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# All-Sky Spectroscopic Surveys and 6dF

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**Abstract.** 6dF is a robotic multi-fibre spectroscopy system for the 1.2-m UK Schmidt Telescope (UKST). It replaces the manually-configured FLAIR system, and will enter service during 2001. This paper reports on the current status of 6dF and outlines its potential not only for an all-sky 6dF galaxy survey, but for other large-scale spectroscopic surveys as well. While 6dF is currently unique, the possibilities for extending sky-coverage to the northern hemisphere are also examined.

## 1. Introduction

The all-sky optical imaging surveys that have underpinned observational astronomy over the last five decades were only possible because of the extraordinarily wide field (∼10 deg) of large Schmidt telescopes. Such telescopes are also well-suited to large-area spectroscopic surveys, as demonstrated by the success of the FLAIR system on the UK Schmidt (Watson et al. 1993, Parker & Watson 1995). Optically, the Schmidt design lends itself well to multi-fibre spectroscopy, since it is perfectly telecentric and feeds the fibres at an ideal focal-ratio (Watson & Terry 1995).

The main barrier standing in the way of all-sky spectroscopic surveys with a large Schmidt has been the capital cost of an automated fibre positioner. Even the largest present-day Schmidts are only 1-metre class instruments (albeit specialised ones) and it is not straightforward to justify the investment required (∼GBP0.4M).

This barrier has now been overcome at the UK Schmidt. The potential of an all southern-sky ($|b| > 10$ deg) galaxy redshift survey complete to $B \sim 16.5$ and $K' \sim 12.8$, together with a follow-up peculiar-velocity survey, has proved sufficiently persuasive for the Anglo-Australian Telescope Board (AATB) to approve the construction of a 150-fibre robotic multi-object spectroscopy system. The instrument, known as 6dF (for 6-degree field) is nearing completion at the time of writing (December 2000). Under the guidance of a 6dF Science Advisory Group, it will embark on the survey during the first half of 2001. The availability of 6dF on the UK Schmidt will complement 2dF on the AAT, and will provide a new dimension in wide-field spectroscopy.

## 2. Background

For multi-object spectroscopic applications, a useful metric for comparing optical telescopes of widely disparate sizes and types is the $A\Omega$ product: the collecting area multiplied by the area of field. It is a crude measure of the total photon throughput of the optical system.

The $A\Omega$ product is not a good performance indicator in the general case because it neglects spatial resolution. However, in multi-object spectroscopy, this is usually less significant than in imaging applications.

In Table 1, the $A\Omega$ product for seven existing or proposed spectroscopic survey telescopes is given. They are arranged in order of increasing $A\Omega$, and the contribution of field-size is immediately apparent. It is because of this that the UK Schmidt Telescope can remain competitive in a list that includes telescopes in the 8-m class. However, the combination of 4-m aperture and Schmidt-type optics in the Chinese LAMOST proposal scheduled for completion in 2004 (Chu & Cui 1996) provides a leap in $A\Omega$ of almost an order of magnitude.

Table 1. $A\Omega$ Product for Some Spectroscopic Survey Telescopes

| Telescope | Aperture (m) | Field (deg) | $A\Omega$ ($\mathrm{m^2deg^2}$) |
|---|---|---|---|
| Gemini | 8.1 | 0.17 | 1.8 |
| WHT | 4.2 | 0.5 | 4.4 |
| Sloan | 2.4 | 2.5 | 36 |
| VLT | 8.1 | 0.4 | 52 |
| AAT | 3.9 | 2.0 | 61 |
| UKST | 1.2 | 6.6 | 65 |
| LAMOST | 4.0 | 5.0 | 400 |

It may be remarked that telescopes primarily intended for imaging also cover a wide range of $A\Omega$ values. The 4.0-m VISTA telescope in its optical-imaging mode (Emerson, these proceedings) ranks highly, with $A\Omega = 64\ \mathrm{m^2deg^2}$. It is eclipsed, however, by the proposed 8.4-m (6.3-m equivalent) Large-Area Synoptic Survey Telescope (Tyson, these proceedings), whose $A\Omega$ product is 360 $\mathrm{m^2deg^2}$. At the other end of the scale, the 100-m ESO OWL proposal (Gilmozzi and Dierickx 2000), with a 25-arcsecond MCAO-corrected field, boasts an $A\Omega$ product of only 0.5 $\mathrm{m^2deg^2}$—rather less than that of a standard 35-mm camera lens.

