Performance of AAOmega: the AAT multi-purpose fibre-fed spectrograph.

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ABSTRACT
AAOmega is the new spectrograph for the 2dF fibre-positioning system on the Anglo-Australian Telescope. It is a bench-mounted, double-beamed design, using volume phase holographic (VPH) gratings and articulating cameras. It is fed by 392 fibres from either of the two 2dF field plates, or by the 512 fibre SPIRAL integral field unit (IFU) at Cassegrain focus. Wavelength coverage is 370 to 950nm and spectral resolution 1,000-8,000 in multi-Object mode, or 1,500-10,000 in IFU mode. Multi-object mode was commissioned in January 2006 and the IFU system will be commissioned in June 2006.

The spectrograph is located off the telescope in a thermally isolated room and the 2dF fibres have been replaced by new 38m broadband fibres. Despite the increased fibre length, we have achieved a large increase in throughput by use of VPH gratings, more efficient coatings and new detectors - amounting to a factor of at least 2 in the red. The number of spectral resolution elements and the maximum resolution are both more than doubled, and the stability is an order of magnitude better.

The spectrograph comprises: an f/3.15 Schmidt collimator, incorporating a dichroic beam-splitter; interchangeable VPH gratings; and articulating red and blue f/1.3 Schmidt cameras. Pupil size is 190mm, determined by the competing demands of cost, obstruction losses, and maximum resolution. A full suite of VPH gratings has been provided to cover resolutions 1,000 to 7,500, and up to 10,000 at particular wavelengths.

Keywords: Anglo-Australian observatory, Double beam spectrograph, fibres

1. INTRODUCTION
The two degree field facility (2dF²⁻¹) of the Anglo-Australian Telescope (AAT), had its original spectrographs mounted on the telescope top end ring. This was mandated by the capabilities of fibres at that time, and the spectrographs were designed for the primary science goal - a large redshift survey of moderate brightness galaxies. However, they were of limited utility in obtaining spectra of fainter objects, or at higher signal-to-noise or resolution. The reasons for this were:

- Restricted size and weight, with implications for instrument stability and format
- Flexure and temperature variations, compromising both spectral and spatial stability of the system
- Imperfect optics giving variable point spread function (PSF), leading to systematic error in skyline subtraction that could not be reduced by increased integration.
- Significant scattered light and halation problems, limiting the dynamic range within and between spectra.

Despite these limitations, both spectrographs performed admirably resulting in a multitude of high quality scientific results over their 10 year careers. In August 2005 spectrographs 1 and 2 were retired from service to make way for installation of the next generation AAT multi-purpose optical spectrograph, AAOmega.

The mechanical³ and optical⁴ design of AAOmega has been presented previously elsewhere. In what follows we briefly describe the as commissioned capabilities of AAOmega. The commissioning program is outlined in table 1.

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Table 1. AAOmega was commissioned November 2005 - January 2006 following the project time line outlined below.

| Date          | Status                                                                 |
|---------------|------------------------------------------------------------------------|
| August 2005   | Decommission 2dF spectrographs                                         |
|               | Remove 2dF fibre retractors to install AAOmega fibres                  |
| November 2005 | First on sky commissioning (6 nights)                                  |
|               | 2dF positioner upgrade and new field plates                            |
|               | Instrument and telescope control software integration                  |
|               | AAOmega guide fibres                                                  |
|               | Limited AAOmega slit units                                            |
|               | (2 Plates × 3 Bundles × 10 fibres)                                    |
|               | Blue camera only                                                       |
| December 2005 | Second commissioning run (7 nights)                                   |
|               | Red and Blue cameras                                                  |
|               | Fully populated slit units                                            |
| January 2006  | Final commissioning run (5 nights)                                    |
|               | Full system integration                                                |
| January 2006  | Science verification (8 nights)                                        |
|               | 9 programs substantially completed                                     |
|               | Testing the full range of AAOmega capabilities.                        |
| February 2006 | Commence routine science operations                                    |
| - May 2006    | 10 scheduled programs, 41 nights                                      |
|               | Active service program                                                 |
| June 2006     | SPIRAL IFU Scheduled for commissioning                                 |

