Multiple Object Fiber Optics Spectrograph Feed For The Hale Telescope

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Abstract

A preliminary design of a fiber-optics feed for the prime-focus spectrograph of the Hale telescope using computer controlled movable fiber has been completed and a test of a prototype configuration carried out. The complete design will divide a 76mm square field into 10 strips and will place two movable fibers in each strip. The fiber pickups, which are moved by stepper-motor driven lead screws, may be placed anywhere in the strip subject to the limitation that they not pass each other.

The prototype consisted of a single strip with two fibers operated with manual input to the stepper motors. In tests performed at the 5 meter Hale telescope in April of 1981 spectra of two bright O stars (B = 8.5 mag) separated by 5 arc minutes were photographed with a 3 minute exposure using a 1200 line/mm grating and unbaked 103aO plates. The performance of the prototype configuration was within a factor of two of the unmodified prime-focus spectrograph indicating a potential for a ten-fold increase in the effective utilization of the telescope for spectrographic survey work when fitted with the 20-fiber feed.

Introduction

The traditional design of astronomical spectrographs places the spectrograph entrance slit on the optical axis in the focal plane of the telescope. Depending upon the dispersion desired any of the various foci (Newtonian, Cassegrain, coude, etc.) may be used, but all locations suffer from the limitation that in general only a single object can be observed at a time. It has recently been demonstrated that it is feasible to connect the focal plane to the spectrograph slit with optical fibers to permit the simultaneous observation of many astronomical objects in a small angular field. The referenced demonstration was with fibers fixed in position in the focal plane in order to intercept the light from a given set of astronomical objects, and it was necessary to prepare a different fiber assembly for each image field observed. It did, however, show that light loss through the fibers was reasonable and that a large increase in observing efficiency was possible.

Objective

The objective of this task was the demonstration of the feasibility of constructing a fiber-optics spectrograph feed suitable for use on the 200-inch Hale telescope of Palomar Observatory. The requirement on the proposed device was that it use optical fibers to couple the light from several objects in the image at the prime focus of the telescope to the existing prime-focus spectrograph in such a way that the fibers could be moved under computer control to take up the positions required for each successive observation field. It was not the objective to demonstrate computer control per se but only to demonstrate a design adaptable to computer control. The specific objectives were to do a design-trade-off study to select a general approach, construct a prototype instrument using at least two fibers, and test it by observations at the telescope.

General Design Considerations

There are several possible designs for a system which provide for a number of fibers in the focal plane of a telescope arranged so that they can move under computer control. The major questions that must be answered in arriving at an acceptable configuration are: (1) How many fibers must be provided in an operationally useful system? (2) What constraints must be placed on their motion? (3) Will they be moved simultaneously or sequentially? (4) Will a fine adjustment be needed to locate the position of maximum signal for each object and if so how will this be done? The first two questions are particularly closely related. If each fiber is free to move anywhere in the field subject to the limitation that it is excluded from regions close to each of the other fibers, fewer fibers will be needed than if each fiber is restricted to a more limited region of the focal plane. The last two questions are likewise closely related. The initial setup of the fibers for a given field can certainly be done sequentially without occupying an excessive amount of the observing time. It can, for example, be done while the telescope is being slewed to a new field. If,

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however, peaking-up is required, the question becomes critical to the design because the peaking-up must be done with the telescope tracking the measurement field.

A possible articulation of the fibers so that each is free to move over a large portion of the field is shown in Fig. 1. This has been described as the "fishing-pole approach. The mechanisms are mounted around the edge of the field at equal intervals. Each mechanism is able to move its fiber in polar coordinates so that it can be placed anywhere in a sector of radius at least equal to that of the field. The fibers are kept from colliding with each other by having the entire process under computer control and by having contact switches as a backup. The figure illustrates such a system with 20 fibers applied to a hypothetical star field.

The opposite extreme, that of subdividing the field into a number of independent areas each with a fiber movable only within that area, is shown in Fig. 2. In this particular example the field has been divided into 36 squares and the system applied to the same hypothetical star field used in Fig. 1. The fibers intercepting objects are shown by the solid circles; while the unused fibers are indicated with open circles. There are 4 objects, shown by an "X" through a circle that were intercepted by fibers in the fishing-pole system but are not picked up here.

