SPIRAL Phase A: A Prototype Integral Field Spectrograph for the AAT

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ABSTRACT

As telescope apertures increase, fundamental limits for doing efficient slit-based spectroscopy are being reached. We propose that lens arrays feeding fibre bundles be used in the focal plane of large telescopes to counteract these problems and in the process add the capability of integral field spectroscopy. A description of the first phase of the SPIRAL (Segmented Pupil/Image Reformatting Array Lenses) project is presented. This system will provide spatially mapped spectroscopy with high spectral resolution and high throughput. An alternative mode in which the lens array is used to segment the pupil rather than the sky is also described. Finally, we briefly discuss our future instrument development plans.

Keywords: spectrographs, optical fibres, single object spectroscopy, integral field spectroscopy

1. INTRODUCTION

The Phase A SPIRAL prototype is being built jointly by the Institute of Astronomy in Cambridge and the Anglo-Australian Observatory (AAO). The objectives of the phase-A study are to develop the construction techniques for a new type of fibre-fed spectrograph and to test it on the AAT by carrying out competitive scientific observations. The design philosophy for SPIRAL is that every part of the system from the focal plane of the telescope through to the detector is optimised to give the best overall performance - SPIRAL is not simply an add-on to an existing spectrograph. We have also kept the phase-A programme simple in order to achieve our goals as quickly as possible.

The SPIRAL concept offers high efficiency, high spectral resolution 3D spectroscopy on a 4m telescope such as the AAT and because it feeds a large 2D area of sky into the spectrograph it offers accurate spectrophotometry. But perhaps the biggest advantage of SPIRAL is that it can be easily transferred to 8m class telescopes. This is in marked contrast to designing a traditional slit-based spectrograph[1] for an 8m telescope which requires a reduction of the slit width (slit losses) or a larger beam size (cost) or a reduction in spectral resolution (oversampling). The option of increasing the beam size to avoid slit losses and maintain spectral resolution requires gratings larger than the standard commercially available ones and an exceptionally fast camera.

The SPIRAL phase-A prototype consists of four basic optical systems: the fore-optics, the lenslet array, the fibre feed and the spectrograph. The first 3 of these are being made in Cambridge while the spectrograph is being made at the AAO. There are 3 separate options for the fore-optics module each providing either a sky or pupil image with different image scales. The lenslet array is coupled directly to the fibre feed. The spectrograph is a simple Littrow arrangement offering high throughput and a relatively high spectral resolution compared to a conventional Cassegrain spectrograph.

2. FORE-OPTICS

In principle for integral field spectroscopy one can place an array of microlenses directly in the focal plane of the telescope. However in practice there are several advantages in having some fore-optics between the focal plane of the telescope and the lens array. These include being able to build a lens array at a convenient scale, allowing pupil-segmentation and making the system from the lens array onwards essentially independent of the telescope and therefore potentially useful on many telescopes including 8m class telescopes.

2.1. OBJECT IMAGING (Integral Field Spectroscopy)

Two lenses, as shown in Figure 1, image the sky onto the lens array. Each fibre sees a different region of an extended object, such as a small galaxy in the case of our figure. The image scale at the f/8 Cassegrain focus of the AAT is 6.6" mm^{-1}.

