

MIKE: A Double Echelle Spectrograph for the Magellan Telescopes at Las Campanas Observatory.

Rebecca A. Bernstein^{a,b}, Stephen A. Sackett^b, Steve Gunnels^c, Stefan Mochnacki^d, Alex Athey^a
^aAstronomy Department, 830 Dennison Bldg, University of Michigan, Ann Arbor, MI, 48109-1090
^bCarnegie Observatories, 813 Santa Barbara St., Pasadena, CA, 91101
^cParagon Engineering, 18231 Old Ranch Road, Tehachapi, CA 93561;
^dUniversity of Toronto, P.O. Box 360, Richmond Hill, ON L4C 4Y6, Canada

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ABSTRACT

The Magellan Inamori Kyocera Echelle (MIKE) is a double echelle spectrograph designed for use at the Magellan Telescopes at Las Campanas Observatory in Chile. It is currently in the final stages of construction and is scheduled for commissioning in the last quarter of 2002. In standard observing mode, the blue (320-480 nm) and red (440-1000 nm) channels are used simultaneously to obtain spectra over the full wavelength range with only a few gaps in wavelength coverage at the reddest orders. Both channels contain a three-group set of all-spherical, standard optical glass and calcium fluoride lenses which function as both camera and collimator in a double pass configuration. A single, standard echelle grating is used on each side and is illuminated close to true Littrow. Prism cross-dispersers are also used double-pass, and provide a minimum separation between orders of 6 arcsec. Spectral resolution is 19,000 and 25,000 on the red and blue sides, respectively, with a 1 arcsec slit. Typical rms image diameter is less than 0.2 arcsec, so that resolution increases linearly with decreasing slit width. The standard observing mode will use a slit up to 5" long, however a fiber-fed mode will also be available using blocking filters to select the desired orders for up to 256 objects at a time. In this paper, we describe the optical and mechanical design of the instrument.

1. INSTRUMENT OVERVIEW AND DESIGN GOALS

General goals for the design of MIKE were to produce a high efficiency, high resolution spectrograph with complete optical wavelength coverage (320nm – 1 μ m) while minimizing complexity, size, and cost. Given these goals, there are several advantages to the double-beam arrangement. In addition to the obvious efficiency provided by taking two spectra simultaneously, the red/blue wavelength split allows the parallel channels to be optimized for higher throughput and optimal dispersion in several ways. First, we have used prisms rather than gratings for cross-dispersion because of the higher throughput they provide; dual beams allows us to use a highly dispersive prism on the red side, which would be opaque below 400nm. On the blue side, fused silica prisms can be used with negligible losses. Second, the dual-beam configuration allows us to use gratings with different rulings on the red and blue sides, minimizing the variation in the linear free spectral range and optimizing the blaze angle for each side. Finally, the limited red and blue spectral ranges gives us better control over the image quality and chromatic aberration in the refracting cameras, and better efficiency in anti-reflection coatings and detectors.

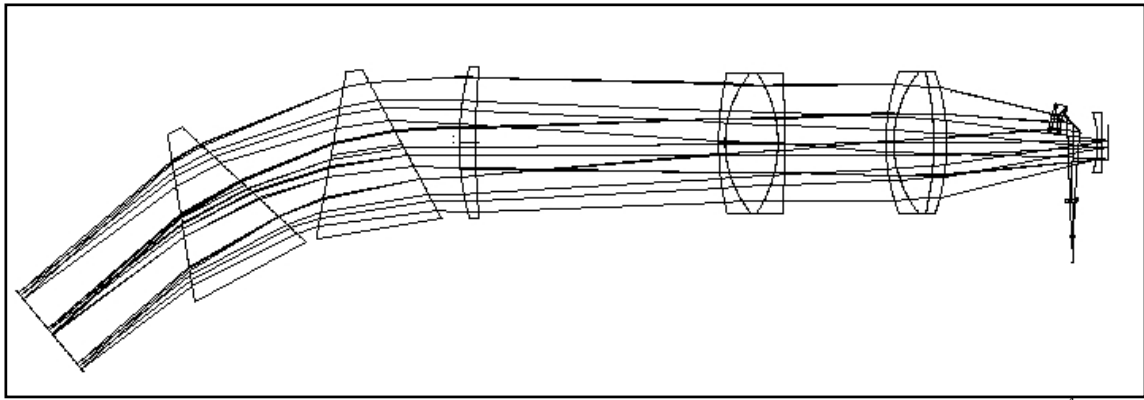
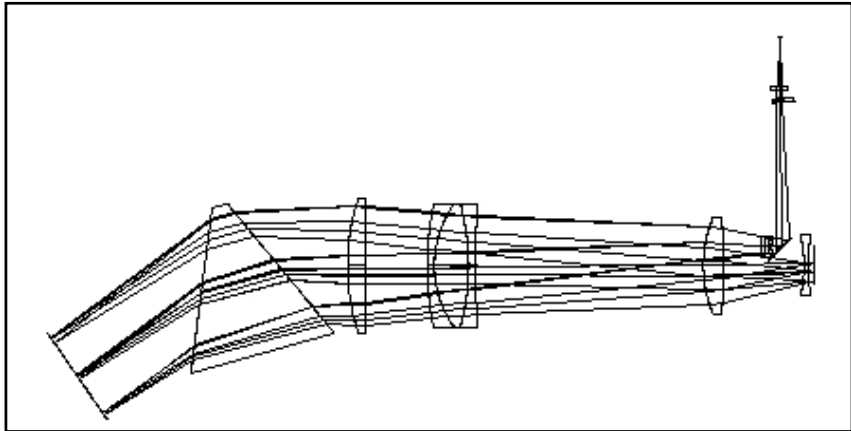
The double-pass system also provides several cost, complexity, and size advantages. It allows the instrument to be relatively compact and minimizes the number of large customized optics that need to be fabricated, not to mention bonded and mounted. In addition, the dual pass configuration minimizes the number of moving parts by limiting the possible adjustments to only camera focal position, grating angles (red and blue independently), and slit geometry. As the entire echelle format on each side fits on a single 2k x 4k CCD, adjustments to the grating positions should be infrequent.

