IMAGE-SLICERS

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A) INTRODUCTION

The diameter of stellar images produced by Earth-based telescopes often exceeds the width of the entrance slit of the associated spectrograph. It is not uncommon for more starlight to be wasted on the jaws of the slit than is transmitted by the slit. The purpose of an image-slicer is to redirect the light from the slit jaws into the slit; to do so, the length of the slit illuminated by starlight must be increased, either by stacking slices of the image along the slit, or by elongating the image and superimposing full-length slices of it. Thus, in order to work, an image-slicer of whatever type must lose spatial resolution of the sky along the slit.

B) THE BOWEN AND WALRAVEN IMAGE-SLICERS

The first image-slicer was designed by Bowen[1] in 1935. It simply reflects the nearly-focussed starlight to go parallel to the slit, at a slight angle, then reflects slices of it into the slit using very thin mirror-facets whose widths equal the slit width as shown in Figure 1. It is described by Pierce[2]. An elegant, modern version of the Bowen image-slicer by Walraven[3], shown in Figure 2, uses a special, right-angle prism made from two pieces of glass; the reflections are internal so this image-slicer has very little reflection loss. The principle of operation is that the light is trapped in a plane-parallel plate except where it has optical contact with the hypotenuse of the prism. The prism is tiny in most applications, its length equalling the starlit portion of the slit.

One disadvantage of the Bowen-type image-slicer is that the illumination of the slit is discontinuous, with gaps between slices of the image, and the number of slices, thus the length of the illuminated portion of the slit depends on the seeing which is variable. Bowen overcame the very streaky appearance and variable width of spectrograms by locating a cylindrical lens near the focus of the spectrograph to image the pupil (i.e. grating) in one dimension (perpendicular to dispersion) thus producing a continuous illumination along the spectral lines. This solution is feasible only if the spectrograph camera is slow, i.e. has a long focal ratio, because the optical aberrations introduced by the cylindrical lens degrade the spectral resolution of even moderately fast cameras.

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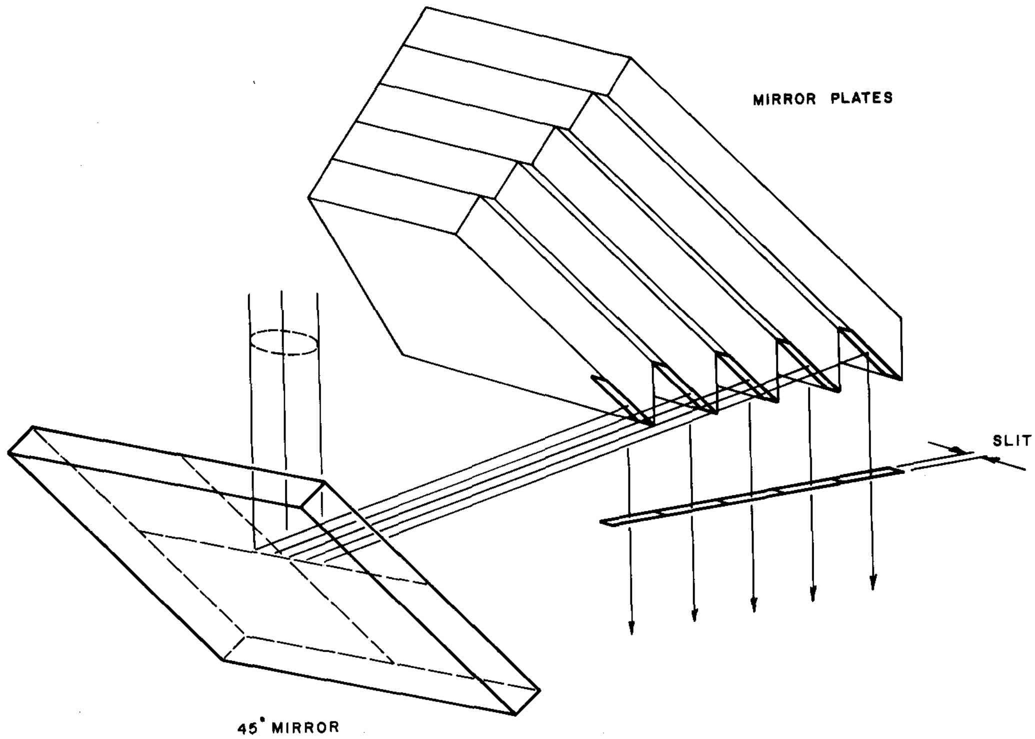

Figure 1. Optical layout of Bowen image-slicer.

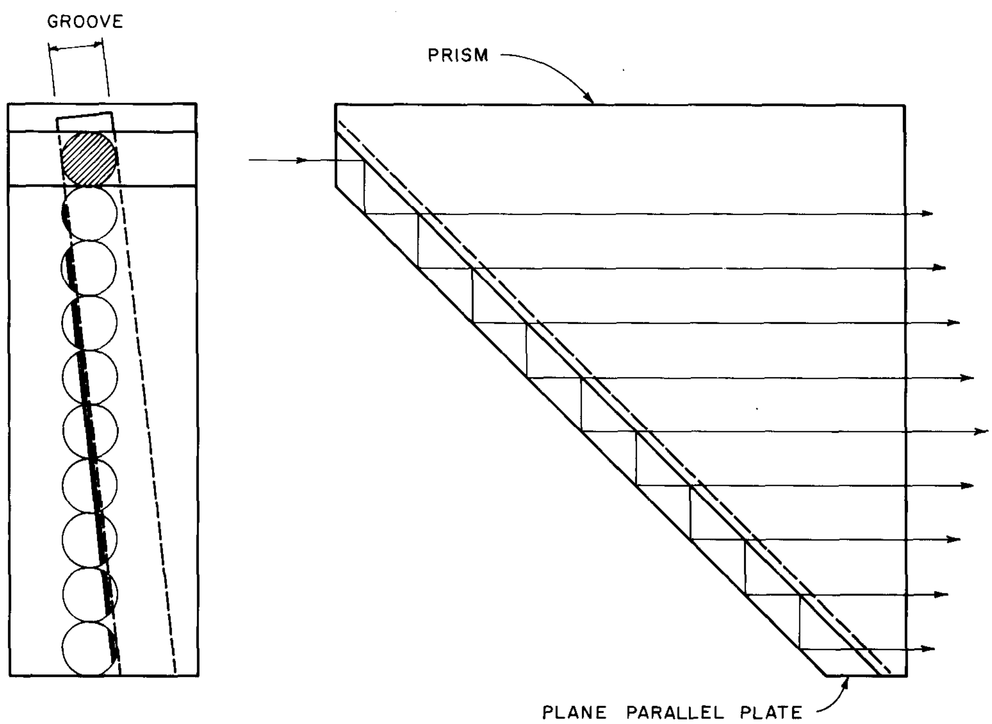

Figure 2. Optical layout of Walraven image-slicer.

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Another inherent disadvantage of the Bowen image-slicer is that only one slice is in focus on the slit. The defocussed images, in addition to losing some light on the slit jaws, can produce fluctuating, non-uniform illumination on the collimator of the spectrograph (and grating) which can cause fluctuations in intensity and shifts in the positions of spectral lines. Tull found the Bowen image-slicer at McDonald Observatory to be unsatisfactory. The Walraven image-slicer does its slicing even further from the focus, on average, than the Bowen image-slicer.

Bowen image-slicers have found application in solar spectroscopy, where they slice a sunspot and stack the segments along the slit, but, ironically, they have been unsuccessful in stellar spectroscopy for which they were designed.

C) THE MULTIPLE-REFLECTION SUPERPOSITIONING IMAGE-SLICER

In 1966, Richardson[4] designed an image-slicer in which all slices were in focus and superimposed on the slit and which required only four mirror segments to produce any number of slices by multiple-reflection from the same mirrors. Each mirror segment is of convenient size, much wider than the slit. A pair of lenses is associated with the mirrors. The lenses decrease the divergence of the starlight in one dimension to provide space on the collimator (and grating) which can then be filled with light from slices of the stellar image normally obstructed by the slit jaws.

