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The Hobby-Eberly Telescope Low Resolution Spectrograph: mechanical design

G. J. Hill[a*], H. Nicklas[b], P.J. MacQueen[a], W. Mitsch[c], W. Wellem[b], W. Altmann[d], G. L. Wesley[a], and F.B. Ray[a].

[a] McDonald Observatory, University of Texas at Austin, RLM 15.308, Austin, TX 78712, USA

[b] Universitäts-Sternwarte, Georg-August-Universität, Geismarlandstr. 11, D-37083 Göttingen, Germany

[c]Universitäts-Sternwarte , Ludwig-Maximillians-Universität, Scheinerstr. 1, D-91679 Munich, Germany

[c]Konstructionsburo Werner Altmann, Sonnenstr. 41, Haselbach, 94113 Tiefenbach, Germany

ABSTRACT

The Hobby-Eberly Telescope (HET) is a revolutionary large telescope of 9.2 meter aperture, located in West Texas at McDonald Observatory. The Low Resolution Spectrograph (LRS, an international collaboration between the University of Texas at Austin (UT), the Instituto de Astronomía de la Universidad Nacional Autónoma de México (IAUNAM), Stanford University, Ludwig-Maximillians-Universität, Munich (USM), and Georg-August-Universität, Göttingen (USG)) is a high throughput, imaging grism spectrograph which rides on the HET tracker at prime focus. The remote location and tight space and weight constraints make the LRS a challenging instrument, built on a limited budget. The mechanical design and fabrication were done in Germany, and the camera and CCD system in Texas.

The LRS is a grism spectrograph with three modes of operation: imaging, longslit, and multi-object. Here we present a detailed description of the mechanical design of the LRS. Fabrication, assembly and testing of the LRS will be completed by mid 1998. First light for the LRS on the HET is expected in the summer of 1998.

Keywords: Astronomical instrumentation: spectrographs: mechanical design

1. INTRODUCTION

The HET[1,2] is a unique telescope with an 11 m hexagonal-shaped spherical mirror made of 91 1 m Zerodur™ hexagonal segments that sits at a fixed zenith angle of 35°. HET is a collaboration of the University of Texas at Austin, Pennsylvania State University, Stanford University, Georg-August-Universität, Göttingen, and Ludwig-Maximillians-Universität, Munich. A multi-axis tracker follows stars[3], and the telescope can be moved in azimuth to access about 70% of the sky visible at McDonald Observatory. The LRS rides in the Prime Focus Instrument Package (PFIP) on the tracker, allowing it to image as well as take spectra. This paper, along with two others in these proceedings[4,5], describes the LRS.

Figure 1 shows the PFIP and LRS out of the tracker. The PFIP and LRS will be lifted onto the HET tracker this summer. The PFIP framework is divided into two: an outer structure takes the load of the LRS and other instrumentation, while the 4-mirror corrector has its own frame of Invar 36™, supported on a gimbal in the outer frame so as to decouple the stresses exerted on the outer frame from the mirrors. The PFIP includes an optical bench which houses pick-off mirrors, the acquisition camera and the guide system. Three guide-probes, 7 mm in front of the HET focal plane, feed a guide camera. The PFIP ring mounts to the tracker rotator, which in turn is supported by hexapod positioning legs that produce the wide range of motions required to follow the HET focal surface during a track[3].

* Send correspondence to G.J.H.
G.J.H.: E-mail: hill@astro.as.utexas.edu; H.N.: E-mail: nicklas@uni-sw.gwdg.de; P.J.M.: E-mail: pjm@wairau.as.utexas.edu;
W.M.: E-mail: mitsch@usm.uni-muenchen.de; G.L.W.: E-mail: gwesley@astro.as.utexas.edu; F.B.R.: E-mail: fbr@astro.as.utexas.edu

