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# Use of Optical Fibers in Spectrophotometry

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Short Title: Optical Fibers in Spectrophotometry

## Abstract

Optical Fibers have become quite useful in a wide variety of astronomical instrumentation. They have been most commonly employed to spatially multiplex, that is to observe with a single instrument a large number of objects over the field of view of the telescope. The application we will discuss, however, is the use of a single or small numbers of fibers in astronomical spectroscopy with the goal of achieving greater spectrophotometric and radial velocity accuracy. The properties of multimode step index fibers which are most important for this application will be outlined as will our laboratory tests of currently useful commercially available fibers.

## Introduction

Optical fibers have been used in an increasing variety of astronomical instruments in the past decade. This has largely been the result of the paper by Angel et al. (1977) which pointed out the excellent properties of the fused silica fibers. Previous attempts to use fibers had been frustrated by the poor transmission properties of earlier plastic and glass fibers. In spite of this they did find their way into some specialized instrumentation for solar research [Livingston, 1972]. It is clear, however, that the development of high quality fused silica core step index multimode fibers for the communications industry has supplied the impetus for the recent application to astronomy.

The majority of recent work using optical fibers has concentrated on the spatial multiplexing advantages that they afford. By placing individual fibers at the location of target objects in the focal plane of the telescope and rearranging those fibers to form the "slit" of a spectrograph substantial throughput gains can be realized when observing objects that occur at densities greater than about 10 per square degree. This was first done by Hill et al. (1980). This and the work of Gray (1983) has spawned many imitators and attendant improvements as such "Multiple Object Spectroscopy" (MOS) systems are becoming common.

A different application of fibers has been to remove instrumentation from the back of the telescope. Coupling existing spectrographs to telescopes was pioneered by Hubbard et al. (1979) and Heacox (1980). At Penn State we have specifically developed spectrographs for fiber optic coupling to our 1.6 meter telescope at cassegrain focus beginning early this decade [Barden et al., 1980; Ramsey et al., 1981]. We will describe here some of our experience with our current generation spectrograph which is called the Fiber Optic Echelle (FOE) and is now at Kitt Peak National Observatory.

## Advantages and Disadvantages of Fibers

The advantages of fibers in MOS work is obvious. One can rationally ask why one would employ fibers in a single object spectrograph where one is apparently inserting an unnecessary optical element in the light path. There are several advantages of fiber coupling even a single object spectrograph. Of primary importance is the high illumination stability afforded by the scrambling capability of the fiber. Seeing and guiding fluctuations at the input are converted to intensity variations over the entire pupil in the spectrograph. This leads to superior flat field performance as the calibration lamp and star both illuminate the instrument in a similar way. This is extremely important in doing very high signal-to-noise (S/N) work with CCD's. It also provides excellent radial velocity stability since the zonal errors enumerated by Tull (1972) are greatly reduced. Heacox (1986) gives a good generalized discussion of these scrambling properties.

Removing the instrument from the back of the telescope allows flexure free instruments to be built with standard optical bench hardware saving both design time and cost. Such a bench spectrograph can be placed in a controlled environment enhancing both system stability and reliability. A bench instrumental system also has the important advantage of being relatively easy and economical to re-configure or upgrade.

The disadvantages of fiber coupling are becoming significantly less than when first implemented earlier this decade as fibers have improved but disadvantages still exist and should be carefully considered. Basically all the disadvantages are due to the fact that the fiber must transmit light with some wavelength dependent losses and a throughput loss due to the fact that the focal ratio of the beam exiting the fiber is almost always smaller than that entering it. A slit or aperture transmits all wavelengths equally and preserves the focal ratio. Figure 1 illustrates this. The difference between the input and output beams in any spectrograph represents a decrease in the throughput-resolution product over what one would have without fiber. This behavior has come to be called Focal Ratio degradation (FRD) in most of the astronomical literature. Often in the literature the term numerical aperture (N.A.) is used to describe the solid angle of the incident and exit beams. The focal ratio or f-number (f/#) and N.A. are related by

