A RAPID SCANNING LOW NOISE SPECTROMETER FOR STUDY OF SUNSPOT SPECTRA

D. E. Blackwell, E. A. Mallia and A. D. Petford

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SUMMARY

A rapid scanning high resolution photoelectric spectrometer designed for the study of sunspot spectra is described. The spectrometer employs an on-line computer for signal integration, and to reject scans that are contaminated by false light due to ‘seeing’. The apparatus is installed at the Gornergrat, Switzerland, at a height of 3090 metres. An example of its performance is given.

1. INTRODUCTION

It has been clear for several years that photoelectric scanning of solar spectra (1–7), and indeed of the spectra of other astronomical bodies also, offers considerable advantages over the more conventional photographic technique. Apart from the obvious convenience of linearity of output, the chief advantage is that with a suitable data recording system it is possible to integrate the output of a spectrometer over indefinitely long periods of time and thus to continue to improve the signal to noise ratio of the observed spectrum. As has been commented elsewhere (1), noise levels as low as 0.007 per cent may be obtained in this way in the solar spectrum at an effective scanning rate (which is not necessarily an actual instantaneous scanning rate) of about 1 Å h⁻¹, and using a slit width of \( \Delta \lambda / \Delta \lambda = 2 \times 10^5 \). If longer integration times \( T \) were to be used there is no doubt that these low noise levels could be further improved.

It is important to be able to apply a photoelectric technique to similar studies of the spectra of sunspots. However, the irregular fluctuations in the focus position, and of the form and position of the spot image, that are due to ‘seeing’ make this a peculiarly difficult problem, for not only is the light that is received from the observed part of the sunspot umbra fluctuating irregularly, but seeing also introduces into the umbral light a varying proportion of spurious light from the surrounding photosphere. Of course, there will also be a substantial contribution to the spurious light from longer range scattering of photospheric light by the Earth’s atmosphere and by the image forming system, but this is common to both photographic and photoelectric systems and will not be considered here. In the present system this former difficulty has been overcome by use of a rapid scanning technique. Moreover, it is shown that the use of a small on-line computer offers substantial advantages over a simple data storage system. We also consider in this paper a method by which the efficiency of a scanning system, which is normally very wasteful of energy, can be improved.

2. THE SPECTROMETER

The technique of rapid scanning is not a new one and it has been extensively used in laboratory spectroscopy (8). It has also been used in investigations of the
spectrum of the solar disk by Lynds (5, 6), and by Croce & Biase (7). Livingston (9)
has considered various designs of optical system for rapid scanning. In deciding
upon our own design of spectrometer for the study of sunspot spectra we have laid
particular emphasis upon the requirements of (a) linearity of scanning motion, (b)
little or no loss of observing time (that is, 'dead space') between scans, such as
might be caused, for example, by use of a single rotating mirror to effect the scan,
and (c) smoothness of the scanning motion.

In our system, the scanning is accomplished by means of a rotating drum to the
periphery of which are attached a large number of equally spaced slits, as in a
zoetrope. This method was adopted because, when the rotating mechanism is well
made, it may be expected to give a smooth scan: also, it offers the possibility of
having several slits scanning the spectrum at one time. It has the disadvantage that
the width of the scanning slits cannot readily be changed and that the scanning slits
are not constrained to move along the focal plane: however, with good design this
latter need not be a serious defect. In the following elementary discussion we
consider the factors that limit the length of scan and show that the size of the drum is
the predominant one.

In a Littrow optical system, let the grating be of width \( D \), and the focal length of
the spectrometer be \( F \). Suppose that when the exit slit of the spectrometer is a
distance \( d \) away from the focal plane of the 'camera' mirror, there is produced a
lateral aberration of amount \( a \), given by

\[
a = d \times D/F.
\]

Taking the dispersion of the spectrometer to be given by

\[
d\lambda/ds = k/F
\]

where \( ds \) is measured along the spectrum, the aberration \( a \) expressed as a wavelength
interval \( \delta \lambda \) is given by

\[
\delta \lambda = D \times d \times k / F^2 = kDd/F^2.
\]

Over a total scan length of \( l \) a slit will move a total distance along the axis of the
spectrometer equal to \( l^2/8R \), where \( R \) is the radius of the drum, so that the maximum
deviation from the focal plane \( d \) is given by

\[
d = l^2/16R.
\]

The corresponding maximum aberration is given by

\[
\delta \lambda = kDl^2/16RF^2.
\]

If, therefore, we wish to limit the maximum aberration to an amount \( \delta \lambda \), the
maximum permitted length of scan is given by

\[
l = 4F \sqrt{R \delta \lambda / kD}.
\]

Using the dispersion relation, this corresponds to a maximum length of scan,
expressed in wavelength units, given by

\[
\Delta \lambda = 4 \sqrt{Rk \delta \lambda / D}.
\]
Suppose now that the slit width used is $W_\lambda$, in wavelength units, and that we do not wish the resolution to change over the length of one scan by more than a factor $p$, where $p$ might typically be $0.1$.

