Mechanical Design of VIRUS-P for the McDonald 2.7m Harlan J Smith Telescope

Michael P. Smith\textsuperscript{a}, Gary J. Hill\textsuperscript{a}, Phillip J. MacQueen\textsuperscript{a}, Werner Altmann\textsuperscript{b}, John A. Goertz\textsuperscript{a}, John M. Good\textsuperscript{a}, Pedro R. Segura\textsuperscript{a} Gordon L. Wesley\textsuperscript{a}

\textsuperscript{a} McDonald Observatory, The University of Texas at Austin, 1 University Station C1402, Austin, TX, USA 78712;
\textsuperscript{b} Konstructionsburo Werner Altmann, Sonnenstr. 41, Haselbach, 94113 Tiefenbach, Germany

ABSTRACT

We present the mechanical and opto-mechanical design for the Prototype Visible Integral-Field Unit Spectrograph (VIRUS-P). The VIRUS-P instrument is the single unit prototype for the planned VIRUS instrument which consists of 192 spectrographs for the Hobby Eberly Telescope Dark Energy Experiment (HETDEX). The VIRUS Prototype is a test bed for the design and will be used for a survey on the McDonald 2.7m Harlan J. Smith Telescope. The mechanical design is driven by the need for high stability. The structure of the instrument is aluminum but the internal optical elements of the collimator and the camera are held in alignment with respect to each other using Invar metering rods. The spectrograph is fiber fed with 246 fibers in a hexagonal packing pattern at the telescope focal plane Integral Field Unit (IFU) and arranged in a slit at the input to the spectrograph. The reverse-Schmidt collimator articulates, and the Volume Phase Holographic (VPH) grating rotates independently relative to the fixed Schmidt camera to allow for versatile grating configurations during the prototype testing. Since the VIRUS spectrograph units will be mounted in a gravity neutral configuration on the HET, the prototype instrument is mounted on a gimbal at the folded cassegrain port of the 2.7m Smith Telescope to negate gravity vector changes.

Keywords: Spectrograph, opto-mechanical design, articulating, Invar, VPH grating, IFU, Hobby-Eberly Telescope, Gimbal

1. INTRODUCTION

1.1 Background

The Hobby-Eberly Telescope (HET) is an existing innovative large telescope of 9.2 meter aperture, located at the McDonald Observatory in West Texas. The Hobby-Eberly Telescope Dark Energy Experiment (HETDEX) requires a major upgrade to the HET, including a substantial increase in the telescope field of view, as well as the development and integration of a revolutionary new integral field spectrograph called VIRUS. The Visible Integral-Field Replicable Unit Spectrograph (VIRUS) is an instrument comprising approximately 150-192 individual IFU-fed spectrographs which will be mounted on the telescope structure. The VIRUS spectrographs each consist of an IFU input, collimator, VPH grating and Schmidt Camera. The camera corrector plate performs the role of the cryostat window. The camera mirror, field flatter and detector package are inside the cryostat. The detector package is mounted on a spider and is thermally isolated from the spider and the rest of the camera. A copper cold finger provides the cold link between the cold source (liquid nitrogen Dewar) and the detector package.

Development of VIRUS is following a standard production model. A prototype of the unit spectrograph (VIRUS-P) has been constructed. It is being followed by a pre-production prototype (VIRUS-PP), where value engineering is being used to reduce costs before entering production. The motivation for building VIRUS-P is to provide an end-to-end test of the concepts behind HETDEX, both instrumental and scientific. Here we describe the opto-mechanical design of VIRUS-P.