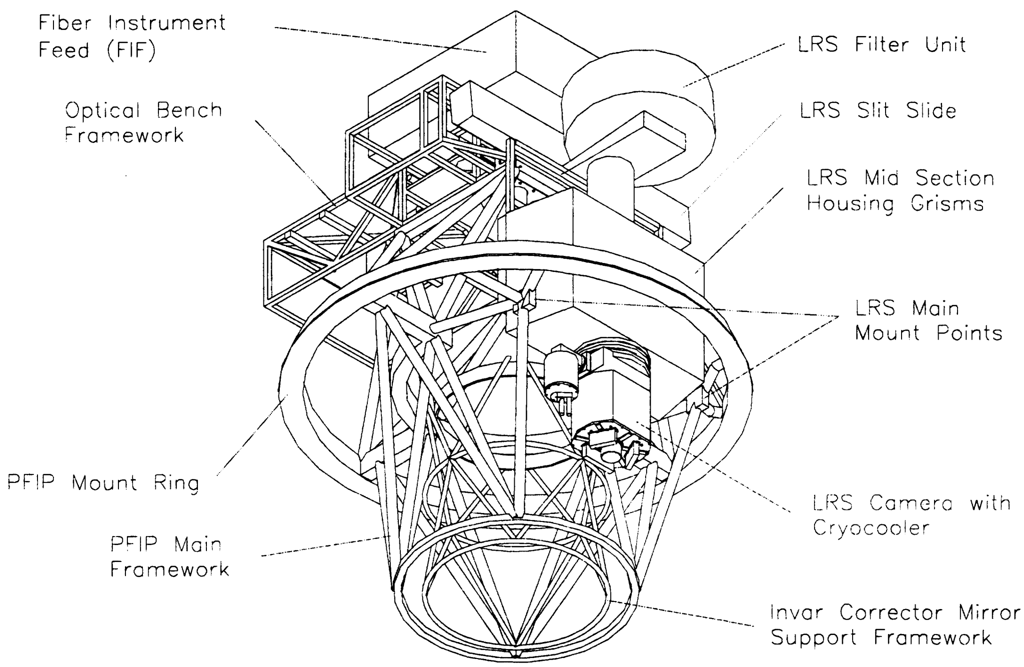

Figure 1. The PFIP and LRS

2. OPTOMECHANICAL DESIGN

General descriptions of the LRS[4] and of the optical design[5] are given elsewhere in these proceedings. Here we discuss details of the mechanical design. The mechanical design, the electronics, and most of the fabrication was done at USM and USG, and the software, camera and CCD system are being developed in Texas. At many points in the mechanical design process we benefited from study of designs for the ESO FORS instrument[6]. The LRS is being transferred from Munich to Austin, where it will be integrated into the PFIP.

3.1 LRS and the HET PFIP

The LRS mounts as part of the PFIP, which rides on the HET tracker. Figure 1 shows the PFIP and the limited space available for the instrument. In addition, there is a weight limit of approx. 150 kg for the LRS. The principal consequence of these constraints is to limit the range of configurations that may be carried by the LRS at any one time[4].

The HET focus, produced by the 4-mirror corrector, is f/4.58 (image scale 4.889 arcsec/mm), and can be directed to a fiber instrument feed (FIF) for the high and medium resolution spectrographs, to a general acquisition camera, or to the LRS. The FIF and LRS foci each have atmospheric dispersion correctors (ADCs) and a set of three guide-probes which feed the images of stars via 2 mm square coherent fiber bundles to the guide camera. The guide probes will primarily access the focal surface in an annulus between 4- and 6-arcmin diameter, but can be moved into the 4 arcmin diameter science field if desired (for example in long-slit spectroscopy).

The HET sits at 35° to the zenith, so there is an approximately constant gravity loading along the axis of the LRS. The PFIP can rotate about the axis of the corrector in order to access different position angles on the sky, but during a typical track the rotation will only change by a few degrees. As a result, flexure during a track is not an issue, but we wish to be able to calibrate observations taken at a range of position angles with a single set of calibration exposures, so it is important that the variation in the direction of the component of gravity loading perpendicular to the instrument axis (approximately 0.6g), not cause flexure of the instrument. This situation is similar to that for a Nasmyth mounted instrument.

The physical constraints of the PFIP dictated that the LRS design be linear with a fold, so a refractive collimator and grism disperser were adopted. The PFIP rides on the hexapod structure of the tracker which moves the payload through the range of angles and rotations required for tracking and the range of rotations required for science. As a result, there is a collision envelope at the lower part of the PFIP that the LRS must not protrude beyond, due to the risk of hitting the camera against parts of the hexapod legs at certain rotation angles.

The refractive collimator has a doublet 85.5 mm behind the slit plane and a triplet 740 mm behind the slit plane. The total optical length of the instrument is 1.43 m, with a fold at 235 mm from the slit to conform to the space envelope. The fold is 85°, rather than a right angle, due to the need to raise the body of the LRS sufficiently (about 20 mm) to avoid the collision envelope mentioned above. This angle change indicates the tightness of the space constraints we were forced to work with. The space between the collimator triplet and the camera is 330 mm to allow room for even the largest echelle grisms (see Sec. 3.3.5). Two grisms can be carried in the LRS at any one time, and are inserted into the beam against hard stops, by pneumatic cylinders. Here again the space limitations were severe and drove the mechanical design. The camera is a f/1.4 catadioptric design using all spherical surfaces. The CCD is housed in a small head with the field-flattener lens as the cryostat window, rather than requiring the entire camera to be evacuated. The details of the design are given in the following sections.

3.2 Top Unit

The top unit of the LRS consists of the slit slide with longslit (LS) and mulit-object spectroscopy (MOS) units, and a filter wheel housing that also includes the shutter. This unit is removable for maintenance as it contains most of the complex units of the spectrograph. It mounts repeatably on the LRS frame, and can be removed in a few minutes and brought down to ground level for trouble-shooting.