## 3. The Road to 6dF

It was the imposing $A\Omega$ product of the UKST that led Dawe & Watson (1984) to suggest that multi-fibre spectroscopy could be carried out with the telescope. The original proposal included the idea of an automated fibre positioner. However, when the technique was implemented using, successively, the FLAIR prototype (1985), the PANACHE upgrade (1988) and the FLAIR II system (1992), budgetary constraints inevitably meant that only manual positioning of the fibres could be employed. Despite this, useful science was obtained from all versions of the system, particularly FLAIR II during its heyday in the 1990s with QAP as instrument scientist.

Upgrades to the FLAIR II spectrograph during that period resulted in improved sensitivity, highlighting the principal deficiency of the system. This was that the manual fibre-reconfiguration time exceeded the necessary exposure time on a given field by a factor of more than four. Even with new magnetic buttons introduced by QAP in 1998 (partly to test the feasibility of 6dF), no more than two fields per night could be observed. This severely limited the usefulness of the system for the large-scale spectroscopic surveys to which the telescope is intrinsically well-suited.

A proposal by MMC, QAP, WS, Gary Mamon (Paris) and others to carry out an all-southern-sky galaxy redshift survey—with the unique additional component of a peculiar-velocity subset survey—was a key element of an options paper for the UKST, presented to the AATB in August 1997. As a result of this, a Phase-A study for an automated fibre positioner was carried out, and construction was approved by the Board in March 1998. Its anticipated cost was $\sim$\$A0.6M and expected delivery was in mid-2000. The scope of the project was increased in September 1999 to include the procurement of a new CCD detector system for the original FLAIR II spectrograph at an extra cost of \$A150k.

Inevitably, both the cost of the project and its construction time have exceeded the original estimates. However, the overruns are not unduly excessive, amounting to $\sim$20 percent in both aspects.

## 4. The 6dF Instrument

### 4.1. Overview

Detailed technical descriptions of 6dF may be found in Parker, Watson, & Miziarski (1998) and Watson et al. (2000). Only a broad outline of the instrument is given here.

The main components are:

1. two interchangeable 6-degree diameter field-plate units (each with its fibre feed permanently attached) that can be loaded either into a fibre positioner for reconfiguration or into the telescope for observing. The only time-on-target lost with this "double-buffered" arrangement is in the exchange between one field plate and the other in the telescope, and the associated calibration exposures. Around 20 minutes are required for these operations;

2. optical cables containing 150×6.7 arcsec science fibres and four 7-fibre guide-star bundles for each field-plate;
3. a robotic pick-place fibre positioner housed in an enclosure within the dome, approximately 5 metres from the telescope. It incorporates a back-illumination facility for the fibres, so that when a field-plate unit is unloaded from the telescope, the slit-unit at the output end of the fibres must also be unloaded from the spectrograph and transferred to the positioner with the field-plate unit. Expected reconfiguration time is 40–60 minutes;
4. the refurbished FLAIR II spectrograph, which is also mounted in a stationary position in the dome, resulting in extremely high spatial and wavelength stability;
5. the upgraded CCD system, incorporating a 1k×1k Marconi CCD47–10 device and SDSU–2 detector controller. The new detector system, together with the *CICADA* software package to run it, has been supplied under contract by the Research School of Astronomy and Astrophysics of the Australian National University.

The improvements in reconfiguration time and overall sensitivity are expected to allow up to six fields (or about 900 targets) to be observed per clear night.

