MOSAIC
A Multi-Object Spectrograph with Adaptive Image Correction

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ABSTRACT

We have proposed a new Nasmyth instrument for the William Herschel Telescope which exploits the potential of wide field-of-view correction of atmospheric turbulence to produce a versatile, high spatial resolution, high efficiency, multi-object spectrograph and imager optimized for the 0.7-1.6 micron region. Using a low-altitude Rayleigh beacon guide star to correct the boundary layer turbulence which dominates the atmospheric seeing at La Palma on more than 25% of nights, MOSAIC combines the angular resolution gains of adaptive optics with the observing efficiency gains of multiple-object spectroscopy. Additional operating modes could include a narrow-band tuneable filter and a fibre feed to a bench-mounted high resolution echelle spectrograph. The instrument would provide a unique capability on 4-metre telescopes, opening up a wide variety of new scientific capabilities ranging from spectroscopic studies of crowded star fields to resolved studies of the kinematics of distant galaxies.

1. INTRODUCTION

The 1990's have seen a significant growth in the development of adaptive optics (AO) systems to reduce the effects of atmospheric turbulence on the delivered image quality of ground-based telescopes. Virtually all 4-metre class telescopes now have natural guide star AO systems either under development or in regular use. Some of the best established of these (e.g. the CFHT PUEO system[1]) are in use on a significant number of nights (25-30%) by non-specialist observers. The William Herschel Telescope on La Palma has been part of this growth and will see the commissioning of a common-user high-order adaptive optics system (NAOMI) within the next 12 months. Exploiting the NAOMI adaptive optics system with state-of-the-art instruments is seen as one of the important strategic developments of the WHT facility in the next few years.

One of the major limitations of all current adaptive optics (AO) systems is that the corrected field-of-view is relatively small[2]. Typically, the point-spread function (PSF) is sharpest in a small region around the reference star (laser or natural) and degrades with angular distance from the reference. The typical angular radius over which the image quality degrades by a factor of 2 can be <20 arcsec in the J-band, depending on site conditions, and even smaller at shorter wavelengths. There are two consequences of this effect: (a) the usable field-of-view over which acceptable correction can be obtained is very limited and (b) even over this small field of view, there is a variation of the PSF which limits the photometric accuracy of images and spectra, and significantly complicates any attempts at image deconvolution. The cause of the observed angular anisoplanatism in AO is the 3-dimensional nature of atmospheric turbulence (Fig. 1); regions of high optical turbulent strength occur in layers distributed at heights of between 0 and 20km above the telescope. A single wavefront corrector can fully compensate for the turbulence only along one direction of propagation. The wavefronts from off-axis sources undergo different overall distortion, because the light received at the pupil has sampled laterally sheared versions of the layers at different heights when compared with the on-axis beam.

One solution to this problem is to have multiple wavefront sensors and multiple correctors which are optically conjugate to different heights above the telescope. This multi-conjugate approach is now being considered by the Gemini Project for the Gemini South AO system at Cerro Pachon[3]. It offers the best long-term prospect for very high image quality over modest (1-2 arcmin) fields of view, but requires a significant increase in cost and complexity over existing AO systems, including the use of multiple natural or laser. An alternative, complimentary, and less costly approach involves not trying to correct the turbulence at all ***heights***, but only the turbulence which is common to all ***points*** in the field of view. In other words, one deliberately chooses not to correct turbulence at high altitudes, since the effect of this turbulence on the wavefront decorrelates most rapidly with angular offset. For such a 'restricted conjugate' AO system, the residual perturbations are just the natural seeing in the uncorrected layers. These residual errors, although producing images which are instantaneously different at different points in the field of view, are the same on average in all directions, and thus a long-exposure image will show no residual anisoplanatism from these layers.

