3D Optical Spectroscopic Methods in Astronomy
ASP Conference Series, Vol. 71, 1995
G. Comte, M. Marcelin, eds.

Solar Imaging Spectroscopy: Multichannel Subtractive Double Pass Instruments

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Abstract. Several MSDP instruments are used in solar physics to observe simultaneously 2D-fields in a number of wavelengths.

We describe briefly the needs of 3D-data in solar physics, the different spectroscopic methods in use, and the principle of MSDP spectrographs. We discuss the relationships between spectral resolution, field of view and efficiency. We summarize the capabilities of the instruments, either presently working (Meudon, Pic du Midi, Tenerife and Wroclaw), or associated with the THEMIS project.

The solar results take into account the main performances of the MSDP, that is to say the very high spatial resolution and the high speed to cover a wide area on the sun within a short time (coordinated campaigns with space probes).

We conclude by a brief discussion of the capabilities which could be expected from the MSDP in night-time astronomy.

1. 3D-Spectroscopy in Solar Physics

The physical quantities that are needed to modelize the solar plasma (temperature, density, pressure, velocity, magnetic field,...) are most often derived from spectral line profiles. They depend on the 3 space coordinates x, y, z (and also on the time t). To some extent, different spectral lines (strong/weak), and also the profiles of strong lines (core/wings) provide information about the vertical structure of the solar atmosphere (that is to say versus z). So, time series of 3D spectral data (x, y, λ) are necessary to modelize these physical quantities versus x, y, z. Moreover, many fundamental physical mechanisms of the solar atmosphere (heating, wave propagation,...) are localized in very small structures, which are not easily tracked with slit-spectrographs. The 3D spectrocopy is the only way to progress in the analysis of such mechanisms.

Many kinds of spectroscopy are performed in solar physics. For some of them, the table (I) gives an estimate of the best resolving power, the variables which are observed simultaneously, and those which are sampled by scanning.

https://doi.org/10.1017/S0252921100023307 Published online by Cambridge University Press

Instrument	Resolving Power	Simultaneous	Scanning
Spectrograph	600000	x, λ	y
FTS	2000000		x, y, λ
Filter (UBF)	40000	x, y	λ
Filter (UBF+FP)	250000	x, y	λ
MSDP	100000 (250000)	x, y, λ	

Table I: Solar spectroscopy techniques: best spectral resolving power (orders of magnitude), variables observed simultaneously and successively.

The highest resolving power is obtained by the Fourier Transform Spectrometer, but so far this technique is not generally used for imaging spectroscopy in solar physics. Long spectrographs allow also high spectral resolutions, but 3D spectroscopy is generally restored by scanning along one coordinate, although slicers or multiple slits are sometimes used to obtain simultaneous spectra in 2D fields. The Universal Birefringent Filters, with or without Fabry-Pérot, can provide high space resolution for instantaneous images. But the fast fluctuations of seeing distortions imply destretching techniques to get rid of smearing effects (as far as possible) if spectroscopy is needed.

The MSDP is really a 3D-spectroscopy method. It provides a series of 2D images in several wavelengths simultaneously. The spatial resolution is very high, because it is not degraded by any slit, and because the seeing effects are the same in all the channels. But the spectral resolution is moderate ($\sim$ 100000), and the number of channels is limited (typically 10 or 20). However, the resolution will be improved in the near future ($\sim$ 250000), with an increase of the channel number (30 or 60) in the THEMIS instrument.

2. MSDP Spectrographs

2.1. Optical layout

Solar imaging spectroscopy was proposed many years ago by the use of subtractive double monochromators (Öhman 1950). The Capri *Chromatograph* (Stenflo 1968,1973) and the Meudon *Double Pass Spectrograph* (Mein et al. 1972) followed similar optical schemes. But the scanning necessary to restore a full line profile was still degrading the spatial resolution for 3D spectroscopy.

The *Multichannel Subtractive Double Pass* (MSDP) was built in Meudon (Mein 1977) to solve this difficulty. The principle is shown on figure 1. A rectangular field stop (FS) is put at the entrance of the spectrograph, instead of a slit. A spectrum (convoluted with the field of view) is formed in (S). A series of N parallel slits selects the wavelengths, and is followed by N prisms translating the beams with different shifts ("beamshifter" BS). After a second pass on the grating (G), the dispersion is cancelled, and N images of the field of view are obtained on the detector (D). The processing of the N images provides N points of the spectrum in each point of the field of view.