The historical antecedents to the optical layout of MIKE are the echelle spectrographs at the 2.1m Struve reflector at McDonald observatory (see McCarthy et al.¹) and at the Las Campanas 2.5 m du Pont Telescope (Sackett²), both of which incorporate prisms and cameras in a double-pass arrangement. Both of these instruments, however, use simpler cameras and injection optics to convert the beam from the telescope focal ratio to the proper focal ratio for collimation through the main (camera) optics. MIKE also includes an astatic support to minimize flexure that is based on a cantilevered counterweight design used on the McDonald echelle. The designs for the MIKE cameras started from a

Figure 1: (top) Red optical path.

Elements are as follows (from the slit): dichroic slide, field lens, flat mirror, injection triplet, camera (R5, R4/3/2, R1), prism, grating (drawn as a mirror).

(bottom) Blue optical path. Elements are as follows (from the slit): field lens, flat mirror, injection triplet, camera (B7/6/5, B4/3/2, B1), 2 prisms, grating. The dichroic reflection is omitted from the diagram of the blue side for simplicity.



doublet-triplet-doublet arrangement similar to the camera and collimator designs for COSMIC (see Kells et al.⁴). All lens surfaces in MIKE are spherical. The optical layout of the instrument is illustrated in Figure 1. The red and blue optical paths are traced individually for clarity and displayed at the same scale. The only optical elements common to the two optical paths are the slit and dichroic. Photographs of the assembled instrument are shown in Figure 2.

2. OPTICAL DESIGN

2.1 Dichroic

The first optical element in MIKE beyond the slit is a 4mm thick glass window with a dichroic coating on the first surface that reflects blue light and transmits red. The crossover wavelength is at 455nm with 80% reflectance by 440nm and 80% transmission by 480nm. The crossover wavelength was chosen to allow similar optical quality in both cameras, dictated by $dn/d\lambda$ of standard optical glasses, and also to minimize the number of astronomically interesting spectral features that would fall near the dichroic split. With the dichroic in place, spectra can be taken with the red and blue channels simultaneously. However, it is also possible to use the red or blue side alone by replacing the dichroic with a mirror or a clear glass window.

The dichroic is positioned in the optical path so that the incidence angle of the beam is 30 degrees from normal. Angles less than 45 degrees are preferable to minimize polarization effects and to keep the crossover interval to a minimum. The back surface of the dichroic slide is AR coated. The ideal AR coating would be optimized to work best in the crossover region, work well into the red, and work poorly (or not at all) in the blue. The logic for this is that in the narrow crossover range, some light (say 50%) will get through the dichroic and <5% of that could unfortunately be reflected *back* towards the dichroic-coated surface from the AR coated back side. This light can then be reflected again by the dichroic, and a small ghost image will appear in the red-side spectra at the far blue range of its operation. Likewise, ghosts will appear on the blue side as well. The current dichroic has a uniform AR coating, and the described effect is visible in spectra we have taken of the sun and comparison sources in the lab. The dichroic is trivial to replace and other dichroics will be available shortly.



Figure 2: Top view of MIKE with covers off. The main box contains the red and blue optical benches (labeled). The blue box contains the 2 blue prisms and the R2.6 grating (towards top left corner). The red box contains the red prism and R2 grating (lower left). Light comes from the telescope through the mounting flange at the top right of the photo.

2.2 Cameras

The red camera is F/3.3 and consists of a singlet-triplet-singlet lens with one calcium fluoride element in the center of the triplet. The remaining elements are standard Ohara glasses. The blue camera is F/3.6 and consists of a singlet-triplet-triplet lens with calcium fluoride in the center of both triplets. The remaining elements are all Ohara i-line glasses with good transmission at 330nm. The prescription for both cameras includes a field flattener as the dewar window and sits 10mm in front of the CCD. All camera lenses are smaller than 220mm with no vignetting. Both cameras have a 150 mm diameter pupil and were designed with an external stop at roughly the spacing to the center of the echelle grating (400mm on the red side, 600mm on the blue side). Ray traces through the cameras are shown in Figures 1. The total transmission through the red side should be roughly 60-70% based on reported glass, RTV, and AR coating efficiencies, and grating reflectivity. The total transmission on the blue side is predicted to be 73-90% at wavelengths longer than 340nm, falling to 40% and then 5% at 330nm and 320nm, respectively.

Both lenses were optimized over a field 35mm in radius. The merit function was defined to constrain rms spot sizes every 100nm over each band-pass but it allows lateral color as cross dispersion makes this irrelevant to the camera performance. The spot diagrams in Figure 5 illustrate the final image quality (including injection optics) for both optical trains. The average rms spot radius for the cameras alone (once through) is $2.8\mu\text{m}$ for the red and $2.9\mu\text{m}$ for the blue. The average rms spot radius through the entire optical system is $5.2\mu\text{m}$ on the red side, and $5.9\mu\text{m}$ on the blue side.

2.3 Injection Optics

The conversion from F/11 (telescope output) to F/3.3 and F/3.6 for the camera/collimators is accomplished using a set of small injection optics, which immediately follow the dichroic in the red and blue optical paths. Again, this allows the two sets of injection optics to be optimized in transmission and image quality for the red and blue wavelength ranges. The injection optics on both sides consists of a field lens and a triplet with negative power. As in the cameras, the central element of both triplets is calcium fluoride.