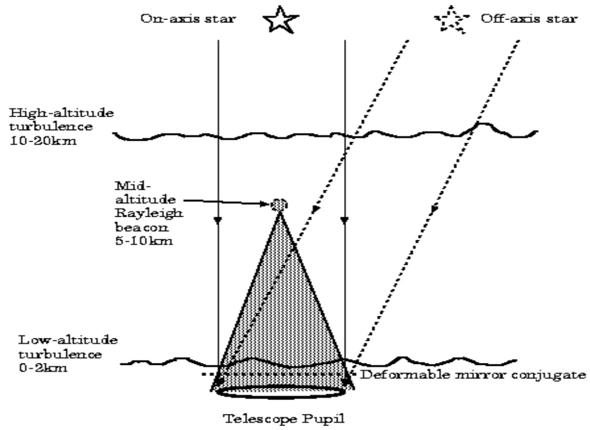


Figure 1. Restricted conjugate adaptive optics uses a low-level Rayleigh guide star to isolate only those turbulence layers which are common to a wide range of field angles.

The restricted conjugate AO concept depends critically on the vertical distribution of turbulence at the observing site. The ideal structure is a dominant low altitude layer with any residual turbulence located at a moderately high altitude. This allows clean separation of the seeing layers by using a low-altitude Rayleigh laser guide star to reject the high altitude turbulence from the wavefront measurements. Artificial Rayleigh beacons have been in regular use for AO since the mid-eighties, mainly by the military[4]. Their efficiency drops dramatically with beacon altitude but, in this particular application, this is not a disadvantage. The JOSE site evaluation programme at WHT[5] provides the best indicator of the vertical distribution of turbulence at La Palma, and the results for the 1996-98 campaign (16 nights) have been fitted with a simple 2-layer model. This fit has been verified against independent SCIDAR data on at least one occasion. The 2-layer model indicates that during ~25% of nights there was a dominant slow-moving layer located below an altitude of 900 metres (which is the limiting resolution of the measurements). In the calculations below, we have assumed that the layer is actually located at 900 metres on all nights, which is a somewhat pessimistic assumption. The present model does not include laser beacon projection (cone) effects with respect to the lower layer, but a preliminary assessment indicates that this contribution will be fairly small because the Rayleigh beacon can be positioned significantly higher than the upper layer (minimising lower layer cone effects). Point spread functions have been modelled for restricted conjugate correction at observing wavelengths of 0.7 (R), 1.2 (J) and 1.6 (H) microns. At an intermediate off-axis position 60'' from the guide star, the resulting FWHMs are 0''.20, 0''.18 & 0''.15 respectively, compared with an uncorrected value of 0''.6 (Fig. 2).

Whilst restricted conjugate AO does not result in diffraction-limited images, under the appropriate conditions (not necessarily those with the 'best' uncorrected seeing) it provides a large gain in spatial resolution and enclosed energy over a much wider field (~5 arcmin) than possible with conventional, 'single-conjugate' AO. The scientific capability of such a system is therefore complementary to conventional AO systems (like NAOMI) which target high-Strehl ratio imaging over relatively small fields of view. To fully exploit restricted conjugate correction over a wide field, one would also like to take advantage of the tremendous gains in efficiency which can be afforded by the use of multi-object spectroscopy techniques. This is the rationale behind the MOSAIC proposal.

2. SCIENTIFIC CASE

The science case for adaptive optics and its exploitation with imaging and spectroscopic instruments has been dealt with in numerous published reports[6]. Whilst the possibility of a wide field of view is not explicitly considered in these documents, it is certainly clear that many of the science cases considered would benefit substantially from a wider field of view. Specific examples which exploit the combination of high spatial resolution and a field of a few arcminutes diameter include:

- Studies of Galactic nebulae and star formation regions. In many cases these cannot be studied in isolation without complementary information about the surrounding regions. Dramatic HST images of planetary nebulae and star formation regions have also revealed the wealth of detail in shock fronts and embedded structures on scales <1 arcsec within these extended areas.

- Starburst galaxies. Many of the nearer starburst galaxies subtend angles of a few arcminutes, whilst individual giant HII regions and super starclusters in these objects are < 1 arcsecond in diameter. Spatially resolved spectroscopy across the extent of these galaxies is required to understand what triggers and propagates the star formation .