VIRUS-P is in service and has already been used to conduct a pilot survey of Ly-\textalpha emitting galaxies in support of the HETDEX project, and for several other projects. VIRUS-P is also designed to be a facility instrument on the McDonald 2.7m Smith Reflector, and it dominates the dark-time usage on that telescope.
1.2 Optical Design

The final optical design is shown in Figure 1. The input focal ratio is f/3.65 and the camera focal ratio is f/1.33. Details of the design will be given elsewhere. It consists of a reverse-Schmidt collimator, where the input fibers are arrayed pointing perpendicular to the spherical collimator mirror so as to create an axis-less system. A cylindrical lens is coupled to the fibers to provide immersion of the ends and the lens has an AR coated exit face for maximum efficiency. A fold mirror is introduced for compactness and to allow flexibility in the design of the integral field unit interface. The disperser is a volume phase holographic grating with 831 fringes/mm sandwiched between fused silica plates. The camera is a Schmidt with aspheric corrector plate and an aspheric surface on the back side of the field flattener lens, both of fused silica. It was found that the correction for both the collimator and camera could be achieved with a single asphere on the camera corrector, which also acts as the window for the vacuum housing of the camera. This design achieves superb images, far superior to those achieved with the refractive designs we investigated.

1.3 Mechanical Constraints

The VIRUS prototype is being developed for use as a test bed for the design and will be used for an extensive survey of Ly-α emitting galaxies on the McDonald 2.7m Smith Reflector. As a result, we required it to operate with high stability under a wide range of temperature from -5 to +25 degrees Celsius. We specify that the instrument not require recalibrating for the positions of the fiber images over the full temperature range. This corresponds to shifts smaller than 0.5 pixels (1/10 of a resolution element) at the detector. In addition, we designed the prototype to test all possible modes of the instrument, including a range of resolving powers and wavelengths, even if these will not be options for the majority of VIRUS units in practice. The mechanical constraints for the prototype need to be consistent for both the final application of the spectrograph on the HET and for the pilot survey on the 2.7m Harlan J. Smith Telescope. On the
HET, the VIRUS spectrograph will be mounted on the telescope structure which is at a fixed azimuth angle and hence the spectrographs do not experience a change in the gravity vector. The prototype will be mounted on a gimbal mount attached to a folded cassagrain port of the 2.7m Harlan J. Smith Telescope.

2. COLLIMATOR ASSEMBLY

The Folded-Schmidt Collimator assembly consists of an input fiber-slit which injects light through a fold mirror onto the spherical collimator mirror. The collimated return beam is displaced by the fold mirror onto the VPH Grating. The collimator and VPH grating are independently articulated relative to the camera and instrument structure to enable multiple grating configurations of the spectrograph in order to test various resolving powers and wavelengths.

2.1 IFU

The IFU has been developed and built in partnership with Astrophysikalisches Institut Potsdam (AIP). Each VIRUS accepts the light from 246 fibers. Each has diameter 200 microns and area 1.0 square arcseconds on the sky (1.13 arcsec. diameter) at f/3.65. The fibers are arranged in a hexagonal close pack (HCP) with a square format as shown in figure 3. There are 17 rows of 14 or 15 fibers. We will refer to the rows as banks. The fill-factor of the active area of the fibers will be close to 1/3 in order to provide maximum area coverage in three dithered exposures. The spacing for this fill-factor will be set by inserting the fibers in precision glass capillary tubing with close tolerance on the ID to match the OD of the fibers, or by inserting them in a precision aperture plate. The IFU bundle will have a layer of at least 1 buffer fiber around its outer edge to minimize variations in throughput due to focal ratio degradation. The fibers will be polished and bonded to a thin fused silica plate with anti-reflection coating on its outer face.
Development of the prototype IFUs at AIP and UT has explored several ways of setting up the required matrix of fibers at the input end. Drilled plastic aperture plates can achieve the desired spacing accuracy but present problems for polishing as the plastic smears. Setting up a matrix of fused silica capillary tubes to set the spacing proved very successful. The fibers are easily threaded into tubes with only 5 \( \mu \)m clearance on the diameter, and these arrays were measured to have final fiber position errors of less than 5 \( \mu \)m rms. This is well within the requirements. One fiber bundle (designated VP1) has been assembled with Polymicro FBP fibers, using this method at AIP. A second bundle of length 15 m has been manufactured by Frank Optic Products in Berlin, using the capillary technique and a variety of fiber types. A third long IFU cable is being assembled by Ceram Optec, using a micro-drilled ceramic block to locate the fibers at the input. Another fiber bundle has been produced by FiberTech using drilled aperture plates of stainless steel.