Then

$$\delta \lambda = p \times W_\lambda$$

and

$$\Delta \lambda = 4 \sqrt{\frac{RkW_\lambda p}{D}}.$$ 

An important feature of interest is the number of resolution elements available to the spectrometer during one scan: this is given by

$$N = \frac{\Delta \lambda}{W_\lambda} = 4 \frac{\sqrt{Rk}}{D}.$$ 

This relation shows that the applicability of the technique depends upon the grating having a large angular dispersion, which is given by the quantity $k$. It is, therefore, particularly adapted for the use of an echelle grating because such a grating is used at a large angle of incidence. It is also especially useful for high resolution work, where $W_\lambda$, the slit width in wavelength units, is small. The diameter of the drum should be as large as possible. Further, although the focal length of the spectrometer is not a factor in the expression, it should be as long as convenient because in this way the use of very narrow scanning slits is avoided. The relations for $\Delta \lambda$ and $N$ will give the correct order of magnitude for these quantities, but the true performance will be rather better than is indicated by these expressions because the out-of-focus aberration will not be quite equal to the calculated quantity $\delta \lambda$. Such a modified calculation indicates that a scan length of 8 Å can be obtained with a drum diameter of 45 cm at a maximum resolving power of 220 000 which is degraded to a minimum of 180 000 because of the curvature of the scanning arc.

3. TELESCOPE AND SPECTROMETER DESIGN

The whole installation of coelostat and spectrometer is situated in the north tower of the Kulm Hotel of the Zermatt Gemeinde, which stands on the Gornergrat in Switzerland at a height of 3090 m. The top of the tower contains a polar coelostat of diameter 40 cm which, in conjunction with a secondary mirror and an off-axis paraboloid of focal length 16.1 m gives a solar image of diameter approximately 14 cm in the basement below the tower. All mirrors are of fused silica. This solar image is focused on a table at a height of about 1 m above the floor of the spectrometer room: a small hole or slit in the table defines the area of the solar image being used. Before the light reaches this hole about 6 per cent of it is reflected to one side by a beam splitter and a subsidiary image of a spot formed, which is subsequently used for photoelectric guiding. The guider consists of a rotating blade which gives error signals in right ascension and declination: these are used to tilt the primary mirror in its cell, to correct in declination, and to change the speed of a stepping motor that drives the coelostat in right ascension. Apart from its use in correcting errors of drive in right ascension, such a guider is essential to the operation of the apparatus because, since the Sun moves in declination at speeds of up to 1 sec arc per min, during a 15 minute integration time a spot umbra may easily move over a distance that is greater than its diameter.
Light from the entrance aperture is fed into a monochromator which uses a Littrow prism of fused silica and off-axis mirrors. The spectrum formed by the monochromator is then focused on to the entrance slit of the main spectrometer. The optical system of the main spectrometer uses two off-axis mirrors of focal length 600 cm and incorporates a 25 cm Bausch and Lomb echelle grating of 300 lines mm$^{-1}$ which gives a dispersion of 5.3 mm Å$^{-1}$ at 5000 Å. The spectrum is scanned using a drum of diameter 45 cm around the periphery of which are mounted 28 slits each of width 0.09 mm. The drum is rotated smoothly by a synchronous motor at a speed of 0.45 rev s$^{-1}$, which gives a scanning rate of 134 Å s$^{-1}$ in the spectrum at 5000 Å: thus the spectra are scanned at the rate of 12.5 spectra s$^{-1}$, i.e. each one is scanned in a time of 80 millisecond, during which time either 720 individual elements, or up to three times this number, are scanned. In the usual mode of operation a single lens is mounted inside the drum behind the slits, which focuses, via an inclined mirror, an image of the grating on to the cathode of an E.M.I. photomultiplier of type 9558. A mirror can be placed in front of the scanning slits so that the spectrum can be viewed on a ground glass screen before it is scanned.