- Gravitational arcs. Individual giant arcs may be several arcsec along their long dimension, but are usually unresolved at 0''.3 arcsec resolution orthogonal to this. The multiple images for a given background galaxy will also be spread over a few arcminutes on the sky. Spatially resolved spectroscopy of these images will allow detailed studies of the kinematics of high redshift galaxies on scales that will be unobservable in any other way.

- The cores of moderate redshift clusters of galaxies subtend angular sizes of a few arcminutes diameter. Recent observations with HST have revealed luminous disk galaxy populations which are absent from rich clusters at low redshift. An important challenge is to directly measure the growth of the halo ***mass*** distributions in these clusters via the Tully-Fisher relation. Spatially resolved rotation curves are essential for these measurements to accurately determine the maximum turnover velocity.

In addition to multi-object spectroscopic capability, an effective way to search for emission-line sources (e.g. star-forming cluster galaxies, extragalactic planetary nebulae, QSO environments) is to use a tuneable narrow-band filter[7] (TTF). The availability of a large collimated beam space in MOSAIC would make incorporating such a facility relatively straightforward. Because of the need to detect compact faint sources above the background, TTF observations gain substantially from the resolution gains of restricted conjugate AO and can also easily exploit its wide field.

3. TECHNICAL DESCRIPTION

INSTRUMENT CONCEPT

The schematic layout of the MOSAIC concept is shown in Fig. 3. It is intended that field derotation will be compensated via the Nasmyth instrument rotator with the instrument supported on a static bearing. The instrument can then be broken down into 4 major subsystems:

1. a Rayleigh laser beacon with wavefront sensor and tip-tilt pickoff

2. a low-order wavefront corrector and associated AO control system

3. a fully transmissive spectrograph with multi-aperture masks and a TTF mode

4. an optical/infrared detector system

It is likely that the optical/infrared detectors will be manually interchangeable. These subsystems are discussed in more detail below.

LASER BEACON

The proposed implementation of the guide star system is via an on-axis medium-order wavefront sensor which will be time-gated and synchronised with the Rayleigh beacon. An additional peripheral natural guide star tip-tilt sensor will also be required. These two sensors will drive a medium-order wavefront corrector (based on a micro-deformable mirror or LC phase modulator) and a conventional steering mirror for tip-tilt. It should be noted that the JOSE data indicate a very slow moving lower layer, so the bandwidth specifications on both the wavefront sensors and corrector are relatively relaxed.