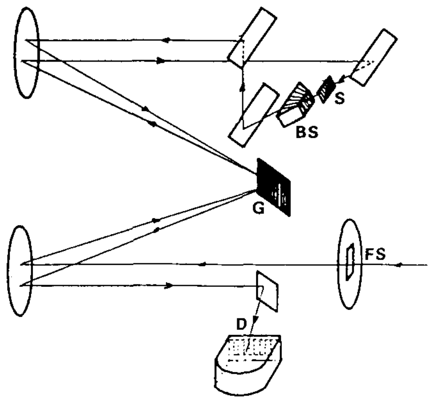

Figure 1. Optical layout of a typical MSDP spectrograph: multiple slit selecting N wavelengths in the spectrum (S) and prisms shifting the beams (BS), second pass on the grating (G) cancelling the dispersion, N images formed simultaneously on the detector (D).

2.2. Specific optical schemes

The structures of the MSDP instruments depend on the spectrographs. When the collimator mirror is large enough, it can be interesting to feed the grating for the second pass, not through the camera mirror, but through the collimator. This layout is used at Pic-du-Midi (Mouradian et al. 1981, Mein 1981) and Wroclaw (Rompolt et al. 1994). It allows to keep the detectors at the same place as in single-pass spectroscopy, after the camera mirror.

The best solution consists in using two spectrographs successively. The scattered light is reduced, mainly because the illumination of the grating by the first pass (usually eliminated by wide-band filtering) is suppressed. In the THEMIS instrument, the very long predisperser allows such a layout (Rayrole et al. 1993).

2.3. High spatial resolution

The MSDP spectrographs do not degrade the image quality of the telescope, whatever the widths of the slits are (which is not the case in single-pass spectroscopy). Moreover, the widths of the slits, and consequently the photon flux, can be optimized for each spectral line, so that the MSDP provide the highest speed and the shortest exposure time (the best spatial resolution) compatible with the desired spectral resolution. Taking into account this specific capability, it was promising to build such instruments in very good sites, to still increase the resolution. One MSDP was attached to the refractor of the turret dome at Pic du Midi and an other one to the german VTT telescope of the Canary Island Observatory at Tenerife (Mein 1991).

2.4. Simultaneous MSDP images in several spectral ranges

In the latter case, the available space at the focus of the spectrograph allows to observe simultaneously two spectral ranges (two line profiles). The figure (2) shows the same field of view on the solar disk (approximately $220 \times 30 arcsec$) across the profiles of the H_α line and the NaD_1 line, observed with 70mm film. In each case N=9. Presently, this MSDP is equipped with 2 CCD 1024×1024.

2.5. Field of view, spectral domain and channel number

It can be easily seen, from the location of line profiles in the channels, that the wavelength is increasing from one channel to the next one, and also inside each channel from one edge to the other one. The figure (3 $left$) shows the two "data cubes" observed simultaneously in the 3 coordinates x (parallel to the dispersion of the spectrograph), y (perpendicular) and λ (wavelength). The planes xy and $x\lambda$ would correspond respectively to the observations with narrow-band filters and single-pass spectroscopy.

The figure (3 $right$) presents the projection of a data cube on the plane $y\lambda$, in the case of a 28-channel MSDP (THEMIS project).

If N is the number of channels, if $\delta\lambda$ is the shift between successive channels (spectral resolution) and if $\partial\lambda/\partial y$ specifies the dispersion of the spectrograph (Å/ arcsec), the fields $\Delta\lambda$ and Δy over λ and y are bound by the relationship

$$N\delta\lambda \leq \Delta\lambda + \Delta y \partial\lambda/\partial y \qquad (1)$$

The field Δx over x is simply the width of the spectrum accepted by the spectrograph in single-pass mode.

2.6. Software

The data consist generally in a great number of cubes (number of lines $\times$ number of elementary fields of view $\times$ number of times). They are processed with existing codes according to 3 successive steps:

1 - The geometry of the channels is defined accurately (distortions taken into account if necessary)

2 - The calibration is derived from images out of focus of the solar disk

3 - The line profiles are restored and analysed. This part includes the modelling using theoretical results of radiative transfer, according to the kinds of lines and structures under study. Doppler maps are often computed across the full field of view.

Details about the data processing can be found in Mein (1991) and Roudier et al. (1991).

