Integral field spectroscopy with the GEMINI Multiobject Spectrographs

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ABSTRACT

The most innovative feature of the GEMINI multiobject spectrographs (GMOS) is the capability for integral field spectroscopy. This will allow the GEMINI telescopes to obtain spectra over a contiguous rectangular field of area 50 arcsec^2 with a sampling of 0.2 arcsec. The field will be reformatted into two long slits so that each element in the field is dispersed into a long spectrum containing up to 900 resolution elements at spectral resolutions up to 10,000. Background subtraction will be carried out via a separate field with identical optical characteristics. This will support a number of background-subtraction techniques including beam-switching. The integral field unit will be loaded into the focal plane in the same way as a slit mask to allow a rapid changeover between integral field and aperture spectroscopy. The design employs a combination of optical fibres and microlens arrays with enlarging fore-optics. The fibres give the desired reformatting ability to maximise the length of the spectrum while the microlenses provide both contiguous field coverage and optimal matching to the slow telescope and spectrograph optics. The integral field capability may be augmented and upgraded by adding different units. Of particular interest are options for finer spatial sampling (0.1 arcsec) and for operation in the near-infrared.

Keywords: Integral field spectroscopy, large telescope instrumentation, multiobject spectroscopy

1. INTRODUCTION

Both GEMINI telescopes will be equipped with multiobject spectrographs of almost identical design[1,2]. As well as providing a capability for multi-aperture and single-aperture spectroscopy with a wide range of dispersion options, the instruments will include a system for integral field spectroscopy. This paper describes the design of the Integral Field Units (IFUs) which will be supplied with each GMOS instrument as part of the baseline system. The possibility of adding further IFUs with different formats or wavelength optimisations is discussed.

2. REQUIREMENTS

Integral field spectroscopy[3–8] is a technique to produce a spectrum of each spatial element in an extended, two-dimensional field. This can be also be done with scanning Fabry-Perot systems and longslit spectroscopy, where the slit is stepped across the target, but these do not record the data simultaneously and so are much less efficient.

The scientific advantages for studies of extended objects are obvious but work on single unresolved objects or integrated spectroscopy of extended objects also benefits because light from the full extent of the image is sampled simultaneously without the need for a wide slit which would degrade the spectral resolution. In this way, an integral field spectrograph works as an image slicer to optimise the product of spectral resolution and throughput.

The scientific applications are numerous. Here we emphasize three which serve to define the practical technical requirements of the system.

The first example is the use of the Tully-Fisher relationship at intermediate redshift, $z \simeq 0.6$. At this distance a typical spiral galaxy has a magnitude $I \simeq 22.5$ and scale length ~2kpc (~0.5 arcsec). To trace the velocity field via emission lines to several times the scale length (1-2 arcsec) requires the exceptional tip/tilt-stabilised images that the GEMINI telescopes will deliver in good conditions (50% energy enclosed in a diameter of ~0.3 arcsec) and spatial sampling by the IFU of 0.1-0.2 arcsec. In order to achieve a signal to noise ratio of 20 for each sampled annulus when the equivalent width of the [OII]3727 line is 2nm requires exposure time of ~3 hours. The two-dimensional dataset allows the full velocity field to be measured so that the correct global rotation velocity can be determined.

The second example is the study of high redshift ($z > 0.6$) radio galaxies. The cause of the co-alignment between the optical and radio structures is still controversial. Further progress depends on two-dimensional mapping of emission line ratios, continuum fluxes and the velocity field over the ≤10 arcsec extent of the optical emission. This requires both a large wavelength range, so that several emission lines can be observed simultaneously, and high spectral resolution, to give good velocity resolution. This application also highlights the desirability of working in the near infrared where many of the strongest lines will be found at these high redshifts.

The third example is kinematical studies of the nuclei of nearby and moderately distant galaxies. This requires good spectral resolution obtained from several spectral features spread over a wide wavelength range. The particular problem with this work is likely to be errors in background subtraction which may dominate the photon noise errors. Since the galaxy will often completely fill the field of the IFU it is necessary to provide a separate field dedicated to background subtraction displaced from the main (object) field by a distance large compared with the typical size of the galaxies.