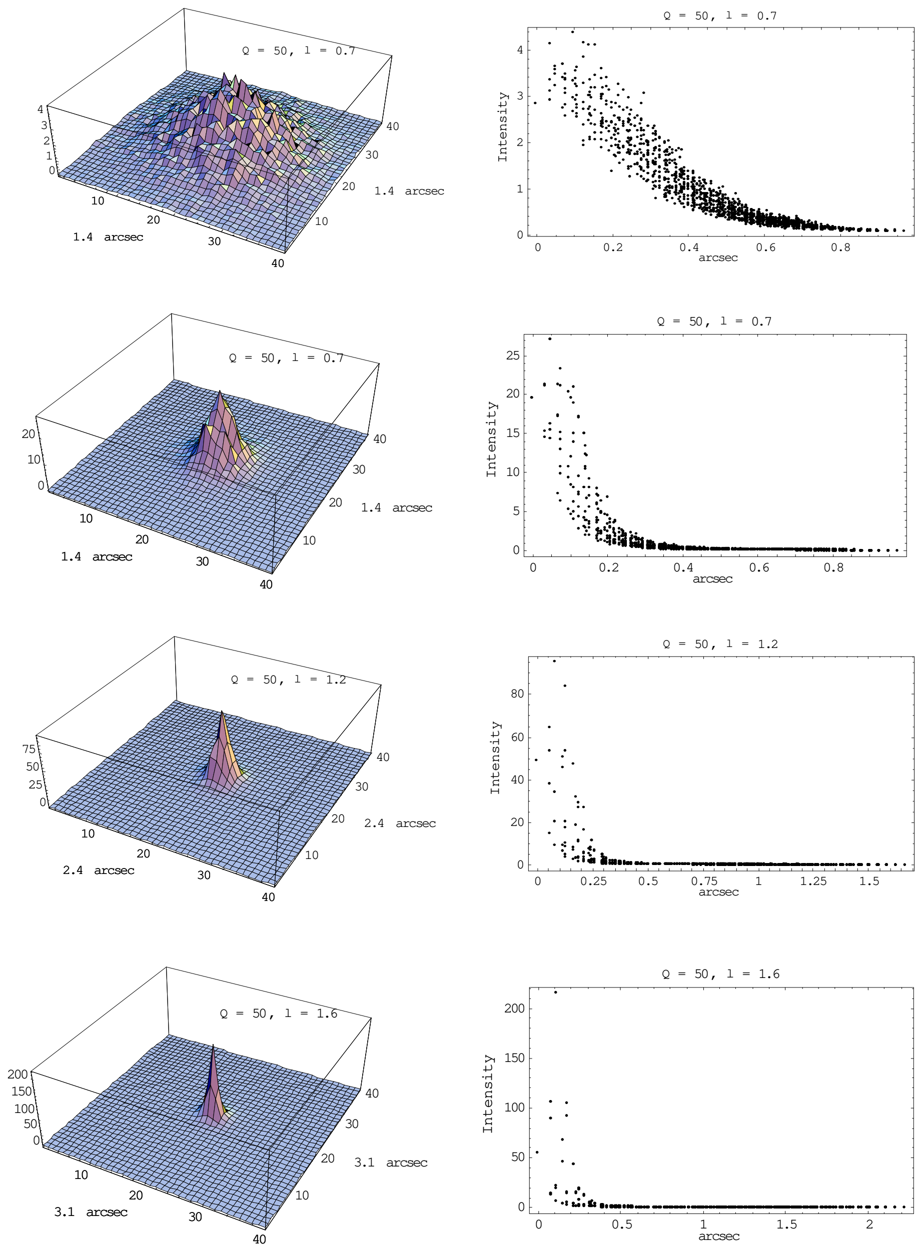


Figure 2. Surface plots and radial profiles of point spread functions for restricted conjugate adaptive optics. From the top these are (i) uncorrected seeing V-band, corrected R-band (0.7µm), corrected J-band (1.2µm) and corrected H-band (1.6µm). The corrected PSFs are calculated at a distance of 60 arcsec from the laser guide star under 25-percentile seeing conditions.

The laser system, modulator and wavefront sensor time-gating are being fully prototyped as part of a current R&D programme extending over the period 2000-2001. The candidate laser is a 5W frequency-doubled YLF. This is a compact unit with wall-plug power and cooling/mains unit connected via an umbilical. Athough this R&D project will involve a WHT laser launch, this will not be in a suitable configuration for common-user operation. The prototype Rayleigh beacon will be launched *monostatically* through the WHT itself. For routine use a *bistatic* launch is proposed, using an auxilliary telescope at the side of the WHT main mirror.