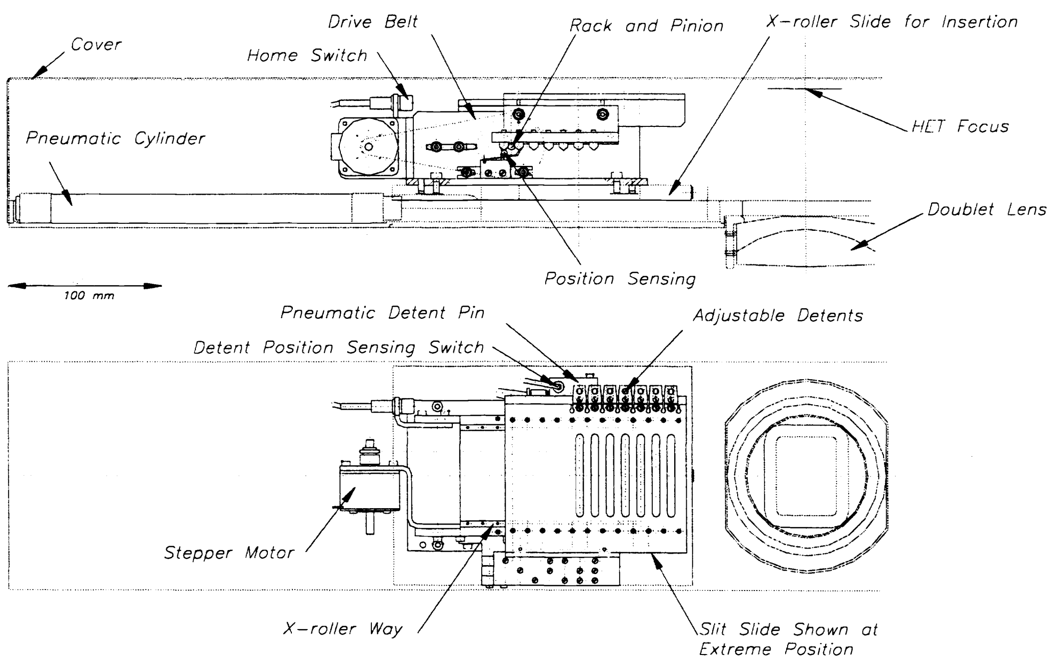

Figure 2. Slit Slide and Longslit Unit

3.2.1 Slit slide

Three modes are available for imaging and spectroscopy: the LS unit that allows remote changes between 5 fixed slits of different widths, the MOS unit with 13 individually configurable slitlets, and an open position for imaging. The LS and MOS units are mounted on linear ways (manufactured by Schneeberger) and inserted into the beam with pneumatic cylinders. This simple approach (also adopted for the grism insertion, see Sec. 3.3.5) fits in the restricted envelope around the HET focus at the LRS port, and is extremely simple to control. Very accurate repeatability of insertion of the slit units is assured by the use of hard stops, against which the pneumatic cylinders push. The force exerted by the cylinders is far in excess of any varying loads due to gravity, so flexure is avoided. The slit units may be configured while out of the beam, and then inserted accurately and rapidly on axis. This feature allows the LRS to be used in imaging mode for setup on faint objects without disturbing the slits at all, thus ensuring the greatest repeatability for calibrations and setups. The slides and cylinders are mounted to an aluminum back-plate, and a sheet aluminum cover provides protection for the mechanisms and light tightness. The back plate mounts to the filter unit (see Fig. 4).

The doublet of the collimator mounts in a cell that is attached to the ground plate of the slit unit, thus ensuring accurate alignment and spacing between it and the focal plane. The cell is shown in Fig. 2, and will be mounted on shims to allow permanent adjustment of the focus of the instrument independent of the focusing unit. The doublet and triplet of the collimator have similar powers, so an axial translation of either will produce a change in focus. The principal focus adjustment will be to move the triplet (Sec. 3.3.3). It is conceivable that errors in manufacturing may put the required focus range outside the range of adjustment of the focus unit, so shimming the position of the doublet will overcome any such errors. The collimator design is very forgiving in this respect. Tolerance analysis of the collimator shows that once the two multiplets are bonded accurately, the delivered image quality is not very sensitive to their relative positions. The doublet cell includes adjustments for centering the two lenses during bonding (with Norland 61 UV-curable optical adhesive), and holes around the circumference for the injection of a silicon RTV compound (to provide the radial constraint and to seal the lenses in the cell).

The seven-position LS unit is shown in Fig. 2. Since the pneumatic cylinders have only two positions, there is no mechanism to vary the insertion position of the whole LS unit in the beam, so it has a small crossed-roller linear slide on which the long-slit mask is mounted. The crossed-rollers are 1.5 mm in size, manufactured by Schneeberger. The photochemically-etched mask will have slits of dimension (0.205, 0.307, 0.409, 0.511, 2.05) mm x 50 mm, or (1.0, 1.5, 2.0, 2.5, 10) arcsec x 4.1 arcmin The remaining two positions will have a set of 0.1 mm diameter holes for focusing the LRS and a single 0.3 mm diameter hole for high speed spectroscopy. The mask is not shown in the figure for clarity, and is currently being procured. The variation in width over the length of the slits is expected to be about 10 μm, resulting in ~3% or smaller variation for all slits except the 1.0 arcsec, which will have a 5% variation.

