FACILITY FORM 602

N70-29616
(ACCESSION NUMBER)

(THRU)

35
(PAGES)

1
(CODE)

CR-110247
(NASA CR OR TMX OR AD NUMBER)

14
(CATEGORY)

750-14

PHOTOHELIOGRAPH

REQUIREMENTS FOR A SPECTROGRAPH

August 12, 1968

S. E. Persson

Approved by: J Denton Allen
J. Denton Allen, Task Leader,
Photoheliograph Task

JET PROPULSION LABORATORY
CALIFORNIA INSTITUTE OF TECHNOLOGY
PASADENA, CALIFORNIA

FOREWORD

This report covers work on one phase of the photoheliograph development task, NASA Code 945-84-00-01-00, for the period November 1967 through June 1968. The photoheliograph has been proposed to NASA for the Apollo telescope mount (ATM) by Caltech, with Professor Harold Zirin as the principal investigator and Dr. Robert Howard of Mt. Wilson and Palomar Observatories the co-investigator (see TM 33-369, November 1967). The objective of the investigation is to obtain high resolution cinematographs in white light near ultraviolet and narrow band hydrogen alpha. Because of the ATM program uncertainties, emphasis has been placed on areas of technology that are somewhat mission-independent, but the ATM spacecraft has been used to establish design constraints.

ABSTRACT

The requirements and constraints for an ATM spectrograph are described. The system to be considered is an echelle spectrograph with a spectral resolution of approximately 500,000, a wavelength range of approximately 4500Å, and a vidicon display of the entire range of wavelengths about as often as the instrument can record a spectrum.

The solar features to be studied include many small (< 1.0 arc sec) structures that have never been observed spectroscopically before. These features are described, the exposures required for each are given, and the resulting constraints on the design of the spectrograph and recording instrumentation are considered.

SUMMARY

In order to extend the usefulness and versatility of the ATM photoheliograph, a high resolution spectrograph will be designed to utilize the full spatial resolving power of the solar telescope in order to examine small scale (< 1.0 arc sec), as well as large scale features in the solar atmosphere. These features include photospheric granules, the spaces between granules, narrow flare filaments, knots of emission in prominences, the umbrae and penumbrae of sunspots, small scale structure in the chromosphere, the limb of the sun, and other phenomena as yet unstudied spectroscopically.

The instrument has certain requirements placed upon it, in order that guidelines in design of the system may be followed. It must be adaptable to the photoheliograph with a minimum number of changes in that system. It could be of a size and shape that is immediately compatible with the ATM; it could, for example, occupy one quadrant of the ATM cannister. The spectrograph and its associated electronics will be designed to gather spectral information over a large wavelength band, at high resolving power. The system must be capable of resolving spatial features along the spectrograph slit, and should have a minimum number of moving parts and a relatively simple mechanical design. The resolving power, wavelength band and integration time will be optimized with respect to each other, and the recording instrument resolution will be great enough to easily resolve spectral and spatial features. It should be possible to place the spectrograph slit anywhere on the image of that part of the solar disk being photographed, and the exact location, orientation, width and length of the slit must be known at all times.

The record/display system should be capable of displaying the entire spectrum at given time intervals in order to follow time evolution of spectral features and correlate them with the time development of the appearance of these features in Hα, ultra-violet, or integrated light. The system should have as few reflecting surfaces as possible in order to decrease the necessary exposure time, especially in the near ultraviolet.

As a constraint on the ATM itself, high pointing accuracy and stability must be attainable so that the full spatial resolution of the telescope can be utilized. In this way, fine solar features can be isolated for periods of time long enough to obtain spectra.

The echelle spectrograph, or some modification of it seems to present a fair combination of several of the desired features. Its principal advantage lies in its capability for displaying a broad wavelength spectrum all at once. This is important for temporal studies of spectral features. A television display is also easily digitized for further data reduction and analysis, but the entire system suffers from doppler shifts of the wavelengths due to space craft orbital motion. These problems will be examined in detail later.

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INTRODUCTION

The scientific gains to be made from solar observation above the earth's atmosphere are considerable. The photoheliograph telescope is being designed to operate in a near diffraction-limited condition, and the resulting spatial resolution of this instrument should approach 0.2 seconds of arc, or about 150 km on the sun's surface. This kind of resolution is unequaled above or below the atmosphere, and the information about the solar atmosphere from UV, Hα and white-light pictures should prove most valuable. The next step in solar observation is to examine the fine spatial features spectroscopically. When high enough spectral resolution is available, the spectral data in the form of spectrograms, or spectrophotometric tracings increases the usefulness of the light gathering instrument greatly. The velocities, temperatures and element abundances of various features in the solar atmosphere can be deduced as a function of time, and thus in principle the entire physical history of an event or feature can be found. Instead of examining one spectral line, (Hα) as the photoheliograph will do, a spectrograph will yield information about many of the solar spectral lines simultaneously. Since the instrument will resolve 0.2 sec of arc, a spectrograph should be capable of obtaining spectra of regions of approximately this size or greater. The solar phenomena open to spectral investigation will be described briefly. It is noted that there is a great range of feature types - due to the resolution of the telescope, essentially all of the features will never have been observed spectrographically before.

One of the main tasks of the photoheliograph will be to examine in high spatial resolution the granular structure of the photosphere, as a function of time, proximity to sunspots, and heliocentric angle (longitude on the solar surface). For this reason, good spectra of the granules should be available for correlation with the white light photos. The temperature and velocity information from the spectra of the edges of granules, and between granules will be used to aid the development of a theoretical description of gas motions in the photosphere. Since the spectrograph slit should be long enough to include several granules, simultaneous spectra of various phases of the time development of adjacent granules should be available.

In connection with granular studies, the spectra of granules in sunspot umbrae and around sunspot pores, and (penumbral) filaments will also be studied. Since the penumbral structure has a distance scale across the filaments of about 1 arc second, spectra should be taken of these regions. The characteristic time scale of the development of photospheric structure near sunspots is greater than in inactive regions, thus longer exposures may be made without line broadening due to non-systematic motions in the solar atmosphere.

Flares often develop around sunspots. They are characterized by a rapid brightening of the surface accompanied by a high UV and particle flux, magnetohydrodynamic waves propagating out from the flare area, and changes in prominences which may be magnetically suspended in the corona above the active area. Flare development is very rapid, and is accompanied by profound changes in the spectrum, especially in the UV. It will be of great interest to correlate white light, Hα and UV photographs with the spectra of flares. It may be difficult to shorten exposure times sufficiently to study the flare spectra with good time resolution; these problems will be studied in detail to determine just how much can be gained by taking flare spectra. Certainly the high spatial resolution will be valuable.

The prominences and knots in prominences will be studied spectrographically, as their fine structure has not been properly resolved as yet. The spectra of these features will be examined during active periods, and correlated with the appearance and spectra of the sunspots, flares and fine flare filaments.

The spectra of the chomospheric network and structure can be examined. This is especially valuable in the UV, where only low spatial resolution spectra have been obtained. The spectra in the UV will necessarily have longer exposure times due to the lower light levels, but the strong CaII lines near 3900Å, are useful for study of the chromosphere. The extended exposure times will reduce spatial resolution (due to image motion), but not severely. Motions, temperatures and structure of the chromospheric network, spicules, and features in the chromosphere above the surface are all open to study, as functions of time and position on the sun.

The limb of the sun will be observed in high resolution for the first time, (in UV) and spectra taken near the limb and just above the limb in the chromosphere and low corona will yield new information on temperatures and structures of spicules, spicule bushes and other features.

To summarize: in spectral studies at high spectral and spatial resolution, virtually all the solar features that have fine structure and high enough brightness can be observed and most of these features will never have been studied in such detail before. Thus a spectrograph of some compact design is a highly desirable piece of auxiliary equipment in studying solar phenomena from above the earth's atmosphere.