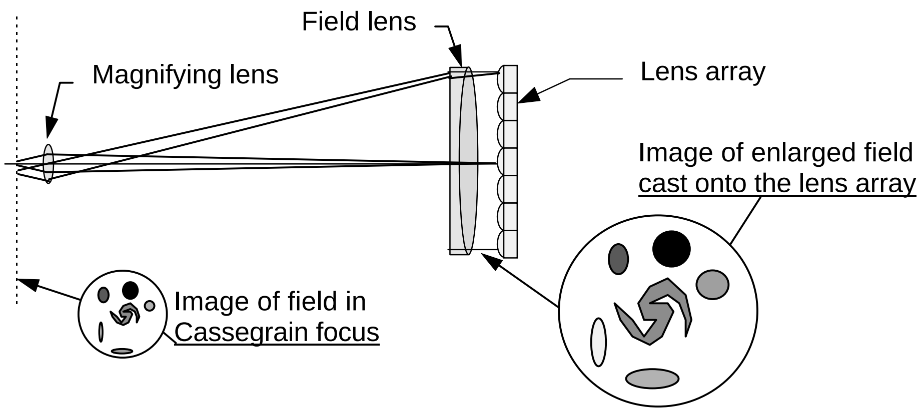


Figure 1: Fore optics for the IFS mode

Trying to match the fibres to the seeing so that each lens sees 0.5" without using fore-optics would mean using lenses with a diameter of 75μm. Although lens arrays with such small lenses are available commercially they are difficult to align precisely with the fibres and they introduce focal ratio degradation (FRD) because the pupil image formed at the fibre is not telecentric across the entire face of the fibre. Both of these effects arise because the microlenses are only slightly larger than the core diameters of the fibres themselves.

We have chosen to make our lens array out of hexagonal lenslets that measure 4mm across and so the fore-optics in this mode deliver an image scale of 0.125" mm^{-1} giving a magnification of 53x and 0.5" per lenslet. The first doublet lens of the fore-optics provides the magnification and the larger field lens ensures that the exit pupil of the fore-optics is at infinity. There is a small pupil image just behind the first lens and this is conjugate with all of the fibres receiving light from the lenslet array. There is a critical magnification scale for which the fibre core diameter is matched to the pupil image size and this has a corresponding size for the projection of the sky on to the lenslet. If the pupil image is smaller than the fibre core then no light is lost so fore-optics that provide spatial sampling at the critical scale or finer are allowed. In practice our fore-optics are at this critical limit with a small allowance for misalignments and image quality.

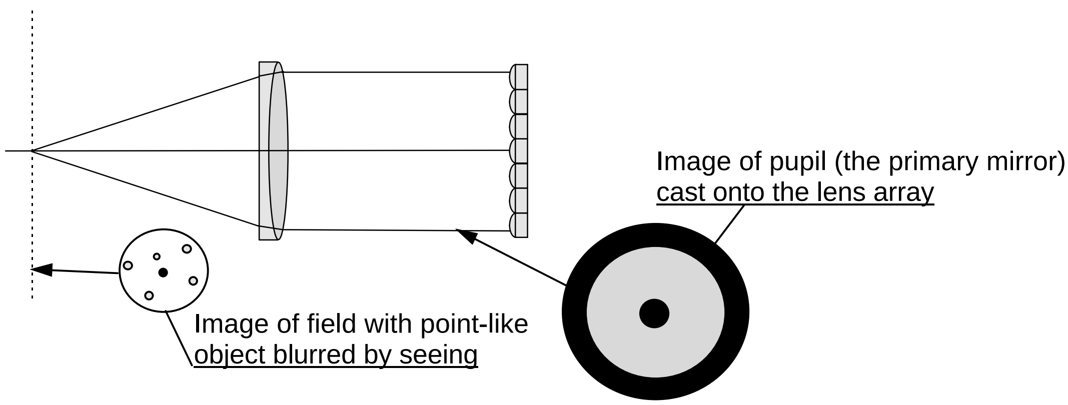


Figure 2: Fore optics for pupil imaging

2.2 PUPIL IMAGING (Point Source Spectroscopy)

Here, only one lens is used to project the image of the pupil (i.e. the primary mirror) onto the lens array. (See figure 2). Although in this case spatial mapping is lost (each fibre looks at the same area of sky) by adjusting the power of the lens the effective area of the sky seen by each fibre and hence the spectrograph can be changed. The appendix at the end of this paper explains in more detail how this mode works. For SPIRAL phase-A we will have two fore-optics options one in which the pupil image fills the lenslet array and the other in which the pupil image is approximately half the size of the lens array. In the first case each fibre sees 3.6” and in the second case the fibres see 2.2”. This means that we can match the spectrograph to the current seeing conditions without having to sacrifice resolution or loss of throughput.