A third approach is shown in Fig. 3. Here the field is divided into 10 strips each containing two fibers. The fibers are free to move anywhere within the strip subject to the

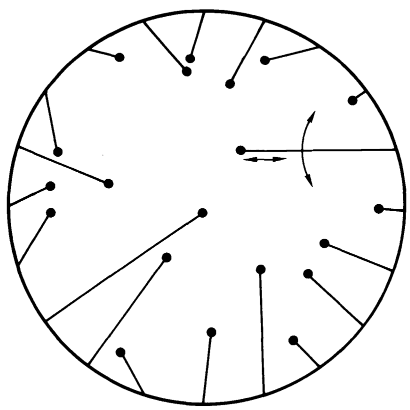

Figure 1. Hypothetical star field with "fishing-pole" actuation of the fibers.

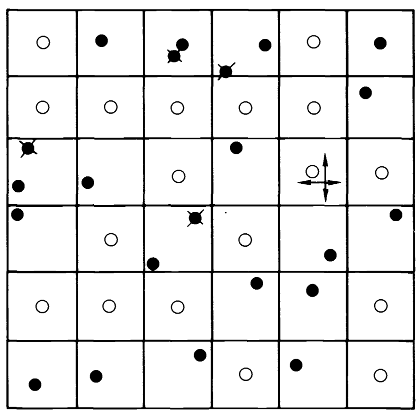

Figure 2. Same hypothetical star field with fibers distributed in a grid pattern. Solid circles indicates fibers intercepting objects. Open circles are unused fibers. A circle with an X indicates objects not intercepted by fibers.

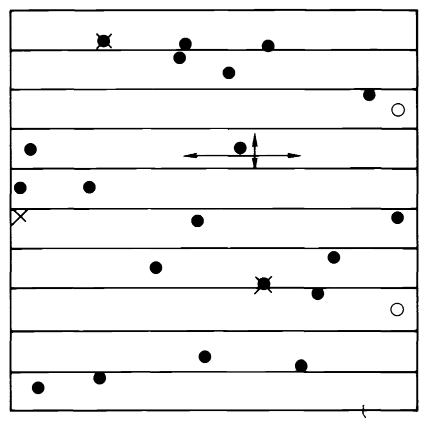

Figure 3. Same hypothetical star field with fibers distributed in strips. Note that there are three unintercepted objects and two unused fibers.

limitation that they may not pass each other. They are kept from colliding by a combination of computer control, limit switches, and mechanical stops. The system, when applied to the hypothetical star field, intercepted 17 of the 20 objects and one additional one outside the original field.

In order to select a design for the fiber articulation, it is necessary to make an estimate of the number of fibers required for a useful system. Since there is some light lost in going through the fibers, the number of objects observed at one time must be great enough to make a significant reduction in total observing time. If the factor by which the observing time is to be reduced is arbitrarily set at 5, and if a factor of two is used to allow for transmission losses and the inability to utilize every fiber when observing a given field; we arrive at 10 as the minimum number of fibers. It is not as easy to set an upper bound, but the general complexity of any system probably limits the number of fibers to no more than 40.

The first of the three designs offers the greatest flexibility in fiber utilization. The chief problem with it is the difficulty of protecting against fiber collisions. The first line of defense is the computer program that moves the fibers. The second level of protection, limit switches to shut off actuators if one fiber comes close to another, does not present unusual problems. However, the third level, that of mechanical stops, cannot be readily provided for this design without a considerable increase in complexity. The second design provides good protection against fiber collisions. Each fiber is assigned a definite area and can be protected from incursions of all other fibers by physical stops. The difficulties with this design are that fiber utilization is not very good and a larger number of fibers and fiber actuators are required than in other designs. The third design offers a compromise solution. It provides-fair-to-good fiber utilization, relatively simple mechanical design and good protection against fiber collisions. This was the design finally selected for the instrument. A possible addition to this design is to provide for the rotation of the entire instrument about the axis of the telescope. This allows the strips to be placed in any orientation with respect to the field being observed to maximize fiber utilization.