1.1. Improvements over the original 2dF system

While maintaining the high multiplex (392 fibres) and low observational overhead (via configuration of one field plate during observation of the other) of 2dF, the key design goals for AAOmega have been to overcome many of the problems experienced with the original 2dF system:

- Improved sensitivity at all wavelengths, even with the increased fibre run length.
- Spectroscopic stability - removal of thermal and flexure effects
- PSF uniformity - dramatically improved sky subtraction and higher velocity accuracy
- Higher maximum resolution
- Greater wavelength coverage at a given resolution
- Minimisation of systematic effects, such as scattered light and light leaks
- Improved support for Nod-and-Shuffle observations[5].

As an alternate to the 2dF MOS fibre feed, the SPIRAL Integral Field Unit (IFU) mounted at the Cassegrain focus, will also be available to AAOmega. SPIRAL will be commissioned in June 2006 and hence we defer discussion of the IFU feed until a later time.
2. DETAILS OF THE FINAL IMPLEMENTATION OF AAOMEGA SYSTEMS.

2.1. Fibre positioner and fibre run
AAOmega retains much of the 2dF fibre positioner system at the prime focus of the AAT and hence we refer the reader to the previous review[^2] for a detailed review of 2dF. The major departures from the original system are the replacement of the 8m fibre run with the 38m run required to deliver the fibre slit units from prime focus to the Coudé west laboratory to feed the bench mounted dual beam AAOmega spectrograph. A continuous fibre run design was considered preferable to a system with a fibre connector, to eliminate light losses and focal ratio degradation at a connector. The fibre run remains permanently attached to 2dF and is routed to the spectrograph via the Serrurier truss, the Coudé tunnel and the horseshoe bearing before arriving at Coudé west. The Polymicro Broadband fibres[^2] have a nominal core diameter of 140um, cladding diameter 168um and polyimide buffer diameter of 196um. Measured throughput is 72% at 400nm and 96% at 800nm.

2.2. Guide bundles
Each 2dF field plate was originally equipped with four coherent bundles, constructed from a close packed arrangement of seven fibres. For AAOmega an additional four guide bundles per field plate were added, greatly increasing acquisition accuracy in normal use. It also allows four guide stars to be acquired in each telescope position of a Nod+Shuffle cross-beam-switching pair (see section 3.4).

2.3. The spectrograph
The spectrograph design has previously been described[^3,4]; we here focus on the comparison between design and in-use performance.

The design has a 145mm fibre slit, with a field lens to make it telecentric (or more correctly, pupil-centric); an f/3.15 Schmidt collimator incorporating a dichroic beam-splitter upstream of the corrector (this necessitates two correctors but minimises pupil relief); in each arm there is then a collimator Schmidt corrector; an articulating VPH grating; then an f/1.3 Schmidt camera with a doublet corrector, spherical mirror, a field-flattening lens of S-YGH51 glass, and a 2K x 4K E2V CCD with the long axis in the spatial direction. Optics, coatings and detectors were all specified separately for each arm.

The design emphasised excellent optics and image quality, to give a uniform PSF and hence good skyline subtraction. The most difficult components were the 230mm diameter aspheric doublet corrector plates for the wide-field (8° off-axis angles), fast (f/1.3) Schmidt cameras. These were made by SE Laser Physics St Petersburg. The overall surface quality was close to the half-wave specification, but small scale radial gradient errors were a concern.

The dichroic beam-splitter was manufactured by Precision Optics at CSIRO Lindfield, and meets the very demanding specification (figure 1). Only a single beam-splitter, with crossover at 570nm, is currently in use, but others are envisaged as needed for particular science programs. The present cross over wavelength is chosen to give continuous wavelength coverage, at low resolution, from ~370nm to ~880nm, while still placing the strong blue sky line at 5577 Å within the coverage of the blue spectrum. The line is used to allow relative fibre throughput calibration, a process required for sky subtraction using dedicated sky fibres (see section 3.4), avoiding the need for costly offset sky calibrations.