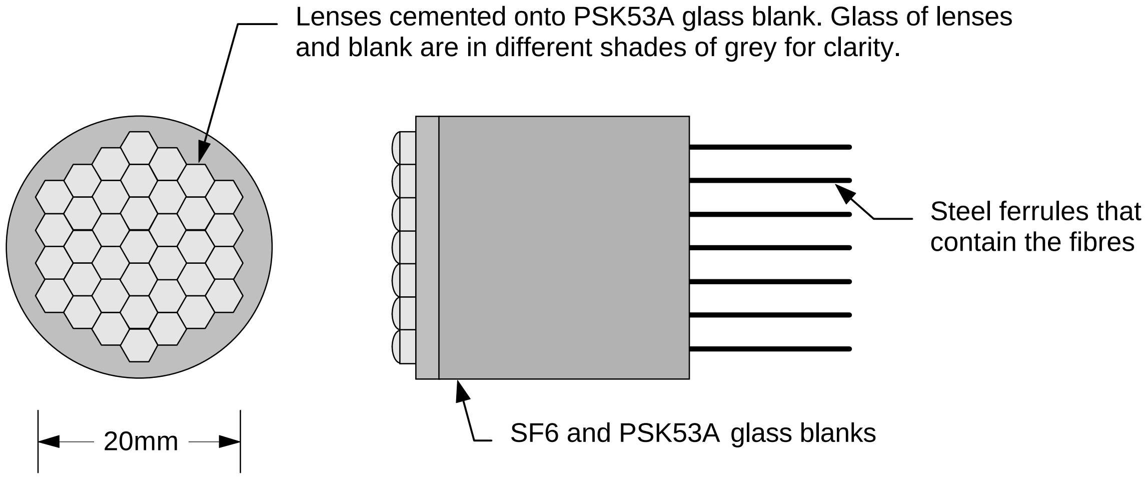


Figure 3: The assembled lens array and steel ferrules

3. THE LENSLET ARRAY

The array is composed of 37 hexagonal lenslets which are close packed to form a large hexagonal pattern as shown in Figure 3. Each lenslet is made of PSK53A glass and is 4mm across the corners. The front face of the lenslet array is AR coated. The lenslets can be easily manufactured by traditional means and allow the fibres to be individually aligned with very high precision during manufacture. The lenslets are glued onto two cylindrical pieces of glass that form an achromatic doublet with the focal plane on the back face of the cemented glass block. By forming a solid glass block with the lenslets attached we provide an extremely rigid base for the fibres to be positioned and permanently fixed.. We chose the input f-ratio of the fibres, F_{fibre}, to be $f/5$ as this minimises any FRD and also leads to a simple spectrograph design. The smaller the diameter of the fibres the higher the spectral resolution that can be obtained as this defines the width of the input slit of the spectrograph. By choosing a fibre diameter of 50µm we also match the fibres with the detector pixel size (Tek 1024^2 with 24µm pixels) which enables us to use a Littrow spectrograph.

