Construction of the Hectospec: 300 optical fiber-fed spectrograph for the converted MMT

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ABSTRACT

The Hectospec consists of a robotic positioner that will position 300 optical fibers at the f/5 focus of the converted MMT and a bench mounted moderate-dispersion spectrograph. Hectospec will be the first wide-field instrument to be used at the converted MMT and is now under construction at the Smithsonian Astrophysical Observatory. Commissioning at the converted MMT is scheduled for mid 1999, shortly after first light at the f/5 focus. The innovative features of the instrument are described, emphasizing recent developments.

Keywords: Optical and multi-object spectroscopy

1. INTRODUCTION

The conversion of the Multiple Mirror Telescope (MMT) to use a single 6.5 m primary mirror is expected to be complete by mid 1999. One of the most important features of the converted MMT is an f/5 wide-field focus optimized for optical fiber-fed spectroscopy over a 1° diameter field and direct imaging over a 0.5° diameter field. This focus is enabled by a 1.7 m secondary mirror[1] and a refractive corrector[2] designed by Harland Epps. Hectospec is a moderate dispersion spectrograph that helped drive the development of this wide field. Its 300 optical fibers terminate in magnetic buttons[3] that are positioned over the 1° field by a pair of 5-axis robots working in tandem. We expect to commission Hectospec in mid 1999 shortly after commissioning of the converted MMT's f/5 focus. Hectospec is now being assembled at the Smithsonian Astrophysical Observatory. Here we report on design developments since the 1994 SPIE Instrumentation in Astronomy VIII conference where Hectospec was first described.[4] A companion paper at this conference describes the targeting and sequencing algorithms for the Hectospec's optical fiber positioning robots.[5]

The Hectospec consists of three major parts: (1) the fiber positioning unit that is mounted on the telescope (Fig. 1), (2) a large stationary spectrograph mounted on a 1.8×3.7 m Invar-surfaced optical bench (Fig. 2) and (3) a 26 m-long bundle of optical fibers connecting the fiber positioner and spectrograph. We describe the innovative features of the fiber bundle in Sect. 3. The Hectospec fiber positioner and optical fibers are also used with a high-resolution echelle spectrograph described at this conference: Hectochelle.[6]

2. IMPROVED OPTICAL FIBER FOR ASTRONOMY

At the time of our previous report[4] we planned to place the bench mounted spectrograph in the back of the telescope, which would have allowed a total fiber length of ~10 m. However, the logisitics of storing the fiber positioner and two bench spectrographs forced us to move both spectrograph benches to a permanent, but more remote home above the observing floor. As a result, the required fiber length grew to 26 m, and transmission losses in the fiber became of greater concern. Traditionally two types of all-silica optical fibers have been available: high OH fibers that transmit well into the blue, but that have OH absorption

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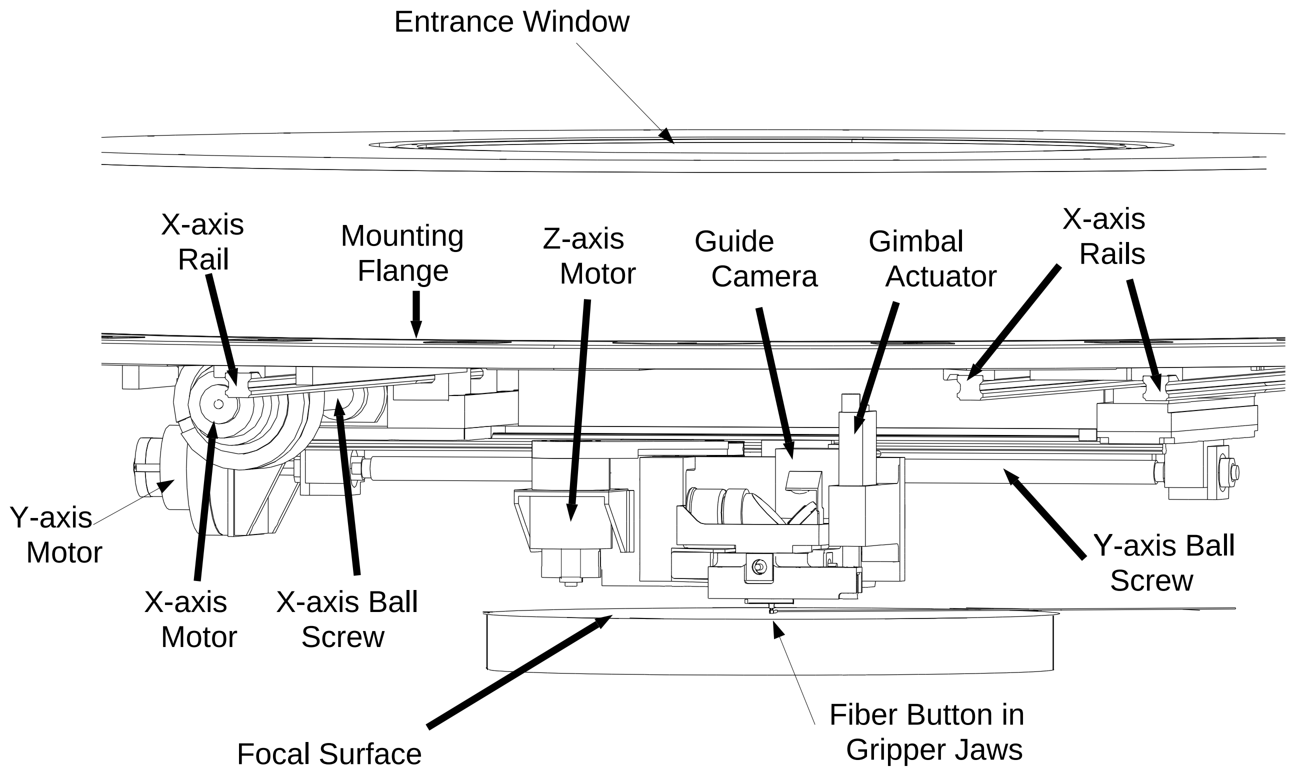

