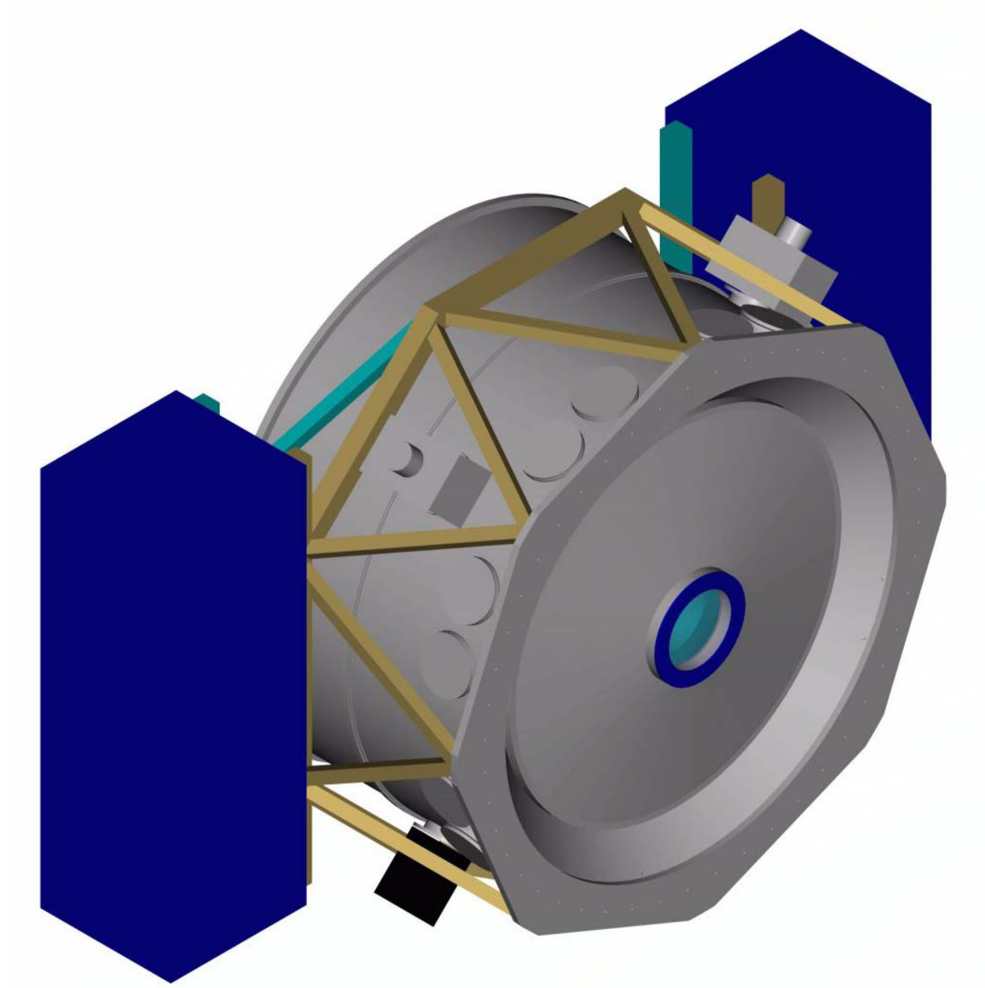
A NEAR-INFRARED MULTIPLE-OBJECT INTEGRAL-FIELD SPECTROMETER FOR THE VLT

EXECUTIVE SUMMARY



UK Astronomy Technology Centre

Document Title	KMOS Executive Summary
Document Number	KMOS-PhaseA-0001
Issue	1.0
Date	29-08-2003
Prepared by	Ray Sharples, Ralf Bender

CHANGE RECORD

Issue	Date	Section affected	Change Description
1.0	29-08-2003	All	Phase A release

APPLICABLE DOCUMENTS

Reference	Document Title	Document Number	Issue & Date
AD2	Science Case	KMOS-PhaseA-0002	V1.0 29-08-2003
AD3	Science Design Requirements	KMOS-PhaseA-0003	V1.0 29-08-2003
AD4	Operations, Calibration and Maintenance	KMOS-PhaseA-0004	V1.0 29-08-2003
AD5	Systems Architecture	KMOS-PhaseA-0005	V1.0 29-08-2003
AD6	System Design	KMOS-PhaseA-0006	V1.0 29-08-2003
AD7	Optics Design Architecture	KMOS-PhaseA-0007	V1.0 29-08-2003
AD8	Mechanics Design Architecture	KMOS-PhaseA-0008	V1.0 29-08-2003
AD9	Electronics Design Architecture	KMOS-PhaseA-0009	V1.0 29-08-2003
AD10	Instrument Software User Requirements	KMOS-PhaseA-0010	V1.0 29-08-2003
AD11	Data Analysis Software Architecture	KMOS-PhaseA-0011	V1.0 29-08-2003
AD12	Phase B Management Plan	KMOS-PhaseA-0012	V1.0 29-08-2003
AD13	R&D Study Reports	KMOS-PhaseA-0013	V1.0 29-08-2003