From the above discussion, we may define the main requirements for the GMOS IFU as:

- Spatial sampling: ≤0.2 arcsec
- Field of view: ≥50 arcsec^2 (with aspect ratio 1-2)
- Large wavelength range and high spectral resolution implying a large number of spectral resolution elements.
- A separate field for background estimation displaced from the object field by several arcmin.
- High throughput with contiguous spatial coverage

In addition, operational requirements dictate that it should be possible to switch rapidly between the aperture and integral field spectroscopy modes.

3. DESCRIPTION OF THE DESIGN

3.1. Overview

A design satisfying the requirements is summarised in Table 1. Figure 1 illustrates how this format matches the typical scale of objects at moderate redshift.

Table 1: Summary of the GMOS baseline Integral Field Unit

Spatial sampling	0.2 arcsec
Object field area	50 arcsec^2
Object field aspect ratio	$\sqrt{2}$
Object:background field area	10:1
Object-background field distance	2 arcmin
Number of reformatted slits	2
Width (FWHM) of spectral resolution element	0.27 arcsec
Maximum number of spectral resolution elements	900
Number of spatial resolution elements	1600

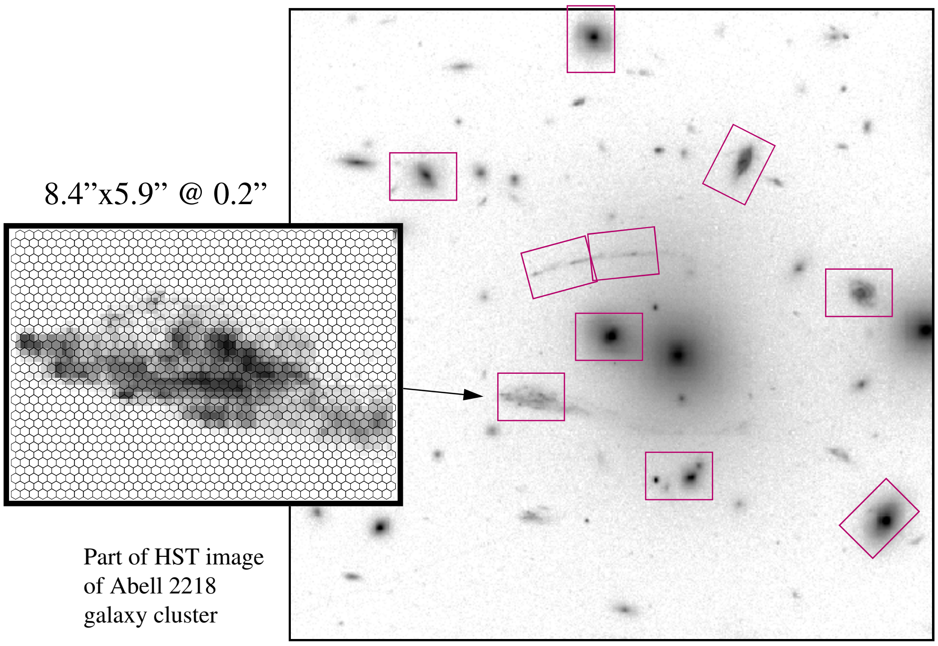

Figure 1: A simulation of the sampling pattern of an Integral Field Unit covering an area of 50 arcsec^2 in a format of 42×37 (8.4×5.9 arcsec) where the horizontal distance between adjacent hexagonal microlenses is 0.2 arcsec. This is compared with an HST image of part of the galaxy cluster Abell 2218 (Sharples, private communication) containing gravitationally-lensed objects to show how the field is matched to the scale of many objects of interest.