### 4.2. Personnel

The main players in 6dF can be grouped as follows:

- *AAO Project Team:* Gabriella Bogatu (Project Manager), Chris Evans (Initiating Project Manager), Fred Watson (Project Scientist), Peter Gillingham, Stan Miziarski (mechanical design), Brian Hingley, Lew Waller (electronics design), Tony Farrell, Ken Russell, Niki Frampton (software);
- *Commissioning Team:* Quentin Parker (Galaxy Survey Manager), Will Saunders (Galaxy Survey Scientist), Fred Watson;
- *6dF Science Advisory Group:* Matthew Colless (Chair), Gary Mamon (IAP), John Huchra (CfA), Ofer Lahav (IoA), John Lucey (Durham), Elaine Sadler (Sydney), Ken-ichi Wakamatsu (Gifu), Dominique Proust (Meudon) and the members of the Commissioning Team.

### 4.3. Current Status

*Field-plate units and fibre feeds* These items are now complete except for minor adjustments. The two field-plate units are designed to match the dimensions of the telescope's photographic plateholders, and each incorporates a circular steel field plate 320-mm (5.99 deg) in diameter, whose front surface is a segment of a sphere matching the focal curvature. Surrounding the field-plate are 154 retractor units into which the 150 science fibres and four guide fibre bundles can withdraw. A tangential drive allows the field plates to be rotated by up to $\pm 5$ arcmin in position angle for field acquisition.

The 11-metre long science fibres have a core diameter of $100\mu$m (6.7 arcsec) and are drawn from a broad-band Heraeus STU preform (Polymicro FIPA 100110125250STU). They are terminated in slit-units that provide telecentric feed to the Schmidt-type collimator.

The four guide fibres consist of bundles of seven fibres hexagonally-packed to provide pseudo-imaging at four positions on the field plate. They are approximately 5 metres long. Each bundle covers 23 arcsec on the sky to allow acquisition and guidance on the target fields.

*Fibre Positioner* The $(r, \theta)$ fibre positioner is now complete and undergoing testing. The positioner uses air-bearings throughout. The $\theta$-bearing allows rotation through more than 360 degrees, while the gripper carriage moves along the $r$-arm on a curved track to match the radius of curvature of the convex field-plate beneath it.

The gripper itself uses air bearings and pneumatic control to provide:

- $z$-motion control,
- jaw open/shut control,
- frictionless rotation of the jaws to avoid the need for active control of fibre-button rotation.

The jaws themselves are in the form of a collet to match the cylindrical casing of the fibre buttons. The manufacture of this component has proved problematic, as very fine tolerances are required. Pick-up/put-down tests have been carried out to ensure that the repeatability of fibre placement is within $\sim 2\mu$m. The overall positioning tolerance is $\pm 15\mu$m, and this is currently being tested.

The positioner will be located in a light-tight enclosure within the telescope dome, along with the control system rack.

*Control System* The 6dF control system is now complete. It consists of a workstation running Linux with I/O bus cards. The robot $(r, \theta)$ drives utilise linear and rotary DC brushless motors with high-resolution incremental encoders. They are controlled by ServoStar motion controllers which have serial links to the control computer. The $z$-motion and gripper are operated pneumatically by six solenoid valves with inductive switches to sense position. The system also controls various safety interlocks.

*Software* The 6dF software suite comprises:

- pre-observation software (off-line) to plan fibre allocations before observations take place;
- robot control software to facilitate the accurate positioning of fibres on the plate;
- pipeline data-reduction software;

- detector control software;
- a fibre database for use in instrument maintenance.

The first three of these are based on software written for 2dF on the AAT. The *Configure* program has been adapted for use by either 2dF, 6dF or the VLT fibre positioner OzPoz, and is switchable between the three instruments. Likewise, the existing *2dfdr* data reduction suite is being modifed to generate *6dfdr*. The robot control software, which is currently undergoing final testing, is being generated by porting the 2dF software to the PC, retaining only the functionality required by the simpler 6dF system.

The upgraded CCD system is run using the *CICADA* software package, developed by the Research School of Astronomy and Astrophysics of the Australian National University.

*Detector Upgrade* The new detector was installed in the existing Schmidt-type camera of the FLAIR II spectrograph in December 2000 and is now undergoing commissioning. The Marconi CCD47-10 device offers optimal sampling (13$\mu$m pixel-size), very high DQE (∼80 percent at 5000 Å) and extremely low read-noise ($\sim 2e^-$).