REFERENCE DOCUMENTS

Reference	Document Title	Document Number	Issue & Date
RD1	KMOS-1 Detector and Acquisition System Design Report	VLT-TRE-ESO-14660-3120	V1.0 25/01/2002

1. Introduction

KMOS is a cryogenic near-infrared multi-object spectrometer with integral field units (IFUs) intended for use at the European Southern Observatory Very Large Telescope on Cerro Paranal in Chile. The KMOS Phase A Design Study was undertaken by a consortium of institutes in the UK and Germany working in partnership with the European Southern Observatory. The KMOS Consortium currently comprises:

- Universitäts-Sternwarte München (USM)
- MPI für Extraterrestrische Physik (MPE)
- UK Astronomy Technology Centre (UKATC)
- University of Durham
- University of Oxford
- University of Bristol
- European Southern Observatory (ESO)

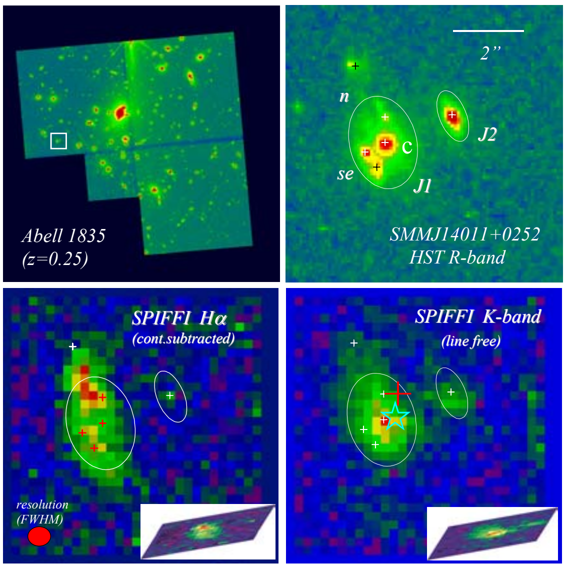
This Executive Summary gives an overview of the primary scientific drivers for KMOS and a presents a viable baseline design for the instrument. It also discusses the routes taken by the consortium to prototype new technology requirements and to limit technical risk by exploring alternative concepts to the baseline design. The final section presents the management structure, estimated costs for equipment and manpower and a preliminary schedule for Phase B, together with the experience and track record of the consortium members.

More detailed descriptions of all aspects of the instrument can be found in the associated Phase A documentation set listed in the following table and available on CD:

Doc. No.	Document Title	Authors
0001	Executive Summary	R Sharples, R Bender
0002	Science Case	M Lehnert et al
0003	Science Requirements Document	M Lehnert et al
0004	Operations, Calibration & Maintenance Document	S Ramsay Howat et al
0005	Systems Architecture	C Tierney
0006	Systems Design	C Tierney et al
0007	Optical Design Architecture	D Lee
0008	Mechanical Design Architecture	P Hastings & C Dickson
0009	Electronics Design Architecture	H Hess et al
0010	Instrument Software User Requirements Document	B Muschielok et al
0011	Data Analysis Software Architecture	N Thatte et al
0012	Phase B Management Plan	G Rae
0013	R&D Study Reports	R Hofmann et al

2. Science Case and Design Requirements for KMOS

Two of the defining influences on the properties of galaxies are Nature and Nurture. These two factors underlie the diverse range of the galaxy populations we see around us in the Universe today and provide the physical origin of such fundamental characteristics of the galaxy population as the integrated star formation history and the morphology-density relation. Charting the balance between Nature and Nurture is thus one of the major goals of cosmology in the next decade and provides a powerful technique for testing models of the formation and evolution of galaxies. Within the next few years it is likely that photometric redshifts, allied with deep wide-angle optical-IR surveys and the current generation of wide-field instruments at large telescopes, will provide distances to unprecedented numbers of young galaxies in the range 1<z<5. These large redshift surveys will be capable of determining the global properties of the galaxy population such as its luminosity evolution and the three-dimensional clustering. The next logical steps will be to investigate the physical processes which drive galaxy formation and evolution over this redshift range and to differentiate between the intrinsic and environmental processes acting on galaxies. To achieve these goals requires a capability to map the variations in star formation histories, spatially resolved star-formation properties, merger rates and dynamical masses of well-defined samples of galaxies across a wide range of environments - stretching from the cores of the richest, highest density clusters out to the low density field - at a series of progressively earlier epochs. A few of the brightest examples are now being observed using single IFUs on 8-metre telescopes (e.g. Fig. 1) but a statistical survey of these galaxy properties will require a multi-object approach. This is the capability which we propose to deliver to the VLT with KMOS.