$$f/\# = 1.0/2.0\ (\mathrm{N.A.}).$$

## The Spectrograph Design

The details of the FOE configuration and spectral format are described in Ramsey and Huenemoerder (1986). The primary accommodations in a spectrograph design with optical fibers is that one must match the collimator f-ratio to the expected fiber output and not to the telescope. The second point is to avoid a central obstruction. This is because the image of the secondary obstruction of most telescopes is scrambled away by the fiber. In our system an optical fiber feeds a 100 mm diameter f/6 parabolic collimator at prime focus. This f/6 collimator accepts about 90% of the light exiting the fiber when an f/8 beam is inserted into it. The fiber holder is small so the central obstruction is negligible. The dispersed light from a 79 l/mm echelle is cross dispersed by a prism and focused onto a RCA SID 501 CCD by a 200 mm f/2 camera. Over 30 orders covering about 75% of the spectrum from 390 nm to 900 nm is obtained in a single exposure. To obtain this coverage the orders are closely packed, narrow and have a gaussian-like cross section. With about 2.2 pixels per resolution element on the RCA CCD we have a resolution of about 12000.

## Some Comments on Spectrograph Performance

On the coude feed telescope a 0.2 mm fiber subtends about 5 arc seconds and is fed by an f/9 beam. The total system efficiency, defined as percentage of photons incident on the telescope that are delivered to the CCD, was 5.4% at 700 nm decreasing to 4.4% at 550 nm and 2.4% at 450 nm. The poorer blue response is due more to the spectrograph refracting camera optics than to the optical fiber itself. The FOE performance compares very favorably with the coude spectrograph camera No. 5 at the same resolution. The FOE has about twice the throughput at 600 nm and similar throughput at 400 nm. Of course the FOE has the overwhelming advantage of greater wavelength coverage when that is desirable. A one hour exposure on the 0.9 meter feed telescope will yield a S/N = 50 spectrum of a V = 8.8 magnitude star.

The above numbers compare very well with our two years previous experience with this instrument at Penn State. Unlike the coude feed telescope at KPNO the fiber coupling the 1.6 meter Penn State instrument to the spectrograph moved considerably as objects were tracked across the sky. Other than some slight intensity differences which could be due to flexure causing collimation differences in the coupling box, we have not noticed any effects of this motion. The illumination pattern remains the same.

Without making any special efforts, radial velocities can be measured to 0.1 pixel with only one reference spectrum during the night. The greatest problem in achieving higher accuracy is to eliminate small drifts in the LN2 dewar. We detected drifts as much a 0.06 pixel/hour in some dewars, but a drifts of less than 0.1 pixel/night are more common. With simultaneous reference spectra we hope to obtain RV accuracies of some 10 meters/sec for astereoseismology.

The superb stability of illumination allows us to obtain spectra with S/N nearly the same as what would be expected from photon statistics and the readout noise of the detector. Figure 2 shows the S/N of spectra of Epsilon Ori versus ADU. The S/N is determined by looking at the deviation of individual spectra from the mean. This is especially interesting when one considers that fringing effects in the red spectral region on this CCD modulate the spectrum by up to 20%. Such fringing severely limits the achievable S/N on standard slit spectrographs as consecutive spectra may not illuminate the detector the same way due to seeing and guiding variations.

Unlike a conventional slit or aperture the fiber scrambles the atmospheric dispersion spectrum information and thus there is no discernable illumination difference with wavelength in the spectrograph. Of course, there may be systematic wavelength attenuation as some of the image dispersed by the atmosphere falls outside of the aperture defined by the fiber. The fiber does allow us to do relative spectrophotometry in any given spectrum. We normally observe one or more Hayes standards at different zenith distances during a given night to enable us to determine the sensitivity function.

## Properties of Optical Fibers Critical For Future Applications

Future applications for optical fibers include their use in astereoseismology as well as spectropolarimetry which will make increasing demands on the absolute stability of the instrumentation. It is also clear that the photometry community is finding applications for fibers. Caton and Pollock (1986) describe a multiple star system using fibers. In order to better understand the properties of fibers that might affect their use in these and other demanding applications, we have undertaken a laboratory program to understand their behavior.