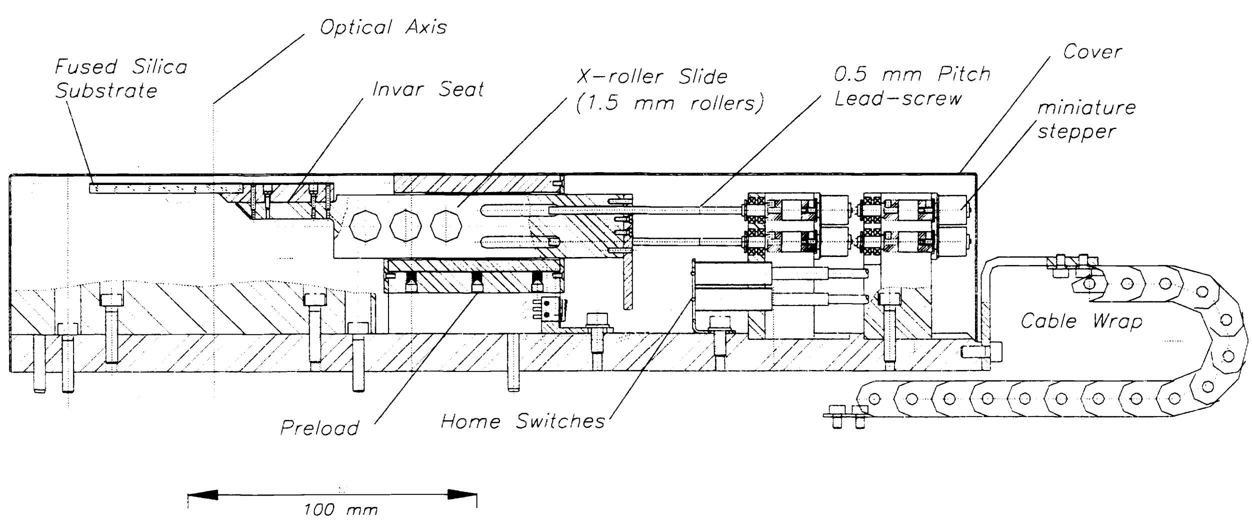

Figure 3. The MOS Unit

The constrained space, and the desire to avoid relative encoders, which are a significant source of heat, led us to adopt a non-encoded motion with an active detent and micro-switches for position sensing. The detent has a microswitch to sense when it is disengaged (and therefore that it is safe to move the slide). This is somewhat complicated to control, but should be very repeatable. A pinion is driven, via a slip-clutch and belt, by a stepper motor. A home is provided by a My-Com G™ micro-switch (accurate to +/-1 μm), and a regular, sealed micro-switch provides the other limit. Once positioned, a conical detent is inserted with a miniature pneumatic cyclinder (from FESTO), to pull the longslit-slide into the correct position. The position of the slide is monitored by a bank of three micro-switches, which encode the position as a binary number with sufficient accuracy to ensure that the detent is not engaged at the wrong place. The pneumatic detent has sufficient force to overcome the clutch, but the motor is also powered down when the detent is engaged. The detent and miniature pneumatic cylinder move on a miniature crossed-roller table to ensure stability of the detent axis. The hardware is mostly from PIC and Schneeberger, the stepper is from ESCAP.

The MOS unit (Fig. 3) is based on precision miniature cross-roller ways (custom-manufactured by Schneeberger), miniature geared stepper motors (F. Faulhaber GmbH, distributed by Micromo in the USA) and custom 0.5-mm pitch lead screws (A. Steinmeyer GmbH). MyCom G^{TM} microswitches are used for homing. This unit was chosen over the more usual etched or punched masks due primarily to queue-scheduling issues[4]. The layout has 13 slits, each 1.5 arcsec wide by 15 arcsec long, spaced on 19.6 arcsec (4 mm) centers. The field of view accessed by the MOS is 4 x 3 arcmin^2, with the slits aligned with the longer dimension. The miniature size of this mechanism did not allow the slit jaws to be driven independently (as in the FORS instrument, for example[6, 7]), so a different approach is adopted. The slitlets themselves are vacuum-deposited in aluminum on precision fused-silica substrates of dimension 3 x 3.7 x 52.5 mm, being manufactured by High Lonesome Optics, Fort Davis, Texas. These substrates are cemented to Invar 36^{TM} holders which mount to the individual axes of the MOS unit. Every other substrate has an Invar 36^{TM} mask cemented to it, to baffle the gaps between the slits. The masks are produced by photochemical etching from 200 μm thick sheet. The MOS unit mechanism is currently undergoing testing, and this unit will be discussed in a later paper, but it seems likely that this prototype will perform as required.

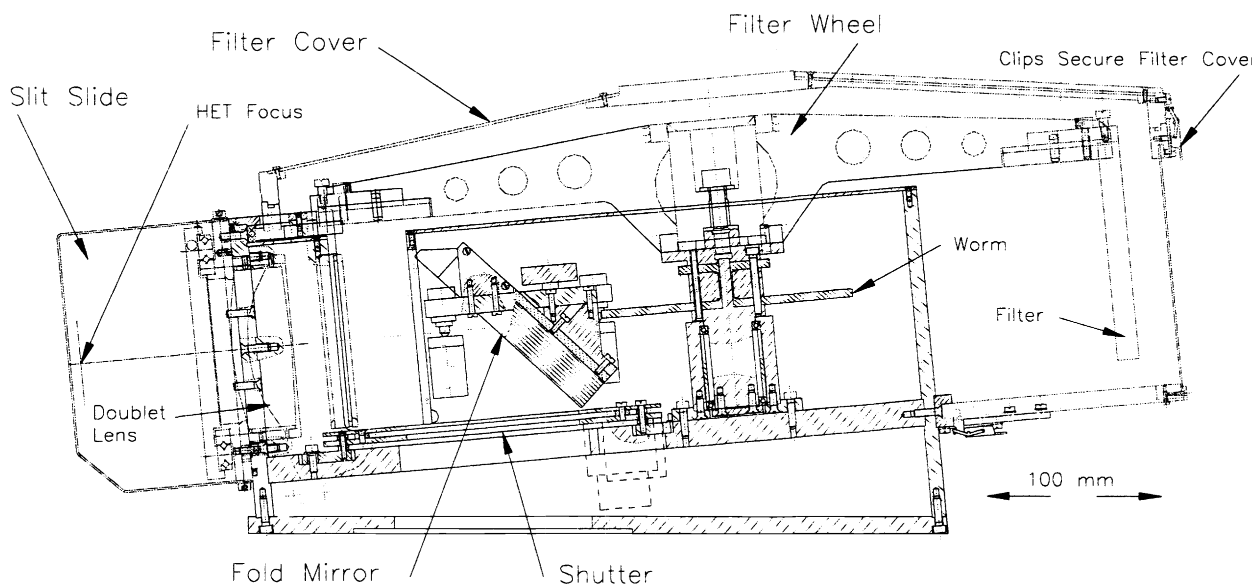

Figure 4. Cross-section of the Top Unit of the LRS, showing the filter wheel, shutter, and fold-mirror.

