walk statistics of phase cells, as mentioned by Mariotti. For speckle work, the improvement is quite small. In the early days of speckle observing, we used to select among millions of images. Keeping the bad images does not make much difference because the bad images contribute little to the correlation, owing to the quadratic response of the autocorrelation process. Besides, the contribution from a "poor" speckle image remains a valid contribution if the image is exposed short enough and filtered enough for temporal coherence.

J.E. Noordam: A single speckle frame from a large telescope consists of a collection of smaller and larger "blobs", each due to a seeing cell above the aperture. Small seeing cells (r_0 < 10cm) give large diffuse blobs and large seeing cells, with a long phase coherence length, give small intense blobs. Fringes can be seen where two or more blobs coincide, and they are more intense if small blobs coincide.

The quality of the speckle image improves enormously if all large blobs are rejected and the small blobs are all made to coincide. This cannot be achieved by speckle frame selection, but only by independently accepting and shifting the blobs coming from different subapertures.