SPECTROGRAPH REQUIREMENTS AND CONSTRAINTS

A. QUALITATIVE CONSIDERATIONS

There must be several stringent requirements placed upon an instrument of the type described here. Perhaps the first problem to be considered is the one of insuring compatibility of the spectrograph with the spacecraft and the telescope itself. Ideally, the two instruments would be mated with a minimum number of design changes being made in the photoheliograph. This may require some foresight in the details of the design of the camera package of the photoheliograph as it will be necessary to divert some fraction of the light near the telescope focal plane to the entrance slit of the spectrograph. As a first estimate of the size of the spectrograph, the volume and shape of one quadrant of the ATM canister is chosen. The spectrograph should occupy no more space than this, but its associated electronics will probably occupy some part of another quadrant. As a result of this size constraint, an echelle-type design deserves attention, as it can be made compact, and has other desirable features. Several optical designs will be considered later, and their advantages pointed out. No matter what the design, however, it is important to consider photoheliograph/spectrograph compatibility, and it may be useful also to consider ATM/spectrograph compatibility. At present the size and shape of the ATM itself does not appear to present any insurmountable problems in design of the instrument.

In connection with spacecraft constraints are mechanical design considerations. A spectrograph of the size and resolution described here should have mechanical simplicity. It would be desirable, but not absolutely necessary to design an instrument with no moving parts. Here the information (resolving power, exposure level) requirements take precedence over simplicity of design. It may be impossible to achieve the desired wavelength range and resolution without moving at least one optical component. Also, the mode of data recording (film or TV) involves camera, power supply, and mechanical design considerations. The exposure times and TV and film resolution capabilities will determine which recording devices must be used. These problems will be examined later, when the science requirements are firmly established.

Of prime importance also are the scientific requirements of the instrument. It will not be useful to orbit a spectrograph which has a small wavelength range or low spectral resolution. A lower limit on the spectral resolving power $\lambda/\Delta\lambda$ can be given as 400,000 in white light. A resolving power of 500,000 or greater would, of course, be preferable. Since the telescope is designed for use in the UV, it will be desirable to utilize this capability of the spectrograph as fully as possible. Light levels and exposure times will probably determine the low wavelength spectral cutoff; at this time 3000Å is a reasonable estimate. It will also be desirable to extend the wavelength range into the infrared. An upper limit of 8000Å would be sufficient, but this number may have to be relaxed somewhat. Thus, the wavelength range W should approach 5000Å, but $W \sim 4000$Å might be more realistic. The ultimate value of W will be a function of resolving power, exposure time, and instrument design.

The third important aim of the spectrograph should be to use fully the spatial resolving capabilities of the photoheliograph. Theoretically, the telescope should be able to resolve 0.2 seconds of arc or 150 km on the solar surface. It will thus be desirable to design the entrance slit of the spectrograph to cover approximately 0.2 arc seconds at the solar surface. The true design figure would probably be larger than this but not so large as to nullify the high resolution of the telescope. The length of the slit will be determined by the physical size of the instrument, and the total area of film or TV camera aperture that can be exposed to cover the entire spectral range. It would be useful to study several granules along the slit, and to correlate the spectra with the solar pictures of the area. In order to fully utilize the high resolution of the data recorder and thus make the vertical (spatial) resolution equal to the horizontal (spectral) resolution, the slit length will have a rather small upper limit in numbers of arc seconds. The slit length, resolving power, exposure times and wavelength range must be optimized with respect to each other, as will be shown in Part B as a preliminary calculation.

Several secondary requirements are necessary also. It would be useful to have simultaneous pictures in white-light, Hα and UV of the small area on the surface which is being photographed spectroscopically. Clearly, this is a requirement as regards identifying the spectra with solar features. In addition, useful correlations of appearance in the three wavelength ranges, and spectral character (motions, temperatures, abundances) can be made, as pointed out in the Introduction.

It would be useful to have the capability of selecting slit size and location at the telescope focal plane. Translating and rotating the effective position of the slit would thus be necessary; however, image translators and rotators could be incorporated into the design to accomplish the task.

Since UV spectra are important, it is advisable to minimize the number of reflecting surfaces. If a prism is employed in a Littrow configuration for an echelle spectrograph, its UV absorption should be minimized also.

The final important constraint, is one of stabilizing the image in the telescope over the period of time of the exposure of the spectrograph. In Part D a rough calculation will point out the need for high pointing stability, in order to achieve the desired resolving power and wavelength range. Since a sensor capable of detecting drifts of 0.1 arc sec over a period of an hour will be available, the image reaching the spectrograph entrance slit may have to be internally guided.

In Part E the effect of doppler shifts in the spectrum caused by spacecraft motion will be shown to be prohibitively large for the long exposure times needed. Several possible alternatives in design and spectrograph data acquisition modes will be suggested.

B. PRELIMINARY CALCULATIONS FOR RESOLVING POWER AND WAVELENGTH RANGE FOR AN ECHELLE SPECTROGRAPH

There are several spectrograph or spectrometer systems that deserve study as possible candidates for a flight instrument. In this section some preliminary calculations will be given for several spectrograph parameters. Ideally, a general set of variables would be given, which would apply to all spectrographs. This cannot be done simply, however, and thus an echelle-type design is chosen here as an example of what sort of requirements must be met. The echelle spectrograph combines many desirable features such as high resolving power and compactness of optics. As will be seen later, however, the echelle brings with it problems of data display format, and hence optimization of detector capabilities. These problems will thus lead to similar studies of other spectrograph/recorder systems.

The echelle spectrograph consists basically of a grating, a collimator and a predispersing element such as a quartz prism. Typical configurations are shown in fig. 2. The echelle grating does not have a great number of lines ruled per mm, but makes use of high incident and refracted angles and hence high spectral orders.

In fig. 2(a) the light enters slit S from the f/50 telescope beam. The telescope focus is at the position of the slit. The diverging beam is then deflected by a quartz prism P to a collimating achromatic lens C. The quartz prism Q predisperses the light which falls on the grating E, and is then highly dispersed into many overlapping spectral orders. The prism separates these orders as the light is returned through the system to C and on to the focal plane F. The resulting output at F is shown schematically in fig. 3. The dotted lines L maintain one spectral order per vertical cycle.

In fig. 2(b), collimating mirros M_1 and M_2 replace the lens C, but the operation of the system is otherwise identical.

Fig. 4 shows a cross-sectional schematic view of the grating itself. The light is incident from the left and makes an angle α with the normal to the grating plane. The step width is s, the step depth t, and the grating constant a is thus equal to $(t^2 + s^2)^{1/2}$. A is the aperture and W the length of the grating; β is the angle of reflection, and is nearly equal to α.

The basic formulae relating these quantities are:

$$m\lambda = \frac{W}{N} (\sin \alpha \pm \sin \beta) \tag{1}$$

where m = order of the spectrum and N = total no. of lines on grating.

Since the resolving power y is equal to Nm and $\alpha = \beta$,

$$y = \frac{2W}{\lambda} \sin \beta \tag{2}$$

from (1) $m d\lambda = \frac{W}{N} (\cos \alpha d\alpha + \cos \beta d\beta)$ and for a constant angle of incidence α,

$$\frac{d\beta}{d\lambda} = \frac{Nm}{W \cos \beta} = \frac{2 \tan \beta}{\lambda} \tag{3}$$

and thus the linear dispersion D is

$$D = \frac{2f \tan \beta}{\lambda} \tag{4}$$

where f is the camera focal length.

Since $A = W \cos \beta$, from (4)

$$D = \frac{2W \sin\beta}{\lambda} \quad \frac{f}{A} = y \frac{f}{A}$$

so (5)

$$y = A \frac{d\beta}{d\lambda}$$

The resolving power is thus the product of the aperture and the angular dispersion. The free spectral range is the spectrum interval lying between successive spectral orders. In terms of grating parameters, it is given by

$$F_\sigma = \frac{1}{2t} \text{ (in cm}^{-1}\text{)}$$

or

$$F_\lambda = \frac{\lambda^2}{2t} \text{ (in Å)}$$

The intensity within a spectral order is shown schematically in fig. 5 (Harrison 1949). The parameter F_λ thus determines the step size of the grating.