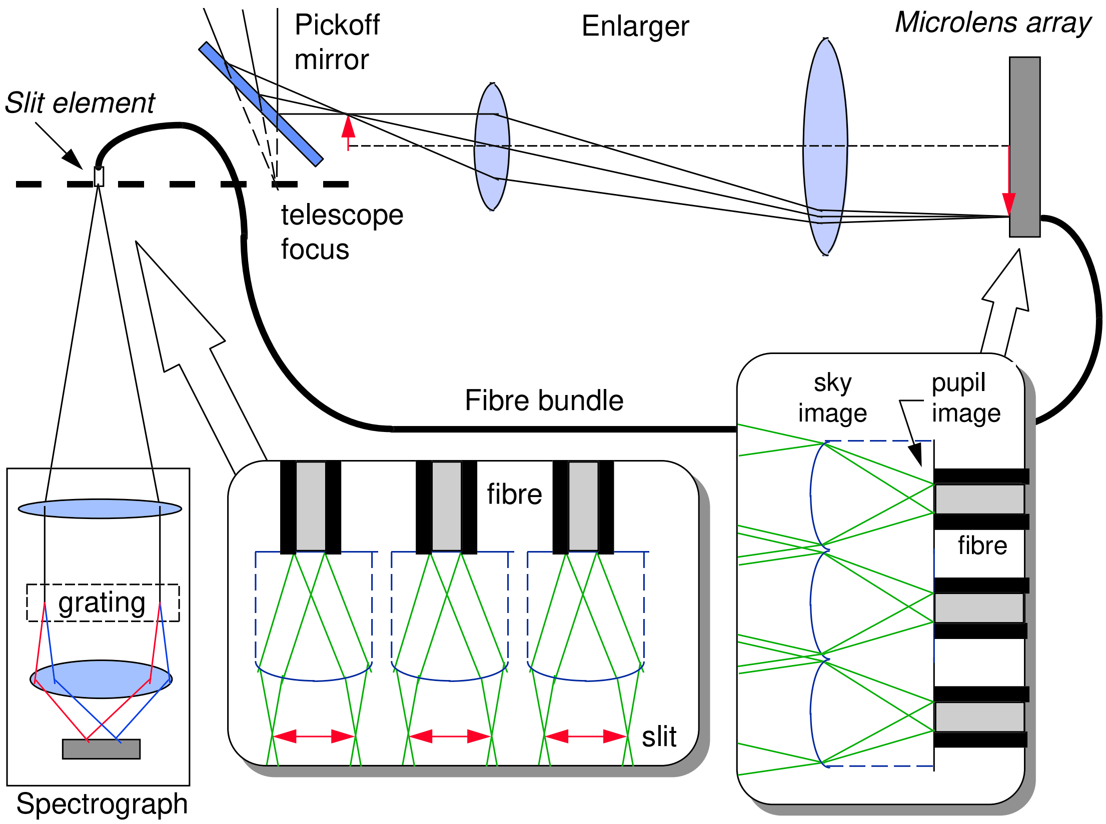

Figure 2: A schematic diagram showing the layout and principles of the GMOS integral field unit.

The basic principle of the design is indicated schematically in Figure 2. The f/16 beam from the telescope is picked off from in front of the focal surface by a mirror and sent through an enlarger to magnify the image formed by the telescope by a factor of ~4. The enlarged image is sampled by a microlens array which forms images of the telescope pupil at the entrance to optical fibres. The pupil images have a smaller diameter than the aperture of the microlenses so no loss is experienced at the gaps between fibres cores. This leads to a filling factor which is determined only by the microlens array (~95%). The spatial sampling is determined by the pitch of the microlens array which is defined by the spacing between opposite edges of the hexagonal lenses. The microlenses speed the beam to ~f/5 to reduce focal ratio degradation so that the beam emerging from the fibres is only marginally faster than at the input. The fibres are reformatted to form two long output slits which are located at the original telescope focal surface. The slits are actually defined by the pupil images of the fibre outputs formed by a linear microlens array. Alternatively, the re-imaging process can be viewed as a restoration of the original sky image after scrambling by the fibres since the fibre output is itself a scrambled version of the telescope pupil. The output microlenses also convert the beam to somewhat slower than the f/16 required by the spectrograph to fully illuminate the spectrograph pupil. This helps to counter the effect of diffraction in the IFU which would otherwise lead to overfilling of the spectrograph optics and grating.