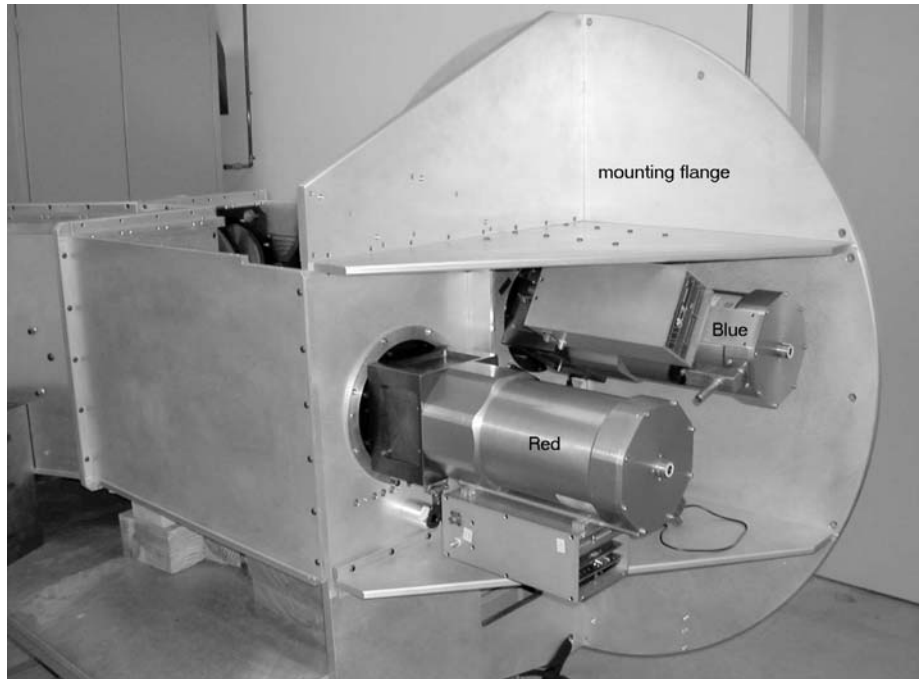


Figure 3: Dewar-end view of MIKE in horizontal position. Light enters the spectrograph at the center of the mounting flange from the right of the photo.

The design of the injection optics was constrained significantly by the packaging of the instrument. On the blue side, packaging was especially difficult, as the dichroic reflects the beam back towards the mounting flange and limits the space allowed for the blue camera. For this reason, we elected to cross the ingoing and outgoing beams as shown in Figure 1, which gives us roughly an extra 30mm of path length between the dichroic and the blue camera. Special care was taken to eliminate possible reflections back towards the CCD off the injection triplet by tilting and offsetting it to constraining the angle of the incident (and possibly reflected) rays. The data we have taken in the lab shows that we did successfully eliminate ghosts.

The injection optics essentially form a virtual image of the slit in the focal plane of each camera and substitute for the field flattener (dewar window) in the first pass through the cameras. The triplet and a flat mirror occupy less than half of the focal plane of the each camera, as can be seen in Figures 1 and 4. The optical axes of the cameras are offset by about 30mm from the optical axes of the injection optics. Light goes through the red injection triplet relatively on-axis, while the chief ray goes through the blue injection triplet roughly 6mm off-axis. The alignment of the blue side is therefore slightly more sensitive than the red side.

2.4 Prisms and Gratings

MIKE uses one replicated echelle grating from Richardson Grating Lab on each side. The red side uses a 6x12 inch R2 grating with 52.6 gr/mm and a 63.5 deg blaze angle. With our 500 mm focal length camera, the free spectral range of the reddest order (number 31, centered at 10977A) is 66 mm long, which does not quite fit on a 2k x 4k x 15 μ m CCD. However, coverage is complete blueward of 10470A (order 33). The grating can be positioned to obtain, for example, orders 31 to 69 (10977-4931A) or orders 39 to 73 (8725-4661A). Cross-dispersion is provided by a single prism made of Ohara PBM2 glass with an apex angle of 47 deg.

The blue side uses a 6x16 inch R2.6 grating with 52.7 gr/mm and 69.0 deg blaze. With the 550mm focal length camera, the reddest order (number 74 at 4790A) is 39 mm long and fits easily on the blue side 2k x 4k x 15 μ m CCD. Two fused silica prisms with 38 deg apex angles provide the equivalent of a single 62 deg apex angle prism on this side. The spacing between orders 74 to 107 (central wavelength 3313A) is 29mm, which just fits onto the CCD (~31mm wide).

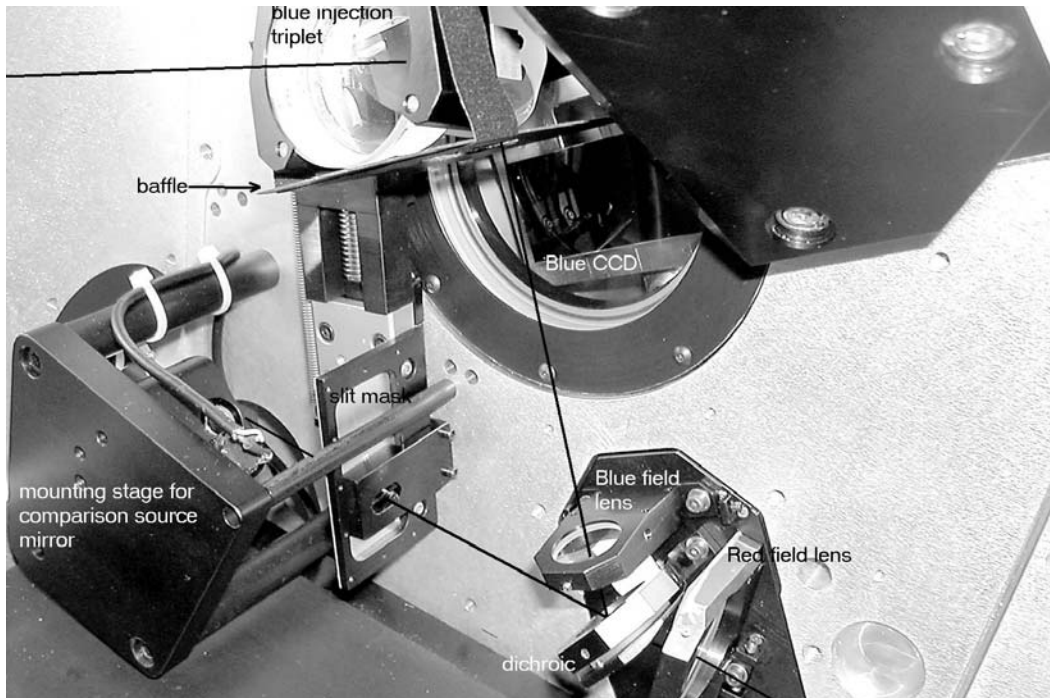


Figure 4: The blue plate. Various elements are labeled. The thick black line indicates the path of light from the slit to the dichroic, reflecting into the blue side and transmitting into the red.

