Precision cryogenic mechanisms for the Michelle mid-IR spectrograph

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ABSTRACT

The UKATC[1] has recently delivered and commissioned the Michelle mid-IR spectrograph[2] on UKIRT[3]. This instrument has a variety of precision vacuum-cryogenic mechanisms that utilize technology developed over a number of years at the UKATC[4] in instruments such as IRCAM[5], CGS4[6], SCUBA[7], GMOS[8] and UIST[9]. In these applications it is critical that the mechanisms operate reliably and with a high degree of precision. In most cases the mechanisms support optical elements that must be rigidly held in place when the instrument is tilted during observations on the telescope. This paper describes the level of performance achieved with the Michelle mechanisms and the critical elements of their design.

Keywords: Cryogenic, mechanisms

1. MICHELLE AND ITS MECHANISMS

The Michelle instrument an all-reflective 8-25 micron long-slit spectrometer and imager which is built at the UKATC for operation on both the UKIRT 4 meter and the Gemini 8 meter telescopes.

This section describes the mechanisms and their design requirements, all operate at 60K.

1.1 Grating exchange/wavelength selection mechanism

The grating exchange mechanism is a turret device that allows the selection of one of four gratings or an Echelle. Once a grating is selected it can be tilted to any angle in the allowable range. The grating tilt angle is maintained to a high precision during an observation by passive means, the mechanism is very rigid.

Grating exchange – facts at a glance	
Indexing mass	45Kg
Gratings/Echelle mass	7Kg
Mechanism type	Worm and wheel
Indexing ratio	200:1
Indexing range	360 degrees
Grating tilt ratio	120:1
Grating tilt range	-20,+20 degrees (-10,+70 for echelle)
Motor	Stepper motor
No. Gratings	4 + 1 echelle
Indexing repeatability requirement	±30 microradians
Grating tilt repeatability requirement	±10,±20 microradians. spectral and spatial resp
Flexural stability requirements (20 deg tip)	0.5, 1.0 microradians, spectral and spatial resp. 100 microns displacement.
Main axis bearings	Duplex FF pair matched and preloaded angular contact
Grating tilt axis	Axially pre-loaded deep groove ball bearings
Datum or home	microswitch
Time to re-configure	60 seconds

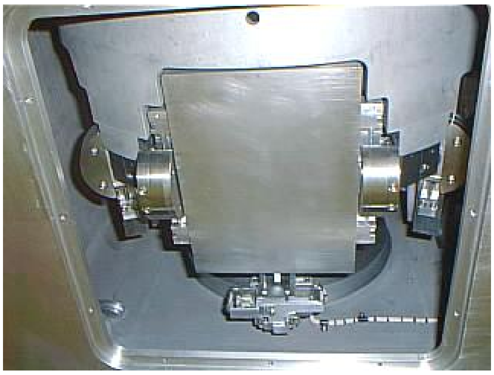

Fig. 1: GEM mechanism

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1.2 Slit rotation/selection mechanism

The slit rotation mechanism allows the selection of up to 7 slits by indexing the slit wheel. Once selected, a slit can be set to any angle in the allowable range. The selection and angle of the slit must be repeatable to high degree of precision.

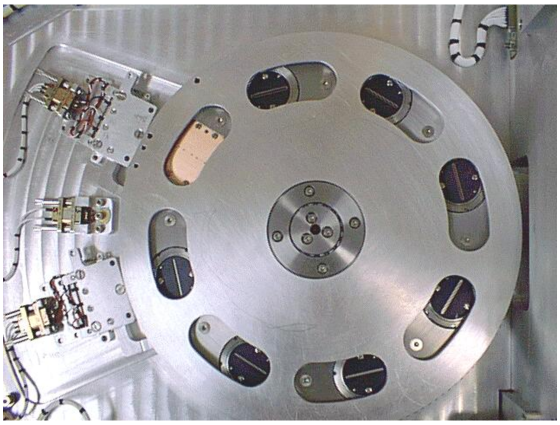


Fig 2: Slit rotation/selection mechanism

Slit rotation mechanism – facts at a glance	
Moving mass	2Kg
Mechanism type	Worm and wheel
Indexing ratio	120:1
Indexing range	360 degrees
Slit rotation range	±45 degrees
Motor	Stepper motor
Number of slits	7, one position for pinholes
Indexing repeatability requirement	±100 microradians
Slit rotation repeatability requirement	±100 microradians
Flexure rotation for 20 degree tilt	±40 microradians and ±100 microradians, in slit plane and out of it resp.
Main axis bearings	Axially pre-loaded deep groove ball bearings
Slit holder bearings	Preloaded angular contact
Datum or home	microswitch
Time to re-configure	30 seconds

1.3 Filter mechanisms

The two filter mechanisms allow the selection of up to 23 filters each by indexing the filter wheel. The selection of the filter must be repeatable to high degree of precision.

