ECHIDNA - a novel multi-fibre feed for astronomical spectroscopy

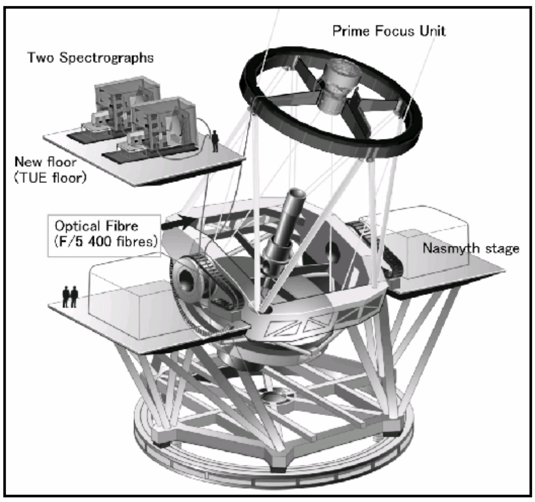
Introduction

In optical astronomy, an extremely powerful, heavily used technique is to analyse the light from stars by splitting it according to its colour (i.e. its wavelength) in a spectrograph. The strip above shows just a small fraction of the visible spectrum from our nearest star, the Sun. The dark lines are due to light at particular wavelengths being absorbed by atoms of gases in the cooler outer layers of the Sun. Traditionally, only one star at a time could be studied in this way, with its image focussed by the telescope onto the entry slit of the spectrograph. A few decades ago, new techniques were devised to increase efficiency by feeding light simultaneously from many celestial objects into the spectrograph. The method which allows the greatest multiplicity uses optical fibres to connect the telescope to the slit of the spectrograph. This requires that the feeds to the fibres be very accurately located in the telescope focal plane to align them with the many objects of interest.

The Anglo-Australian Observatory (AAO) has led in the world-wide development of fibre feeds, firstly for its own 4 metre diameter Anglo-Australian Telescope (AAT) and 1.2 metre UK Schmidt Telescope and more recently for major foreign observatories. The application with the greatest number of fibres has been the 2dF (for 2 degree field) instrument on the AAT, which uses a special robot to place 400 magnetic buttons on a steel plate at the focus of the telescope. Each button has a tiny prism directing light into an optical fibre. The field within which the buttons can be placed is nearly 500 mm in diameter.

Impressed by the AAO's success in building and exploiting 2dF, the Japanese Subaru Observatory requested that the AAO design a 400 object multi-fibre feed for near infrared spectroscopy on their 8.2 metre telescope in Hawaii. This was to be the most innovative and challenging component of the new FMOS (Fibre Multi-Object Spectrograph) instrument. FMOS has been designed and built under an international collaboration, including Australia (AAO), the UK (Oxford and Durham Universities) and Japan (Subaru Observatory and Kyoto University).

Figure 1 is a view of the observatory enclosure near the summit of Mauna Kea, a 4300 m high dormant volcano. Figure 2 shows the telescope and figure 3 is a CAD model showing where the main components of FMOS will be positioned. The figures of two people standing on a Nasmyth platform of the telescope give an indication of the scale. The prime focus field on this telescope is only about 150 mm diameter. So the challenge was to devise a system that would serve as many fibre feeds as 2dF but in less than 1/10th the area. It was clear that shrinking the components used in 2dF was not practical so a new approach was required.



Figures 1, 2, 3. Japanese Subaru Telescope: enclosure; telescope; model, showing FMOS components. Echidna will be installed in the Prime Focus Unit.

Basic design of Echidna

An alternative that appeared attractive, but very challenging technically, was to have each fibre fed from a probe which could be independently driven anywhere within a circle centred on its home position. Such an approach would suit many important applications in which the objects are scattered randomly over the field. For 400 probes evenly spaced within the field, the separation between neighbours' home positions is 7 mm. If each probe can be placed anywhere within a circle with a radius of 7 mm, about 85% of 400 astronomical targets randomly scattered within the field can be served by a probe. The remaining 15% of fibres would not be wasted, since measurements on empty sky are required for data analysis. Figure 4 shows the results of allocating fibres to such a randomly scattered set of targets.

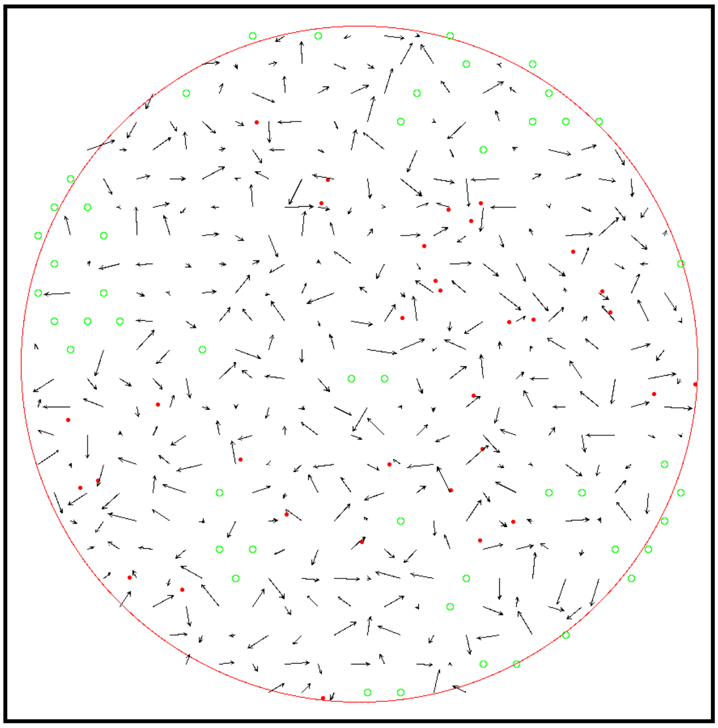


Figure 4 Example of allocation of fibres to 400 targets randomly scattered in the circular field. Targets not reached are shown as red dots; fibres which could not be allocated are shown by green circles at their home positions. Successful fibre allocations are represented by arrows with their tails at home positions and points at the target positions.

Each fibre core (the part of the fibre that transmits light) was to be 100 μm diameter. So, if the collection efficiency was not to suffer, each fibre feed had to be positioned within about 10 μm of its ideal position. Complex concepts, in which each probe was articulated and driven with two rotary motors, were considered but sufficiently small motors with the required precision could not be identified and wiring for their control would have been very problematic.

Fortunately, it was soon realised that, with the relatively fast focal ratio (~ f/2) at the Subaru prime focus, it would be acceptable to make each probe as a cantilevered spine, pivoting in two coordinates around a centre. With 7 mm radial range, a spine 160 mm long would have a maximum tilt of about 2.5° and the inefficiency through its misalignment with the telescope optics would be acceptable. Once the design effort was concentrated on such spines and their drives, the instrument was given the name Echidna.

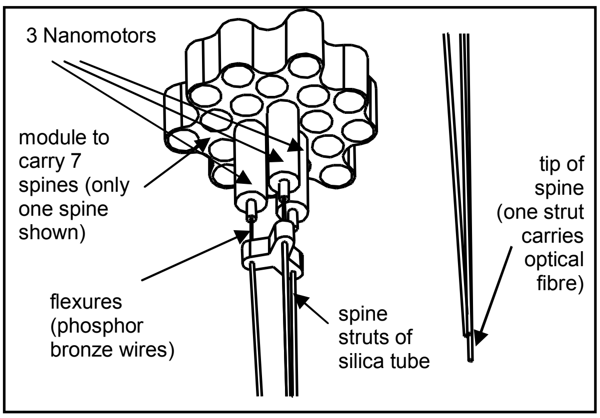


Figure 5. Arrangement of spine drive with Nanomotors.

Development of spine drive concepts

With three Nanomotors

The first successful concept for driving spines used three axial drive motors (Nanomotors, from the German firm Klocke Nanotechnik) for each spine, as illustrated in figure 5. Each motor had an outside diameter of 3.3 mm and could drive its spindle in steps as small as 10 nm over a few mm. The motors were connected with thin wire flexures to a base which carried a tripod made from silica tubes. By driving the three motors, the apex of the tripod could be positioned with a resolution of ~ 1μm through the required radial range of up to 7 mm. However, the Nanomotors were not entirely reliable when the highest drive force was required – to tilt the tripod upwards against gravity. Also, the cost of the 1200 motors needed would have been very high.

