Design and Construction of the Fibre System for FMOS

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ABSTRACT

A consortium of Japanese, Australian and UK groups has developed a fibre-fed near IR (J & H band) multi-object spectrographic facility (FMOS) for the Subaru telescope. In this second-generation instrument, a novel prime focus 400-fibre multi-object positioning system, ECHIDNA, is optically linked via twin cables to dual IR spectrographs. The spectrographs are located some distance away, on a dedicated platform two levels above Nasmyth. The Centre for Advanced Instrumentation at Durham University oversaw the design and construction of the optical fibre system linking ECHIDNA to the spectrographs. A modularised connector within the cable scheme and an integral back illumination unit additionally featured as part of the Durham work-package. At the time of writing (mid 2008) FMOS, including the fibre system, is installed and functional on-telescope, with commissioning currently underway. This paper provides an overview of the design and construction of the optical fibre system.

1. INTRODUCTION

FMOS is a versatile near infrared (0.9μm – 1.8μm) multi-object spectrographic facility designed for the 8-m class Subaru telescope. There are four major components that constitute the complete instrument:

- The ECHIDNA multi-object fibre positioning system.
- Two similar NIR spectrographs, IRS1 and IRS2.
- The connectorised fibre system linking ECHIDNA to these spectrographs.

Before describing the fibre system in depth, the fundamental features of these system components shall be briefly summarised:

1.1 ECHIDNA

Within this instrument, a prime focus corrector delivers a 30-arcminute circular telecentrically corrected field of view. Light is collected at 400 re-configurable point locations over the field via individually steerable optical fibres, arranged in a regular, hexagonally packed array. Each fibre is supported in a 'spine' that can be discretely positioned by means of piezoelectric actuators. Polished fibre tips at the ends of the spines are thus able to be precisely located over objects of interest. ECHIDNA was designed and built at the Anglo Australian Observatory, and it was delivered to Subaru in 2007.

1.2 The Spectrographs, IRS1 and IRS2

For practical reasons of limited space, the spectrographs are sited on a dedicated platform, the 'TUE-IR floor' which is located two floors above the Nasmyth platform instrument room at the telescope. Although several principal components are common to both spectrographs, IRS1 was designed and constructed in Japan (Kyoto University) and IRS2 was designed and built in the UK (Oxford/RAL).

To minimise thermal emission towards the longer (1.8 μm) wavelength range the spectrographs are cooled to 200°K. The spectrographs have an innovative design feature whereby the sky background emission lines are optically removed. To achieve this, a mask mirror is employed onto which the spectrum is initially dispersed. Regions on the mirror

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corresponding to the locations of sky emission lines are uncoated, leaving gaps in the reflective surface; light from these portions of the spectrum is therefore lost. Subsequently, two spectrograph operational modes are available: *High resolution*, whereby the dispersed spectrum is fed to the spectrograph camera directly after the OH emission lines have been removed, furnishing approximately 0.2 µm bandwidth, or *low resolution*, whereby the dispersed spectrum is optically re-compressed by a volume-phase holographic (VPH) diffraction grating, permitting the full 0.9 µm spectral range of the instrument to be recorded onto the detector.

1.3 The Fibre System

A fibre-optic cable is required to convey light collected by the object fibres to both spectrographs. The CfAI has been responsible for this entire fibre system and all associated cabling and cable management, from the prime focus through to, and including, the spectrograph input slit units. Since ECHIDNA is only one of a suite of instruments that can be installed at the Subaru top-end, it has to be removable. Therefore the cable must include a connectorised break.

The light arriving at prime focus has a focal ratio of ~ F/2. In addition the fibres see a small angle (up to 2.4°) if the spines are tilted, and there is a residual non-telecentricity, equivalent to about 1.2° at the edge of the field. Therefore for maximum light gathering the fibre should possess a significantly high numerical aperture. However, at the spectrograph-end of the system such a divergent exit beam would require impractically large optics. Moreover, a low focal ratio is far from optimal when conducting light through appreciable fibre lengths. Therefore the focal ratio must be increased before leaving the immediate vicinity of the telescope top-end.

A source of back-illumination is required so that a field-patrolling camera can detect individual object fibre positions prior to each exposure on sky. Position detection is necessary because the pulsed actuators driving the spines have no absolute positioning precision, leading to a cumulative positional uncertainty over multiple exposure cycles. Therefore, spine locations need to be visually calibrated at a specific 'home' position before an exposure is made. The most obvious point to site a back-illumination source is in the optical break within the connector coupling.

2. FMOS FIBRE SYSTEM PRIMARY REQUIREMENTS

2.1 Key optical requirements

Wavelength range	0.9 - 1.8 µm
Incident focal ratio (from telescope)	F/1.98 average
Number of sampling elements within the field	400
Required focal ratio conversion at connector	~ F/2 : F/5
ECHIDNA fibre core diameter	Pre-defined as 100 µm
Fibre core diameter at slit unit	Pre-defined as 280 µm
Total required fibre system throughput	>60%
Spectrum format	Two sets of similar spectra (200 fibres each) one per spectrograph, maximum slit lengths: 120 mm

2.2 Key engineering requirements

- Total fibre length from the focal plane of ECHIDNA to the site of the connector: 7.6 m (includes contingency).
- Total fibre length from the connector to the spectrographs: 62 m (again, includes some contingency).
- Within launch connectors[2] all fibres should be interchangeable in case of spine failure.
- The connector must also furnish individual, switchable back illumination for each fibre.
- The connector must occupy a pre-defined and somewhat restrictive space envelope.

[2] Since the light path routes across the connectors from ECHIDNA through to the spectrographs, connectors on the ECHIDNA-side of the system are termed 'launch-side', and connectors on the spectrograph-side of the system are termed 'receiver-side'.

- The cable must be suitably ruggedised, to withstand the rigors of the telescope cable wrap & general observatory environment.