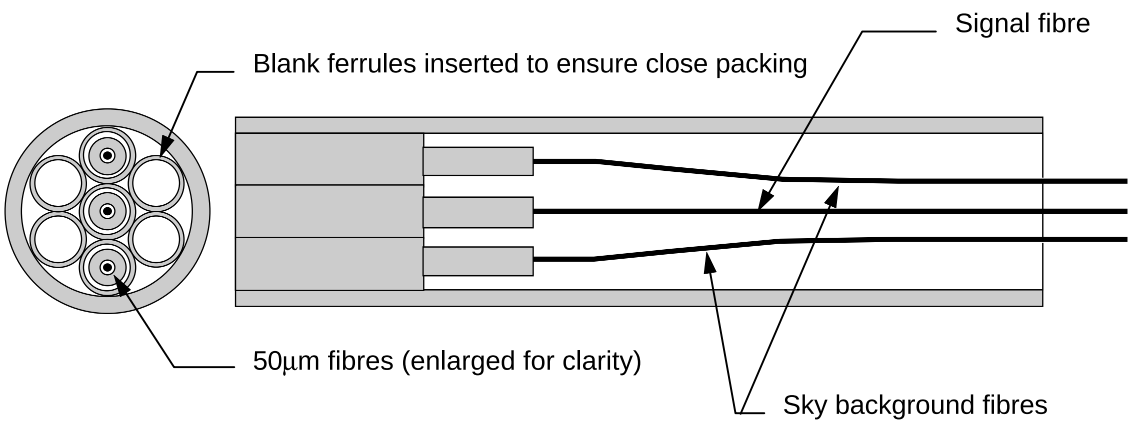


Figure 4: Detail of a steel ferrule

A 2mm diameter steel ferrule holds seven smaller steel tubes in a close packed formation (Figure 4). Three tubes on a line in turn contain finer ferrules with a single 50µm fibre glued inside each one. The central fibre is aligned with the optical axis of the hexagonal lenslet and the ferrules are glued in place on the glass flat with UV setting glue. The two extra fibres act as sky subtraction fibres in the pupil imaging mode, avoiding the need for a sky background exposure. The lens array and fibre ferrules are protected by a machined housing which sits at the Cassegrain focus of the telescope behind the fore-optics.

As the fibres are over 18m long (and very fragile!) we need to protect them from the environment - to this end they are placed in a flexible steel-wound conduit. This has a 'strain relief box' which contains a single loop of the optical fibres, allowing the length of the conduit to change without stressing the fibres themselves.

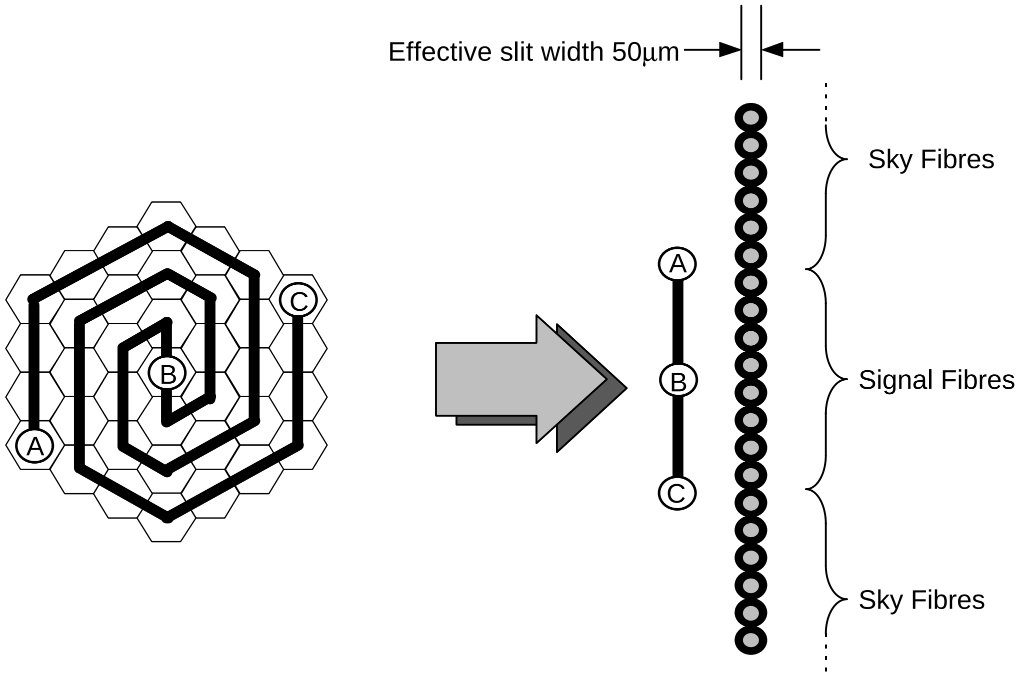


Figure 5: Showing how the fibres are arranged from the lenses to their positions on the slit

4. THE FIBRE SLIT

The fibres are rearranged into a vertical slit which then feeds the Littrow spectrograph. They are held in place between two brass blocks, one of which has grooves cut into its surface. After the two blocks are glued together and the fibres threaded into place the block face is then polished, along with the fibres, and an AR coated optical flat is cemented across the fibre ends. The central (object) fibres are arranged in the centre of the slit and the sky fibres are above and below them. There is also a particular relationship between the input and output end positions for the object fibres which ensures that fibres that are adjacent on the slit are also adjacent on the sky (see figure 5). The object fibres are well separated on the detector for the integral field mode whereas the sky fibres are close-packed to allow on-chip binning.