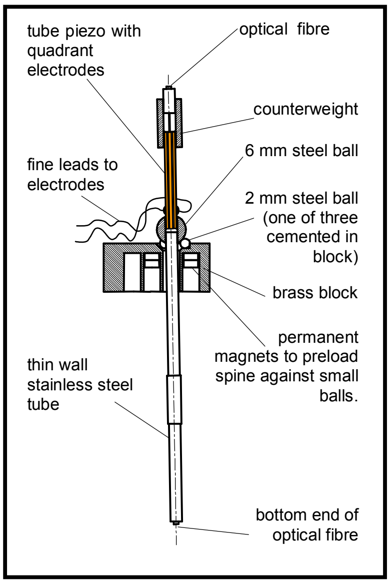


Figure 6. Ball spine layout.

The ball spine concept

A new concept was developed from an idea proffered by David Henderson of the US firm Burleigh Instruments Inc. Figure 6 illustrates its main features. This drive had the advantage that the tilting spine could be balanced, with its centre of gravity at the centre of the ball, so that it was more tolerant of the attitude at which it had to be driven. (It will save time to re-configure the array of spines without returning the telescope to a particular attitude.) The piezo was fed with a sawtooth waveform voltage, promoting angular stepping of the spine. A few prototype models using this drive principle were made. Appropriate accuracy, stability, and range of movement were demonstrated but there were practical difficulties in making electrical connections to the electrodes on the tilting piezos and the assembly of all 400 such drives would have been hard to service.

Ball spine with fixed piezo

Anna Moore, then Project Scientist for Echidna at the AAO, had the insight which led to a more practical arrangement, much better suited to the dense array of spines that was needed. The piezo tube was fixed at its base and the ball of the spine supported at three points at the top of the piezo tube. The principle of operation is illustrated in figure 7. Now there was no need to make the electrical connections to the piezos with extremely small diameter flexible wires and a spine could be readily withdrawn from its piezo drive if necessary for service.

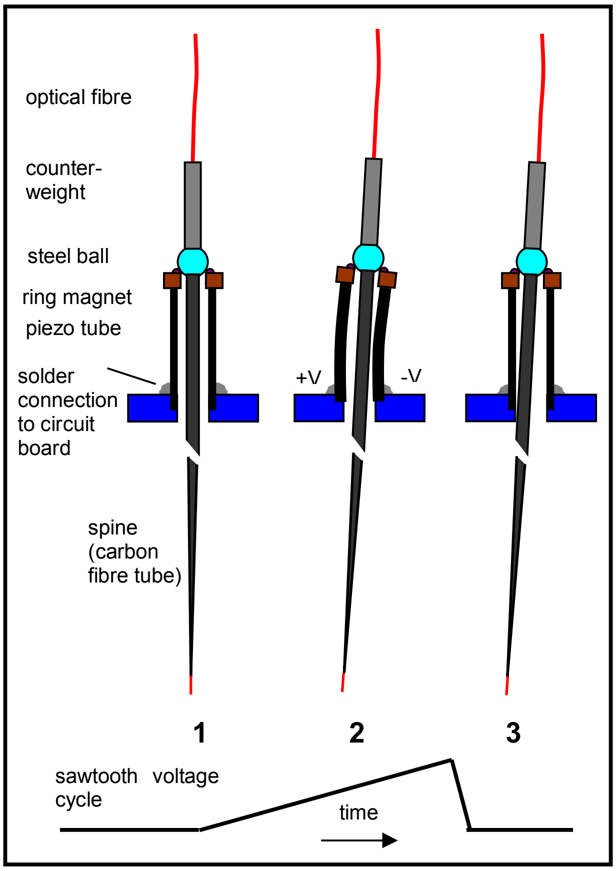


Figure 7. Principle of spine drive with fixed piezo. A voltage is applied across the opposite electrodes of the piezo tube. The voltage increases then quickly drops to zero. The tube bends, tilting the spine, then when the voltage falls to zero, the steel ball slips on its contacts, leaving a net spine tilt (greatly exaggerated in this illustration).

Details of spine drive

Figure 8 shows the components of a spine and its drive. The quadrant tube piezo actuator has four external electrodes. When a voltage is applied across opposite electrodes, the tube bends. When the voltage goes through a cycle like that illustrated in figure 7, the spine is left with a small incremental tilt and the spine tip is displaced a little laterally. Applying a voltage cycle to the other pair of electrodes results in the spine tip being displaced in the other coordinate direction

Figure 9 is a plot of the displacement v time derived from a high speed movie taken (courtesy of Vision Research Australia) of a spine tip being driven with a regular sequence of voltage cycles. The camera captured 10 000 frames/second while the voltage cycles were at 70Hz. The spine tip is seen to progress by about 4 pixels or 60 µm for each voltage cycle. Vibration at roughly 1000 Hz is also evident.

Spine tips can move through steps as small as a few µm and, with higher voltage swings, as large as about 60 µm.

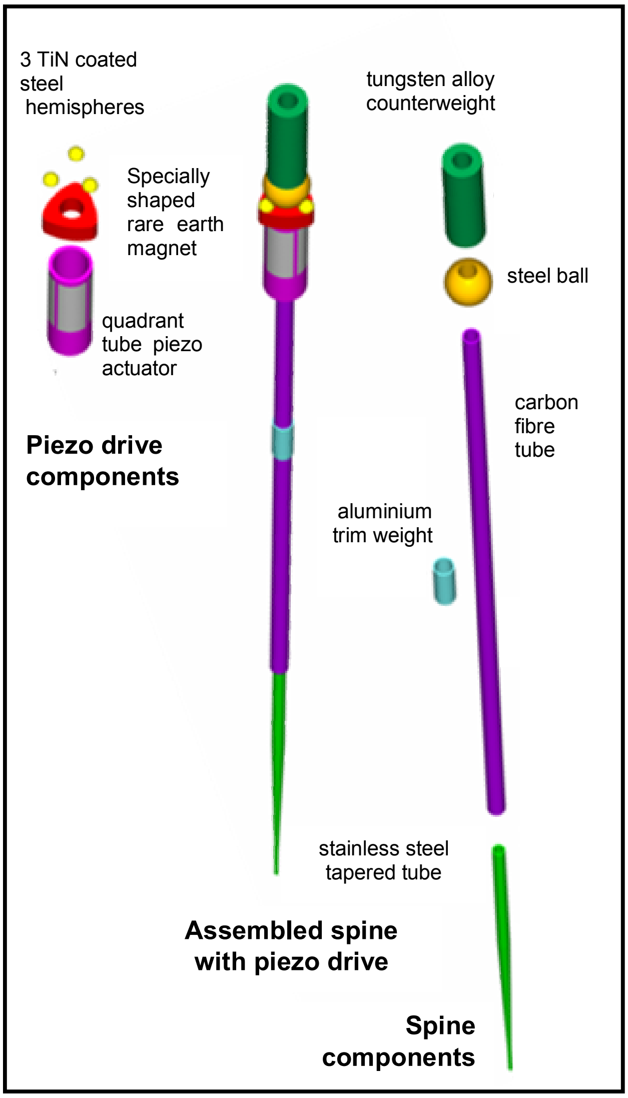


Figure 8. Components making up a spine.