It appears to be certain that peaking-up will be required. The combination of errors in the measured positions of the objects under study coupled with their proper motions will create sufficient uncertainty in their location that an operation maximizing the signals from the individual objects will be required. The mode in which this is done is determined by the properties of the particular telescope. If the telescope is able to execute a precise raster scan pattern, this can be used for the peaking-up operation. The Hale telescope can execute such a pattern, and the sequence of operations would be the following: During the slew to a new field the fibers would be driven to the nominal locations of the objects to be studied, and the grating in the spectrograph would be replaced by a plane mirror. This will concentrate the light from each object on a single point of the detector and convert the system into a multi-channel, broad band photometer. Once the pointing of the telescope has been established in the nominal location in the new field, the telescope will be programmed to move in a small raster pattern and the output of each fiber at each point in the raster stored by the computer. At the end of the raster the telescope returns to the nominal position for the field, and the computer determines from the stored photometric values the amount each fiber must be moved to achieve the maximum output. The fibers are moved the few steps required to bring them to the position for maximum signal while the mirror is being replaced by the grating. The system is then ready to begin the observation. Since the time to replace the mirror with the grating is long compared to the time to move the fibers, the fibers can be moved sequentially.

Detailed design

A schematic of the prototype system is shown in Fig. 4. The pickup fibers are mounted on carriages driven by stepper motors. A viewing system, which is movable in the direction of carriage motion, allows visual inspection of the field to confirm that the correct objects are being intercepted by the fibers. A second viewing system mounted outside the main field allows offset guiding to be used. The drive electronics moves the motors under manually commanded digital control. The spectrograph is the existing prime-focus instrument modified with a mount for the fibers at the entrance slit and with the normally-used Schmidt cameras replaced with a simpler one for this experiment. The individual portions of this system are discussed in detail below.

Actuators

The actuation scheme as it could be used in the final instrument is shown in Fig. 5. One quarter of the assembly is shown in two views. The basic form of the carriages that move

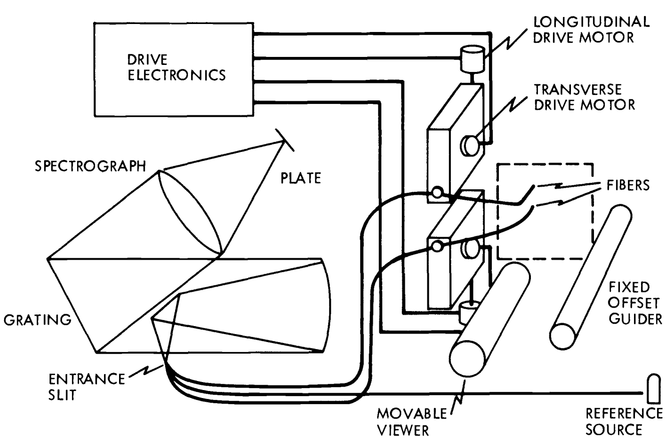

Figure 4. Block diagram of prototype system.

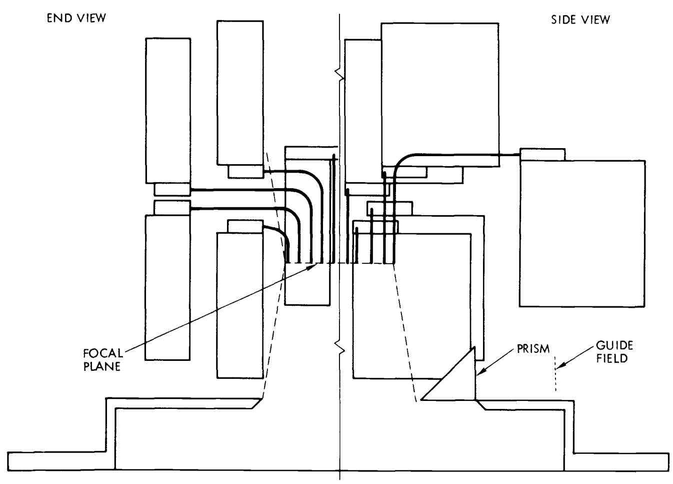

Figure 5. Actuation of the fibers in the design for the complete instrument.

the fibers is that of a rectangular block with its long axis parallel to the telescope axis, its intermediate axis parallel to the long dimension of the strips, and its shortest axis in the transverse direction. The ways on which the carriages move are pairs of rods. Eight of these support two carriages while the other four support single carriages. This arrangement packs the articulation of 20 fibers into a reasonably compact space.