5. THE SPECTROGRAPH

As mentioned above we chose a fibre size of 50µm so that we could use a Littrow spectrograph with $f_{cam} = f_{coll}$ and have a monochromatic slit image which is well matched to 2 detector pixels. The lenslets in the array feed the fibres at f/5 so we have designed a spectrograph which can accept light at f/4.8 to allow for some FRD (which is comparatively low at these f-ratios). The design we have adopted is a large Petzval lens with a focal length of 720mm which acts as both the collimator and the camera and provides a beam size of 150mm diameter (see figure 6). The spectrograph is very efficient because it is fully transmitting with no central obstruction and the grating is used in the Littrow configuration. The Petzval lens has 6 air-glass surfaces which are AR coated. This design was chosen because it could be built quickly and inexpensively yet it still provides excellent image quality and a large beam size so that high spectral resolution can be obtained. The high spectral resolution capability of SPIRAL is a feature we are keen to emphasise. The system does however suffer from chromatic aberration so low dispersion spectroscopy with a large wavelength range cannot be focused properly across the

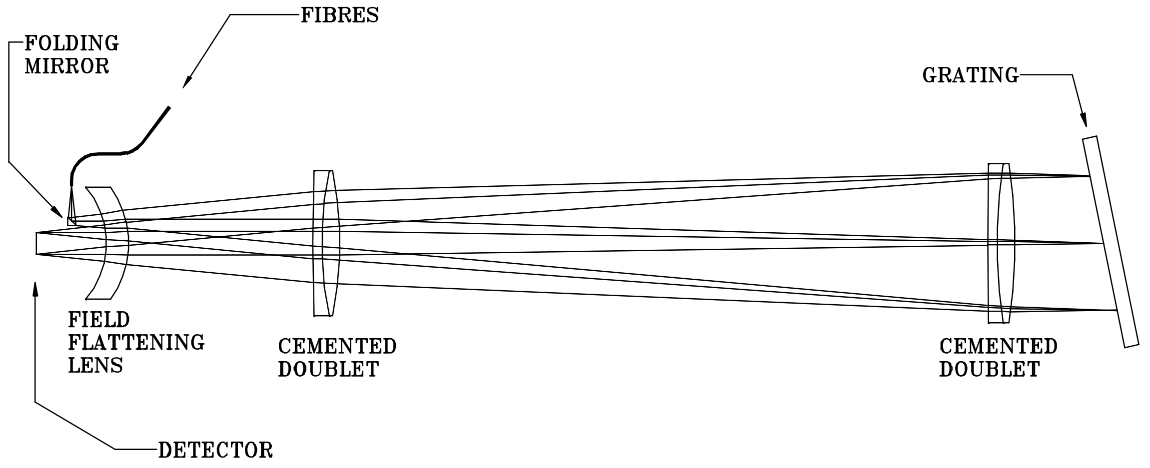


Figure 6 – The Littrow Spectrograph

CCD. High dispersion spectroscopy can be done at any wavelength from 370-900nm by adjusting the CCD tilt and focus. The dispersion with a 1200g/mm grating in first order is 10.17 Å mm^{-1} giving R=17,400 and a wavelength coverage of 250Å at 8500Å. Even higher spectral resolution can be obtained at higher spectral orders.

6. CURRENT STATUS AND FUTURE WORK

At the time of writing the lenslet array and the fibre bundle have been manufactured. The next stage is to mount the fibres on the back of the lenslet array and complete the fibre slit. The spectrograph optics are currently being manufactured at INAOE, Puebla, Mexico. First light is scheduled for November/December 1996 on the AAT.