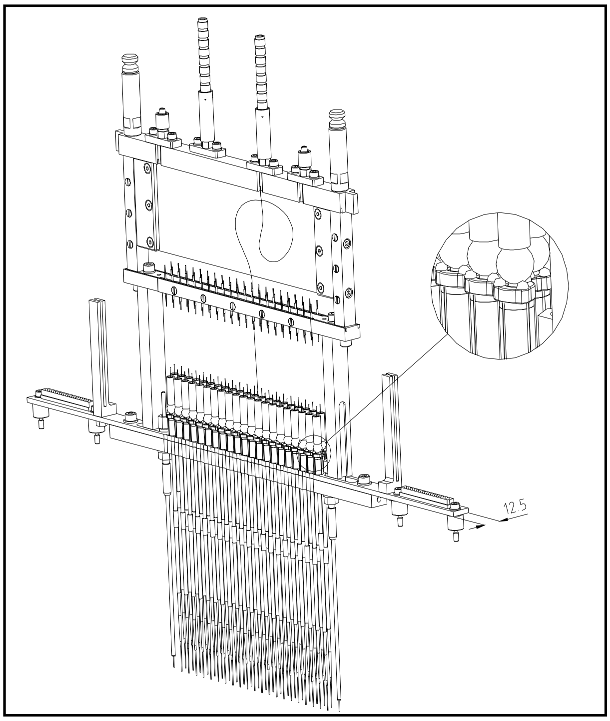
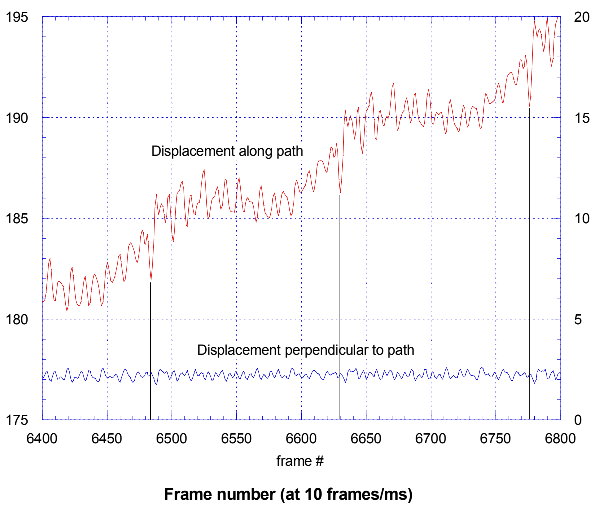


Figure 10. CAD model of an Echidna module with electronic switching boards not fitted and with only one fibre shown.

Below: Figure 11. View from below spine array with some modules fitted.



Left: Figure 9. Plot from fast CCD camera observing backlit spine tip at 10 000 frames/sec while it was driven with a 150 V sawtooth at 70 Hz.
Displacement units are pixels, each equivalent to 15µm at spine tip.

Arrangement of spines

For ease of assembly and maintenance, spines are mounted in interchangeable modules, each of which carries 40 science spines (i.e. spines for allocation to spectroscopic targets) in two rows. Twelve modules, closely packed together, make up the full set. 400 of the science spines have their home positions within or just outside the circular field (which covers 0.5º diameter on the sky – about the diameter of the moon). At each end of each module there is also one guide spine and one fiducial spine (which is not drivable). Figures 10 and 11 show modules and figure 17 shows the arrangement of science and guide spines.

Testing and calibration of spine drives

Due to manufacturing tolerances of the spines and piezo-mounts, each spine-piezo combination behaves slightly differently. To achieve optimal performance, the Instrument Control System (ICS) software maintains a calibration database for each spine. By recording previous behaviour, the database gives an improved prediction of the movement of a spine (based on its driving signal).

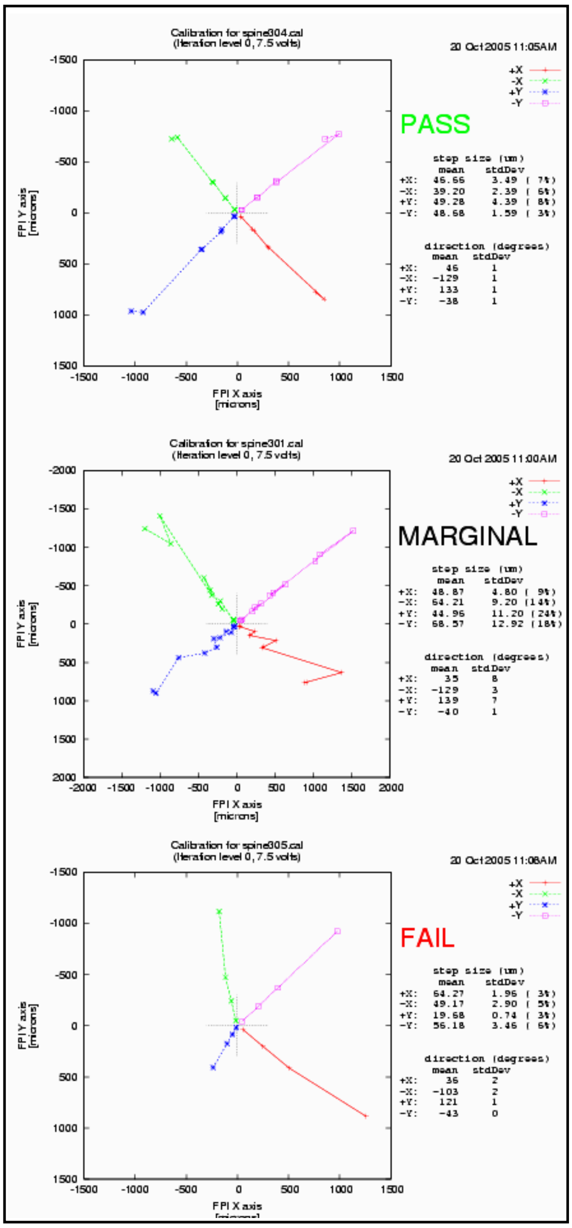


Figure 12. Plots produced by the spine testing and calibration routine. The size and consistency of steps and the consistency of their directions are measured and used to accept or reject the spine-piezo combination.

When a spine is first inserted into a mount it is calibrated. This involves moving the spines a fixed number of steps in each of the four coordinate directions and measuring the offset of each move. The results are then stored in the database.

After performing an initial spine calibration test, the ICS utilises the spine calibration database during field configurations to estimate the ideal direction and number of steps to drive each spine. Information about the resulting move is also fed back into the database, to ensure it is kept as accurate as possible.

It is possible to graphically view the calibration database for a spine - a useful check of the behaviour and history of individual spines. See figure 12.

Electronics for spine drive

All spines are driven in parallel to minimise the time taken for a re-configuration. To drive each spine the required distance in each coordinate, the computer-controlled electronics employ switches specific to each spine, which terminate the train of sawtooth voltage pulses after the appropriate number of steps.

The drive electronics were designed and built in house. The requirements of compactness, low cost and minimal cabling were addressed by an architecture based on two pairs of inverting and non inverting high voltage amplifiers. Their drive outputs are distributed to the piezo tubes' electrodes by switch cards that plug directly into the ends of the module PCBs. In order to reduce the cabling, the digital control signals to the switch cards are multiplexed. The switch cards carry demultiplexors and the solid state relay switches that distribute the drive signals to the desired electrodes.

The challenge of making 86 connections to the electrodes of the piezo tubes on each module that could handle 300 volts peak to peak in the very constrained space envelope was solved with the design of a 23 layer PCB. Very high dimensional accuracy requirements were met in close cooperation with a local PCB manufacturer, Artronic Productions. The module PCB is divided in half electrically so that a switch card can plug in to each end, otherwise connections would not have been possible in the very limited space. Figure 13 shows the switching circuit boards attached to spine modules (when only three modules were installed)

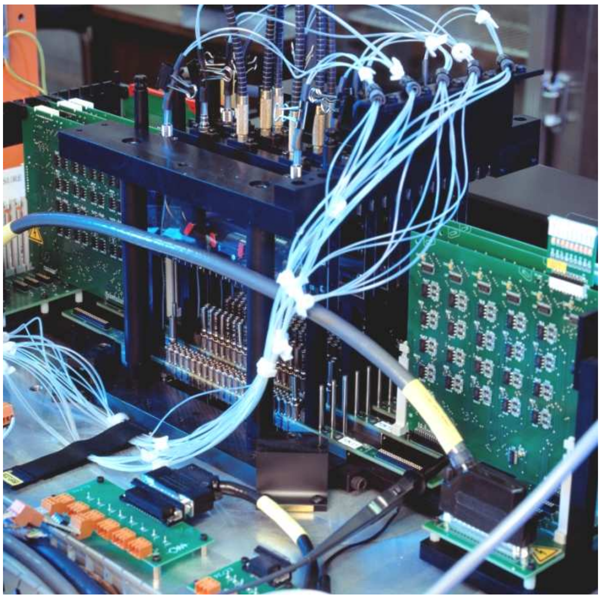


Figure 13. Echidna partly assembled showing (vertical) circuit boards for switching spine drives.

Making the connections from the module PCB to the piezo tube electrodes required fine tuning of soldering techniques and adaption of tooling to make reliable solder joints while avoiding the risk of de-poling the piezos through overheating.