The routing path on the telescope is indicated in Figure 1 by the line linking ECHIDNA at Subaru prime focus to IRS1 and IRS2 on the TUE-IR floor.

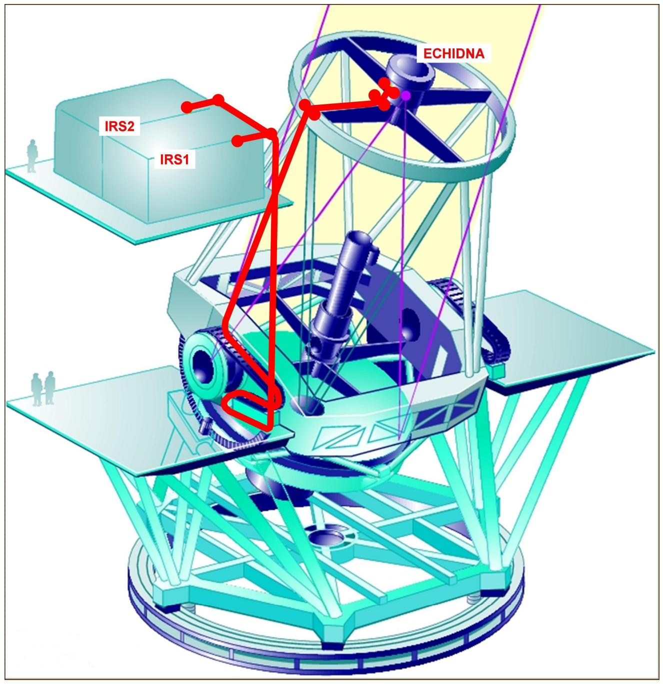


Figure 1. The cable route on Subaru.

3. OVERVIEW OF THE FIBRE SYSTEM SCHEME

3.1 The ECHIDNA fibres

As outlined in the list of primary requirements, both the launch & receiver-fibre core sizes were pre-defined. Final diameters evolved from consideration of the practicalities of the FMOS design as a whole, and the proposed science targets that FMOS is intended to study.

On the ECHIDNA-side of the system the fibres possess a 100 µm core. This core size was derived from a signal-to-noise optimisation of a continuum for a faint object (20.5 magnitude, H-band) and corresponds to an angular size on the sky of 1.2 arcseconds. The fibres are sourced from Polymicro Technologies (STU-D type, having been drawn from Heraeus ultra-low OH fused silica performs). The fibre displays very high, comparatively uniform transmission in the near IR spectral region[3]. A fibre numerical aperture of 0.26 was selected. However, the measured value for the delivered fibre was found to be 0.255,; slightly low but within the manufacturer's specification. This NA will lead to a resultant loss in throughput, of the order of a few percent (which varies depending upon spine tilt). In this respect a short fibre length is advantageous. Although higher numerical aperture fibres are commercially available, at the time of purchase a tradeoff was made in order to utilise a relatively standard, affordable product. The fibres are 7.6 m long, to cover the routing distance between the focal plane and the ECHIDNA-side connector. The fibres have a core-to-clad ratio of 1:1.4. This

[3] The overall NIR performance of STU-D fibre is improved at the expense of UV transmission, by minimizing the OH content of the glass. As a result, STU-D fibre exhibits a minimal OH absorption (a comparatively large throughput reduction is normally observed in silica fibres between 1.3 µm and 1.5 µm).

minimises light loss due to evanescent waves[4] at the core/clad interface. The buffer material is polyamide (outside diameter 170 microns). The fibres at the ECHIDNA focal plane are terminated and polished as an assembly, consisting of an epoxy-bonded inner polyimide strain relief sleeve and an outer stainless steel tube ferrule. Throughout the system (both launch & receiver-side) the fibres are conveyed in furcated sub-bundles, of which more in Section 3.10.

3.2 The spectrograph fibres

Polymicro ultra-low OH fused silica fibres with polyimide buffer were again used on the spectrograph-side, but here they are of 280 μm diameter core. The core size is a compromise between the spectrograph and connector requirements; For efficient coupling in the connector the receiver-side core diameter should be to an extent oversized. This is necessary to permit a 100 micron launch fibre to be re-imaged with the ~F/2-F/5 focal ratio conversion (i.e. a ~2.5 × magnification) while accommodating sensible manufacturing tolerances in the centering of fibre axes within the connector. However, an upper limit to fibre size is primarily imposed by the fact that the resolution at the mask mirror degrades with increasing fibre size, reducing the efficiency of OH suppression. Furthermore, with increasing fibre size the spectral overlap at the detector will become significant.

3.3 Optical design

For optimal propagation along the fibres from the telescope to the spectrograph, a focal ratio conversion is required. From previous optical fibre work and simulations at the CfAI, an estimate for focal ratio degradation (FRD) exhibited by the spectrograph-side fibre train was derived for a range of propagating focal ratios[5]. With this model the focal ratio conversion was fine-tuned by adjusting the connector lens parameters to maximise the *total* throughput of the FMOS system, including spectrographs. The model also incorporated detailed figures for alignment tolerances within the connector, and manufacturing tolerances that were specified for components used in the connector construction. This furnished a range of possible lens design solutions. However there was a further consideration; the connector should also provide a source of back-illumination for the ECHIDNA-side fibres. The only practical place in the cabling scheme into which back-illumination light can be introduced is within the connector inter-lens gap. The gap must be sufficiently large therefore to permit the introduction and removal of a suitable beam delivery component. A plano-convex lens coupling design has been devised (Ohara S-BSM4 launch lens, fused silica receiver lens) which satisfies all requirements. The inter-lens gap in this case is 4.99 mm and the magnification factor M = 2.49.
Multi layer broadband AR coatings were utilized on both external faces to optimise the throughput, and wherever fibres interface directly with lenses a suitable index-matching UV cured epoxy was utilised to minimise reflective losses.