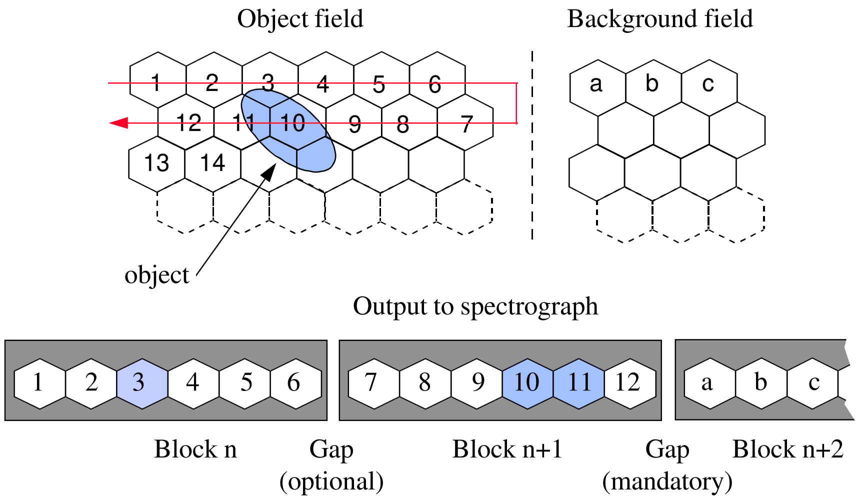

Figure 3: A schematic diagram illustrating the mapping between the input and output of the integral field unit. In this example each row of the IFU object field maps to one slit block.

3.2. Estimated performance

The field area is determined by the number of elements in the IFU which is itself fixed by the spacing between the elements in the reformatted slits, the width of the detector in the spatial direction (4096 pixels) and the number of reformatted slits (2). The minimum element spacing is determined by the size of the output microlenses since their aperture exceeds the size of the image formed at the slit. It is important to note that we do not require complete isolation between the images formed by adjacent microlenses provided that we ensure that they originate from adjacent regions on the sky. This can be arranged by mapping complete columns or rows in the rectangular input field to blocks of elements in the slit. (Figure 3). This mapping scheme also provides a natural way to produce clear gaps between groups of spectra from which the instrumental background (for example, due to scattered light in the spectrograph optics) can be assessed and to correct for non-telecentricity by permitting the blocks to be individually angled with respect to the spectrograph optical axis.

For the configuration described in the table, we estimate a total throughput from the input to the IFU, including fresnel losses, manufacturing errors, internal vignetting and diffraction, to be ∼80%. Figure 4 illustrates the detection process excluding the effect of the enlarger and diffraction losses in the spectrograph optics.

We can increase the field area by reducing the spacing between slit elements but this results in a reduction in the aperture of the output microlenses leading to vignetting. A tradeoff analysis including diffraction effects suggests that the field area could be increased to 70 arcsec^2 at the expense of a reduction in throughput of 5%. Further increases in field area would result in a more significant loss of throughput.

3.3. Dispersion options

The baseline design reformats the IFU field into two slits defined by the relayed position of the (scrambled) sky image. The full range of dispersion options provided by the GMOS dispersion system (a turret which positions