Focal plane imager (FPI)

The average step size for each spine tip is not predictable with sufficient accuracy to complete the moves from one configuration to the next with a single sequence of steps. So a device termed the focal plane imager, comprising a CCD camera carried on an X-Y positioner, is used to measure all the spine tip positions and allow calculations of the next moves. The camera uses a telecentric lens giving about 3x reduction onto the CCD. Telecentricity confers the benefit that the scale in the image plane does not change if the focus changes. The lens has considerable radial distortion but this is stable and is calibrated to give an accuracy in measurements of spine tip positions of better than 2 µm rms. The optical fibres are backlit with LEDs during re-configuration.

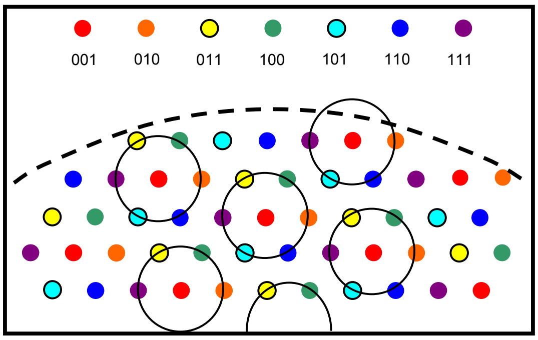


Figure 14. Binary encoding of sequence of three LED flashes when back-lighting fibres. This encoding allows unambiguous discrim-ination between spine tips whose ranges (indicated for the red encoding by the circles) overlap.

To allow discrimination between neighbouring spines whose ranges overlap, the backlighting is encoded. Three CCD exposures, closely spaced in time, are made for each measurement; this allows binary coding to be applied with 7 different codes 001, 010, 011, 100, 101, 110, and 111, where 1 represents the backlighting LED lit and 0 represents it off. Figure 14 illustrates this scheme.

Several iterations are needed to get all spine tips to the required positions, with radial errors measured as 8 µm or less. With allowance for the measuring errors, the radial errors then range up to about 10 µm. The time to complete a re-configuration averages approximately 10 minutes.

The X and Y stages of the FPI motion are both driven with ball screws and servo motors combined with high resolution resolvers. The resolvers are used to control the servo motions, giving tight feedback and allowing fast response, but having significant errors because of compliance and hysteresis between the motor/resolver and the carriage. Linear optical encoders with 0.5 µm resolution are used directly on each axis for determining the carriage positions at the instants that CCD exposures are taken. Figure 15 shows the FPI in relation to the spine array. Figure 16 is a plot of the FPI Y carriage velocity compared with the velocity demand, during a move from one measuring position to the next, showing that it was completed in about 0.35 second. There is scope for further reduction of the configuration time with more servo tuning.

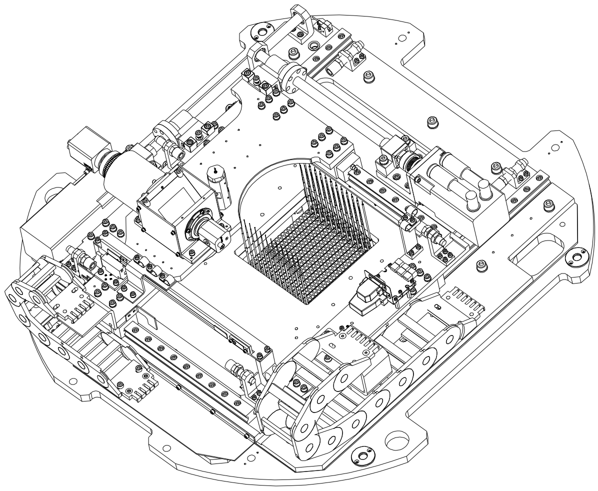


Figure 15. CAD model of Echidna assembly, inverted from normal to show FPI. Science spines are not shown, only fiducial spines.

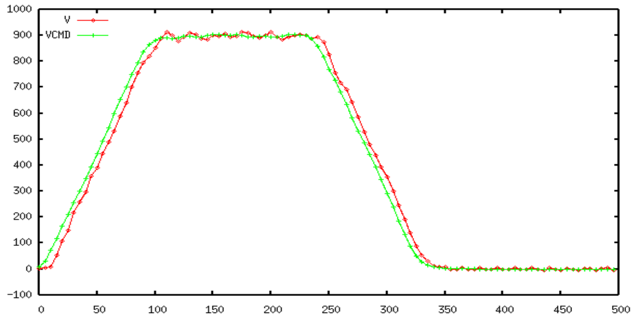


Figure 16. Plot of demand velocity and measured velocity for a typical move of the Y carriage between two measuring points. Time scale is milliseconds.

Strategy for reconfiguration

When the spine array is to be changed from one configuration to the next, the first stage is to return all spines to their home positions (with a relaxed tolerance, compared with that applied for aligning with target positions). These moves and all subsequent moves are made in one coordinate, X or Y, at a time. The return to home and the separation of X and Y moves minimises the risk that spines will interfere with each other as they move (remembering that the ranges of neighbouring spines have considerable overlap).

After each set of spine moves, the FPI follows a stepwise raster, dwelling to measure centroids at FPI coordinates which ensure that the rectangular fields of the CCD camera overlap and so allow measurement of all spine tip positions, with some tips measured twice and some four times. Comparison of the positions reported for a particular spine on the repeated measures gives a measure of the accuracies of the FPI positioning and of the CCD camera distortion calibration.

Iterations and re-measurements with the FPI continue until all spine tips are measured to be within 8 μm radially of their desired positions.

Software preparation for observing

An astronomer awarded observing time will prepare a computer file with data for setting up the Echidna configuration. Software has been developed to make this operation user-friendly. Figures 17 and 18 show the graphical user interface for this purpose. This allows the astronomer to oversee the allocation of the list of target objects (typically galaxies) to individual spines for each observation. The allocation software accepts as input a list of targets with associated sky coordinates, priority, magnitude, etc and outputs a file which specifies all of the necessary information required by Echidna to configure itself for the observation.

The primary task of this software is to optimise the allocation of targets to spines whilst obeying all physical constraints of the system. For example, the software must ensure that a particular allocation doesn't cause neighbouring spines to collide when being driven (in parallel) to their destinations, and there is a physical limit to how closely spines can be positioned relative to each other. There are also many other less-critical constraints that the allocation software tries to optimise. For example, the astronomer can specify a priority with each target, causing the software to preferentially allocate higher priority targets where possible. Figure 18 shows the display after the allocation process.

When the observation is about to begin, software allowances will be made for several factors which could not be predicted at the time of the fibre allocation. An example is allowing for the refraction due to the Earth's atmosphere; this depends on the pressure and temperature and, critically, on the range of telescope attitudes that will be required to follow the target field during the observation.