Transmission is usually characterized by the manufacturer quite adequately. While the violet transmission of the fibers previously detailed [Angel et al. 1977: Ramsey and Huenemoerder, 1986] in the astronomical literature was a problem, this has been an area where the industry has shown substantial improvement. The violet absorption properties are largely due to small concentrations of metal impurities, and technological advances have allowed substantial increases in the purity of the fused silica core material. Transmission on the order of 80% down to 320 nm for 5 meter lengths is currently available. In the red transmission for lengths up to 20 meters is near 90%. Fibers in moderate lengths of about 10 meters, which is usually enough to remove an instrument from a telescope, are very competitive over the visible region with a single aluminum mirror reflection.

The focal ratio degradation (FRD) is not addressed by manufacturers and should always be measured since it is sensitive to both the manufacturing and packaging process. The particulars of how the astronomer mounts and retains the fiber can also have important consequences. Barden et al. (1981), Gray (1983) and Powell (1983) have presented measurements and have discussed its causes. Figure 1 presented above illustrates the basic effect and shows how the fiber can lower throughput by increasing the speed of the output beam relative to the input beam. FRD is primarily caused by microbends, which are defects which cause the fiber to depart from a perfect cylindrical waveguide. These defects are on a scale of a few tens to a hundred microns in most fibers and can be induced by the external world by mechanical forces. See Heacox (1986) for an analytical treatment of this phenomenon in an astronomical context.

This FRD effect is the most important difficulty encountered in using fibers to couple telescopes to spectrographs. It may not seem an important consideration for applications in broad band photometry at first since one is not dealing with the throughput-resolution products as a figure of merit in these systems. However, fibers that have poor FRD properties are likely to have less stable photometric properties in that they do show a sensitivity to microbending. Anything which causes small changes in microbending can cause small, but detectable, variable attenuation in principle and thus lead to photometric instability.

From the initial results of Angel et al. (1977) and Barden et al. (1981) one would at first think that one should feed the fiber with as fast a f/# as one can since there is less throughput loss. These measurements, however, were only relative measurements in that they give the proportion of light in the solid angle characterized by a given f/#. Our recent instrumentation now allows us to compare the output and input beam directly to determine the absolute transmission within a given output f-ratio. Figure 3 illustrates some recent results. What is clear is that faster beams are absolutely more lossy. This is easily understood in that more of the input light is in modes that propagate near the critical angle. These modes are easily lost due to microbending and curvature effects.

There may be small effects of the illumination due to seeing and guiding fluctuations in the total throughput of a fiber. Our spectroscopic experience would indicate that these are at less than the 1% level but they have not been explored in a systematic way. One might also be concerned about the absolute transmissivity of a fiber as it bends while a telescope (tracks across the sky. The NBC study of losses due to fiber deformation (Engelsrath et al., 1986) would indicate that losses due to the varying geometry as the telescope tracks across the sky should be small. Their sensitivity was only a fraction of a percent and the sensitivity of fiber attenuation to changing geometry needs to be further explored. At Penn State we have made some initial steps in this direction. Using a 10 meter fiber illuminated at f/4 we cyclically coiled and uncoiled a 1 meter section from straight to about a 30 cm loop with a period of about 1.5 seconds. Sample time series for both cyclically coiled and static uncoiled case each gave the same average transmission within 0.1%. Power spectrum analysis of the resultant time series is inconclusive with no apparent difference upon eye inspection. We hope to run longer time series in the future to explore this behavior further.