Now using the formulae developed in the last several sections, a spectrograph will be "designed" to optimize the slit length, f-ratio, resolving power etc.

Let us assume the design shown in fig. 2(a). The entering beam is f/50, and let us use a 2.5 meter focal length. The beam will thus fill a 5 cm aperture, at the position of the collimating lens C. Let us choose a 4500Å bandpass, from 3300Å to 7800Å. These cutoff wavelengths are chosen so that the input number of ergs/cm^2-sec-μ is the same at each end of the wavelength band (see fig. 1). The minimum flux is thus 7×10^5 ergs/cm^2-sec-μ, the maximum is 15×10^5 ergs/cm^2-sec-μ, at the spectrograph entrance slit. In choosing the above wavelength band it is recognized that it would be preferable to extend the range several hundred Angstroms in either direction, but the information carrying capacity of the recording system should not be exceeded.

Now the resolving power must be chosen. A figure of 500,000 would be useful, therefore, let us assume an R.P. of 5×10^5 at 5000Å, since the R.P. will decrease to longer wavelengths (see fig. 8). Now since the system is used in near-autocollimation;

$$\text{R.P.} = y = \frac{2W \sin\alpha}{\lambda}$$

$$= \frac{2\,Na \sin\alpha}{\lambda} = \frac{2Nt}{\lambda}$$

Thus (Nt) is given by

$$Nt = \frac{5 \times 10^5 \times 5000\text{Å}}{2}$$

$$= 12.5 \text{ cm.}$$

We now wish to determine W, the width of the grating, given A = 5.0 cm and W cos α = A.

Since $y = \frac{2A \tan \alpha}{\lambda}$

we have

$$\tan \alpha = 2.5000$$

$$\alpha = 68^\circ 12'$$

$$= 1.1901 \text{ radians}$$

$$\cos \alpha = 0.37137$$

and

$$W = 13.463 \text{ cm}$$

$$= 5.3 \text{ inch}$$

In fig. 10 is given a schematic of the spectral display for small m. It is seen that to put most of the spectral information onto one TV camera, it may be necessary to use some optical elements in the camera beam. In fact, due to the resolution and bandwidth requirements, it may be impossible to display all the information on one vidicon.

We now have to select t, and N, by choosing how much information we wish to display across the vidicon screen. In connection with the information content on the vidicon screen, is the problem of selecting an entrance slit. The longer the slit, the greater the prism dispersion, and the wider each spectral strip will be at the spectrograph focal plane.

It would be useful to be able to compare white light solar features on a one-to-one basis with the associated spectral features. The telescope focal plane display format is 1.8 cm x 2.4 cm corresponding to 114 arc sec x 152 arc sec. If we assume the entrance slit to be vertical in the field and S cm in length (or S′ arc sec in length), then the fraction of the field height taken by the slit is $\frac{S'}{114}$ or $\frac{S}{1.8}$. Now assuming that the resolution capabilities of the spectrograph vidicon are the same as those of the white light recording system, we can photograph at most $\frac{114}{S'}$ strips (for an echelle) across the field, and still preserve resolution in the vertical direction. (This means essentially that the light along the slit is not integrated by the spectrograph system; one resolution element in white light corresponds to one resolution element along a spectral line.)

Now let us arbitrarily choose the number of grating grooves to be N = 1000. Thus

$$a = 1.3463 \times 10^{-2} \text{ cm}$$

$$t = 1.2500 \times 10^{-2} \text{ cm}$$

Then

$$F_\lambda = \frac{\lambda^2}{2t} = 4.356\text{Å at } 3300\text{Å}$$

$$F_\lambda = 24.336\text{Å at } 7800\text{Å}.$$

The length of a spectral strip at the focal plane of the spectrograph is given by

$$L = f \frac{\partial \beta}{\partial \lambda} \Delta\lambda = f \frac{y}{A} F_\lambda.$$

This reduces to

$$L = f \frac{2Nt}{\lambda A} \frac{\lambda^2}{2t} = \frac{f}{A} N\lambda$$

$$= 50\ N\lambda,$$

since the focal ratio is f/50.

So

$$L_{3300} = 1.634 \text{ cm}$$

and

$$L_{7800} = 3.894 \text{ cm}.$$

Fig. 11 gives L in graphical form.

Now the resolving power at 3300Å (fig. 8) should be 7.5×10^5, however, we have only 1.634 cm to display 4.356Å, i.e. 653 elements, at 40 line-pr/mm. Thus the resolving power at 3300Å is only 5×10^5. A simple calculation shows that the spectrograph has detector limited resolving power for $\lambda < 5000$Å, and the R. P. follows a $\frac{2Nt}{\lambda}$ law for $\lambda > 5000$Å.

The above exercise suggests altering N in order to get detector limited resolving power for much of the wavelength range. The number of orders becomes fairly large, however, for higher R. P., which is necessary for detector-limited R. P. at higher wavelengths.

We can get a rough idea of the number of spectral orders N_s required to display the entire spectrum, by computing the average value of $F\lambda$.

$$\langle F_\lambda \rangle = \frac{1}{4500} \int_{3300}^{7800} F\lambda \, d\lambda$$

and

$$N_s \langle F\lambda \rangle = 4500\text{Å}.$$

This gives $N_s \sim 346$ strips. Since one vidicon can display $\frac{114}{S'}$ strips (at most), we see that for $S' = 1$ arc sec, we need at least 3 vidicons. This rough calculation takes no account of space left between spectral orders or curvature of the strips.

Another problem is that of the length of the strips (~4 cm at 7800Å). A rather large vidicon would be required at these wavelengths; clearly a red-sensitive system is necessary also. Large, red-sensitive, 40 line pr/mm vidicons do not exist, so a careful balancing of requirements will be necessary.

It is noted at this point that it would probably be reasonable to sacrifice some of the wavelength range in order to use a longer slit. Rather than display the entire spectrum at once, the grating could be rotated to cover different (narrower) ranges. In the section on the Recording System, it will be seen that moving one or more of the optical components would have one other important advantage.

The above indicates some of the problems inherent in the design of an echelle spectrograph with the science requirements quoted previously. It may in fact be impossible to meet all these requirements. A detailed examination will be necessary to optimize the design, and to determine the performance of the hypothetical instrument.

In later sections, several other designs will be considered, and their relative merits considered in some detail. In the next section, the exposure times will be found in order to put a limit on image motion at the photoheliograph focal plane.