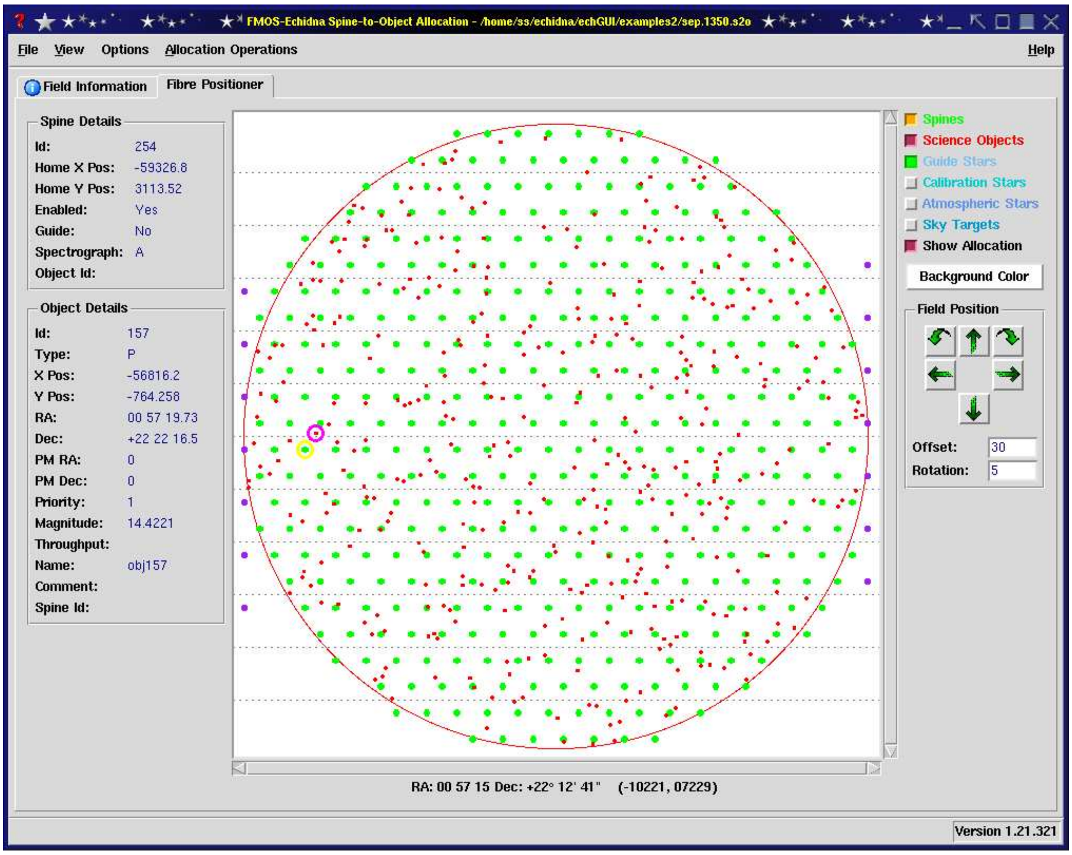


Figure 17. Screenshot from the FMOS-Echidna allocation software. This is responsible for allocating a list of target objects to individual spines for each observation. **Before allocation** Red dots are targets; green are spines at home positions. Violet are guide spines.

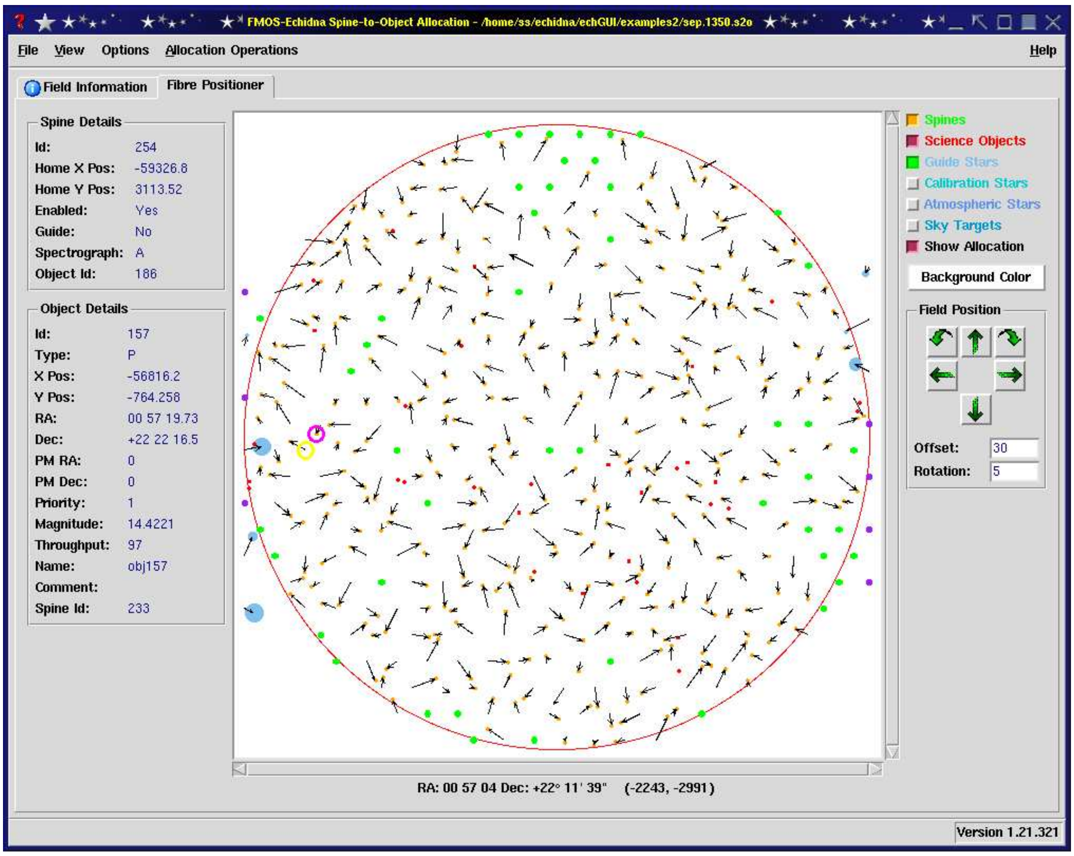


Figure 18. Screenshot from the FMOS-Echidna allocation software **after allocation**. Arrows point from a spine's home position to the target to which it is allocated. The same applies to the guide spines. Guide star brightnesses are indicated by the sizes of the blue circles. Green dots are unused spines; red dots are targets not served.

Control electronics overview

A significant challenge for the electronics was to fit all of the control electronics for Echidna, including a control computer, into a light tight enclosure that sits above the Echidna spine array. Furthermore, to keep costs down, as much use as possible was made of commercially sourced components. The control electronics uses a computer based on a PC architecture in an industrial format (PICMG). A single board computer running the Linux operating system plugs in to a passive backplane housed in an industrial PC chassis. The passive backplane architecture provides easy access to the single board computer, as well as the digital and analogue input/output interface, video frame grabber interface and sky camera interface boards. The computer controls the Echidna positioner, FPI, guide camera, and back illumination systems. For reasons of reliability and robustness the computer has no hard disk drive. Diskless operation is implemented by starting a network boot loader from a flash memory disk device. The network boot loader then uses TCP/IP protocols to start Linux from a server on the network. The system also employs a power control switch with an embedded web server which allows the computer to be remotely powered on or off..

Multiplexing is used in the back illumination systems to minimise cabling. The guide and fiducial back illumination system has a matrix of 48 LEDs driven directly by AAO designed and built electronics. Science fibre back illumination is driven by electronics supplied by Oxford University and controlled by AAO designed and built electronics. The Echidna electronics communicates with the science fibre back illumination drive system via a full duplex fibre optic serial link designed and built in house at the AAO.

The cooled enclosure also houses the control electronics and servo amplifiers for the FPI X and Y drives, back illumination control electronics, and the controller electronics for the cooled guide camera.

Light Contamination and temperature control

Light contamination of astronomical instruments must be avoided. So during the design phase, careful consideration was given to minimise or eliminate any emission sources in the visible and 900 – 1800 nm wavelength range. The computer and drive electronics are housed in a cooled enclosure mounted directly above the spines. The most critical function of the cooling is to maintain less than 1ºC temperature difference between the exterior of the enclosure and ambient air temperature, to minimise blurring of telescope images through the mixing of warm and cool air in the optical beam. The electronics enclosure contains the light from the numerous LEDs which are common in commercially sourced electronics.

Tests of FPI accuracy

A special graticule having 100 μm diameter holes etched through a metal coating on glass, at grid positions accurate to 1 μm, was manufactured for calibration and testing of the spine camera and FPI carriage motion. The graticule has a rectangular grid of holes on 20 mm pitch in x and y covering the full range of the FPI and a central grid at 2 mm pitch to cover the field viewed instantaneously by the spine camera.

Figure 19 shows an example of the residual errors after fitting lens distortion to measures using the fine grid; the maximum radial residual was 4.6 μm and the rms radial residual 1.75 μm. Figure 20 shows residual errors after measurement over the full FPI range; the maximum radial residual was 4.8 μm and the rms radial residual 2.2 μm. The tests of FPI accuracy were repeated for the instrument at a range of attitudes with good results.

Fitting the test graticule will not be feasible as a regular test when Echidna is installed on the telescope. To provide a check that the measurement accuracy is maintained, a fiducial spine has been fitted at each end of each module with provision for back-lighting. These spines are not driven and are designed for minimal flexure with changing telescope attitude. For tests made with zenith angles up to 60º, the positions of the fiducials as measured with the FPI differed from those measured at the zenith by up to only 1.9 μm rms. This confirmed that the fiducials will be satisfactory for their intended purpose.

Telescope guiding

Guiding corrections, needed to keep the telescope precisely tracking celestial objects as the Earth rotates, are normally provided by special cameras picking off part of the periphery of the field ahead of the focal plane. In using Echidna, because there will be some gravitational flexure of the spines, it was concluded that it would be best to build the guiding facility into the spine array. So at each end of each module there is a special drivable spine which carries a bundle of seven fibres rather than a single fibre. As the guide spine construction is identical to that of a science spine and the weights of the fibres are negligible in both cases, the flexure suffered by the spines (which is, in any case, small ~ 20 µm) will be automatically compensated through using these guide spines.

