Spectroscopic Capability

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Y.1. INTRODUCTION

This report describes a fiber-fed CCD spectrograph as originally conceived by Furenlid & Cardona (1988) for use at the CHARA Array. Modifications to this design have been made to incorporate improvements from CHARA's experience in building such an instrument for our Multi-Telescope Telescope, located at GSU's Hard Labor Creek Observatory. During periods of poor seeing the seven telescopes in the interferometer will not be in interferometric use, while on other occasions we may wish to have simultaneous spectroscopic and interferometric information for, say, a short-period spectroscopic binary. The auxiliary instrumentation described here takes advantage of the availability of one or several telescopes for non-interferometric observations and allows all telescopes to be employed at all times (weather permitting), thus leading to fullest possible utilization of the facilities. The main purpose of the spectrograph is to provide complementary data for the interferometry program stars, but observations of any object within appropriate magnitude limits are of course possible.

The spectrograph is designed to generate three levels of dispersion (although only two of these dispersions are planned to be used at present) to be used for different types of stars as well as for different types of measurements. The high dispersion, around 4 Å/mm, is intended primarily for the determination of very high precision radial velocities of sharp-lined stars. The medium dispersion, around 20 Å/mm, will be used primarily for radial velocities of broad-lined stars, which will by necessity generate lower precision in the measurements. An optional low dispersion mode could be used, for example, for spectral classification.

A highly automated mode of operation is planned for the spectroscopic observations, in order to permit the facility operator to obtain these observations without generating an undue burden of additional work. For the majority of stellar objects the only input data necessary to trigger an observation are telescope(s) to be used, object name, dispersion, and central wavelength. All other data needed, such as position and integration time, can be derived from a computer listing of an appropriate star catalogue.

For bright sources it will be possible to use the optical spectrograph and CCD to detect the interferometric signals at high spectral resolution.

Y.2. GENERAL CONSIDERATIONS

The spectrograph design known as the off-plane Ebert-Fastie (Ebert 1889, Fastie 1952) was selected for reasons that will become clear in the following discussion of the design and its properties. Basic features sought in the design are structural and photometric stability and optical simplicity, allowing high efficiency and easy remote operation.

The Ebert-Fastie design contains only two optical components: one parabolic mirror, which serves both as collimator and camera objective, and one grating. Additional elements are input slit or optical fiber head, detector and mechanical devices for focusing, changing grating and grating tilt and for optical alignment. The off-axis Ebert-Fastie, shown schematically

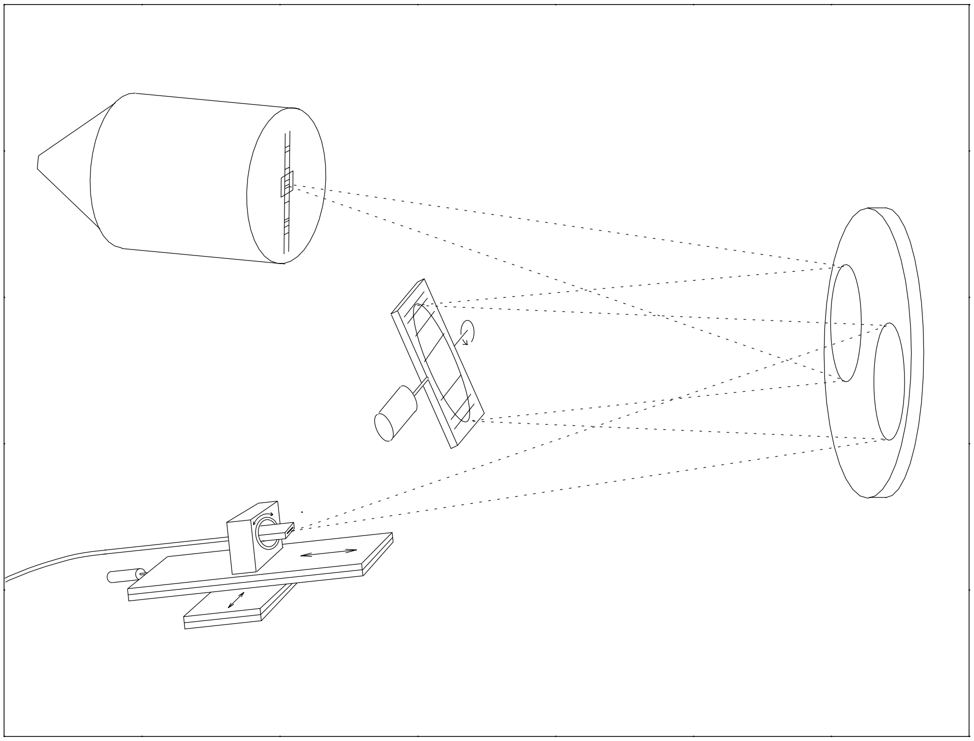

FIGURE Y.1. Schematic overview of the spectrograph shows the main components (not to scale, angles exagerrated).