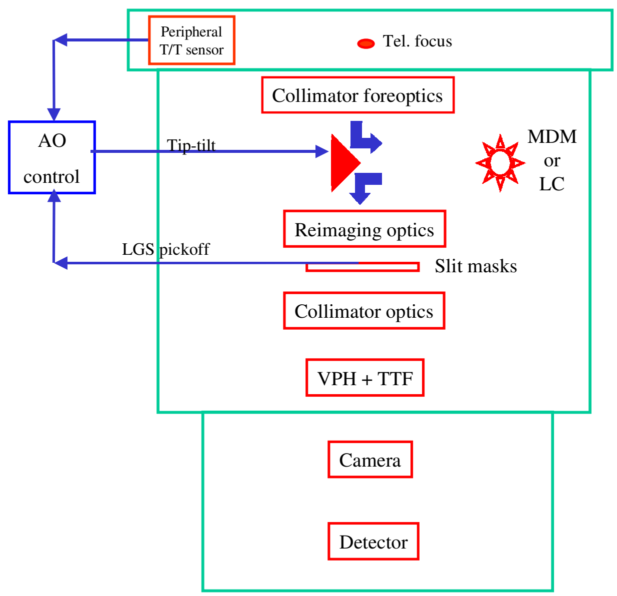


Figure. 3: Schematic block diagram of the MOSAIC concept

ADAPTIVE OPTICS

Our research programme on liquid crystal (LC) adaptive optics[8], and also the work of other groups worldwide, has shown that LC devices are a maturing technology for wavefront correctors. An LC device controls optical path length by varying the refractive index, unlike a mirror which controls real path length. The advantages of LCs are compactness, low power consumption, lack of hysteresis, and simplicity of control. Of the various wavefront corrector technologies they also have the potential for the largest number of actuators. The main disadvantage of using LCs in an astronomical adaptive optics system has been their relatively slow temporal bandwidths. This problem is now being addressed by the use of dual frequency LCs which have much faster response times, giving closed loop bandwidths up to 20Hz. This appears to be quite sufficient to correct the slowly moving low-altitude layers which dominate the La Palma site. An alternative low-cost technology we are investigating is the use of micro-machined deformable mirrors (MDMs)[9]. An issue specifically relevant to wide-field adaptive optics, which will need to be addressed during the next design phase, is the angular dependence of correction for an LC device versus a mirror.

SPECTROGRAPH DESIGN

The baseline specification for the MOSAIC spectrograph is:

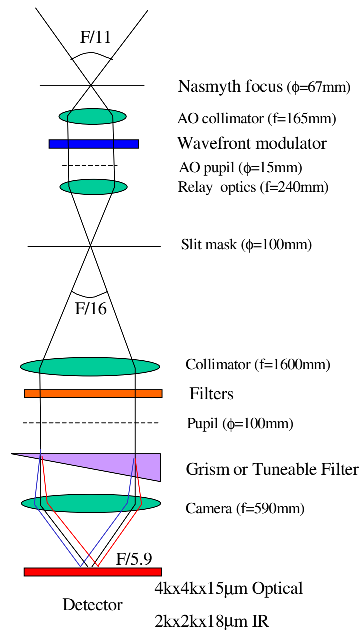
1. minimum 5’ field with multi-slit masks

2. high throughput 0.7 – 1.6 µm

3. high dispersion grisms or volume phase gratings to give R>3000 with 0''.3 slit
4. option of deployable tuneable filter
5. optical (0.7–1.0µm) deep-depletion CCD detector, 4kx4k with 0''.1 pixels
6. infrared (0.9–1.6µm) HgCdTe detector, 2kx2k with 0''.15 pixels

These criteria are driven by the need to Nyquist sample a 0''.3 arcsec slit, minimum machinable slit size of 100µm and the desirability of charge shuffling on the CCD at optical wavelengths. The minimum resolution is driven by the requirement for digital OH suppression in the J & H bands. Because the instrument is not cooled, the H-band performance will be compromised beyond 1.6µm. The optical layout of MOSAIC is shown in Fig. 4. Because of the use of narrow (0''.3) slits, the overall dimensions of the instrument are quite modest (1.8m long excluding detector) given the large field (5') and resolution (R=3000).

Figure 4. MOSAIC - Optical Schematic (not to scale)



For conceptual design purposes we have produced a Zemax model for the spectrograph (Fig. 5) by scaling the optical design of the Gemini GMOS spectrographs[10]. To produce an image scale such that 2 pixels = 0.3 arcsec matches 100µm at the slit mask plane (to be within the capabilities of a laser mask maker such as that used by GMOS) requires a collimator focal ratio of f/16. The linear size of the 5 arcminute field is then 100mm. The pupil has been kept at 100mm, but could be easily reduced for compatibility with smaller grisms or etalons. The camera has been slowed slightly from f/4.8 to f/5.9 to deliver an image scale of 0.15 arcsec/18µm pixel (the optical design shown in Fig. 5 has unmodified apertures which would be much reduced in practice). This system, even without re-optimisation, provides satisfactory image quality performance from 0.6 to 1.7µm over a field corresponding to 5 arcminutes diameter without requiring refocussing for different wavelength ranges (Fig. 6). Since the main remaining aberration is defocus, it is clear that refocussing would improve the image quality even further. The GMOS design was originally developed to give high glass transmission over this entire wavelength range, and can be used with MgF2/sol-gel bi-layer antireflection coatings to give high total throughput (75-85%) over a substantial part of this range. All the surfaces are spherical.