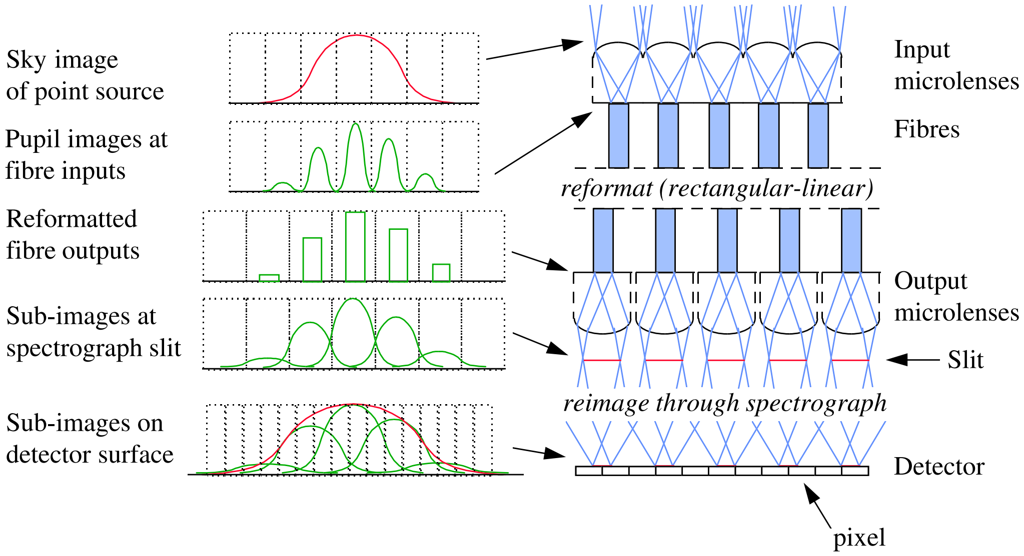

Figure 4: An illustration of the detection process in the integral field unit. The optical path (excluding the enlarger) is shown on the right while the corresponding light distributions are shown on the left. The distributions are highly schematic and exaggerate the effect of aberrations.

one of a selection of tiltable gratings in the beam) will be available with the single restriction that the maximum spectrum length will be half that possible from a single slit in aperture spectroscopy mode. This requires the use of a passband filter to define the ends of the spectrum accurately to avoid cross-talk between the spectra from each slit. The narrow effective slit width (defined by the FWHM of the light distribution at the slit) means that resolving powers approaching 10,000 will be possible.

It may be possible to increase the spectrum length to fill the entire length of the detector (6144 pixels), yielding $\sim$1800 resolution elements, by masking off one slit. This means that the field area will be halved but, by appropriate mapping between the IFU input and output, it will be possible to make the reduced field contiguous as shown in Figure 5. The halved field will maintain the same aspect ratio as the original field and one half of the background field will also be available for background subtraction.

3.4. Background subtraction

The two-dimensional nature of the IFU field permits the spectrum of the night-sky, which is dominated by bright emission lines, to be subtracted from the object spectrum by defining clean areas of the IFU field from which the background may be estimated. Despite this, background subtraction may still be a problem in some circumstances. Firstly, when the target object is large enough to completely fill the field of view so that there are no clean areas from which the background may be estimated. Secondly, bright night sky emission lines may be incorrectly subtracted if there are variations in the profile of the light emerging from different elements of the IFU sampling the object and background regions. This problem could arise because of manufacturing defects which induce anomalous stresses in some fibres with the result that they suffer greater than expected focal ratio degradation. This would speed up the beam emerging from the affected fibres resulting in a change in throughput, which can be easily removed by flat-field calibration, and a change in the shape of the point-spread function (PSF), *which is much more difficult to remove.*

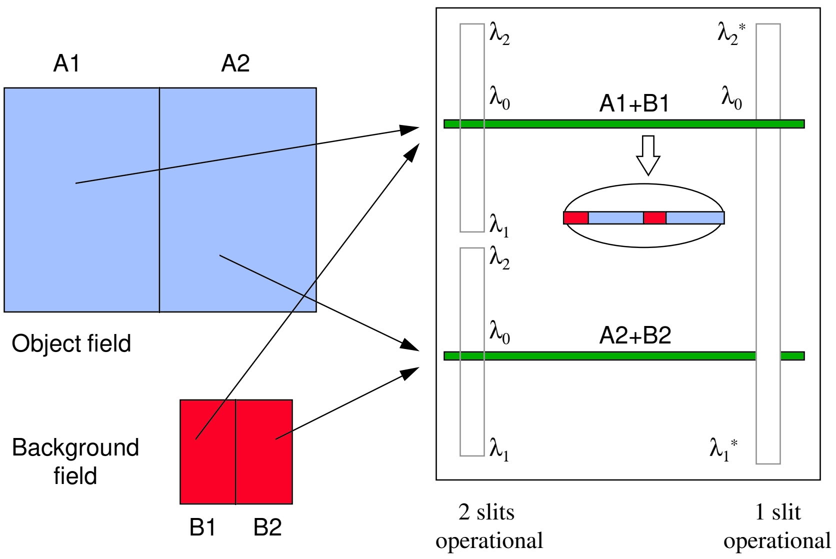

Figure 5: A schematic diagram showing how the object and background fields can be mapped to the reformatted slits so as to allow either one or both slits to be used. The single slit option gives the maximum spectrum length. Here λ_1 and λ_2 indicate the extreme wavelengths of the spectrum where λ_0 is the central wavelength. The expanded view of one slit shows how the object and background blocks are interleaved.