3.2.2 Filter unit

The slit unit mounts to the body of the top unit, which contains the filter wheel, fold-flat, and shutter (Fig. 4). The filter wheel has twelve positions, and the filters are 100 mm diameter by 8 mm thick. The filter cells include pockets to insert copper plugs that balance their weights to reduce moments on the drive mechanism. The wheel is driven by an ESCAP stepper motor and worm wheel, and is absolutely encoded via a belt off the drive axis. The filter wheel is a lightweight, welded aluminum structure which is removable from the drive axis. In order to provide access to insert the largest grisms it is necessary to remove the filter wheel cover and the wheel, which overhang the grism access ports. This is achieved by making the cover top separate (it is also removed to change filters), and the cylindrical body of the cover slides off the back of the top unit once the filter wheel is removed. Pins and clips ensure the registration of these parts. The cylindrical body of the filter cover is fabricated from 1 mm thick FR-4 PC board material with the copper surface interior. This material is very stiff and lightweight, and much more resistant to denting than aluminum, and the copper will be chemically treated to blacken it.

Space in the top unit is very constrained, and a custom tip-tilt-piston mount for the fold mirror was designed to fit. The mirror substrate is Zerodur™ and it is bonded to an Invar 36™ plate with epoxy, ensuring a compact, simple mount, free of differential expansion stresses that could warp the mirror. Three precision screw adjusters from Newport provide the orthogonal motions required. The radial constraint is provided by a 10 mm hardened ball in a conical socket referenced to a flexure. The flexure allows vertical adjustment of the mirror but is stiff in the other dimensions. Rotation about the ball-cone axis is constrained by an adjustable stop and a spring preload.

The shutter is a ϕ100 mm model from Prontor. The centering of the shutter is adjustable, as the beam-size at that point is ϕ99 mm. We have used this shutter on several instruments at McDonald Observatory with great reliability. The shutter is driven by a solenoid, but we remove the standard dropping circuit (which dissipates a lot of energy) and drive the solenoid directly with our CCD electronics.

3.3 Mid Section

3.3.1 LRS Frame and mounts

The aluminum frame which supports the various components of the LRS was finite-element modeled to ensure adequate stiffness within the weight limits. It combines solid members where components mount, and tubular members elsewhere. The desire was to produce accurate surfaces to set the initial relative alignment of the various components (e.g. collimator triplet and focus mechanism, see below) to high precision (0.1 mm typically). This goal was realized through an iterative machining procedure. The solid members of the frame that were to be machined were made 5 mm oversize. After welding by Windelband GmbH, the frame was transfered to USG where it was first heated to ~150 °C for 24 hours, to relax the stress. Then 2-3 mm of material was removed from the surfaces that were to be machined, followed by another thermal relaxation cycle. This was repeated several times removing progressively smaller amounts of material, until the specified tolerances were met. This was time-consuming, but we believe the final result will be very stable over the long-term.

The LRS mounts to the PFIP at three points which have adjustments to align the LRS to the telescope. The two lower mount points (see Figs. 1 and 7) support most of the weight of the instrument and are adjustable in all dimensions by +/ 5 mm. The upper mount point, just below the slit slide, adjusts the slit plane to the HET focus. These mounts are not strictly kinematic, but we do not expect to dismount the LRS once it is aligned.

