Results from a pinhole spatial filtering system at COAST

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ABSTRACT

We present details of the design and construction of a new pinhole Spatial Filtering system at the Cambridge Optical Aperture Synthesis Telescope and show the results from the first astronomical observations with the system. We discuss the advantages of using such a system to reduce uncertainties in visibility observations with an optical/IR interferometer. We compare simultaneous observations with and without the system and show the potential to improve both the quality and quantity of scientific output of an interferometer. We also show that filtered observations are much more robust to changes in atmospheric seeing than unfiltered observations, improving the accuracy of calibrated visibility measurements while reducing the need for repeated calibration. Given the simplicity and high throughput of pinhole spatial filters we suggest that they could be a valuable addition to many current and future arrays.

Keywords: COAST, interferometry, spatial filtering, pinhole, visibility calibration, fringe contrast

1. INTRODUCTION

Measurement uncertainties in visibility observations are one of the largest limitations to astronomical optical interferometers. Such large uncertainties arise from instrumental and atmospheric effects. Instrumental based uncertainties result from aberrations in the optical train which vary slowly, if at all, with time. Atmospheric turbulence causes rapidly changing phase corrugation across a stellar wavefront which affects measured visibilities. All modern interferometers attempt to compensate for these effects by making frequent observations of a calibrator source, however the rapidly changing nature of the atmosphere means that calibration of the measured visibility is poor and results in the large uncertainties that limits telescope performance. If the measured visibility of an astronomical source could be made less dependent on atmospheric seeing conditions then the use of calibration, which always takes place before and after the science observation, could better estimate the true visibility of the source. Consequently fewer observations would need to be taken of a science object, and its calibrator, to gain the same degree of accuracy currently seen.

One way to achieve this goal is by spatial filtering (henceforth SF) of the incoming stellar wavefronts.[1] This technique has been used to great success by such instruments as FLOUR on the IOTA and CHARA arrays[2] using single-mode optical fibres. Atmospherically perturbed wavefronts contain phase corrugations at all spatial scales, however much of this is compensated by systems in place at modern interferometers. Piston (zeroth order Zernike term) is removed by fringe tracking or long sweeps while tip-tilt (first order Zernike terms) is removed by fast guiding. Despite this level of compensation the wavefronts are still highly phase corrugated and when combined with another wavefront, which is corrugated essentially independently, the degree of coherence between the beams is reduced, and hence the measured visibility is artificially low. The degree to which the visibility is reduced depends critically with atmospheric conditions and so varies quickly. By removing the high spatial frequencies of phase corrugation from each beam they will be better matched when combined and hence the measured visibility will be higher. More importantly the level of coherence loss will be more stable with time and hence the statistical uncertainty of visibility measurements will be reduced. In addition SF can result in an increase in the signal-to-noise ratio of visibility measurements for apertures larger than about 1.4 times the Fried parameter (r_0).[3]

In this paper we describe a pinhole SF system recently installed at the COAST interferometer in Cambridge.[45] We show initial results from the system and discuss the implications these results have for future scientific observations with the instrument.

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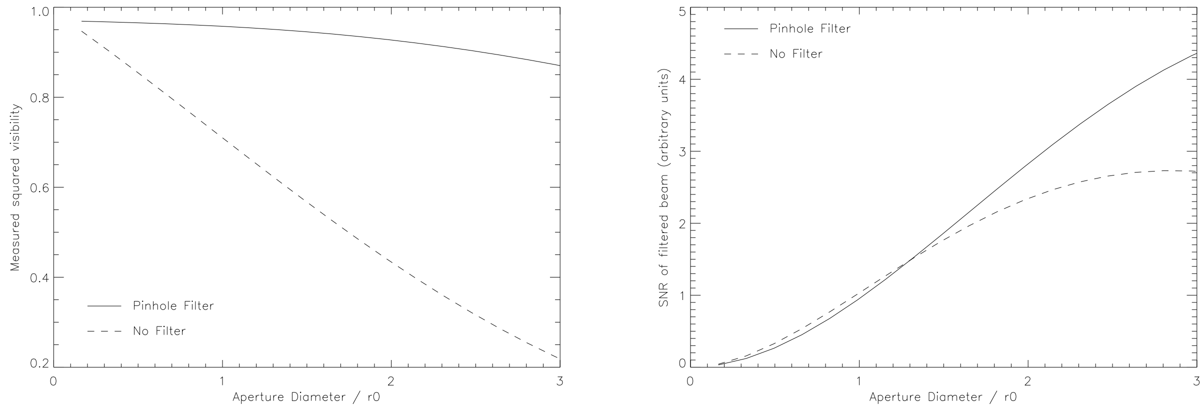


(a) (b)