We are currently planning the phase-B system which we expect to be given approval once we have successfully demonstrated the phase-A system. Phase-B will have an array with approximately 400 hexagonal lenslets arranged in a pattern with an aspect ratio of 4:1. The spectrograph will use a 2048x4096 pixel thinned CCD and not suffer from chromatic aberrations, offering a full octave of wavelength coverage at R=2000 or reduced wavelength coverage at spectral resolutions up to 25,000 (with an echelle grating). The total wavelength range will be 350nm-1000nm. We are also considering the possibility of zoom systems for the fore-optics. An important aspect of phase-B will be the development of data inspection and data reduction software. Phase-B will not be a fully-fledged facility instrument in order to keep down costs and reduce time scales. Phase-C of this project will be to upgrade the phase-B hardware to a facility instrument.

7. ACKNOWLEDGEMENTS

We wish to thank Damien Jones for the design of the spectrograph, Jim Pritchard for the engineering drawings and François Piché for his help with laying out 120 very long optical fibres.

8. REFERENCES

1. R.G. Bingham, “Grating Spectrometers and Spectrographs Re-examined”, *Q. Jl. R. astr. Soc.* **30**, 395-421 (1979)

APPENDIX: What does the pupil mode do?

The diagrams on the right illustrate the principle of the pupil mode. By varying the power of the fore-optic lens the size of the image of the pupil on the lens array can be adjusted. This means that each fibre effectively sees a smaller size telescope, D_{sub}

$$\alpha_{sky} = \frac{\Phi_{fibre}}{F_{fibre}.D_{sub}}$$

In (a), the pupil illuminates 36 lenses. As the pupil is an image of a 3.9m primary mirror, each lenslet is now receiving light from an area of D_{sub} =0.60m.Putting this value into the equation above gives a sky area of 3.6”.

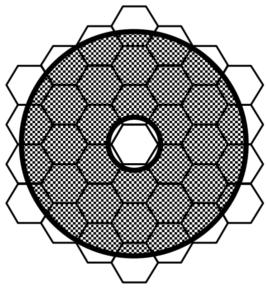
In (b), there are now 18 fibres receiving light from the pupil image and these fibres are accepting light from a segment of the primary mirror diameter 1.0m, giving a fibre sky area of 2.2”

Finally,(c) has 7 illuminated fibres with D_{sub} =2.0m. and α_{sky} =1.1”.

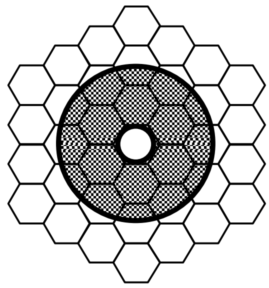
So, by varying the power of the fore-optics the amount of sky the fibres subtend can be matched to the current seeing conditions, thus maximising the signal to background that the signal fibres receive. By replacing the lens with a zoom lens the matching could be smoothly adjusted for any seeing.

As a pupil image is cast onto the lens array, an image of the sky is cast onto the fibres - so the two sky fibres can now be used to provide sky subtraction without the need for beam switching.

The advantages for single object spectroscopy are great - no longer do you lose light on the edges of the slit jaw and there is no longer any slit that needs to be widened to match the seeing - hence no loss of resolution!



(a)