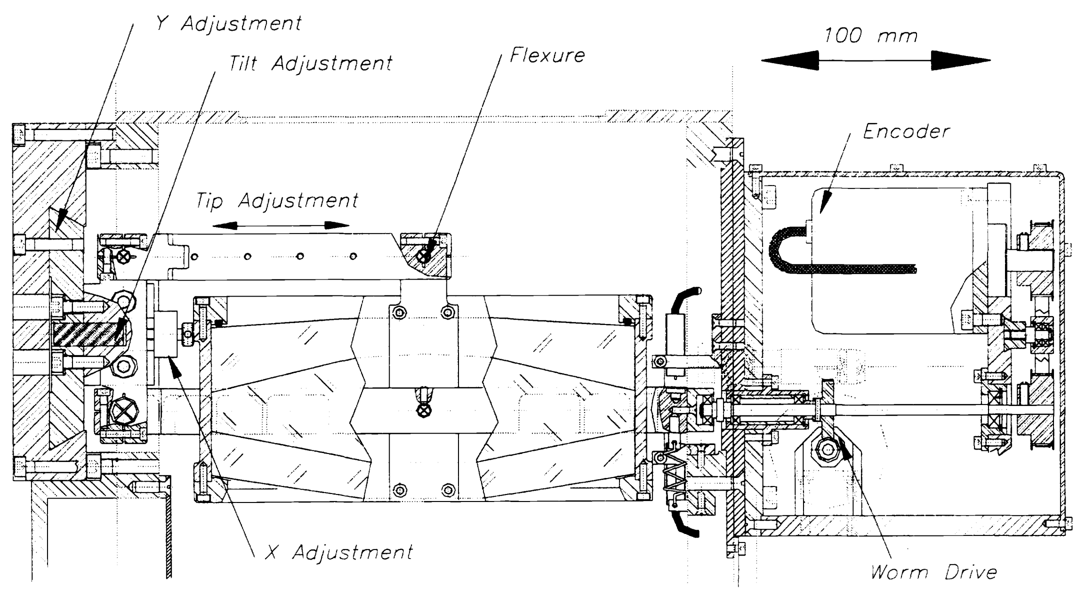

Figure 5: Triplet mount and focus mechanism

3.3.2 Collimator triplet mount

The triplet of the collimator consists of a CaF_2 biconvex lens sandwiched between K5 and LLF1 mensicus elements[5]. The large wavelength coverage of the LRS required the use of CaF_2, which is a fragile material, sensitive to thermally-induced shock breakage. The collimator cell also had severe space requirements, resulting from the need to provide clearance for the insertion of grisms. The adopted cell design is shown in Fig. 5, and consists of a titanium barrel with aluminum end plates. The barrel wall is only 5 mm thick due to the space constraints. Titanium was adopted due to its great strength and because its CTE is a close match to the K5 and LLF1 glasses radially, and to the composite CTE of the triplet in the axial direction[4]. As a result, the triplet can be mounted in the cell with close tolerances that will ensure the relative registration of the elements[4].

3.3.3 Focus mechanism

Instrument focus is achieved with small motions of the collimator triplet, and a range of +/-2 mm is sufficient to account for differences in filter thickness and changes in temperature. Here again the very tight space constraints required an innovative solution. We adopted a parallelogram support for the triplet cell, based on Bendix Free-Flex™ flexures, and driven by a cam at one edge (Fig. 5). This mechanism is adjustable +/-1 mm in all directions except focus, for initial setup. Tests confirm <10 μm flexure of the triplet position in this mount for +/-45° tilts, comparable to the decenter caused by the parallelogram at the extremes of focus. The tolerance on the centering of the triplet is much larger (0.1 mm). The focus mechanism is unusual, but has the virtues of extreme compactness, translation without introducing tilts, and a mass considerably less than that of the optic which is being moved. Care must be taken during transport however as the structure is not designed to withstand large shocks.

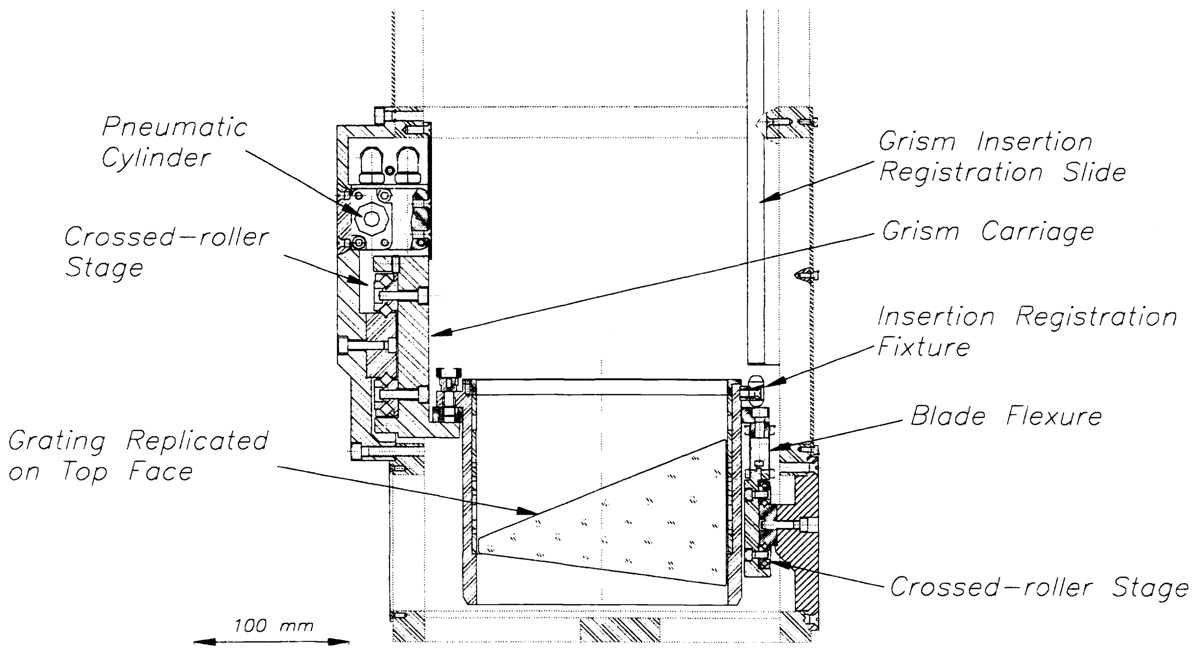

Figure 6. Cross section of grism exchange mechanism and Grism 2

3.3.4 Grism cells

The LRS was designed to use grisms of 150 mm width, the largest available in a wide range of blaze-angles and groove densities[4]. The space between the triplet and the camera vertices is 330 mm, necessary to fit the largest (echelle) grisms, which are 270 mm tall. The grism cell is shown in Fig. 6 for Grism 2. The orientation of the grisms is opposite to that usually adopted: the light is first incident upon the grating surface instead of on the glass surface. The cell has an inner aluminum sleeve into which the grism is bonded with silicon RTV elastomer. The gap between the glass and sleeve is 0.5 mm radially. The sleeve then inserts into the main cell and is secured with a screw clamp ring. The cell includes fixtures for alignment and insertion. An insertion registration fixture (Fig. 6) fits into a slide on the LRS frame in order to guide the grism into the body of the instrument with the correct orientation. A handling fixture attaches to the grism for this purpose.

