Mon. Not. R. Astron. Soc. **000**, 1–15 (2000) Printed 8 May 2001 (MN LaTeX style file v1.3)

# The Anglo-Australian Observatory's 2dF Facility

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8 May 2001



## ABSTRACT

The 2dF (Two-degree Field) facility at the prime focus of the Anglo-Australian Telescope provides multiple object spectroscopy over a 2° diameter field of view. Up to 400 target fibres can be independently positioned by a complex robot. Two spectrographs provide spectra with resolutions of between 500 and 2000, over wavelength ranges of 4400Å and 1100Å respectively. The 2dF facility was built at a true total cost of approximately A$8M over a period of 7 years and began routine observations in 1997.

2dF was designed primarily for doing galaxy redshift surveys and has a number of innovative features. Its field of view and number of fibres are both about a factor of ten larger than any other multi-fibre system on a 4m-class telescope. The large corrector lens incorporates an Atmospheric Dispersion Compensator, essential for wide wavelength coverage with small diameter fibres. The instrument has two full sets of fibres on separate field plates, so that re-configuring can be done with minimal loss of observing time. The robot positioner places one fibre every 6 seconds, to an accuracy of 0.3 arcsec ($20\mu$m) over the full field, achieved partly through the use of linear electric motors. Other innovations include using 'naked' fibres so that multiple cross-overs are allowed, substantially increasing the yield of fibres on targets, and a pumped helium gas cryogenic system for cooling the CCD detectors. All components of 2dF, including the spectrographs, are mounted on a 5m diameter top-end ring. This keeps the fibre lengths short to maximise UV throughput and means that the entire instrument can be easily put on and off the telescope. There is a pipeline data reduction system which means that the results of each set of exposures can be fully analysed while the next set is in progress.

2dF has essentially achieved its initial astronomical goals. The redshift surveys are obtaining spectra at the rate of up to 3000 galaxies per night, yielding a total of about 200,000 objects in the first four years. Typically a B magnitude 19 galaxy gives a spectrum with S/N better than 10 per pixel in less than an hour; redshifts are derived for about 95% of all galaxies, with 99% reliability or better. Total system throughput is about 5%. The failure rate of the positioner and fibre system is about 1:10,000 moves or once every few nights and recovery time is usually short.

In this paper we provide the historical background to the 2dF facility, the design philosophy adopted, a full technical description and a summary of the performance of the instrument. We also briefly review its scientific applications and possible future developments.

**Key words:** instrumentation: spectrographs – techniques: spectroscopic – surveys – galaxies: distances and redshifts – large-scale structure of Universe

## 1 INTRODUCTION

The value of equipping telescopes with a large field of view has been recognised for some time. In 1986 the Royal Astronomical Society report "Review of Scientific Priorities for UK Astronomical Research 1990–2000" (RAS Report 1986) put a wide-field multi-object spectroscopic facility at the top of their priority list for new projects. Subsequently the UK Large Telescope Panel recommended that a wide-field survey facility be pursued in tandem with an 8 metre telescope project.

The general scientific case for a wide-field spectroscopic facility on a 4m telescope was two-fold: to provide spectra for large samples of objects found in the multi-colour imaging surveys from the UK, ESO and Oschin (Palomar) Schmidt telescopes; and to generate targets for the coming generation of 8-10m optical telescopes. The biggest specific science driver was to obtain redshifts of tens or even hundreds of thousands of galaxies and quasars, to elucidate the three-dimensional structure and evolution of the universe. Other major projects required spectra for large samples of stars, to determine their kinematics and composition and hence the dynamical and chemical history of our Galaxy; for similar studies of the Magellanic Clouds; and for detailed studies of star clusters and clusters of galaxies.

One possibility was to provide a multi-fibre upgrade to the 3.9 metre Anglo-Australian Telescope (AAT). This was particularly advantageous for two reasons. Firstly, the optical design of the telescope (a hyperboloidal primary mirror and relatively slow f-ratio of f/3.3 at prime focus) enabled a wide field of 2° to be achieved using a large but straightforward optical corrector. Secondly, the Anglo-Australian Observatory (AAO) already had extensive experience with multi-object fibre spectroscopy. This dates from the pioneering days of optical fibres and its brass plug-plate system FOCAP (Gray 1983) and more recently the fully automated AUTOFIB fibre positioner system (Parry & Gray 1986).

At the end of 1988 the AAT Board (AATB) commissioned a detailed design study of a wide-field fibre-optic spectroscopic facility for the AAT which was concluded at the end of 1989 (Taylor & Gray 1990). Following further detailed investigations into cost and budgets and in the expectation of some additional funding from both the Australian and UK Governments, the AATB gave its approval to begin the Two-degree Field (or 2dF) project in March 1990. Initially the direct budget allocated was A$2.25M (for components and certain specific tasks which could not be done in-house by current staff) and it was expected to take 4-5 years to complete. Keith Taylor was Project Scientist and Peter Gray was Project Engineer; since the project would dominate the AAO's activities for several years, a Project Management Committee was established, chaired by Russell Cannon as Director and with several external expert members.

In developing the 2dF facility we wished to build on the techniques already used for the fully automated AUTOFIB instrument in use at the Cassegrain focus of the AAT. Since 2dF would offer almost an order of magnitude increase in multiplex advantage over AUTOFIB and would be located at the more challenging prime focus of the AAT, several technical problems required addressing before final approval was given for commencement of the project.

The technical problems were addressed in the initial design study reports and covered areas such as the accuracy required of the robotic positioner, the design of the fibre retraction systems, location and design of the fibre spectrographs and the requirement for a double fieldplate system to maximise observing time.

The mechanical constraints were eased by the strength and rigidity of the telescope tube structure and the size of the dome which meant that a large instrument could be housed at prime focus without clearance and flexure problems.

Commissioning of the 2dF facility began with the new prime focus corrector in the latter part of 1993. The instrument was officially declared open at a ceremony on $20^{th}$ November 1995, and the first spectroscopic data were obtained in mid 1996. The facility began to provide scheduled scientific observations in September 1997 with almost full functionality. By then the project was about 40% over the original time estimate and 20% over budget (these two are linked, in that it could have been completed sooner had more funds been available). These figures may seem worrying, but are perhaps not too bad for a project which incorporated many technical innovations. The effective total cost was subsequently estimated to have been about A$8M, including all staff costs and overheads. The bulk of the design and construction work was eventually done in-house using the AAO's facilities in Sydney and Coonabarabran, partly because many aspects involved innovative design features which could not be easily specified or contracted out, and partly to contain costs.

Progress reports describing the evolution of the design of 2dF have already been published (Gray & Taylor 1990; Gray *et al.* 1993; Taylor, Cannon & Watson 1996; Cannon 1997; Lewis, Glazebrook & Taylor 1998a; Lewis, Glazebrook & Taylor 1998b) and have featured regularly in the quarterly AAO Newsletter.

In this paper we provide a full technical description of the 2dF facility and its performance. Section 2 gives an overview of the instrumentation and its relationship to other multiple object fibre spectroscopy systems. In section 3, a detailed description of the individual components of the 2dF facility is given. Operation of the 2dF facility is covered in section 4 and actual performance is detailed in section 5. Up to date technical information and signal to noise calculators are available on the 2dF WWW pages (http://www.aao.gov.au/2df/).

## 2 OVERVIEW OF INSTRUMENT

### 2.1 Objectives and design philosophy

The 2dF facility was developed with the aim of providing the AAT with a dedicated prime focus spectroscopy facility, with order of magnitude improvements over existing systems in terms of the field area and number of objects that it is possible to observe simultaneously (the multiplex advantage). While 2dF was designed from the outset to be a versatile common-user instrument, suitable for a wide range of astronomical projects on a bi-national research facility, it was always clear that the dominant project would be to obtain redshifts and hence distances for a very large sample of galaxies (a few times $10^5$ objects) to map out the three-dimensional structure of the relatively local universe.

This meant that 2dF had to be optimised to obtain low dispersion spectra of a few thousand targets per night, over a wide wavelength range, for mainly non-stellar objects in the magnitude range $15 < B < 20$ and spread across more than 1000 square degrees of sky. These requirements are very well met by a system providing two sets of 400 fibres covering 3 square degrees of sky, and capable of reconfiguring one set of fibres in about an hour, which happens to be equal to the elapsed time needed to take adequate signal-to-noise ratio (S/N) spectra of 19-20 magnitude galaxies.

Whenever choices had to be made on design features, instrument parameters or priorities, the driver was to maximise 2dF's efficiency as a redshift engine. The requirements of other projects, such as taking higher resolution spectra of stars, doing longer integrations on fainter galaxies, or working on densely clustered targets, were incorporated where possible, but not if they involved any compromise of performance for the big redshift survey.

