The Low Resolution Imaging Spectrometer for the Keck Telescope

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ABSTRACT

The Low Resolution Imaging Spectrometer is designed for use at the Cassegrain focus of the Keck 10—meter telescope. It provides the capability of acquiring low resolution (R = 1000 to 5000) digital spectra, as well as 6 x 8 arc-minute moderately high spatial resolution (4.65 pixels/arc-second) direct images. Spectroscopy can be carried out with single slits which are 3 arc-minutes long. In addition punched multi-slits can also be employed which allow for the acquisition of at least forty spectra simultaneously.

Since the instrument is designed to be as efficient as possible, it is a double spectrograph, with a dichroic splitting the blue and red light into separate optical paths after the collimator. Only the red side has been constructed thus far. With a 2048 by 2048 thinned Tektronix CCD as the detector the total efficiency of the red side at the peak of the grating blaze is predicted to be nearly 40%.

Results of the commissioning observing runs will be described.

1 INTRODUCTION

During 1988 a committee was set up to choose the first optical auxiliary instruments to be built for the Keck 10—meter telescope. Preliminary designs were developed for low-, medium-, and high-resolution spectrographs. When preliminary estimates of the cost of these instruments were obtained, it was clear that only two of them could be built. The Keck Science Steering Committee decided that the low- and high-resolution spectrographs should be designed and built. The initial design of the low-resolution instrument was supervised by Dr.J.Miller at Lick Observatory. The final design and construction was done by the California Institute of Technology. It is this instrument, the Low Resolution Imaging Spectrometer, (LRIS), that is described in this paper.

There were a number of design requirements and goals for the instrument. These included the following: (a) The instrument should be capable of obtaining both low resolution spectra and high quality direct images since there was no plan for a Keck instrument devoted exclusively to imaging. (b) The instrument should be capable

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of making proper use of telescope images as small as 0.5 arc-sec. (c) The field of view should be as large as possible. (d) At the lowest spectral resolution, the instrument should be designed to work on very faint stars and galaxies. The noise should be dominated at all wavelengths by the sky background level. (e) The highest spectral resolution should be sufficient to measure the velocity dispersion in unresolved stellar systems such as galactic nuclei. (f) The spectral range of the instrument should be from 3100 Å to 10,000 Å. (g) The instrument should have the minimum possible flexure. (h) The instrument should have the maximum possible sensitivity and as little light loss as possible at the entrance slit. (i) There should be as little vignetting as possible within the instrument. (j) It should be possible to use a multi-slit technique to obtain many spectra simultaneously. (k) There should be provision for a multi-fiber system. (l) The instrument should operate at the Cassegrain focus so that polarimetry and spectropolarimetry could be done efficiently. (m) The instrument weight must conform to that allowed at the Cassegrain focus of the telescope. (n) There should be CCD cameras on the instrument for acquisition of and guiding on targets.

In order for the whole spectral range from 3100Å to 10,000Å to be observed simultaneously it was decided that the instrument should be a double instrument similar to the Double Spectrograph on the Hale 5−meter telescope[1]. In the imaging mode, this would allow two pictures in different filters to be taken simultaneously. This would alleviate to a considerable extent any problems with thin cirrus.

As the design of the instrument proceeded it became clear very quickly that the cost of the full instrument would exceed the allotted budget. It was therefore decided that there should be provision for the fiber system, but that it would not be implemented at first light. It was also decided to carry out a design for the blue side of the instrument, but not actually build it. In addition the decision was made that the detector would be a Tektronix 2048 by 2048 pixel back illuminated CCD with 27μ pixels.