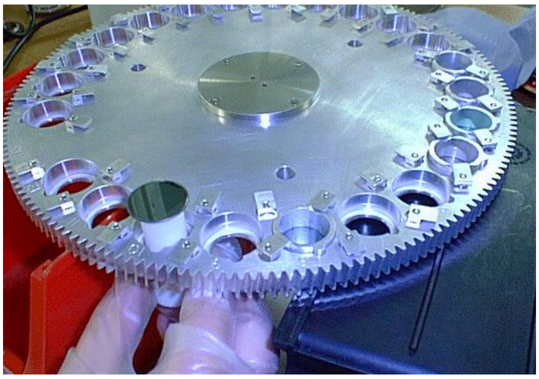


Fig. 3: Filter mechanism

Filter mechanism – facts at a glance	
Moving mass	1Kg
Mechanism type	Worm and wheel
Indexing ratio	120:1
Indexing range	360 degrees
Slit rotation range	-40,+40 degrees
Motor	Stepper motor
Number of filters	24 (one blank)
Indexing repeatability requirement	±100 microradians
Flexure tolerance for 20 degree tip	±50 microradians
Main axis bearings	Axially pre-loaded thin section AC bearings
Slit holder bearings	Preloaded angular contact
Datum or home	microswitch
Time to re-configure	30 seconds

1.4 Image rotator mechanism

The image rotator mechanism provides rotation of the image by rotation of a three mirror assembly mounted on a worm wheel. The image can be rotated to any angle.

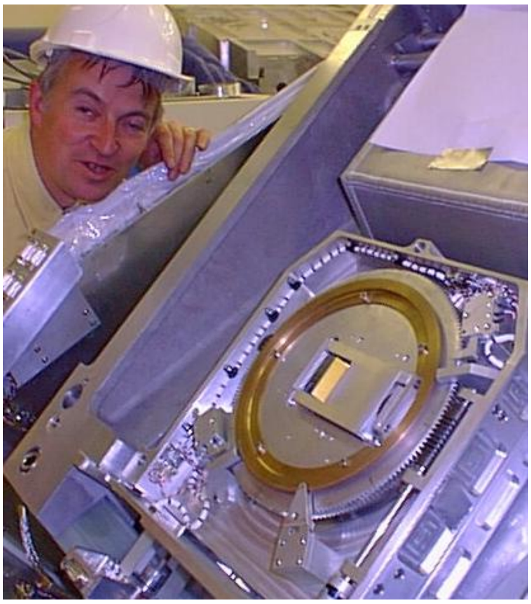


Image rotator mechanism – facts at a glance	
Moving mass	1Kg
Mechanism type	Worm and wheel
Indexing ratio	120:1
Rotation range	340 degrees
Motor	Stepper motor
Indexing repeatability requirement	±100 microradians
Main axis bearings	Thin section AC pair
Datum or home	microswitch
Time to re-configure	30 seconds

Fig. 4: Image rotator mechanism

1.5 Image inject and extract mechanisms

The mirror deployment mechanisms deploy folding mirrors by means of a linear slide and lead screw. The deployed mirror position and tilt are defined by a semi-kinematic mirror mount onto which the mirror is pushed by three springs. This relaxes the precision requirements of the slide and lead-screw.