### 2.2 Other multi-fibre systems

Previous multi-object fibre spectroscopy systems on 4 metre class telescopes have used smaller fields of view and significantly smaller multiplex advantage. For example the William Herschel Telescope's Autofib-2 (Parry *et al.* 1994) and WYFFOS (Jenkins *et al.* 1993) instruments provide fibre spectroscopy of up to 150 objects over a 1° field (40′unvignetted). The HYDRA instrument (Barden *et al.* 1994) on the 3.5m WIYN telescope uses approximately 100 optical fibres to cover an unvignetted field of 1°. Earlier fibre instruments on the AAT were FOCAP (50 fibres; (Gray 1983)) and AUTOFIB (64 fibres; (Parry & Gray 1986)), both covering a 40 arcmin field at the Cassegrain focus.

Some smaller telescopes offer a larger field of view or larger multiplex advantage: for example, the 2.5m DuPont telescope at Las Campanas with a 2.1°field and up to 200 optical fibres (Shectman 1993), which has been used for the largest previous galaxy redshift survey; the original FLAIR at the 1.2m UK Schmidt Telescope, with 92 fibres covering a 6°field (Watson *et al.* 1993), and its new semi-automatic successor 6dF (Parker, Watson & Miziarski 1998); and the 2.5m Sloan Digital Sky Survey telescope with a 3°field of view and 620 optical fibres (Owen *et al.* 1998), which is using a dedicated telescope to carry out both multi-colour imaging and a spectrosopic survey of a million galaxies. Multi-object systems are being built for several of the new 8-10m class telescopes; these will be able to work fainter but cover much smaller fields of view. The 2dF facility at the AAT is unique in that it is a general purpose common-user instrument on a 4m-class telescope.

### 2.3 Key features of 2dF

Multi-object fibre systems come in three varieties: plug plates or other off-line field preparation; mechanisms to independently place each fibre, for example MX (Hill & Lesser 1986) and MEFOS (Guerin *et al.* 1993)); and systems involving consecutive placement of fibres with a single robot. The most versatile are the single robot systems, but they have the drawback that placing the fibres wastes a significant amount of observing time. 2dF gets around this by having two independent sets of 400 fibres and two field plates, mounted

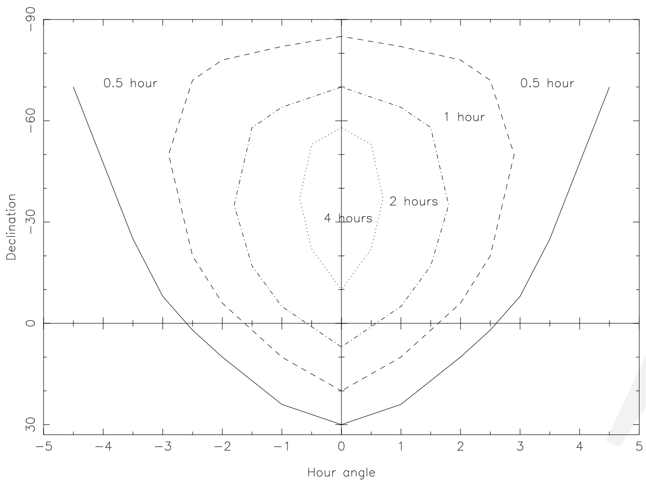


**Figure 1.** The effect of differential atmospheric refraction. The contours show the maximum possible observation times for 2dF fields centred at different Hour Angles and declinations, if all targets are to remain substantially within their fibres.

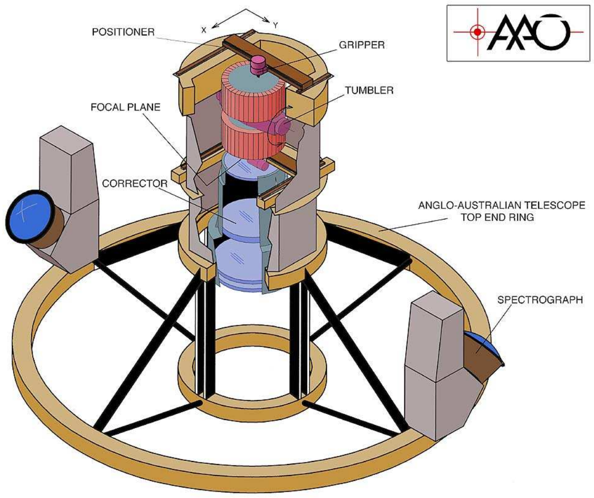


**Figure 2.** Schematic diagram of the 2dF top end showing the main components located on the mounting ring.

back-to-back on a tumbler assembly within the instrument. While one set of fibres is being used for observations, the second set is being reconfigured for the next target field.

For any one target field configuration, the maximum exposure time is set by the effect of differential atmospheric refraction across the field which moves the target objects out of the fixed fibre apertures during the course of the exposure. If we specify that a target field must be reconfigured once the target objects have moved more than a third of the fibre diameter (2.1″ in the case of 2dF), this defines the maximum time available for the robotic positioner to reconfigure the next set of fibres. The effect of differential refraction is dependent on hour angle and declination as shown in figure 1. Evidently a reconfiguration time of at most an hour is required for an efficient system which can access most of the sky with minimal loss of observing time.

In order to give an unvignetted field of over 2° with a flat focal plane, a special corrector lens system had to be designed and manufactured (Taylor & Gray 1994). Another problem with small diameter fibre systems is caused by atmospheric dispersion. This effect is quite separate from the spatial distortion due to differential atmospheric refraction. The atmosphere is a refracting medium whose refactive index depends on wavelength. For example, at a zenith distance of 60°, the light from a point source with wavelengths between 365nm–1100nm is spread out over 4.2″, which would make it impossible to use 2″ fibres for low dispersion spectroscopy over a wide wavelength range. 2dF has an Atmospheric Dispersion Compensator (ADC) built into the front two elements of the corrector. The two elements are slightly prismatic and are automatically counter-rotated during observations to provide an equal but opposite dispersion, to counteract the atmosphere as the telescope tracks across the sky.

The fibres feed a pair of spectrographs which are mounted at the top of the AAT near the prime focus, to keep the fibres short and maximise the UV throughput. Each spectrograph takes 200 spectra simultaneously, with resolutions of between 500 and 2000, on Tektronix 1024 pixel square CCD detectors. Mechanisms inside the spectrographs switch the fibre feeds in phase with the tumbling of the field plates.

All of the hardware making up the 2dF facility including the spectrographs and electronics racks is mounted on a purpose-built top end ring allowing fast interchange with the other three original alternative top ends of the AAT. In particular, the entire fibre system can be left assembled and available for maintenance when 2dF is not scheduled on the telescope.

## 3 MAIN COMPONENTS

### 3.1 Top End Ring

The new 2dF top end ring (figure 2) is a direct copy of the three original AAT top end rings (f/8 and f/15 + f/35 secondaries and f/3 prime focus) (AAO Observing Guide 1991). This allows a fast (<1 hour) interchange between top ends using the semi-automated interchange mechanisms built into the AAT dome.

The assembly of the 2dF components on a dedicated top end means that the entire system is available for maintenance and testing when 2dF is not on the telescope.

### 3.2 Design constraints on the prime focus corrector

At the heart of the 2dF facility is the corrector lens system which provides the 2.1° diameter field of view at the AAT. The development of a corrector was initiated with a design by C.G. Wynne (Wynne 1989) offering a 2° field with 1.5″ images using a 4-element corrector. Further work by D. Jones and R.G. Bingham emphasised the need for an atmospheric dispersion compensator, the importance of chromatic variation in distortion (CVD) and of the telecentricity of the optical design. A relatively flat focal plane was also a constraint.

The atmospheric dispersion of uncorrected images when sampled with a small fixed aperture size (an optical fibre) will reduce the throughput of the system significantly, by an amount which varies strongly with wavelength and zenith distance. When combined with small positioning and astrometric errors this will place severe limits on the ability to flux calibrate the resulting data. In order to minimise this effect an atmospheric dispersion compensator built into the corrector optics must provide a variable amount of dispersion in the opposite direction to the atmospheric dispersion, for as large as possible a range of zenith distances.

All of the initial designs (except for a significantly aspheric design by Bingham) exhibited chromatic variation of distortion (CVD) to some extent. This effect causes off–axis, broadband images to be spread radially by up to about $2''$ for the 350nm to 1000nm wavelength range. This is a smaller effect than that of atmospheric dispersion and is independent of zenith distance; it defines the ultimate limit to spectrophotometric accuracy with 2dF.

The telecentricity of an optical corrector design defines how the principal ray of each cone of light reaches the focal plane of the telescope. For an ideal fibre system the principal ray should be orthogonal to the focal surface. If the input light cone is not perpendicular to the focal surface then even in the absence of fibre focal ratio degradation (FRD) the effective focal ratio of the output beam is decreased. In initial designs the angle of the principal ray varied across the field (usually increasing towards the edge of the field) by as much as $4°$ from the normal to the focal plane. This variation in input angle is effectively the same as reducing the input focal ratio of light to the fibre from f/3.5 to f/2.3. Note that this is a much more severe effect that that of FRD within the fibre itself, which is minimal when working at this input focal ratio.