The design of the individual carriages is shown in Fig. 6. Although only two were constructed for testing in the prototype, the design is the one intended for the final instrument. The interior of the prototype instrument with the carriages and fibers is shown in Fig. 7. The outer portion of the actuator carriage is a set of parallel links with flexure

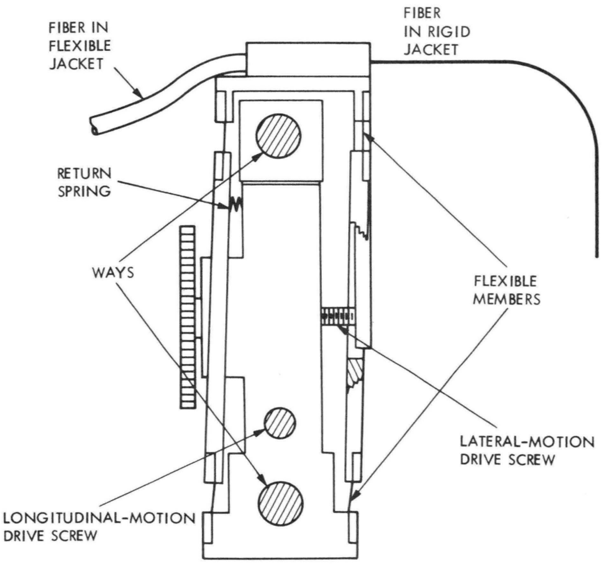

Figure 6. End view of a fiber carriage.

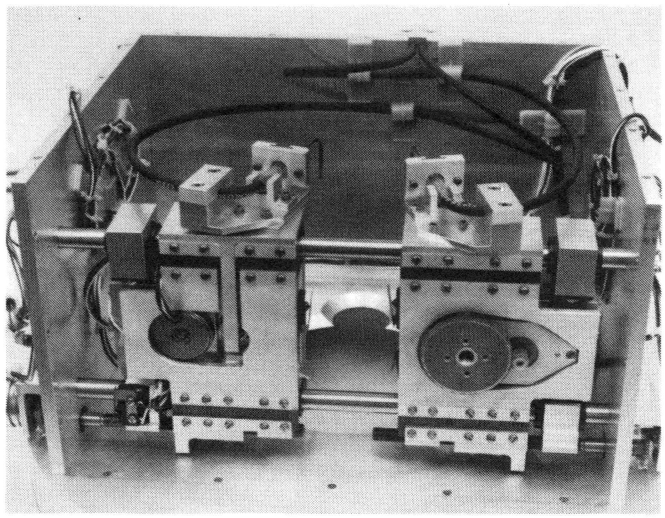

Figure 7. Interior of prototype instrument showing fibers and fiber carriages

hinges. This linkage supports the fiber and allows motion across the width of the strip. Motion along the length of the strip is provided by moving the entire carriage on a pair of cylindrical ways with linear ball bearings. Two of the bearings are mounted rigidly in the carriage while the third is on a stiff leaf spring. The small amount of compliance provided by the spring accommodates variations in the spacing of the ways. This particular design was chosen for several reasons: It lends itself to the stacking required to accommodate 20 fibers by having its shortest dimension perpendicular to the axis of the telescope, a direction in which space is limited, and its longest dimension in the direction of the axis where space is available. The configuration allows the flexure members to have a substantial width, which makes for greater mechanical stability. In addition, flexure members eliminate some of the problems of backlash and lost motion sometimes encountered with sliding or rolling motions.

Both motions, longitudinal and lateral, are driven through lead screws by 90°, permanent-magnet stepper motors. The lead screw pitch is 52 to the inch, and this combined with a 6 to 1 gear ratio gives a displacement of .0008 in or approximately 0.25 arc second per step corresponding to 1/4 of the best-seeing diameter from a point source. Permanent-magnet motors were chosen because of the detent action that remains when the power is off. The resulting system has proved to be very stable. It was found that the fibers held their positions from one night to the next over a period that involved a full night's observing at Cassegrain and numerous attitude tests during the day.

Fiber cable selection

Fiber-cable selection criteria were spectral transmission, core and cladding diameters, numerical aperture, flexibility, and protective jacketing. A requirement for transmission over a wavelength range from 0.3μm to 0.7μm indicated the use of glass core rather than plastic waveguides. Typical image diameters of 100 to 200μm at the telescope focal plane due to seeing conditions led to the selection of a core diameter of 250μm. The fiber numerical aperture was required to be adequate to accept and conduct the cone of light from the primary mirror. This did not present a problem because the numerical aperture of the telescope is 0.14 and the majority of the multimode, glass-fiber waveguides available have numerical apertures in excess of 0.25. A jacketing design which provided for strain relief and protection against abrasion along with flexibility adequate for a bend radius of one inch was also required.