Figure 1. A closeup of one of the two Hectospec fiber positioning robots with one of the 300 fibers.

features in the red, or low OH fibers that transmit well from ∼0.5–2 μm. Neither of these choices appeared ideal so DGF contacted Hereaus-Amersil, a large supplier of fiber optic preforms to explore the limitations of fiber preform technology. After a period of research, Hereaus-Amersil developed a new type of broad-band, low OH fiber preform ("STU") that transmits well from 0.35–1.8 μm. This development is described elsewhere,[7,8] so we restrict ourselves here to comparing the transmissions of 26 m of the conventional low OH, high OH and STU fibers in Fig. 3. The STU transmission for the Hectospec fiber exceeds the minimum performance specified by Hereaus-Amersil. The intrinsic focal ratio degradation in this fiber is very low: ∼95% of all the light transmitted by a 25 m length of fiber remains within an f/6 cone if the fiber is fed with an f/6 beam and care is taken to avoid stressing the fiber.

3. FIBER MOUNTING AND ROUTING

The mounting of the optical fibers in their magnetic buttons and at the spectrograph input slit as well as the handling of the fibers between the fiber positioner and the spectrograph can have a large effect on the spectrograph throughput. The focal ratio of the light emerging from the fiber is easily degraded (made faster) if the fiber is stressed.[9,10] The overall transmission of the fiber is usually unaffected, but to avoid degrading the image quality we place a mask on the Hectospec grating that limits the collimated beam diameter. For us, therefore, focal ratio degradation (FRD) translates directly to a loss of throughput. Attention to detail is important if the excellent focal ratio preservation that we measure under ideal conditions in the laboratory is to be realized at the telescope. We have invested a good deal of time in prototype testing in an effort to uncover and eliminate sources of focal ratio degradation.