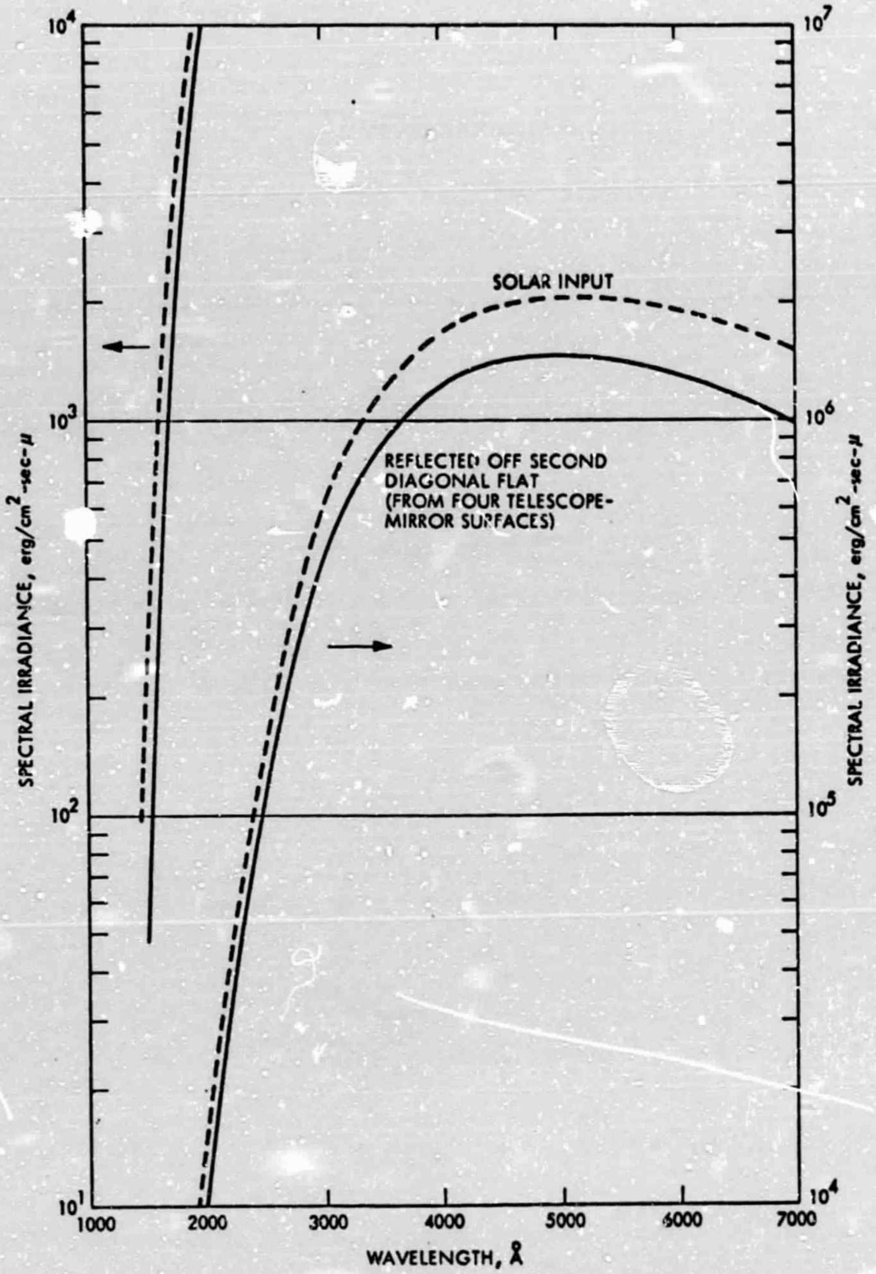


Fig. 1. Reduction of Solar Irradiance by the Four Reflecting Surfaces of the Telescope