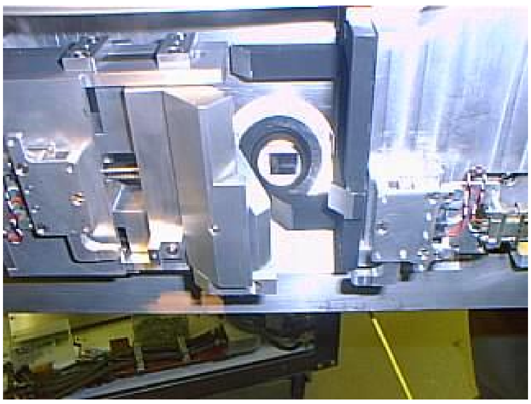


Fig. 5: Image inject mechanism

Imager relay mirror mechanism – facts at a glance	
Moving mass (translation)	0.5Kg
Mechanism type	Linear slide and pre-loaded lead screws
Lead screw pitch	1mm
Translation range	45mm
Motor	Stepper motor
Translation repeatability requirement	±2.5 microns
Flexural stability	±2.5 microns, ± 10 microradians
Slides	Machined Al alloy, Vespel runners
Datum or home	microswitch
Time to re-configure	30 seconds

1.5 Detector focus/translation mechanism

The detector focus translation mechanism provides parallel motion of the detector assembly in the focus and dispersion directions. This is achieved by mounting the assembly on parallel flexures. G10 blades are used on the focus stage, and necked down pivots in Aluminium alloy are used for the translation stage. Lead screws driven by stepper motors are used to control the position.

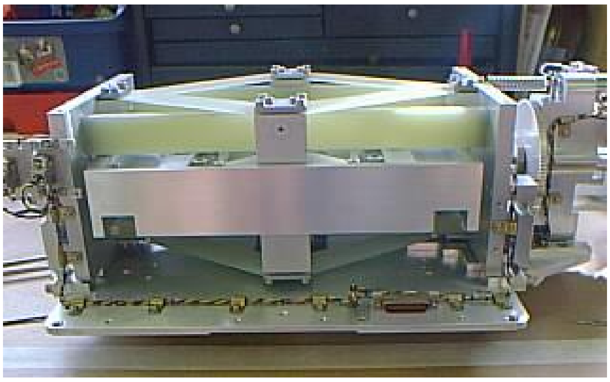


Fig 6: Detector focus/translation mechanism

Image rotator mechanism – facts at a glance	
Moving mass (translation)	5Kg
Moving mass (focus)	2Kg
Mechanism type	Pre-loaded lead screws
Lead screw pitch (trans.)	1mm
Lead screw pitch (focus)	1.25mm
Translation range	±0.25mm
Focus range	±2.5mm
Motor	Stepper motor
Translation repeatability requirement	±1 micron
Focus repeatability requirement	±20 microns
Flexural tolerance for 20 degree tip (dispersion)	±1 micron, ±5 microradians
Flexural tolerance for 2o degree tip (spatial)	±2 microns, ±5 microradians
Flexures	G10 glass fibre composite blade flexures and Aluminium alloy pivots
Datum or home	microswitch
Time to re-configure	30 seconds

2. CRYOGENIC MECHANISM ELEMENTS

2.1 Bearings and bearing housings

This aspect of precision cryogenic mechanism design is crucial. The principles involved are very simple, the bearings are stainless steel and not a good match for thermal contractions to the Aluminium alloys typically used for the housings. This is particularly true of precision bearings with low clearance and for bearing pairs that are pre-loaded and have no internal clearance. The Following describes the bearing types used in Michelle and how they are housed.

2.1.1 Small deep groove ball bearings for stepper motors(ID,6mm)

The bearings are stainless steel, ordered without shields or lubrication and have a 'C3' radial clearance class. This is a higher radial clearance than standard, has more tolerance to crushing from the housing and establishes a higher contact angle when axially pre-loaded by the coils spring inside the motors.

Motor bearing housings

The bearing housings are an integral part of the motors and are not modified. On cool-down the housings crush down on the bearing outers but the increased radial clearance prevents excessive bearing loads.

2.1.2 Small deep groove ball bearings for drive shafts and small spindles (ID 6 and 10mm)

The bearings are flanged and stainless steel and are ordered without shields or lubrication. They are axially pre-loaded with disk springs.

Drive shaft bearing housings
For these bearings, the housing diameters are relieved to have approximately 24 and 40 microns clearance respectively warm. Nominally, they are size for size at the operating temperature.