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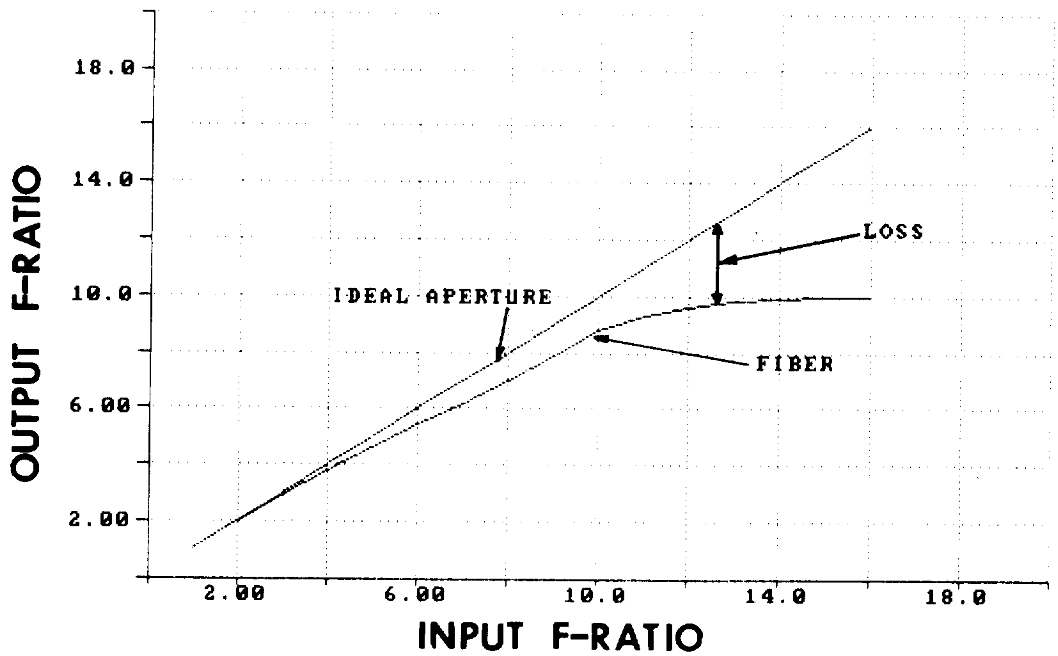


Figure 1. The dashed line represents the behavior of the output beam of a fiber for an input f/# as given on the x-axis. The solid line would be characteristic of a slit or circular aperture behavior. The difference between these two represents a throughput loss in a spectrometer with the resolution held constant.

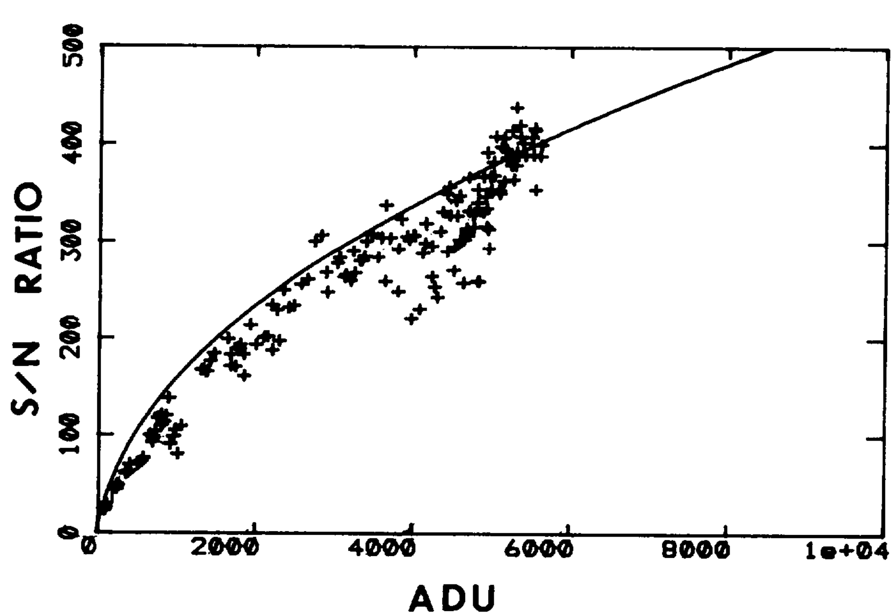


Figure 2. The solid line represents the predicted S/N estimated from the ADU (Analog-to-Digital Units) and noise characteristic of the RCA CCD used for the observations. The crosses are the observed values.