The image-slicers usually have wide-band multilayer coatings on the lenses and mirrors, thus blue and red, and sometimes ultraviolet image-slicers are usually made for each spectrograph.

A full explanation of the operation is given in sections C(i) and (ii). Sections C(iii) to (x) detail alignment techniques, etc. Section D on the mounting and E on estimated gains would be of more general interest.

(i) The cylindrical and field lenses

A basic feature of this image-slicer is that the spatial resolution along the slit is destroyed before any slicing operation begins by means of a cylindrical lens placed in front of the slit at a distance usually equal to the focal length of the lens, shown in Figure 3. The effect is to produce two line images from the stellar image: (a) on the slit, one line parallel to the slit (let us say vertical) whose light distribution along the line is a one-dimensional image of the exit pupil, i.e. the primary mirror, of the

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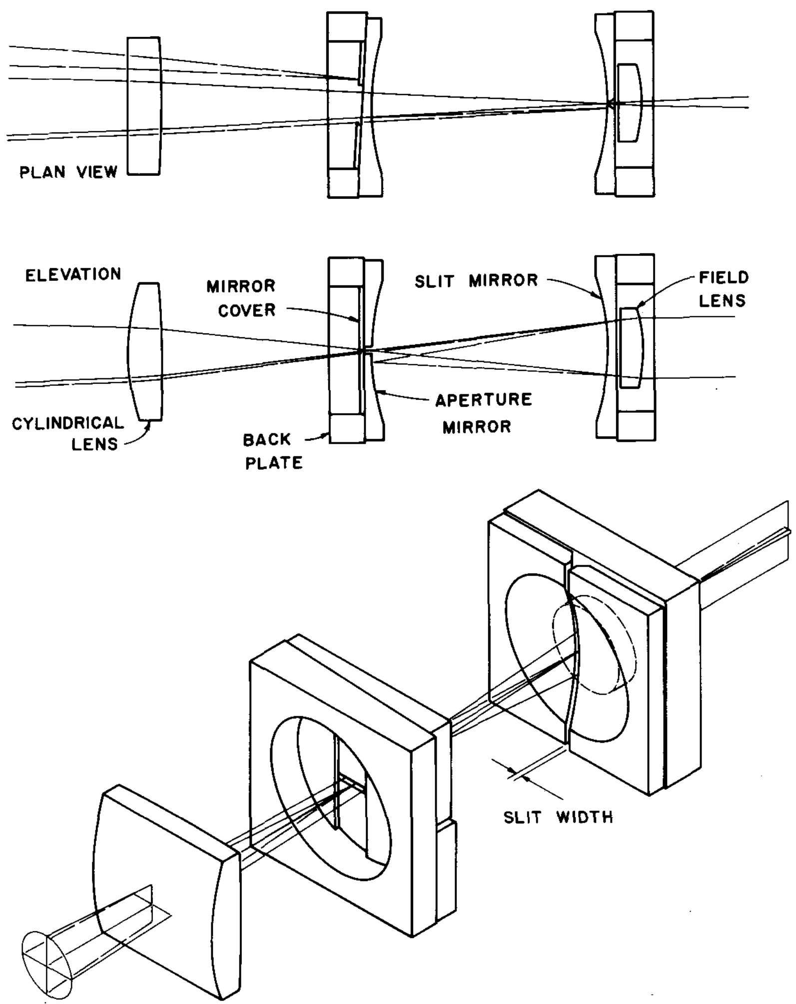

Figure 3. Optical layout of Richardson superpositioning image-slicer.

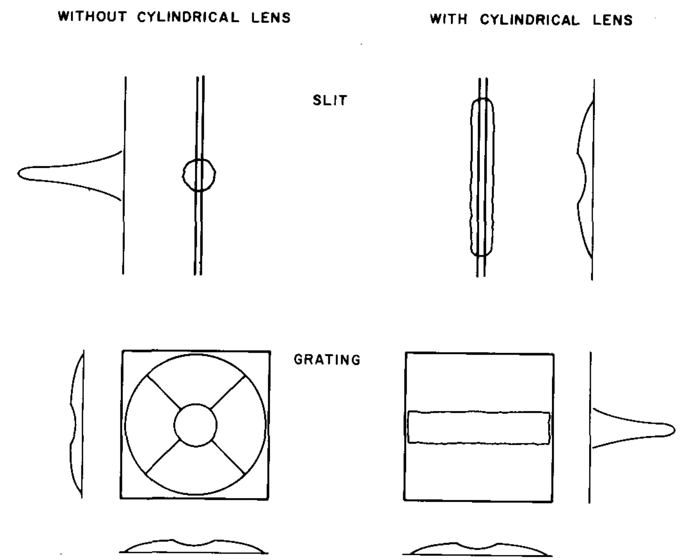

Figure 4. Distribution of starlight on slit and collimator (or grating) with and without a cylindrical lens in front of the slit (and a field lens at the slit).

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telescope, while the distribution across the line is that of the stellar image; (b) at mid-point between the lens and the slit, a horizontal line (perpendicular to the slit) whose vertical distribution is that of the stellar image and whose horizontal distribution is that of a one-dimensional image of the primary mirror, out of focus in proportion to the width of the stellar image (measured at the slit). The ratio of the height-to-width of the light at the slit should equal the number of slices intended. A second positive lens, called the field lens, located immediately after the slit, images the horizontal line onto the grating of the spectrograph. Thus, these simple lenses could enable the spectrograph to operate with a much smaller grating having shorter rulings, or grooves, but the same width, i.e. the same number of illuminated grooves as before. The reduction of the dimension perpendicular to the direction of dispersion of the illuminated area on the grating, shown in Figure 4, is in exchange for the loss of resolution along the slit. The spectral resolution and the slit transmission are unchanged.

(ii) The aperture and slit mirrors

The purpose of this shrinking by the lenses of the illuminated area on the grating in one dimension (vertical) is to make space available for a stack of these line images on the grating, each coming from a different slice of the stellar image, thus increasing the transmission through the slit. This is done by locating pairs of concave mirrors, shown in Figure 3, at the line images formed by the cylindrical lens mentioned above. The pair of mirrors at the vertical line image is called the slit mirror and forms the entrance slit of the spectrograph. The segments are concave to the incident light with a radius of curvature equal to the distance to the horizontal line image thus reimaging it at the same distance. The slit mirror segments in Figure 5 and 6 are displaced with respect to each other parallel to the slit so that the images are not superimposed on the original horizontal line image, otherwise the light would be reflected back out of the image-slicer to the telescope; instead, the images lie above and below the original image and are, of course, mirror images (i.e. reversed). The slit mirror segments are ground and polished with no separation so that when they are displaced to form the slit their centres of curvature are separated by the slit width. The two halves of the mirror are bonded to a backing plate at the correct displacements; this is done in the optical shop using a special jig. The edges of the mirror segments that form the slit are bevelled (as is done with conventional slit jaws).

A second pair of concave mirror segments, called the aperture mirror, is located at the horizontal (first) line image with a slot separating the mirror

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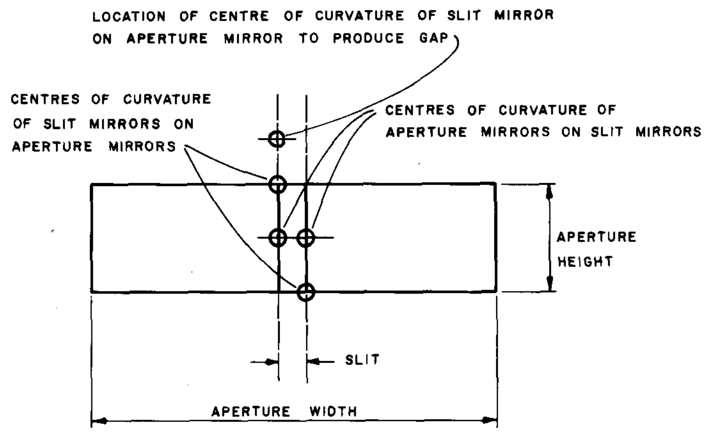

Figure 5. Slot in aperture mirror. Locations of centres of curvature of the two segments of the slit mirror are indicated.