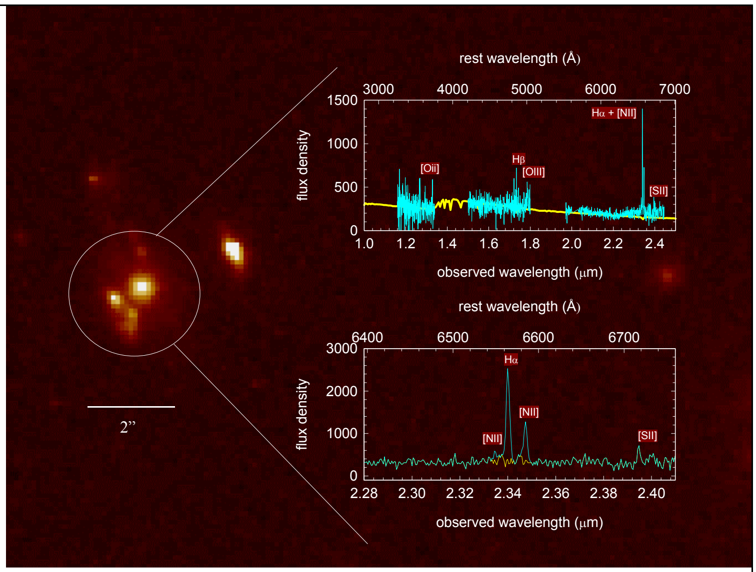


Figure 1(a): The SCUBA galaxy, SMM J14011+0252 (z=2.565). *Top: HST R*-band images; *Bottom:* Hα (*left*) and *K*-band continuum (*right*) images obtained with SPIFFI. In the lower insets are shown the morphologies of the Hα and *K*-band maps when correcting for a lensing magnification of 5 along a position angle of 10 deg.

Figure 1(b): SPIFFI spectra of the central 2.5" of SMM 14011+0252 centred on source J1c. *Top right: JHK* spectrum showing a typical starburst emission-line spectrum. *Bottom right:* zoom into the region around Hα emission showing the narrow line widths, with a blueshifted residual wing that is probably due to a superwind (yellow curve). The line ratios suggest that SMM J14011+0252 has been forming stars for several hundred Myrs .

For any instrument to address these fundamental questions about how galaxies evolve it needs to possess several generic characteristics: 1) high-redshift galaxies are faint, so to take advantage of precious 8-m time the instrument should have a substantial multiplex capability, commensurate with the surface density of accessible targets; 2) to understand the physical properties of galaxies and because galaxies are often complex morphologically (with unpredictable emission-line characteristics – see Fig. 1(a)) it should have the ability to obtain more than just integrated or one-dimensional information; 3) to measure the physical growth of galaxies it should be able to resolve relatively small velocities observed in their rotation curves, velocity dispersions, and relative galaxy velocities in merging pairs; 4) to be able to observe merging galaxies and high redshift cluster galaxies efficiently it should have the ability to observe several targets concentrated in a small area of sky; 5) to take advantage of the large amount of empirical and theoretical information on the optical properties of galaxies, and to gauge more accurately the evolution in the galaxy population, it is essential that the instrument has the capability to observe high-redshift galaxies using the well-studied rest-frame optical diagnostic features used at low redshift (c.f. Fig. 1(b)). These general characteristics suggest a near-infrared multi-object spectrograph using deployable integral field units (IFUs). In addition to the capability of mapping objects with complex continuum and emission line morphologies, the use of IFUs also enables a higher S/N to be achieved and opens up the possibility of deep 3D surveys for emission-line objects. With the capability to cover the *J*, *H*, and *K* bands, such a spectrograph would allow for the investigation of the rest-frame optical properties of galaxies over the redshift range of approximately $0.7 < z < 5.3$ and to make the first explorations of the very high redshift universe $z>7$ by blind spectroscopic area surveys for Ly-α emitters. Moreover, in the crucial redshift range $1.2<z<2.5$, where the morphologies of present-day galaxies emerge, important emission lines are only accessible in the near-infrared.

In the Science Case document (see AD2) we have investigated a number of detailed observational programmes which exploit these general capabilities in order to determine a specific set of baseline design characteristics which any instrument delivering these capabilities should strive to meet. A summary of these design characteristics is given in Table 1. More details of these considerations and the scientific drivers for the baseline design are given in both the Science Case (AD2) and Science Design Requirements (AD3) documents.

Requirement	Baseline Design
Throughput	J=30%, H=40%, K=40%
Sensitivity	J=22.0, H=21.0,K=20.5
Wavelength coverage	1.0 to 2.45 µm
Spectral Resolution	R=3380,3800,3750 (J,H,K)
Number of IFUs	24
Extent of each IFU	2.8 x 2.8 sq. arc seconds
Spatial Sampling	0.2 arc seconds
Patrol field	7.2 arcmin diameter circle
Close packing of IFUs	≥3 within 1 sq arcmin
Closest approach of IFUs	≥3 pairs of IFUs separated by 6 arcsec

Table 1: Baseline capabilities for the KMOS instrument.