Small spindle bearing housings (10mm ID bearings)
These are precision spindles that carry optical grating assemblies that must be rigidly held and repeatably positioned in angle both warm and cold. It is therefore not possible to have clearance in these housings. To overcome the crushing effects of the Aluminium Housing on cooling, a thick stainless steel sleeve is used. The sleeves are made from 416 series stainless steel to closely match the bearings. The bearings are a light push fit into the sleeves when warm.

2.1.3 Angular contact duplex pairs (ID 25mm- 125mm)
These bearings are used in precision spindles that define rotational axes for optical elements. In the Michelle instrument they were used to support the main axle of the grating exchange mechanism. They consist of a matched pair of angular contact bearings in stainless steel mounted face to face. The vendor grinds the bearing races such that when they are axially clamped together, a pre-load is established between the bearings. This eliminates clearance and increases the stiffness of the bearing set.

Duplex bearing pair housings
As these pre-loaded bearings have no internal clearance, they are mounted in a thick walled (10mm) 416 stainless steel sub-housing that in turn fits into the Aluminium structure. It was not practical in this case to increase the thickness of the housing further. Even with this level of protection, the Aluminium housing itself had to be relieved to prevent significant crushing of the bearings.

The housings comprise of an inner hub and an outer rim each with annular end plates that clamp the bearing inners and outers together. The inner hub has a tapered inner diameter and tapered Colett that clamps to the mechanism axle. This is a self-contained sub-assembly and was tested independently assembled to a dummy Aluminium housing in a test cryostat. The degree of crushing of the bearings can be determined by monitoring the turning torque against temperature. The pre-load on the bearings can be relieved as required by shimming the outer rim and the effectiveness of relieving the housing can also be determined.

2.1.4 Lubrication
The smaller bearings were lubricated with a Molybdenum Disulphide dry lubricant. This is first sprayed sparingly onto the bearings that are then run in for a time and cleaned to remove the resulting debris.

The larger bearings were ordered with a proprietary Tungsten Disulphide dry film lubricant. They too were run in for a time under pre-load and cleaned.

2.2 Worm and wheel drives
Worm and wheel drives are employed on all of the Michelle rotary mechanisms. These provide a high reduction ratio (100-200:1) with only two moving elements. The worm wheels are machined from Aluminium alloy and the worms are made from Vespel[9] SP3, a self-lubricating Polyimide plastic.

2.2.1 Balancing
The loads on the worm wheels are balanced for the following reasons:

1. This removes the dependency of drive torque on orientation.
   This enhances the reliability of the mechanism in terms of it functioning at different instrument orientations.
   As the stepper motor mechanisms are ‘open loop’ this enhances the accuracy and repeatability of the mechanisms operating at different instrument orientations by limiting wind-up in the drive train

2. Reduces the drive torque required.
   This is of obvious benefit in motor selection. Small motors can be used to drive a large balanced load with suitable gear reduction and ant-friction bearings
   There is less wear on drive train components such as the worm.
3. Reduces orientation dependent flexure
   With a balanced mechanism there is no orientation dependent torque and therefore no tendency for the mechanism to flex in rotation. This can be very useful if high angular stability is required.
4. Reduces stick-slip instability when 'down hill' driving
   With these mechanisms there is an unstable mode when they are driven 'down hill'. This is less likely if the mechanism is balanced i.e. the mechanism is neutral in any orientation.
5. Reduces the brake force required
   Brakes are desirable for reasons listed below but it is advantageous to limit it to that which is necessary.

2.2.2 Brakes

All of the rotary mechanisms have brakes. These are implemented as passive friction brakes that are permanently active. The brakes comprise of a rigid parallel flexure tangent arm and Vespel-SP3 brake pads sprung loaded onto the rotor. The brakes are required for the following reasons.

1. Stability of the mechanism during tracking/slewing.
   The mechanisms must not move during or between observations. The brakes must therefore provide a greater frictional torque than the inertial torque generated during tracking and slewing. This also allows some error in the level of balancing required.
2. Friction damping
   The brakes provide friction damping that tends to enhance the dynamic stability of the mechanism and damp resonances that stepper motors are prone to generate
3. Powering down the motors
   There is no tendency for the mechanism to move when the motors are powered down

2.2.3 Backlash

The worm and wheel drives have considerable backlash. This is necessary to account for differential contractions and desirable from the point of view of manufacturing tolerances. The backlash is controlled by always moving the mechanism in the same direction in the final move. The passive brake ensures that the mechanism does not wander within the backlash.