If the spectrograph collimator is oversized to allow for this decrease in focal ratio, then we will reduce the spectral resolution for a fixed spectrograph beam size and camera focal ratio. Alternatively, if the collimator is sized correctly for the f/3.5 beam, fibres accepting light from near the edge of the field (the worst affected) will be severely vignetted. Unfortunately, the non-telecentricity of the optical design means that the principal ray varies by up to $4°$ from the orthogonal case. This effect is partly compensated for in the design of the fibre probes (detailed in section 3.4). A slight oversizing of the spectrograph collimator also reduces the effect of the non-telecentricity and any fibre FRD.

The design of corrector finally selected (Jones 1994) contains counter rotating prismatic doublets as the first two lens elements (see figure 3). These provide atmospheric dispersion compensation for zenith distances of $< 67°$. The prismatic lenses are designed to give zero deviation of the optical path. CVD is maintained below $1.0''$ across the field for the maximum bandbass used by the spectrographs. The CVD is zero at the centre and edges of the field and reaches its maximum value at $20'$radius.

The 2dF project is exceptional in that the scientific imperatives drove the design towards a large field and high multiplex advantage, while the fixed fibre size, realistic astrometric errors and relatively poor average site seeing (mean value 1.5-1.8 arcsec) all reduce the importance of the absolute imaging performance of the corrector optics. In response to these criteria and the three design issues raised above, extensive system modelling was performed on the design (Taylor & Gray 1993). The system modelling allowed us not only

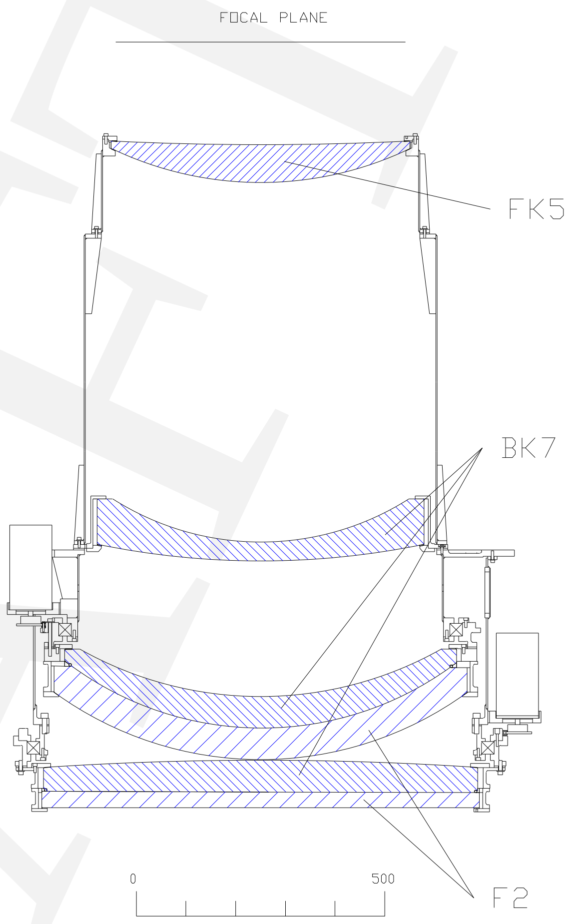


**Figure 3.** Schematic diagram of the 2dF prime focus corrector in cross-section. The lower two lens elements are the prismatic doublets making up the ADC, these are the first and second elements of the corrector in the light path.

to assess performance issues but also to assess the cost and risk implications of each potential design as work proceeded.

### 3.3 Building the corrector lens

At 0.9 metre diameter, the corrector optics contain some of the largest refracting elements made for an astronomical telescope.

The glass blanks for the corrector were manufactured by Ohara (Japan). Since some of the corrector lenses are of a deep meniscus shape, a technique known as slumping was used to avoid a large and expensive wastage of glass and prolonged grinding. Instead of cutting a lens from a thick blank, a thinner glass blank was heated and allowed to soften and slump under gravity over a convex mould. This technique does have the risk of increased internal stress and hence variable refractive index within the slumped blank. Tests before and after slumping showed that any variations in refractive index were within specification.

The internal transmittance, particularly in the UV and blue, was also an important consideration in selection of the glass. The catalogue specification of UV and blue transmit-

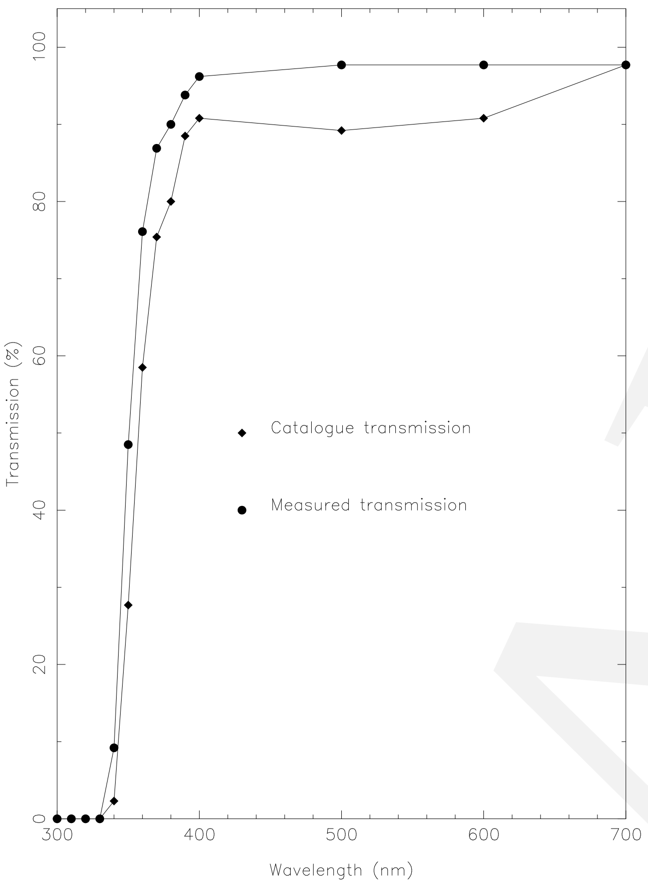


**Figure 4.** Total corrector glass bulk transmission (catalogue and measured values). Air–glass losses not included. The actual transmission exceeds 95% for wavelengths greater than 380nm, falls to 50% at 350nm and is negligible below 340nm.

tance of BK7 and F2 glass types is significantly worse than that of UBK7 and LLF6 glass. However, discussions with the glass manufacturers revealed that the actual melt values were likely to be substantially better than the catalogue specification. Figure 4 shows the actual glass melt transmittance measurements, compared to the catalogue values for the glasses used in the 2dF corrector.

The glass blanks were delivered to Contraves (USA) for figuring, coating with a $MgF_2$ anti-reflection coating and mounting. The mechanical design and manufacture of the corrector mounting as well as the optical figuring were included in the contract.

The two ADC elements are prismatic doublet lenses with the BK7 and F2 elements in contact to reduce the number of air-glass surfaces. An optical coupling compound is used between each of the lenses making up the doublets.

After optical alignment in the corrector cells using temporary adjustment screws, the glass elements were mounted using flexible silicone rubber which allows for the differential thermal expansion of the steel corrector housing and the glass.

The two lens elements that form the atmospheric dispersion compensator are each rotated using a stepper motor. These automatically move the ADC elements to the required position whenever the telescope is slewed and they track continuously during observations. A mechanical switch

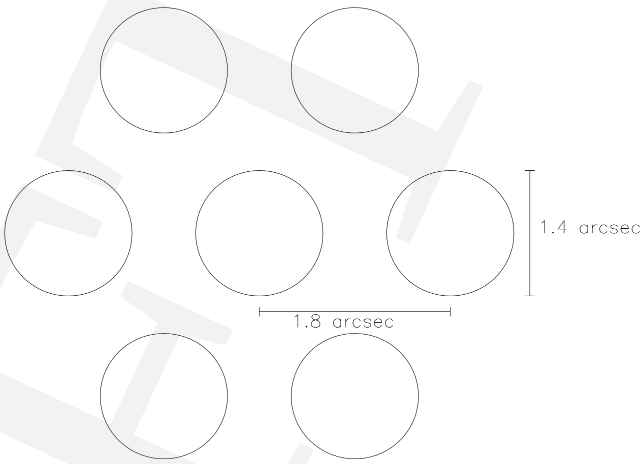


**Figure 5.** Fibre arrangement for a single guide fibre probe showing the arrangement of the seven individual optical fibres and their size and separation on the sky

acts as an index mark for each ADC element. Step counting is used to measure the position angle of the dispersing element. Each long slew of the ADC elements takes up to 3 minutes and includes a pass through the index marks to ensure that lost steps in the stepper motor do not accumulate and contribute to incorrect positioning of the lens elements.