in Figure Y.1, has the input aperture and the detector placed symmetrically on each side of the grating in a direction along the grating grooves. The direction of dispersion is thus parallel to the grating edge nearest to the spectrum with no part of the spectrum overlapping the grating.

Y.3. SPECTROGRAPH PARAMETERS

The specification of the components of the spectrograph will generally determine the properties of the emergent spectrum, even though the optical arrangement itself provides some of the constraints. An f/10 telescope feeding an optical fiber, serving as the input device for the spectrograph, will decide the f-ratio of the spectrograph mirror through the beam spread of the light emerging from the fiber. Dispersion requirements coupled with groove spacings of preferred gratings decide the focal length of the mirror. Weighing in these considerations, the choice was made of a focal length of 800 mm and a focal ratio of f/3.3 for the mirror, parameters selected to match an optical fiber beam spread of 1:8. A mirror diameter of 240 mm guarantees freedom from vignetting.

Combining the focal length given above with a grating of 1200 grooves/mm and a blaze angle of 45° gives a dispersion in the second order of 3.7 Å/mm, suitable for high precision radial velocity determinations in sharp-lined stars. A grating of 300 grooves/mm and a blaze angle of 10° will produce 20 Å/mm in the second order, a dispersion more useful in measuring radial velocities in broad-lined stars. The wavelength coverage in a single CCD frame will be around 50 Å for the high dispersion and around 250 Å for the medium dispersion.

Y.4. FOCAL SURFACE

A comprehensive study of mirror spectrographs by Mielenz (1964) treats also the off-plane Ebert-Fastie design, using an eikonal approach to derive expressions for the focal surface in approximations up to fourth order. In the second order approximation the general focal surface is given by

$$f(x,y,z) = (x/r) + [1 - 3(m/r)^2](y/r)^2 + [1 - (m/r)^2] - 1/2 = 0 \tag{Y.1}$$

where r is the radius of curvature of the mirror, m is the distance from center of curvature to grating and x, y, and z are Cartesian coordinates with their origin at the center of curvature of the mirror. The coordinate x is directed towards the mirror along the optical axis, y is parallel with the direction of spectral dispersion and z perpendicular to the dispersion.

The condition for a flat field along the direction of dispersion, which is required by a CCD, is found by eliminating the y coordinate from Equation Y.1, *i.e.,*

$$(m/r)^2 = 1/3 \tag{Y.2}$$

The focal surface is now defined by

$$(x/r) + (2/3)(z/r)^2 = 1/2 \tag{Y.3}$$

valid for the paraxial region. The paraxial, or second order, approximation is perfectly adequate for describing the focal surface of a CCD, because of the small size of the detector. Figure Y.2 shows a plot of Equation Y.3 for $r = 1600$ mm, where the length of a Tektronix CCD with 512 pixels has also been indicated. The complete computation of the focal surface using the fourth order approximation has been made, using the spectrograph parameters defined above. A study of the results (see Table Y.1) shows that the focal surface is flat to within $\pm 2\,\mu$m, and the only noteworthy effect is a tilt of 3°.8 of the focal surface relative to the y/z plane, *i.e.*, there is a slight focal length dependence on the value of z, as shown in Figure Y.2. A substantial part of the tilt disappears with the introduction of the slight tilt of the optical fiber head needed to correctly illuminate the mirror. The rest of the effect is easily compensated for by a small tilt of the CCD around an axis parallel with the z axis.