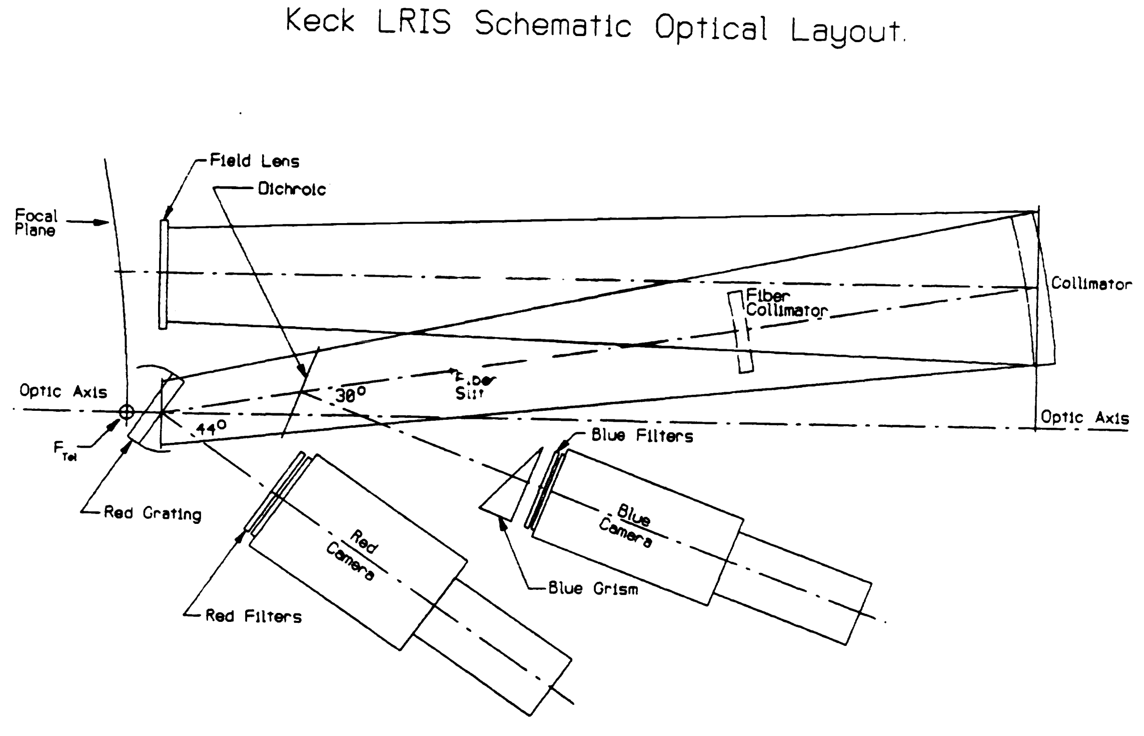

Figure 1. Schematic optical layout for the Keck LRIS. The layout includes fiber optic components, dichroic, and blue camera components which are not yet built or planned. Note the location of the telescope optical axis relative to the field of view used. This maintains high quality imaging capabilities. The collimator focal length is

2 THE OPTICAL DESIGN

The Keck 10—meter telescope is a Ritchey-Chretien design. The image field at the Cassegrain focus has a diameter of 20 arc-min or 0.873 meters and a radius of curvature of 2.180 meters. The Cassegrain focal length is 150 meters, so the nominal focal ratio is f/15. The scale at the Cassegrain focus is 1.375 arc-sec/mm. Therefore any instrument with a field of 6 arc-minutes or more must have an entrance aperture of over 250 mm. Because the mirror is made of hexagonal segments the outer edge of the mirror is not round; the outer perimeter of the mirror has a diameter of 11 meters, which gives a real focal ratio of f/13.7.

The spectrograph is a very basic one. The mirror collimator reverses the light travel direction and puts parallel light onto a dichroic filter. The transmitted red and near-infrared light proceeds to a plane reflection grating which is located near the focal plane of the telescope. The diffracted light from the grating comes off at a 44° angle to the incoming beam and goes through a lens camera. The blue light reflected off the first surface of the dichroic proceeds to a grism and a blue camera. The design is shown in Figure 1.