The VPH gratings were made by Ralcon Development Lab. The blue (<570nm) gratings used commercial Starphire glass, post-polished to give half-wave image quality; the red gratings used pre-polished BS7 substrates. All gratings are 20mm thick. At the time of procurement we were not able to locate good quality affordable BK7/UBK7 substrates; this situation has now changed (e.g. www.infiniteoptics.com).

The optical design gave a theoretical PSF which was closely Gaussian, with a full width at half maximum (FWHM) of 3.2 pixels, and a variation of less than a few percent over the detector. The actual, in-use PSF is indeed almost perfectly Gaussian (figure 2). The blue camera has a FWHM and uniformity as good as specified, with actual FWHM in the range 3.1-3.3 pixels. The red camera is less satisfactory, giving 3.3-3.6 pixels, but extremely uniform for any particular wavelength.

[^2]: http://www.polymicro.com/products/opticalfibers/products_opticalfibers_fbp.htm
Figure 1. Response of the 570nm dichroic currently available for use with AAOmega. Note the abrupt transition region and generally smooth profile.

Figure 2. Examples of the blue (left) and red (right) fibre PSF show the system to be satisfactory, and highly Gaussian. The poorer red performance is believed to have its origins in charge diffusion in the deep-depletion CCD.
The poorer red focus was surprising in light of the generally easier optics for the red camera. The strongly suspected explanation is the combination of fast optics with the deep-depletion (DD) CCD. Our results suggest an extra contribution from charge diffusion of order 1 pixel (15µm) for the red camera. The DD silicon thickness is 40µm, vs 16µm for the blue arm CCD, and the typical penetration of the photons will be proportionately larger. This leads to increased charge diffusion even for on-axis incoming light, but the effect is compounded for a fast beam such as ours. In practice, the poorer than expected red camera focus leads to no problems except a 10% lower resolution than anticipated.

Scattered light performance has been excellent, with 5% (red, average at low dispersion) and 23% (blue) of the overall light incident on the detectors not being extractable into spectra. This results from the relatively small number of optical surfaces in the spectrograph (13) and the excellent performance of the gratings themselves. The higher scattering in the blue camera is due to residual “moisture” contamination from initial assembly and is improving with time (see section 5.11).

2.4. The cameras

The overall camera design remains the same as in previous discussions of AAOmega\[3\]. During routine operations vacuum hold times have proven longer than intervals between scheduled interventions in their operation as part of the commissioning process (∼3 weeks). Achieving the detector operating temperature of 160K in the Epping laboratory prior to installation at the AAT, proved difficult, a potential problem for the blue camera due to the intrinsic dark current. Further investigation showed this to be due to the radiative thermal load on the detector, through the camera optics, in the warm clean room. There has been little problem achieving the required set-point once installed at the AAT.

3. AAOMEGA IN USE

3.1. Acquisition and guidance

The guide fibres are filtered at λ5000Å and imaged with a Watec CCD camera giving improved intensity control and sensitivity over the older 2dF Quantex video system. The preferred guide star magnitude range is currently V=14-14.5 mag(Vega) (although for all practical purposes B, V or R band limits are interchangeable here) with 15 mag representing the lower practical limit. During bright time observations, 12 mag stars are more practical. The Watec camera has a limited dynamic range, and hence the spread in guide star magnitude during any individual observation should be constrained to be Δmag<0.5 for the best results. An auto-guider system provides translational motion on the 1-5 sec scale, and also estimates any field plate rotation corrections. The latter is required both to correct for small amounts of declination-dependent flexure in the 2dF system, and also to (partially) correct for changes in differential atmospheric refraction as the field tracks across the sky.

3.2. Detector modes

AAOmege is a general purpose instrument providing many modes of use. Windowing and spectral binning are supported. Each detector can be read out through one or both amplifiers at a variety of read speeds. We have achieved read noises of 3.8e− and 4.5e− at NORMAL (125s full frame single amplifier readout time) and FAST (74s) read speeds.