Together with the improvements gained from better fibre performance, the new CCD will have a dramatic effect on the sensitivity of 6dF compared with FLAIR II.

## 5. The 6dF Galaxy Survey

### 5.1. Overview

During 1999, the 6dF Science Advisory Group (6dFSAG) began to plan for the scientific, technical and logistic implementation of the 6dF Galaxy Survey. The issues considered included scientific strategy, input catalogues, survey size, timescales, data evaluation and scientific oversight during the observational phase.

The survey has now been specified as a near-infrared-selected survey covering the 18,000 deg$^2$ of the southern sky with $|b| > 10$ deg. It will have two components: a redshift survey (the $z$-survey) of 120,000 galaxies with $K' \leq 12.8$ drawn primarily from the 2MASS catalogue, and a peculiar-velocity survey (the $v$-survey) of some 15,000 early-type galaxies in a volume-limited ($cz < 15,000$ kms$^{-1}$) subset. Peculiar velocities will be derived using the $D_n - \sigma$ relationship.

The strategy for carrying out the survey has evolved somewhat during 2000. In the "classical" 6dF survey, as originally proposed, the redshift and peculiar velocity surveys were envisaged as independent campaigns, with the $z$-survey being completed before the $v$-survey sample was drawn from it and observed. A more recent "modest proposal" (Saunders, private communication) has suggested that the idiosyncrasies of the instrument (in terms of minimum proximity of targets [5 arcmin], field-dependent coverage restrictions, etc.) are better matched to a single survey that fulfills the role of both the $z$- and $v$-surveys with multiple passes over the sky. That is now the preferred option, though its tractability is critically dependent on the characteristics of the spectrograph, most notably its imaging performance. Either way, an adaptive tiling technique will be employed to maximise the number of targets that can be observed in any one pointing of the telescope.

The survey will be managed by the Wide-Field Astronomy Unit of the University of Edinburgh, with scientific oversight being provided by the 6dFSAG. The reduced data will be non-proprietory and will be issued in staged releases.

Further information on the 6dF Galaxy Survey may be found on the World-Wide Web at http://www.mso.anu.edu.au/colless/6dF.

### 5.2. The $z$-survey

The survey will be of a $K$-band-selected galaxy sample from the 2MASS Extended Source Catalogue (XSC). It is expected that star/galaxy separation will be checked against higher-resolution DENIS $I$-band imaging. The survey will also include fainter galaxies than $K' = 12.8$ to be complete to $H = 13.5, J = 14.1, I = 15.0, r_F = 15.5, b_J = 16.5$.

For the "classical" $z$-survey, it was envisaged that ~1h exposures would be required to obtain spectra at a resolution of ~ 3 Å/pixel with coverage of ~3900–7500 Å and S/N of ~10. The more exacting requirements resulting from the proposed merging of the two surveys means that these parameters will now remain unspecified until the commissioning of the new detector in the FLAIR II spectrograph is complete, early in 2001.

### 5.3. The $v$-survey

The primary goal of the $v$-survey is to measure peculiar velocities over the entire southern sky to obtain the local mass distribution. 2MASS and DENIS photometry will be combined with the observed velocity dispersions for the selected subset of ~15,000 early-type galaxies with $cz < 15,000$ kms$^{-1}$ to obtain $D_n - \sigma$ distances.

The "classical" $v$-survey demands ~ 0.8 Å/pixel over the range ~4700–5500 Å, requiring ~4h exposures. Again, the push to combine the two surveys means that these requirements are being re-evaluated in the light of the actual performance of the spectrograph.

It is possible that the optimum execution of the Galaxy Survey may require the procurement of Volume-Phase Holographic (VPH) gratings, and may demand the adoption of a hybrid strategy that allows both surveys to proceed simultaneously, but with two different dispersions used sequentially for each pointing of the telescope.