2.3 Linear motion mechanisms

The cold linear mechanisms in Michelle include two similar linear slides used to deploy fold mirrors in the imager mode and linear flexure mechanisms to move the detector assembly in focus and translation.

2.3.1 Imager mode mirror slides

These devices are similar and comprise of a linear slide formed from a machined slot in an Aluminium slide and a Vespel-SP3 'shoe' acting as a plain bearing on the moving part. The movement is provided by a 1mm pitch leadscrew operating on a Vespel nut carried on the moving part. The leadscrew is driven by a stepper motor via a right angled bevel drive.

The mechanism retracts and inserts a flat mirror and is required to have a high degree of repeatability only at the inserted position. This is achieved effectively by having a 'floating' mirror that is forced against three stops arranged in a semi-kinematic arrangement. The mechanism overdrives until the mirror is seated on its pads, there is therefore no need for high precision in the direction of motion or indeed in the plane of the flat mirror.

2.3.2 Focus mechanism

This mechanism consists of a set of G10 fibreglass flexures that provide parallel motion. The focus movement is provided by a 1.25mm pitch leadscrew driven by a stepper motor via a bevel gear. The leadscrew operates on a Vespel nut attached to the moving detector assembly. Prel-load is applied by a compression spring.

2.3.3 Detector translation mechanism

This mechanism consists of a set of Aluminium flex pivots that provide parallel motion. The translation movement is provided by a 1mm-pitch leadscrew driven by a stepper motor via a spur gear. The leadscrew operates on a Vespel nut attached to the moving detector assembly. The backlash in the leadscrew and nut is removed by spring pre-load of the detector assembly.

2.3.4 Counter balance

The detector assembly has very stringent requirements on its stability during tracking and moving of the telescope. A problem here is gravity-induced flexure of the detector assembly as the instrument changes in orientation relative to the gravity vector. To counteract this effect a counterbalance mechanism was employed in Michelle consisting of a counterbalance weight and lever system. This acted in the spatial direction.

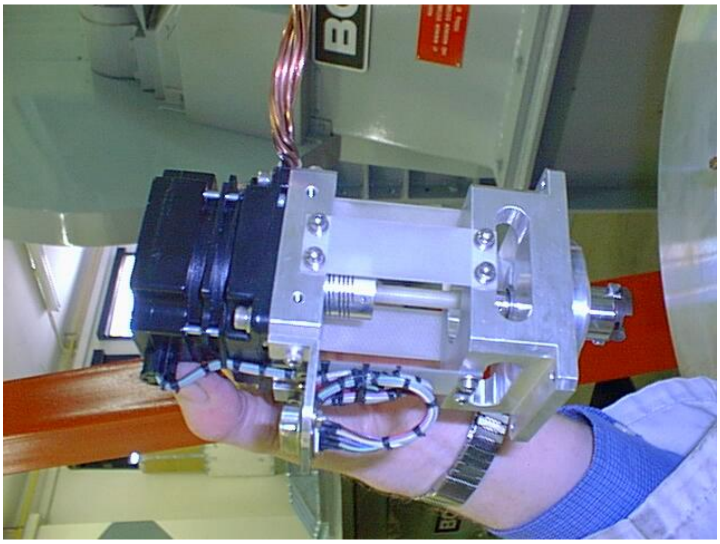
2.4 Stepper motors

The motors used in Michelle are all identical Berger Lahr VRDN 564/50 LNA 5 phase stepper motors modified for cryogenic/vacuum use. These provide a nominal 30 Ncm torque at room temperature and 500 steps per rev in full step mode. There is no appreciable loss of torque when cold. The use of the same motor to move mechanisms ranging from 0.5Kg to 40Kg is somewhat non-optimal but there are clear advantages in commonality. The motors were run in half step mode for the most part to give smoother operation.

2.4.1 Preparing the motors

The motors are disassembled and cleaned.
The standard motor bearings are replaced by vacuum and cryo-prepared stainless steel bearings.
The replacement bearings have a high radial clearance
During the disassembly and re-assembly, a keeper cylinder is used to prevent de-magnetisation of the motor.

Fig. 7: Motor and drive shaft assembly



2.5 Microswitches

The mechanisms all use micro-switches to define a home position. The positions are then determined by step counting from that position.

