Recent Developments in Spectroscopy

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Abstract

Recent developments in spectroscopic techniques for 4-8m telescopes are reviewed, including the use of integral field spectroscopy as a tool to exploit the gains in spatial resolution from adaptive optics. A specific example is given of the TEIFU fibre-lenslet integral field unit being built for optical-infrared spectroscopy using adaptive optics at the William Herschel Telescope. The future prospects for using multi-object spectrographs with wide-field adaptive optics are briefly discussed.

Key words: Spectroscopy; Integral Field; Adaptive Optics

1 Spectroscopy on 2-4m Telescopes

Spectroscopic studies of astrophysically interesting objects usually make stringent demands on light grasp and efficiency. They are naturally suited to exploitation by the new generation of 8-10m telescopes. The role of 2-4m class telescopes in this era therefore needs to be carefully explored. There are three main areas where spectroscopic capability on smaller telescopes can provide a complimentary facility. These are:

- Support for 8-10m follow-up
- Exploiting unique modes
- Fast-tracking new technology

The first of these is the traditional role of smaller telescopes as survey engines. However, the concept of using surveys to locate selected targets for spectroscopic follow-up with larger apertures, extends beyond the classical multi-colour imaging surveys. Access to the new generation of large telescopes (at least for UK astronomers) will be sufficiently restricted that spectroscopic studies of the brighter end of complete samples will necessarily have to be carried out on 2-4m telescopes. There will also be a developing role of telescopes in this class as *spectroscopic* survey engines, where complete samples are studied at lower spectral resolution or signal-to-noise, to generate more restricted target lists suitable for detailed follow-up on 8-10m telescopes.

The second niche for spectroscopy on 2-4m telescopes is to exploit unique modes of operation in the XY-λ-t parameter space. This, for example, could be very high or very low spatial resolution spectroscopy, unique regimes of wavelength coverage and spectral resolution, or time-resolved spectroscopy on targets where minimum readout time is more critical than signal-to-noise. One example of this where smaller telescopes currently have a very competitive advantage, is in optical spectroscopy of adaptively corrected images using laser guide stars (Longmore, these proceedings).

Finally it should not be forgotten that development and exploitation of new technologies for astronomical instruments requires access to suitable facilities on which to commission and refine their operation. The need for large telescopes such as Gemini to service a wide-ranging community with common-user instruments will inevitably make them less able to respond to fast-track developments of new instrument concepts. This is a future role for 2-4m telescopes who's potential to trigger real advances should not be underestimated.

2 Integral Field Spectroscopy

Integral field spectroscopy (IFS) is a mode of observation which delivers spectroscopic information over a full 2-dimensional area. It has gained considerable attention in recent years as a means to study regions with complex spatial structure. Scientific applications include (i) stellar kinematics in the cores of nearby galaxies, (ii) kinematical studies of galaxies at intermediate redshift, (iii) redshifts of strongly gravitationally-lensed images, and (iv) probes of the circumnuclear environment in active galactic nuclei.

Integral field spectroscopy is a particularly powerful way to exploit the gain in spatial resolution afforded by an adaptive optics (AO) system, since an image of the field can be reconstructed under the same seeing conditions as when the spectra were taken. Because of the spatially and temporally varying nature of adaptively-corrected point spread functions, this can be crucial in interpreting the resulting data. There are three major techniques which can be employed to obtain IFS with full area coverage. (Fig. 1).

The first of these uses a microlens array to segment an image formed by the telescope into multiple telescope pupil images which are then dispersed into a number of discrete spectra by a spectrograph. This technique has been