The optical corrector was received from Contraves as a complete unit and commissioned on the AAT between July 1993 and October 1993, by taking direct night sky images with photographic plates and both cooled and uncooled CCD detectors (Taylor & Gray 1994). These tests included verification of the broad band imaging performance and the operation of the atmospheric dispersion compensator, as well as the initial distortion mapping of the corrector and telescope optics.

### 3.4 Optical fibres and retractor units

The focal plane of the telescope is populated by a total of 404 deployable optical fibre probes which may be moved to cover any part of the available field of view of the corrector. The fibre probes are divided into two types; one for target objects and the other for guide stars. The 400 object fibres each consist of a single 8m long optical fibre of diameter 140$\mu$m (2.1$''$ on the sky, with 7% variation across the field). The 4 guide fibres each consist of a 4m long coherent bundle of 7 100$\mu$m diameter fibres in which 6 fibres are arranged in a hexagon around a central fibre (figure 5). Each individual fibre probe can access an area extending from the edge of the focal plane to just beyond the centre of the focal plane, and can cover a sector with apex angle of 28°. For the object fibre probes there is sufficient overlap between adjacent fibres to allow full field coverage. The four guide fibres can access a total of about 30% of the focal plane. The guide fibres are arranged at the four cardinal points on each fieldplate.

At the focal plane the incoming light is folded into the optical fibres using 92° prisms (1.2mm on a side) made from SF5 glass with the input face anti-reflection coated. The prism is glued to the polished end of the optical fibre using UV–curing cement, after being optically aligned with the fibre core. The 92° angle of the prism was chosen to be

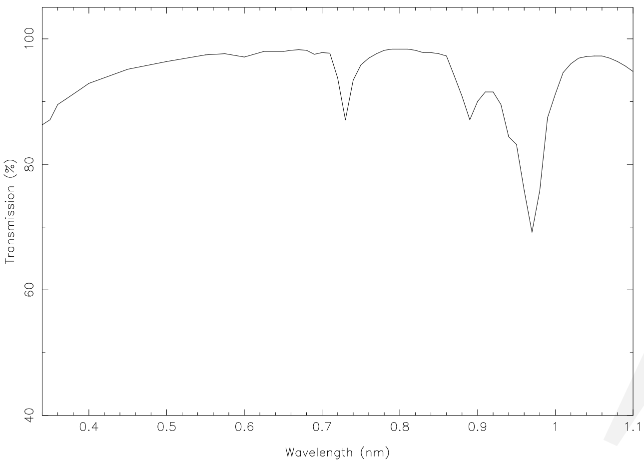


**Figure 6.** Optical fibre throughput as a function of wavelength (ignoring end losses). Fibre is Polymicro FVP 8m in length.

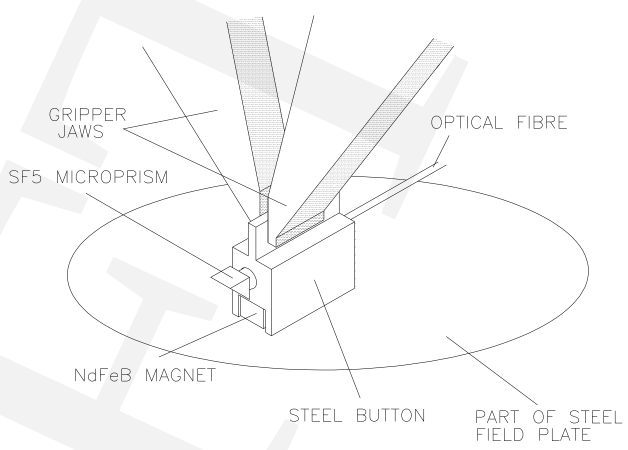


**Figure 7.** Diagram showing design of fibre probes

half way between the extreme ranges of the beam angle for the non-telecentric corrector design. The prism material is a high refractive index glass (SF5) so that the fast focal ratio input beam is totally internally reflected on the prism hypotenuse. This removes the requirement to aluminise the external reflecting face which would result in lower efficiency.

The optical fibre used is a high OH or wet fibre manufactured by Polymicro Technologies. This has the advantage of good blue throughput at some cost of additional OH absorption bands in the far red (figure 6). The optical fibre is a step index fibre with core diameter of 140$\mu$m, cladding diameter of 168$\mu$m and a Polyimide protective buffer 198$\mu$m in diameter.

Each fibre and prism assembly is held in the focal plane by a small steel button 4mm long and 2mm wide containing a rare earth magnet (NdFeB) in its base (figure 7). The magnet holds the button in place on a steel field plate located just behind the telescope focal plane. The button has a vertical fin or handle to allow a robotic gripper to grasp the button easily. Particular care was taken in the design of the button, with extensive simulations to minimise the impact of the fibre probe footprint on the success rate with which fibres could be assigned to objects (Lewis *et al.* 1993). An overlarge fibre probe footprint would affect the success with which fibres could be assigned to target objects clustered on relatively small scales, thus potentially imposing an instrumental signature on the observations.

The output ends of the optical fibres at the spectrograph slit are aligned together in multiples of 10 fibres which form a slitlet. The 10 fibres are aligned and cemented onto a brass block using an assembly jig to provide the necessary fibre to fibre separation. The fibre separation projects to 5 pixels at the detector. The brass block and optical fibres are then polished together as a unit. The slitlets are held in the focal plane of the spectrograph in a group of 20 slitlets to form the spectrograph "slit" of 200 fibres. The fibres are fanned out to optimise the light path through the spectrograph optics.

Unlike previous AUTOFIB–type fibre positioners, our fibre probes do not have protective stainless steel tubes along their length in the focal plane area. These tubes had a number of uses, they protected the fibre against breakages, avoided any risk of fibre tangles and simplified the fibre allocation process. However, these steel tubes suffer from the fact that when the fibre probes are parked at the periphery of the focal plane the steel tubes must be accommodated outside of the fieldplate area which increases the overall size of the instrument. This was not a problem with previous Cassegrain focus instruments on the AAT, but would have led to loss of light at prime focus. A second disadvantage with steel tubes is that they severely restrict the use of fibre–fibre cross-overs in the fibre allocation process, thus considerably limiting the number of fibres that can be allocated to target objects. This bare fibre approach necessitated the development of compact retractor units to deal with the excess fibre when the fibre probe was located near the edge of the focal plane.

At the edge of the focal plane the fibres enter a series of 40 retractor units which maintain the fibres in a straight line on the fieldplate. Each fibre is mounted on a pair of pulleys within a retractor unit and maintained under 30g constant tension independently on every fibre probe using constant force springs (Parry *et al.* 1993). After exiting from the retractor units each bundle of 10 optical fibres is protected by a single PTFE tube and is routed through the tumbler rotation axis and across the telescope top end ring spider vanes to the periphery of the top end ring where the spectrographs are located. The tumbler rotation axis is accommodated by allowing the fibres to twist.

Each retractor unit contains 10 fibres (11 fibres for the 4 retractor units per plate that also carry a guide fibre) to match the fibre slitlets. This allows for the exchange of a complete retractor unit for subsequent repair. A total of 40 retractor units are arranged around the circumference of each of the fieldplates. This gives a total of 404 fibres per fieldplate and 808 fibres overall.

This system has the advantage of maintaining the fibres in a straight line between the button and edge of the focal plane without increasing the footprint of the fibre probe in the focal plane. A drawback of this system is the complexity of the retractor units themselves and the high reliability required, since a failure of the retractor unit will cause a loop of slack fibre to protrude over the fieldplate which may lead to tangles.

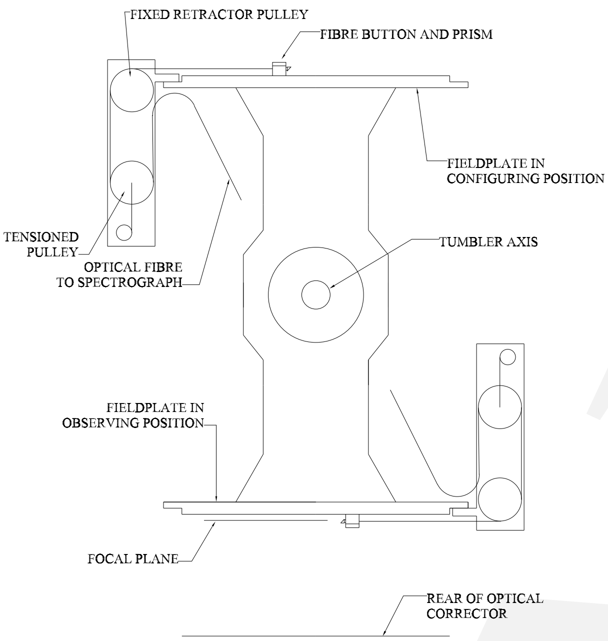


**Figure 8.** General arrangement of tumbler unit, fieldplates and fibre retractors. Drawing deliberately not to scale to show detail, only one of forty retractor units shown on each fieldplate for clarity.