At the guide spine tip, the seven fibres, which have cores 50 µm diameter rather than 100 µm as in the science fibres, are closely packed into a hexagonal array. At the output from the guide bundle, the seven fibres are splayed out as illustrated in figure 21. This display is from the computer which analyses the signal from the high

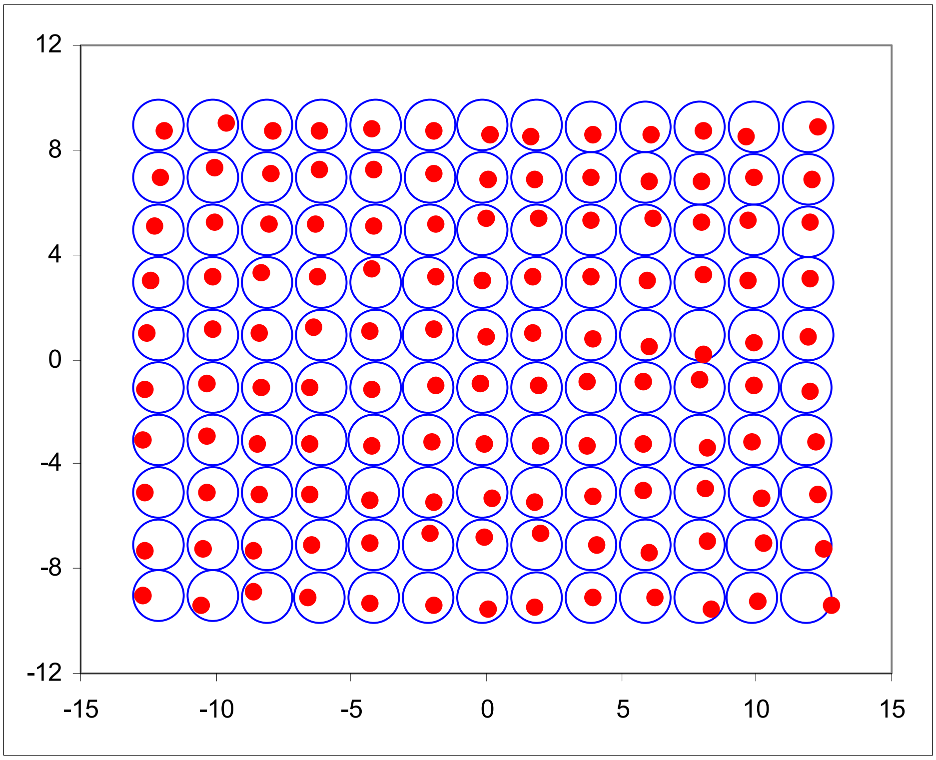


Figure 19. Residual errors after fitting distortion terms to measures of centroids on test graticule with spine camera. Circle centres are at nominal hole positions on a rectangular grid 24 x 18 mm.
Positions calculated from camera measures are shown as dots with errors magnified 200 x. Circle radii represent 5 µm error. Greatest radial error is 4.6 µm and rms radial error 1.75 µm.

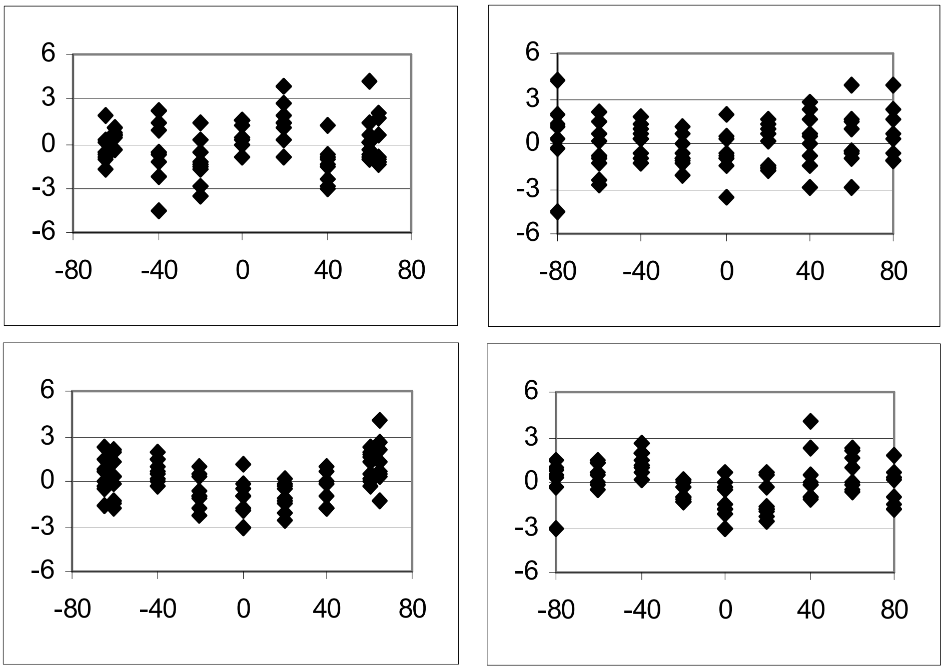


Figure 20 Residual errors after measuring graticule hole positions over the full travel of the FPI. Plots are of residual errors (µm) v position (mm) for
top: X errors
bottom: Y errors
left: as a function of X
right: as a function of Y

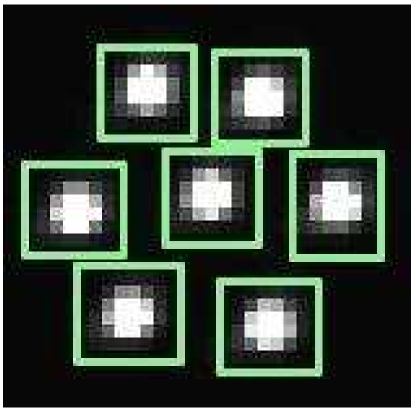


Figure 21. Computer display of images from output of guide fibre bundle.

sensitivity CCD, onto which 16 of these fibre bundle outputs are imaged. The lens for this re-imaging is a special Nikon 1:1 copying lens collecting and focussing f/2 beams.

The square boxes show the areas within which signal is integrated to determine the tracking error. For this exposure, the seven fibres were equally illuminated at their entrance. When used for guiding on a star, a large fraction of the light will be in the central box with small fractions in the outer six boxes. Asymmetry of light intensity between the outer boxes is used as a measure of tracking error.

Correcting lens ahead of Echidna

The field at the focus of the Subaru telescope primary mirror needs a lens near the focus (a "prime focus corrector") to give sharp star images over the full field. A lens with three glass elements, the largest being 600 mm in diameter, was designed by the AAO, initially in consultation with Damien Jones of Prime Optics, and manufactured by the firm KiwiStar in New Zealand. Figure 23 shows the cross section of the lens elements in an illustration of the arrangement for the final test of the lens. Figures 24 and 25 show the lens front element and the set up for the acceptance test and figure 26 shows the front of the lens protruding below the cylindrical structure (the "top end") which will carry Echidna. For this picture the top end was in its storage area in the telescope enclosure in Hawaii, removed from the telescope.

Spectrographs to be fed from Echidna

Two spectrographs, each accepting 200 fibres, have been built, one in the UK, one in Japan, to a near identical design. They will analyse radiation in the wavelength range 900 to 1800 nm (i.e. in the near infrared) and will incorporate means for minimising the interference from radiation in the Earth's atmosphere. One is installed in the telescope enclosure and the second is to be installed later this year. Figure 3 indicated where they will be mounted.