The fiber waveguide selected was Valtec PC10, with a core diameter of 250μm and a cladding diameter of 280μm. The core is fused silica, the cladding is silicone RTV, and the numerical aperture is 0.30. Jacketing is in the form of an inner tube, which fits loosely around the fiber, a layer of Kevlar fibers for tensile strength and cushioning, and an outer jacket of polyurethane.

The fibers are supported and protected by stainless-steel tubes from the carriage to the vicinity of the focal plane. These tubes are bent through a 90° curve and terminate about 10mm from the focal plane. All jacketing is removed from the immediate tip of the fiber to permit clear viewing of the end. The outer jacket is clamped to the carriage just beyond the end of the steel tubing and is clamped again at the point where it passes through the wall of the housing around the focal-plane assembly. The jacket is also clamped at the spectrograph, and the fibers are terminated immediately beyond the clamps with commercial ferrules cemented to the ends of the fibers. These are clamped in a block which aligns them parallel to the axis of the spectrograph and directs the light into the entrance slit. At the spectrograph end the fibers were optically polished after being mounted in the ferrules. At the focal plane the ends were cleaved. Although this slightly reduced the light-collection efficiency, it met the practical requirement of allowing easy renewal of the fiber end in the event of breakage. Three fiber cables were prepared. Two were used to pick up stellar images and one was used for a spectral reference source. The end treatment of each cable was the same and allowed the reference fiber to serve as a spare.

Viewer and guider optics

Two sets of viewing optics were provided in the instrument, one for viewing the field covered by the fibers and one for offset guiding. The latter was one which had been built for the prime-focus spectrograph and was used unmodified. It was mounted to view a region just outside the three-inch square main field. The other utilized a pair of projection lenses as relays and was equipped with an illuminated reticle conjugate to the plane of the fibers. This viewer was mounted on a slide which permitted it to be moved in the direction of the long travel of the fibers. Each fiber and the surrounding field could be viewed at any point in its travel.

Spectrograph

The spectrograph used in this work was the one designed specifically for use at the prime-focus of the Hale telescope by Bowen in 1950. It is a plane-grating instrument with a Newtonian collimator and a Schmidt camera. Since the Schmidt camera is inconvenient to use, it was replaced for these tests with a Kodak Aero Ektar f/2.5, 7 inch focal length and a 4x5 film plane. With the 1200 lines/mm grating used this gave a plate factor of 33A/mm. The entrance slit was not used to determine the spectral resolution. Instead the ends of the fibers served as the entrance slit. This gave a resolution of approximately 10A.

Drive electronics

Since actual computer operation was not required for the study, the drive electronics could be kept quite simple. The control unit was built by Anaheim Automation as a variation on one of their standard units. It is arranged so that control may be switched to each of the four motors in turn and operate each in any of three modes: run, jog, or index. In the "run" mode the motor operates as long as the control button is held down. The "jog" mode operates the motor through a single step each time the button is pressed. The "index" mode allows operation through a predetermined number of steps set on thumb-wheel switches. Automatic ramping of the motor speed is available in the "index" mode. Each motion of the carriages was fitted with limit switches that are switched in when the motor that drives that motion is operating.

Guide fiber

As part of this task a design and fabrication study of a system for the automatic guiding of the telescope was carried out. The objective of the study was a system which could allow the observer to place a specially designated fiber on a selected guide object and have guidance signals sent to the computer controlling the telescope. The plan investigated was that of combining four fibers into a single "guide fiber" of four close-fitting quadrants by careful lapping of the adjoining edges of each fiber and leading the light intercepted by each quadrant to a separate detector. The dividing lines between the quadrants were to be aligned in the north-south and east-west directions. The north-south guiding signal would be generated by taking the sum of the signals from the north-west and north-east detectors minus the sum of the signals from the south-west and south-east detectors. Similarly the east-west signal would be generated by the difference between the sum of the north-east and south-east signals and the sum of the north-west and south-west signals.

A signal-to-noise analysis was performed and detectors selected. These were EG&G model HAD 1000A, which are silicon photodiodes followed by an integral operational amplifier. A fabrication procedure for the fiber was designed and shop tests carried out. A prototype was successfully constructed, but difficulties were encountered in a final assembly. Since there were insufficient resources to put a large effort on this aspect of the study no further work was done. It was concluded from the work that was accomplished, that with sufficient effort a fiber-optics quadrant guider could be constructed. Visual guiding was used for the prototype tests.