3.3. Astronomical use of VPH gratings

VPH gratings\[6\] offer great advantages for astronomy over traditional reflection gratings. They are cheaper, more efficient, can be designed to any desired specification, can be made in large formats, have less scattered light, offer much better pupil relief, and there is now a three-way choice of manufacturer. The drawbacks are that the response is more strongly peaked, and that they do not work well at very low resolutions. In several respects, they differ greatly in use from reflection gratings:

- The wavelength coverage for a particular grating angle is determined by the camera angle, which must hence be adjustable
• The peak efficiency wavelength can be altered by adjusting the grating angle; this has secondary effects on the wavelength coverage and resolution

• In any given setup, the resolution is more strongly wavelength dependent than for reflection gratings

Since there is an extra degree of freedom over reflection gratings, great care is needed in setting up the observations in the most efficient way. To help with this, a grating calculator† has been provided. All transmission gratings used in Littrow mode suffer from a 0\textsuperscript{th} order ghost image of the slit, caused by dispersed light reflected off the CCD, recollimated by the camera optics, diffracted in 1\textsuperscript{st} order mode back into an undispersed beam, and reimaged onto the camera. The ghost typically amounts to a few percent in intensity compared with the actual spectra. This ghost can be moved off the detector by tilting the grating, and hence breaking the Littrow symmetry, and most of the AAOmega gratings have their internal refractive index fringes slanted (like a Venetian blind) to allow this symmetry breaking without damaging the efficiency characteristics.

3.4. Sky subtraction modes

The single greatest limitation for fibre-fed spectroscopic data is accurate sky subtraction. For precision stellar work, accurate subtraction of the solar spectrum is essential; for faint object red spectroscopy, a forest of OH telluric skylines dominates the sky spectrum and must be subtracted precisely. AAOmega offers a variety of methods for sky subtraction, offering a trade off between this systematic noise vs statistical noise and number of targets that can be observed.

The most common mode is sky subtraction with dedicated sky fibres. In this mode, a fraction of the fibres are allocated to sky positions, and their outputs median combined to form a single, high S/N sky spectrum, which is then scaled and subtracted from each object spectrum. The most efficient number of sky fibres to use in terms of maximising the combined S/N of all object spectra, for sky limited observations, is $N_{\text{sky}} = 1.25 \sqrt{N_{\text{fibres}}}$

The matching of sky to object spectra can be done either from the median strength of strong sky emission lines, or from separate offset sky or twilight sky frames. Overall, we are aiming for 1\% precision for the sky subtraction in this mode, which matches the Poisson noise in the strongest sky lines for exposures of about an hour. This is achieved routinely but not yet consistently, due to residual PSF variations and spectrophotometric errors. Sky subtraction accuracy, using dedicated sky fibres, is demonstrated in figures 3 and 4.

For observations requiring more accurate sky subtraction, we use Nod&Shuffle (N&S) sky subtraction\cite{5}. In this mode, the telescope is nodded between targets and sky, on a \sim 1 minute timescale; simultaneously, the spectra are charge-shuffled up and down the detector, so as to build up separate sky and object spectra. In this way, we observe the sky through exactly the same fibres and over the same timescale as the objects.

The simplest variant of this mode is called mini-shuffling; in this mode, spectra are shuffled a few pixels, to produce minimally resolved sky and object spectra. This allows all fibres to be used, and tests suggest a sky subtraction accuracy of 0.3\% can be achieved. However, there is a throughput hit of a factor 2 compared with dedicated sky fibres, because of the extra sky noise and reduced time on target. Mini-shuffling has not yet been fully commissioned.

Classic N&S involves using only half the fibres, and shuffling into the vacated spaces on the detector. Sky subtraction is good to at least the 0.1\% level; the achievable level has never yet been tested, since even multi-night observations are now Poisson-limited in their sky-subtraction.

Nod&Shuffle can be combined with Cross-Beam Switching (CBS), where two fibres are allocated to each source, with fixed physical separation; the telescope is nodded back and forth to put the light down each set of fibres in turn. This again halves the number of objects that can be observed, but ensures that each is observed continuously.