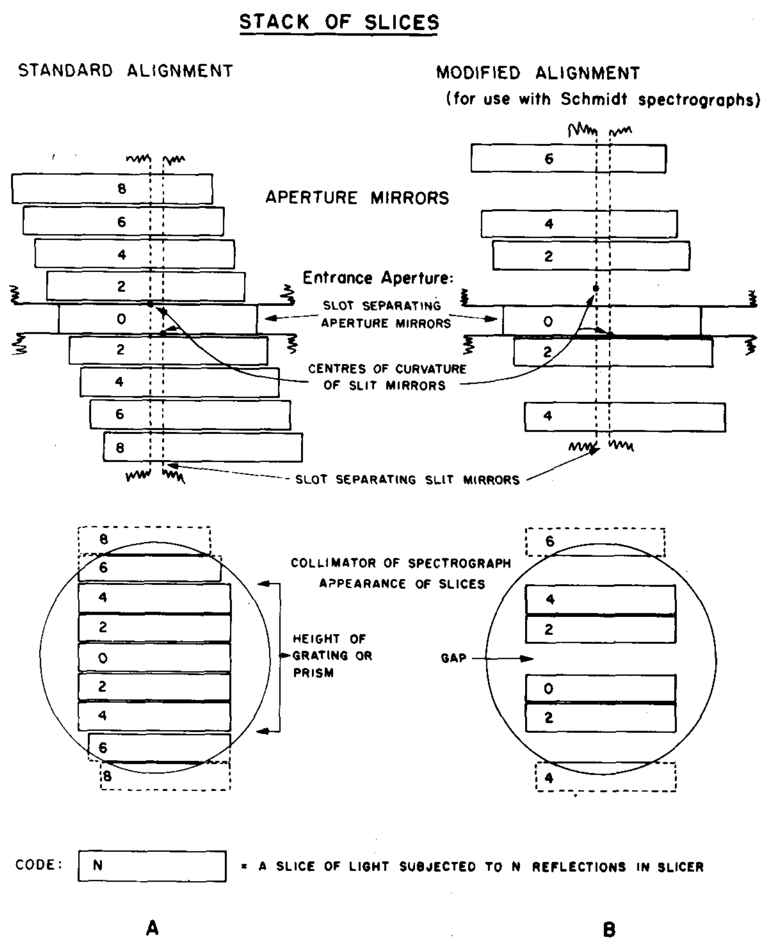

Figure 6. Multiple images of entrance slot seen through slit for (a) an off-axis or lens spectrograph (requiring no gap), and (b) a spectrograph with central obstruction (which is avoided by the gap).

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segments equal to the height of the first line image, i.e. the chosen seeing. The aperture mirror has the same curvature as the slit mirror with its concave surface facing the slit mirror. The aperture mirror segments are separated by the slot width during grinding and polishing because no separation of the centres of curvature is desirable perpendicular to the slot, i.e. parallel to the slit. The segments are bonded to a backing plate with a horizontal displacement (parallel to the slot and perpendicular to the slit) exactly equal to the slit width.

The surfaces of the aperture mirror segments that form the slot are not bevelled and are polished to minimize scattering and to maximize the space available on the concave surface of the aperture mirror for stacking slices.

(iii) Alignment of the mirrors

The aperture mirror is mounted so that is centres curvature lie exactly on the edges of the slit of the slit mirror at the centre of the slit mirror. Thus, light falling on the slit mirror (i.e. missing the slit) is folded over the slit (and inverted) causing a slice of light, superimposed on the previous slice, to pass through the slit. The folded light that does not pass through the slit (because the slit is too narrow) falls on the other half of the slit mirror and the process is repeated. The slit mirror is mounted so that at least one if its centres of curvature, shown in Figures 5 and 6,lies on the edge of the slot of the aperture mirror but displaced by one half of the slit width from the centre of the aperture mirror (the centre of curvature of the other segment being, of course, displaced by one half of the slit width in the other direction). If the second half of the slit mirror is located on the other edge of the slot, then there will be no gap in the stack of images of the entrance slot (i.e. of the horizontal image), seen in Figure 6a. This is suitable for off-axis spectrographs or for spectrographs with a very small central obstruction. Otherwise, the centres of curvature of the slit mirror segments should be separated by more than the aperture-slot height (narrow dimension) so that the centre of curvature of the second segment then lies off the edge of the slot and on the aperture mirror; this results in a gap between each pair of slot images, shown in Figure 6b, thus providing a gap in the illumination of the spectrograph so that no light is lost on central obstruction in the spectrograph camera. This arrangement is suitable for a multiple-reflection image-slicer with a maximum of four slices, otherwise the gap would be repeated, as shown in Figure 6b.

Alignment can be carried out by looking into the lensless image-slicer using a magnifying glass of focal length somewhat more than the separation of the mirror, or using a microscope with about the same working distance, the

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image-slicer being illuminated by a diffuse light source such as a light table, or a wall or the sky. When one looks in through the slit there should appear a skew stack of images of the aperture slot; with focussed light the stack is not skew for the middle slices which are to be used, also shown in Figure 6, which is what is seen if one looks in using a behind-the-slit viewer of the spectrograph with the telescope illuminated by star or sky. The non-skewness also appears if the diffuse illumination is vignetted on one side by an opaque sheet. By mistake the first image slicer was made to show a non-skew stack under diffuse illumination, which resulted in a skew stack when illuminated by focussed starlight, now corrected by the displacement of the centres of curvature of the slit mirrors perpendicular to the slit by the slit width, as mentioned above. If misaligned parallel to the slit, alternate images of the aperture slot begin to disappear under their neighbors. Misalignment perpendicular to the slit causes fading or disappearance of all images on one side of the aperture slot (above or below).

Viewed through the aperture slot, one sees multiple images of the slit, shown in Figure 7. If the alignment is imperfect, alternate slit images begin to disappear under their neighbors and gaps appear when misalignment is perpendicular to the slit; if misaligned parallel to the slit (i.e. perpendicular to the aperture slot) all of the images on one side of the slit grow faint or disappear.

It is usually possible to identify the central slice because it is not coloured by the high-reflectance mirrors. It is also the last slice to disappear as the dekker is moved across the slit, finally obstructing it.

(iv) Looking into an assembled image-slicer

The internal alignment of an assembled image-slicer can be checked without disturbing its optics.

The field lens images the aperture slot near infinity so by looking through the field lens one sees the stack of slot images, skew for diffuse illumination but with a straight shadow if the illumination is vignetted by, for example, a card near the cylindrical lens or by a window frame if one is viewing the diffuse sky.

If one looks in through the cylindrical lens one sees an image of the aperture slot magnified in one dimension, with a blur of light at its centre, this blur being many images of the slit shrunken in height to fit into the narrow dimension of the aperture slot. It is the cylindrical lens that shortens the slit images and causes the long sides of the slot to appear, in focus, at the distance of the slit.