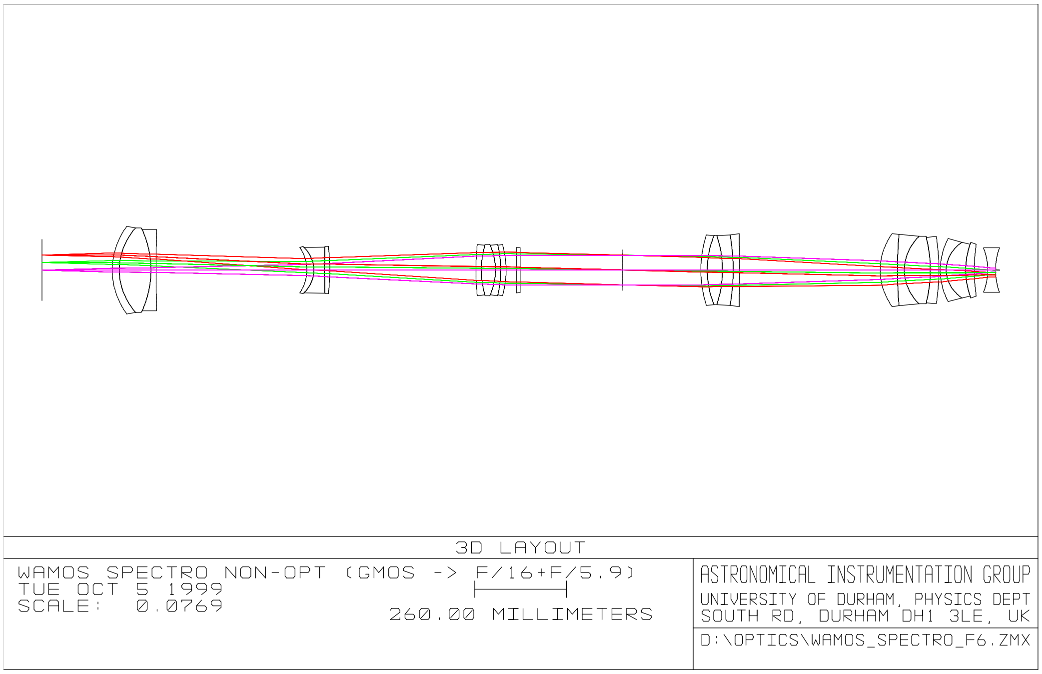


Figure 5. Zemax model of the MOSAIC spectrograph.

By using state-of-the-art optics and coatings, MOSAIC will therefore significantly (more than a factor 2) improve on the sensitivity of the existing LDSS-2 spectrograph, and provide an extension into the short-wavelength infrared. The enclosed energy curves implied by Fig. 2 indicate that for high spatial resolution work (0''.3 arcsec slits), MOSAIC will also be competitive with multi-slit spectrographs on 8-metre telescopes, when the latter are operating in median conditions (0''.6 seeing).

DETECTORS

MOSAIC will require 2 detector systems to work through the full 0.7-1.6μm spectral region. These will be based on a Rockwell 2kx2k HgCdTe detector for the IR and a mosaic of 2x2kx4k MIT CCDs for the optical. Depending on availability, the Rockwell arrays could be MBE devices with a 1.6μm cutoff to reduce the need for thermal blocking filters and for reduced readout noise and dark current. The baseline detector controllers are assumed to be SDSU-2.

DATA REDUCTION

We do not anticipate any special data reduction needs for MOSAIC. General purpose routines for multi-slit spectral reduction are available within IRAF and would be implemented as part of a data reduction pipeline.