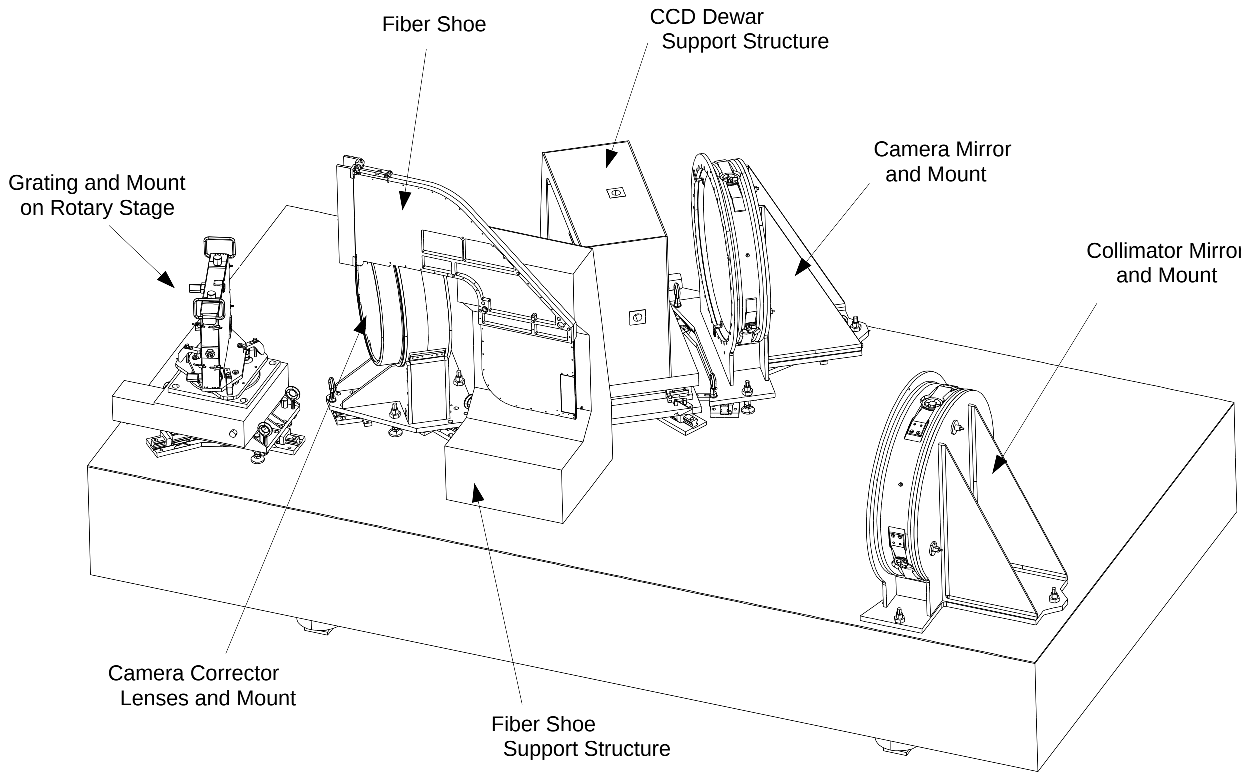

Figure 2. The Hectospec spectrograph

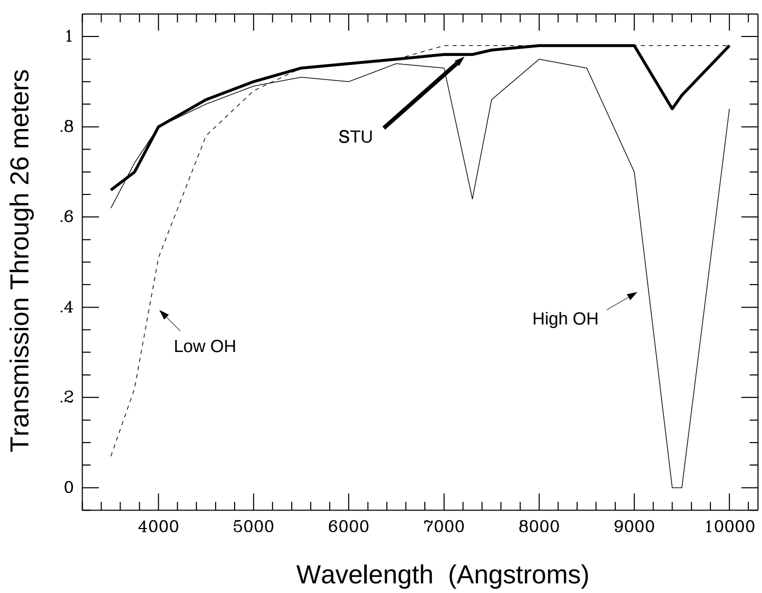

Figure 3. Transmission through 26 m of 3 different optical fibers: high OH (light line), low OH (dashed line) and the new STU broadband fiber (heavy line).

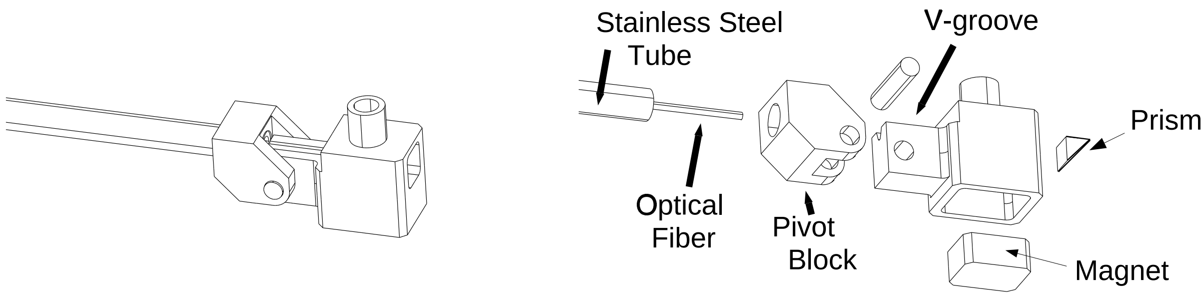

Figure 4. The Hectospec fiber button.

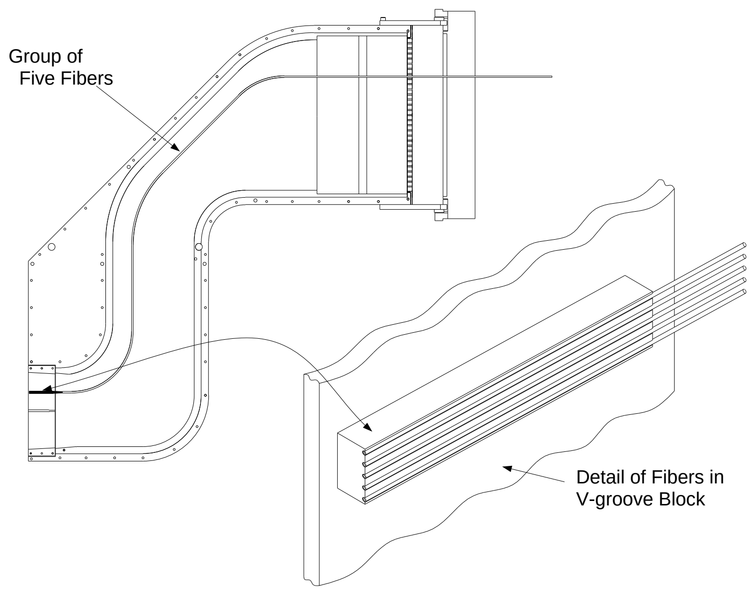

Figure 5. The fiber slit assembly (or "shoe") at the spectrograph input.

3.1. V-grooves for fiber termination

We have known at least one good method of terminating fibers for some time: attaching them to carefully machined and deburred V-grooves with small drops of silica-filled epoxy.[11] We have had such good luck with this approach that we adopted it for Hectospec without further investigation. Both the fiber button and the spectrograph input slit have machined V-grooves as shown in Fig. 4 and Fig. 5. We spent most of our time worrying about the 26 m of fiber between these V-grooves!

3.2. Teflon tubing for fiber protection

Optical fibers are commonly placed in plastic tubes of some variety as a first level of protection, and we have found no way of improving upon this plan. The ideal plastic tube would be very slippery (to avoid putting frictional loads into the fibers), kink-proof and with no "memory" (for ease of handling). We find that TFE Teflon tubes have the first two properties, which we think are most important. To reduce frictional loads further, we find that a loose fitting Teflon tube is advantageous: we use a tube with a 1.4 mm ID surrounding an 0.3 mm OD fiber. We group five teflon-clad fibers together in a woven, slippery, nylon tube for additional protection, ease of handling and fiber identification.