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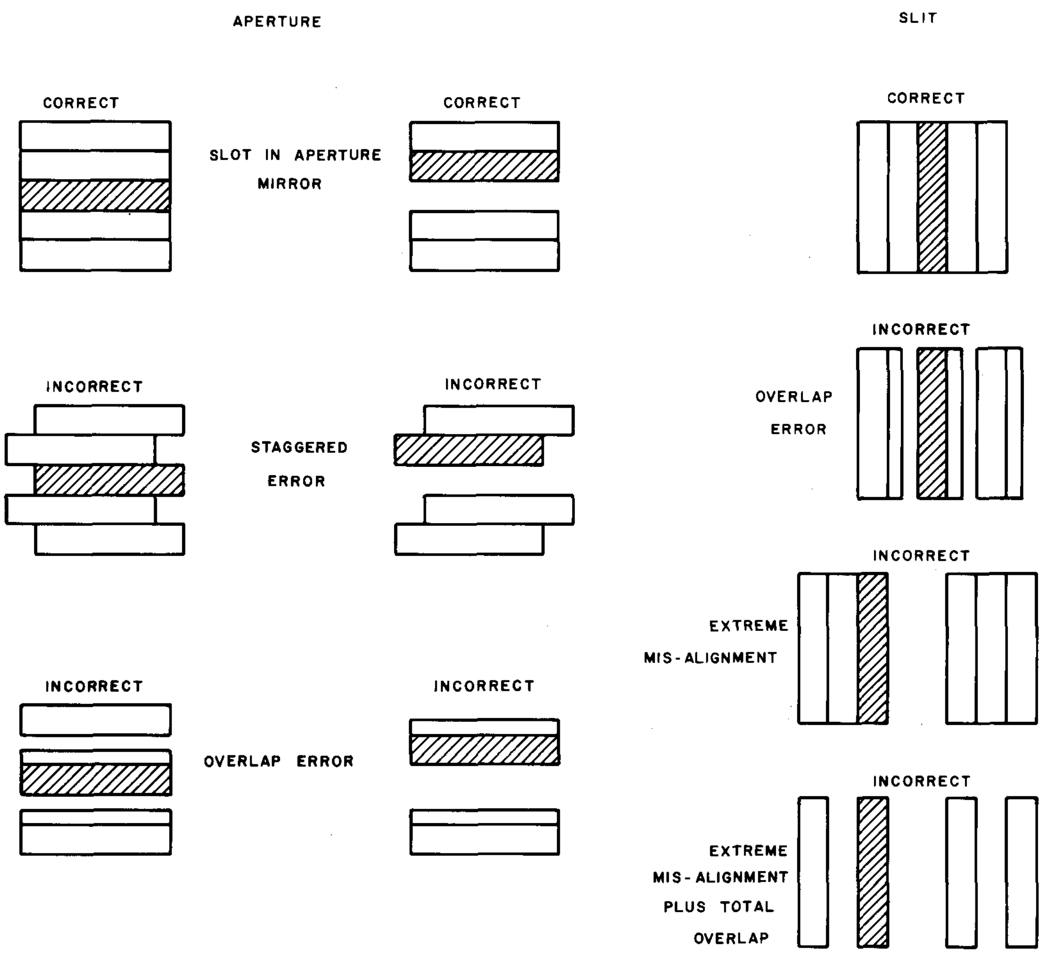

Figure 7. Appearance of slices when image-slicer mirrors are correctly and incorrectly aligned. The multiple images of the entrance aperture slot are seen when viewed through slit, and the mulitple images of the slit are seen when viewed through aperture slot.

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(v) Alignment to the spectrograph and telescope

The ideal light source for the external alignment of an image-slicer is the sun focussed by the telescope because the sunlight is on the telescope's optical axis and the slices can be easily seen inside the spectrograph on the collimator or grating and the bright spectrum is seen at the focus of the spectrograph. For spectrographs with an exposure meter, slices appear on the shutter protecting the photomultiplier where a mask is needed to admit only those slices which are intercepted by the grating (when not directed to the exposure meter).

The object of alignment is to get a stack of slices centred on the collimator, with minimum staggering, and to have the spectrum produced from each slice superimpose a the focus. Staggering, or horizontal displacement of alternate slices, occurs if the aperture-slot of the image-slicer is not centred on the optical axis of the telescope-spectrograph. This is corrected by rotation of the image-slicer about an axis parallel to the slit using the adjusting screws attaching the image-slicer to the mounting plate. Superimposing of slices on the slit is achieved by rotating the image-slicer about a horizontal axis and/or by sliding the cylindrical lens vertically, the result being to cause the central ray to pass through the slit at the location of the centres of curvature of the aperture mirrors.

The final adjustment in this "external" alignment is to locate the images of the aperture-slot vertically on the grating so that the slice that passes through the image-slicer after reflection is located either at centre or slightly above or below centre adjacent to the central obstruction in the spectrograph so that the gap beside the centre slice appears on the obstruction. This adjustment is done by moving the field lens vertically.

Many Directors take a dim view of bright illumination of the coude by sunlight. In that case, one can use skylight, or at night, a bright star, with the observer looking into the image-slicer using a behind-the-slit viewer which can be focussed either on the aperture mirror, to check staggering, or on the slit mirror to check superpositioning of slices. The vertical location of slices on the collimator or grating can be checked using a bright, artificial light shining into the image-slicer because the location is not effected by the axis of the illumination.

If the field lens is spherical instead of cylindrical, the lateral centering of the stack of slices on the collimator can be adjusted by moving the field lens horizontally. The screw holes in the mounting of the field lens are oversize to permit its adjustment.

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(vi) Technique for auto-guiding with an image-slicer

Guiding by an observer viewing light before slicing was described above in section C(iv) where the fine guiding is done by trial and error after the light has mostly disappeared into the entrance aperture. However, the slices which emerge from the image-slicer contain information as to the direction in which the starlight must be moved to obtain maximum transmission. To extract this information in an exposure meter requires a special reflective chopper and preferably, but not necessarily, two photomultiplier tubes instead of the usual one. No such "smart exposure meter" has been built

An alternative, which is less mechanically complicated, is to guide with a computer which peaks the signal by trial and error but remembers which way the starlight was drifting.

(vii) Moonlight suppressor

The purpose of a moonlight or skylight suppressor or eliminator is to increase the length of spectral lines without increasing the amount of skylight. This function is achieved with an ordinary slit either by trailing the star up-and-down the slit and moving a mask (dekker) with it, or by inserting a rocking plate behind the slit and leaving the mask and star stationary. An image-slicer is a natural skylight suppressor with no moving parts because the cylindrical lens lengthens the spectral line without increasing the amount of skylight passing through the entrance aperture. The image-slicer's mirrors are not involved, except that the slots in them for the slit and entrance aperture. Thus, a one-slice image-slicer would give no gain in slit transmission but would act as a skylight suppressor. However, an image-slicer's entrance aperture must be square, or rectangular whereas a conventional sky suppressor could have a circular aperture which could block a little more skylight.

(viii) Optics for comparison source

Most existing image-slicers are optically and mechanically designed to put starlight along the central portion of the slit and comparison light above and below it. This comparison light could be introduced simultaneously with the starlight but in practice the starlight is obstructed by the optics introducing the comparison light. The comparison light should have three or four times shorter focal ratio than the starlight because it is introduced above and below the converging beam of starlight incident on the image-slicer. What the image-slicer sees is the primary mirror of the telescope with comparison light above and below it. If the comparison light is focussed to a point on the axis of the image-slicer where the starlight is focussed by the telescope, the cylindrical lens places the light along the slit above and below the starlight.

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This arrangement produces a very bright comparison spectrum using a faint source, such as hollow cathode tube. A simple alternative is to place a diffusing screen in front of the image-slicer and flood it with comparison light, having set the dekker to block the centre of the slit.

(ix) Field lens options

If the field lens is cylindrical, then the second surface of the cylindrical lens can be flat when the focal ratios of the telescope and spectrograph are the same. However, most field lenses are made spherical because it is cheaper, in which case the second surface of the cylindrical lens is made a weak, positive sphere to compensate for the small increase in focal ratio caused by the field lens which, because of its finite thickness, etc., cannot be located exactly at the slit resulting in a slight magnification. Not only are spheres easier to make than cylinders, but existing tools and test glasses can be found for their manufacture from the very large selection available at a major commercial optical shop. However, an image-slicer with an exceptionally wide slit should use a cylindrical field lens because the change in location of the pupil by the spherical lens would begin to have some effect, causing an appreciable widening of the beam on the collimator.

Because the distribution of light along the slit is a one-dimensional image of the primary mirror, there is a decrease in intensity at the centre, perhaps 30%, caused by the central obstruction in the telescope. Spectrograms taken on photographic plates show this effect. The illumination can be made more uniform by moving the spectrum a fraction up and down during exposure by means of a rocking field lens. A rocking field lens is thick, with the convex surface close to the slit and with the horizontal axis of rotation passing through this surface. The reversed lens has greater spherical aberration which is corrected by making the lens hyperboloidal instead of spherical. The improvement in the appearance of the spectrograms is cosmetic only: accurate photographic spectrophotometry can be done without it.