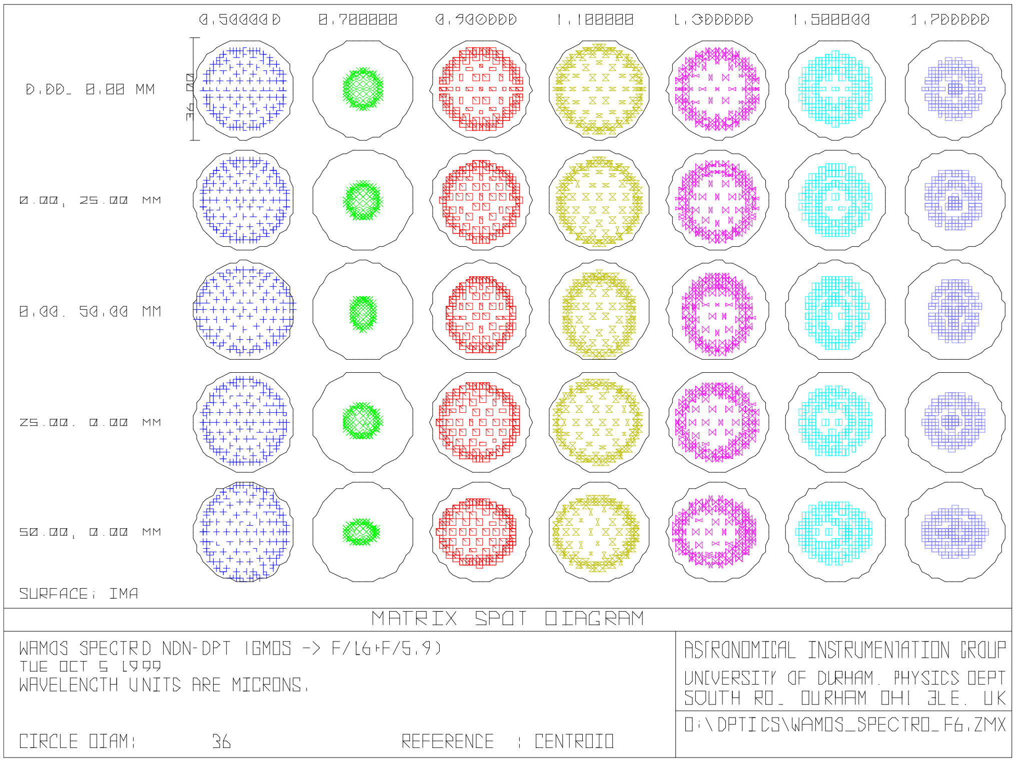


Figure 6. Spot diagrams with circle = 2 pixels (0.6-1.7µm). Columns denote different wavelengths (microns). Rows refer to different positions within the field (100mm=5').

HIGH RESOLUTION SPECTROGRAPH FIBRE FEED

It is expected that MOSAIC would be permanently mounted at one of the Nasmyth platforms. One possibility would be to install MOSAIC on the platform currently occupied by the high resolution UES spectrograph and to reconfigure the latter to take a fibre feed from the corrected MOSAIC focal plane. This would have the advantage of preserving high-resolution high-stability echelle spectroscopy at the WHT and also making effective use of poor seeing nights when wide-field AO correction is not available. Depending on the order of correction available in MOSAIC, the encircled energy in a single fibre (or pair of fibres) could be impressively high because the required field is so small.

OPERATING MODES

The wide-field mode of MOSAIC requires operation in the 25 percentile conditions during which there is a dominant lower turbulence layer which is below approximately 1km. Determining when these conditions occur could either use the imaging capability of MOSAIC directly or, more quantitatively, via a real-time SCIDAR measurement (possibly using the MOSAIC wavefront sensor). The percentage of nights available will increase if the full 5' field is not required for some projects. In either case some form of flexible scheduling would be an advantage, as is true for all AO instruments.

4. ACKNOWLEDGEMENTS

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5. REFERENCES

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