3. Instrument Description

KMOS will be a multi-IFU spectrograph designed for operation on the VLT in the J, H and K near-infrared bands. The instrument will mount on the Nasmyth rotator and will use the Nasmyth A&G facilities. The top-level requirements are: (i) to support spatially-resolved (3-D) spectroscopy; (ii) to allow multiplexed spectroscopic observations; (iii) to allow observations across the *J*, *H*, and *K* infrared atmospheric windows (extension to shorter wavelengths will be incorporated at lower priority). The baseline design employs 24 configurable arms that position fold prisms at user-specified locations in the Nasmyth focal plane (Fig. 2). The sub-fields thus selected are then fed to 24 advanced image slicer integral-field units (IFUs) that partition each sub-field into 14 identical slices, with 14 spatial pixels along each slice. Light from the IFUs is dispersed by three cryogenic grating spectrometers which generate 14x14 spectra with ~1000 Nyquist-sampled spectral resolution elements for each of the 24 independent sub-fields. The spectrometers each employ a single 2kx2k HgCdTe detector. Our goal is to employ careful design choices and advances in technology to ensure that KMOS achieves a comparable sensitivity to the current generation of single-IFU infrared spectrometers.

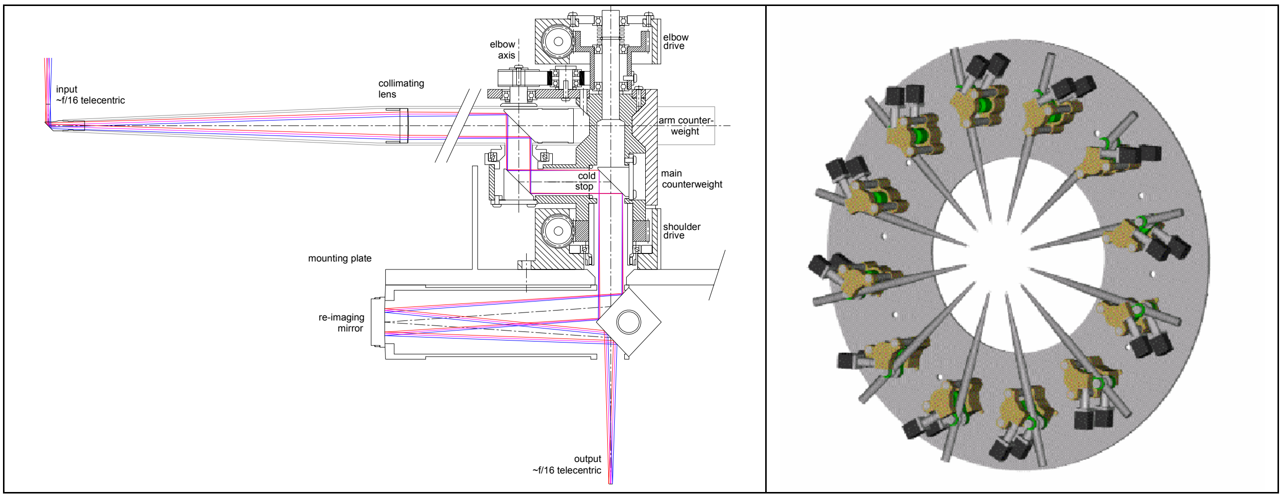


Figure2. *Left:* Mechanical design and optical path through a KMOS pickoff arm; *Right:* Layout of one layer of 12 pickoff arms around the field.

The patrol field of the pickoffs is 7.2 arcmin in diameter, which is the diameter of the unvignetted field at the VLT Nasmyth focus, thus minimising the thermal background in the K-band. Each IFU has a square field of view of 2.8x2.8 arcsec; anamorphic magnification in the IFU foreoptics ensures uniform spatial sampling of 0.2x0.2 arcsec whilst maintaining Nyquist sampling of the spectral resolution element at the detector. Experience with SPIFFI indicates that this pixel size is a good compromise for faint objects even in excellent seeing conditions (i.e. < 0.4 arcsec). Significantly smaller pixels would likely make it difficult to detect low surface brightness extended features. The field of view for each IFU is large enough to allow local sky-subtraction for compact high-redshift targets, doubling the effective multiplex gain over systems which require beam-switching. A crossed beam-switching mode is also possible for multiple extended sources or for critical applications which require minimal systematic effects. The use of focal-plane pickoffs allows considerable flexibility in selecting targets and the important capacity to deal with strongly clustered or close-paired sources. In addition to observing multiple individual sources, KMOS will also have the capability for integral field mapping of contiguous areas (~1.0 sq. arcmin) in a 16-point dither pattern. This mode is useful for very extended sources or blank-field surveys. The three spectrographs may be configured independently to allow simultaneous observations (of different targets) in the J, H or K bands. The spectral resolution of R~3500 provides velocity resolution for studies of low-mass objects and is optimal for OH-avoidance in the J & H bands. Lower resolution modes will allow simultaneous J+H or H+K observations. Since we cannot predict all science applications in the future, our goal is to make KMOS as versatile as possible without compromising reliability or increasing complexity significantly.