(x) Beam arranger

The distribution of light in the pupil of a telescope with large central obstruction is shown in Figure 8a and the resulting spectrograms have a noticeable central band of decreased intensity. This decrease can be filled in by mirrors before the image-slicer which reflect light from the edge of the pupil into the centre. That is, it takes light from the ends of spectral lines and adds it to the centre. A beam arranger was made for the coude image-slicers at the DAO but was abandoned because it was not worth the bother, and the later

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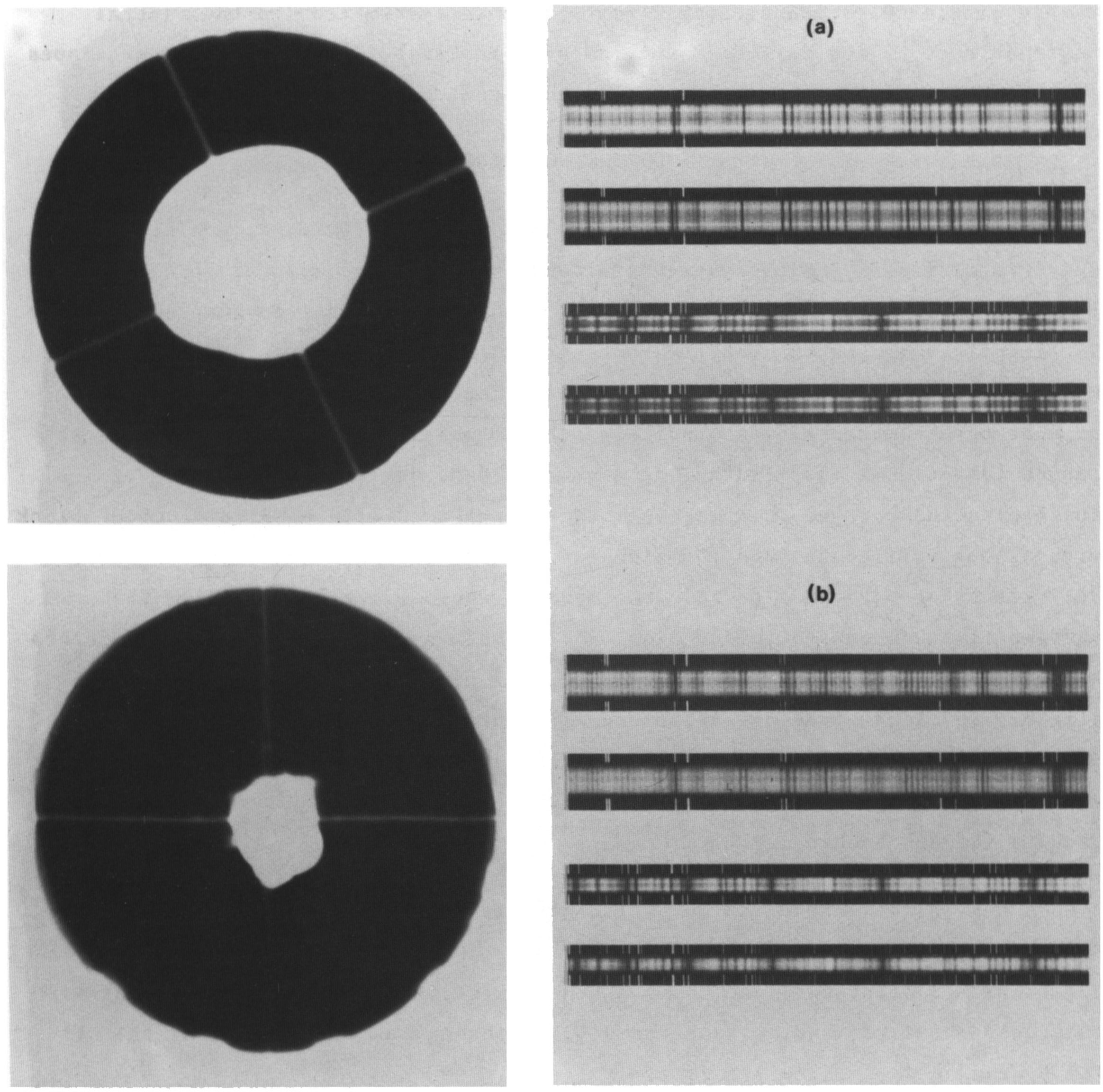

Figure 8. (a) Photographs of pupil of 1.2 metre telescope at DAO taken when telescope had a large coude secondary mirror, and spectra taken with image-slicer showing decrease in central intensity caused by the obstruction. (b) Photographs of pupil and spectra taken after installation of small secondary mirror. The pupils were photographed at the collimator of the spectrograph.

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change of the telescope to a small-mirror coude system reduced the central obstruction to a negligible amount, as seen in Figure 8b. Very large telescopes of the future will probably have modest central obstructions.

D) THE MOUNTING

The first prototype mounting, made in 1967, was a failure. The slit and aperture mirrors (with the segments already bonded) were mounted in cells which could be moved in a tongue-in-groove way to allow the small movements necessary to align the mirrors but they did not stay in alignment when clamped. However, the slicing action of the mirrors had been checked previously by simply separating the mirrors by a vertical piece of metal tubing, cut to the correct length (about 3cm) and sliding one mirror by hand until slices appeared. Therefore, the core of the image-slicer was replaced with a solid aluminum block with a hole drilled through, of diameter smaller than the width of the mirrors but widened at both ends so that the mirrors would lie slightly below the surface of the block for protection. Screws with nylon washers held the mirrors against the block. When almost unclamped, the mirrors can be made to slide slightly by manual pressure and eventually into correct alignment. After the mirrors are clamped down, the alignment is very stable: image-slicers checked years afterward have been found in perfect alignment, even after having been dropped (if not broken).

A dekker is located inside the image-slicer as close as possible to the slit. A recent mounting is shown im Figure 9. The dekker has two or three positions: (1) for starlight, open at the centre, (2) for comparison light with the centre blocked, and in some cases (3) exposing the full length of the slit.

The main body of an image-slicer where all optics are mounted is fastened by adjusting screws to the base. The independent adjustment of the field lens is achieved by oversize holes for its screws. The cylindrical lens is mounted in a cell that can be slid perpendicular to the axis of the cylinder which is parallel to the slit.

The mountings are designed for quick-release from the spectrograph allowing interchange with another image-slicer or with an ordinary slit in less than one minute.

E) ESTIMATED GAIN

The gain in slit transmission of an image-slicer is not equal to the number of slices except in the fictitious situation of a square, uniformly illuminated

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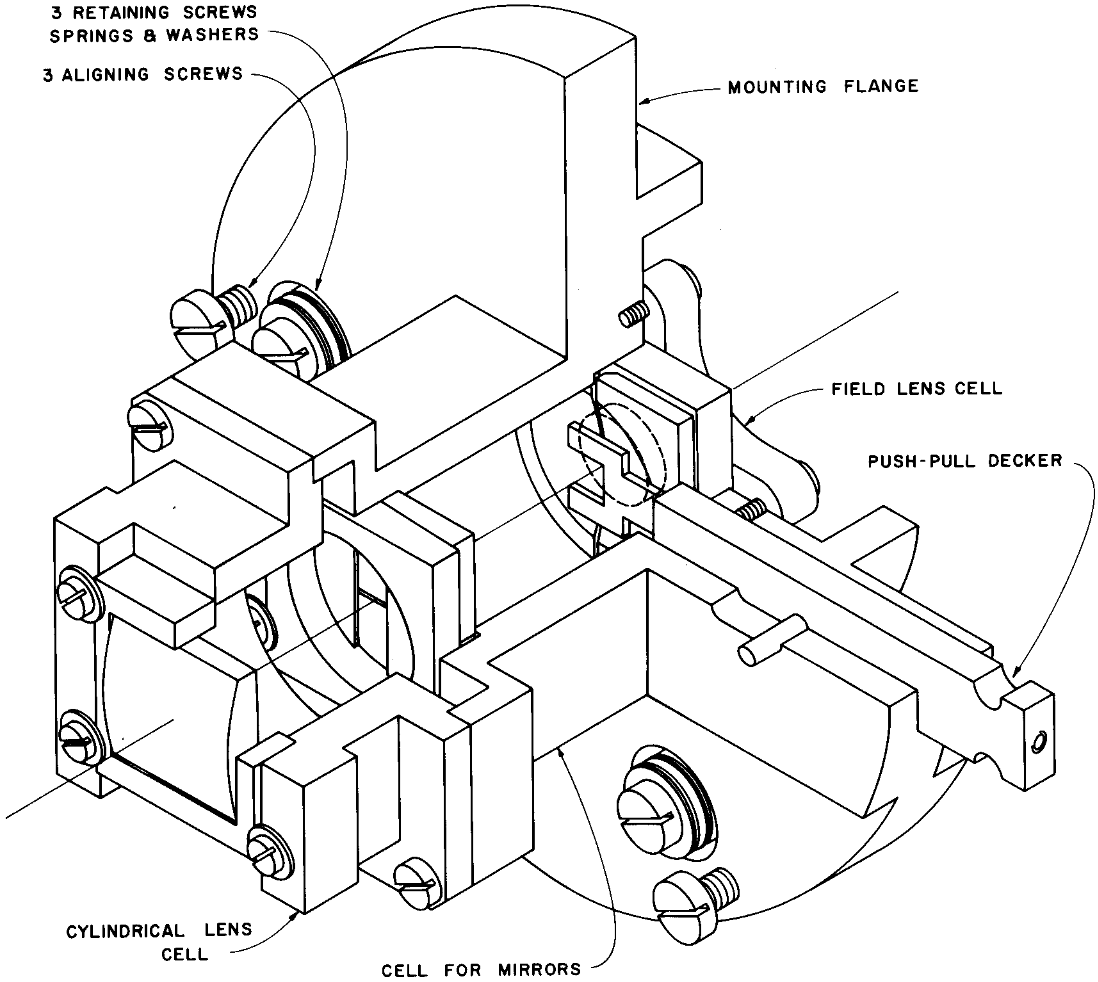