The blue camera will transmit and form good images down to at least order 110 (3222Å). These bluest wavelengths can be obtained if the grating is appropriately positioned. The echelle format for the two sides is shown in Figure 6.

Minimum order separation is 6 arcsec on both the red and blue sides (1 arcsec = 105 μ m on the red side, 115 μ m on the blue side). Spectra taken in the lab demonstrate that there is very little scattered light in the images, so that the spacing between orders is more than adequate for sky subtraction (see discussion below).

Both camera designs form images with >95% encircled energy within 1 pixel (15 μ m), so resolution is limited by slit size. For a minimum slit width of 0.35 arcsec, the maximum resolving power is 54,000 on the red side and 71,000 on the blue side. The resolving power is 19,000 and 25,000, red and blue respectively, with a 1 arcsec slit.

All three prisms are more than 8 inches thick at the base. In order to obtain the glass for these prisms, we ordered glass blanks of roughly one half the required thickness and had them fabricated in two halves with one surface of each half-prism normal to the cylindrical axis of the blank. We then bonded the two halves together using optical RTV, as described below.

2.5 Bonding triplets and prism

All triplets and prisms have been bonded with Sylgard 184, which is an optical RTV made by Dow Corning. We prepared and tested a 10mm sample of this RTV and found it to have roughly 90% transmission efficiency at 310nm and essentially 100% transmission at longer wavelengths. The RTV bonds in the camera triplets are 0.009 inches thick. Plastic shim stock (0.006in) held in place with double-sided scotch tape (0.003in) was used to control the RTV thickness at three places around the edge of the elements. Finite element analysis of our triplets indicates that this thickness provides adequate stress relief for thermal changes between elements. To test the adhesion strength of the glass-RTV bonds, we conducted torture tests on bonded pieces of standard window glass. We found no evidence of adhesion failures for temperature differentials of more than 50 deg C between the panes for bond layers 0.009 inches thick.

The median operating temperature in the Magellan domes is about 10 deg C with a range about the median of about 10 deg. The RTV will set in about 2 days at room temperature, but takes as long as 2 weeks at 15 deg C. As a compromise

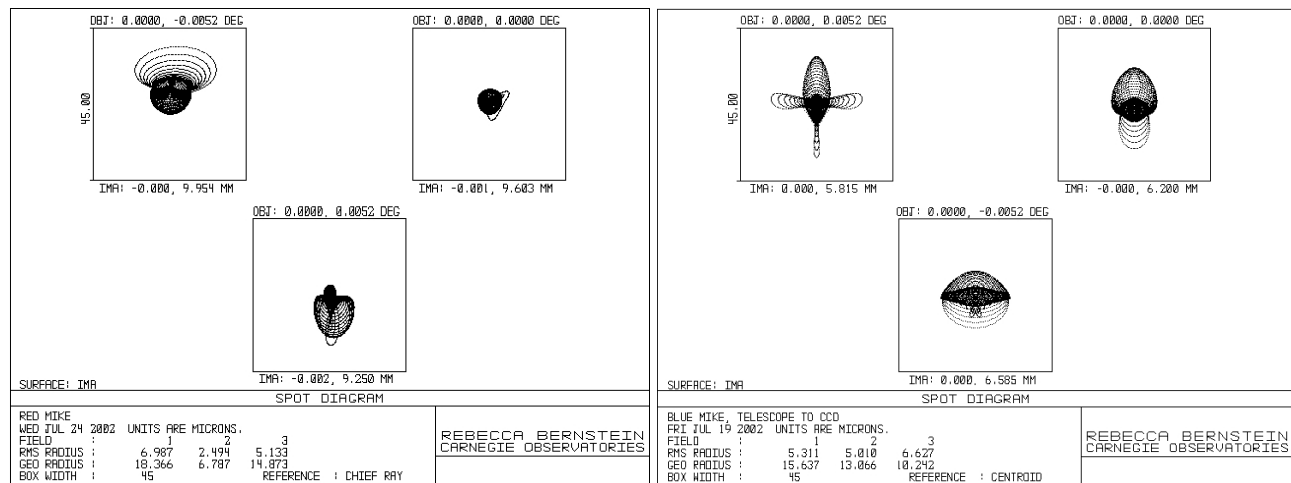


Figure 5: Spot diagrams. Three field position along a 6arcsec slit for the red side at 6700A (left) and for the blue side at 4100A (right) are shown in 45µm square boxes (3x3 pixels). The spots show a representative range of image quality.

between timely setting and median operating temperature, we bonded all of the triplets at 15 deg C. A humidity-controlled cold room was built at Carnegie Observatories for this purpose. The prisms were bonded at room temperature, since differential thermal expansion is not a problem along a flat joint between glasses of the same type. For the prisms, scotch tape spacers were used to assure that the bond layers were uniformly 0.003 inches thick. The triplets in the small injection optics were bonded at 15 deg C with 0.003 inch spacers.

2.6 Glass fabrication and coatings

All of our lenses and prisms were figured and polished by Harold Johnson Optical Labs. All lenses were figured to stock test-plate radii and were fabricated to specifications without incident. Newport Thin Films provided coatings on four of the red camera elements. Spectrum Thin Films coated the remaining elements, including the blue camera, prisms, and all small injection optics. The coatings on the red and blue optics have average reflectivity less than 1.0% and 0.75%, respectively.