3.3.5 Grism exchange mechanism

Two grisms are carried at a time, on independent carriages. The grism exchange is made with pneumatic cylinders, in the same way as for the slit units, against hard stops to provide excellent repeatability. Severe space constraints force the cylinders to be used back-to-back, and offset from the center of mass of the grisms (Figs. 6, 7), but the resulting moments are well within the capacity of the recirculating Schneeberger crossed-roller bearings used to support and move the grism carriages. A second pair of smaller crossed-roller bearings support the other sides of the grism carriages via blade flexures, which allow some non-parallelism of the two ways (Fig. 6). Flexure tests have not yet been made, but the tolerance on the centering of the grisms is +/-0.5 mm in translation and +/-2 arcmin in rotation, which should be achieved easily. The grisms can mount in either carriage, and the grism cells include four adjustable conical registration fixtures, a pair for each carriage, to allow their positions to be adjusted and then fixed. In this way the grisms can be mounted in either carriage with no change in properties. The slides have two positions, and when the grisms are out of the beam they may be exchanged from above.

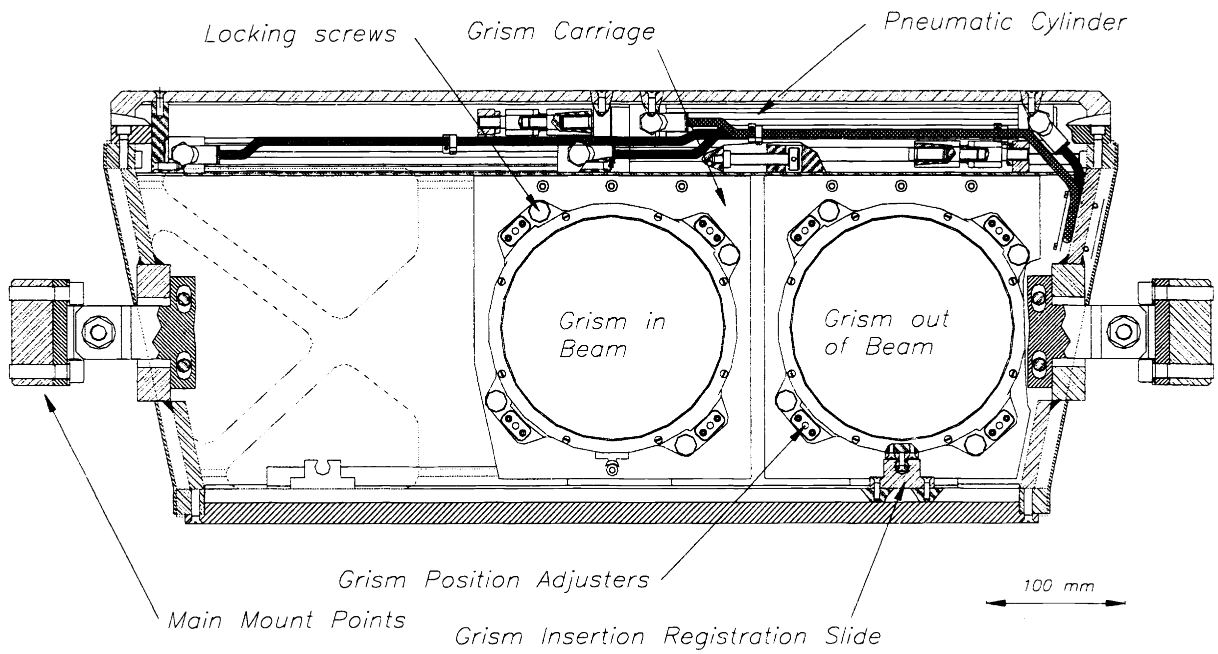

Figure 7: Plan view of the LRS grism exchange mechanism, frame, and mount points

3.4 Camera

The camera is an integral unit which includes the CCD head and a cryocooler. The CCD system is being developed by McDonald Observatory, and will be discussed in detail elsewhere. The camera accepts the collimated beam, so its alignment with the rest of the instrument is not critical, and we envision removing it for maintenance.

3.4.1 Camera body and optics

The camera is a f/1.4 catadioptric with all spherical surfaces[5] (Fig. 8). The camera is divided into three sections to allow relative adjustment of the position of the corrector lens doublet, the camera mirror, and the CCD head for optical alignment. The corrector lenses are both fused silica and will have a multi-layer AR coating covering 360-1000 nm. Tolerance analysis indicates that the image quality is sensitive to the relative positions of the two lenses, but not to the position of the doublet as a unit. Once the doublet is set in its cell, using silicon RTV to seal the lenses into the mount, the cell can be located to normal machine tolerances, without further need for adjustment.

The mirror is Zerodur™ with a diameter-to-thickness ratio of about 6. Avoidance of the collision envelope described in Sec. 3.1 requires two cords to be cut off the mirror, as seen in Fig. 8. The mirror will be overcoated with the Denton Vacuum FS99™ enhanced silver coating used on the rest of the HET. The images are most sensitive to deformations of the mirror, so we adopted a conservative approach to the mounting. The axial support consists of six contact points in pairs on levers. Each point supports 1/6 of the mass, and has a Newport screw to adjust the mirror. There is always a component of gravity directly along the optical axis, so there is no need for a pre-load to hold the mirror on the axial supports. Finite element modeling indicates undetectable print-through from these supports, as would be expected. The central radial support is a flexure assembly, fabricated from Invar 36™, bonded into a through-hole in the mirror with a 0.1 mm thick layer of epoxy. The central ϕ35 mm region of the mirror is not illuminated. The flexure attaches to the end of a hardened ground shaft which is free to move axially in a pre-loaded linear ball bearing. The range of adjustment is limited to +/- 0.5° or +/- 2 mm, far more than should be needed.