For this reason, the GMOS IFU includes a separate background field which is displaced from the object field by as much as practical ($\sim$2 arcmin). The optical system for both fields is identical (except for the size of field) to remove first-order variations in the shape of the PSF. The element-to-element variation in the PSF is hard to assess since it depends entirely on the details of the manufacture of the IFU which will not be known definitively until a system of this scale and complexity is manufactured and tested. Our strategy has been to assume that this problem will be present at some level and to allow the object and background fields to be used for beam-switching. This should completely remove the effect of PSF variations since the same IFU elements sample both the object and background fields. This is illustrated schematically in Figure 6. For part of the observation cycle the telescope will be pointed so that the target is sampled by the A field while field B samples the background. For the rest of the time, the telescope is offset so that field B samples the target while field A samples another background area.

It can be shown that, in an idealised situation, the uncertainty in the background subtraction, expressed as a variance, is

$$\sigma^2 = \frac{2S}{e^2}$$

for the true beam-switch field (defined by the extent of B) and

$$\sigma^2 = \frac{4S}{e^2}$$

for the rest of the field (defined by the extent of A), where S is the total number of photons detected in both cycles for one element of the IFU and e is the typical system efficiency. The quality of subtraction outside the true beam-switch field is degraded because this region is observed for only half of each cycle. This should be compared with the case where the background signal is estimated from a different region within the same field in

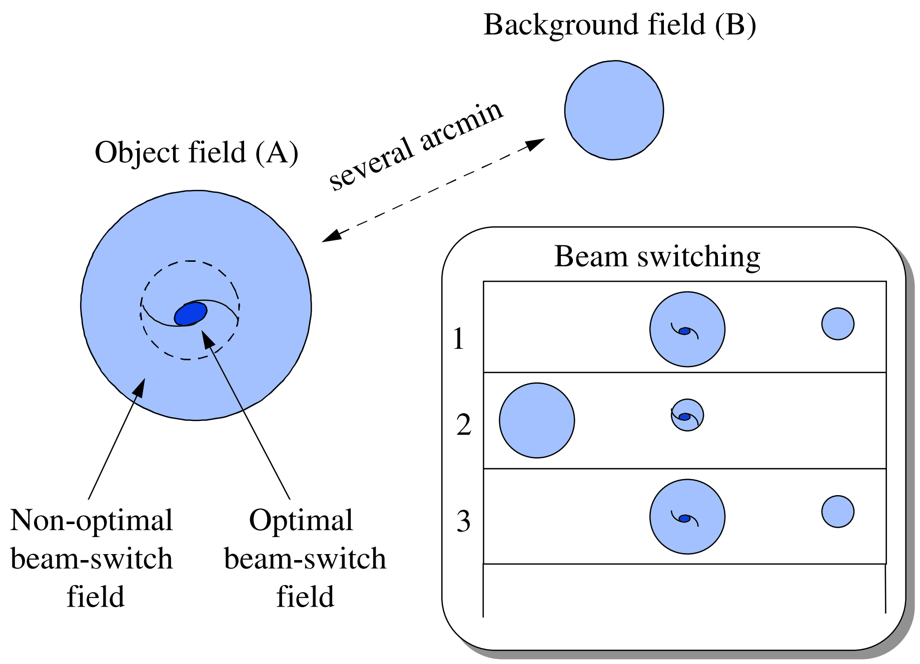

Figure 6: A schematic diagram illustrating the principle of beam-switching between two fields of unequal size.

which case the uncertainty in the background subtraction is

$$\sigma^2 = \left(1 + \frac{1}{N}\right) \frac{S}{e^2} \left(1 + \frac{\sigma_P^2 S}{e^2}\right)$$

where N is the number of elements used to estimate the background signal and σ_P represents the uncertainty caused by element-to-element variations in the PSF shape. (This should not be confused with the effect of throughput variations, which can be ignored since they can be calibrated out by flat-fielding.) This last term does not appear in the expression for beam-switching because the object and background signals are recorded using the same elements so there is no residual due to the uncertainty in the shape of the PSF. It can be seen that this term dominates at high signal levels.

Comparing these expressions, it is apparent that beam-switching will be the preferred option for high signal/noise observations where accurate background subtraction is vital. For observations of faint objects where photon noise dominates, the best option would be to take the background signal from field B, without beam-switching, or from the edge of field A.