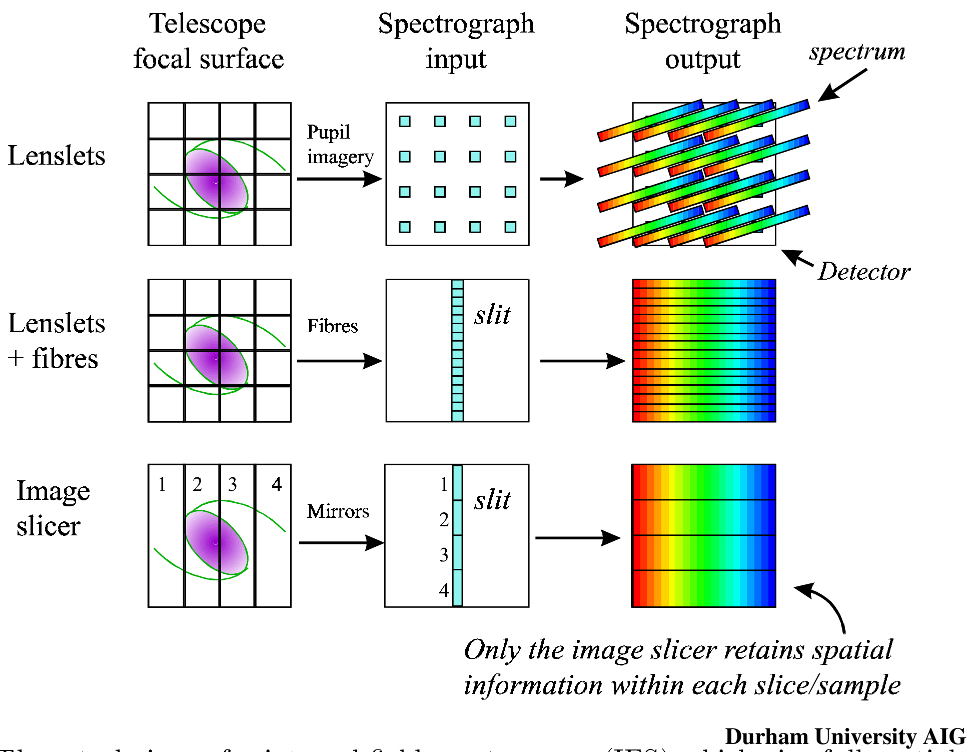

Fig. 1. Three techniques for integral field spectroscopy (IFS) which give full spatial coverage at the input focal plane.

successfully employed in the *TIGER* and OASIS instruments (Adam et al. 1997). The main drawback is the need to avoid overlapping the spectra on the detector, which limits the wavelength coverage available at high spectral resolution. The second method illustrated in Fig. 1 uses an array of hexagonal lenslets to image the telescope pupil onto a close-packed bundle of fibres, which are then reformatted into a pseudo-slit and dispersed as in a conventional long-slit spectrograph (Haynes et al. 1998). This provides a stable spectrum format and maximum efficiency in terms of filling the available detector area. Finally, Fig. 1 also illustrates the use of image slicers to rearrange a rectangular field into one or more narrow long-slits, which can then be dispersed. The advantages of this approach are that full spatial information is maintained along the slices and, if constructed from reflective optics, the system can easily be cooled to cryogenic temperatures for operation at wavelengths $\lambda > 1.6\mu$m (Content 1997).

Over the past two years the Astronomical Instrumentation Group at Durham University has been developing the *Thousand Element Integral Field Unit*. TEIFU is a fibre-lenslet IFU designed to provide spectroscopic capability at visible wavelengths when working with the ELECTRA AO system (Buscher et al. 1996). The input microlens array of TEIFU is divided into 2×504 fibre subfields. An ingenious pickoff system allows the separation between these t-wo subfields to be varied, so that they can either be combined into a single

1008-element field covering 54 square arcsec at 0.25 arcsec sampling, or used as separate object and sky fields within the 70 arcsec diameter field of view of ELECTRA. The location of these two fields is always maintained symmetrically with respect to the guide star of ELECTRA in order to minimise the effects of scattered light on sky-subtraction. The output from the fibres feeds the WYFFOS spectrograph, which is an optimized fibre spectrograph also located on the same Nasmyth platform as ELECTRA/TEIFU (King & Worswick 1998). The full range of cameras, gratings and filters for WYFFOS is then available. TEIFU is due to be commissioned with the ELECTRA AO system at the WHT in June 1999, followed by a period of service mode science. Further details on the construction of TEIFU can be found in (Haynes et al. 1998).