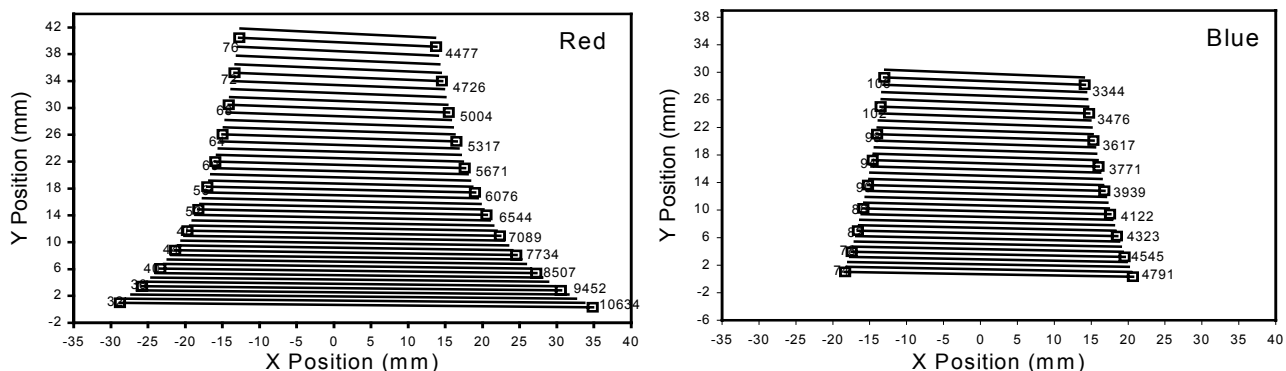
3. MECHANICAL STRUCTURE

The outer structure of MIKE is made from aluminum tooling plate (3/4-inch and 1/2-inch thick) with all joints screwed together and keyed to prevent light leaks. The strategy with this approach was to make the structure modular and allow easy changes to individual plates should the need or desire arise. The red box was fabricated at Rettig Machine (Redlands, CA). The rest of the structure was fabricated at Martinez & Turek (Rialto, CA) and by Robert Storts at OCIW.

The main box of the structure houses two independent optical benches (red and blue). These are each mounted on flexures that allow the entire optical bench to move ±1mm along the optical axis, providing the focus adjustment for the cameras. The position of the cameras can be adjusted remotely by rotating an eccentric cam drive with a motorized worm gear mounted under the optical benches to focus the instrument. The cameras are thermally sensitive, as expected, due to the changes in refractive index with temperature (dn/dT). To compensate changes of up to 5 degrees in temperature, the optical benches each include invar plates that are fixed at one end to the structure and at the other end to the optical benches. These provide partial passive focus compensation via the thermal expansion of the aluminum.

Two separate boxes house dispersion elements: the red box contains the single red prism and the red R2 grating; the blue box houses the two blue prisms and blue R2.6 grating. Although the gratings and prisms were not intended to be changed during the life of the spectrograph, the structure is modular enough that changes could be made to the red and blue boxes individually if the motivation to do so were significantly great.

Figure 6: Red and blue echellograms.



All of the small optics are mounted on two small plates about 1 ft square (see Figures 2 and 4), which are removable from the main perpendicular flange at the dewar end of the main box. The dewars also mount onto these plates. The blue plate contains all the optics and mechanics upstream of the dichroic as well as the blue injection optics and the red field lens. It also contains a single electrical connector through which the slit motor drive, shutter controls, and flipper-mounted, comparison-source mirror are controlled. The red plate contains the injection optics for the red side. The small optics can all be easily removed, replaced and adjusted without opening the cover to the main box that houses the cameras. In addition, the field lenses and dichroic are all mounted on a small block (about 5x3 inches), which can be removed without removing the blue dewar or the rest of the blue plate. This module can be swapped out for other modules, which will include copies of the field lenses and will allow the dichroic to be replaced by a window or mirror by the instrument support staff at the observatory in a few minutes.

The camera elements are all held in simple kinematic mounts which have two radial defining pads made of silicone rubber and a spring preloaded floating pad at the top of the mount. Axially, the elements are constrained by a fixed ring on one side and a spring preloaded ring on the other. The mounting plates are fixed to the optical benches with vertical gusset plates and are reinforced for lateral stability. Push/pull screws and slotted holes allow enough control for lateral alignment. Height and tilt are adjusted with shims. Prisms are similarly constrained radially. Tabs are in place to prevent the prisms from falling but provide no axial constraint. All contact to glass is exclusively through silicone pads (60 shore), which are fixed to the aluminum with contact-cement or double-stick tape. The radial constraint on the triplets is applied only to the outer elements; no contact is made directly with the calcium fluoride. All small optics are held in custom mounts and constrained axially only with nylon-tipped set screws and spring plungers. The gratings are also kinematically mounted with spring preloads against opposing nylon defining pads. The positions of the gratings are controlled manually with altitude and azimuth screws. Dial gauges indicate the position in both directions. All optics (gratings included) can be removed from their cells should the need arise.

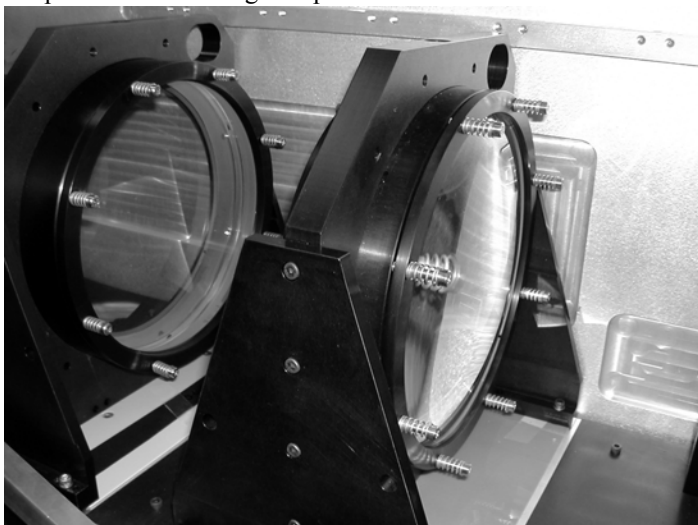


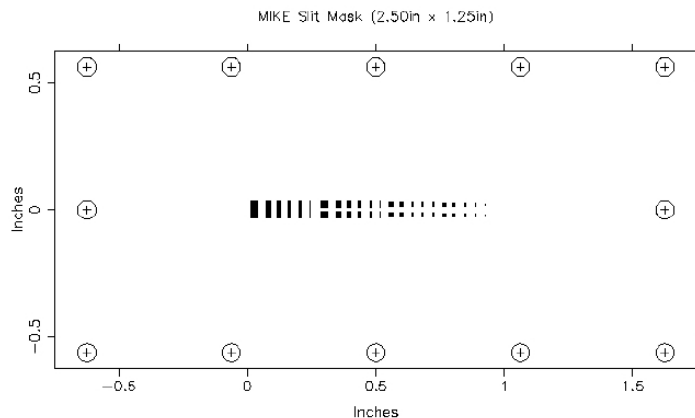
Figure 7: Lens mounts. Two of the blue camera elements (B1/2/3 and B4/5/6) are shown in their mounts on the blue optical bench inside the main box of MIKE.