The specifications and goals listed above along with the choice of CCD indicated that the beam size inside the instrument should be about 150 mm. The collimator focal length was then set at 2000 mm and the camera focal length at 304 mm. Since a field of 8 arc-minutes was desireable this meant that the collimator would have to have a diameter of about 20 inches. The only practical solution for the collimator was an off-axis parabolic reflector. The usual design for an off-axis parabolic collimator was found to produce very bad images over the 8 arc-minute field. An alternative design, where the parabolic collimator axis was coincident with that of the telescope and where the accessed field was off axis, was found to be excellent. This excellent performance is achieved at least partly because the center of curvature of the Cassegrain field is nearly coincident with the center of curvature of the collimator as in a Schmidt design.

Because the Cassegrain telescope optics create a pupil near the telescope secondary, the spectrograph collimator makes a pupil which is too far from the collimator to make a good spectrograph design (i.e. one where the pupil is at the grating) possible. The solution was to place a field lens just beyond the telescope focus and near the entrance aperture. This low-powered meniscus lens moves the pupil close to the infinite-distance focus of the collimator where the red gratings are located. The pupil is also located at the grism in the proposed blue side of the instrument. The pupil has an outside diameter of 146 mm and therefore standard 6 x 8 inch plane reflection gratings or grisms can be used.

The field of view which can be used is 6 x 8 arc-minutes. In the 6 arc-minute direction (called x) the field is off axis from 4 to 10 arc-minutes, while in the perpendicular direction (called y) it is + or − 4 arc-minutes. The telescope, field lens, and collimator have been ray traced from 4 to 9 arc-minutes in the x direction and from 0 to 4 arc-minutes in the y direction. Over most of this field the rms image diameters are 0.19 to 0.28 arc-sec with 79 to 94% of the light falling in a 0.33 arc-sec diameter circle. The points at 10 arc-min off axis in the x direction will be slightly worse than this. These figures assume that the telescope optics was built as designed. The spectrograph collimator is about a factor of 3 better than it needs to be. The collimator, which has a diameter of 21 inches, is large enough so that there is no vignetting over the specified field of view.

The remaining optical design is that of the camera. This camera, designed by H.Epps, has a focal length of 304 mm, and an entrance aperture of 228 mm. It consists of a CaF_2 singlet, a triplet including a CaF_2 element, a doublet, and a field flattening lens and Dewar window. There are 2 aspheric surfaces in the camera with aspherical amplitudes of nearly 1 mm. The focal plane is flat and nearly achromatic over the whole surface of a 55 mm square CCD. The rms image diameters provided by the lens are only about 30μ between 4000 and 11,000Å. Images can be as large as 40μ and can be as small as 15μ depending on focus and wavelength range. The lens can be used down to 3800Å, where the images begin to deteriorate and the transparency of the lens decreases.

Filters are normally placed just in front of the camera lens in the parallel light beam. These must have excellent optical surfaces and should be 241 mm in diameter. It is also possible to put filters just behind the entrance aperture which is where the spectropolarimeter is located.

After the spectrograph was designed and fabricated Tektronix changed the pixel size of their CCDs to 24μ instead of 27μ. This means that the detector is slightly smaller than originally planned. As a result, the field of view in the y direction is 7.8 arc-minutes instead of the 8 arc-minutes originally anticipated. In the other direction, the CCD is oversized for direct imaging but is fully utilized in the spectroscopic mode. The somewhat smaller pixel size provides an improvement over the original design since the telescope image quality should prove to be better than originally aniticipated. The actual scale at the CCD is 0.215 arc-sec/pixel.

One of the problems with the thinned Tektronix CCD is that its light sensitive surface is slightly curved with a radius of curvature of about 2000 mm. (The center of the chip is higher than the edges.) The curvature is somewhat different in perpendicular directions. The change of focus over the chip would degrade the image quality significantly. To alleviate the problem, the Dewar window has a spherical surface ground onto it to serve as a field flattener. Unfortunately this field flattening correction is in the same direction as that built into the original Epps lens. Ideally the correction for the CCD curvature should have been incorperated into the original Epps lens design. Fortunately, the additional field flattener degrades the image quality only slightly.