From a hardware perspective the instrument partitions into the following key subsystems:

- Pickoff subsystem
- IFU subsystem
- Spectrograph subsystem
- Detector subsystem

Each of these is mechanically supported, and cooled, by an annular optics bench that is enclosed in a vacuum chamber which mounts onto the Nasmyth flange. The estimated total weight of the instrument is 2200kg with a mass moment of 1750 kg m (Fig. 3).

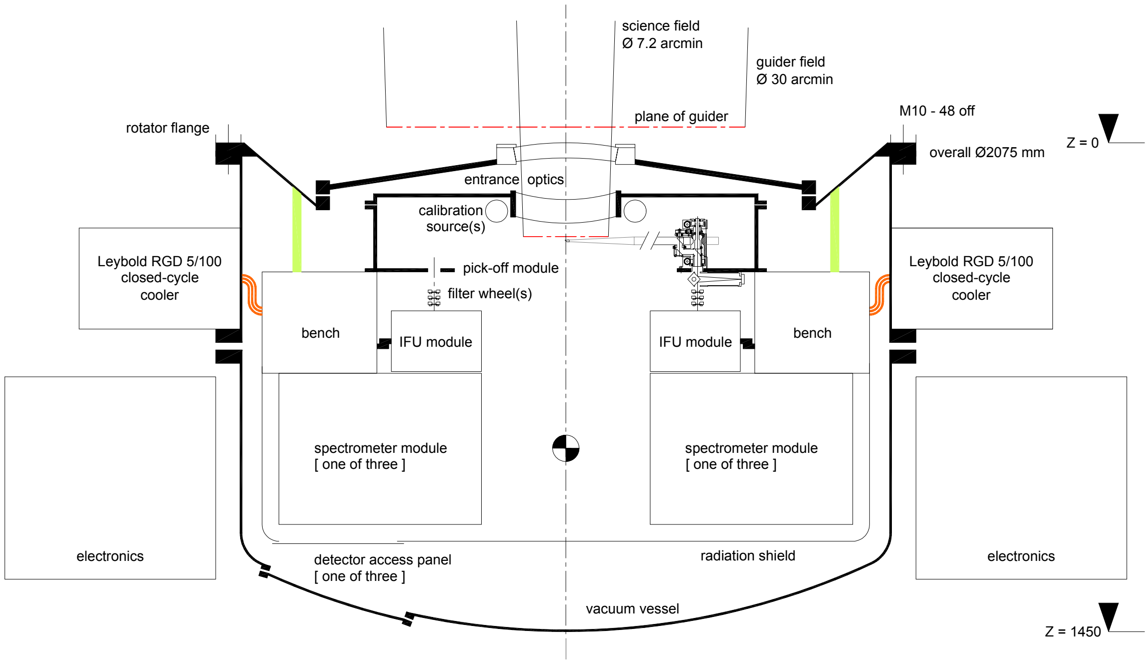


Figure 3. Cross-sectional schematic view of KMOS looking down towards the Nasmyth platform. The vacuum vessel is cylindrical with its axis of symmetry aligned with the Nasmyth axis. The electronics racks are supported from the Nasmyth rotator flange by a framework (not shown) which is independent of the vacuum vessel. The annular bench carries all the cooled subsystems and is supported from the rotator flange by a thermally insulated truss structure.

The *pickoff subsystem* contains fore-optics to produce a flat, telecentric Nasmyth focal plane, a set of mechanical arms driven by cryogenic stepper-motors that can be configured to pick off sub-fields of the 7.2 arcmin diameter Nasmyth field, and optics/mechanisms to filter the resultant output beams. In addition, the sub-system houses a calibration unit that provides the ability to verify and calibrate the end-to-end performance of the instrument. The use of a flat, telecentric focal plane allows the arms to patrol in one of two flat planes perpendicular to the optical axis and minimizes contention of the arms during object acquisition. The cryogenic mechanisms employed have demonstrated high reliability and have been the subject of extensive technology tests (see Section 4).

The *IFU subsystem* contains optics that collect the output beam from each of the 24 pickoffs and reimage with appropriate anamorphic magnification on the image slicers. The slices from groups of 8 sub-fields are aligned and reformatted into a single slit for each of the three spectrographs. The IFU sub-system has no moving parts and has gold-coated surfaces diamond-machined from aluminium for optimal performance in the near-infrared and at cryogenic temperatures. The design and manufacture of the IFUs draws heavily on experience we have developed in building other cryogenic integral-field spectrometers.

The *spectrograph subsystem* is comprised of three identical units, which supply three detector sub-systems. Each spectrograph uses a single off-axis toroidal mirror to collimate the incoming light, which is then dispersed via a reflection grating and refocussed using a 5-element transmissive camera. The gratings are mounted on a 6-position turret which allows optimized gratings to be used for the individual J,H,K bands together with two lower resolution gratings and the option of a z-band grating to enhance versatility.

The *detector subsystem* is comprised of three units, which house identical 2048x2048 HgCdTe arrays with 18 micron pixels. Each detector is mounted on a three-axis translation stage in order that focus can be adjusted and, if required, some components of flexure can be compensated.