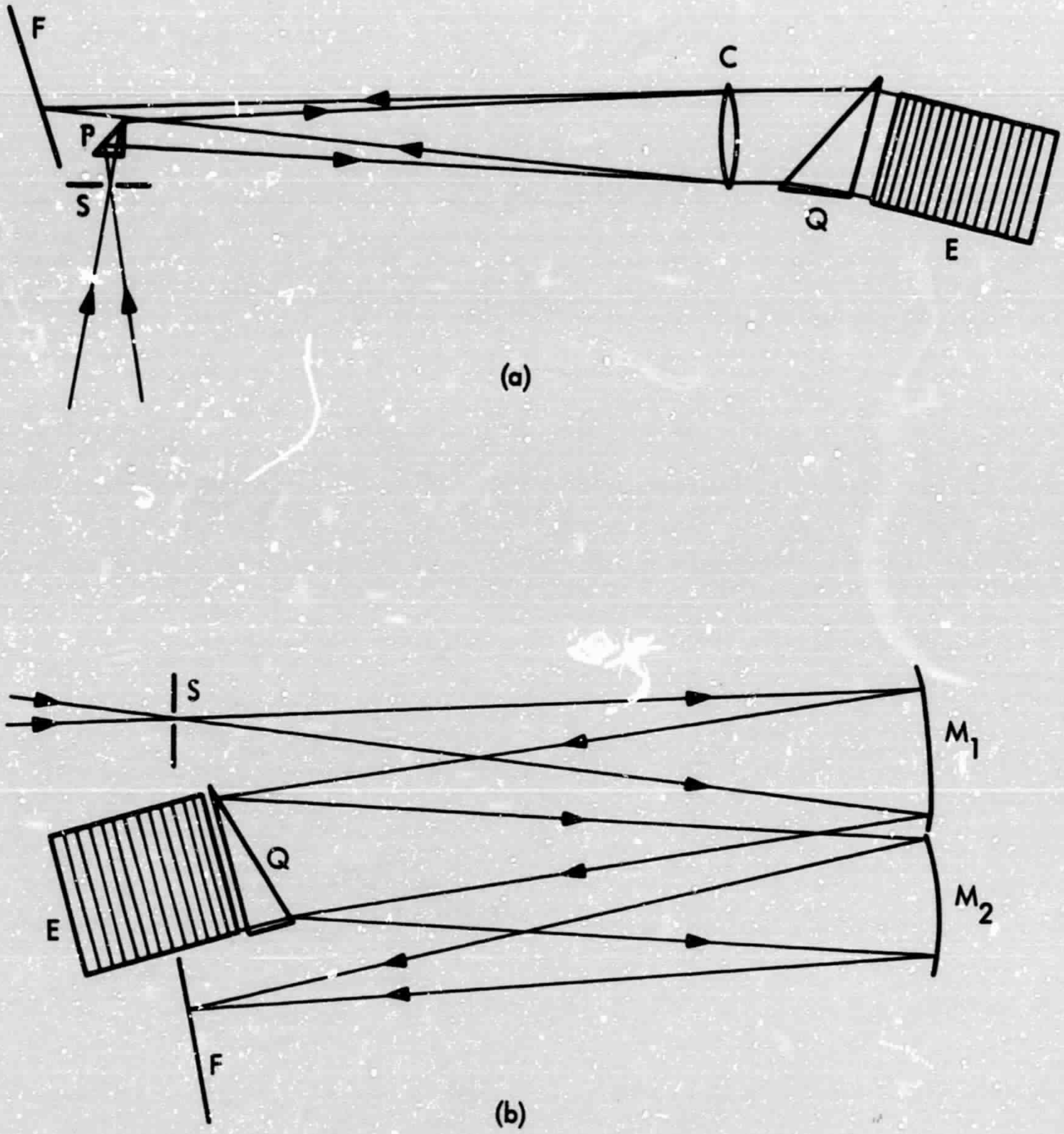


Fig. 2. Echelle Spectrograph Configuration

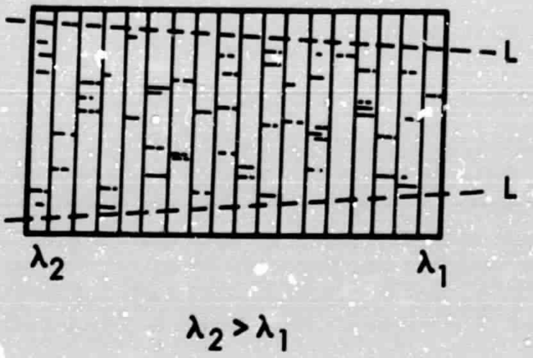


Fig. 3. Schematic Data Display

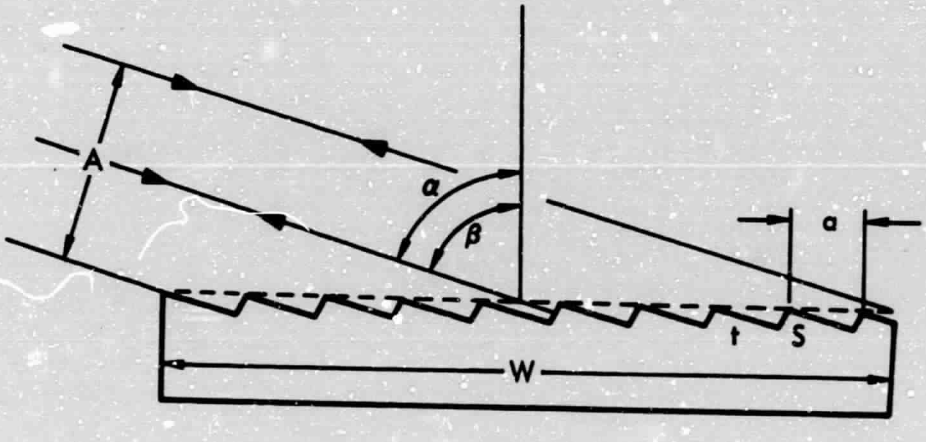


Fig. 4. Grating Parameters

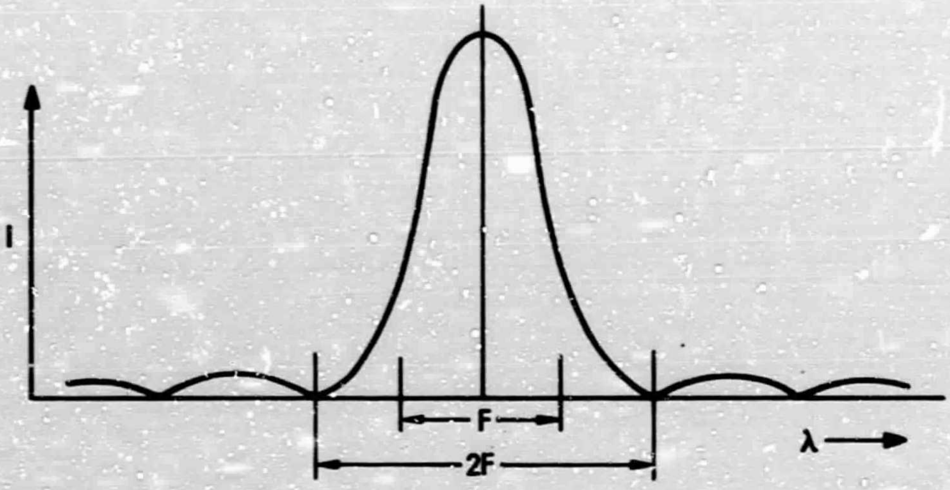
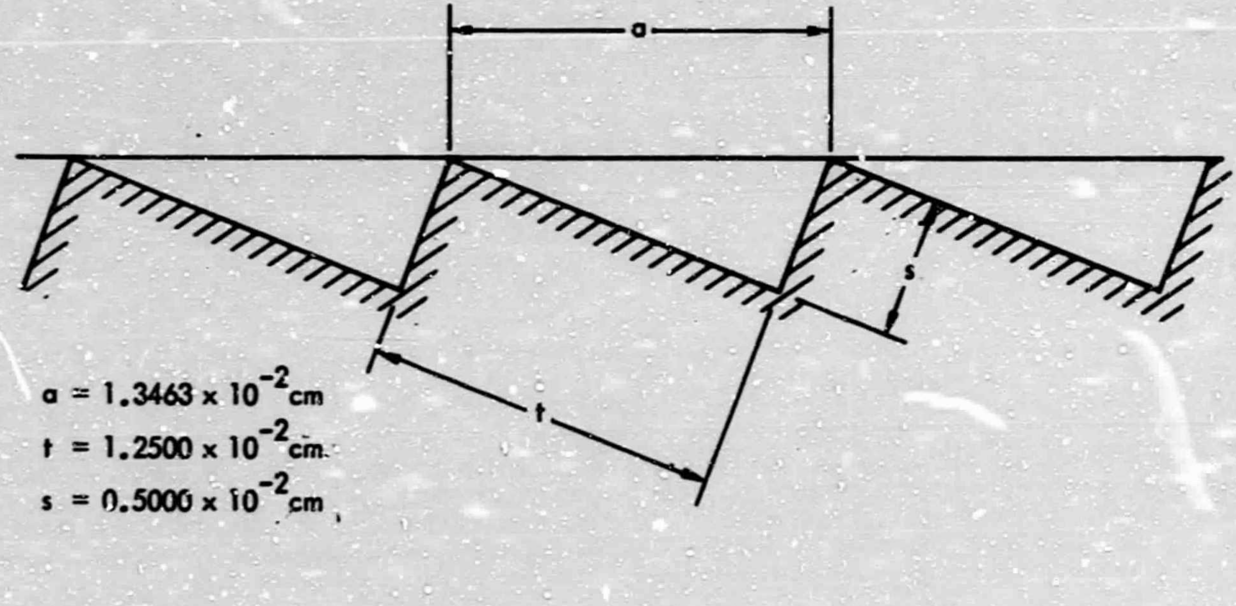