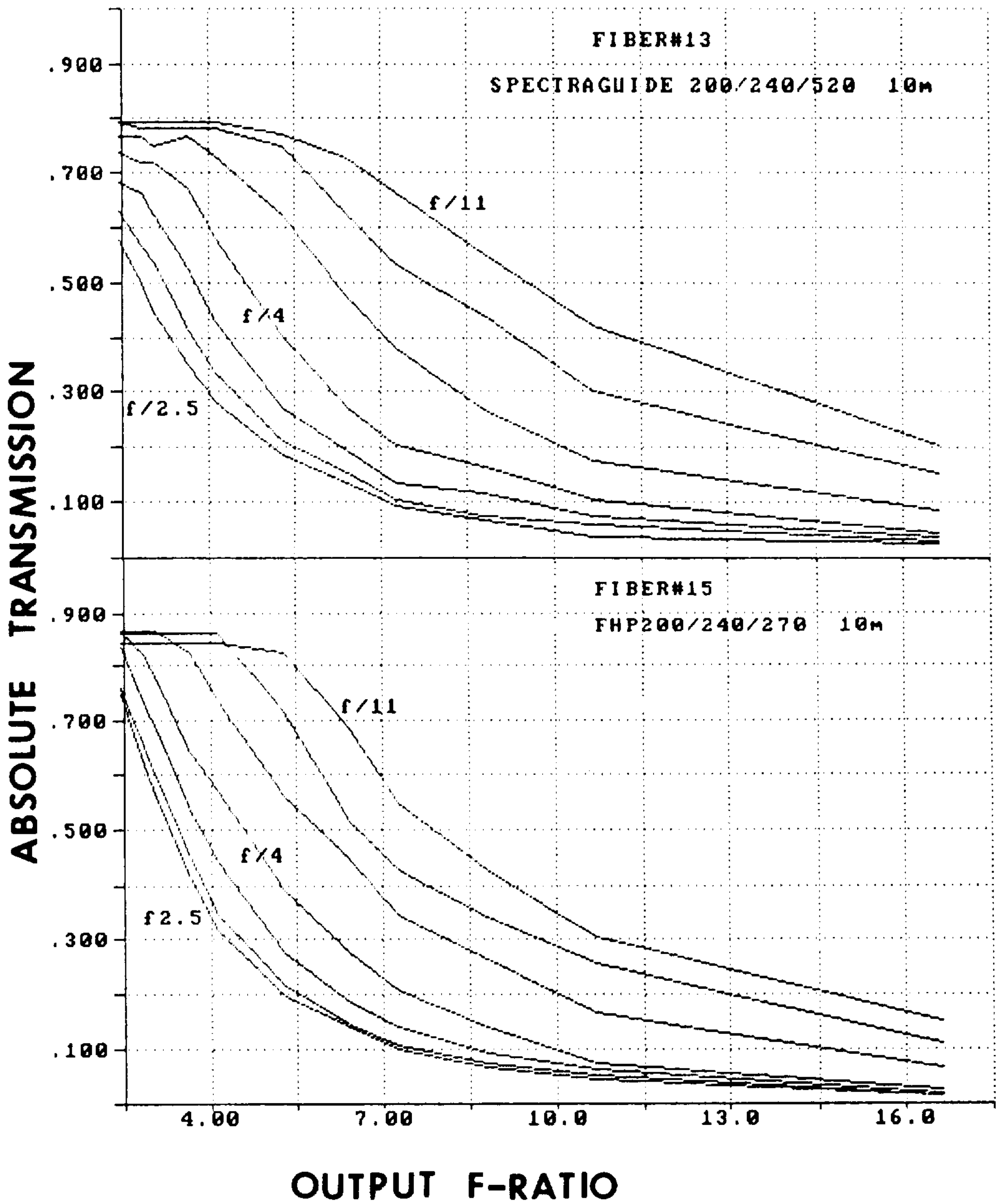


Figure 3. FRD characteristics of two recently tested fibers. The vertical axis is the absolute transmission at 600 nm. The horizontal axis is the output f/# at which the fiber output was sampled. The top panel is a Spectran 200 micron core fiber (Spectraguide SG840) and the bottom panel is a Polymicro 200 micron core fiber (FPH 200/240/270). Both samples are 10 meters in length. The difference in the FRD is apparent. It is also easily seen that the faster beams are systematically attenuated more.