The radial constraint on the triplets is applied only to the outer elements; no contact is made directly with the calcium fluoride. All small optics are held in custom mounts and constrained axially only with nylon-tipped set screws and spring plungers. The gratings are also kinematically mounted with spring preloads against opposing nylon defining pads. The positions of the gratings are controlled manually with altitude and azimuth screws. Dial gauges indicate the position in both directions. All optics (gratings included) can be removed from their cells should the need arise.

4. OBSERVING WITH MIKE.

We expect to use MIKE primarily at the Nasmyth port, although it can also be attached at the auxiliary ports. The instrument was constructed to be

Figure 8: Slit mask plate. Maximum slit length is 5arcsec. Slit widths are between 2 arcsec and 0.37 arcsec. For on/off source spectra, pairs of square holes have also been cut.



instrument in this position, the net effects of atmospheric dispersion are minimized and there is additionally no possibility for flexure, so that observations are maximally stable. The East Nasmyth platform is therefore the ideal position for MIKE. To further minimize the effects of atmospheric dispersion, an atmospheric dispersion corrector (ADC) would be very helpful. Magellan 1 has a full-field ADC for standard operations. We intend to supply a small ADC sufficient for the MIKE field of view to be used when MIKE is mounted on Magellan 2.

A slit mask with slits of various sizes is mounted on a motorized stage. The observer selects a single slit of the desired geometry by positioning it appropriately in front of a blocking plate. A slit-viewer is used to do this. The slit-viewer will also be used to position the source in the slit. A sketch of the slit mask and available slit sizes is shown in Figure 8. The maximum slit length for complete wavelength coverage is 5 arcsec. (Order separation is 6 arcsec.) Widths are between 0.37arcsec and 2 arcsec. Scattered light in the instrument is very low (see below). Nevertheless, we anticipate that a desirable slit geometry will be one in which the slit is separated into two isolated apertures, with the object positioned in one and the other used for sky. This will allow very clean separation between sky flux and object flux, and will minimize the sky contribution to the source spectrum. Spectra taken through a pair of 0.37 arcsec (with 2.5 arcsec in between) are shown in Figures 9, 10, and 11.

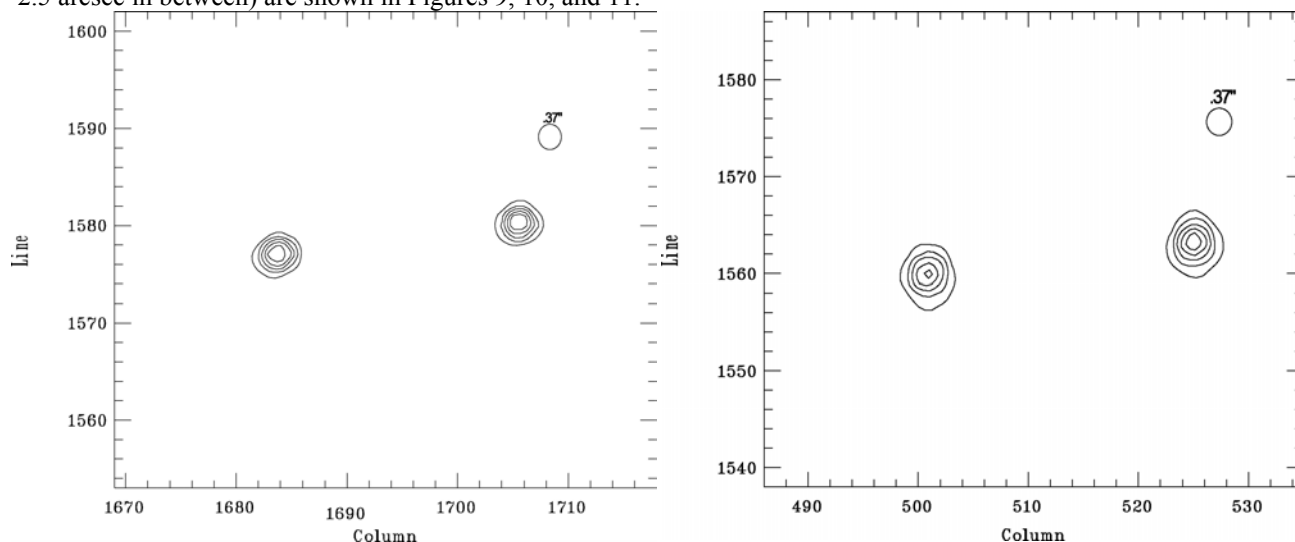


Figure 9: Comparison source lines imaged through 0.37arcsec aperture pairs (red on the left, blue on the right).

attached to the Nasmyth instrument rotator and so includes a counterweight fixture that provides astatic support against gravity. If an observer wants the slit to maintain a particular orientation across an object, this rotating mode can be used. However, we expect that the preferred strategy will be to leave MIKE parked at roughly a 30 deg angle with the grating-end lower than the telescope optical axis at the East Nasmyth platform. The logic for this is as follows. In a horizontal position, the instrument's slit is perpendicular to the horizon when the telescope is at zenith and atmospheric dispersion is zero, but it is parallel to the horizon when the telescope is pointed to the horizon and atmospheric dispersion is maximized. Positioned at roughly 30 deg, atmospheric dispersion is *parallel* to the slit at roughly the median zenith angle for typical observations. By leaving the