3.4 Ferrules & tolerancing

As will be discussed in Section 3.5, the connector assemblies hold the launch & receiver fibres to a high positional tolerance. But it should be noted that a comparatively significant lateral displacement of the launch fibre/lens assembly *as a whole* with respect to the receiver fibre/lens does not result in a significant loss of throughput (provided the receiver lens clear-aperture does not vignette the incident beam). This is because such a translation will not result in a displacement of the image of the launch fibre core on the receiver fibre. This advantageous feature stems from the fact that coupling scheme is near-collimated. Nevertheless when arrays of fibres are managed within assemblies of multiple (concentrically assembled) components, cumulative misalignments can develop that will impact upon throughput. Such misalignments can be broadly categorised as:

- Lateral position error between the launch fibre and optical axis of the launch lens.
- Lateral position error between the receiver fibre and optical axis of the receiver lens.
- Tilt of the launch optical axis with respect to the receiver optical axis.

All these issues were evaluated when sourcing fibre management components. Zirconia ceramic components can be made to sufficiently high tolerances, typically ±1μm on inside / outside diameter, concentricity, and ellipticity. They are

[4] It is a simplification to assume that light is totally internally reflected at the interface between the core and clad indexes; the light standing wave actually penetrates about λ/4 into the second media while being reflected. This penetrating wave is called an evanescent wave. It decays exponentially with distance from the interface, with a characteristic penetration depth of 50nm to 100nm. If the cladding is too thin, each reflection will experience a corresponding loss through the clad and out of the fibre. When selecting core-to-clad ratios for small diameter fibres it is important to make sure that the cladding is sufficiently thick that the evanescent wave does not create unwanted losses. As a rule of thumb the cladding thickness should be at least 10 times the operational wavelength.
[5] The output focal ratio feeding into the spectrograph will exhibit an additional divergence corresponding to a convolution of the input focal ratio with a Gaussian of approximately 4° to 5° FWHM (in the ~F/5 case).

also relatively inexpensive. Therefore such ferrules formed the basis of all fibre management within the connector heads. On the launch side however, the fibres must be interchangeable or removable in case of spine failure. This additional feature was achieved by terminating the fibre within a complete collimator, the whole component forming a high-precision insertable 'plug' which locates in the connector faceplate. The collimator assemblies are a composite construction; a ceramic ferrule-terminated polished fibre and launch lens are located and bonded within a common bore in a precision zirconia ceramic sleeve. A groove machined circumferentially around the body of the sleeve allows it to be securely retained by means of a tangentially located nylon pin. A flanged shoulder at the back of the ceramic sleeve defines to a high precision the depth to which the collimator assembly locates within the connector head, hence accurately defining the longitudinal position of the launch lens.

The receiver-side does not employ interchangeable discrete collimators, thus it is a simpler construction consisting of a plain ceramic ferrule and receiver lens only, bonded directly into a common bore within the connector faceplate.

A rigorous analysis of lens, ferrule, fibre and connector tolerances was undertaken in order to derive a specification for the coupling lenses: A degree of under-sizing must be employed when considering a suitable size for the launch fibre image on the receiver fibre core, in order to accommodate expected axial misalignments. Yet the image of the launch fibre on the receiver fibre core was finally defined as only ~10μm undersized, so even a strict tolerancing will statistically result in some light loss from misalignment between the re-imaged launch fibre and the receiver fibre core (albeit some image misalignment beyond the clear aperture of the receiver fibre can in fact be tolerated, because percentage throughput loss per unit misalignment is highly non-linear, due to the nature of the re-imaged PSF). At first consideration therefore a lens coupling that furnishes such a large a fibre-core image seems an unsuitable choice for efficient throughput. However, this should be considered as one loss factor amongst a range of potential loss contributions from the total FMOS cabling scheme. In such a total-system analysis, a surprising result is obtained; for a decreasing fibre core image size, the FRD loss *increases* within the spectrograph-side fibre - the size of the re-imaged fibre core is, broadly speaking, inversely related to the degree of FRD *and* sensitivity to induced FRD that will be exhibited by the receiver fibre train. Therefore the throughput shows a maximum for an unexpectedly large fibre image of 270 μm. In short, FRD losses due to undersizing of the fibre core image are greater than oversizing / misalignment losses. A final point to note is that the connector lens design can accommodate relatively large variations in inter-lens gap (± 100 μm) with minimal resultant change in throughput. This is by virtue of the fact that the lens scheme is near-collimated; substantial inter-lens displacements are required before any significant defocus is observed.

3.5 The general connector scheme

The connector is formatted as an array of sub-connectors. The ECHIDNA-side array is housed in a rack-style enclosure which also contains a drive mechanism for back-illumination and associated electrical cabling, as well as offering a substantial mechanical interface to the PFU, capable of supporting the combined weight of all the cabled receiver-side connectors when they are installed on the front interface. The spectrograph-side consists of an array of self contained, discrete sub-connectors. When ECHIDNA is not in use, the spectrograph-side sub-connectors are located on a permanent parking plate at the top end of Subaru. A photograph showing the launch-side connector array installed on the exterior of the ECHIDNA instrument is shown in Figure 2. The receiver-side connectors are shown in Figure 3 in the park position.

3.6 The field mapping – redundant elements

The ECHIDNA instrument is configured in twelve modules mapping alternately between spectrographs. A module carries two rows of 20 fibre positioning spines. The full array is therefore rectangular, possessing 480 elements. The connector head is similarly configured; twelve individual launch & receiver sub-connector pairs address discrete modules. The spectrographs however only see a circular patch fitting within the 480-element rectangular field, corresponding to 400 elements (200 elements per spectrograph). All the elements within the full rectangular field are nevertheless supported by functional spines & science fibres, and the fibres are terminated within the connector head launch-side by serviceable coupling lenses. Furthermore, the fibres installed at the ECHIDNA-side of the connector head are interchangeable. However, within the receiver-side sub-connectors only those 400 active elements that actually map through to the spectrographs are served by fibres and associated lenses. The 80 elements in the receiver-side connectors that lie outside the 30 arcminute diameter working-field are left as unpopulated channels and are blanked-off. In this way a degree of redundancy on the ECHIDNA-side is permitted in the event of a broken field element; by re-ordering combinations of modules & corresponding launch sub-connector heads, and at the same time interchanging fibres on the launch-side, it is possible to re-locate damaged elements to regions outside the working field.