Figure 1. Simulated results with SF. (a) shows the expected squared visibility of a distant point source due to atmospheric phase perturbations with and without pinhole SF with changing aperture diameter (as measured in multiples of the atmospheric seeing parameter, r_0). (b) shows how the relative signal-to-noise ratios change as the aperture size is increased with and without SF. For more information see[8]

2. PINHOLE SPATIAL FILTERING

Spatial filtering can be carried out by placing an aperture in the image plane of a beam. By allowing only the central portion of this image through, the higher spatial frequencies are removed. Most current systems employ single-mode fibres for this task as they allow only one mode of propagation and hence combined beams have no coherence loss.[6] For this reason they are known as "perfect spatial filters". However, we have shown that using a pinhole as the aperture[17] in the focal plane is expected to give competitive results (both in signal-to-noise ratio and stability of visibility measurements) for aperture diameters smaller than $3r_0$.[8]

Figure 1(a) shows the expected squared visibility measurements for a point source with and without pinhole SF as the individual aperture diameters are increased (relative to r_0). Figure 1(b) shows the relative signal-to-noise ratios for the same visibility measurements as in figure 1(a)[8] assuming the low light-level case. In all of these calculations the pinhole size was chosen to optimise the signal-to-noise ratio of observations.[8]

Perhaps the most important result to notice from these figures is how changes in atmospheric conditions effect the measured visibilities. Typically r_0 can alter by as much as a factor of two over periods of hours or minutes, however filtered observations are much less effected by such changes and so should provide more accurate visibility calibration which remains useful over longer time periods.

3. DESIGN REQUIREMENTS AND CHALLENGES FOR SPATIAL FILTERING

While simple in concept, spatial filtering systems for optical interferometers do present some interesting challenges in optical design.

3.1. Alignment

In order to work effectively the filter aperture (eg. a pinhole or single-mode fibre end) must be aligned to a small fraction of its diameter (typically a few seconds of arc). This accurate alignment needs to be maintained for long periods in three dimensions (two axes of position and one of focus). If observations are needed in several spectral bands with the same instrument then the filter aperture may need to be modified during an observing night, therefore realignment of the new filter needs to be rapid as well as accurate.

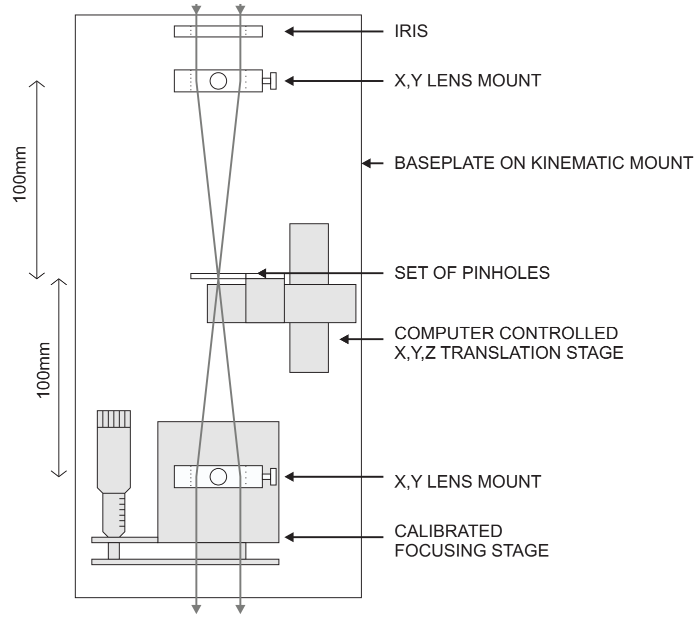


Figure 2. Schematic of the pinhole spatial filter at COAST (not to scale)

3.2. Choice of optics

As the optimum filter aperture size is comparable to the central peak of the point-spread function of the telescope aperture the optics used to couple into the filter must be of a very high standard. Typically this means using high quality achromatic lenses optimised for the near infrared or off-axis parabolic mirrors with a high surface quality.

3.3. Tip-tilt compensation

In order to achieve a high signal strength it is vital that the centre of the stellar image is projected onto the centre of the filter aperture. To achieve this the tip-tilt component of atmospheric phase perturbations must be removed. This is done by fast guiding at all modern interferometers as a matter of course, consequently it is important that the spatial filter be placed after the fast guider in the optical train.