Y.5. ABERRATIONS

A complete specification of the optical performance of the described spectrograph also requires the determination of the point aberrations — spherical aberration, coma, and astigmatism — in the focal plane of the instrument. The use of a parabolic mirror as collimator/camera eliminates spherical aberration. The symmetry of the path of the central ray in the off-plane Ebert-Fastie guarantees that coma and astigmatism become vanishingly small on the central ray in the spectrograph. Following Welford (1965) we can use the field angle, θ, as the independent variable and write the wavefront error due to coma as

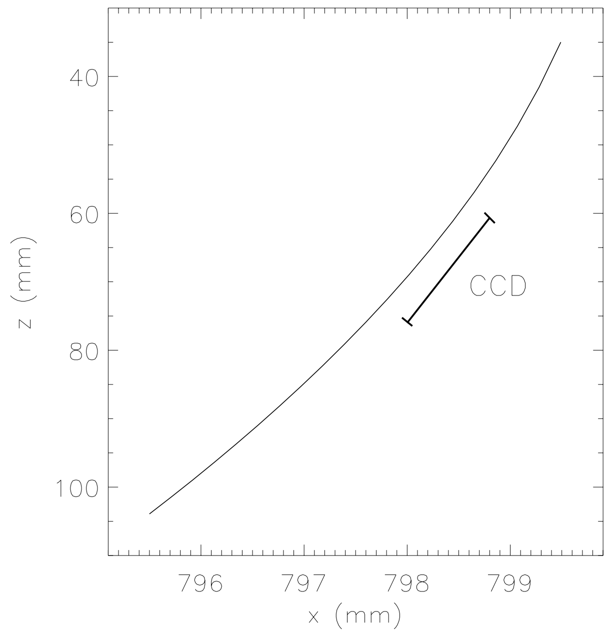

FIGURE Y.2. The curved focal surface in an Ebert-Fastie. The length of a typical CCD is indicated.

$$\frac{-vm\theta(u^2+v^2)}{r^3} + \frac{Qv\theta(r-m)(u^2+v^2)}{r^3} \tag{Y.4}$$

where u and v are now coordinates in the plane of the grating, with origin at the grating center and Q is the asphericity coefficient, equal to -1 for a parabolic mirror. The coordinate u is measured along the grating grooves and v perpendicular to the grooves.

The astigmatism is given by

$$\frac{(m^2v^2\theta^2)}{r^3} + \frac{Qv^2\theta^2(r-m)^2}{r^3} \tag{Y.5}$$

with all designations as above.

The negative sign of Q leads to the same negative sign for both terms in Equation Y.4 for the coma, whose terms are thus additive, whereas in the case of astigmatism, the terms in Equation Y.5 have different signs. Further, the field angle θ is a small quantity which enters linearly into the coma and by its square into the astigmatism; we find for the case at hand that coma is the most dominating aberration of the two.

Inserting the appropriate values into the equations for the aberrations and transforming the wave front errors into blur spot diameters in the focal plane, we find for the coma at the extreme edge of a typical CCD a value of $11\,\mu$m. The blur spot diameter due to astigmatism has a maximum diameter of only $1\,\mu$m. None of these aberrations is thus of any consequence for the quality of the spectral image, considering the $30\,\mu$m pixel size of the CCD.

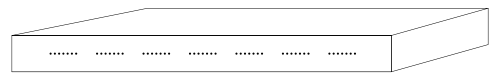

FIGURE Y.3. The optical fiber head, showing the arrangement of the seven linear fiber arrays.

Y.6. FIBER OPTICS

A major advantage of a fiber optic feed for a spectrograph is the positional stability of the light input. Image motion at the telescope end of the fiber is converted to intensity variations at the spectrograph end. This stability is particularly important in radial velocity work, where a major source of error in data from conventional slit spectrographs is image wander on the slit.

Both the high and medium dispersions require a small diameter optical fiber in order to preserve the resolution in the spectrograph. A fiber diameter of $50\,\mu$m will correspond to $1\farcs0$ on the sky, and projects to somewhat less than two pixels on the detector, providing an acceptable upper limit of fiber size. A fiber bundle with individual fibers having a diameter of $50\,\mu$m can thus make a workable coupling between telescope and spectrograph.

The light for the spectrograph will be picked off after the beam reducing telescopes and before the interferometric beam combination. Remotely actuated pickoff mirrors will be driven into 1 or more of the beams. The light of each beam will be diverted into a camera lens and an image of the star formed at approximately f/10 on the end of a fiber bundle.

This bundle consists of seven fibers arranged in a circle at the telescope and in a straight line at the spectrograph end. All fibers come together at the spectrograph from the light input, as shown in Figure Y.3. One or several telescopes can be used simultaneously, entirely independent of each other, as the spectra will be separated on the CCD. The only constraint on simultaneous observations is that they will use the same grating and therefore have the same dispersion and wavelength coverage. The gratings, as indicated in Figure Y.1, may be mounted on a triangular base (thus giving us the option of adding a third grating); choice of grating and wavelength setting are made through computer-controlled stepping motors.