More detailed descriptions of the above subsystems, and the infrastructure module which provides common support and services, can be found in the Systems Architecture (AD5) and System Design (AD6) documents. The architectures adopted for optics, mechanics and electronics are described in documents AD7, AD8 and AD9 and the detector subsystem in document RD1.

In use at the telescope, KMOS will be a complex instrument requiring high-level software control and pipelined data analysis. We have studied extensively the operations requirements including field setup, acquisition, calibration and data reduction, building on our extensive experience with commissioning the SPIFFI(VLT) and UIST(UKIRT) integral field spectrometers within the past 12 months. These requirements are described more extensively in the Operations, Calibration and Maintenance document (AD4). A full description of the instrument control software and the data reduction software is given in the Instrument Software User Requirements (AD10) and Data Analysis Software Architecture (AD11) documents.

4. Proof of Technology Studies and Alternative Design Solutions

The development of a multiple-object near-infrared integral-field spectrometer would be a significant step forward in the capabilities for an 8-m telescope. No such instrument has yet been built, although several 8-m telescopes have single near-infrared IFUs either commissioned or in the final build phase (e.g. VLT-SPIFFI, Gemini-CIRPASS, Gemini-GNIRS, Keck-OSIRIS). We have therefore undertaken a number of technology demonstrator programmes, both to verify the baseline technology for KMOS and to explore alternatives to the baseline concept presented in Section 3. Full reports on these activities are given in the R&D Study Reports (AD13) which we summarize here.

Prototype Pickoff Arm. One of the more novel aspects of the KMOS design is the use of robotically controlled pickoff arms to select the sample of multiple objects for IFU spectroscopy. The KMOS baseline design uses optical components mounted in a carbon fibre pick-off arm to relay sub-fields of the VLT focal plane onto the integral field system. Positioning systems of this type offer the versatility required to address the science programmes illustrated in the KMOS Science Case (AD2) and the capacity to engage entirely new areas of study which will undoubtedly be developed in the next 8-10 years. Prototyping of the carbon-fibre arm technology has been undertaken via the POPS project (Precision Optical Pickoff System) funded through the UK PPARC Industrial Support Scheme. The goals of the POPS project were (i) to demonstrate the use of carbon fibre in a cryogenic environment; (ii) to confirm that tight tolerances on positioning and alignment can be met and maintained; (iii) to develop an industrial link to investigate manufacturing issues for a significant numbers of arms. The first phase of this project is complete indicating that basic positioning accuracies can be achieved; a prototype arm is shown in Fig. 4.

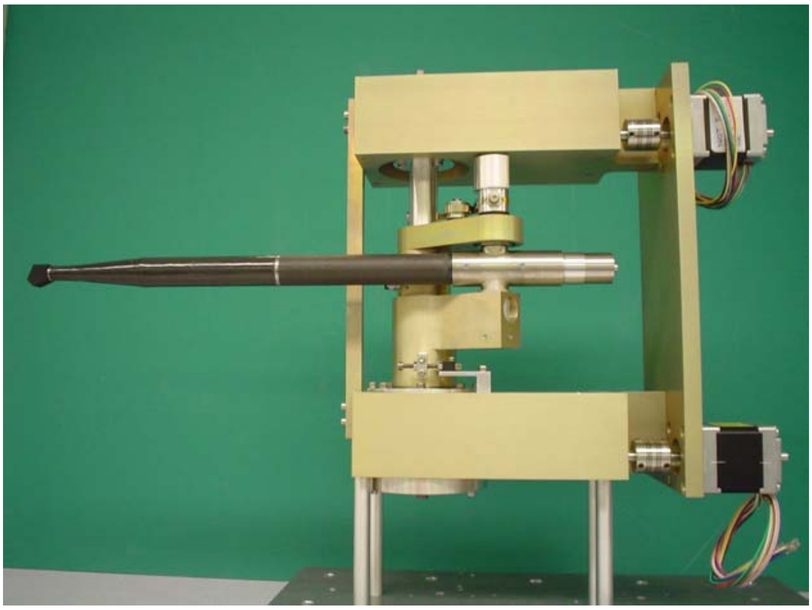


Figure 4. The assembled POPS pickoff arm. The KMOS pickoff arms will have a more compact housing but will use the same positioning mechanisms.

Image Slicer IFUs. The principle aims of this study were to: (i) investigate methods of multiplexing multiple IFUs into a single spectrograph; (ii) investigate the quality of diamond-machined IFU elements; (iii) investigate the practicality of using arrays of optical elements to reduce alignment errors; (iv) investigate the feasibility of manufacturing multiple IFUs. These have all been explored within the context of also producing a single IFU system for the Gemini GNIRS spectrograph. Optical designs for multiplexing 8 IFUs into a single spectrograph have been successfully produced which require only 4 different designs for the foreoptics and have common slicer, pupil and slit mirror arrays. The monolithic optics approach appears viable with typical P-V surface errors of $\lambda/2$ and RMS of $\lambda/25$; the use of diamond-machined aluminium components with monolithic integrated mounts effectively eliminates any problems of differential thermal expansion on alignment. A concept for manufacture and alignment of multiple identical components has been explored with a specialist machining company thus alleviating concerns over manufacturability. The risk of a single source of supply remains, however, which we are attempting to alleviate by developing an independent manufacturing capability within the consortium.