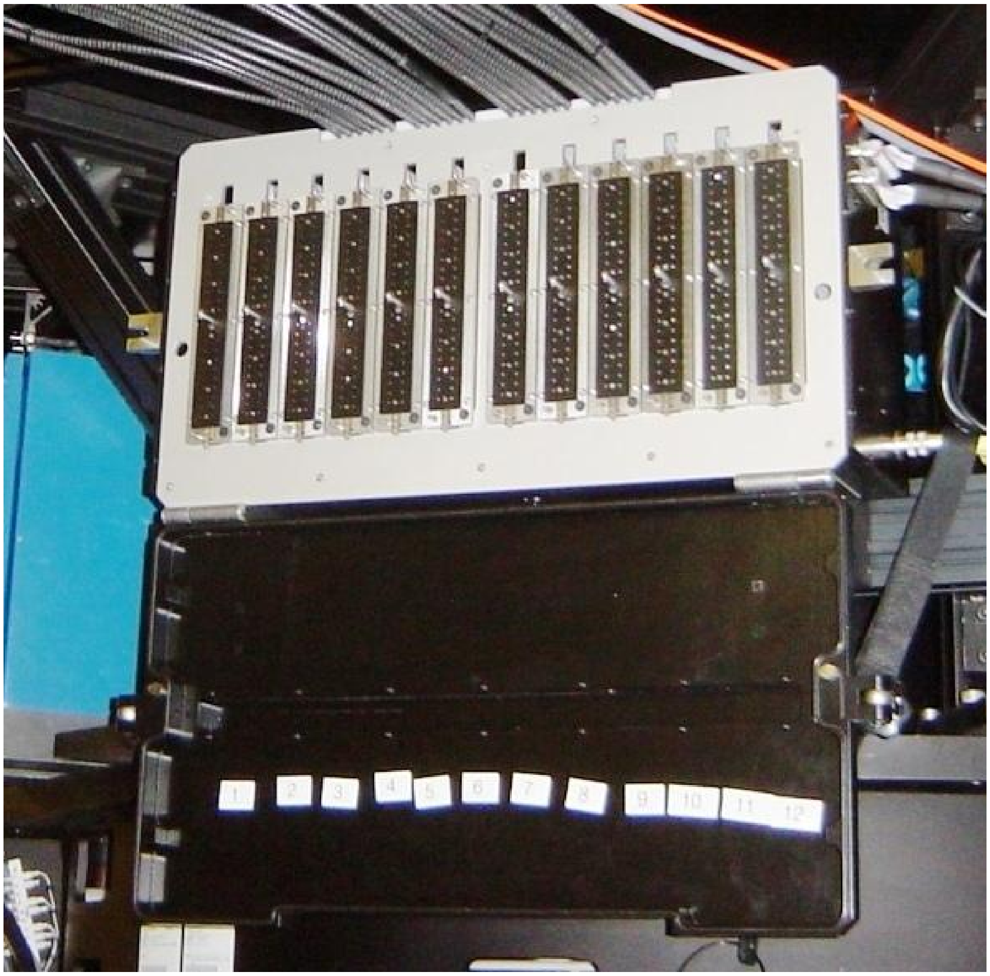


Figure 2. The launch-side connector array.

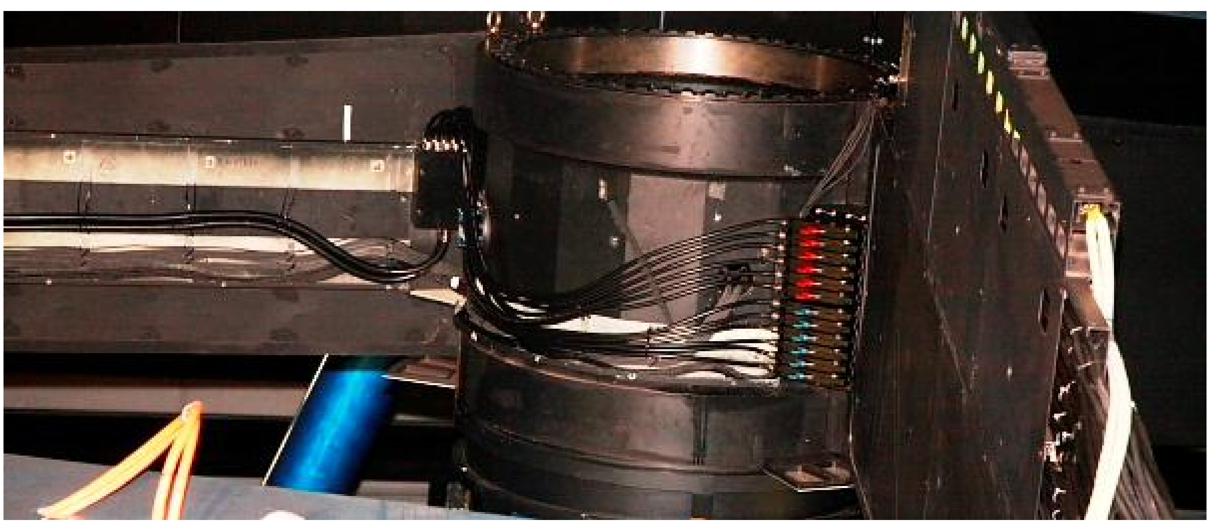


Figure 3. The receiver-side connectors parked at the telescope top-end.