Although it would be desirable to maximise the benefit from beam-switching by making fields A and B the same size, it should be remembered that the size of the total (A+B) field is limited by the number of fibres, which is determined by the detector format (and the requirement to maximise throughput). Therefore it would only be possible to equalise the fields at the expense of reducing the main (object) field. In fact, this format is well matched to observation where the signal level is highest in the centre of the field (e.g. a galaxy nucleus) since this is where the best subtraction accuracy is required. In the current design, field B has 10% of the area of field A, but this can easily be modified if necessary.

It is not expected that the individual fibres will experience variations in either throughput or PSF shape as the telescope tracks because they will be fixed permanently in position once the IFU has been assembled. Other design features which should improve the data quality are the provision of clear gaps between slit blocks, to allow scattered light in the spectrograph to be assessed and subtracted, and the interleaving of object and background blocks to reduce field-dependent subtraction errors.

3.5. Target acquisition

An advantage of integral field spectroscopy is that it is possible to form a slightly degraded broad-band image of the field by summing each spectrum over wavelength and reconstructing the original geometry of the field. Therefore it is possible to recover the pointing of the telescope after the observation so that the target does not need to be acquired with great precision. However there will be cases where it will be necessary to recreate an earlier pointing to great accuracy and it will always be necessary to ensure that the target is acquired with an accuracy that is much smaller that the size of the field. This can be done by making use of the imaging mode of the spectrograph which involves inserting a plane mirror into the beam and withdrawing the IFU. An aperture offset can then be calculated from the position of the image of the target on the detector and the telescope offset accordingly. It will be possible to reposition the IFU in the focal plane with sufficient accuracy to support this option. Another technique, which does not involve repositioning the IFU, is to form a reconstructed image in real-time and to adjust the telescope position until the target appears at the correct position within the IFU field.

4. PRODUCTION

The IFU design outlined here has $\sim$1600 fibres with 50μm cores which need to be positioned accurately to an accuracy of $\sim$10μm with respect to each other and to the microlens arrays. The key to this is a fibre holder which contains a regular array of holes with diameters precisely matched to the outer diameter of the fibres. The array of holes must be absolutely regular and the pitch must be measured to great accuracy before the microlens arrays are made so that the pupil images are correctly matched to the fibre cores. The whole system fits within a space envelope of roughly $100\times250\times500$mm. The small size and necessity of multiplexing between input and output so as to optimise the performance of the system creates additional complications in the routing of the fibres.

Figure 7 shows an IFU design with separate object and background fields. The square plate to which the object and background-field bodies are attached is the same size and shape as a slit mask so that the IFU can be stored in the intrument and deployed via a common loading mechanism

Although the production of this system is a challenge, it requires only a modest extrapolation of the fibre-handling techniques already developed for multiobject instrumentation by the Astronomical Instrumentation Group in Durham. The group has already identified promising solutions for the manufacture which will be tested as it follows a development path which includes the manufacture and testing of IFUs for 4-m telescopes containing 100-1000 elements.

5. UPGRADE OPTIONS

Upgrades to the integral field capability of GMOS are easy to implement since the IFU can be exchanged with another unit conforming to the same mechanical and optical interface and there are no internal moving or electrical parts. Up to three such units can be loaded in the instrument at any one time. The envisaged upgrades are of two main types:

The first type of upgrade is to exploit proposed enhancements to GMOS. It is planned to upgrade one or more