Figure 9. Mounting of Richardson superpositioning image-slicer. The main body, holding the mirrors, is cut from a single piece of aluminum. The dekker blocks the central, starlit portion of the slit when the image-slicer is flooded with comparison light; its second position blocks the outer portions of the slit when the central portion is illuminated by comparison light in a Hartmann focus test. The dekker is not needed during exposures on star or sky because the optics determine the length of the slit that is illuminated.

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seeing patch and 100% reflectivity of the mirrors. In practice, not only is the seeing disk circular, so there is less light in off-centre slices, but it is often brighter at the centre, thus decreasing even further the brightness of the outer slices. Fortunately, the bright central slice passes through without being reflected, and need lose only about 3% at the anti-reflection coated lenses; the next two slices have two reflections each, then the next two have four reflections, etc. Thus, the slices that suffer the greatest reflection loss have less light to start with so the loss constitutes a smaller percentage of the total transmission.

At the DAO a 4-slice image-slicer has a gain of about 2.5 over an ordinary slit of the same width.

The first slice through an image-slicer with 100% transmission thru the lenses would equal that of an ordinary slit with a sky suppressor, i.e. a dekker with the same opening along the slit as the height (on the sky) of the aperture-slot of an image-slicer. This is less than the transmission of a long ordinary slit because light in the wings of the stellar image would enter the long slit but not the image-slicer (or sky suppressor).

Many measurements of the gain of early image-slicers were made at the coude focus of the 1.2M(48-inch) telescope at the DAO using the behind-the-slit exposure meter. The exposure meter was masked so that only four of the many slices produced could enter: the same four slices intercepted by the collimator and grating of the spectrograph.

The ordinary slit could be interchanged with an image-slicer in less than a minute using quick-release clamps.

The total amount of light in the stellar image was measured by opening the slit very wide, then narrowing the slit to produces plots of slit transmission vs width shown in Figure 10. From these profiles for good, average and poor seeing, the transmission of image-slicers can be predicted, taking into account mirror reflectivities and alignment imperfections. In making predictions for other observatories, it was assumed that the seeing profiles would be the same, but would, of course, be scaled to suit the site and the magnification of the telescope.

The slit transmission if an image-slicer were installed at a given telescope-spectrograph can be estimated based on measurements taken at that telescope under various seeing conditions. The maximum allowed (to match detector) length of the ordinary slit should be divided by the number of slices

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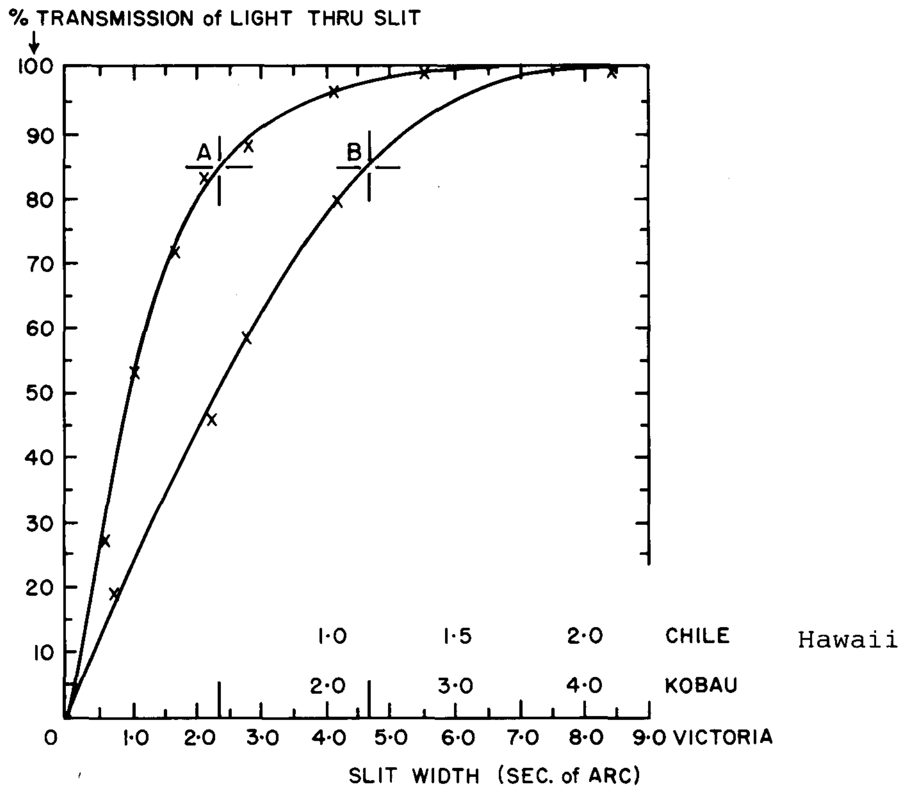

Figure 10. Measured slit transmission vs width (no image-slicer) at coude focus of 1.2 metre telescope at DAO, with estimated scaling to other sites.

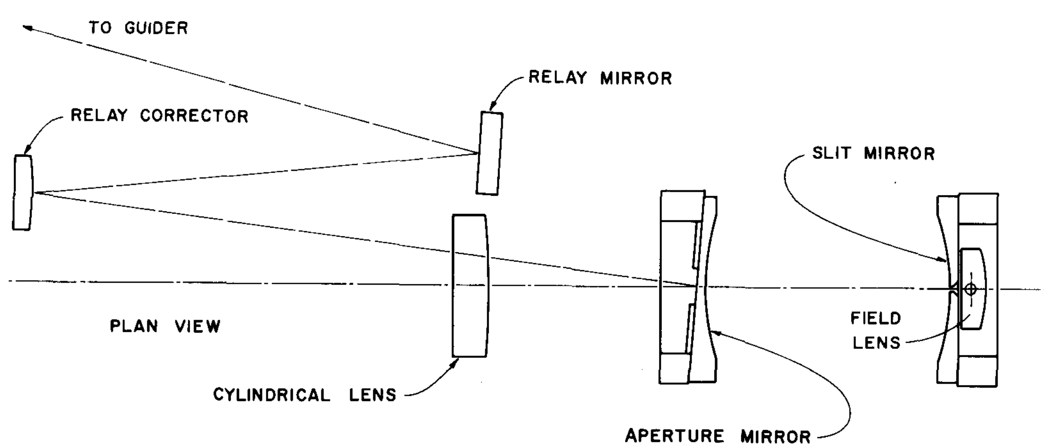

Figure 11. Optical layout of Richardson image-slicer for coude of Palomar 5-metre telescope with extra optics to match image-slicer to existing guider.