3 MECHANICAL DESIGN OF THE SPECTROMETER

Since LRIS is designed to be mounted at the Cassegrain focus which is enveloped by the mirror cell support structure, it is not feasible to have access to the instrument during observing. Furthermore, we would eventually like to operate remotely over the ethernet from the Keck headquarters in Kamuela, and perhaps eventually from California. Therefore, all spectrograph changes are motorized and computer controlled. The main such mechanisms are discussed below.

The slit mask changer: The instrument has a magazine which can hold 10 slit masks at a time. These masks are approximately 11 by 14 inches. They are tilted and folded slightly to match the curved focal plane of the telescope. Three of the masks have fixed slits which are 3 arc-minutes long, with widths of 0.5, 1.0, and 1.5 arc-sec. (The widths can be adjusted, but only by removing the fixed slits from the telescope and dis-assembling them.) One mask is an open position, needed for direct imaging. The remaining six masks are provided by the observer for the particular fields being observed. The masks are punched in thin metal plates by a numerically controlled machine specially built for that purpose.

The red grating changer: This is a turret with five positions. One position has a mirror for direct imaging, the remaining four have plane reflection gratings. At present, the gratings are 300, 600, and 1200 g/mm, with a 158 g/mm grating to be added soon. Special gratings can be put in if required. The gratings are the standard 6 by 8 inch grating made by Milton Roy. Each grating can be rotated to select the wavelength coverage desired. The mirror can also be rotated, but is normally set at a fixed angle for direct imaging.

The red filter changer: This has a magazine which holds 6 filters. One position must be clear for spectroscopy. The other positions hold standard broad band filters. Special filters can be inserted if required.

CCD focus: Because the instrument is designed as a double instrument, the single collimator should not be used for focus. Focus on the existing red side is done by moving the Dewar with the CCD and field flattening optics. Focus can be read to 1μ. The focus range needed because of temperature changes is only 50 to 100μ.

Guiders: There are two CCD guide cameras (made by Photometrics). One of these is fixed and is designed to look at the fixed slits which are polished and aluminized. The field of view is 97 by 73 arc-sec. The second guider is an offset guider to be used for direct imaging and for slitmask operations. It is situated at one end of the 6 by 8 arc-minute field. It has an instantaneous field of view of 152 by 114 arc-sec, and can travel in the x

direction approximately 6 arc-minutes. This second guider has an automatic focus change device since the focal plane of the telescope is curved. Both guiders have four position filter wheels.

Light sources: Because the field of view is physically very large, some care must be taken in illuminating the field or slits in the field. Internal lamps illuminate the dust cover which is white and which is about 12 inches in front of the large entrance aperture. The lamps are mounted one on each side of the field to help provide more uniform illumination. Lamps include Hg, Ne, and Ar for wavelength calibration of the fixed slits and slitmasks, and two quartz halogen lamps for general field illumination. These lamps are controlled through the LRIS motor system software.

In the imaging mode, flat fields should be done through the whole telescope optical train. Two overhead projectors illuminate an 11-meter diameter spot on the inside wall of the dome directly in front of the telescope. During observing, these dome flats are best obtained by leaving the telescope fixed in position and rotating the dome so the shutter opening is outside of the field. Two pairs of projectors are provided with different lamp intensities for broad band or spectrum flat fields.

Dust cover: This is mounted about 12 inches in front of the telescope focal plane. When open, it allows light to fall through the full entrance aperture of the spectrometer, and on the moving and fixed guiders. When closed, it keeps dirt off the entrance aperture, light sources, moving guider assembly, and the guiders themselves. The underside is white to provide a screen for internal calibration as mentioned just above.

All of the functions described above are computer controlled using an X-windows environment[2]. All settings are made by clicking on menus or inserting numbers into small boxes. In one of the windows, a status display is shown consisting of a cartoon of the spectrograph, with all the devices in the optical train identified and their current status given. Color is also used as a clue. For example, error messages concerning devices in incorrect positions (trap door closed during observing, for instance) appear in red. Exposure times are controlled through a separate window, as is the storage and archiving of data.