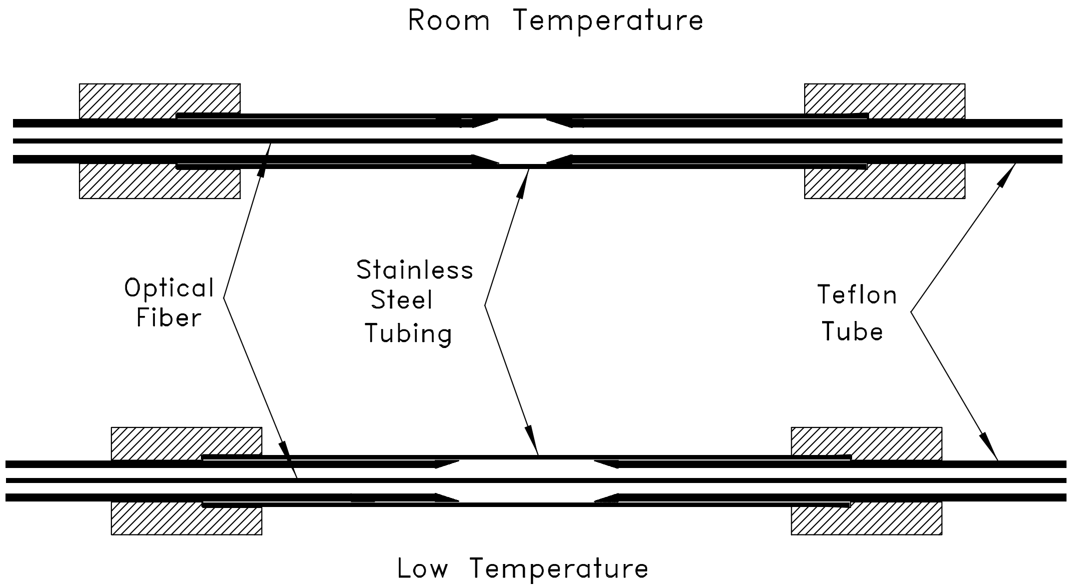

Figure 6. Conceptual design of a fiber thermal break.

Even though friction between our polyimide buffered fibers and the Teflon tubes is low, we have experimentally determined that the large difference in the coefficients of thermal expansion of Teflon (or any other plastic) and the silica fiber can lead to stress and FRD. We constructed a long optical fiber refrigerator in the laboratory to search for FRD associated with the differential contraction at the low temperatures encountered at the telescope. Our fiber refrigerator was constructed from nested copper tubing, cooled by liquid flowing between the tubing. This configuration allows efficient cooling and a dry fiber. During such a test the fiber should *not* be coiled, because in this case the clearance between the fiber and its protective tube may take up much of the differential contraction. The most severe case appears to be the most realistic one: when a few bends are introduced in an otherwise straight run of fibers. Here, the increased friction at the bends prevent the Teflon tube from freely slipping by the fiber and the shrinking tube pulls the fiber against the bend.

3.3. Thermal breaks to avoid thermal stress

We developed a simple means of relieving the stresses caused by the shrinking Teflon tube that we call a "thermal break". A thermal break is simply a break in the Teflon tube to ease differential thermal contraction. The cut ends of the Teflon tube must be carefully deburred and kept in alignment (we use metal tubing) to avoid creating stress points. A schematic thermal break is shown in Fig. 6. We place thermal breaks at every major bend in our fiber run.

3.4. Guide chain for fiber protection

Fibers are sometimes gathered in large diameter metal or plastic tubes for protection over the long run between the telescope and spectrograph. Although this bundling technique is straightforward mechanically, it may introduce stress and FRD as the bend direction of the tubing changes. The path length differences for fibers on the inside and outside of the bend are potentially large, and the fibers will attempt to move sideways past each other in the tube as it is bent in opposite directions. We have minimized stresses due to changing path lengths by adapting cable carriers (see Fig. 7) that were designed to carry electrical cables

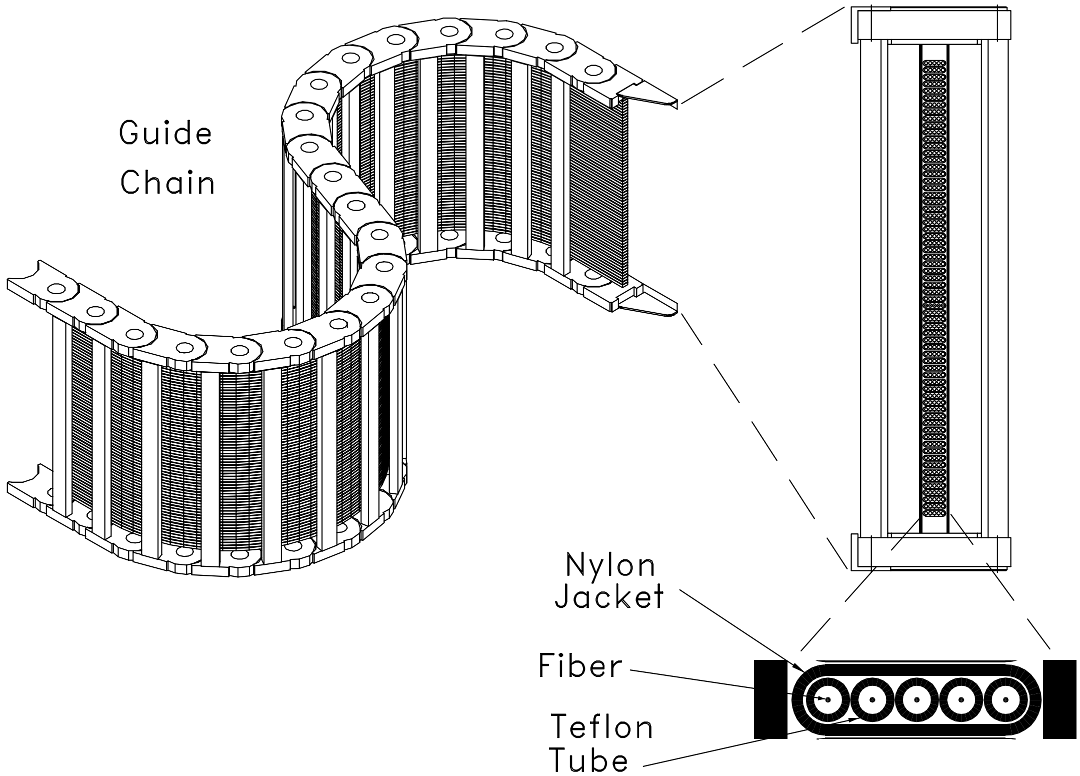

Figure 7. The fibers in the guide chain.

between a stationary point and a moving linear stage. These cable carriers are constructed as chains, and can be designed to bend in only one direction or to bend into S-shapes. We use both types in our fiber run. We minimize the path length changes imposed on the fibers by holding them very near the central axis of the guide chain with soft Velcro strips.