3. GENERAL DESIGN PRINCIPLES

General design principles have been established in the development of cryogenic mechanisms at the UKATC. Our experience in developing the Michelle mechanisms have underlined their importance and they are listed below.

3.1 All mechanism must be designed to function and perform equally well warm and cold

This allows the great majority of the integration and testing to be performed warm. The work can be performed earlier in the development and iteration cycles dictated by test results are faster as there is no need for a cryostat and repeated cool-down cycles. This does not remove the need for cold testing.

3.2 All rotary mechanisms must be balanced and large linear devices counterbalanced

Balancing the mechanisms is often not popular as it adds mass, requires more space and requires extra components. The benefits nearly always outweigh these perceived disadvantages. The benefit in terms of mechanism actuation include a reduction in the torque required to move the mechanism and de-sensitivity to changing gravity vectors. This enhances the positional repeatability. The benefit in terms of flexural stability include de-sensitivity in respect to tilts of the mechanism (displacements for linear mechanisms) to changes in the gravity vector.

3.3 All rotary mechanisms have passive friction damping of the moving elements including free rotating elements of the drive train

This measure is not obviously of benefit as friction is normally minimized in a precision device. There are however a number of benefits that far outweigh this perceived disadvantage. For a nominally balanced mechanism the amount of braking required is small. If the mechanism has a brake, it will not tend to move with the motor de-powered due to changing orientations and slew accelerations on the telescope. The moving element has negative friction damping which enhances the dynamic stability of the control. In most cases this makes the drive operate smoothly, but in some cases it can prevent serious instability and loss of steps.

3.4 Employ modular design allowing testing at subsystem level

An example of this in Michelle is the bearing modules for the grating exchange mechanism spindle. These sub assemblies comprise the bearing housing, bearings, pre-load shims and taper lock hub. The bearings are preloaded within this assembly and were tested independently warm and then cold in a small test cryostat. They did not require assembly to the main cold structure for testing avoiding long and costly thermal cycling.

3.5 Test the mechanisms in as realistic an environment as is practical

This is not a design principle as such, but the testing of the mechanisms in different orientations warm and at the operating temperature has always proven to be useful. For large sub assemblies and instrument the infrastructure required is considerable. At the UKATC we employ a modified welding manipulator as a telescope simulator. This has proven invaluable for detecting problems and evaluating remedial work prior to delivery of the instrument to the telescope where modifications are difficult time consuming and expensive.

4. MECHANISM TESTING

The mechanisms in Michelle underwent extensive testing as part of the Integration and Test of the instrument prior to delivery. The tests progressed through individual elements of the mechanisms, through sub-assembly testing and finally using the fully operational instrument mounted on a telescope simulator.

4.1 Bearing mount testing

A simple test of the bearing ‘athermal’ mounts was carried out by cooling individual mechanisms in liquid Nitrogen and confirming that the bearings rotated freely.

A more sophisticated test was done for the larger duplex pairs by cooling the bearing sub-assembly and dummy housing in a test cryostat and monitoring the turning torque. This was done simply using torque screwdriver via a vacuum feed through.

4.2 Warm functional tests

On assembly the mechanisms awere first checked by operating full range by hand and noting the level and consistency of turning torques. With the motors removed, the turning torque was measured for comparison with the 30Ncm expected motor output. The backlash is also checked for the worm wheels at the start, mid and end of travel.

The mechanisms were then operated warm using the software and the various functions checked such as 'homing', moving to position, anti-backlash moves and so on.

Some level of reliability checking was then done by repeating operations and monitoring for failure.

4.3 Warm flexure tests

Warm flexure tests were carried out on the critical mechanisms. These included the grating exchange mechanism and the detector focus translation mechanism.

4.3.1 Grating exchange mechanism warm flexure tests.

These tests were done by measuring direct tilts of the gratings using high-resolution (0.1 micron) LVDT probes. The probes were mounted on the GEM rotating sub assembly by purpose made bracketry. The entire assembly was then tilted with respect to gravity and the displacements recorded. This gave the flexures of the grating relative to the GEM spindle.

These tests were repeated with the rotating part assembled to the GEM casting. This includes the flexures from the GEM main bearings.