The banks of fibers will be arrayed at the input of the spectrograph collimator into a slit arrangement. The fibers are bonded to a monolithic substrate, made of Invar or stainless steel. Note that, with a Stainless steel substrate, the change in position of the outer fibers is 17 microns for 35 degrees C temperature range. This is probably acceptable. The input requirements are complex, as it is necessary that the fibers point normal to the surface of the collimating mirror at the appropriate field angle for their position in the input array. The fibers will be immersed against the concave face of a cylindrical meniscus lens so as to minimize exit losses. The ends of the fiber banks must be polished curved, or the fibers pre-polished before assembly on the monolithic substrate. The fibers will be immersed to the concave lens with setting type optical couplant.
The IFU pseudo-slit is mounted to the reference plate of the collimator. It is inserted on two alignment pins (one round and one diamond-shaped in cross section to avoid over constraint) which mount it repeatably onto the collimator reference plate. The IFU has no adjustability so it becomes the reference to which the rest of the collimator is aligned.

2.2 Collimator Mirror and Fold Mirror

The IFU, collimator mirror and fold mirror are contained within an aluminum structure. Internal to the aluminum structure is an Invar rod metering system which maintains the axial distance between the optical elements over a wide temperature range. The IFU is rigidly attached to the aluminum structure at the attachment point of the Invar rods and this mount plate forms the reference for the collimator. The other two optical elements are attached to the Invar rods by flexure adjusters to enable positioning and alignment. The ends of the Invar metering rods furthest from the IFU are attached to the aluminum structure with diaphragm flexures to enable the axial growth of the aluminum structure to the Invar rods. This arrangement maintains the alignment and axial spacing of the collimator elements and maintains the angles between the collimator, grating and camera. There is an axial spacing change between the collimator and grating but this has essentially no effect, as the beam is collimated and the thermal motions are small.

The fused silica collimator mirror has an Invar disk bonded to its back side for mounting. The Invar disk is bolted to an aluminum adjuster plate using a central shoulder bolt in a reamed hole and an off center shoulder bolt through a radial slot. The adjuster plate attaches to the Invar metering rods at its three corners. The mounts to the Invar rods consist of a spherical bearing mounted in a bored hole with a clamping flexure. The spherical bearing has a slit cut in it using an EDM machine. The Invar rod is locally threaded on its outer diameter and the adjuster plate spherical bearings are mounted between two nuts and a preload spring on the rods. The mirror is then adjusted in tip, tilt and piston using the nuts. When the alignment is set, the spherical bearings are clamped down providing a rigid orthogonal clamp to the metering rods. This slit-spherical bearing attachment method is also used on the fold mirror and camera mirror mounts.

Figure 5: Collimator assembly

Figure 6. The left image shows the mounting of the collimator mirror to the Invar metering structure. The mirror is glued to a disk and bolted to the triangular mounting plate. The mounting plate clamps to the Invar metering rod through a split spherical bearing contained in a flexure clamp. In the center is a detail of the spherical bearing clamp and adjuster nuts. The green diaphragm flexure attaching the Invar rod to the aluminum structure can also be seen. The right image shows a detail of the mount for the fold flat mirror. The slot in the mirror through which the light from the fibers diverges can be aligned to the fiber pseudo-slit by adjusting the mirror within the cell. Three adjusters mount the cell to the Invar metering assembly. Flexures at the three spherical bearing adjusters prevent over-constraining of the system.
The fold mirror is mounted in an aluminum cell. The oversized pocket in the cell allows the fold mirror to be aligned in rotation and translation to the central IFU input slit which protrudes through the mirror. The cell is mounted with adjusters to the Invar rods in the same way as the collimator mirror. Blade flexures between the cell and the adjusters avoid over-constraining the cell.