Fig. 5. Intensity vs Wavelength in one Free Spectral Range



$a = 1.3463 \times 10^{-2}$ cm

$t = 1.2500 \times 10^{-2}$ cm

$s = 0.5000 \times 10^{-2}$ cm

Fig. 6. Grating Parameters

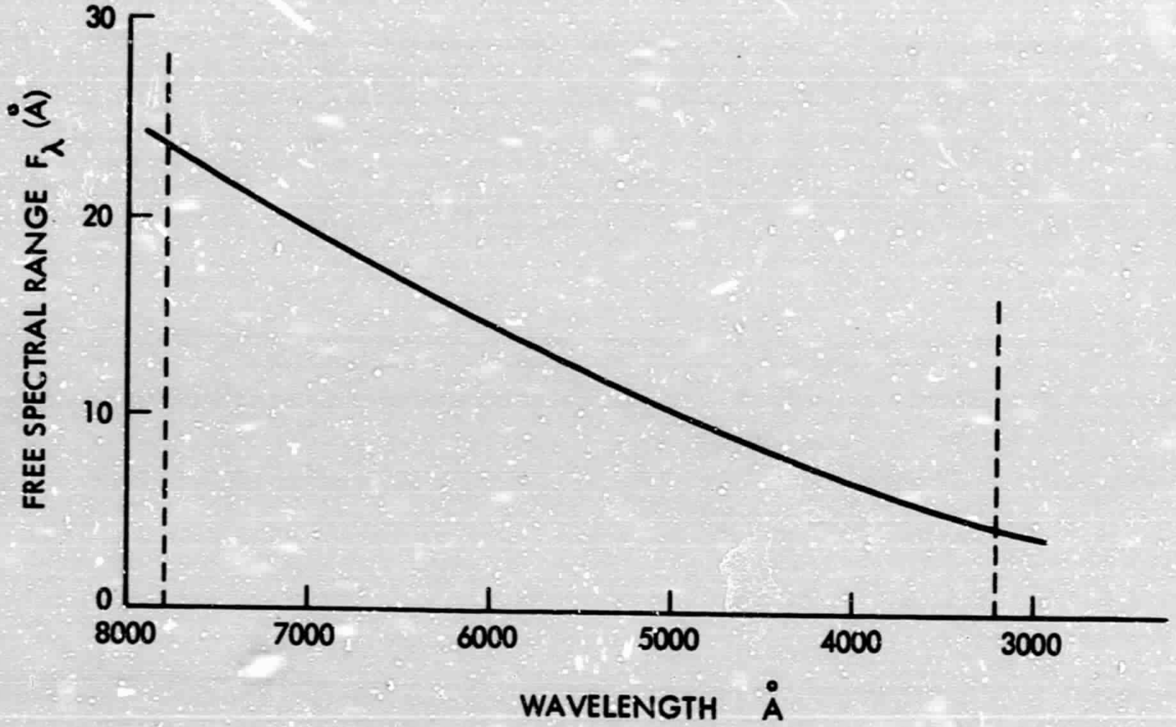


Fig. 7. Free Spectral Range vs Wavelength

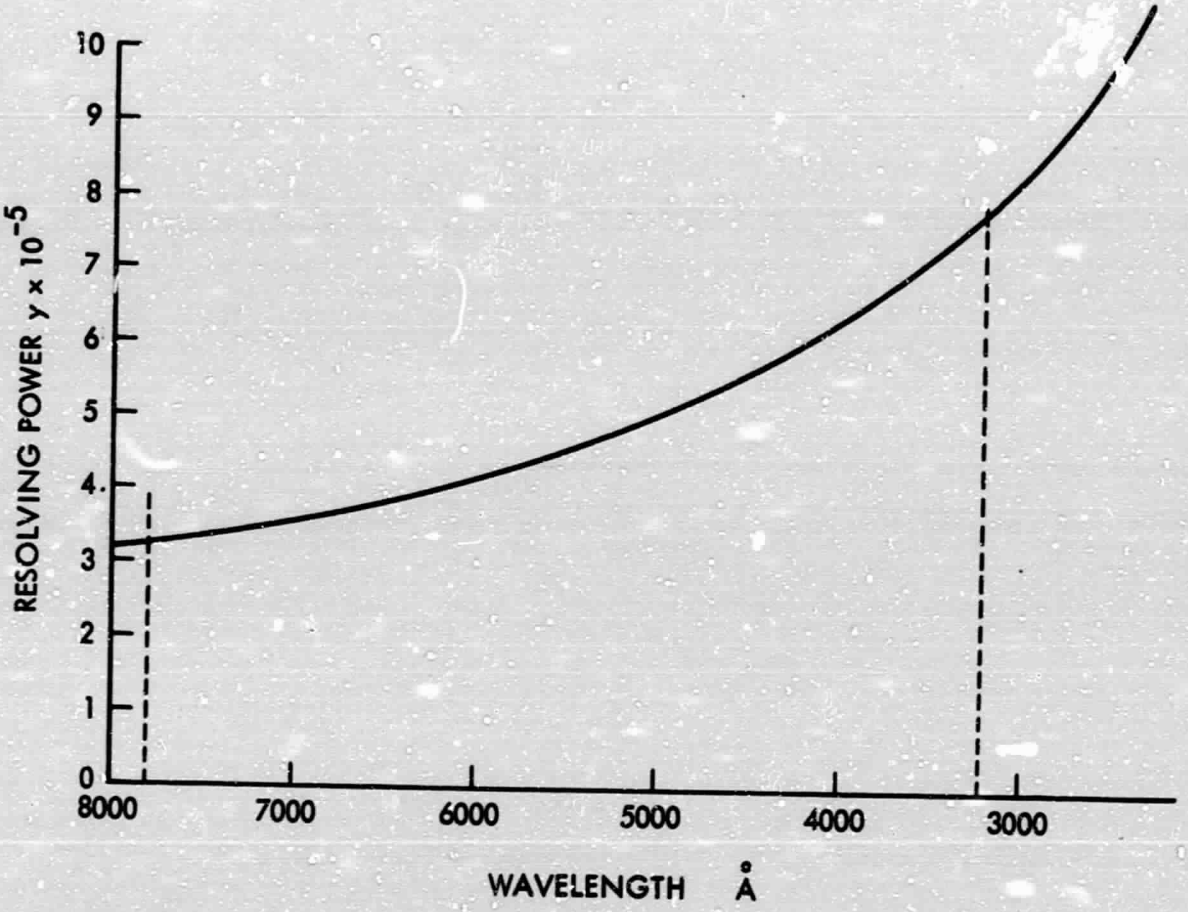


Fig. 8. Resolving Power vs Wavelength

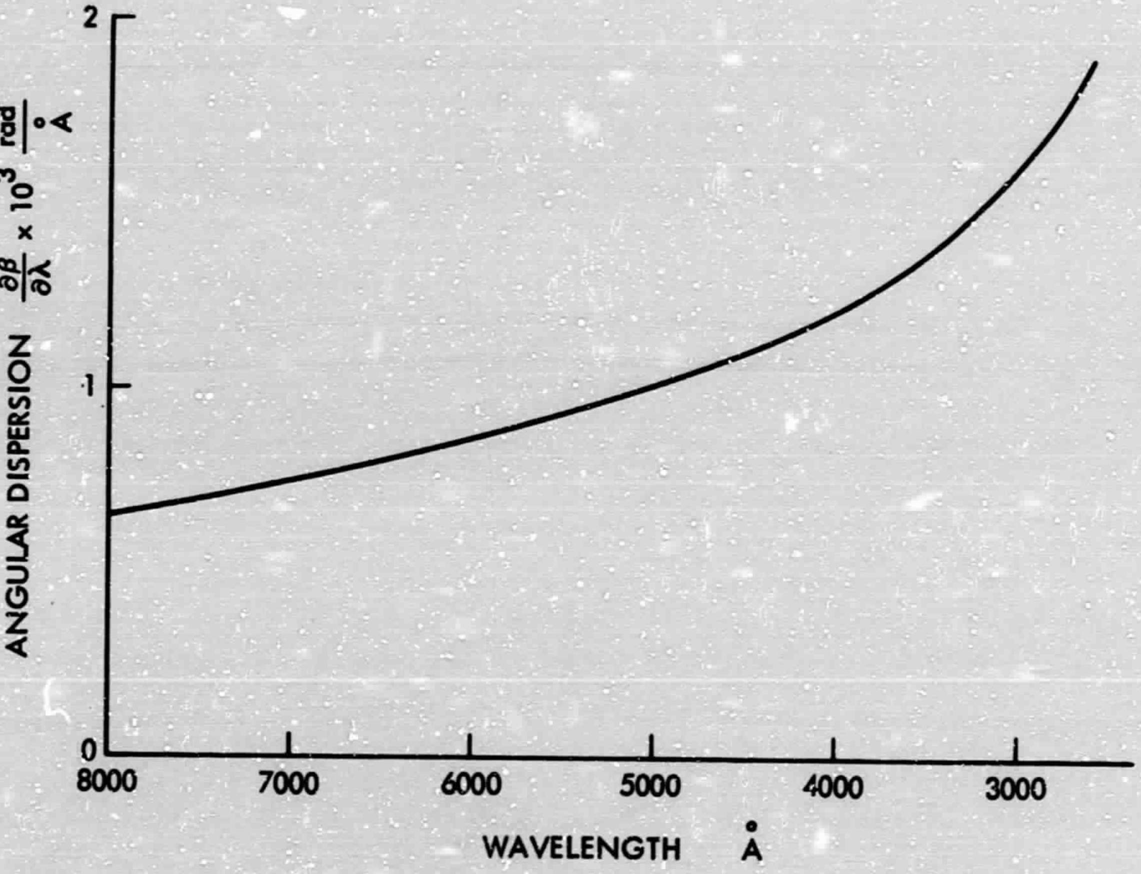


Fig. 9. Angular Dispersion vs Wavelength

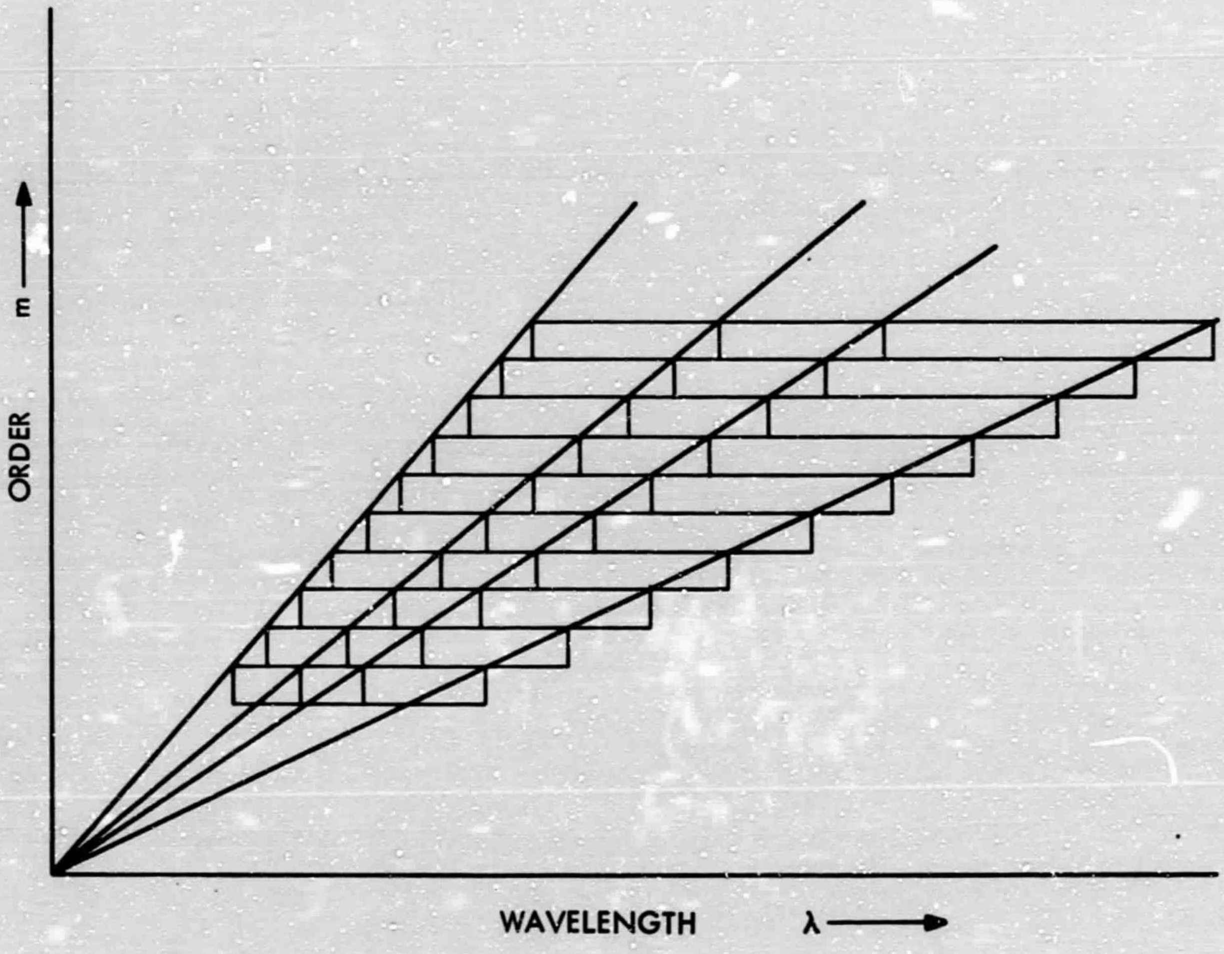


Fig. 10. Spectral Order vs Wavelength Schematic

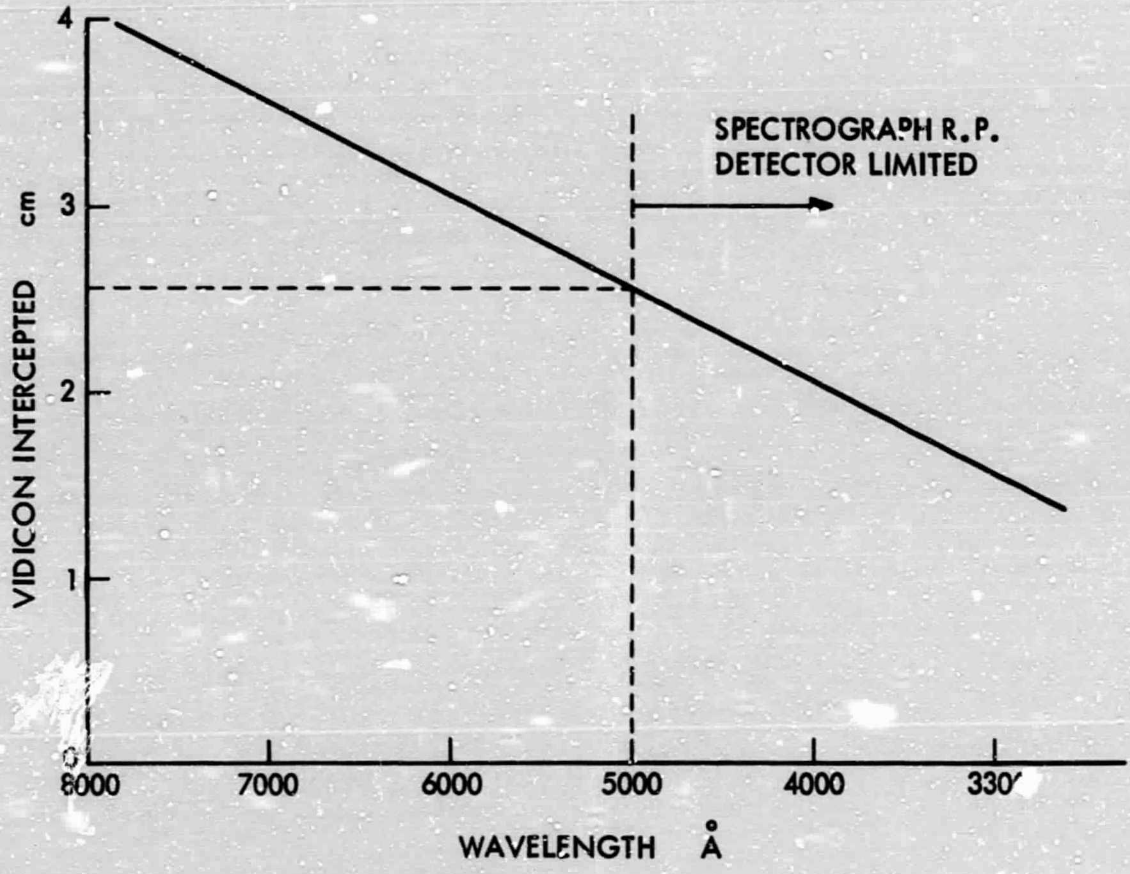


Fig. 11. Length of Spectral Orders at Spectrograph Focal Plane

C. PRELIMINARY CALCULATIONS FOR SLIT SIZE AND EXPOSURE TIMES

Let us assume the same parameters for a hypothetical instrument as were given in the last section, and thereby derive estimates of the slit size and exposure times needed. Let:

F = power reaching detector in ergs/sec

f = camera focal length (choose = 250 cm)

s = slit length

h = slit width

H = length of grating grooves

B_λ = brightness of input spectrum in ergs/cm^2 - sec -(unit wavelength)

$\Delta\lambda$ = wavelength bandwidth (i. e., λ/resolving power.)

T_G = trasmittivity of grating

then F is given by (Stroke 1967)

$$F = k_f \times \frac{1}{f} \times \frac{R.P.}{D} \qquad (9)$$

where

$$k_f = s\,h\,H\,B_\lambda\,\Delta\lambda\,T_G$$

$$R.P. = \text{resolving power} = y \qquad (10)$$

$$D = \text{linear dispersion } (\text{mm}/\mathring{A}).$$

Now

$$D = f\,\frac{\partial\beta}{\partial\rho} = f\,\frac{y}{A}$$

$$\frac{R.P.}{D} = \frac{1}{f\text{ - ratio}} = \frac{1}{50}$$

and thus

$$F \cong s\,h\,H\,B_\lambda\,\Delta\lambda\,T_G \times \frac{1}{50} \times \frac{1}{250\ \text{cm}}$$