4. THE PINHOLE SPATIAL FILTER AT COAST

The design requirements for Spatial Filtering at COAST were :-

- to fit within the current optical train
- to be mountable and demountable over short time scales
- to improve the accuracy of visibility measurements while not significantly reducing the sensitivity of the interferometer
- to be able to operate anywhere within the wavelength range 600nm to 1000nm with up to 10% bandwidths
- to be able to move between observing wavelengths in a few minutes

To meet these requirements we concluded that a pinhole SF system incorporating a set of precision pinholes mounted on a three axis computer-controlled translation stage would be most suitable. Focusing is carried out by using precision near-infrared achromatic lenses with anti-reflection coatings ($<1\%$ reflectivity between

700nm and 1550nm). By mounting all of these components on a kinematic base the entire system can be removed in one piece and replaced to high degree of accuracy in a few seconds. Once the systems has been properly aligned the computer can move between pinholes (and hence observe at a different wavelength) in a few minutes. By incorporating a large hole (approx. 3mm across) into the set of pinholes the system can be neutralised without the need to demount it.

Currently the fine adjustment of the pinhole position is carried out manually through a computer interface, however work to automate this is in progress. This should make moving between wavelengths much quicker.

Figure 2 shows a schematic of the system design. Both lenses are placed on two-axis translation mounts and the output lens as also mounted on a micrometer screw translation stage for focusing. The computer controlled pinhole mount is accurate to less than half a micron in all three dimensions. The entire system is placed on a magnetic kinematic base plate.

5. OBSERVING STRATEGY AND RESULTS

The COAST pinhole SF system was first used to find stellar fringes on the night of 28th to 29th July 2002. Observations were made of the star α Lyrae (Vega) with a single short baseline. With this baseline the source is essentially unresolved at visible wavelengths and the intrinsic visibility is not expected to change by more than a small fraction of one per-cent over the course of the observations.

COAST uses a pupil plane beam combiner which produces four equal outputs. For this observation two of these outputs were used contemporaneously, one with and one without the pinhole SF system. Measurements of visibility were made at 780nm with a 30nm bandpass. Further observations were made with both outputs at the same wavelength without any spatial filtering in place. A second, identical, observing sequence was carried out approximately an hour after the first. Little difference was observed in the intensity or visibility measured between the two unfiltered outputs. In summary, four data sets were produced, one filtered and three unfiltered, each involving two observing runs separated by over an hour. Data sets 1 and 2 (see Table 1) were recorded simultaneously, as were data sets 3 and 4. Data sets 1 and 3 were taken from the same output beam, as were data sets 2 and 4.

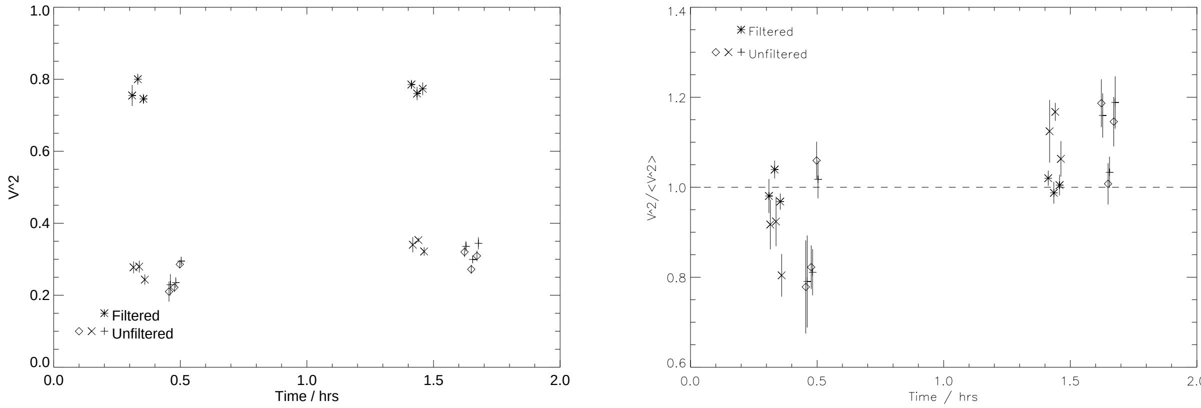
Figure 3(a) shows the measured squared visibilities and the time (taken from an arbitrary point near the beginning of the night) of the observation. Error bars indicate the amount of variation in visibility within each observation and take no account of any systematic errors which may be present. Figure 3(b) shows the same results but each data set is scaled to make the mean value equal to unity. This second chart gives an indication of the accuracy of calibrated data. Table 1 shows mean squared visibilities for the earlier and later runs for each data set, as well as combined results.

Figure 3(a) shows that observations made with the pinhole SF system give squared visibilities at least 2.5 times higher than unfiltered observations. If we assume that the filter is working as predicted we can infer from figure 1(a) that r_0 is approximately half the aperture diameter (ie. $r_0 \simeq 8$cm at 780nm). This is supported by observations made on the same night with a differential image motion monitor (DIMM).[9]

The optical throughput of these preliminary results was only about 31% of that predicted by theory (theoretical maximum throughput for an aperture diameter around $2r_0$ is approximately 55%). This is thought to be due to an alignment problem and so throughput is expected to improve significantly in future observations.