Tests

The assembled instrument is shown in Fig. 8. Three sets of laboratory tests were performed. The first of these were interferometric tests of the carriage motions. The results of one of these tests is shown in Fig. 9. The indication is that the deviation from the average position is within ±0.1 arc second across the field of view of the instrument. The second test was the measurement of the transmission through the fibers in the visible region of the spectrum. This was found to be 85%. The test was performed with the fibers in their installed configuration where there were several sharp bends contributing to the loss. These curves will be smoothed out somewhat in the final design which will further reduce the light loss. The third laboratory test was a series of exposures of spectra to determine the dispersion and to check the focus.

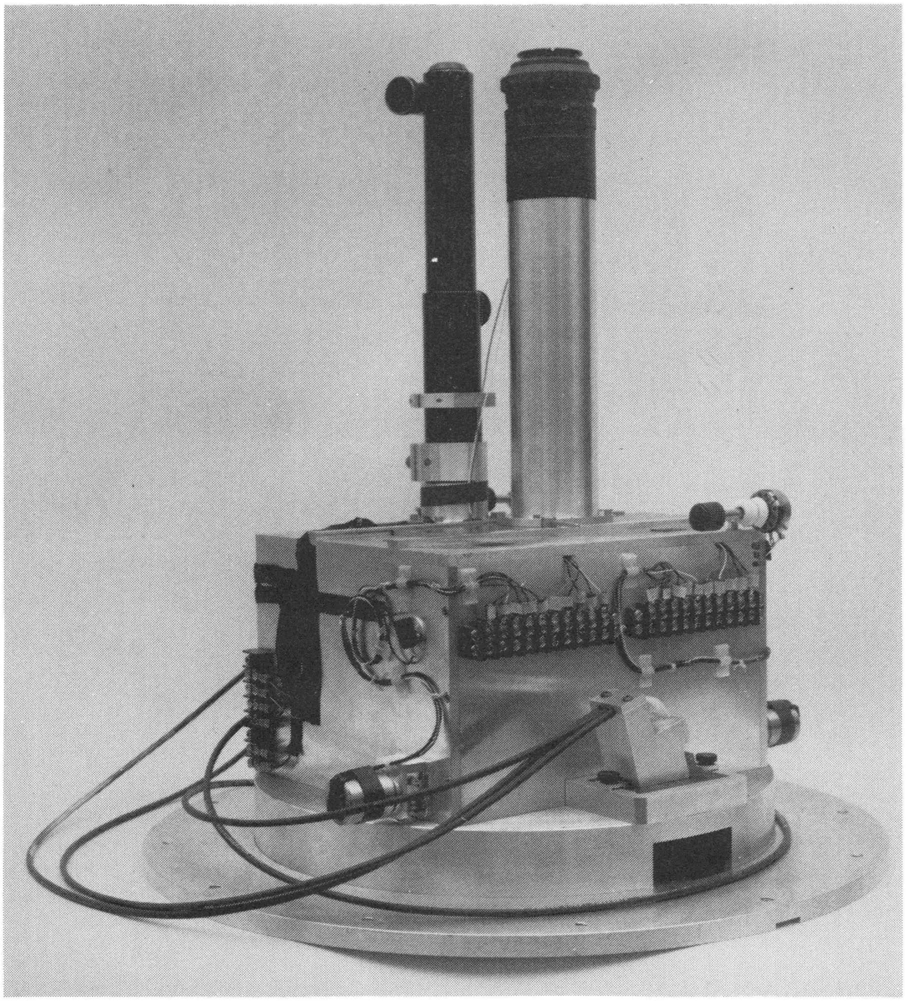

Figure 8. Exterior of prototype instrument. The fiber are in the configuration for transportation. The block on the near side of the instrument is mounted on the spectrograph slit for operation.