3.7 The Back Illumination System

As explained in Section 3.3, launch & receiver lenses are specified such that light passing across the inter-connector gap is essentially collimated, and a relatively large inter-lens distance is afforded. This feature of the design facilitates the incorporation of an insertable back-illumination source. The scheme, together with the lens to lens coupling is shown in the cross-sectional sketch in Figure 4:

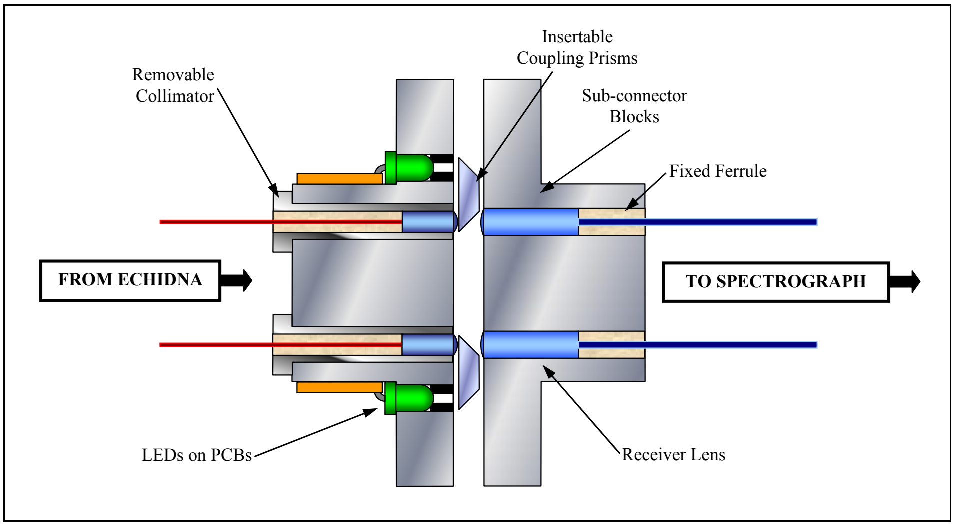


Figure 4. A cross section through a launch and receiver sub-connector pair.

Back illumination light is introduced into the exit face of the launch lens via a prism screen that can be inserted into the inter-lens gap when required. This screen supports an array of dove prisms that have been aluminized and are here used in a 180° fold configuration. The prisms deliver illumination from columns of adjacent diffuse-lens LEDs. The prisms alternate with holes through the screen, so that when the prisms are moved out of the way the through-beam from the sky passes across to the receiver lens uninterrupted. The back illumination system delivers ample power at F/2 from the ECHIDNA spine tips, with a good quality gaussian beam profile detectable by the focal plane imager (FPI) camera.

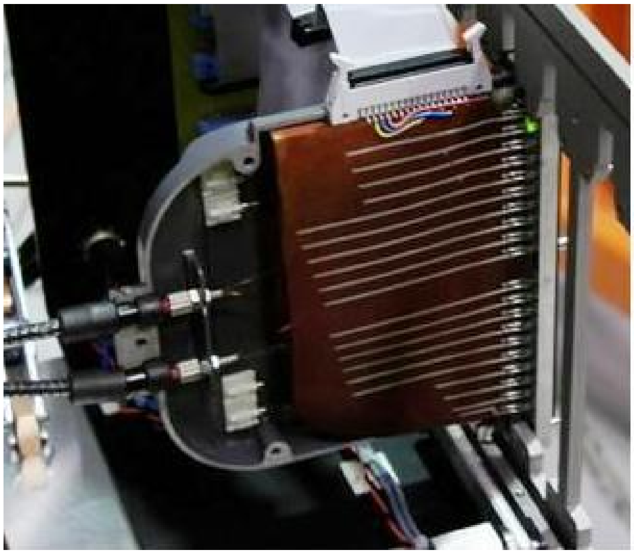
3.8 ECHIDNA-side (launch) sub-connectors

An individual launch sub-connector consists of an accurately machined faceplate that carries two columns of 20 launch collimators (described in Section 3.4), back-illumination LEDs and associated circuitry, back-illumination coupling prisms and the mechanical transport to switch these prisms into the inter-lens gap. The sub-connector also serves as an enclosure that manages the fibres and supports the termination of the furcation tube pairs feeding directly from the corresponding ECHIDNA spine module. Two views of a launch-side sub-connector are shown in Figure 5.

Two conical dowels on the front of each faceplate serve as a precision location for the corresponding spectrograph-side sub-connectors. In the centre of each faceplate there is a fixed locking pin. These pins engage with corresponding locking mechanisms in the receiver-side sub-connectors. The sub-connectors are enclosed by aluminium casings.

The prism screen supports the prisms in an insertable, flat array and allows their transport into position when required. They travel on a central, linear bearing rail that is bisected to allow the connector locking pins to protrude. Each screen is made from two precision cut sheets. One retains the prisms themselves and the other acts as a light-tight cover and baffle, to minimise stray back-illumination light at the spectrographs. The cover also offers mechanical protection during the connect/disconnect procedures. When not in use, the screens are parked so that light from the sky passes through holes that alternate with the prism locations. The prism screens are moved into & out of the optical path via a linking magnetic button which passes through the back of the connector faceplate and out of the bottom of each sub-connector housing, (visible at the top in Figure 5, right). The button engages with a common actuator pushrod, driven by a geared DC motor. Position determination is achieved with dual hall-effect sensors.

Within sub-connectors the back-illumination LEDs are carried in two rows of 20 on single flexistrip PCBs folded in two, (see Figure 5, left) and are connected to the remote back illumination control unit via a pair of common connecting ribbon cables that run along the top of the full suite of sub-connectors, one cable for each of the IRS fibre systems.