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†http://www.aao.gov.au/cgi-bin/aaomega_calc.cgi
Figure 3. This 2hour ($4 \times 1800$ sec) raw AAOmega frame shows the full 2D CCD frame containing the 392 science fibre spectra. Dispersion runs left to right in the low resolution red ($\lambda_{cen}=7250\,\text{Å}, R\sim1300$) unextracted spectra. Note the spectral curvature in the unsubtracted sky emission lines.

4. EXAMPLE PROPOSED LARGE SCIENCE PROGRAMS

AAOmega, with both its MOS and SPIRAL feeds, is in high demand as a general user facility at the AAT, accounting for $\sim67\%$ of the requested time in Semester 2006B (the second in which it was offered, and the first proposal round after first light). However, perhaps the best way to showcase the capabilities of AAOmega is to examine a subsection of the application for large programs which it has engendered. What follows is a brief, and incomplete, summary of some such projects with which the instrument team has some familiarity. At the time of writing (April-May 2006) the decision of the time assignment committee as to which programs to undertake, was still pending.

4.1. Dark Energy experiments

Since being declared by much of the popular scientific press as one of the most important scientific questions of the new millennium many different strategies have been proposed to determine the nature of the Dark Energy. The success of the Baryon Oscillations measurements, independently determined by the 2dF Galaxy Redshift Survey (2dFGRS\cite{7,8}) and the SDSS Luminous Red Galaxy program (LRG\cite{9}) has naturally given voice to the possibility of using AAOmega to make the next step in such measurements. Measuring baryon oscillations at a higher redshift than current detections provides a lever arm with which to constrain the evolution of dark energy. Two such programs currently under consideration by AATAC, both of which promise their first results constraining dark energy on the 2-3year time frame, are:

“WiggleZ” - Drinkwater et al.

“The AAOmega Luminous Red Galaxy Redshift Survey” - Croom et al..

While both surveys target galaxies over the redshift range $0.5<z<0.9$, AAOmega-LRG will target luminous
red galaxies in the same manner as the previous SDSS-LRG and 2SLAQ surveys, relying on the many continuum features and breaks in LRG spectra to determine a redshift, while WiggleZ will use a low redshift implementation of the Lyman break selection technique\cite{10}, using imaging data in the UV from the orbiting GALEX satellite mission, to select emission line galaxies. WiggleZ is a high target density, small area study, while AAOmega-LRG would cover 4,500 deg$^2$, using the ESO VST-ATLAS survey (Shanks et al.) as its primary input catalogue.

For success, both programs require the high sensitivity available with AAOmega, particularly in the redder wavelengths, and 1% sky subtraction. Both will require around 150-250 nights of telescope time over the next 3-4 years to achieve their goals.

4.2. Stellar surveys

While many highly successful stellar population and radial velocity studies were undertaken with the 2dF system, the improved stability and higher resolution offered by AAOmega have generated a number of exciting proposals for galactic or galaxy structure astronomy.

The AAOmagellanic project (van Loon et al.) aims to “provide radial velocities and abundance estimates for 300,000 stars, sampling all structural, kinematical, chronological and chemical stellar populations in both Magellanic Clouds and the Magellanic Bridge.”

The ARGUS project (Lewis et al.) proposes “a comprehensive investigation of the fossil evidence of the processes shaping our Milky Way Galaxy that is unprecedented in its scope. The Galactic survey will determine the kinematics and chemical compositions of some 250,000 stars located in the bulge/central bar, inner disk/spiral arms and outer thin/thick disks. This near-field cosmology approach will enable a large number of outstanding fundamental issues in galaxy evolution to be addressed”
AAOmega was first offered to the community for semester 2006A and began routine operations in February 2006. While for the most part commissioning was smooth and uneventful, culminating in eight nights of high quality Science Verification (SV) data, a number of outstanding issues and lessons learned remain to be addressed.

5. PERFORMANCE AND USE

5.1. Overall instrument performance

Commissioning observations indicate that the red arm is currently performing at 75% of the expected sensitivity (21% peak efficiency). At time of writing, the blue arm however appears to only achieve 50% of expectations (16% peak efficiency). It is believed that a ~20% sensitivity gain will be achieved by correcting the known outstanding issues outlined below.