An additional benefit of the bare fibre approach is that it is possible for each fibre to cross over many other fibres on its way from the edge of the focal plane to its target object. This considerably reduces the restrictions on allocating fibre probes to objects, at the cost of extra software to ensure that no attempt is ever made to move a button while its fibre is overlaid by other fibres.

### 3.5 Tumbler and field plates

The fibres are held in the focal plane of the telescope's prime focus by magnetic buttons on a flat circular magnetic stainless steel field plate 560mm in diameter. Two of these plates are arranged back to back on a tumbler arrangement (figure 8). The tumbler can be rotated back and forth through 180° to bring either field plate into play at the focal plane of the telescope. The other field plate is then ready to be accessed by the robotic fibre positioner.

Embedded in each fieldplate are 21 reference marks in a grid pattern, which are illuminated by light emitting diodes (LEDs) via optical fibres. These reference marks have accurately known positions within the fieldplate and are the primary reference frame for both the gripper and focal plane imager gantry coordinate systems.

### 3.6 Robotic Positioner

A single fast robotic positioner (Smith & Lankshear 1998) is used to manipulate the individual optical fibre probes. Once the robot is given a list of X,Y positions (converted from astronomical coordinates provided by the observer), the positioner control software works out an optimal way to reconfigure the fibres from their current locations to the required positions. This usually requires moving a number of the fibres out of the way (i.e. parking them) at the periphery of the field before moving the majority of the fibres directly to their target position. This is considerably faster than the more simplistic approach of parking all of the fibres before moving each fibre to its new target position.

The robot itself consists of a complex gripper unit mounted on an X-Y Cartesian gantry, itself mounted above the tumbler field plate at the top of the 2dF central section (figure 2). The gripper gantry has two X axes and a Y axis cross–beam in an H configuration. The axes are driven by linear AC servo motors. The use of linear motors over the more conventional leadscrews allows faster and more accurate motor control and eliminates the effects of backlash. Positional information is determined from independent linear optical encoders for each axis, with a resolution of 1.25$\mu$m.

All movements of the XY gantry are balanced by counterweights that move in the opposite direction to the gantry, resulting in zero net momentum at the prime focus when the positioner is operational during observations. With these precautions there is no measureable effect on the tracking of the telescope due to the movement of the gripper gantry during observations.

The gripper unit contains a rotational $\theta$ axis to allow the gripper to be aligned with the (approximately radially aligned) off–axis button handle, a Z axis to raise and lower the gripper unit and a set of jaws to grasp the individual button handles. The handling of the fibre probes is monitored by a small video CCD camera and optics built into the gripper unit. The optical fibres are back–illuminated by light projected into the optical fibre from the spectrographs. The robotic positioner can 'see' the illuminated end of the fibre and knows the physical offset to the button handle which it grasps. This system allows the gripper to monitor fibre placement at the new target position, measure any positioning errors and if necessary correct those errors if they are deemed to be too large (Lewis & Parry 1990; Parry *et al.* 1993). This has the advantage that the robot positions the fibre core at the required position regardless of any actual manufacturing or assembly errors in the fibre button assembly.

The gripper unit was built under contract by the University of Durham to an AAO design, following earlier development work for the initial 2dF design study.

The design of the gripper jaws used in this process is particularly important and went through several prototyping stages (Wilcox 1993) in order to achieve repeatability at a level better than the overall accuracy requirements. One of the pair of gripper jaws is fixed to the XY-$\theta$ gantry and forms a reference surface while the second is movable. To grasp a fibre button the fixed jaw is positioned against the button handle using the XY-$\theta$ gantry, then the movable jaw is closed onto the handle to avoid knocking the fibre button unnecessarily. Releasing the button requires the movable jaw to be moved away from the button handle slightly before the fixed jaw is backed away from the button handle using the XY-$\theta$ gantry.

The robotic positioner is capable of configuring a full target field of 404 fibres in about an hour. This requires on average a total of 580 fibre movements to untangle the previous field and configure the new target field at a speed of under 6 seconds/fibre. The average positioning error is $11\mu m$ ($0.16''$) with all fibres required to be placed within $20\mu m$ ($0.3''$) of the demanded position; if necessary, the robot picks up and replaces the button until the position is within tolerance.

The effect of any offset due to flexure between the gripper gantry and fieldplate is removed using the grid of reference marks embedded in each fieldplate. These are measured with the gripper CCD video camera before positioning the fibres on the fieldplate. This process is always performed after a tumble operation or after the telescope has been slewed to a new position, before any fibres are moved.

### 3.7 Focal plane imager

A second XY gantry, almost identical to the gripper gantry, is located immediately behind the final element of the optical corrector (figure 2) and in front of the observing fieldplate. Instead of a gripper unit, this gantry carries a pair of CCD cameras. One camera is a simple video CCD camera which can only view the back-illuminated fibres and field plate, while the second is a Peltier cooled Princeton Instruments CCD camera, facing in the opposite direction, which can view the sky when its gantry is appropriately positioned. This gantry system is known as the Focal Plane Imaging (FPI) system and is the primary means of determining the relationship between RA,Dec and X,Y on the field plates. This sky viewing camera can also be used for target field acquisition and seeing measurements. The image scale of the focal plane imager CCD is $0.3''$/pixel.

The focal plane imager gantry also surveys the reference marks embedded in the field plates, in a similar manner to the gripper gantry, to correct for registration and flexure before centroiding the images of reference stars.

### 3.8 Fibre Spectrographs

With a fibre linked spectrograph one has to balance the merits of using long fibres to feed a remotely located bench spectrograph, against using very short fibres and mounting the spectrographs close to the fibre positioner. Each approach has its merits and drawbacks. The remotely mounted spectrograph has the advantage of providing a stable spectrograph and making the engineering much simpler but with the drawback of the lower UV throughput of long optical fibres (30 metres). Using short fibres with a locally mounted spectrograph reduces the UV light losses due to the fibre length but increases the mechanical design difficulties and subjects the spectrograph to variable gravitational flexure, and ambient temperature variations, as the telescope tracks across the sky.

The choice between a single monolithic spectrograph accepting all 400 optical fibres compared to a pair of smaller spectrographs each accepting 200 optical fibres was largely resolved by the availability of Tektronix 1024 pixel square CCD detectors. These limit each detector to 200 fibres spaced by 5 pixels on the detector. Larger detectors were promised but not available during the predicted time frame of the instrument construction. Limiting each spectrograph to 200 fibres also eased the design somewhat, since it required a shorter slit assembly.

The decision was made to keep the fibre lengths as short as practicable by locating the spectrographs at the top end of the telescope (Smith & Lankshear 1998). Initially they were to be mounted above the robot positioner (Taylor & Gray 1990) with an extremely short fibre length. The final design, however, was constrained by the available space envelope and the spectrographs were mounted at the edge of the top end ring as shown in figure 2. This resulted in a fibre length of 8 metres.

The overall construction of the spectrographs is depicted in figure 9. The spectrograph design is based on an f/3.15 off–axis Maksutov collimator generating a 150mm beam. This allows the use of the existing $150 \times 200$mm Cassegrain RGO spectrograph reflection gratings. The collimator is slightly oversized compared to the prime focus corrector focal ratio of f/3.5 to allow for some focal ratio degradation in the optical fibres and further reduce any effect of the non-telecentricity of the corrector design. The off–axis design has the benefit of no central obstruction so the fibre slit and its associated shutter, filter wheels and slit interchange mechanism do not vignette the beam.

The 200 optical fibres from the focal plane are arranged in a single line to form a pseudo-slit. A shutter is located immediately in front of the fibre slit. The shutter is moved in a direction perpendicular to the slit axis and therefore only requires a short travel to open and close over the slit width as defined by the fibre diameter of $140\mu m$.

Two filter wheels, each with four apertures, are provided behind the shutter. One aperture in each filter wheel is kept as a clear aperture leaving a maximum of six filter spaces of which three are currently used to hold order-sorting filters for high resolution observations. The filters themselves are 2mm thick and are cut specially for this application. Filters currently available include GG495, S8612 and RG630. Use of a filter requires a change in the spectrograph focus as the filters are located in the diverging beam behind the fibre slit and shutter.

The spectrograph camera is located at a collimator–camera angle of $40°$ and is a fast, wide–field Schmidt camera with a CCD at its internal focus (Jones 1993). The main difficulty with the camera is that the pixel matching requirements of imaging such a large number of fibres onto such a small detector force it to have an f-ratio as fast as f/1.2 in the spatial direction (f/1.0 in the spectral direction) while retaining its wide $\pm 5.5°$ field of view. The camera uses a severely aspheric front corrector plate, to give good performance over the full wavelength range and field angle required to image the spectra.