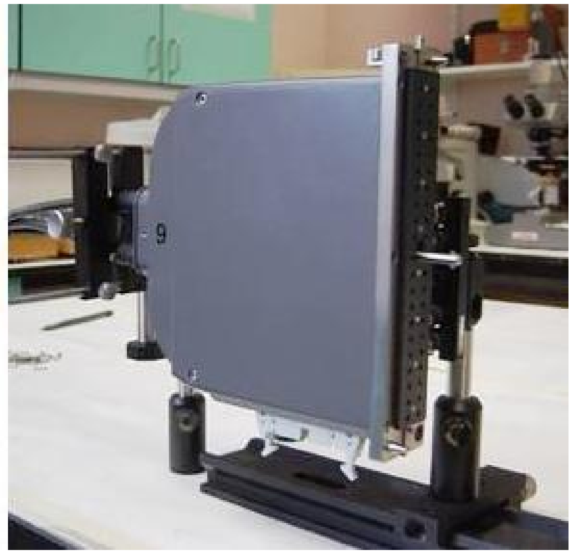


Figure 5. On the left, a launch-side sub-connector is shown open during back illumination testing. The PCB is visible and one LED is illuminated. On the right a completed unit is shown (upside down in the picture). The prism screen and locking pin can be seen on the front.

3.9 Spectrograph-side (receiver) sub-connectors

The spectrograph-side of the connector array (Figure 6) is simpler, having fixed fibres and no complex mechanisms. The sub-connector is of a similar general pattern to the launch-side, having a precision faceplate and a cover formed as two aluminium shells. The unusually narrow design of these connectors is defined by the highly restricted space envelope at the parking location. The fibres are managed within the housings very near to their minimum bend radius. The array of sub-connectors does not share a common protective housing, each is instead a discrete unit, and they are designed also for regular handling. Because of this the furcated sub-bundles are protected by ADAPTAFLEX® conduits. Locking pins protruding from the launch-side sub-connectors engage with barrels in the spectrograph-side sub-connectors. Full lock is achieved in a quarter turn of a folding handle at the rear of each sub-connector.

Figure 6. Two views of receiver-side sub-connectors. On the left, a single sub-connector is shown open and partially complete. Fibres and foam-block strain relief can be seen, but the handle attached to the locking mechanism has yet to be fitted. On the right a suite of six sub-connectors are shown face-up. Lenses are just visible, as are the blank plugs that are inserted in the unused channels.

3.10 Cable Structural Design

Throughout the system, the fibres are carried in furcated sub-bundles. The furcation tubing is a 5mm MINIFLEX® product comprising a segmented polymer tube. MINIFLEX® is a relatively rugged thick-walled tube, which is flexible yet exhibits a safe minimum bend radius, low extension under load, and high crush resistance. Each main cable section contains a central, Aramid® fibre tensile element. This prevents the cables from extending under their own weight over the drop from the top end ring to the Nasmyth cable wrap. Figure 7 shows a cross section through the main cable.

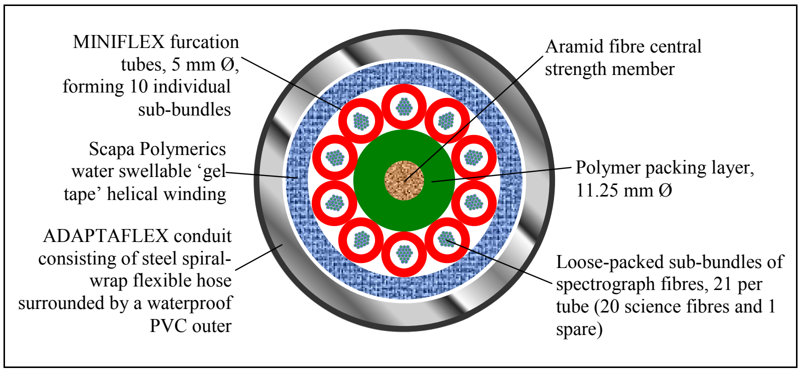


Figure 7. Main cable cross-section.