3. Capabilities of MSDP Spectrographs

3.1. Instrumental constraints

The main limitation concerning the spectral resolution is due to the "beam-shifters" which translate the beams after the multiple slit, before the second pass on the grating. Many kinds of beamshifters are used (see Mein 1991). Figure (4)

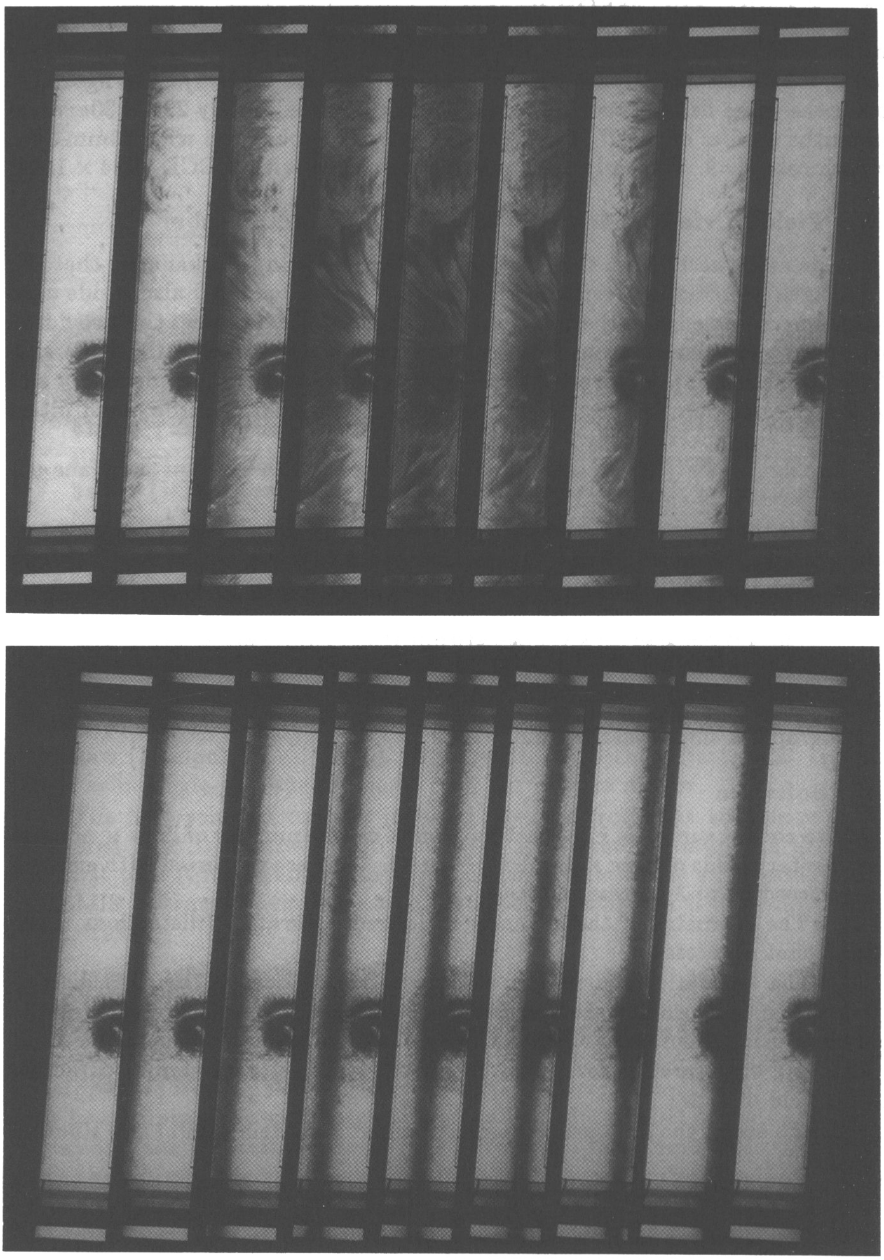

Figure 2. Example of simultaneous MSDP images obtained across the H_α line and the NaD_1 line with the german VTT telescope (Canary Island Observatory).

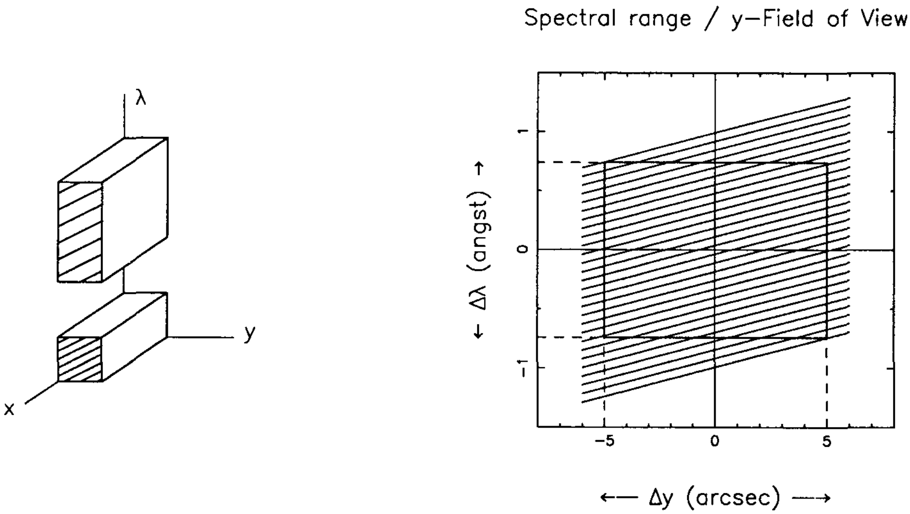

Figure 3. (*left*) Two ***data cubes*** observed simultaneously and covering two line profiles with two different spectral resolutions. (*right*) Projection of a MSDP data cube on the plane $y\lambda$.