The results from the probes were converted to tilts of the gratings and line of sight equations used to determine the resulting image motion on the detector focal plane. This number was compared to the allocation in the top down error budget.

4.3.2 Detector focus translation mechanism

These tests were done by measuring direct displacements of the detector housing using high-resolution (0.1 micron) LVDT probes. The probes were mounted on the detector focus/translation sub assembly by purpose made bracketry. The entire assembly was then tilted with respect to gravity and the displacements recorded. This gave the flexures of the detector housing relative to the focus translation baseplate.

The cold flexure tests were done with the fully assembled instrument mounted on a telescope simulator. Imaging an illuminated pinhole at the slit plane, the image motion due to mechanism flexure and connecting structural flexure was directly measured.

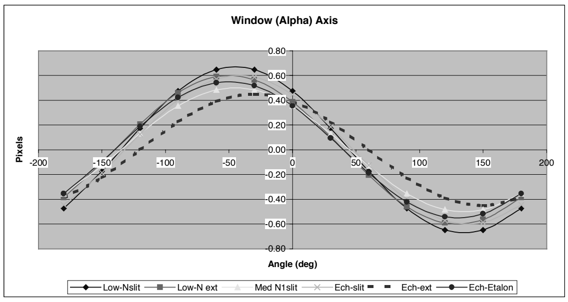
4.5 Remedial action

As a result of the warm tests, the bearing arrangement and spindles on the Grating Exchange Mechanism underwent extensive re-design with larger and stiffer bearings. The cast supports for the gratings and the echelle were also re-designed and re-manufactured. In addition the bracket on the focus translation mechanism was re-designed to enhance its rigidity. The tests were repeated after the modifications were completed.

5. FULL SYSTEM TESTS ON THE TELESCOPE SIMULATOR

The fully assembled instrument was tested on the telescope simulator using the science arrays and software. The mechanism functions and performance were verified and full system flexure measured as shown here.

Fig. 8: Fully assembled instrument on the telescope simulator and typical results



5.1 Remedial action

The tests indicated a flexure that was about twice that of the original specification in the spectral direction. Using the warm tests data this was attributed partially to the various mechanisms in the optical train, partly to the internal and external structure. It was decided to utilise a look up table and the detector translation mechanism to compensate for this residual flexure in those observations that were long enough to warrant it. In order to do this the flexure has to be smooth and predictable. Initial tests showed that the flexure was not smooth and this was attributed to differential flexure between the GEM worm wheel and the drive worm. A modification to the drive software ‘de-stressed’ the drive once positioned and this resulted in the smooth flexure curves seen in figure 8 above.

6. HOW WELL DOES IT ALL WORK IN PRACTICE?

The Michelle instrument saw first light on the UKIRT telescope in Sept 2001. Since that time it has had 50% of telescope time with no unplanned down time attributed to mechanism failure. The reliability and flexure performance of the instrument mechanisms in service is acceptable. The instrument is scheduled for installation on Gemini North in January 2003.

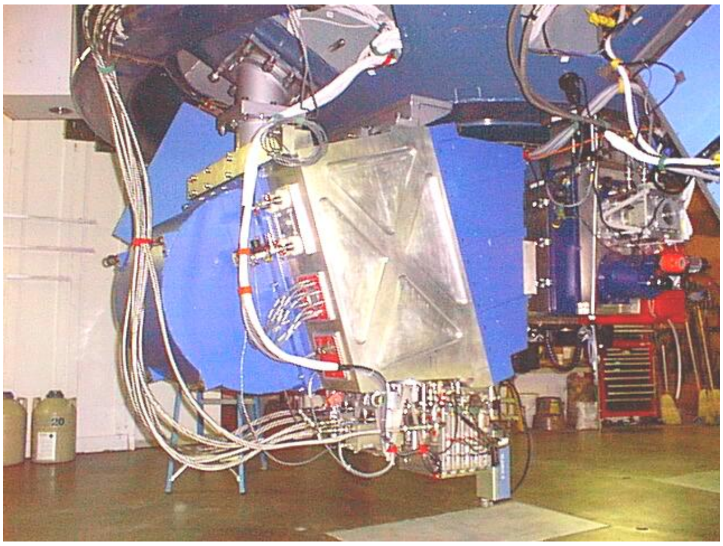


Fig. 9: Instrument installed on UKIRT

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