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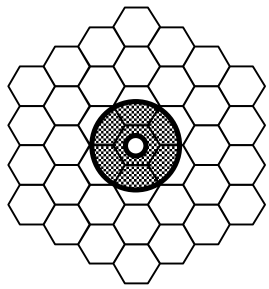
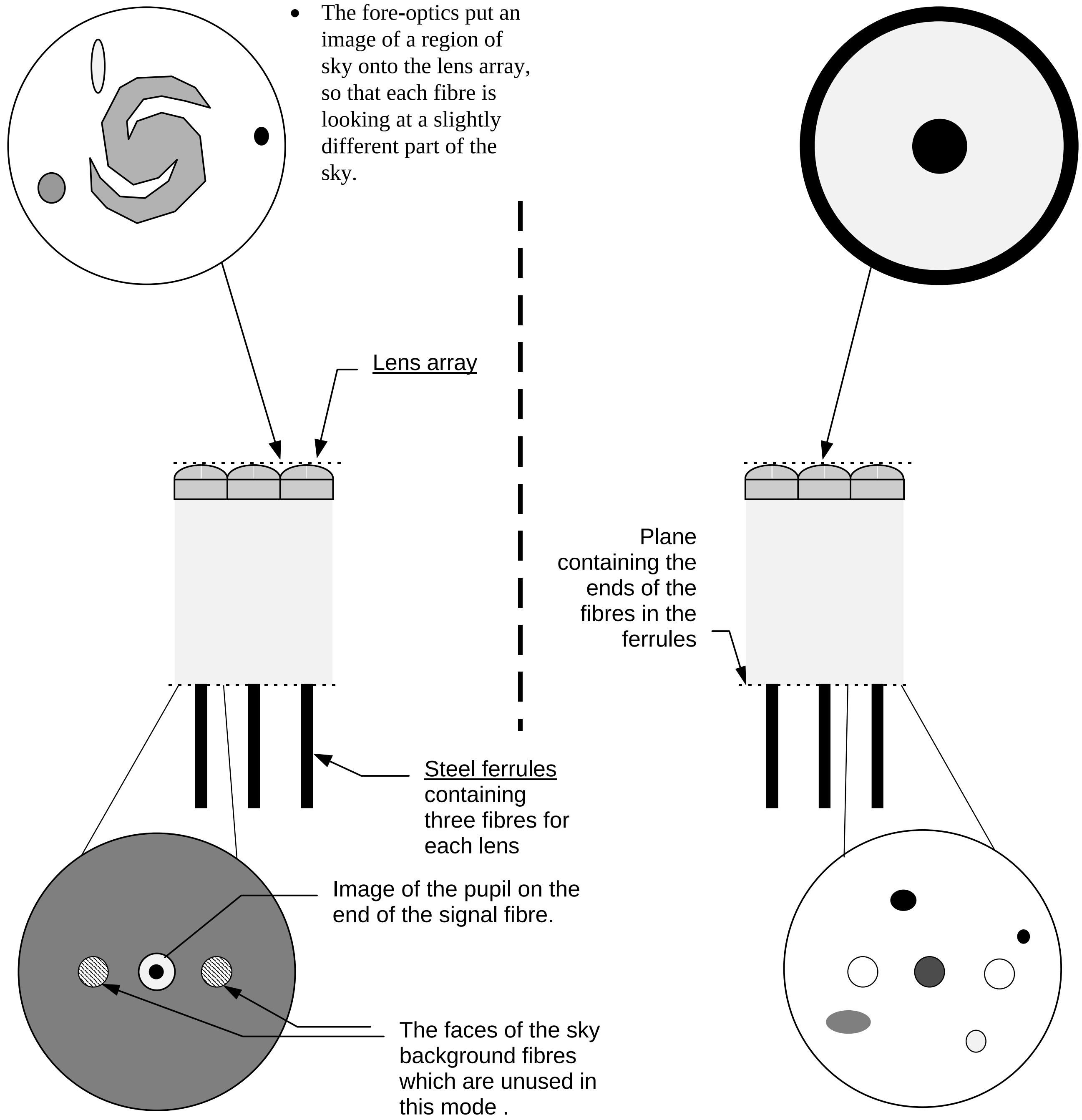


(c)

APPENDIX: How the additional sky background fibres are used.

Integral Field Mode | **Pupil Imaging mode**

- The fore-optics put an image of a region of sky onto the lens array, so that each fibre is looking at a slightly different part of the sky.



- In the integral field mode, an image of the pupil is projected onto the end of the signal fibre, leaving the two sky fibres unused.
- In the pupil imaging mode the SKY is projected onto the plane of the fibres, and the two sky fibres now take in light from sky background regions near the object.