Concerning the fiber bundles, it is of interest to mention that a program of collaboration has been established between CHARA at GSU, and Instituto Nacional de Astrofisica, Optica y Electronica in Tonantzintla (INAOE), Puebla, Mexico. One part of the collaboration is the development of a spectrograph, which is now in operation. The spectrograph is of the Ebert-Fastie type, like the one described here, and is equipped with a CCD and an optical fiber bundle. This instrument is now in use at the 2.14 m telescope of the Cananea Observatory, operated by INAOE.

As mentioned in the Introduction, a modified spectrograph has more recently been constructed by CHARA for use with the Multi-Telescope Telescope. Fiber bundles have been construced in-house by graduate student Donald Barry, and these are being incorporated into the MTT spectrograph as of this writing (Bagnuolo et al. 1992).

Y.7. OTHER CONSIDERATIONS

It is of crucial importance that the spectrograph be equipped with an optical fiber feed in order for it to achieve the highest possible precision in the measurements, particularly in radial velocity determinations. The primary reason is that a fiber feed permits the spectrograph to be used as a table top instrument, which ensures highest possible mechanical stability; the addition of good thermal insulation minimizes possible temperature effects.

A schematic outline of the spectrograph has been shown in Figure Y.1. One of the seven auxiliary telescopes with its associated fiber bundle is used to show the way light is fed to the spectrograph. The fibers end in a fiber head where they are aligned so as to produce separate spectra on the CCD detector. Light from the fiber head passes the side of the grating, is reflected into a parallel beam, strikes the grating, and is dispersed. Part of the mirror serves as a camera objective and focuses the resulting spectrum on the CCD detector, after overlapping orders have been eliminated by appropriate blocking filters. Each auxiliary telescope contains a mount for its associated fiber bundle and also a device to hold two other fibers, each of which can be selected to feed light into the spectrograph fibers. These other fibers provide illumination for comparison spectra or flat field spectra for wavelength and flat field calibration of the CCD frames. A central comparison source in the form of a hollow cathode lamp, and a flat field source in the form of an incandescent lamp, feed light through these other fibers to the slide at each auxiliary telescope. An input beam spread of 1:12 ensures calibration illumination similar to the one from the stellar images.

It is expected that spectroscopic observations will be carried out by remote control by a central facility operator. It is therefore necessary to design these units in such a way that mechanical and optical adjustments will hold for long periods of time, so that automatic guiding of the main telescopes is sufficient to ensure correct alignment through the whole system. A number of key units will also need encoders to allow computer control of their respective functions. A structured observing schedule should allow computerized reductions to be carried out in a fully automated mode.

Y.8. PERFORMANCE

The central wavelength in an off-plane Ebert-Fastie is given by the expression

$$\lambda = (2d/n) \ * \ sin\, i, \tag{Y.6}$$

where λ is the wavelength, d is the groove spacing, n is the grating order and i is the angle of incidence.

The dispersion is given by

$$d\lambda \ /dl = d \ * \ cos\, i \ /nf, \tag{Y.7}$$

where f is the focal length of the spectrograph camera mirror.

The limiting magnitude for one of the main telescopes can be estimated in the following way. We assume in standard fashion that a zeroeth magnitude solar type star is characterized by 1000 photons per second, per cm^2, per Å, in the visual region above the Earth's atmosphere.

TABLE Y.1. Estimated quantum efficiencies of spectrograph components at 0.65 microns. For the discussion of telescope efficiency (up to the spectrograph pickoff point) see Appendix R.

Source	DQE
telescope efficiency	0.51
pickoff efficiency	0.90
optical fiber	0.70
blocking filter	0.70
spectrograph optics	0.90
grating efficiency	0.70
CCD quantum efficiency	0.60
window	0.91
Total efficiency	0.077

The fractional loss of light through the system leads to the fraction of photons detected, the DQE, of the total system, is estimated in Table Y.1.

Very high precision in the measurements requires a signal-to-noise ratio (S/N) of 100 or more. Assuming a S/N of 100 and a one hour integration time for the high and intermediate dispersions, we find a limiting magnitude of 10.4 for the high dispersion and 12.2 for the 20 Å/mm data.