3.5. Fiber routing inside Hectospec

The most complex part of the fiber run between the focal plane and the spectrograph is inside the fiber positioner as shown in Fig. 8. The fibers must be gathered from their radial positions at the edge of the focal surface into a more compact arrangement, and run through a derotator that compensates for the motion of the MMT's (alt-azimuth mount) instrument rotator. After leaving the focal surface, the fibers pass through: (1) pivot points, (2) bi-level horizontal separator trays that allow $\pm 3°$ of lateral motion, (3) Teflon guide tubes and (4) vertical separator trays where a fiber coil takes up the length changes associated with the radial fiber travel across the focal surface. Upon exiting the vertical shelves, the fibers are gathered into groups of five and dressed around a central cone to take up differences in the fiber lengths between the focal surface and the entrance to the fiber derotator. The derotator uses a length of guide chain and is passively driven by the MMT's instrument rotator.

4. OPTICAL CONFIGURATION AND PERFORMANCE

Since 1994, a few details of the Hectospec spectrograph optical configuration have changed. We have purchased a fiber with a 250 μm core diameter drawn from STU preform by Polymicro Technologies. This fiber subtends 1.5$''$ at the converted MMT's f/5 focus. We have also purchased a pair of 2048$\times$4608 EEV

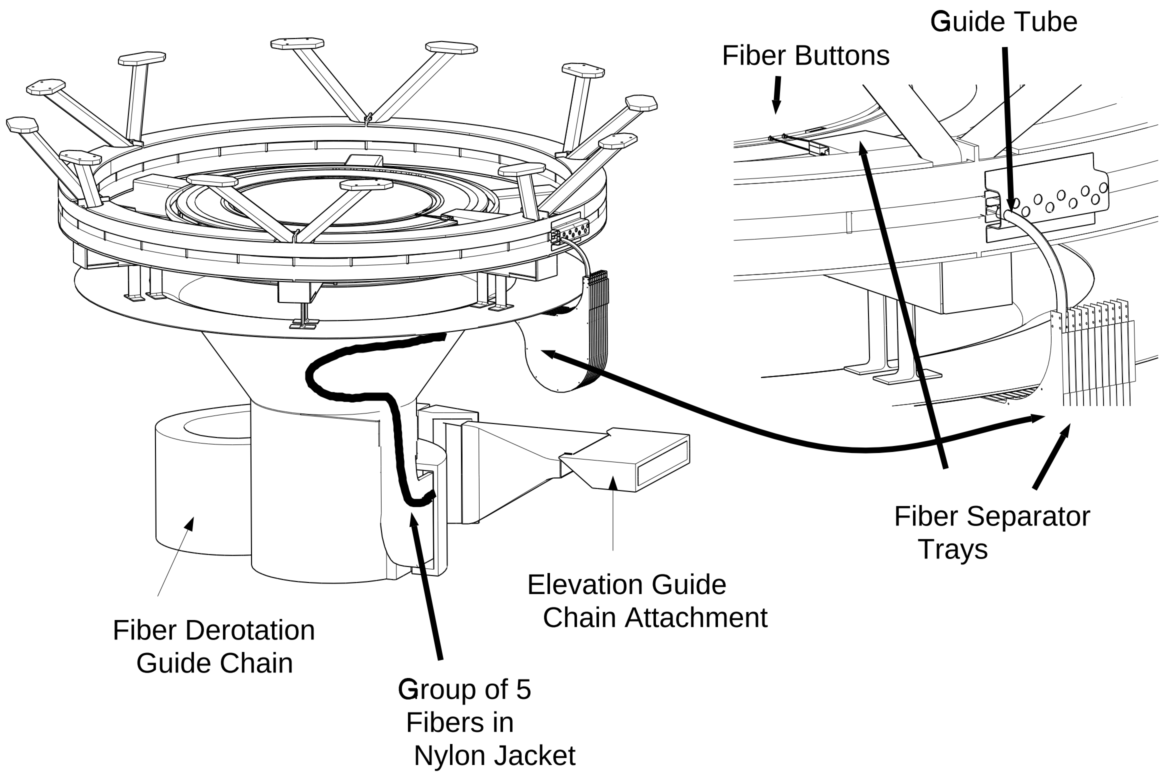

Figure 8. Fiber routing from the focal surface to its exit from the fiber positioner. The upper portion of the fiber positioner containing the mounting flange and positioning robots is removed for clarity.

CCDs with 13.5 μm pixels for Hectospec; we expect to standardize on this CCD for the converted MMT's wide-field instruments. We nominally use about 80% of this CCD's format and the performance shown in Tab. 2 refers to this reduced format: 3400$\times$3400 pixels. Hectospec's vital optical statistics are summarized in Tab. 1.

We have ordered a single 270 groove/mm grating blazed at 5200 Å from David Richardson Grating Laboratory. The spectral coverage, spectral resolution, anamorphic magnification, grating angles and RMS image diameters with this grating and two higher dispersion gratings, all centered at Hα, are shown in Tab. 2.