The camera is fully evacuated with the aspheric Schmidt corrector lens acting as a dewar window. The CCD is cooled by use of a cold finger attached to a CTI cryodyne closed cycle Helium cooler. A Helium compressor is mounted on the telescope in a gymbal mount and is used to drive both cryodynes. The cool-down time for the CCDs is relatively long, about 3.5 hours from ambient temperature to their operating temperature of 170K. The performance of the cryostats is sufficiently high to maintain their performance for up to 21 days.

In addition to the basic design of the spectrographs, the double buffering of the fibre positioner system and the back illumination of the fibres provide some extra engineering problems. Each spectrograph actually accepts 400 fibres,

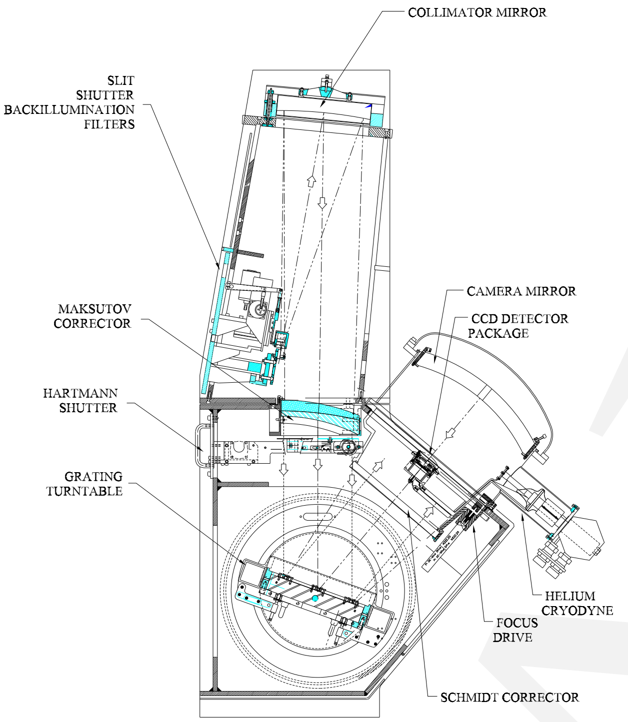


**Figure 9.** Spectrograph general arrangement showing the main components and the optical path

200 from each field plate, which must be located in the focal plane of the spectrograph when required. The non-observing fibres must be illuminated with a light source bright enough to be seen by the robotic positioner's gripper TV system since fibre positioning is done simultaneously with observing. These two requirements mean that each spectrograph must have a slit interchange mechanism, a bright light source for the fibre back–illumination, and a reliable means of completely shielding this light source from the rest of the optical path.

The spectrograph is focussed by moving the detector within the cryogenic camera. Both focus and tilt adjustments of the CCD are available and can be driven remotely.

With the exception of the selection of the grating (which has to be manually inserted before observations start), all functions of the spectrographs are remotely controlled. This includes slit changeover, filters, Hartmann shutter, grating rotation and spectrograph focus. Gratings can be automatically recognised by the spectrograph control system which reads magnetic barcodes present on all of the grating cells.

The complete spectrograph configuration is inserted into the data FITS header information to allow automatic pipeline data reduction.

### 3.9 Calibration systems

2dF contains its own remotely–controlled calibration systems. Two white flaps may be inserted into the telescope beam below the corrector, blocking off sky light and forming a reflective screen. A variety of calibration lamps can be used to illuminate this screen, with the resulting scattered light travelling through the 2dF corrector and illuminating the focal plane. Two intensities of quartz lamps for fibre flats and a variety of hollow cathode arc lamps (Copper–Argon, Copper–Helium and Iron–Argon) are provided.

Requesting an arc or fibre flat exposure will result in the control system automatically inserting the reflective flaps and turning on the requested calibration lamps. At the end of the exposure the lamps are turned off and the flaps either removed from the telescope beam or left in place if further calibration exposures are required. This automation avoids accidentally leaving calibration lamps turned on and reduces observing overheads.

All calibration exposures have appropriate FITS header items added to the data frames as an aid to the pipeline reduction of the data.

### 3.10 Control systems

The 2dF facility uses the AAO DRAMA (Farrell, Bailey and Shortridge 1995) infrastructure to build a fully integrated control system across several computers and operating systems.

The graphical user interface is written using Tcl/Tk and provides for control of all aspects of the positioner system, the spectrographs, ADC and CCD control, all from one simple to use interface. The same interface allows the observer to control the AAT directly, for example when slewing to a new target field. The graphical user interface is provided by several windows spread across two computer screens with controls arranged by subsystem.

Individual parts of the 2dF facility are controlled by software tasks which are running on the most appropriate control computer (VxWorks, Solaris, VMS) and DRAMA allows the many separate tasks to communicate and work together seamlessly.

### 3.11 CCD operation.

The two Tektronix 1024 CCDs are controlled using the standard AAO controller hardware, the AAO External Memory (XMEM) and OBSERVER software interface on a VAX/VMS computer system. With a slight adaptation, the OBSERVER software communicates with the rest of the 2dF control system (running on Solaris and VxWorks computer systems) using DRAMA to enable it to add all of the more specialised 2dF FITS header items from the 2dF control system to the data files for archiving. The two CCDs are operated and read out simultaneously, but using separate controllers and data links.

### 3.12 Acquisition and Guiding systems

On each fieldplate there are four guide fibres which do not feed to the spectrographs. These guide fibres consist of a coherent bundle of seven individual fibres with six fibres in a hexagon pattern surrounding a central fibre (figure 5). The separation of the individual fibres in a guide fibre at the input end is $1.8''$. Each guide fibre may be positioned on a guide star in the focal plane to allow for acquisition of the target field. The output from the four guide fibres is collected by a Quantex intensified TV system, with its output visible to the telescope night assistant and observer.

A guide star is accurately centred when the central fibre of a guide fibre appears brightest on the TV display and the six surrounding fibres are uniformly illuminated.

A minimum of two guide fibres are recommended for each target field, although it is preferable that all four are used in case of inaccurate stellar positions. The Quantex TV system can detect stars down to a magnitude limit of $V = 15.5$ for normal acquisition purposes in average conditions. The system was designed to include an option to rotate the field plates for target acquisition and, if necessary, during tracking. However, this has not been implemented. It turns out that the instrument is sufficiently stable, and the flexure is small and predictable, so that it is better to remove any overall field rotation in the positioner software. Often, larger errors would be introduced by attempting to use the fiducial stars to correct rotation, especially since the design of the probes can make it difficult to access reference stars near the edge of the 2dF field.

The pointing of the AAT is normally good enough ($<2''$) that target field acquisition is a simple procedure of slewing the telescope and the guide stars will be visible somewhere in at least one of the guide fibres. Fine acquisition is performed manually by offsetting the telescope by very small amounts until all four guide stars are well centred in their respective guide fibres.

If for any reason the guide stars cannot be seen after slewing the telescope or there is any ambiguity in the guide star acquisition (for example due to a very crowded field in a globular cluster or due to poor guide star positions) the focal plane imager CCD camera can be used to image a small section of sky around each guide star to verify acquisition. A simple offset will then place the guide stars onto the guide fibres after which the focal plane imager can be removed from the focal plane.

Once a target field is acquired, guiding can be done in one of two ways. The normal guiding method is manual guiding using the excellent tracking of the AAT and making small adjustments every 10 minutes or so.

An automatic autoguider has also been developed which uses the video output from the Quantex TV system to control the telescope. While this has been shown to work successfully, the extra calibration required and problems with the dimensional stability of the Quantex TV image tube at different gain levels means that it has not normally been used. It is intended to replace the Quantex TV system with a CCD based system, after which the autoguiding should be implemented.

## 4 OPERATION OF 2DF

### 4.1 Input data, astrometry and guide stars

The successful operation of an Autofib–type fibre system depends on the provision of accurate positions for the target objects in a known reference frame. Target positions are usually measured from Schmidt telescope photographic plates, using the Automatic Plate Measuring (APM) or SuperCOSMOS plate measuring machines, although more recently astrometry from CCD mosaics is becoming more common and reliable. With care, these provide astronomical coordinates with a relative accuracy of $0.2 - 0.3''$across the full $2^\circ$ field of 2dF.

To place optical fibres on target objects, 2dF needs to know the conversion from astronomical coordinates to physical coordinates in the focal plane. This conversion is determined by measuring the X,Y positions of sets of astrometric standard stars, using the FPI CCD camera. The observed centroids of the star images are matched to their expected positions, as corrected for atmospheric refraction, known telescope pointing errors and the distortion introduced by the 2dF corrector lens. A least–squares minimisation determines the fitting parameters; the six free parameters are the scales in X and Y, the overall rotation and skewness of the field, and any offset of the centre of the optical distortion pattern from the optical axis. Any non-perpendicularity of the axes of the gantries, or mechanical shifts between the gantries and the field plates, should be automatically removed by the survey of the fiducial reference points on the field plates (section 3.7).