When a slit reaches the beginning of its useful scan, one end of it passes through a narrowly collimated light beam and produces a pulse in the output of a photocell. This pulse, which we call the A-pulse, is used to initiate data collection by a Digital Equipment Company PDP-8 data processor. The photomultiplier behind the slits feeds an amplifier and thence a voltage/frequency converter which has a maximum output frequency of 5 MHz. On receipt of an A-pulse, samples of the output of the voltage/frequency converter lasting 70 μs are taken every 80 μs, the extra 10 μs being needed for transferring the sample to the store. These samples are then transferred to successive addresses in a buffer in the computer until the correct number have been stored: the system is then made ready for the next A-pulse. At the end of a scan, a decision may be taken whether or not it should be included in an integrated scan. When scanning the spectrum of the solar disk, all scans are usually included. However, when the spectrum of a spot umbra is scanned, a particular scan is rejected if the sum of the intensities of all the elements in it is greater than a pre-set amount. It is possible in this way to reject scans of spectra that contain more than a predetermined proportion of spurious photospheric light. Similarly, when scanning the spectrum of the penumbra it is, in addition, possible to reject scans that contain more than a predetermined proportion of spurious umbral light by arranging for the sum of the intensities to be greater than a preset limit. In studies of sunspot spectra the amount of spurious light produced by long range scattering from the disc is determined by making a drift scan across the solar limb: when doing this, the drum is stopped and a slot in it is used to isolate a narrow band that is approximately 1 Å wide in the middle of the spectrum region that has been scanned.

The method of scanning described here is evidently very wasteful of energy, for in it each element of the spectrum is examined separately. However, the spectrometer can be used in another mode which uses two photomultipliers, each one receiving energy from its own slit in one half of the spectrum. In this mode, the single lens behind the slits is replaced by two lenses of half the width, which are also prismatic, so that light from each half of the spectrum is directed on to its own photomultiplier. The number of scanning slits on the drum is doubled and two A-pulse generators are fitted, one at the beginning of each half-length of spectrum. This procedure doubles the available energy (and also the frequency at which spectra are
Plate I. Finding charts for the identifications (marked between the bars). Scale is 15" arc mm⁻¹. North-east is at the top left-hand corner of each chart.
scanned) and, therefore, halves the time needed to reach a certain signal to noise ratio. In principle, it could be extended to any number of channels providing sufficient storage capacity is available in the computer. In both modes, the output of the spectrometer is presented on an oscilloscope screen which displays the integrated spectrum at any time, and is finally printed out on a Teletype, and a paper tape punched, when a satisfactory noise level has been reached.

The speed of scan was chosen in an arbitrary manner, bearing in mind the characteristics of the PDP-8 computer and making a reasonable estimate of the frequency spectrum of solar seeing. The performance of the spectrometer shows that the choice of speed is a satisfactory one, and indeed had the results of the excellent work of Brandt (10) on solar image motion been obtained when the instrument was designed we should not have changed the frequency.

4. TECHNICAL DETAILS

One difficulty in the construction of such a spectrometer is that a large number of accurately parallel sided slits are needed, each having the same width to within a precision of perhaps 5 per cent. The slits were successfully made for the spectrometer most skillfully by Mr C. W. Band of the Clarendon Laboratory, Oxford, using a photographic etching process: those slits actually used were selected from many times the number required, and their widths were well within the permissible spread.

A further difficulty has been to get the drum to rotate smoothly, the total error at each instant being required to be less than a small fraction of a slit width. After experimenting with different devices, the drum was finally driven against its periphery through an idler wheel running on the shaft of a synchronous motor. This method produced a sufficiently smooth drive.

5. PERFORMANCE

Apart from the noise level, which is determined by the detector, the most important parameter is the optical and mechanical stability of the spectrometer. If, for example, there is any drift of the spectrum in wavelength with time, or if the speed of the drum is fluctuating, then repeated scans will not superimpose exactly on each other and there will be a loss of resolution. The ultimate test of this is the profile of a laser line: this will be considered in another publication but the results that will be presented there demonstrate that malfunctions of the kind mentioned above produce a negligible widening of the instrumental profile.

The performance on disc and sunspot spectra is demonstrated by Fig. 1 which shows a scan of the spectrum of a spot umbra (a) in the wavelength region 5160 Å, using an aperture of 2 sec arc, and a corresponding disc spectrum obtained at a distance of about 1 min arc from the spot. Under these conditions it is possible to obtain a signal to noise ratio of 0.5 per cent in a time of about 4 min on the disc, and in a time of about 6 min on the umbra of a sunspot. A convenient feature of this technique is that the procedure for correcting the observed spot spectrum for scattered light is very easy numerically once the relative proportions of scattered light and umbral light are known because it involves only manipulating the numbers in the corresponding cells. For the purpose of this demonstration we have made an estimate of the proportion of scattered light within the spot umbra by making scans
of the Fe II line at 5197.576 Å and supposing that this line is completely absent in the true umbral spectrum. Part (c) of this diagram shows the spectrum (a) corrected for false light in this way, supposing that the false light originates in the photosphere.

In practice, this procedure is not necessarily an accurate one because much of the false light in the umbra is presumably of penumbral origin and, therefore, may have a quite different spectrum. This matter will be examined in subsequent papers.
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Department of Astrophysics, University Observatory, South Parks Road, Oxford.

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