The body between the CCD section and the mirror (not shown in the figure) will be fabricated from stainless steel to reduce the thermal defocus effect, but we will still need to compensate for temperature changes by adjusting the position of the triplet slightly for $\Delta T > 15$ °C. The focus set at the start of the night should be adequate in most cases.

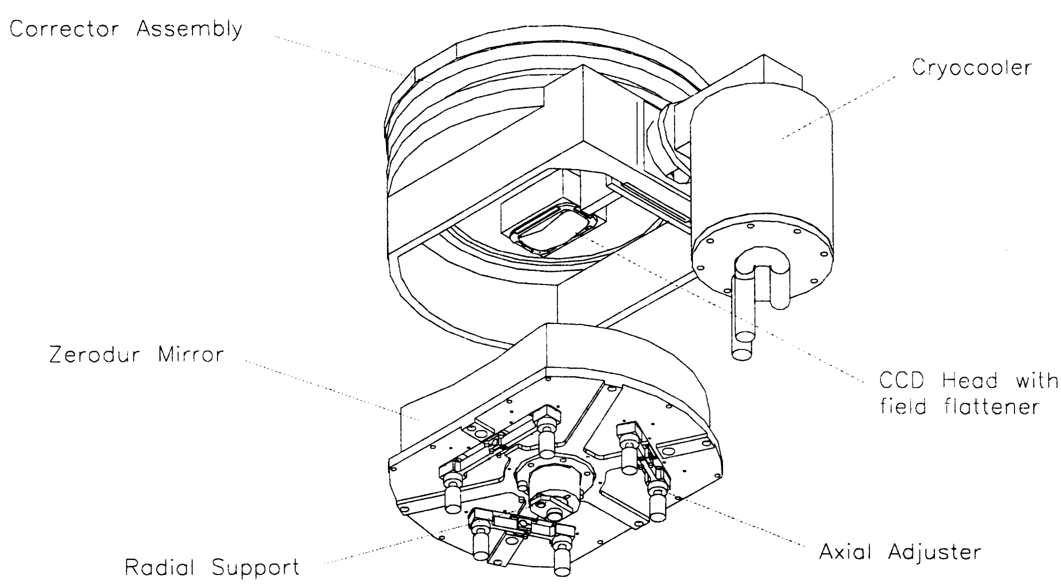

Figure 8: LRS camera

3.4.2 CCD head

The CCD is a 3072 x 1024 @ 15 μm pixel (pxl) Ford Aerospace device. Figure 8 shows the CCD head, which is a miniature cryostat with the field-flattener lens as its window. We adopted this approach in order to simplify the camera at the expense of some extra obscuration[4]. The head must be adjustable in tip and tilt to align the field flattener with the optical axis, but we intend to define the axis to go through the center of the lens, so adjustments in other dimensions are not necessary. The mount allows these adjustments, while maintaining the center of rotation at the center of the CCD, to minimize their effect on focus. Covers over the adjusters seal the camera body, and we intend to periodically purge the body with dry nitrogen in order to avoid any possibility of condensation on the CCD dewar window.

An APD Cryogenics Inc. CryoTiger™ cryocooler will be used to maintain the CCD operating temperature at ~90 K. The compressor will be located off the tracker and flexible lines run through the tracker cable wraps in a ~70-foot total run.

3.5 Control

Apart from the MOS unit, control of the basic functions of the LRS is relatively simple. Rather than introduce the complexity of an on-board computer to control functions, we use four RS-232 fiber-optic connections between the LRS and its control Sun™ workstation in the HET control room.

Table 2: Summary of Control functions

Function	Actuator	Encoder
LS unit insertion	pneumatic	Inductive switches with built-in oscillator coil
MOS unit insertion	pneumatic	Inductive switches with built-in oscillator coil
Grism insertion x 2	pneumatic	Inductive switches with built-in oscillator coil
Filter wheel	stepper motor + worm drive	absolute encoder
Focus	stepper motor + worm drive	absolute encoder + home switch
LS unit translation	stepper motor + rack & pinion	home, limit and position switches
LS unit detent	pneumatic	switch to sense detent removal
MOS unit x 13	miniature stepper motors + lead screws	limit switches

A Cyberpak Co. HS-20™ 4-axis indexer is used to control the main functions of the instrument via a single fiber-optic RS-232 connection. This unit controls the filter wheel, focus and LS unit stepper motors. The pneumatics are controlled, and the limit switches sensed, via the I/O registers of the HS-20. The two absolute encoders (from COPI) provide continual readout to the control workstation via two more RS-232 links, and the fourth link is used to address the four HS-20 indexers which control the MOS unit (up to 16 of these indexers can be ganged on one line, and each motor can be addressed individually). Software on the LRS workstation tracks the positions of the various components, either through the encoder readouts or the status of the switches. The resulting system is simple, inexpensive, yet flexible. Experience with similar systems on other McDonald instruments leads us to expect robust performance.

5. SUMMARY AND PLANS

The HET LRS is nearing completion and will see first light this summer. Optical design started in late 1995, mechanical design in mid 1996, and construction in spring 1997. This has been an aggressive schedule given the limited funding available from the HET partner institutions. The LRS will undergo testing on the HET this summer and enter operations by autumn 1998.

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