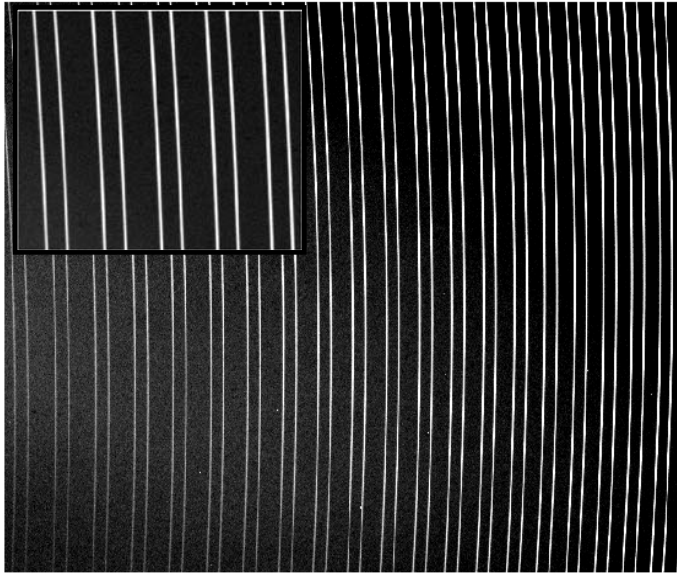


Figure 10: Red-side spectrum of a continuum source through the 0.37 arcsec aperture pairs. A zoomed in region is inset in the upper left.

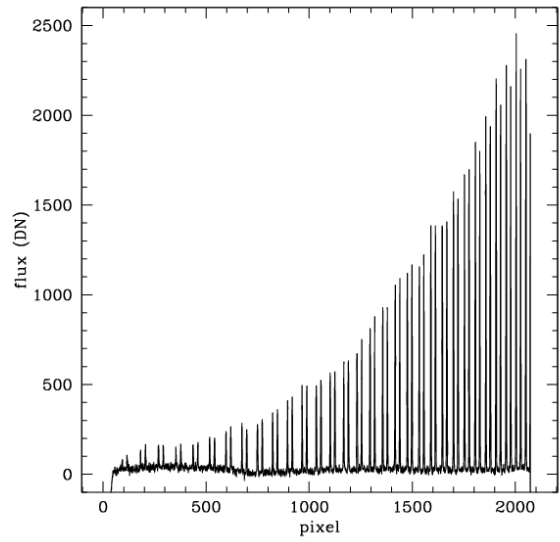


Figure 11: Scattered light and order separation on the red side. The plot shows a horizontal cut through the continuum spectrum in Figure 10.

Wavelength calibration can be done at any time by using a New Focus motor-controlled flipper mount to move a mirror into the optical path and redirecting light from an internal hollow-cathode lamp. (The comparison source assembly is not shown in photographs above.) Flat field images (“milky flats”) can be taken by manually positioning a fused silica diffuser side into the optical path downstream of the slit. This will be done from outside the spectrograph. Daytime spectra of sunlight in the dome can then be used to obtain echelle spectra with sufficiently low spatial and wavelength resolution to be used as flat fields at even the bluest wavelengths.

In addition to standard slit observing mode, a fiber-fed mode will also be available with MIKE. The fiber system is currently under construction by Mario Mateo and Alex Athey at Univ. of Michigan and will be installed on MIKE in early 2003. The fiber system includes two sets of 128 fiber optic inputs, wavelength-optimized for red and blue channels, respectively. The fibers will be manually positioned over the 30 arc minute Magellan field of view using a plug-plate system modeled after the one used at the Las Campanas 100” (see Sackett 1993). In order to correctly position the ends of the fibers, regardless of their radial position in the field, they will be pushed through to contact a telecentrator lens that assures that light passes into the fibers along their optical axis. Each fiber is fitted with a ferrule that holds a 1.4 arcsec aperture stop and an AR coated drum lens which converts the F/11 beam to F/3.5 and images the pupil onto a 175 μ core Polymicro Technologies custom drawn fiber. At F/3.5, focal ratio degradation is minimized in the fibers and is well matched to the camera optics. The minimum spacing between fibers in the focal plane of the telescope is 13 arcsec (4.15 mm). The fibers pass into the structure through guide channels that can be fitted into the cover of the main box of MIKE. The fibers and a slightly modified version of the field flatteners then replace the standard injection optics. It will also be possible to position a narrow external slit in front of the fibers inside MIKE to increase spectral resolution over that provided by the 175 μ fiber cores. To use the full complement of 128 fibers, a narrow band filter can be used to select out a single order of the observer’s choosing. Multiple adjacent orders can also be obtained if fewer fibers are used. Red and blue fibers can be plugged into the focal plane and used simultaneously.

To use the fibers, MIKE will sit on its handling cart away from the telescope on the Nasmyth platform. The fibers themselves are relatively short to minimize focal ratio degradation: 7.5 feet for red and 8.0 feet for blue. The fiber system will be described in greater detail elsewhere.

5. DETECTORS

Each MIKE CCD detector system uses a 2K x 4K back-illuminated device, with 15 μ m pixels and two output amplifiers. At present, both the red and blue channels use SITe ST-002A CCDs. We anticipate replacing the CCD on the blue side

with a Lincoln Labs CCID-20. The CCDs all have standard, broadband AR coatings. Each detector is mounted in a rectangular aluminum housing. The dewar window on each side is the field flattener of the camera.

The CCD housing is coupled to an IR-Labs ND-5 cryostat, with the CCD control electronics box attached to the side of the dewar (see photo in Figure 3). Each CCD is liquid nitrogen cooled and has roughly 15 hour hold time in the horizontal position. Inside the housing, the CCD is connected to a rigid-flex preamp board, which brings the signals out on a flex cable to a hermetic connector.

Each CCD controller is a compact, dual-channel digital signal processor based system, capable of both high-speed and slow-scan readout. We plan to operate in slow-scan mode, using only the better of the two CCD output amplifiers for the lowest noise performance. Lab tests show that read noise is ~ 4 e-/pixel for the SiTe device. Even better performance is expected for the LL device. The two detector systems are mounted side-by-side on the instrument (see Figure 3) and operate independently with independent shutter-controlled exposure times.