5.2. Fibre positioning and seeing quality

The sensitivity estimates for AAOmega are based on the premise that light from a source can be accurately coupled to each science fibre. The effects of systematic and random error in the field acquisition process are considered in detail elsewhere\cite{11}. Any measure of the performance of AAOmega must factor in the effects of fibre misplacement, either directly attributable to the positioner accuracy (current positioner tolerance is <20µm, <0.3 arcsec), or indirectly via errors in the target astrometry or the sky-to-field-plate astrometric transform. During AAOmega commissioning it has been confirmed that the current 2dF implementation of this astrometric transform is inaccurate due to mechanical deformation of the gripper gantry at the 50-100µm level. Indirect mapping of transformation of each field plate to 2dF positioner internal X/Y positions is to be undertaken. The mapping will utilise a high accuracy illuminated graticule to derive the transformation. The graticule will be milled with a regular grid of back illuminated fiducial holes, at a 20mm pitch, to allow an accurate survey of the gripper gantry deformation.

5.3. Grating characterisation

The VPH grating set, detailed in table\ref{2}, delivered by Ralcon Development Lab, has proved to be of a high quality. However, the fabrication process means that each grating does depart somewhat from its initial specification (in both blaze angle and number of lines per millimetre). A full calibration of each grating is required as each is brought into use. This process is currently 60% complete.

5.4. Pupil misalignment

On integration of the spectrograph and the 2dF positioner, Hartmann shutter focus tests readily demonstrated a minor spectrograph pupil misalignment. Investigations have traced the problem to an unforeseen foible of the manufacturing process for the sub slits that comprise the individual elements of the full AAOmega slit. The support mechanism used to hold the fibres in place within each slit-let, as they are glued into place, has resulted in a depression of the fibres at the end of each slit-let and hence has introduced an error in the launch angle of light from the polished fibres ends.

The medium term solution is a re-shimming of each slit-let installed in the slit to correct the launch angle. Longer term solutions include adjusting the slit unit field lens to steer the beam, or simply re-terminating the 90 slit-lets that comprise the full AAOmega system. Slanting the slit vain is undesirable due to the increased vignetting this would introduce.

5.5. Blackening of the slit unit faces

An unfortunate side effect of the polishing process required to prepare the slit units is that each slit-let is left with a highly reflective polished metal surface in the beam and only ~10s of microns below the science fibre exit faces. These surfaces can give rise to back reflections and scattered light. The effect is most noticeable in arc frames, due to their high contrast data, and is a low level effect. However, to retain the high fidelity of AAOmega data the front of each slit unit will be blackened to suppress reflections.
Table 2. AAOmega grating choices. To aid the astronomer not familiar with the operation of VPH gratings, a grating calculators has been made available on-line: [http://www.aao.gov.au/cgi-bin/aaomega_calc.cgi](http://www.aao.gov.au/cgi-bin/aaomega_calc.cgi)

| Grating      | Blaze (nm) | Useful range (nm) | Coverage (nm) | Angle (Degrees) | Dispersion (nm/pix) | MOS Resolution |
|--------------|------------|-------------------|---------------|----------------|---------------------|----------------|
| 580V         | 450        | 370–580           | 210           | 8              | 0.1                 | 1300           |
| 385R         | 700        | 560–880           | 320           | 8              | 0.16                | 1300           |
| 1700B        | 400        | 370–450           | 65            | 18             | 0.033               | 3500           |
| 1500V        | 475        | 425–600           | 75            | 20–25          | 0.037               | 3700           |
| 1000R        | 675        | 550–800           | 110           | 18–22.5        | 0.057               | 3400           |
| 1000I        | 875        | 800–950           | 110           | 22.5–25        | 0.057               | 4400           |
| 3200B        | 400        | 360–450           | 25            | 37.5–45        | 0.014               | 8000           |
| 2500V        | 500        | 450–580           | 35            | 37.5–45        | 0.018               | 8000           |
| 2000R        | 650        | 580–725           | 45            | 37.5–45        | 0.023               | 8000           |
| 1700I        | 860        | 725–900           | 50            | 37.5–45        | 0.028               | 8000           |
| 1700D        | 860        | 845–870           | 40            | 47             | 0.024               | 10000          |

† The useful wavelength range for the gratings, in particular for the high-res gratings, is larger than the detector width (2K in the dispersion axis). Hence the spectrograph set-up must be tuned to the required wavelength and Blaze.