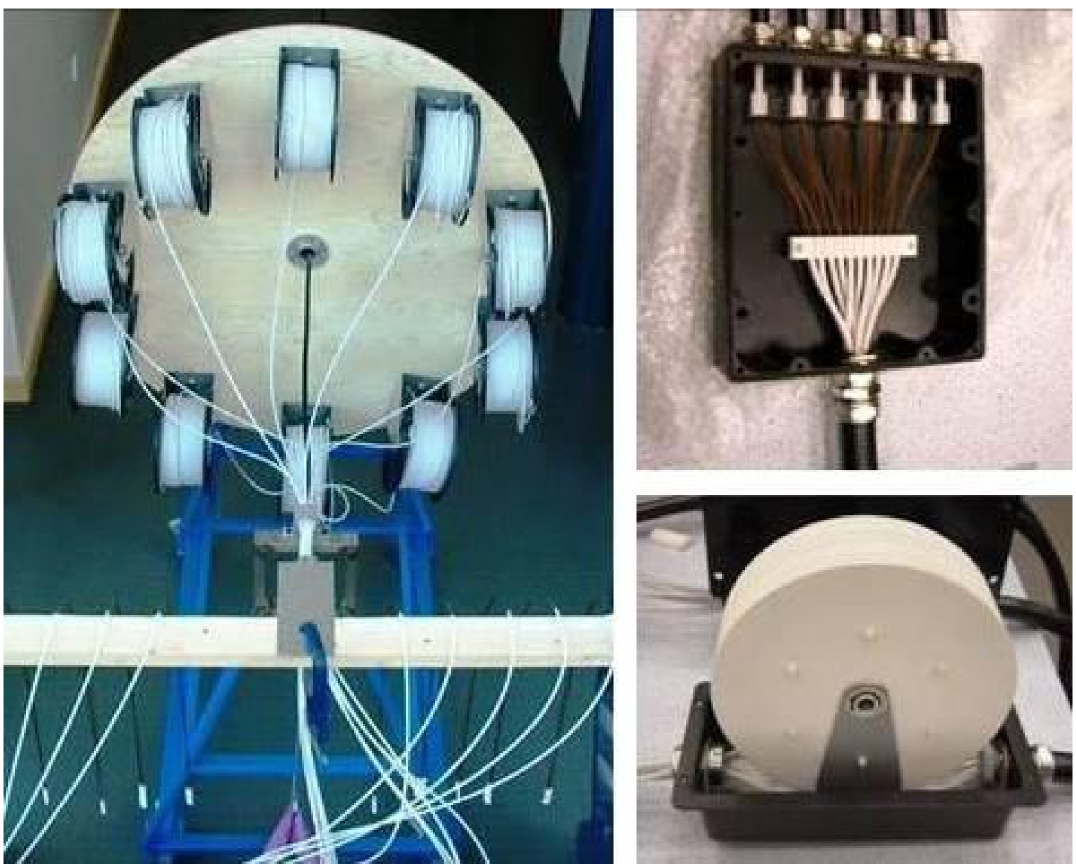


Figure 8. (left) The cable winding apparatus. The anchor is in the foreground, and the tensile element can be seen running through the circular spool at the rear. Surrounding this, ten reels of furcated fibre bundles are visible. (Top right) A breakout box shown open. The fibre re-ordering is evident. (Bottom right) A strain relief box shown open. The discs designed to manage the bare fibre loops can be seen.

Ten furcation tubes are arranged radially around the Aramid® centre, which is built up with a polymer coating to a diameter around which the furcation tubes pack uniformly. The furcation tubes are wound around the core in a spiral pattern. Spiral wrapping avoids differential length problems when bending the conduit, where fibres on the outside edge of the bend follow a longer path than those on the inside. The spiral wound cable is further wrapped in a hygroscopic 'gel tape'. This is a standard cable component and prevents moisture ingress. The cables are sheathed within ADAPTAFLEX® conduit, again a standard for such applications.
Winding the cable posed a significant challenge. After considering various options it was decided to devise a suitable cable winding apparatus. This consisted of a large spool on which all ten reels of pre-furcated fibre were installed. The spool was supported on a trolley, with the tensile element able to pass through the axis of rotation of the spool. From an anchored starting point in a suitably long corridor, the trolley could then be slowly translated. The spool spun by means of a linked guide cable and pulley arrangement, which caused the spool to rotate at a rate governed by its progress along the cable, thus imparting a spiral winding to the cable at a pre-determined and fixed pitch. The gel-tape was wound onto the finished cable by hand as the winding trolley progressed. Figure 8 (left) shows the winding apparatus in use.

3.11 Breakout boxes and Strain relief Units

Within the cable scheme, breakout boxes and strain relief units are also incorporated. There are two breakout boxes, one per fibre cable. Figure 8 (top right) shows one such unit open, during assembly. Each box allows six individual conduits (one from each receiver-side sub-connector) to feed into a single, large ruggedised cable, suitable for routing along the spider arm and off the telescope. In addition, within each box the 200 fibres are re-ordered so that a regular number (20 fibres plus one spare) is conveyed down each furcation tube.
Strain relief units are incorporated into the cables close to either end of the system in order to decouple variations in fibre tension in the main cabling from the fibre end terminations. Such tensions can occur when flexing the cable, or through a settling of the fibre bundles within the cable after the cable system has been hung on the telescope. An additional function is to allow lengths of fibre to be equalised before terminations are fitted. All this is achieved by taking up slack within free fibre loops. Internally, the devices simply consist of an array of plastic spacer discs which manage the fibres in orderly, single loops. The cable tensile element and the ADAPTAFLEX® conduits are anchored directly onto these strain relief enclosures. An open strain relief box is shown in Figure 8 (bottom right).

3.12 The Spectrograph Feed Through & Igus Chain Feed to the Slit Unit

The feed through is designed to manage the furcated fibres through the insulating wall of the thermal enclosure surrounding the spectrograph. Any connecting structure within the wall must incorporate a thermal break between inner and outer terminations, to prevent thermal ingress from the surrounding environment to the 200ºK interior. The feed through also needs to offer a gas-tight seal to avoid loss of the chilled air which is steadily replenished to maintain a slight overpressure within. The feedthrough is a simple G10 composite spindle (a good thermal insulator) onto which the inner & outer adapter flanges are bolted. The whole assembly is filled with insulating foam. Due to structural and material differences in the thermal enclosures of IRS1 and IRS2, the feedthrough designs differed in their general shape.

3.13 Slit units

The slit unit precision-locates ten v-groove chip-array pairs. Each carries 20 fibres and is cut, polished and arranged in such a way that the set of ten arrays approximates the required slit-unit pointing and focal plane curvature. The slit unit is required to be compatible with the 200K thermal environment within the spectrograph enclosures. This imparts several constraints on the choice of materials. All the fibre management components, adhesive, and the structure of the slit unit itself should have a broadly matched, low CTE to maintain dimensional stability and minimize stress induced FRD. Therefore, the fibre v-groove chips are made from Pyrex® and the slit units were made from Invar. The slit unit occupies the focal plane location in a central slot between the two mask mirror halves, hence the narrow profile. The slit unit is attached by an Invar dovetail block which is doweled and permanently fixed to the slit unit casing. The block is profiled to locate in a corresponding keyway in the spectrograph translation mechanism. All cable management materials here were tested to ensure functioning at 200ºK.

The spectrograph optical design calls for a curved slit of radius 887.51 mm, with a gross pointing offset of the exit beams equal to +16.45° defined from the radial centres of each v-groove block location. After accommodating the refractive index of the (silica) fibres, this results in an actual block tilt of 11.29°, with the faces of each block polished tangentially flat to follow the profile of the slit. The slit pointing is thus approximated in parallel groups of 20 fibres.