6. OPTICAL ALIGNMENT AND PERFORMANCE IN THE LAB

Both channels of MIKE have been assembled and tested in the lab. The cameras were each aligned on their optical benches inside the main box using a red diode laser. To do this, we shined the laser through a well-centered 0.002 inch pinhole in an aluminum plate analogous to the dewar mounting plate, and adjusted it until it was parallel to the surface of the optical bench and side-wall of the main box. The laser beam was then taken to define the optical axis of the camera, and we adjusted each lens individually until reflections off the lens surfaces produced spots on the

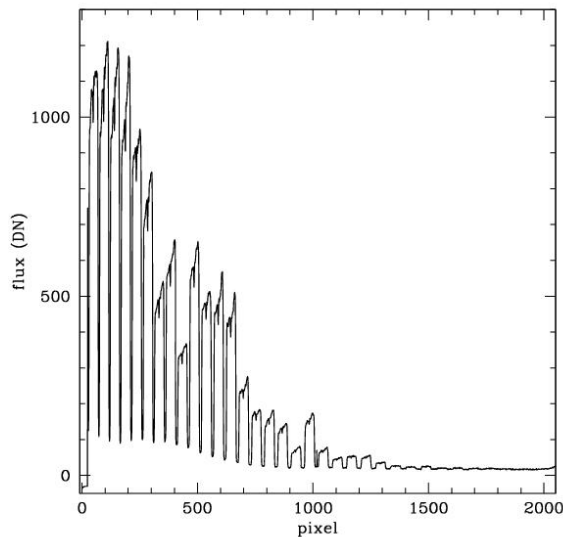
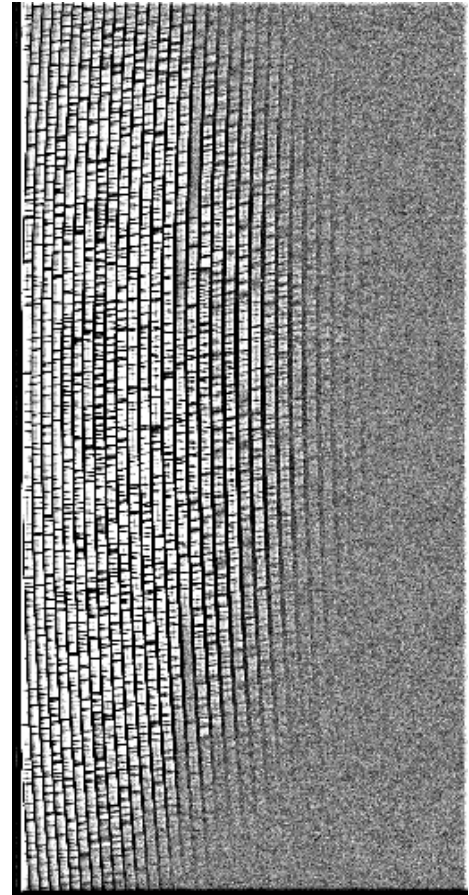


Figure 13: Order separation and scattered light on the blue side. The plot shows a cut through the solar spectrum in Fig 12.

Figure 12: A solar spectrum taken with the blue side through the 0.5 x 5 arcsec slit.



laser mounting plate that were centered on the pinhole. The slit, dichroic, and injection optics were aligned by positioning the laser on the telescope mounting flange and positioning the lenses until the chief ray through the slit hit the injection optics at the prescribed location. Injection optics were placed within 0.040 inches by this method. Fine adjustments to the injection optics were then made based on final image quality.

To assess the optical performance of the system and focus the cameras, spectra were taken of a continuum source and comparison lamps with an F/11 input beam, as would come from the telescope. For these spectra, we used the smallest aperture pairs in the slit mask, which are 0.37" in diameter at the telescope scale, and image to a diameter of 2.8 pixels on the blue side and 2.6 pixels on the red side. When a continuum source is observed through these apertures, the result is two continuum spectra in each order with a spatial width of roughly 3 (2.8) pixels on the blue (red) side over the full image (see Figures 9 and 10). When a comparison lamp is imaged, the result is pairs of points in each order, which are emission lines

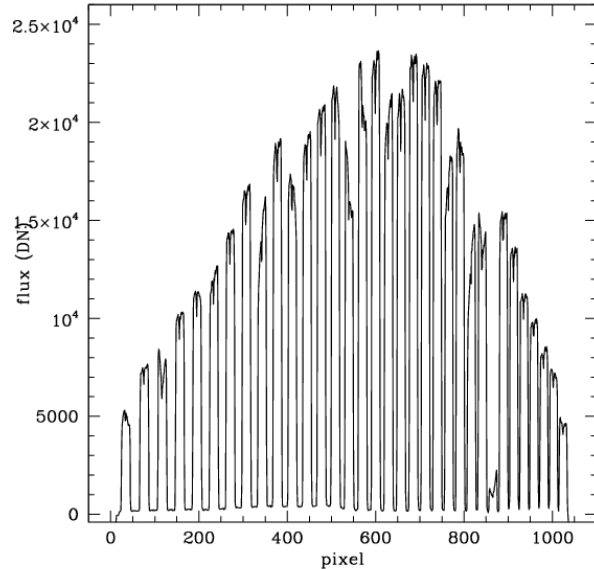


Figure 14: Order separation and scattered light on the red side. The plot shows a horizontal cut through the solar spectrum in Figure 15.

Figure 15: A solar spectrum taken with the red side through the 0.5 x 5 arcsec slit.

with a FWHM of roughly 3 (2.8) pixels on the blue (red) side (see Figure 9). We infer from this that the image diameter delivered by the cameras is consistent with the predicted image quality from ray tracing (sub-pixel).

In addition to the basic image quality, the continuum spectra in Figure 10 and a cross-cut of this image (shown in Figure 11) indicate that there is very little scattered light on the red side of MIKE and negligible cross-talk between orders. This gives us confidence that the 6arcsec separation between orders will be adequate for sky subtraction, even when 5 arcsec slits are used instead of the aperture-pairs. On the blue side, a solar spectrum taken through a 0.5 arcsec wide, 5arcsec long slit demonstrates that the same is true for the blue side. In all of these images, there is some stray light entering the spectrograph because the structure was not completely assembled when the exposures were taken. Images of comparison lamps through both sides also indicate that there are no ghost images or direct reflections on the CCDs, with the exception of minor (~2%) “echoes” along the spectral direction in the crossover region of the dichroic, which we explain above (see section 2.1).

MIKE is currently being disassembled for shipment to Las Campanas in August 2002 and is scheduled for installation on Magellan I in October 2002.

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