5. THROUGHPUT

The Hectospec optical layout is simple enough[4] that very high throughput can be achieved if good reflective coatings are used on the mirrors (2 surfaces) and good antireflection coatings are used on the lenses (6 fused-silica surfaces). We intend to use the same dielectrically-enhanced silver reflective coatings and Sol-gel antireflection coatings that we used in the efficient FAST spectrograph.[12] The Sol-gel coatings are described in a paper by Jeffrey Bohn at this conference.[13] Our predictions for Hectospec's overall throughput are shown in Tab. 3. The column labeled "Add. Fiber Losses" in Tab. 3 includes FRD, end reflection losses, and the losses from misalignments of the fiber axis with respect to the chief ray at the f/5 focal surface.

Table 1. Hectospec spectrograph optical configuration

Collimated beam diameter	259 mm
Camera focal length	397 mm
Fiber core/cladding/buffer	250/275/300 μm
Reduction (spatial)	3.45
CCD format (max)	4608×4096 pixels
CCD format (nominal)	3400×3400 pixels
CCD pixel size	13.5 μm
250 μm fiber sampling	5.4 pixels
Max. mono. beam to camera	259×344 mm
Camera field radius	4.7°
Camera-collimator angle	35°
Camera-grating distance	546 mm
Camera entrance aperture	411 mm

Table 2. Hectospec grating configurations

Ruling Density (grooves/mm)	Spectral Coverage Å	Spectral Resolut. Å	Ana. Mag.	Angle of Incidence (degrees)	Angle of Diffract. (degrees)	Range of RMS Image Dia. (pixels)
270	4488–8664	6.2	1.06	22.83	12.17	1.3–1.8
600	5609–7522	2.6	1.14	29.41	5.59	1.3–1.8
1200	6084–7038	1.1	1.33	41.89	-6.89	1.4–1.7

6. GUIDING

The ease with which the fibers can be initially aligned with respect to the observation targets and the accuracy with which they are kept aligned will affect the overall observing efficiency with Hectospec. The design of the acquisition and guiding hardware deserves a fair share of engineering effort along with high speed positioning robots[4] and efficient reconfiguration algorithms[5] to conserve scarce observing time. Hectospec will be guided with at least two guide stars at all times to measure instrument rotator errors as well as telescope altitude and azimuth pointing errors. To avoid occulting prime observing real estate, guiding will be performed by three independently actuated probes at the circumference of the focal surface as shown in Fig. 9. The probes move along three 100° arcs and each contains relay optics to carry the guide star image to coherent fiber bundles. The three coherent bundles form a trifurcated assembly; the three bundles are brought together to form a single bundle at the input to an intensified CCD guide camera.

In addition, each fiber robot carries an intensified CCD camera that is capable of simultaneously viewing a target object and a backlit fiber through a beam splitter, as shown in Fig. 10. This feature was introduced on the Argus multi-object spectrograph at CTIO.[14] After the fibers are positioned for a given observation, the gripper heads will be sent to the intended position of the guide stars and the rotation and pointing errors of the telescope will be removed. The guide stars will then be acquired in the coherent bundles and guiding can begin. If desired, the gripper heads can then be commanded to one or more target objects and

Table 3. Hectospec throughput with grating blazed at 5200 Å

Wavelength (Å)	Mirror Refl. (2 surf.)	Lens Refl. Losses (6 surf.)	Fiber Trans. (26 m)	Add. Fiber Losses	CCD QE	Vign. by Dewar	Grating Effic.	Final QE
3650	0.81	0.89	0.70	0.80	0.66	0.80	0.37	0.08
4000	0.96	0.92	0.80	0.80	0.80	0.80	0.49	0.18
5000	0.96	0.98	0.90	0.80	0.85	0.80	0.66	0.30
6000	0.97	0.98	0.94	0.80	0.80	0.80	0.61	0.28
7000	0.96	0.98	0.96	0.80	0.75	0.80	0.53	0.23
8000	0.97	0.95	0.98	0.80	0.60	0.80	0.43	0.15
9000	0.97	0.91	0.98	0.80	0.30	0.80	0.37	0.06

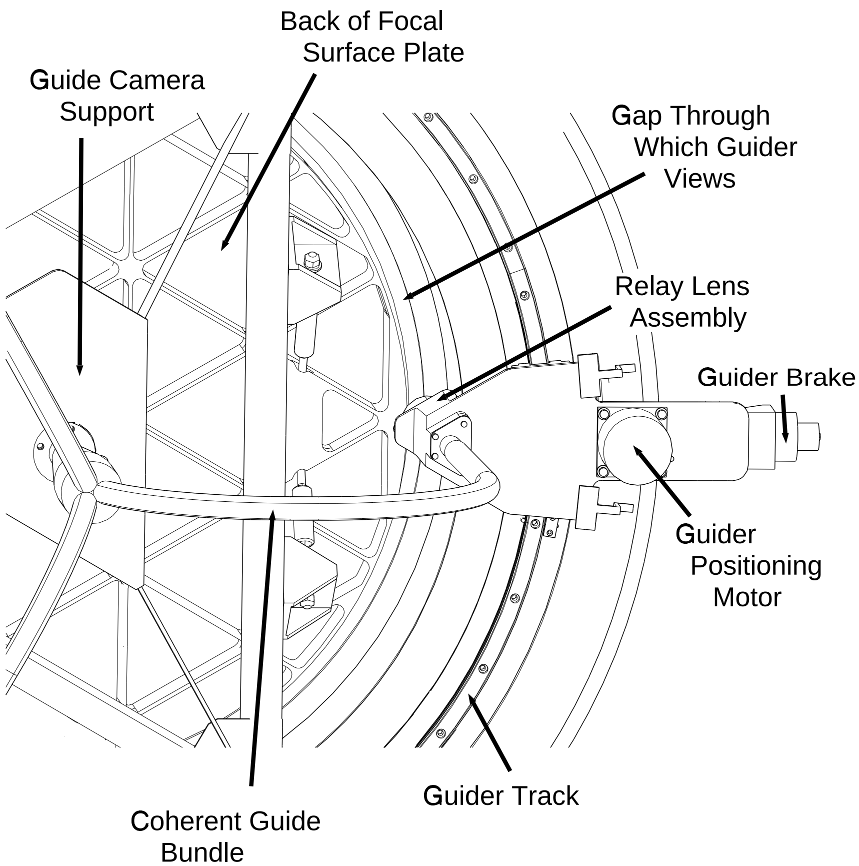

Figure 9. A coherent fiber guider bundle at the edge of the focal surface.

the alignment can be checked with reference to a backlit fiber.