Most of the stars studied interferometrically will be relatively bright and the magnitude limits found permit essentially all stars in the interferometry program to be observed also spectroscopically and photometrically. For the fainter objects the possibility remains to combine observations from up to seven telescopes with an ultimate gain per observation of somewhat more than two magnitudes.

Y.9. A HIGH SPATIAL RESOLUTION SPECTROSCOPIC CAPABILITY

For bright stars, it will be possible to use the spectrograph as an interferometric detector, obtaining high spectral resolution visibilities. The current visible beam combiner concept employs single mode fibers to transport the beams into a beam combiner and low resolution spectrograph. It will be a modest change to feed the same beams into a beam combiner in front of the high resolution spectrograph. This will allow interferometric imagery at high spectral resolution, well suited to study of stellar surface structure by achieving narrow band imagery in resolved line profiles.

Another potential capability of the CHARA Array is to obtain the spectra of individual stars of a spectroscopic binary or of regions of an individual stellar surface by the technique of interspectroscopy (Bagnuolo & Kamper 1990). Consider r_o–sized circular apertures at each of the two output pupil planes (#1 and #2) produced by interfering the light from two telescopes. Suppose a binary star is observed with a projected telescope separation such that the star is at a minimum in visibility. If the output of pupil plane #1 is servoed to the position controls such that the output in #1 is maximized, then the output through pupil plane #2 will be minimized and will consist almost exclusively of the light from the secondary star. The light from each star can thus be obtained, and can be fed to the spectrograph from pupil plane #2 by fibers, in the same way as described in earlier sections of this Appendix. The same principle can be used to feed either the central region or the edges (in one dimension) of a single star to the spectrograph.

For $r_{\circ} = 10\,\mathrm{cm}$, the limiting magnitudes would be brightened by about five magnitudes from those estimates given in Section Y.8, or would be about 5.4 and 7.2 magnitudes for high and medium dispersion, respectively. With compensated imaging, the magnitudes would approach those of the spectrograph itself, or about 10.4 and 12.2 magnitudes.

Potential applications to binary stars include:

- Determining more precise radial velocities and hence improving mass determinations through the "unblending" of otherwise blended lines.
- For fainter stars, providing continua and lower resolution spectra to guide interpretation by spectral subtraction of higher resolution data from conventional spectroscopy.
- "Promoting" to double–lined status those single–lined spectroscopic binaries which cannot now be measured as such.
- Measuring very small radial velocity amplitudes for systems which have completely blended lines to produce new spectroscopic binaries.

Applications to single stars are:

- Directly measuring limb darkening effects by spatially resolving temperature (or pressure) sensitive lines.
- Providing an accurate distinction between rotational and microturbulent broadening.
- Determining the true rotational axes of stars.
- Distinguishing star spots from other surface effects such as pulsation or overall change in luminosity by observing temperature–sensitive lines.
- Better resolving lines of rapidly rotating stars by observing light from the area of radial velocity null.
- Resolving the Zeeman splitting due to locally strong magnetic fields.

This capability for high spatial resolution spectroscopy represents an addition to the overall spectroscopic instrumentation of less than $20,000 with costs primarily devoted to an additional set of optical fibers and the development of software for the control algorithm.

Y.10. COST ESTIMATE

The estimated cost of construction of the spectrograph described above includes the items listed in Table Y.2.

TABLE Y.2. Cost estimate for spectrograph.

Item	Cost
Labor, 10 man-months	$40,000
CCD system	60,000
Gratings	4,000
Mirror	2,000
Mirror cell	1,000
Micro positioners	3,500
Optical fibers	7,000
Light sources	600
Blocking filters	2,500
Materials	600
Stepping motor drives	1,500
Encoders	2,000
Interspectroscopy	20,000
Pickoff Optics	5,000
Remote Actuators	11,000
Total cost	$160,700

Y.11. CONCLUSIONS

A CCD–equipped, fiber–fed spectrograph with specifications that make it suitable as an auxiliary instrument for the CHARA Interferometer has been designed and discussed. The instrument can use one or several main telescopes not engaged in interferomery for spectroscopic observations of any objects within appropriate magnitude limits. The equipment can thus produce data for either objects under simultaneous interferometric study or any other objects of interest, ensuring full use of all telescopes at the facility at any time of acceptable observing conditions. The spectrometer can also be used for high angular resolution spectroscopy, as a detector for the combined beams, and with a new technique for resolving source structure, interspectroscopy, which enhances the contrast between spatially separated regions in the field.

Y.12. REFERENCES

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