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and a dekker set at that shorter length, and the slit width increased by the number of slices. The slit transmission that results should then be decreased by about 15% to account for losses at the surfaces of the optical elements of a typical image-slicer. In practice, the gain of an image-slicer might be as much as 2.7 times in average seeing, decreasing (because the seeing disc exceeds the entrance aperture) to 1.6 in poor seeing (except in the unusual case where the allowed slit length equals the number of slices multiplied by the bad seeing diameter in which case the gain would be slightly better than for average seeing).

F) GUIDING

(i) Optical layout

The backs of the aperture mirror segments are polished flat and wedged so that, after the mirrors are coated, light which does not enter the slot, or entrance aperture, is reflect back off-axis to a guiding eyepiece. Very thin, flat mirrors are bonded to the back of the aperture mirror to cover the unused portion of the slot separating the aperture mirror segments, thus defining the entrance aperture of the image-slicer. Light falling on these thin mirrors is, of course, also reflected to the guider.

All of the light usually passes through the aperture slot and only when the star drifts off-centre does some light begin to appear at an edge of the aperture. Because of small, permissible imperfections in the optical alignments, the position of the starlight for optimum transmission is not usually exactly at the centre of the aperture. Thus, after the observer guides the starlight into the slot he then moves the starlight within the aperture, by trial and error, to get a maximum reading from either an exposure meter sampling part of the light entering the spectrograph, or from the main detector sampling all of the light at the focus of the spectrograph.

A conventional guiding eyepiece (whose optics are surfaces of revolution) should be focussed on the long (horizontal) side of the aperture slot. The cylindrical lens makes the short ends of the slot appear blurred when illuminated by diffuse room-light, but the blur is not so noticeable in starlight which is much less diffuse. The inclusion of toroidal optics with the guider can correct this blur, but this is seldom considered worth the bother. More important would be the restructuring of the image from a line back to a point, i.e. seeing disc, when guiding on a faint star. Another effect of the cylindrical lens is to increase the divergence of guiding light parallel to the slit (perpendicular to the aperture-slot) which can cause the starlight to

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aisappear when it moves far from the slot viewed in a guider designed for an ordinary slit.

Ordinary slit jaws are usually tilted more than is feasible for the back of the aperture mirror (because the aperture mirror cannot be tilted on the other side and should be a thin as possible) so a conventional guider is set at a greater angle to the axis of the telescope and also points at the location of the slit mirror, not the aperture mirror. One solution is to install separate guiding optics for the image-slicer, such as an off-the-shelf alignment telescope. A more elegant (and expensive) alternative is to attach to the side of the image-slicer a pair of toroidal mirrors which put the guiding light on the axis of an existing, ordinary guider and place a virtual line image of the star at the location of the slit so the guider need not be refocussed for an image-slicer. This is being done for an image-slicer, shown in Figure 11, designed for Roger Griffin for use at the coude of the Palomar 5-meter telescope. The added toroids could also change the line-image back into a regular stellar image.

(ii) Guiding errors

In the measurement of stellar radial velocities uneven illumination of the spectrograph slit can result in systematic velocity errors generally referred to as "guiding errors". In the extreme case of a stellar image much smaller than the slit width an error of one half the slit width is possible. Normally guiding errors are reduced during an exposure due to more or less random motions of the star across the slit. Further reductions occur as the stellar image increases in size relative to the slit width. These are all well-known effects. What is of interest here is the effect of "slit" illumination in the case of an image-slicer where there will be more than a single slit (from the point of view of the telescope). A common configuration uses four slits (one real and three images of it). The starlight falls on four adjacent slits generated by the two image-slicer mirrors. As a result of the reflections within the mirror system the four slits are superimposed with top to bottom and left to right folding of which the former is of no interest here. Thus if the intensity distribution across the slit images is as shown in Figure 12 (a) then the distribution across the exit slit is that shown in Figure 12 (b). The slit indicated by the arrow is the actual image-slicer slit whereas the other three are images of that slit.

The question then is how does the intensity-weighted position of the slit change with the location of the star. This is easily simulated with a computer. As a simple model for the light distribution a gaussian was chosen. The "star" is placed in a series of locations across the array of slits and the

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intensity-weighted mean position calculated. The gaussian for the star has a full width at one-half maximum intensity (FWHM) given in units of the slit.

In Figure 13, curve A is the intensity-weighted mean position for a star image with a FWHM equal to one slit width and scanned across a four-slice image-slicer while curve B is for a single slit. Curve C is for one slit of width four units. When the star is centred on the single slit there is no guiding error whereas there is a small but non-zero value for the image-slicer. Curve D depicts the guiding error for a more typical case where the FWHM for the star is 5 slit widths. Here the guiding error is seen to be less than one percent of the slit width.

Normally an image slicer is used only when the stellar seeing disk is much larger than the slit width. Typical cases of seeing may range from 2 to 8 times the slit width with a resulting guiding error of up to about one percent of the slit width. This quantity is generally not a problem. If an odd number of slices is used the small systematic error for a centred stellar image is eliminated.

G) SKY COMPARISON

Most existing image-slicers are designed to place starlight at the centre of the slit and light from a comparison source above and below it, as described above in B(x). The only skylight that falls on the slit is that which is coincident with the starlight. However, to subtract the spectrum of the sky from the spectrum of a star it is required to record a spectrum of skylight beside the star spectrum. This is done by replacing the cylindrical lens with one made from three pieces with the three optical axis displaced parallel to the slit by required separation of the the skylight above and below the starlight on the slit. In other words, the lens sees three primary mirrors of the telescope instead of one. Alternate slices of skylight fall above and the central starlight on the slit. Thus, skylight originating from either side of the star on the sky is distributed to both sides on the slit. An old image-slicer of David Dunlap observatory is now being so modified.

The segmented lens is effectively one in which is cut through above and below the centre in the direction of the axis of the cylinder by a saw whose width equals the sky-star separation. The three pieces are then placed together.

H) THE LEONCITO VARIATION

A special image-slicer was designed for the coude focus of the 2.2 metre telescope destined for the Leoncito Observatory in Argentina. The unusal feature

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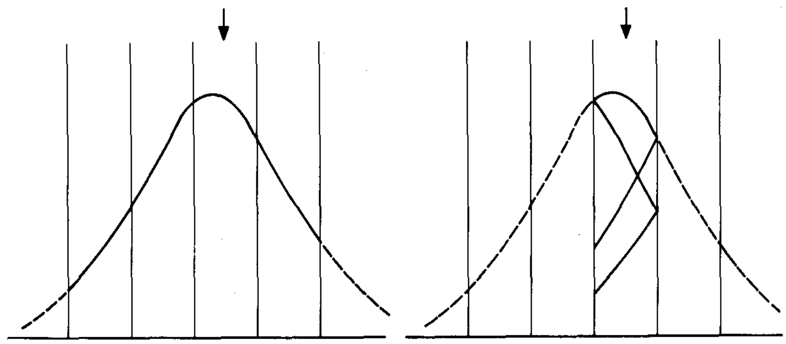

Figure 12. Intensity distribution in seeing disc and in slit of image-slicer from individual slices.

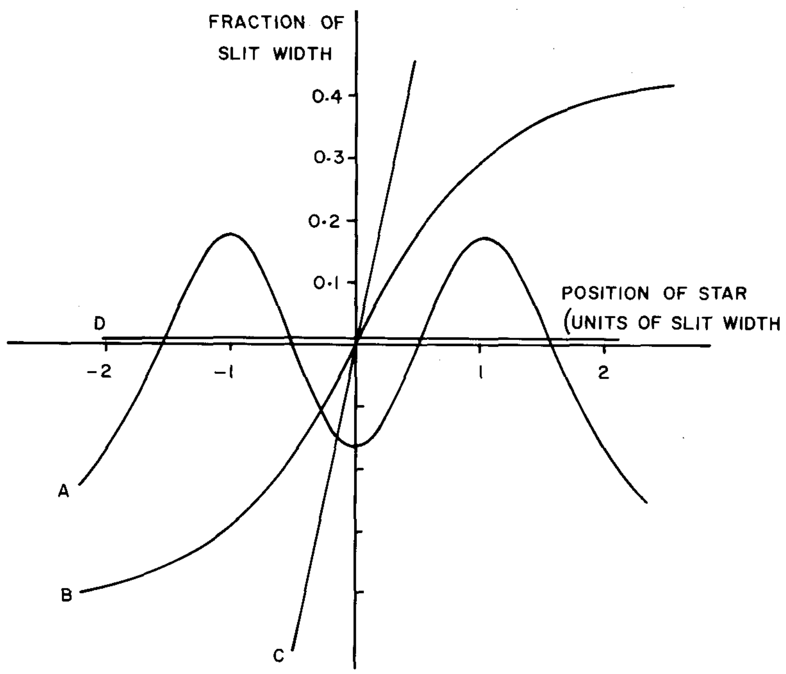

Figure 13. Intensity-weighted mean positions of starlight in slit.