The fiber-optics spectrograph feed was tested at the prime focus of the Hale telescope during February and April of 1981. Three problems were discovered and corrected as a result of the tests. It was found necessary to add general illumination in the vicinity of the fiber tips so that they could be seen with the viewing system. It was also necessary to add an illuminated reticle in the viewing system for focusing. The third problem arose from a failure to recognize that the entrance slit assembly of the prime-focus spectrograph is not perpendicular to the optical axis. This construction allows viewing of the stellar image on the slit by the observer in normal use. The initial mounting bracket holding the fibers at the slit was made to hold the fibers perpendicular to the plane of the slit. The result was that a considerable mount of the light leaving the fibers missed the collimators. This was corrected by reworking the bracket to the correct angle.

Figure 10 shows a simultaneous exposure of HD 46149 and HD 46150 in the Rosette nebula together with a helium comparison spectrum. These two stars are more than 5 arc minutes

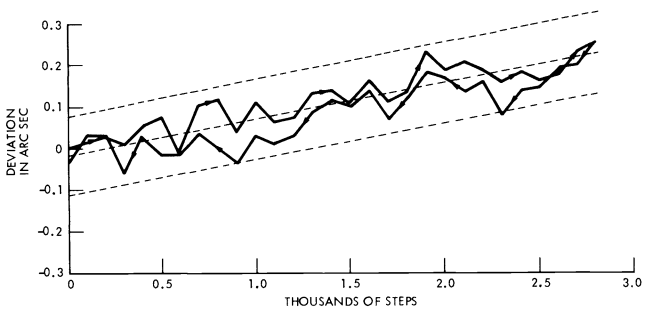

Figure 9. Results of interferometric test of carriage motion. The dashed lines indicate ±0.1 arc-second deviation from the average position. The total carriage travel represented here is 57 mm.

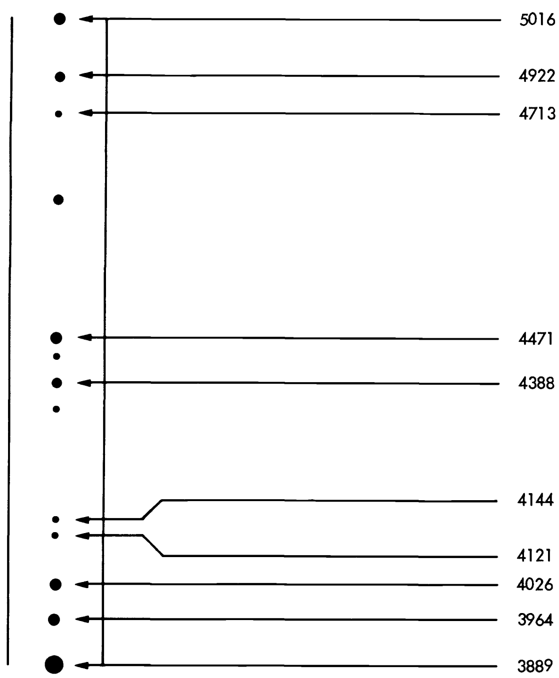

Figure 10. Simultaneous spectra of HD46149 and HD46150 (5 arc-minutes apart in the sky) taken with the prototype FOSF on the 5m-Hale telescope during engineering tests. These are bright 0 stars. The helium comparison spectrum was obtained with an optical fiber with one end viewing the helium lamp and the other end located at the spectrograph entrance slit.

apart in the sky. The fiber positioning functioned well and it was apparent that set up for bright objects is relatively easy. In addition, there was no detectable flexure in the system.

The photographic speed of the instrument was found to be as expected. The best performance of the prime-focus spectrograph with the original f/1 camera as used until about 1970 was quoted by Jesse Greenstein as: B = 16.7 magnitude in 4 hours with a 600 line/mm grating produced a weak but usable exposure on baked IIa0 plates using a 1 by 12 arc second slit. The substitute lens, as has already been indicated, was an f/2.5, 7 inch aerial-camera lens. This lens had somewhat poor image quality towards the edge of the field. The best performance in a very limited amount of telescope time was B = 8.5 magnitude in 3 minutes with a 1200 line/mm grating and unbaked 103a0 plates. Allowing for the change in camera focal length and the change in grating, the lack of trailing required for the fibers, the use of the Wynn corrector lens with the fiber optics spectrograph feed but not for the original spectrograph, the change in aperture of the camera lens, and the difference in the exposure time, the performance comes within a factor of two of the original spectrograph. A firmer statement cannot be made without evaluating more carefully the relative speed of the photographic emulsions and the transmission of the Wynn corrector. It is, therefore, reasonable to conclude on the basis of limited tests that the instrument performed up to expectations

Acknowledgements

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