Since the flux is a function of λ, exposure time varies somewhat over the λ range. This fact may be useful, however, if several cameras are necessary to record the spectrum. It is noted that F (ergs/sec) is spread over ~ 350 strips assuming the recording format given in part B, and ($B_\lambda\,\Delta\lambda$) is the no. of ergs/cm^2-sec, available at the entrance slit.

$B_\lambda\,\Delta\lambda$ at the focal plane of the photoheliograph has been calculated, and is available in graphical form.

Now suppose the full spatial resolution of the telescope is employed, by choosing the slit width just wide enough to include 0.2 arc sec. This is 3.15×10^{-3} cm at the film plane. Assume the slit length h accepts 1 arc sec (thus $h = 1.58 \times 10^{-2}$ cm) (the power F is easily scaled up or down for different slit heights) and h does not affect the exposure times. H, the length of the grating grooves can be estimated to be approximately 5 cm; this number can be easily scaled up or down. $B_\lambda\,\Delta\lambda$ is given in fig. 1; it must be scaled up by the aperture/image area ratio. We cannot assume T_G to be a fixed number as it varies with wavelength, thus it will be left in as a parameter. In addition to a grating transmission factor, there is a transmission factor, T_p due to other optical elements in the spectrograph such as predispersers, image rotators, collimators, etc. The transmission factor for the entire spectrograph can thus be described by a single factor which includes T_G and depends upon the design of the instrument. We shall call this factor T_s. It is noted that $T_s = T_s(\lambda)$ for a particular instrument, and that T_s is of the order of a few percent. The camera focal length has been chosen to be 250 cm.