‡ IFU resolution is somewhat higher, due to the smaller projected fibre diameter

* The 1700D Ca iii grating is a tuned to give maximum performance at 860nm but is unsuitable for observations at other angles.

5.6. Light inside AAOmega

An unfortunate side effect of the ready availability of small, cheap, low power light sources, in a bewildering array of colours, means it now proves virtually impossible to source electronic equipment without status indicator lights. Ensuring that such illumination is bypassed, deactivated or otherwise extinguished has required considerable effort. Limit and proximity switches are noted as the worst offenders. We also require that all optical encoders are deactivated, all encoded motorised actuators de-energised and all pneumatic valve state indicators are suitably light sealed during observations.

That this is essential becomes obvious when one realises that these systems are no longer just inside the dome but actually inside one’s spectrograph! AAOmega has been designed from the start with this in mind, but a consequence of the excellent scattered light suppression, and high sensitivity, is that every last light leak must ultimately be tracked down and eliminated.

5.7. Fringing

At intervals during its working life a varying level of fringing fibres was seen in 2dF observations. These interference fringes were attributed to fractures within fibres, which resulted in air-gaps akin to micro etalons. Fringing occurred in two flavours, a stable mode which could be removed via a flat field, and an unstable mode which could not. Typically unstable fringing indicated a fibre which would soon break or a fibre button which was about to shed its prism. Despite efforts to avoid the recurrence of fringing in AAOmega fibres, a substantial number of AAOmega fibres currently exhibit unstable fringing. Detailed analysis shows that the fringing stabilises with time but instability is provoked by positioning the damaged fibres. A detailed investigation of the characteristics of the fringing suggests that the fracture resides between the front face of the prism at prime focus and the anchor point for the fibre at the bottom of its 2dF retractor and not within the body of the 38m fibre cable, or within AAOmega.

At this time it is believed that the root cause of the fibre fracturing, which appeared mostly between December 2005 and January 2006 during an extreme heat wave, and which has been observed to be stable since mid January 2006, is differential expansion of the steel ferrule and the fibre at the fibre button, which has introduced an air
gap between prism and fibre while still leaving the prism securely attached to its ferrule. Further investigation is under way but if confirmed, the correct solution is the relatively simple task of re-terminating the affected fibres, an operation which would be performed as a matter of course during the life of AAOmega to repair the occasional damaged fibre.

5.8. Blue arm sensitivity
The reason for the reduced sensitivity of the blue arm (currently running at \( \sim 50\% \)) is unclear. Correction of the minor problems listed in this section will account for a 10-20% gain. Further investigations are under way at this time to determine the source of the efficiency loss. Likely culprits are an incorrect coating on an optical surface, poor CCD sensitivity or poor dichroic performance on reflection.

5.9. Arc lamp calibration system
The current calibration system is based on the original 2dF system, whereby the observing field plate is illuminated by arc and flat lamps mounted in the top end chimney via two deployable flaps which are placed into the top end beam. This system allows wavelength calibration from a combination of FeAr, CuAr, ThAr and CuNe hollow cathode lamps. Results are currently measured to better than a tenth of a pixel. Detailed investigations show that this limit to the calibration accuracy, which impacts strongly on the accuracy of sky subtraction when using dedicated sky fibres (see section 5.4), is governed primarily by the difference in f-ratio between the arc lamp illumination and science observations. This issue was suspected with the 2dF system but was not a measurable defect until the advent of AAOmega. A program to implement an upgraded calibration system, whereby the telescope pupil is point sampled with arc light, probably by a fibre fed system, is under way. Observations at redder wavelengths, where sufficient night sky OH air-glow lines are found (such as the Calcium Triplet region typically used to study stellar radial velocities) are not degraded by the use of the current system since the OH lines are used as a secondary calibrator during data reduction.