It was not a trivial task to find astrometric data with the required accuracy (current rms positions to better than 0.25 arcsec across $2^\circ$ of sky) for large enough samples of stars. Initially, the PPM catalogue was used (Roeser & Bastian1988); currently the Tycho–2 catalogue (Høg *et al.* 2000) is the most suitable. Originally the astrometric calibration involved taking data for sets of stars at a range of declinations, for both field plates, and the full process had to be repeated on the first night of every 2dF observing run. Different sets of astrometric parameters were stored and used as appropriate for each target field. After several years experience and many tests, it has become apparent that the behaviour of 2dF is sufficiently stable and repeatable that the flexure terms can be predicted. All that is now needed is to take at least one set of calibration data whenever 2dF is re-mounted on the telescope, to determine any rotation or offset zero-point errors. There are also small plate scale variations which are probably temperature-dependent. The remaining errors in the process should be below the 0.5 arcsec level at the edge of the field, where most effects are worst.

It is important to note that the fiducial or guide star positions should be as accurate as the target object positions and on the same astrometric system. However, for a number of reasons this may not be the case. Firstly fiducial stars are usually in the magnitude range $V = 13 - 15.5$ so that the Qantex TV system is able to detect them. Stars as bright as this can suffer halos and diffraction spikes on the photographic plates which affect their astrometry. Secondly, proper motions of stars can also increase the positional errors, particularly when using old plates. Using fiducial stars towards the faint end of the available range and comparing two plates of different epochs can reduce both these effects. A good solution is to use stars drawn from the target object list, where feasible.

### 4.2 Fibre allocation procedures

Fibres are allocated to target objects using an off-line software program CONFIGURE (Bailey & Glazebrook 1999) to preplan each target field. An example target field configuration is shown in figure 10, which is a reproduction of the mimic display at the telescope. When provided with a field centre and a list of target, fiducial star and blank sky positions, the CONFIGURE program assigns fibres to objects, taking account of the hardware constraints (limited fibre ex-

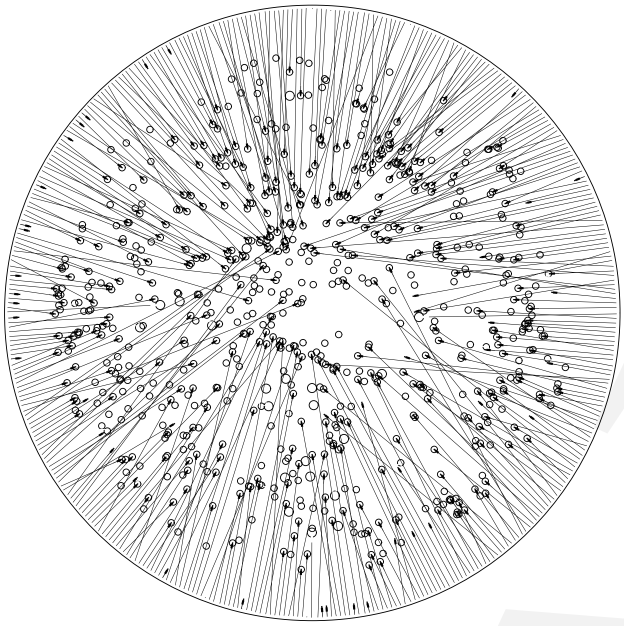

**Figure 10.** An example target field configuration using almost all 400 fibre probes. Unallocated target objects are shown by unfilled circles. A few fibres remain parked at the edge of the field because they cannot access any of the unallocated targets.

tension and deviation from the radial direction) and avoiding illegal hardware collisions. Given the size and shape of the fibre buttons, the minimum separation between two targets is $\simeq$ 30 arcsec on the sky, but this is a strong function of location in the field and of target distribution.

Various options in CONFIGURE allow the user to assign relative priorities to targets and set other parameters, including the planned Hour Angle of the observations, in order to optimise the allocation of fibres. The program works iteratively, to maximise the number of observable targets and minimise the number of fibre crossovers. The CONFIGURE utility includes an option for automatic allocation of fibres to sky positions and allows manual editing of the final fibre configuration, before saving as a file to be used with the 2dF control system at a later stage. One (or more, if the same field is to be tracked for several hours) of these configuration files is required for each target field to be observed during the course of a night.

If the user wishes to observe a contiguous region of sky larger than the available field, or to observe a field with more than 400 targets, the input list must be split into a series of manageable field configurations. This is typically done by setting magnitude cuts or by tiling the circular 2°fields to cover a larger area. It is usually best to restrict the magnitude range of targets in a given field, since bright targets may become saturated or scatter light on to fainter targets in adjacent fibres in the spectrographs.

The offline planning process is usually done well in advance and a set of configuration files sent to the telescope. Before a set of configuration files are used they are normally checked for legality using the current astrometric parameters.

### 4.3 Observing procedures

This section describes the standard observing procedure as used for the major 2dFGRS and 2QZ redshift surveys, although many of the steps are similar for all 2dF programmes. Observing with 2dF is somewhat different from most other observing on the AAT. The corollary to the complexity of the instrument, and the need for a great deal of preparatory work before coming to the telescope, is that is is difficult to make significant changes to the program during the night. Thus there is usually little scope for interactive decision-making by the observers.

Another fundamental constraint is the fact that it is necessary to keep planning ahead, since the configuring of a set of targets takes about one hour, about the same as the time needed for one set of observations for the redshift surveys. Thus the observing and re-configuring have to be carried out simultaneously and almost continuously, so that any time lost in one aspect will lead to problems in the other. Not only that, but the fibres have to be configured for the expected mean HA of the observations to minimise atmospheric refraction losses. One consequence is that if a set of observations is delayed for any reason, it is rarely possible to catch up; the best strategy is to abandon that set and move on to the next set. Having two field plates also introduces extra constraints: in the case of the redshift surveys, the configurations for each field are prepared for one or other specific field plate. Thus if one field is lost, it is not possible to simply move on to the next one; quite often the consequence of losing one field is an overall loss of two hours of observing, since the target configurations that have been prepared are no longer the appropriate ones.

The solution to these constraints is to prepare a detailed observing plan for each night. This plan must include all necessary exposures, including calibrations, with realistic estimates of the necessary elapsed time for each operation.

Before observing starts, and usually well before sunset, the first two configurations of the night have their fibres set up on the two field plates. The night is split into a series of target fields, or repeated observations of the same field. Depending on the declination and hour angle, and on the distribution of targets (centrally concentrated fields can be observed over a much wider range of HA), a target field may have to be observed with multiple configurations to remove atmospheric refraction effects, as demonstrated in figure 1.

For each target field a minimum set of CCD exposures consists of a fibre flat (quartz lamp) exposure, an arc exposure and a set of target object exposures. The fibre flat is used for locating the spectra on the CCD during the data reduction stage, the arc exposure is for wavelength calibration of the spectra. Optional CCD exposures may include offset sky exposures and twilight sky flat exposures, both used for calibrating the fibre–to–fibre throughput variation.

If these special exposures are not taken, the fibre to fibre throughput calibration can often be done using the night sky emission lines in the object data frames; in fact, there is evidence that this method actually gives the best results, since the calibration data are simultaneous with the observations, use exactly the same optical path and do not involve moving the telescope. The night sky line method works best in the near-infrared part of the spectrum which has many emission features, or when particularly strong night sky lines are present, such as [OI] at 5577Å and 6300Å (Bailey *et al.* 2001).

Between target fields, the fieldplates must be exchanged using the tumbler, and the telescope and dome must be slewed to the new target field position. The ADC automatically tracks the telescope position thus removing this complication for the observer. A straight–forward field changeover takes under three minutes. Once the telescope is tracking at the new target field location the robot positioner can start moving the fibres for the subsequent target field.

Observations of single standard stars (radial velocity standards, metallicity standards etc) are possible without reconfiguring all of the fibres. A calculation tool is provided to allow blind offsetting of a standard star into a single spectroscopic fibre, using a nearby guide fibre. This process is however not suitable for observing flux standards, due to the uncertain nature of the final blind offset and the small size of the fibre aperture.

It is not yet clear how accurately it is possible to calibrate the fluxes in 2dF spectra, especially when taken over a wide wavelength range. Absolute fluxes can never be very accurate, since the fibre diameters (2 arcsec) are comparable to the typical 'seeing' disk size, and the overall accuracy of fibre positioning is often no better than 0.5 arcsec. Relative fluxes, i.e. as a function of wavelength, can be determined to higher precision. However, here the CVD inherent in the 2dF corrector lens (3.2) limits the accuracy attainable. Repeatable results should be obtainable for stars near the field centre, where the CVD is small, but over most of the field the combination of fibre positioning errors and CVD means that the slope of stellar spectra varies substantially, even between consecutive short exposures ((Cannon 2000)).

### 4.4 Data reduction

During the design stages of 2dF it was clear that a dedicated pipeline data reduction package would be required to deal with the enormous amounts of data, up to 3000 spectra, which 2dF would be capable of generating during a single night.