4 ACTUAL PERFORMANCE

Throughput. By observing a standard flux-calibrated star using a wide slit where no loss of light occurs it is possible to measure the throughput of the spectrograph absolutely. The only assumption which must be made is the reflectivity of the primary and secondary telescope mirrors; the pair is assumed to reflect 80% of the light. At the peak of the blaze the efficiency is 30% for the 300 and 600 g/mm gratings, and 24% for the 1200 g/mm one. This is the probability that a photon going through the entrance aperture will be detected as an electron by the CCD.

The throughput in the imaging mode is 40-50% between 4000 and 8000Å, after which it falls somewhat as the CCD sensitivity drops sharply. This does not include the effect of any filters used.

Speed of Mechanisms. It takes about 105 seconds to change a slit mask and about 100 seconds to change a filter. Changing gratings and rotating to the desired angle can take up to 3 minutes and 10 seconds. Just adjusting the grating angle rotation takes about 50 seconds.

CCD Readout Time. The CCD, which has 2 working amplifiers, reads out in 60 seconds, and a further 10 seconds is required to complete storage of the the data on disk. The picture is displayed as it is read out, and is completely visible when the 60 second readout is finished.

Multi-slit Astrometry. In tests performed in January, 1994, we achieved alignment in the direction of the dispersion between the stellar object intended to be in a particular multi-slit and the multi-slit itself with an rms deviation of 0.07 arc-sec across a multi-slit mask intended for 33 objects. We therefore believe the model we are using for the astrometry of the telescope focal plane is satisfactory. We intend to model the spectrograph optics as well, which will provide a means of taking a picture of a field with LRIS, measuring the positions of objects in the LRIS camera focal plane, turning that into astronomical coordinates, and fabricating a slit-mask from that data. We expect this to be completely operational by May, 1994.

Flexure. The goal for the overall flexure of the instrument was 10μ from the zenith to an altitude of 30° for any orientation of the spectrograph in its module. The actual flexure is about 120μ instead of 10. There are several contributors to this flexure. First, the spectrograph body contributes about 20μ flexure. The red grating turret and the grating rotators each contribute about $40\text{-}50\mu$. The telescope module in which the spectrograph is mounted bends and distorts the spectrograph, producing flexure values of up to 60μ. This module will be replaced sometime in the near future. Reducing flexure in the grating turret and grating rotators will require major rebuilding.

The flexure is much worse at low altitudes where observations are rarely made. Above an altitude of 30° for any reasonable exposure the flexure will degrade the image quality by an almost imperceptible amount. Measuring line positions for radial velocities can be done a accurately as the intrinsic instrumental resolution allows simply by obtaining comparison spectra before and after an exposure. The main impact of the flexure is on flat fielding of CCD data. Tests suggest that this can often be done using a single flat field taken at some appropriate altitude and position angle and shifting the pictures by a very few pixels. Where flat fielding is critical, it may be necessary to take the flat field at the same altitude and position angle as the object.

Further work is planned commencing about a year from now to alleviate and reduce the flexure.

5 COMMISSIONING RUNS AND SCIENCE THUS FAR

The instrument was shipped to Hawaii and installed on the Keck telescope in May 1993. Since then, we have had a total of 5 commissioning runs covering perhaps 16 nights of observing, and many more days of preparation and of engineering tests. Initially, since we were trying to interface a new instrument to a new, and not completely functioning or debugged, telescope, observing was extremely frustrating, and much time was lost to telescope problems of various kinds. For example, errors in the Cassegrain instrument rotator rates as a function of altitude and azimuth gave sausage shaped images on long exposures for months.

But slowly these problems have been overcome, and the commissioning runs have in fact begun to yield some scientifically interesting data. A paper is in press[3] describing the spectrum of a purported brown dwarf. A paper is just about finished[4] where the redshift of the lens in MG0414+0454 is determined in a definitive way. The first regular observers from Caltech, the University of California, and the University of Hawaii began using the LRIS in early March, just a few days ago.

6 ACKNOWLEDGEMENTS

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