Project management

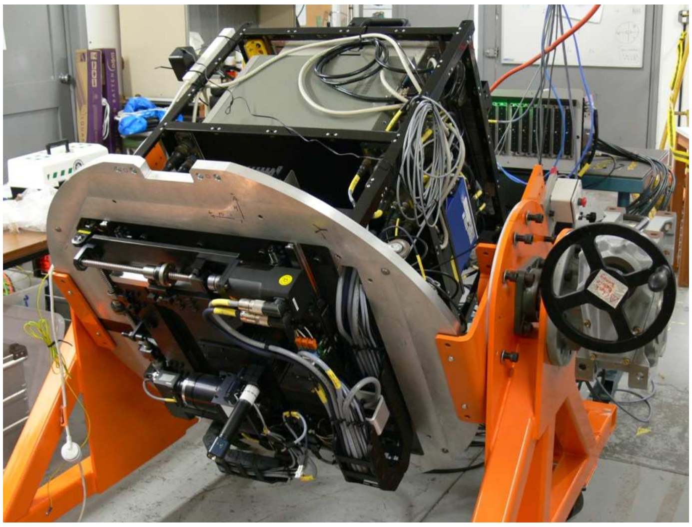


Figure 22. Instrument on its tilting trolley undergoing final tests before shipping to Hawaii. The frame above and to the rear holds the electronics; its enclosure covers are not fitted. The FPI is below and to the front.

The AAO has developed Echidna and the prime focus corrector under contract with the National Astronomical Observatory of Japan (NAOJ). While the AAO prepared a full cost estimate after the concept design phase (in 2000), it was agreed that all work would be done under annual contracts. In spite of Echidna being the most novel and challenging component of the FMOS instrument, AAO has delivered, re-assembled and tested both the correcting lens and Echidna and is now waiting for the collaborators to complete their parts before the commissioning can be completed. The on-sky commissioning of Echidna is planned for January 2008.

The total cost of the AAO's deliverables will be ~ 25% higher than the original estimate. As the cost increases were justifiable, the NAOJ has accepted the price variations.

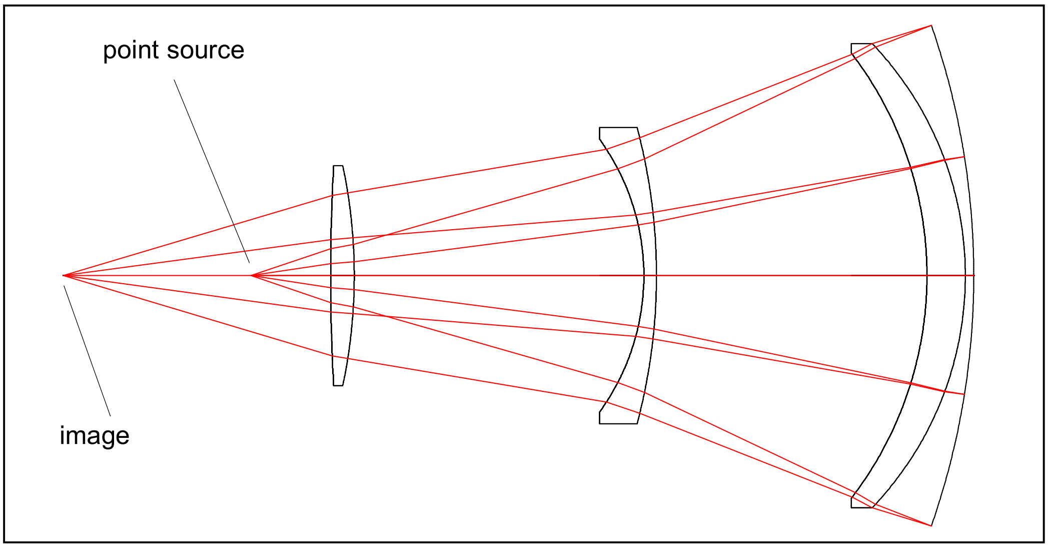
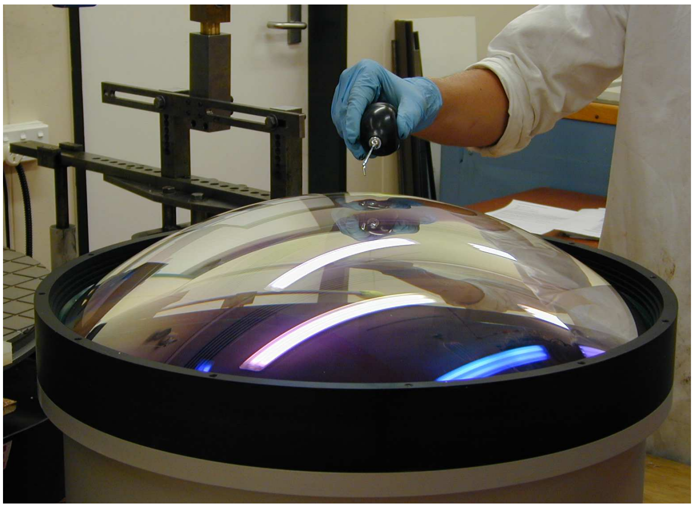


Figure 23
Optical layout of test specified to check performance of fully finished corrector lens. At the far right is a concave spherical mirror specially made for the test. The largest glass element of the lens is ~ 600mm diameter.



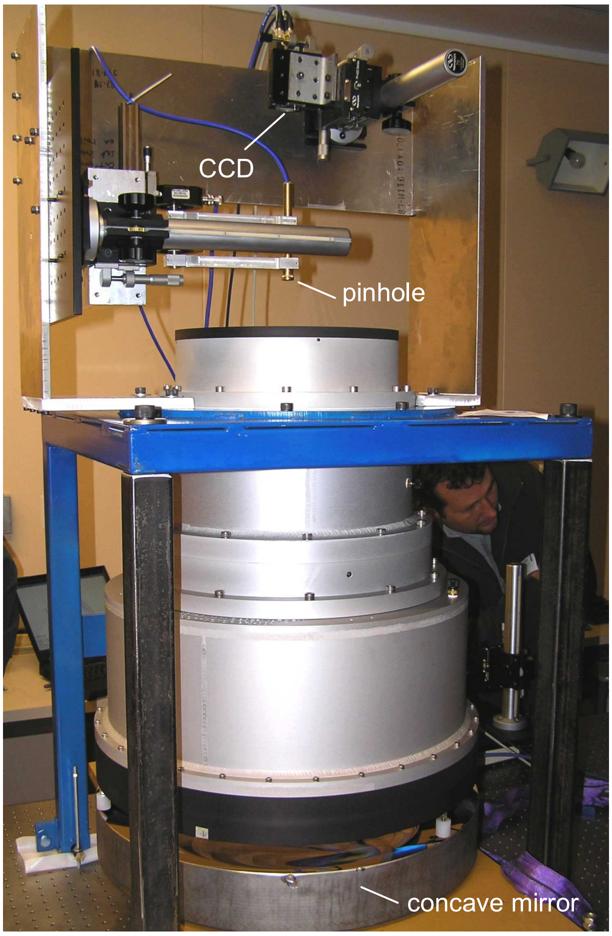


Figure 24, above. Front surface of lens.
Figure 25, right. Corrector set up for test in New Zealand with axis vertical. It was also tested with the axis horizontal.

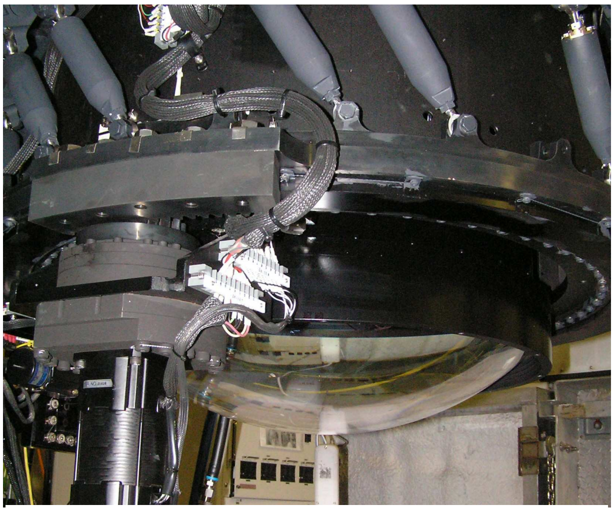


Figure 26. Front of corrector lens protruding below special top end after assembly in Hawaii.