The signal-to-noise ratio of filtered observations was found to be around 40% lower than unfiltered observations instead of the 20% increase as expected for these seeing conditions. However the predicted signal-to-noise ratios assumed a low-light level case which is not relevant for such a bright source.

Perhaps more useful than the actual measured visibility is the variation of the measurements. Figure 3(b) demonstrates that filtered observations remain significantly more stable than unfiltered ones. This can be seen by the size of the errors of each data point and the general scatter of observations. Furthermore the change in measured visibility over time is much smaller in filtered than unfiltered observations. It is assumed that the overall increase in visibility between the early and late unfiltered observations is due to changes in atmospheric seeing. This change in seeing would cause the calibration of measurements made over this timescale to be inaccurate and would require repeated and frequent use of a calibrator source. However results taken with the



(a) (b)

Figure 3. First results with pinhole spatial filters at COAST. (a) shows the actual measured squared visibilities for several observations of α Lyrae with a short baseline. The data is split into four data sets, those marked by a star are filtered and the others are unfiltered. (b) shows the same results but each data set has been normalised so that its mean value is unity.

	Data set 1 ($\circledast$) Output 1 - Filtered		Data set 2 ($\times$) Output 2 - Unfiltered		Data set 3 ($\Diamond$) Output 1 - Unfiltered		Data set 4 ($+$) Output 2 - Unfiltered	
Run	$< V^2 >$	% error	$< V^2 >$	% error	$< V^2 >$	% error	$< V^2 >$	% error
Early data	0.77	2.2	0.27	4.4	0.24	9.8	0.25	8.3
Late data	0.77	0.9	0.34	2.7	0.30	4.8	0.33	4.2
All data	0.77	1.1	0.30	5.7	0.27	6.8	0.29	6.9

Table 1. Mean squared visibility of observations of α Lyrae. Results are separated for early (first three data points) and later observations (last three data points), as well as a combined value. Reference is made to the symbol used for each data set in figure 3. Data sets 1 and 2 were taken simultaneously, as were data sets 3 and 4.

spatial filter are much less dependent on seeing and would require significantly fewer calibrator observations, drastically increasing the number of science observations that can be made.

6. DISCUSSION

We have seen that the COAST pinhole spatial filter can increase the measured squared visibility of an astronomical source by more than a factor of 2.5. This has been achieved at the cost of signal-to-noise ratio (although this is expected to improve in future observations) however the overall accuracy of these visibility measurements is dominated by the variation within a single observing run. This variation in measured visibility over short time scales is significantly reduced by using the pinhole spatial filter, producing more accurate and stable measurements. This reduction in measurement uncertainty means that measurements can be made with far fewer observations.

In the time interval between the early and late observing runs the measured visibilities in unfiltered beams increased by about 25%, implying an improvement in atmospheric seeing. Over the same time period the only observed change in the filtered results was an reduction in their uncertainly. Consequently the filtered observation were found to be much more robust to changes in atmospheric seeing. This means that calibration observation made at one time in the night will remain valid for long periods, drastically reducing the uncertainly in calibrated observations and reducing the need to make repeated calibrator observations.

pinhole SF has the potential to improve measurement accuracy while reducing the number of observations that need to be made and the amount of time spent slewing between source and calibrator. These advantages have come without significantly reducing the sensitivity of COAST or restricting the wavelengths available to it.

We intend to continue work in this area by refining the alignment capabilities of the system to improve throughput and signal-to-noise ratio (which will be vital to observing faint sources) and apply it to the COAST's main astronomical programme. The high potential throughput and wide bandwidths available to pinhole spatial filtering make it an exciting potential addition to the Magdalena Ridge Observatory (MRO) interferometer project.

7. CONCLUSIONS

We have designed and constructed a pinhole spatial filter for use on the COAST optical interferometer. This system reduces the effects of atmospheric seeing on the accuracy and variability of visibility measurements. The system was used to observe Vega and compared to contemporaneous unfiltered observations.

Our major conclusions are as follows.

1. pinhole spatial filtering has been shown to drastically reduce the variation of measured visibilities with atmospheric conditions over time.
2. The uncertainty of visibility has been reduced by more than a factor of 2 for a single measurement and at least a factor of 5 for measurements taken over the course of an hour.
3. Filtered measurements are much more robust to changes in seeing making calibration observations valid for longer periods, reducing the amount of time spent swapping between sources.
4. pinhole spatial filtering has the potential to greatly improve the quality and quantity of scientific measurements with an interferometer.

ACKNOWLEDGMENTS

We would like to thank all of the members of the COAST team for their continued support and input. Special thanks go to Chris Haniff and John Baldwin for their valuable and constructive advice. Thanks also go to Dave Mozurkewich and John Monnier for our spirited and informative chats and to B.P. for designing an antidote to research.

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