2.3 Collimator Articulation

The collimator structure pivots about a bearing which has its axis through the center of the grating. The motion is achieved by a manual lead screw attached to the collimator structure (Figure 2). Once the angle has been set by the lead screw, the collimator structure is clamped to the instrument housing. Blade flexures between the collimator and the housing avoid over-constraining the collimator structure.

2.4 Grating

The VPH grating is mounted in an aluminum cell. The oversized pocket in the cell allows the grating to be rotated within the cell to align the grating lines parallel to the axis of rotation of the collimator and grating articulation. The grating cell is held in a grating rotator which rotates the grating around its center to set the grating angle to the collimated beam. The grating rotator axis and the collimator articulation axis are collinear and the bearings share the same housing assembly. The grating angle is set using a micrometer which pushes a linkage against an opposing spring. The grating rotator is designed to receive different gratings.

3. CAMERA

The camera is an evacuated Schmidt design, with the detector at the internal focus. The mechanical design follows the same principles as for the collimator, using aluminum for the housing and Invar metering rods to maintain focus. The detector and field flattener are suspended in the beam with a stainless spider assembly that carries the cold link and flex circuit along one arm. The optics consist of a fused silica window which has an aspheric front surface (maximum deviation 0.3 mm), a spherical camera mirror, and a fused silica field flattener with a spherical front and aspheric back surface. The design has been optimized for minimum obstruction. The detector and field flattener are suspended in the beam, causing approximately 23% obstruction.

Figure 7: Grating holder and collimator rotator. The grating and collimator rotate on the same hub. The grating rotation is set by the micrometer shown bottom right, which acts against a spring.
3.1 Corrector Plate and Camera Housing

The corrector plate is also the entrance window into the camera housing (which is a vacuum cryostat) and seals with an o-ring against the camera housing. The camera housing is machined out of a solid piece of aluminum. Attempts were made early in the fabrication of this instrument to make the housing completely out of Invar, in order to maximize stability. Fabrication of the Invar housing however was found to be extremely challenging. The only feasible method for the one off prototype was: roll forming two half cylinders from Invar plate; seam welding the two half cylinders together; annealing the cylinder to remove material variations in the heat-affected zone, and then post machining all the critical features such as mount surfaces and o-ring grooves. The fabrication had two large problems: first the thick Invar plate could not be rolled accurately enough into the half cylinders to ensure cleanup of all surfaces on post machining and the welds introduced a significant volume of pores which made the part unsuitable for its vacuum application. For this reason the design was changed to the aluminum housing design with Invar metering between the detector spider and the camera mirror, and the flexure radial constraints. The optical design is insensitive to the small amount of thermally induced axial displacement between the corrector plate and the rest of the camera optics. This design has been successful and provides a very stable base for the camera optics.

The interface between the camera and the collimator is the front flange of the camera housing which bolts to the base plate of the collimator on the opposite side of the plate to the grating rotator. The circular flange locates radially in an accurately machined circular pocket on the collimator base plate. A simple tangential adjustment screw allows the camera to be aligned in rotation before the camera is firmly bolted down. The vacuum gauge and valve fittings are all installed on the standard liquid nitrogen Dewar which shares a vacuum with the camera cryostat.

3.2 Camera Mirror

As with the collimator mirror, the fused silica camera mirror is bonded on its back to an Invar disk. The disk is bolted to a triangular adjuster plate which is mounted to a mount ring. The mount ring is supported on Invar metering legs off the spider and restrained radially by flexures to the camera housing. The mount ring provides a stable base to which the mirror is adjusted and clamped down. The mount ring has three split spherical bearings set in bored holes with integral

![Diagram of Spider and Camera Mirror Assembly](image-url)

Figure. 9. Spider and camera mirror assembly. Top right shows details of the tip-tilt adjusters. Bottom right show details of the flexures constraining the mirror mount plate radially to the camera housing.
clamps. The adjuster plate is fitted with precision studs mounted on integral flexures, the studs are inserted into the bearings and three spring-loaded screw tip-tilt adjusters are used to align the mirror. Since the mirror is spherical, only tip, tilt and piston adjustments are necessary. Once aligned, the clamp on the split-spherical bearing provides an orthogonal clamp.