### 5.4. Survey Timeline

It is expected that the 6dF Galaxy Survey will take up to 75 percent of scheduled time on the telescope from its commencement in April 2001, subject to the continuing support of the Schmidt Telescope Time Assignment Committees (which will carry out a major review of survey progress in June 2002). Depending on the survey strategy finally adopted, the survey's completion is expected in 2004/5.

Applications were invited in September 2000 for up to ~20,000 additional targets to be observed along with the main survey sample. These targets will ensure that all 150 science fibres are used (allowing for sky fibres) in any one pointing of the telescope. Following the same timeline as the main sample, they will be reduced and made publicly available alongside it.

## 6. Non-survey Spectroscopy with 6dF

By December 2001, the UKST's remaining photographic surveys (the H$\alpha$- and $I$-surveys) will be essentially complete. It is expected that photography will then become a minor part of the telescope's programme, being carried out only in the very best seeing. Except for small amounts of time that may be allocated to a proposed 1-degree-field CCD mosaic (an Australian National University/University of Tokyo collaboration), the main activity on the telescope will be 6dF spectroscopy.

The 75 percent of time devoted to the Galaxy Survey will leave some 15–20 percent available for non-survey spectroscopy, and this time will be allocated through the normal Schmidt Telescope Time Assignment Committees. (The first round of applications was invited in September 2000.)

Programmes requiring wide-field spectroscopy of bright ($B < 17$) objects with a number density of $\sim 5\mathrm{deg}^{-2}$ at instrumental resolutions in the range 2–8 Å, and with spectral coverage in the region 3800–9000 Å are well-suited to the capabilities of the instrument.

## 7. Beyond the Galaxy Survey

The completion of the Galaxy Survey around 2005 will open up the possibility of using 6dF for other all-sky spectroscopic surveys. Indeed, that possibility exists already for bright objects, which could be observed during the ~10 bright nights per lunation for which the telescope is currently unscheduled. In either case, external funding would be required to support the operation of the telescope: the AAO's resources are only sufficient to allow the current level of operation until the end of the Galaxy Survey.

Two space-mission follow-up surveys that have already been proposed are

- DIVA follow-up: bright-time spectroscopy of $V < 11$ stars at $R \sim 4000$, preceding and/or following the DIVA launch in 2003. Expected duration $\sim 2$ years, with possible extension to fainter magnitudes;
- GALEX follow-up: spectroscopy of UV sources to $V \sim 18.5$ (stars) and $V \sim 17.5$ (galaxies) at $R \sim 1000$ following the GALEX launch (in 2004); ~60,000 objects/year.

## 8. A Northern 6dF?

The scientific value of both these space-mission follow-up surveys and, more immediately, the 6dF $v$-survey would be greatly enhanced by their extension to the northern hemisphere. There appears to be some possibility that the SDSS will provide velocity dispersions of an equivalent northern sample to the 6dF $v$-survey (Lupton, these proceedings), though a uniformly-selected and observed subset would be preferable.

It would be a relatively straightforward exercise to duplicate 6dF for one of the large northern Schmidts, for example the 1.2-m Oschin Schmidt, or the 1.05-m Kiso Schmidt. (The 1.3-m Tautenberg Schmidt already has a low-multiplex multi-fibre spectroscopy system, TAUMOK: see Marx et al. 1995 and references therein.)

The problem is that most of these telescopes are either already committed (e.g. the Oschin Schmidt, on NEO work) or are on poor sites (e.g. the Kiso Schmidt). It is possible, though, that some smaller (0.9-m class) instruments such as the Haute Provence or Cerga (Observatoire de la Côte d'Azur) Schmidts might be available to utilise a 6dF-type system for all-sky spectroscopic surveys in the north.

## 9. Conclusion

The remarkable progress that has been made in the development of 6dF over the past two years has been driven in part by some commonality between 6dF and the OzPoz fibre positioner being built by AAO for the VLT. Nevertheless, it highlights AAO's project management structure as a significant contributor in the delivery of this fast-track instrument.

When 6dF successfully enters its operational phase, it will ensure the future viability of the UKST for several years to come—perhaps more than a decade. Truly, the telescope will have entered a new era of wide-field astronomy.

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