5.10. Point Spread Function variations
Variations in the full field Point Spread Function (PSF) contribute enormously to poor sky subtraction and were a significant defect in the 2dF spectrograph system. From the start AAOmega has been designed around achieving a stable PSF as a function of wavelength. The observed instrument PSF is found to be surprisingly Gaussian in character. Full Width Half Maximum (FWHM) varies slightly with wavelength, as expected, and from grating to grating (due to variations in grating character) but is satisfactory and stable at \( \sim 3.4 \) pixels. This quality PSF is a key factor in achieving the 1% sky subtraction often seen in AAOmega data to date. Instabilities occasionally seen in the quality of sky subtraction may be due to subtle departures from a uniform PSF across the entire CCD field, and may require a PSF matching routine to achieve AAOmega’s ultimate sky subtraction performance, a task that is made significantly easier from a high quality starting point.

5.11. Camera frosting
Frosting has been observed on the coldest surfaces (including the field flatteners). This is due to “moisture” adsorbed on the large surface area of internal surfaces during camera fabrication. When the cameras are evacuated and cooled this slowly migrates to the coldest surfaces and forms the observed frost. This frosting has been dropping with time, with the aid of a regime of dry nitrogen purging and thermally cycling, and is now minimal. The level will be monitored over the coming months to assess the ultimate level that will be achievable.

6. FIELD PREPARATION AND DATA REDUCTION
An essential part of the instrument is comprehensive software for preparing fields and reducing data. The 2dF field configuration software package has been updated to cater for AAOmega, and a new version is being tested which uses simulated annealing\(^{12,13}\) to find the most efficient allocation of fibres to targets.

The 2dFDR data reduction package has been comprehensively overhauled, with many improvements and new features added:
• A secondary wavelength calibration off sky lines in the extracted spectra is now implemented; this greatly improves both sky subtraction and radial velocity precision

• Tramline fitting and spectrum identification is now fully automated using pattern matching based on the eight missing spectra where the guide fibres would be

• Splicing of low dispersion red and blue spectra is now incorporated

• The software now works on fits files without conversion to ndf format

• Data for partially overlapping fields can now be seamlessly combined on an object-by-object basis

Further improvements are scheduled, including crude spectrophotometric calibration from flux standards and improved self-consistent scattered light subtraction.

7. FUTURE DEVELOPMENTS

AAOmega began routine operations in February 2006. A small number of outstanding sub-systems still require integration and a short program of simple upgrades, suggested during commissioning, will be undertaken over the next six months with the goal of recovering the full AAOmega design specification. In the longer term the AAO is currently considering the upgrade path for AAOmega. The success of the 2dF system and the broad utility of the AAOmega design suggests the possibility of an infrared upgrade to AAOmega. The proposed project, AAOmicron, is currently in the early stages of specification, with the intention to move to a full feasibility study in the later half of 2006. AAOmicron would reuse the 2dF wide field corrector and ADC (providing close to the full 2 degree field of view) and AAOmega fibre runs, all of which have been fortuitously constructed from materials which allow operation in the $ZJ$ and $H$ IR bands. AAOmicron would operate at wavelengths short of 1.8$\mu$m due to the emissivity of the AAOmega fibres at longer wavelengths. A simplified, unarticulated copy of the AAOmega collimator and camera system would be placed inside a -50$^\circ$ cold room to suppress thermal background. The use of a Rockwell Hawaii2 IR array, preferably using the new $K$ blind technology making the chip insensitive to thermal emission longward of 1.7-1.8$\mu$m would allow the camera to operate at higher temperature than typical for a $K$ band system, and allow between 100-200 AAOmega fibres to be projected onto the detector at one time using an only slightly modified AAOmega camera design. With a field of view $\times 16$ that of the Subaru-FMOS system, and a fibre aperture more closely matched to the typical scale length of redshift $z<1.0$ galaxies, the AAOmicron system would represent an interesting complement to currently available IR spectroscopy facilities, and would be the survey instrument of choice in a number of fields.

The AAOmicron will be presented to the Australian community for consideration in May 2006 and, if supported, will proceed to the design study phase in the second half of 2006. It is envisaged that AAOmicron could be in operation by late 2010.

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