The current sampling on TEIFU is 0.25 arcsec per pixel which is well matched to the image quality delivered by the ELECTRA system working in local tip-tilt mode (image FWHM $0.25 - 0.5$ arcsec). A second scale of 0.12 arcsec per pixel is due to be available later this year. Further developments under consideration include an upgrade to the fore-optics to extend the wavelength of operation of TEIFU out to $\lambda \sim 1.65\mu$m, when combined with a suitable dispersing element and infrared detectors. This would provide important early access to an infrared spectroscopic capability with which to exploit the excellent performance of the ELECTRA and NAOMI adaptive optics systems at these wavelengths (Longmore, these proceedings). In the longer term, a fully diffraction-limited IFU, with optimized spectrograph is needed for NAOMI, probably based on an image-slicer design. This is because diffraction effects inside the spectrograph when using entrance apertures close to the diffraction-limited image size can cause major throughput losses unless compensated by over-sized optics. The 1-dimensional nature of the image segmentation in a slicer design, significantly reduces these complications when compared to the 2-dimensional segmentation inherent in the other two designs (Content 1997)

3 Wide-Field Spectroscopy

It is clear that many astronomical programmes, for example spectroscopic surveys of high-redshift galaxies, would benefit from a moderate increase in angular resolution (when compared with normal seeing) over a 'wide' field of view as much as, or more than, diffraction-limited resolution over a very narrow field of view. One of the major limitations of all current adaptive optics (AO) systems is that the corrected field-of-view is relatively small. 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 $\leq 20''$ 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 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: regions of high optical turbulent strength occur in layers distributed at heights of between 0 and 20km above the telescope. One solution to this problem is to have multiple wavefront sensors and multiple correctors which are optically conjugate to different heights above the telescope (Johnston & Welsh 1994). In this multi-conjugate solution, there would ideally be one corrector conjugate to each significant layer of turbulence. This scheme offers the best long-term prospect for high image quality over large fields of view, but requires a significant increase in complexity over existing schemes, including the use of multiple natural or laser beacons.

An alternative, complimentary, 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 large offsets, the optimal on-axis correction of high-altitude wavefronts actually increases the aberration in the high-altitude component of the off-axis wavefront. For such a "restricted conjugate" system, the residual perturbations are just the natural seeing in the uncorrected layers. These residual errors are the same on average in all directions and thus a long-exposure image will show no residual anisoplanatism from these layers. The effect of the AO system can therefore be thought of as decreasing the effective strength of the turbulence to that of the residual layers. At many observatories, which have a strong boundary layer, this effect can be quite dramatic. For the Gemini South site at Cerro Pachon, recent site testing data show that on some nights the effective seeing parameter r_0 at visible wavelengths increases from $\sim$ 11cm to $\sim$ 30cm, if the layers at altitudes less than 1km are removed. This results in a decrease in image FWHM from 0.9 arcsec to 0.3 arcsec and, whilst it does not result in diffraction-limited images, it provides a large gain in resolution and image intensity over a much wider field than possible with conventional, "single-conjugate" AO

For restricted-conjugate AO to work, it is necessary to be able to filter out the contributions of high-altitude layers from the wavefront measurement. One way to do this is to use two or more well-separated stars in the field of view, but this leads to a complex wavefront sensor and will work in only a very few regions of the sky which have high enough natural guide star density. A more practical scheme is to use a laser beacon at low altitude which naturally rejects high-altitude turbulence. This can most easily be achieved using a Rayleigh laser beacon. Rayleigh beacons have been in regular use for AO since the mid-eighties (mainly by the military) but have fallen out of favour because their efficiency drops dramatically with beacon altitude. In this particular application, this is not a disadvantage, and a relatively low-power (500μJ/pulse) turn-key laser system can be used to project a beacon at 5-10 km altitude, instead of the 10-20km altitude normally used with these systems.

We are investigating a possible prototype restricted-conjugate AO system for operation on the WHT to demonstrate the unique capabilities of such a system. The resulting system would provide (i) a demonstration of the feasibility of wide-field moderate-resolution image sharpening; (ii) the UK astronomical community with its first access to a correction system which is not limited by the availability of bright guide stars and with complementary capabilities to the planned facility mesospheric sodium beacon; (iii) a stepping-stone to true multi-conjugate systems.

4 Conclusions

The WHT and the INT should have clearly defined roles in the era of 8-10m telescopes. For the INT it is likely that this will be primarily in the area of imaging surveys, where its smaller aperture can be compensated by deeper exposures over wide fields. For the WHT there is a clear niche to be exploited using a combination of adaptive optics and integral field spectroscopy. The importance of 2-4m telescopes as testbeds for technological development, for example restricted conjugate adaptive optics over wider fields, should not be overlooked.

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