A completely new data reduction software package (2DFDR) has been developed for 2dF (Taylor *et al.* 1996; Bailey *et al.* 2001). The design philosophy of the 2DFDR package is to make as much use of known instrumental parameters as possible. In particular, 2DFDR uses the known optical properties of the spectrographs to predict the format of the data (location of the spectra and dispersion). The FITS headers of the data contain all the information needed to identify the different types of data frame, the location of all the target objects, details of the telescope and spectrograph parameters, and the appropriate calibration frames to be associated with each data frame. The 2DFDR package preserves the integrity of the data headers, together with the statistical variance of each spectrum and the sky spectrum that was associated with each object.

The 2DFDR program can be run automatically and is able to reduce an entire night's data in an hour or less. However, it is normally better to do at least some of the steps interactively, especially the initial determination of the 'tramline' extraction maps for the spectra, and to verify that the results are sensible at each stage. The software package provides several options and many parameters which can be

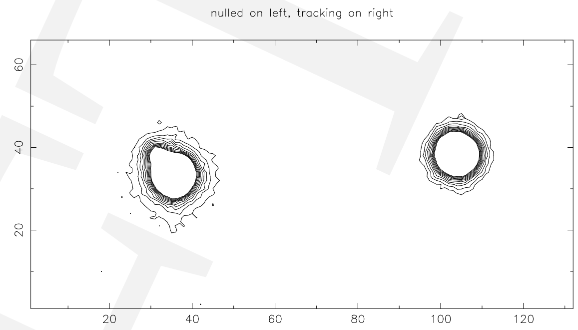


**Figure 11.** Operation of the ADC at 67°zenith distance. The left hand image shows the image quality with the ADC nulled, the right hand image shows the same stellar image with the ADC tracking at the appropriate orientation.

set, and includes a number of diagnostics for assessing data quality.

The data for a particular target field are reduced as two separate sets of data, one for each spectrograph containing 200 individual spectra. For the large redshift surveys, it is normal procedure to analyse the data as the night proceeds, with all observations fully reduced and all redshifts determined by the end of the nights observing.

## 5 PERFORMANCE OF 2DF

### 5.1 Atmospheric Dispersion Compensator

The effectiveness of the ADC has been demonstrated using the focal plane imager CCD camera to take an image of a star at a zenith distance of 67°. A UV and near IR passband filter (Schott BG1) was inserted in the optical path for the images. The results are shown in figure 11. The image taken with the ADC nulled (no correction of atmospheric dispersion) shows a slight separation of the UV and near IR images, the image taken with the ADC operating shows a circular superimposed set of images.

The ADC was initially commissioned in 1993 as part of the corrector acceptance tests. Unfortunately, data taken between 1996 and 1999 was degraded by incorrect positioning of the ADC elements. This was corrected in August 1999 and all subsequent data has the ADC operating correctly.

### 5.2 Positioner

The positioner is routinely capable of positioning the fibres with a total accuracy of 0.3″ rms (positioning and astrometric errors) as measured by configuring fibres for a set of standard stars with accurately known positions and taking short exposures while rastering the telescope. From these results the actual position errors of the individual fibres can be determined.

The positioner can reposition the fibres in just under 60 minutes allowing continuous operation over most of the sky.

**Table 1.** Properties of pairs of gratings available for use with 2dF

| Grating | $\rho$ | $\lambda_b$ | dispersion (nm/pixel) | resolution (nm) |
|---|---|---|---|---|
| 300B | 300 | 420 | 0.43 | 0.9 |
| 270R[1] | 270 | 760 | 0.48 | 1.0 |
| 600V | 600 | 500 | 0.22 | 0.44 |
| 1200B | 1200 | 430 | 0.11 | 0.22 |
| 1200V | 1200 | 500 | 0.11 | 0.22 |
| 1200R | 1200 | 750 | 0.11 | 0.22 |

$\lambda_b$ is the Littrow blaze wavelength. The resolution is the effective instrumental resolution, either the projection of the fibre onto the detector or 2 pixels, whichever is the larger. $\rho$ is the ruling density (lines per mm).
[1] The 270R grating is paired with a 316R grating since the 270R grating master was no longer available when a duplicate was ordered.

This turn around time is well matched to the observations times required for some of the most demanding applications.

### 5.3 Spectrographs

The optical quality of the spectrographs is such that each fibre image is focussed to a point with a FWHM of 2.1 pixels for one spectrograph and 1.9 pixels for the second spectrograph. This yields resolutions with the various gratings as shown in table 1.

Flexure in the spectrographs is at the level of 0.2 pixels per hour. In normal observing we do not expose for longer than 40 minutes due to cosmic rays, so taking an arc exposure for calibration purposes every hour is normal practice.

Duplicates of our most frequently requested gratings (or the nearest available specification) have been purchased, this allows most spectrograph setups to be duplicated in both spectrographs. This is the normal mode of operation.

The level of light leaking from the fibre back illumination within the spectrograph is a potential cause for concern. This can be tested by illuminating the fibres continuously while taking a dark CCD exposure and measuring the excess signal over a similar length exposure with no fibre back illumination. This has to be repeated for both spectrographs and both plate combinations. Typically <1 ADU of additional diffuse background signal is measured from the permanently back illuminated case in a 5 minute dark exposure. In normal use the back illumination is only switched on when the positioner robot requires to see the fibre. This results in a duty cycle of less than 10 per cent so the light leaking from the back illumination is insignificant for the typical length exposures of 20–40 minutes.

### 5.4 Throughput

The total system throughput (including atmosphere, telescope, fibres, instrumentation and detector quantum efficiency) was determined by observing fields of several dozen photometric standard stars to allow an average to be determined over a large number of fibres. With the 300B grating we measured the absolute efficiency as:

(i) A B=17 star gives 0.6 electrons/sec/Å at a wavelength of 440nm, this corresponds to a system efficiency of 2.8%.

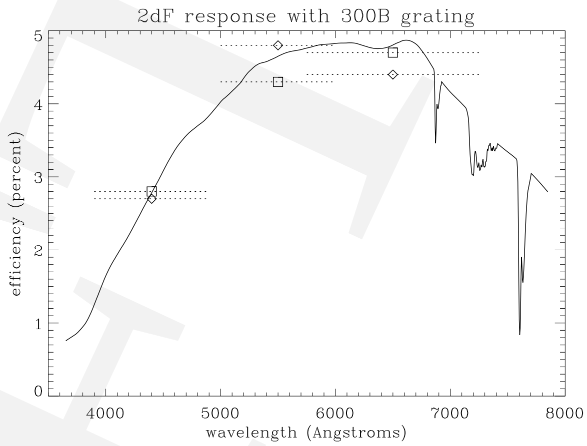


**Figure 12.** Figure showing the total 2dF system efficiency as a function of wavelength. The squares and diamonds represent broadband absolute efficiency measurements from 1997 January and 1999 November, respectively. The solid line was obtained from a relative throughput calibration using data from 2001 January scaled to approximately match the broadband measurements.

(ii) A V=17 star gives 0.6 electrons/sec/Å at 550nm (4.3%).
(iii) A R=17 star gives 0.4 electrons/sec/Å at 700nm (4.7%)

Of course these efficiencies change with choice of grating, the best performance comes with the use of the low resolution 270R and 316R gratings where the blaze of the grating matches the peak of the CCD quantum efficiency. In this case the system efficiency peaks at 9%. For more details and signal to noise calculations see the 2dF WWW pages (http://www.aao.gov.au/cgi-bin/2dfsn.cgi).

Since the wavelength information in such broadband measurements is insufficient we have used a relative throughput calibration using several hundred stars observed simultaneously with 2dF (figure 12.

## 6 2DF SCIENCE

[New section, to follow]

## 7 FUTURE PLANS

In this paper we have described a unique multi-object optical spectroscopy facility.

We are currently performing experiments using 2dF and the technique of charge shuffling and telescope nod (Glazebrook *et al.* 1999; Glazebrook & Bland-Hawthorn 2001) to improve the sky subtraction of extremely faint target objects for which fibre spectroscopy has previously been extremely difficult.

Future plans include replacing the two spectrographs with bench mounted spectrographs using volume phase holographic (VPH) grating (Barden *et al.* 1998) technology. The VPH gratings have the advantage of offering higher efficiency than conventional reflecting diffraction gratings. Upgraded detectors, all transmitting spectrograph optics and new optical fibre materials (Shöltz *et al.* 1998) will allow us to use longer optical fibres and still gain in overall throughput and provide higher resolutions. The advantage of the bench mounted spectrographs will be in their thermal and mechanical stability.

We also plan to use the flexibility of the fieldplate tumbler system to provide one or two fibre feeds for integral field spectroscopy at the currently unused 90°positions of the tumbler unit.

## 8 ACKNOWLEDGMENTS

The authors would like to acknowledge the many AAO technical staff that have made 2dF a reality, the astronomy support staff of the AAO that make 2dF available to the general user. This project has only been possible with extensive support from both the Australian and UK scientific communities.

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