The guide cameras, manufactured by Electro-Optical Services, Inc., use Gen III image intensifiers with maximum gains of 70,000 and quantum efficiencies of >20% from 4250 to 8750 Å. The camera receiving the trifurcated coherent bundle has its image intensifier photocathode deposited on the back surface of its fiber optic input to avoid defocusing at the photocathode. The image intensifiers are coupled through

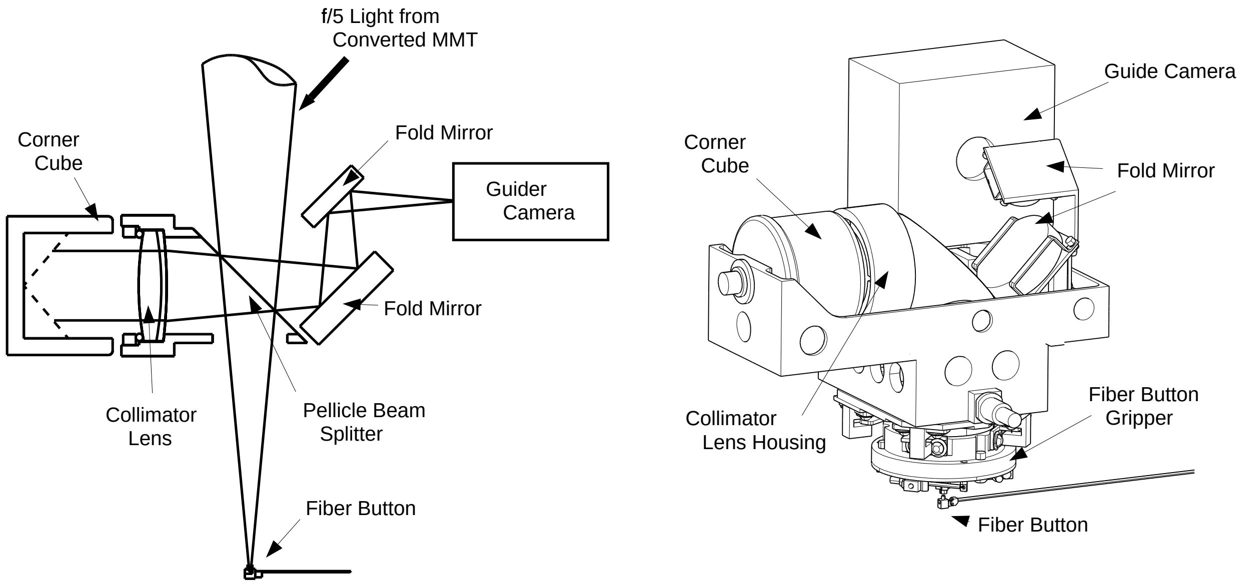

Figure 10. The guiding optics in the positioning robots.

a reducing fiber optic (1.6:1 ratio for the robot cameras and 2.3:1 for the guide camera) to a 768×493 pixel CCD (each pixel is 11×13 μm). The cameras in the fiber positioning robots have a field of view of $\sim 60'' \times 80''$, while the three coherent bundle guiders each have a field of view of $\sim 30'' \times 60''$.

7. TEST PROGRAM

Hectospec is a complex machine by any definition, so we plan nearly a year of test and calibration in the laboratory before it is transported to the telescope in mid 1999. We particularly want to avoid discovering those problems at the telescope that might have been found in the laboratory. Because our goal is to preserve high positioning accuracy at all orientations with respect to gravity while maintaining the ability to position 300 fibers in ∼300 seconds, we must calibrate Hectospec's static deflections and dynamic behavior in several orientations and compare these with the finite element and dynamic models. This is conceptually straightforward, but does require a large structure to move and correctly support a 1400 kg instrument. We have named this structure, shown in Fig. 11, the "telescope simulator" although it contains no optics. Because we are aiming at ∼25 μm positioning accuracy in a large instrument, we have taken pains to avoid imposing forced deflections through the instrument mounting flange. Finite element models of the telescope and instrument rotator predict axial and radial deflections of <25 μm at the flange, which produce positioning errors of <8 μm. If the laboratory tests are to be valid, the telescope simulator must perform as well and this requires a good deal of steel.

Our basic tool for testing and calibrating Hectospec's positioning accuracy is a glass calibration plate (containing an accurate grid of small etched dots) that can be placed on the Hectospec's focal surface. The TV camera aboard each of the robots will be used to centroid the images of the etched dots and to calibrate the motion of the robots at various instrument orientations.