Now to get a rough idea of the energy available at the spectrograph camera plane, let us calculate F for $\lambda = 5000\text{Å}$. From (10),

$$k_f \sim (3.15 \times 10^{-3}\ \text{cm})\ (1.58 \times 10^{-2}\ \text{cm})\ (5\ \text{cm})\ (B_\lambda\, \Delta\lambda)\ T_s$$

$$B_\lambda \sim 1.5 \times 10^{6} \times 4.68\ \text{erg/cm}^2\text{-sec-}\mu$$

where the factor 4.68 = intensity ratio due to aperture/image area ratio.

$$\Delta\lambda \sim 0.01\ \text{Å} = 10^{-6}\mu.$$

$$\therefore\ k_f \sim 1.75 \times 10^{-3}\ \text{erg-cm/sec} \times T_s \tag{14}$$

$$F \simeq k_f \times \frac{1}{50} \times \frac{1}{250\ \text{cm}}$$

$$= 1.4 \times 10^{-7}\ \text{erg/sec} \times T_s$$

This energy intercepts the camera focal plane and covers an area $\underline{\alpha}$ determined by D and h, i.e. $\underline{\alpha} \sim \frac{1}{40}$ mm x 0.158 mm, since we have 40 line-pr./mm resolution. Thus

$$\underline{\alpha} \sim 4 \times 10^{-5}\ \text{cm}^2.$$

Hence the flux, $F/\underline{\alpha}$ at λ5000 is

$$\text{Flux} = 0.35 \times 10^{-2}\ T_s\ \text{ergs/cm}^2\text{-sec} \tag{16}$$

The number of erg/cm^2 required by the detector can be roughly estimated to be between 0.1 and 1.0. For a film development to density 1.0, Kodak Hi-speed SO-375 film requires E = 0.19 erg/cm^2; this is roughly comparable to TV energy requirements.

Thus the exposure time can be estimated to be

$$t = \frac{E}{FLUX} = \frac{0.2}{0.35 \times 10^{-2}\ T_s} \text{ sec} \tag{17}$$

and assuming that $T_s = 0.2$,

$$t \sim 5 \text{ min.} \tag{18}$$

This estimate must be considered to be very rough. Thus we can choose $t \sim 10$ min as a reasonable period of time needed to photograph the spectrum, since the brightness drops off at longer and shorter wavelengths (see fig. 1). In Part D the effects of such long exposure times will be evaluated.

The above calculation indicates the need for a short focal-length spectrograph camera, which could be used with film (but not TV) since the linear dispersion decreases somewhat. The long exposure times are caused by the long photoheliograph focal length, and small wavelength bandpass. As will be seen, 10 minute exposure times present very serious problems in image guiding, and also nullify certain scientific goals.

D. ATM COMPATIBILITY - POINTING ACCURACY AND STABILITY CONSTRAINTS

It is seen that the exposure times for small slit widths and high linear dispersion are on the order of several minutes. If we assume that an exposure of the spectrum takes 5 minutes, what constraint does this place on roll, jitter and drift rates of the instrument? The ATM values of these rates are:

Drift:	±2.5 arc sec/15 min	pitch + yaw
	±7.5 arc sec/15 min	roll
Jitter:	±1 arc sec/sec	pitch + yaw
	±1 arc min/sec	roll

The roll motions of the ATM are not too serious, but the pitch and yaw motions for both jitter and drift would completely nullify the aims of the above described spectrograph. A spectrum would be obtained, but it would be a composite spectrum of several granules, and the fine features we wish to examine would be lost by smearing.

Ref (5) describes a "sun sensor" which can detect a 0.1 arc sec/hour pointing stability. It is clear that a mechanism of this sort must be employed to guide the telescope image at the focal plane. This type of guiding has been used before, (Ref 3) and seems to be a functional solution to the guiding problem. Wedges can be inserted in the beam to continuously hold the image on the spectrograph slit, while the motions of the wedges are determined by the output of the sensor. A [illegible]em of this type is therefore described as being necessary for the successful [illegible]ation of the spectrograph.

E. RECORD-DISPLAY SYSTEM NOTES

Certain requirements are placed upon the recording system of the spectrograph, in order that spectra may be taken as quickly as possible. In the sample calculation given above, a rather modest detector resolution has been assumed. It may be possible to obtain higher resolution and good speed, and thus compress the spectrum on the recording device. This will reduce the area of the detector required by reducing the linear dispersion. It would be premature at this point to state actual design requirements, as the data recording system is dependent upon the exact design of the spectrograph optics. Since the exposure times are long compared to the times between telescope camera exposures (~10 sec) the spectrograph must probably be operated intermittently in order not to cut down on the light entering the spectrograph, when the telescope cameras are not in operation.

The long exposure times seriously impair the time development stuides of spectral features which develop rapidly. Flares, however, have a much higher brightness than the disk, and it may be possible to roughly time resolve the later phases of the flare; approximately steady state phenomena are not affected by long exposure times.

The long exposure times quoted in Section C have one further important effect upon the performance of the spectrograph. If we assume an orbit of the spacecraft which is in the orbital plane of the earth around the sun, the doppler shift of frequencies becomes great enough to smear all wavelengths in the spectrograph if an integrating recording system is used.

Assuming a typical spacecraft orbit, the doppler shift in wavelength at 5000Å is about 0.15Å. Since the spacecraft changes its velocity component parallel to the earth-sun line continuously, the wavelengths at the spectrograph focal plane will shift continuously. Even at those points in the orbit where the velocity is changing slowest with time, the smearing of wavelengths may be two orders of magnitude too great, for an exposure time of 10 minutes. Preliminary calculations show that for one minute exposure times at optimum positions in certain orbits, it may be possible to reduce wavelength smearing sufficiently.

Several possible alternatives remain to be considered: The echelle configuration could be retained, and the possibility of faster (intensifier) vidicons investigated. In addition, certain spacecraft orbits might have to be specified for spectrographic work, as would the spacecraft positions in those orbits, so that the velocity component of the spectrograph parallel to the earth-sun line could be kept as constant as possible. Another approach would be to abandon the integrating spectrograph configuration in favor of a spectrometer, in which the data output could be manipulated electronically to reproduce the true solar spectrum.

Perhaps the optimum approach would be to restrict the wavelength range of the spectrograph, and make the grating rotatable, or the focal plane translatable. The shift at the focal plane for a doppler shift $\delta\lambda$ is given by

$$f\frac{\partial\beta}{\partial\lambda}\,\delta\lambda = \frac{f}{A} \times \frac{2Nt}{\lambda} \times \lambda\frac{\nu}{c}\,,$$

which is independent of wavelength.

Thus several problems (slit length, display format) would be solved by sacrificing some mechanical simplicity and some spectral information.

This approach will be described in greater detail in later papers. At this point it is concluded that the problems inherent in the design of an orbiting spectrograph will need careful study to determine which "requirements" (scientific or otherwise) will have to be relaxed.

REFERENCES

1. Bray, R. J. and Loughhead, R. E., 1967 The Solar Granulation (London: Chapman and Hail).
2. Harrison, G. R., 1949, J. O. S. A. 39, 522
3. Kiepenheuer, K. O., and Mehltretter, J. P., 1964, Applied Optics 3, 1359.
4. Stroke, G. W., 1967, Handbuch der Physik, Vol. XXIX, 426.
5. Wilson, J. A., Kollodge, J. C. 1967, "Fine Accuracy Sun Sensor" (Honeywell)
6. Wood, R. W., 1947, J. O. S. A. 37, 733