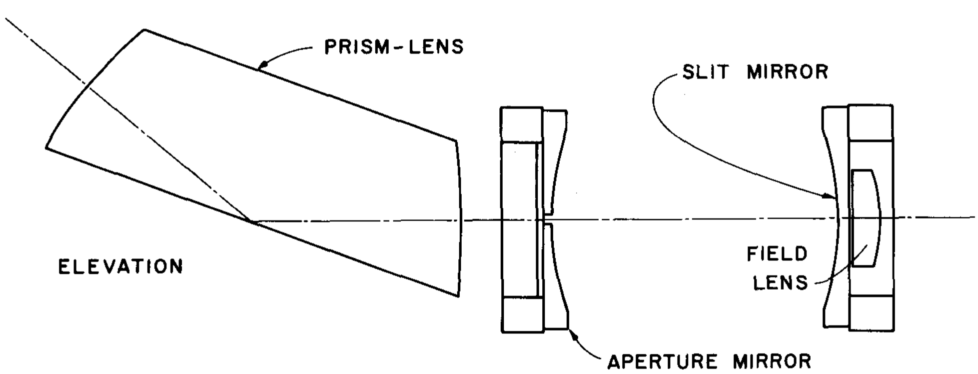

Figure 14. Special image-slicer that includes last coude reflection.

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of this image-slicer is that it incorporates the last reflection of the coude mirror train. This is done by greatly thickening the cylindrical lens into a combined lens-prism with total internal reflection, shown in Figure 14. In this way, the light is turned from the polar axis to the axis of the horizontal spectrograph with 100% reflectivity. (A special image-slicer designed for the Ionnisiani focus of the 6-metre telescope in the USSR replaced the cylindrical lens with a mirror which turned the light through a steeper angle).

I) A MOSAIC SUPERPOSITIONING IMAGE-SLICER

Extremely large telescopes of the future will need image-slicers with many more slices resulting in more reflection loss at multiple-reflection mirrors. Therefore, a new design is being considered where the mirrors are mode from thin pieces matching the slit and aperture slots. Each slice would still be focussed and superimposed, but the maximum number of reflections for any slice would be two.

The thin pieces would be clamped during grinding and polishing, then re-arranged during assembly and final cementing. The aperture mirror would be the simplest to make. On the other hand, two complete slit mirrors need to be manufactured, one symmetrical about the central piece, the other about the space between the central pieces, to finally form one mosaic mirror using alternate pieces from the two original mirrors.

A stack of stainless steel plates, like razor blades, might be a suitable material for the mosaic mirrors.

J) STACKING MULTIPLE-REFLECTION IMAGE-SLICER

Designs of image-slicers which stack slices of the stellar image along the slit, with each slice in focus, are described in the patent[4]. In this case the pupils are superimposed on the collimator (grating) and are circular, instead of square. This smaller area of illumination reduces slightly the aberrations of spectrograph and allows a smaller collimator, but there would in practice be no change in the gratings which are square (rectangular) anyway. The spectra are very streaky, as with the Bowen or Walraven image-slicers, but this could be smoothed by a rocker-plate behind the slit.

K) HOW TO DO WITHOUT IMAGE-SLICERS

An alternative to image-slicers is to simply use a detector of lower resolution, thus allowing the slit to be widened in proportion, and enlarging

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the spectrograph to increase the dispersion to produce the same spectral resolution with the coarser detector. The detector also needs to be enlarged to cover the same spectral region. This has the advantage of avoiding the reflection losses, etc., in an image-slicer which amount to 10-15%, in a focussing (Richardson) image-slicer, less in a Walraven image-slicer. The diameter of the optical elements in the spectrograph should be increased in proportion to the diameter of the primary mirror. For example, the fast, high resolution, Cassegrain spectrograph at the CFHT, (Spectrograph number 2, designed by A Baranne), which uses 20cm gratings would scale up to 83cm for a 15-metre telescope at the same site. Making such a gigantic spectrograph would be very difficult and expensive, and to produce the enlarged detectors might be even more difficult, perhaps impractical. An alternative to enlarging the detectors would be to decrease the focal ratio of the spectrograph camera, which in this example would change from F/1.7 to F/0.4; in the unlikely event that such a fast camera could be made, it would lose a lot of light on its many elements and central obstruction. Even then, the spectrograph would still not have high slit transmission in worse-than-average seeing conditions without an image-slicer.

M) ACKNOWLEDGEMENTS: WHO DID WHAT

The image-slicer was patented by the National Research Council of Canada in the name of E H Richardson who designed the optics and the mirror-mounting, and has done the final assembly and alignment of most image-slicers manufactured. Mechanical parts for early experiments were made by J R White. The vital jig for the bonding of the mirror segments was designed by G A Brealey, professional mechanical engineer, in collaboration with Roy Dancey, then chief optician (now retired) who did the critical bonding of the mirror segments of the first and subsequent slicers, now under contract to Scott Plastics Ltd., Victoria, BC, the company that holds the manufacturing rights. The bonding technique is being passed on to the new chief optician, Bruce Dancey, son of Roy. The mechanical designs were by G A Brealey until recently when W A Grundmann assumed this task. The early optics were made by R Dancey and J Miller but all optics since then have been made by Applied Physics Specialties Ltd., Don Mills, Ont. Multi-layer coatings had been done by commercial firms in the United States, mostly Coherent Radiation Ltd., California, but recently excellent coatings have been produced in our own optical shop by B Dancey and M Waddington. The early mountings were made by F J Johnston, instrument maker here, who still does the final machining-to-fit of the field lens mountings in final assembly. With the exception of final assembly with the optics, manufacturing of the mountings is done by T Wagner for Scott Plastics Ltd. The gains produced in practice by

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image-slicers at the coude of the 1.2M(48inch) telescope was measured by Richardson in 1966 and recently Fletcher has studied performance of the slicing at the telescope and predicted the uniformity of illumination across the slit.

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DISCUSSION

R.G. Tull to H. Richardson: I used a Bowen image slicer at the Coudé spectrograph of the 2.1m telescope over 20 years ago, in an attempt to reduce the seeing noise with an experimental Coudé scanner. The defocussing of the image along the slit produced severe effects: for each defocussed image slice on the slit, only a small part of the collimator was illuminated, so that slit seeing noise was not significantly reduced. This led to the failure of the experiment.

D.D. Walker: What are the relative merits of your image slicer design and the modified Bowen/Walraven type, as used in a (slow) Coudé beam?

E.H. Richardson: My design focusses on the slices on the slit (which reduces radial velocity errors caused by seeing) and superimposes the spectra. The Walraven design has less reflection loss and has fewer parts but it does not focus all of the slices on the slit and it produces streaky spectra. (The streaks could be filled in by means of a rocking plate at the slit but the intensity distribution along the spectral lines would remain seeing dependent.) The lack of focussing can be serious even in a slow Coudé beam judging by the experience of Bob Tull at McDonald Observatory.

D. Enard to E.H. Richardson: I would like to comment on B. Tull's own comment. We have recently used a combination of image slicer and fibre optics. This eliminates completely the seeing noise as well as the guiding problem. Also, the efficiency of any image slicer depends to a large extent on the optician workmanship. We have made a modified Bowen-Walraven image slicer with only 3% internal loss.

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