ACKNOWLEDGMENTS

Due to lack of space, we have not discussed Hectospec's electronics and the 6 km of wiring that control 10 servo motors and 5 stepper motors, but we would like to acknowledge the fine work of our electronic engi-

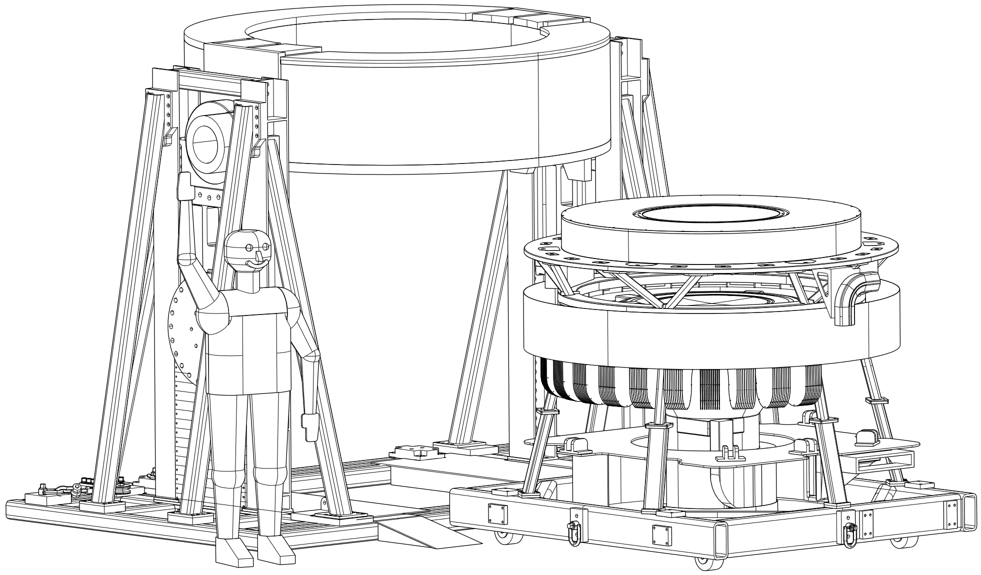

Figure 11. The MMT telescope simulator at the Center for Astrophysics with Hectospec on its handling cart.

neers: Thomas Gauron and David Weaver. Five highly skilled designers have contributed many important ideas: Jack Barberis, Arthur Gentile, Michael Honsa, Jerry Margolycz and Dale Noll.

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REFERENCES

1. R. G. Fata and D. G. Fabricant, "Design and support of the 1.7 m f/5 secondary mirror for the MMT conversion," in *Advanced Technology Optical Telescopes V*, L. M. Stepp, ed., *Proc. SPIE* **2199**, pp. 580–592, 1994.
2. R. G. Fata and D. G. Fabricant, "Design of a cell for the wide-field corrector for the converted MMT," in *Optomechanical Design*, D. Vukobratovich, J. P. Yoder, and V. Genberg, eds., *Proc. SPIE* **1998**, pp. 32–38, 1993.
3. I. R. Parry and P. M. Gray, "An automated multiobject fibre optic coupler for the Anglo-Australian telescope," in *Instrumentation in Astronomy VI*, D. L. Crawford, ed., *Proc. SPIE* **627**, pp. 118–124, 1986.
4. D. G. Fabricant, E. N. Hertz, and A. H. Szentgyorgyi, "Hectospec: a 300-optical-fiber spectrograph for the converted MMT," in *Instrumentation in Astronomy VIII*, D. Crawford and E.Craine, eds., *Proc. SPIE* **2198**, pp. 251–263, 1994.
5. J. B. Roll, D. G. Fabricant, and B. A. McLeod, "Targeting and sequencing algorithms for the Hectospec's optical fiber robotic positioner," in *Optical Astronomical Instrumentation*, S. D'Odorico, ed., *Proc. SPIE* **3355**, pp. ?–?, 1998.

6. A. Szentgyorgyi, P. Cheimets, R. Eng, D. Fabricant, J. Geary, L. Hartmann, M. Pieri, and J. Roll, "Hectochelle: a multi-object echelle spectrograph for the converted MMT," in *Optical Astronomical Instrumentation*, S. D'Odorico, ed., *Proc. SPIE* **3355**, pp. ?–?, 1998.
7. G. F. Schotz, J. Vydra, G. Lu, and D. G. Fabricant, "New silica fiber for broadband spectroscopy," in *Fiber Optics in Astronomy III*, S. Arribas, E. Mediavilla, and F. Watson, eds., *Astronomical Society of the Pacific Conference Series* **in press**, pp. ?–?, 1998.
8. G. Lu, G. F. Schotz, J. Vydra, and D. G. Fabricant, "Optical fiber for UV-IR broadband spectroscopy," in *Optical Astronomical Instrumentation*, S. D'Odorico, ed., *Proc. SPIE* **3355**, pp. ?–?, 1998.
9. L. W. Ramsey, "Focal ratio degradation," in *Fiber Optics in Astronomy*, S. Barden, ed., *Astronomical Society of the Pacific Conference Series* **3**, pp. 26–40, 1988.
10. W. W. Craig, C. J. Hailey, and J. P. Brodie, "Measurement of fibers to be used in fiber fed spectroscopy," in *Fiber Optics in Astronomy*, S. Barden, ed., *Astronomical Society of the Pacific Conference Series* **3**, pp. 41–51, 1988.
11. D. G. Fabricant and E. N. Hertz, "The Decaspec: a fiber optics adapter for multi-object spectroscopy," in *Instrumentation in Astronomy VII*, D. Crawford, ed., *Proc. SPIE* **1235**, pp. 747–753, 1990.
12. D. G. Fabricant, P. Cheimets, N. Caldwell, and J. Geary, "The FAST spectrograph for the Tillinghast telescope," *Pub. Ast. Soc. Pac.* **110**, pp. 79–85, 1998.
13. J. H. Bohn, "Sol-gel antireflective coatings for astronomical optics," in *Optical Astronomical Instrumentation*, S. D'Odorico, ed., *Proc. SPIE* **3355**, pp. ?–?, 1998.
14. T. E. Ingerson, "Factors affecting the design of multiobject spectrometers," in *Fiber Optics in Astronomy*, S. Barden, ed., *Astronomical Society of the Pacific Conference Series* **3**, pp. 99–111, 1988.