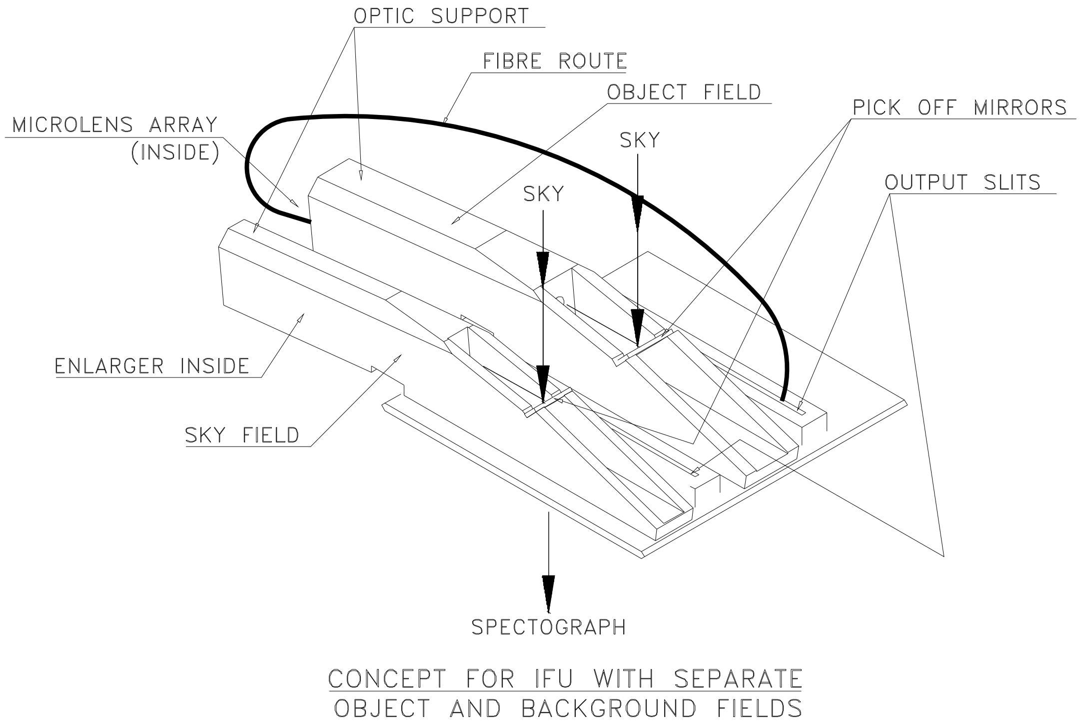

Figure 7: A drawing of a design for the IFU with separate object and background (sky) fields.

GMOS instrument to operate in the non-thermal infrared J and H bands by replacing the CCD mosaic with an infrared detector and changing the antireflection coatings as necessary. IFUs could be provided to work in this wavelength region since the fibres and microlenses of the initial system will be made from Fused Silica which will also work well at these wavelengths. It will only be necessary to revise the antireflection coatings and possibly the enlarger optics. The main challenge will be that the infrared detector may be smaller than the baseline CCD mosaic which would significantly limit the field area. A single 2048×2048 IR array will result in a rough halving of both the field area and spectrum length. However a mosaic of detector arrays offers the possibility of maintaining the full field area and spectrum length. A more subtle problem is that diffraction will increase at longer wavelengths, leading to some loss of throughput or spectral resolution.

The second type of upgrade is to provide different combinations of sampling, field size and spectrum format. We have already outlined how to increase the length of spectrum by halving the field area. There is also great interest in reducing the sampling interval to 0.1 arcsec to better match conditions of exceptional seeing and to exploit improved images produced by the GEMINI Adaptive Optics System[9] through which light can be optionally routed before reaching GMOS. This spatial sampling can be produced with the current design simply by changing the enlarger to give twice the magnification while using the same fibre bundle and microlens arrays. Although the sampling interval has been reduced this does not result in an improvement in spectral resolution since the effective slit width is determined by the fibre diameter which does not change. The area of the field would be reduced to one quarter of the present design, $\sim$12 arcsec^2. An alternative approach is to use an image slicer which would maintain the full instrument spatial resolution (at a scale of 0.08 arcsec/pixel) in the spatial dimension. Current designs[10] are not suitable but a new design is available[11] which would fit within the GMOS IFU space envelope and provide a greater number of spatial and spectral resolution elements than the baseline design. In addition, it would alleviate the problem of diffraction and thermal emission in the infrared.

6. CONCLUSIONS

The GEMINI multiobject spectrographs will include a powerful facility for integral field spectroscopy over a field that is well matched to the scale of many objects of astrophysical interest. The performance of the system has been optimised to maximise throughput while maintaining a large number of spatial and spectral resolution elements. The system can be easily upgraded. The design is currently under detailed development before finalisation for the GMOS Critical Design Review in early 1997.

7. ACKNOWLEDGEMENTS

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