Steering Mirror Units. An alternative concept to moveable focal plane pickoffs for selecting targets for a multiple-object IFU spectrometer would be to tile the focal plane with a set of fixed field lenses, and then use multiple beam steering mirrors located at the re-imaged pupils to select the objects of interest from within the field of view of each lens. Whilst this approach has less flexibility in terms of object acquisition (particularly for objects which are strongly clustered on the sky or which are spread over only a part of the accessible infrared field) the movements required of the steering mirrors are simpler than for the pickoff arms (typically only a few degrees in each of two orthogonal axes) and there is no contention between mechanisms should one of the actuators fail. The challenge in this case is to find a technology which can position the beam steering mirrors accurately and repeatedly whilst operating at cryogenic temperatures and having minimum power dissipation. Concepts for beam-steering mirrors were first explored as part of the GIRMOS design study for a multi-IFU spectrometer for the Gemini telescopes, but no prototypes were developed. We have now discovered a very promising technology based on piezo-actuated Nanomotors using LVDTs as position transducers to measure the displacements. A compact beam steering mirror assembly has been developed and a prototype is currently under test (Fig. 5). This option of replacing the focal plane pickoffs with a set of beam-steering mirrors remains a viable backup plan should the positioning accuracy and reliability of the pickoff arms not fulfil its design requirements. It is not our baseline design, however, because of the reduced functionality in accessing clustered targets which we believe will be an important capability given the timescale for bringing KMOS to the telescope (c.f AD2).

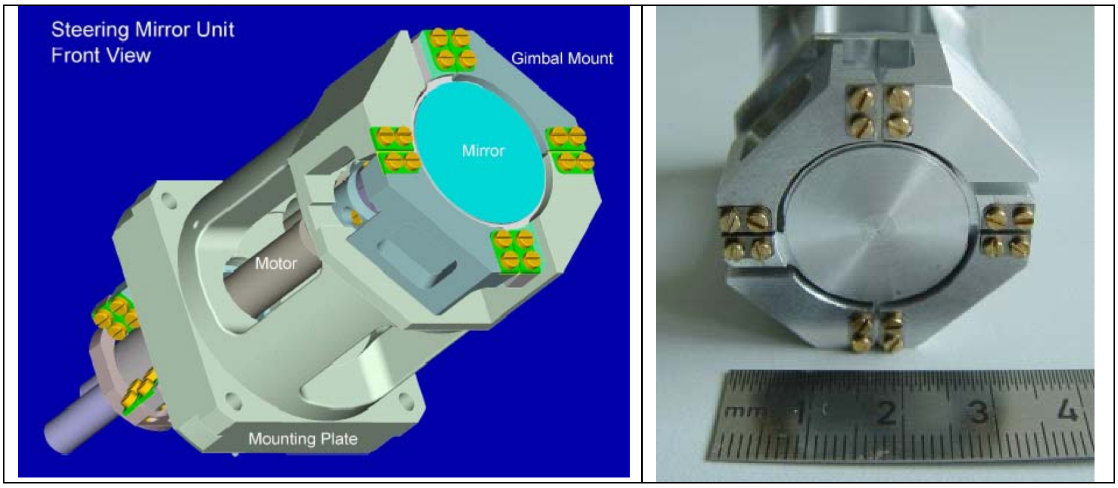


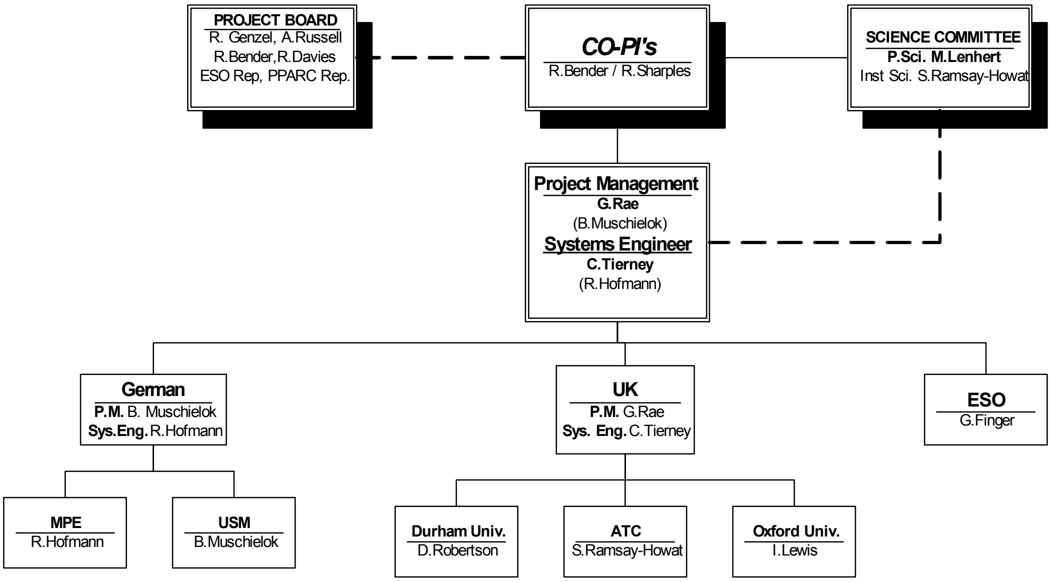
Figure5. 3D model and manufactured prototype beam steering mirror using Nanomoters and LVDTs.