The pitch of the fibres across the face of the angle-cut v-groove chip is 0.56 mm. Slit length, inter-fibre gap, and inter-block distance were all considered when deriving the optimum fibre pitch.

Polishing the fibres at an angle results in an elliptical core profile, but for an angle of ~ 11º this has an insignificant effect upon the beam quality, imparting an additional FRD component of the order of 0.10º FWHM. However the pointing approximation formed by grouping the fibres in discrete rows of 20 results in a significant blurring of the pupil image when traced back to the common pupil location. This effect was simply corrected by bonding a corrective field lens onto the front face of each v-groove chip array. The front face of these correctors in addition carries an antireflection coating, which negates the need to AR coat the fibres themselves. A photograph of a finished slit unit is shown in Figure 9.

Figure 9. A slit unit during test-illumination. The line 200 of fibres can be clearly discerned, in individual blocks of 20.

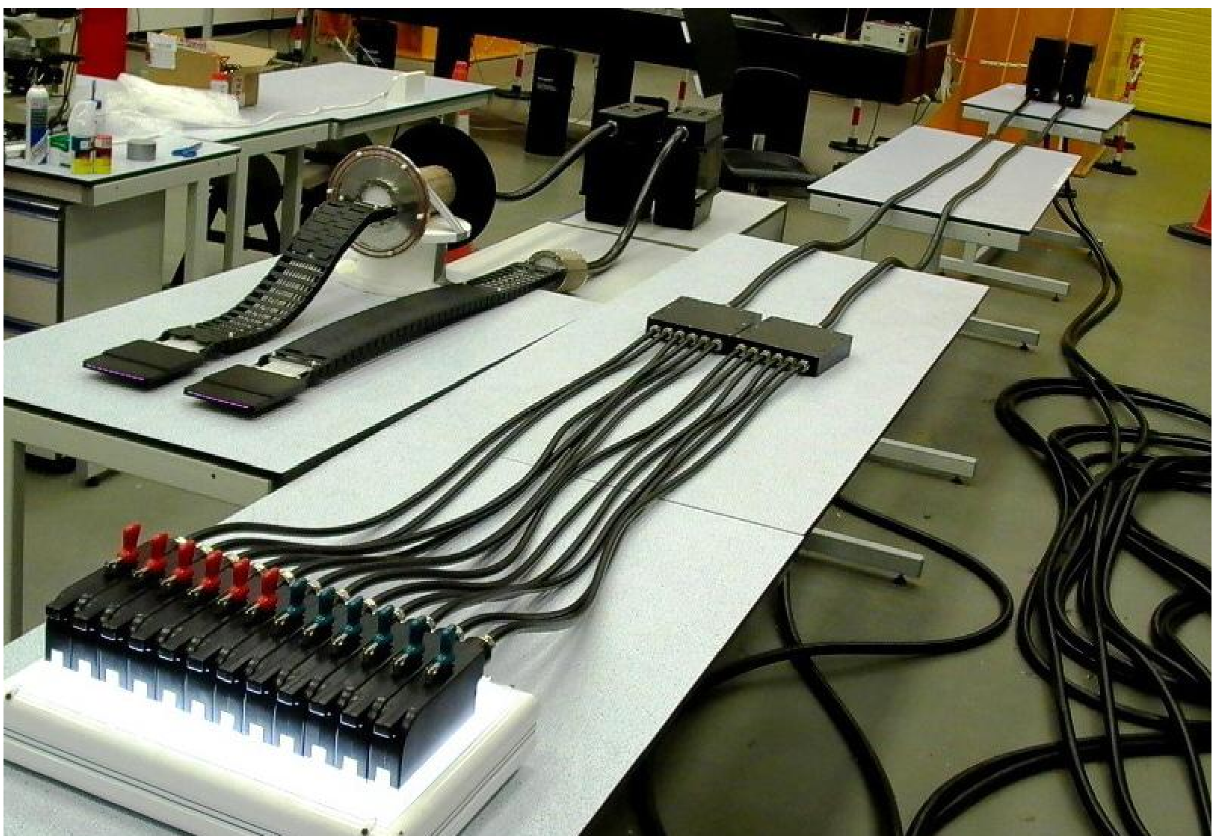


Figure 10. The complete, end-to-end fibre system, on the bench in the lab, prior to shipping.

4. SUMMARY OF THE CURRENT DESIGN & CONCLUSIONS SO FAR

The FMOS fibre cabling system and interconnect have posed numerous engineering and optical design challenges. Fibre core diameters and numerical apertures were pre-defined by instrument and science drivers, and were formulated during the early stages of the FMOS design study. The details of the fibre system were resolved after these parameters had been fixed, the optical design brief being to produce a high efficiency coupling that would unite the somewhat incompatible ECHIDNA and spectrograph optical systems. Optimisation of the fibre coupling therefore operated within these rather disparate constraints.

Precision components employed in the connector heads require extremely high engineering tolerances. Such tolerances are difficult to achieve without for example making launch & receiver sub-connectors as unique, matched and permanently paired modules, where both launch & receiver bores are cut in a single operation. But the requirement for full interchangeability would not have been satisfied if such a manufacturing route had been followed. The imposition of a further requirement that launch fibres within a sub-connector must also be interchangeable further exacerbates the problem of maintaining a sufficiently tight tolerance budget.

Nevertheless, all these challenges have been effectively overcome by incorporating innovative design solutions in an ordered, modular scheme, the full extent of which can be appreciated in the photograph (Figure 10) taken prior to shipping the entire spectrograph-side system to Subaru. The result is a practical and robust, working fibre system that has efficiently satisfied all the FMOS project requirements.

At the time of writing, commissioning is in the early phases and a throughput measurement has yet to be undertaken. However a very rudimentary check has revealed that the total FMOS system throughput (focal plane to detector) is near to the maximum theoretical predictions.

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