Setup of VIRUS-P requires that the camera mirror be adjusted as the final alignment step, which is done with the detector cold. This involves a temporary lid on the camera housing with vacuum feed-throughs to adjust and clamp the position of the mirror. The temporary feed-through lid has six ferro-fluidic rotary feed-throughs with shafts coupled to a hex key inside the vacuum. Three of the feed-throughs are positioned on the back lid to adjust the tip–tilt adjusters and three on the sides to tighten or loosen the clamps. Each of the feed-throughs is mounted on a bellows with enough range to allow the hex key to engage and disengage from the adjustment and clamp screws. Once the length of the hex keys is correctly set the lid can come off and on freely, as the spring force of the bellows disengages the hex keys, and when the housing is evacuated the bellows are compressed, inserting the hex keys into the heads of the adjuster screws. Eventually, for production of VIRUS units, the goal is to be able to setup the alignment at room temperature and not have to adjust it again.

As noted in Section 3.1, the original design intent was for the camera housing to be made of Invar. In that design, the mirror mount plate would have been directly mounted to a flange on the inner diameter of the camera housing, where the radial flexures are now mounted. The decision to make the camera out of aluminum necessitated the design of the Invar metering rods and flexures.

3.3 Spider

The spider suspends the detector and field lens in the center of the beam at the camera focus. It is optimized to minimize obstruction and is designed to be stiff and stable. The spider in service in VIRUS-P is made out of stainless steel with integral flexures in each of the four mount feet. The flexures perform two purposes: 1) they decouple the spider from the expansion of the aluminum housing, using symmetry to keep the detector centered and 2) they allow the outer diameter of the spider to be slightly oversized so that, when inserted in the camera housing, the spider is firmly registered against the inner diameter. (Removable preload clamping blocks facilitate easy insertion/removal of the spider.) The inner hub of the spider has precision mount surfaces for the field lens and the detector package.

![Spider and focal plane assembly. The photo bottom right shows the final fabricated spider.](image-url)
3.4 Focal Plane Assembly

The field lens mounts onto four lands on the spider hub and is pulled down onto the hub with four spring loaded clamps. Its lateral position is constrained by a tight fit between a lip on the inside of the lands on the hub and a machined circumferential step on the back side of the field flattener.

The detector is mounted onto a copper cold block using four spring loaded clips. The cold block has four square pads on the four corners of the mount surface against which the detector is loaded to provide the thermal connection between the detector and the cold block. These pads provide a more controlled contact area and alignment reference for the detector than a single continuous surface. The flatness of the cold block pads, and the clamping force, are critical for good thermal conduction. The lateral position of the detector is controlled by the tight fit of the detector pins into a socket block. The cold block is mounted to the spider through an intermediate part made of Ultem 1000 polyetherimide, which is a good thermal insulator with reasonable mechanical properties.

![Figure 11: Left, the sprung clamp holding the field lens to the spider. The lens sits on a land at its edge and is located radially by a locating fit between the inner edge of the land and a circumferential step turned into the bottom field lens. In the cut view in the center, the sprung clips that hold the detector to the cold block are shown. The detector pins locate the detector laterally. The brown part surrounding the copper cold block is the thermal insulating mount, made of Ultem 1000, that mounts the cold block to the spider. The photo right shows the cold block mounted in the insulating mount block. The mount pads are visible on the top surface.]