Cryogenic Mechanisms. Our baseline design for KMOS uses a large number of cryogenic motors to position the arms and other mechanisms (e.g. the grating turret). It is essential therefore to have confidence in the reliability of these mechanisms and in the correct preparation of the motors for use at cryogenic temperatures. There is considerable experience within the consortium of the preparation and use of cryogenic stepper motors (CGS4, MICHELLE, UIST, SPIFFI, WFCAM). As part of this study we have consolidated the accumulated experience in this area and undertaken extensive soak-testing of the cryo-motors proposed for use in KMOS.

Fibre IFUs. Optical fibres have been used extensively in integral-field instruments at optical wavelengths (e.g. GMOS-IFU, FLAMES-IFU, VIMOS-IFU). They offer an advantage in versatility when coupling the spectrometer input to the focal plane, particularly when a range of spatial scales is required. At infrared wavelengths they have been explored for use in the J & H bands (Gemini-CIRPASS, Subaru-FMOS) but their performance at the cryogenic temperatures required for K-band operations (particularly when interfaced to lenslet arrays) is not yet well understood and we are in the process of studying this question. Whilst fibre IFUs generally have lower transmission and use the detector pixels less efficiently than image slicer IFUs, they would provide a useful backup option in the case of manufacturing difficulties with the slicer IFUs.

5. Management Plan

KMOS will be built by a consortium of institutes in the UK and Germany working in partnership with the European Southern Observatory. The consortium will bring together the combined expertise of instrument groups at each institute which have an established track record in building a range of instrumentation for 4-metre and 8-metre class telescopes. These include SPIFFI (MPE), CONICA (MPE), LUCIFER (MPE), FORS (USM), OMEGACAM (USM), GMOS (ATC/Durham), MICHELLE (ATC), CGS4 (ATC), UIST (ATC), AUTOFIB-2 (Durham), GMOS-IFU (Durham) and FMOS (Oxford/Durham). This combined expertise covers all the critical requirements for the KMOS instrument including robotic positioners, integral field units, cryogenic mechanisms, infrared detectors, instrument control, cryogenic spectrographs and data processing pipelines. The consortium will adopt a strong systems-level approach co-ordinated by a single project management team in order to deliver the instrument within budget and on schedule. The project team structure is shown in the following organogram.



The consortium will be organised as a joint engineering management team with system design responsibilities, and a number of "product teams" each responsible for a clearly identified subsystem or subassembly, within which the team have the appropriate design authority. The subsystem teams will work together via the engineering management team structure to manage the project design process within and across engineering disciplines. The Systems Engineer will act as the focus for all project system design activity by the Consortium. In this arrangement, the Project Manager and the Systems Engineer (and nominated deputies) will operate together to drive forward the design and provision of the instrument. This arrangement of "integrated product teams" with design responsibility within their subsystem, coupled with a system level design team, has worked well on other large international projects.

The estimated costs for the baseline KMOS at the end of the Phase A studies are shown in the following table:

Subsystem	**Capital (kEuro)**	**Manpower (FTE)**
Infrastructure	875	17.0
Pickoff Subsystem	1367	17.0
IFU Subsystem	1348	4.4
Spectrograph Subsystem	542	10.0
Detector Subsystem	2023	2.7
Electronics	558	27.0
Instrument Software	141	25.1
Data Reduction Software	25	9.0
Sub-Total	**6879**	**112.2**
Spares	247	
Overall AIT		12
Commissioning		4
Total	**7126**	**128.2**

We propose that a suitable contingency at this stage of the project would comprise 10% of hardware costs and 20% of manpower costs. Management costs are shown separately below:

Management Costs	Travel/Freight/Hardware	Manpower
German PM	466	9.1
UK PM	375	8.0
Overall PM	50	4.0

The provisional dates for key milestones in Phase B are given in the following table:

Key Milestone	Provisional Date
Phase B Start	May 2004
PDR	April 2005
FDR	March 2006
Start AIV	January 2008
European Acceptance	January 2009
Preliminary Acceptance Chile	June 2009

A detailed description of the consortium work breakdown structure, costs and schedule are contained in the Phase B Management Plan (AD12).