Organisations involved

Client:

Subaru Telescope
National Astronomical Observatory of Japan
(http://www.naoj.org/index.html)

Subcontractors and major suppliers

For prime focus corrector lens:

Ohara Inc. (optical glass supplier)
Japan http://www.ohara-inc.co.jp/en/company/index.html

Electro Optic Systems Pty Limited
Canberra http://www.eos-aus.com/

KiwiStar Optics (sub-contractor to EOS for detailed mechanical design and manufacture of corrector lens)
New Zealand http://www.kiwistar.co.nz/index.html

For printed circuit boards

Artronic Productions (Australia) Pty Ltd (Sydney)

For precision machining

Quality Tool & Die (Sydney)

Intricate Engineering (Sydney)

Benet Precision Tooling (Sydney)

Consultant on optical design of prime focus corrector lens

Damien Jones
Prime Optics, Queensland

Design and manufacture of spectrographs

Kyoto University
Japan http://www.kyoto-u.ac.jp/index-e.html

and

Oxford Astrophysics
University of Oxford
UK http://www-astro.physics.ox.ac.uk/

Design and development of fibre feeds and back-illumination

Department of Physics
Durham University
UK http://www.dur.ac.uk/physics/

Key staff contributors at AAO

Project manager	Gabriella Frost
Project engineer:	Peter Gillingham
Project Scientists	Anna Moore (through middle phase of project)
	Peter Gillingham (in early and later phases)
Project astronomers	Keith Taylor (instigation of project and very early phase)

Scott Croom (consultant on astronomical issues during later phase)

Mechanical design engineers:	John Dawson (manager of mechanical section)
	Jurek Brzeski (all design, testing and assembly other than corrector lens)
	Greg Smith (mechanical design for corrector lens)
	Stan Miziarski (contributed to development in very early phase)
Electronics design engineers:	Lew Waller (manager of electronics section; computer and digital design)
	David Correll (peripheral design and testing)
	Jason Griesbach (spine drive electronics early in project)
Software engineers	Tony Farrell (manager of software section, astrometric software)
	Scott Smedley (instrument control and fibre allocation software)
Electronics technicians	Rolf Muller (electronics manufacture, integration, and testing)
	Don Mayfield (electronics manufacture)
	Ed Penny (electronics manufacture and assembly)
Mechanical technician	Urs Klauser (some design, precision machining and assembly)
Mechanical tradespersons:	Dwight Horiuchi (precision metal machining, fibre polishing, spine assembly)
	Neal Schirmer (precision metal machining)
	Reuben Barnes (precision metal machining)

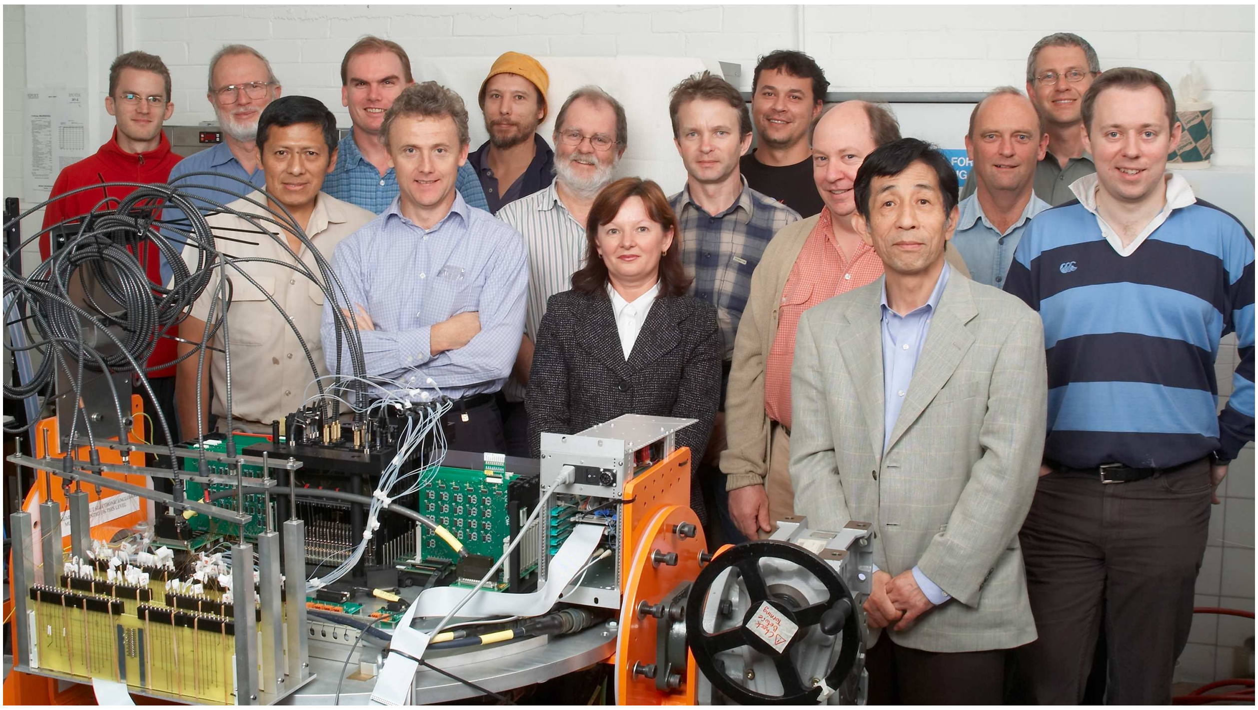


Figure 27. Several of the AAO staff who contributed to Echidna, together with Prof Maihara of Kyoto University, Principal Investigator for FMOS since early in the project.

Outlook for Echidna and its successors

It is confidently expected that the instrument will revolutionise a number of fields of astronomy, from the study of the lowest mass stars, to quantifying the mysterious *dark energy* that has recently been shown to dominate the Universe. The gain in efficiency provided by Echidna will make the Subaru telescope by far the most powerful tool in the world for astronomical infrared spectroscopy. Echidna and the lens have cost about $6 million. Considering that the telescope cost well over a hundred million dollars and that its efficiency in this application will increase by a factor of a few hundred, the Subaru Observatory has chosen well in making this investment.

The links forged through this project between AAO and other Australian astronomers and astronomers in Japan and the UK will be mutually beneficial in pursuing their scientific goals and will encourage further Australian involvement in building cutting edge instruments for international observatories.

The AAO has already done considerable design work on a project, funded by the US National Science Foundation, to build an even more ambitious multi-fibre instrument, with a few thousand fibres feeding about a dozen spectrographs. Such an application could not have been seriously contemplated prior to the invention and development of Echidna.

Scientific journal publications relating to Echidna:

SPIE is an international society advancing an interdisciplinary approach to the science and application of light. **http://spie.org/**

ASP is the Astronomical Society of the Pacific, http://www.astrosociety.org/index.html

Smith, Brzeski, Miziarski, Gillingham, Moore, McGrath, "A survey of fiber-positioning technologies' SPIE 5495, 2004.

Shigeru et al, 'The fiber multi-object spectrograph (FMOS) for the Subaru Telescope III', SPIE 5492, 2004.

Brzeski et al, 'Echidna: the engineering challenges' SPIE 5492, 2004.

Gillingham et al, 'Fiber Multi Object Spectrograph (FMOS) Project – the AAO role', Instrument Design and Performance for Optical/Infrared Ground-based Telescopes, ed. Iye, Moorwood, Proc. SPIE, vol 4841, 2003.

Kimura et al, 'Fiber Multi-Object Spectrograph (FMOS) for Subaru Telescope' Instrument Design and Performance for Optical/Infrared Ground-based Telescopes, ed Iye, Moorwood, Proc SPIE vol 4841, 2003.

Moore, Gillingham, Saunders, 'Extending the Echidna concept; a proposal for a 2000+ multi-fiber positioner', Survey and Other Telescope Technologies and Discoveries. ed Tyson, Anthony; Wolff. Proc SPIE, vol 4836, 299-305, 2002.

Moore, Gillingham, Griesbach, Akiyama, 'Spine Development for the Echidna Fiber Positioner', Instrument Design and Performance for Optical/Infrared Ground-based Telescopes, ed Iye, Moorwood, Proc SPIE vol 4841, 2003

Moore, Gillingham, Saunders, 'A 4000 multi-fiber system based on the Echidna Positioner', Next Generation Wide-Field Multi-Object Spectroscopy, ASP Conference Proceedings, Vol. 280. Ed. Brown, Dey. Astr Soc Pacific, p.109, 2002.

Maihara et al, 'Fiber multi-object spectrograph (FMOS) for the Subaru Telescope', Optical and Infrared Instrumentation and Detectors, ed Iye, Moorwood, Proc SPIE, vol 4008, 2000

Gillingham, Miziarski, Akiyama, Klocke, 'Echidna-a Multi-Fiber Positioner for the Subaru Telescope', Optical and Infrared Instrumentation and Detectors, ed Iye, Proc SPIE, vol 4008, 2000.