4. DEPLOYMENT

4.1 Alignment

The procedure for aligning the optics of VIRUS-P is quite simple. It starts with the alignment of the collimator to the axis of the integral field unit central fiber. This is done using a laser aligned normal to the IFU mount plate, and centered on a cross hair scribed into a Perspex target that is coincident with the center of the IFU. Once this axis is established, the collimator mirror is adjusted in tip and tilt to return the laser on the same axis. The fold mirror in the collimator is initially set to its nominal axial position, and setup to align the slot with the IFU head. It is then adjusted in tip and tilt to direct the laser light to a target which is coincident with the center of the grating diffractive surface, and on another target which is inserted in the grating holder. It turns out that if the cross hair on the Perspex target is used in the beam, the resulting diffraction pattern produces a cross that can be used to align these optics within the tolerances. The final alignment of the collimator is in focus, which was achieved using a SLR camera with a 200 mm f/1.8 Canon lens set to infinity. The collimator mirror axial position is adjusted to focus the camera on the IFU fiber ends.

The camera setup relies on accurate positioning of the detector and field flattener in the detector spider assembly, to establish the optical axis. With the chip carriers of the Orbit and Fairchild detectors, the positioning of the detector surface proves to be an interactive adjustment, with the Ultem 1000 mount being sanded to set the axial position and tilt of the detector surface. A

![Figure 12: Collimator assembly in the lab during integration and alignment.]

Figure 12: Collimator assembly in the lab during integration and alignment.
measuring microscope is used to establish the best-fit plane to the surface of the detector, and to set the detector relative to the seat for the field flattener and the mounting points for the detector spider assembly. This procedure cannot be adopted for 150 units, and leads to tight specifications on the CCD package for the production units.

Final adjustment of the optical system is done with the camera evacuated and the detector cold. The camera mirror provides the final adjustment to align and focus the instrument. An adjuster back is used with vacuum feed-throughs to adjust and clamp the mirror position in tip, tilt and piston. Feedback is provided by observing spectral emission line lamps illuminating the IFU, and the image quality is analyzed as a function of fiber position and wavelength to provide the best overall focus, and alignment of the spectra on the detector. This is quite a lengthy and interactive procedure, but provides very good image quality while maintaining all the fibers on the detector. Interchange of IFUs shows a shift of less than a resolution element in fiber position.

Alignment of the spectrum of the central fiber with rows on the detector is done by rotating the camera in its mount to the collimator and grating assembly. Alignment of wavelengths to the columns requires a small amount of rotation of the grating in its cell.

4.2 Telescope Interface

A set of additional telescope interface equipment needed to be developed and installed near at the telescope focus in order to deploy this instrument on the 2.7m Harlan J. Smith Telescope: A new guide camera was deployed consisting of a pick off mirror, focal reducer and liquid cooled CCD. A Uniblitz shutter was installed before the IFU as VIRUS-P has no internal shutter. A two doublet focal reducer was installed to change the focal ratio from the f/9 of the 2.7m telescope to f/3.65 which is the HET wide field upgrade telescope focal ratio.

A telescope focal plane assembly structure was built to hold all of these subsystems in position and to align them to the focal plane. The structure consists of an aluminum plate structure which is mounted onto the south port of the telescope with tip, tilt and piston adjustment to align to the focal plane of the telescope.

4.3 Gimbal

In order to provide a gravity invariant mount location for VIRUS-P, it is mounted in a gimbal. The gimbal allows VIRUS to hang, aligned by gravity in a single vertical direction as the telescope tracks across the sky. The gimbal can move freely as the telescope tracks 60 degrees in every direction from the zenith. This covers all normal observing tracks. Outside of the 60 degrees of free motion the gimbal runs up against its end stops and does not endanger the instrument, however it will alter the gravity loading of the instrument.

Figure. 13: VIRUS in its gimbal mount on the south port of the 2.7m Harlan J. Smith Telescope at the McDonald Observatory.
The gimbal consists of two main steel welded structures: The yolk which mounts to the telescope port and forks out to two bearings onto which the gimbal cage is attached. The gimbal cage rotates within the yolk and carries another set of bearings to which the instrument is attached by a saddle. The center of gravity of the instrument is located below a point where the two sets of gimbal bearing axes intersect. This ensures that it hangs naturally in a vertically upward direction. Rotation at both sets of bearings is governed by rotational dashpots in order to damp out any sudden movements and to damp out any wind induced swaying of the instrument.

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