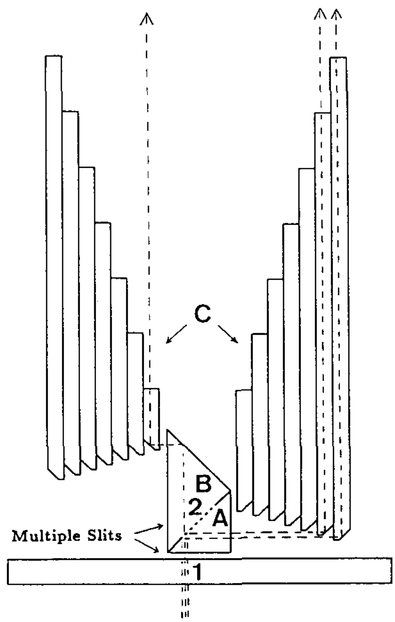

Figure 4. "Beamshifter" for the MSDP attached to THEMIS. The wavelengths are selected by 2 successive multiple slits. The lengths of the prisms compensate the differences between virtual foci.

https://doi.org/10.1017/S0252921100023307 Published online by Cambridge University Press

shows the scheme of the beamshifters under construction for THEMIS, which are expected to produce the best spectral resolution.

A first multiple slit (1) is followed by a second one (2) with a double step, inserted between two prisms A and B. This second multiple slits reflects the odd beams, while the even beams are passing through it. Compared to the case of one multiple slit only, this improves the spectral resolution by a factor 2. The different lengths of the prisms C are adjusted so as to compensate the differences between the foci of the beams.

The step of the first slit defines the smallest resolved spectral element $\delta\lambda$. The maximum distance d between the first slit and the edges of the prisms is roughly proportional to the number N of channels ($d \simeq aN$). The coefficient a is close to the width of prisms C, divided by 4 (factor 2 due to the double multiple slit $\times$ factor 2 because of left and right parts of the beamshifter). In the THEMIS project, an additional factor 2 will be obtained by using one beamsplitter (50%/50%) and two beamshifters per line. If the width of prisms C is 2.5mm, this leads to $a \sim 0.3mm$.

The beams are not mixed before entering the prisms C on the condition that the step of the multiple slit is greater than this distance d $\times$ the aperture of the spectrograph (the pupil is supposed to be at infinity). If we call R the spectral resolving power $\lambda/\delta\lambda$, f the focal length of the camera mirror, D the diameter of the pupil on the grating, and B the blaze angle, this can be written

$$N \leq 2f^2 tgB/(aDR) \tag{2}$$

We shall not discuss here other constraints, which can differ according to the kind of beamshifter involved in the MSDP (in the special case of figure 4, devoted to high spectral resolution, the width of the prisms C may also limit the field of view).

3.2. Spectral Domain and Field of View versus Spectral Resolving Power

Let us assume that, in equation (1), we choose the couple $\Delta\lambda, \Delta y$ so that both terms are equal (this gives a good order of magnitude in all cases). From (1) and (2), we derive

$$\Delta\lambda/\lambda = 0.5N/R \leq (tgB/a) \times f^2/(DR^2) \tag{3}$$
$$\Delta y = 0.5N\delta\lambda(\partial y/\partial\lambda) \leq 2\alpha(tg^2B/a) \times f^2/(\Phi R^2) \tag{4}$$

where Φ is the diameter of the telescope, and $\alpha = 180 \times 3600/\pi$.

We see that we increase the capabilities of the MSDP by using gratings with large blaze angle B and cameras mirrors with long focal lengths f. Moreover, the pupil on the grating D must be small (on the condition that the diffraction limit is not reached for the expected spectral resolution). If necessary, this condition can be easily fulfilled by an enlargement device put at the entrance of the spectrograph (Wroclaw MSDP).

In the present MSDP (Meudon, Pic du Midi, VTT, Wroclaw), the capabilities can be characterized by $10^4 < R < 10^5$, $N \simeq 10$ per line, $0.25 < \Delta\lambda < 1.5\mathring{A}$, $90 < \Delta x < 400 arcsec$, $6 < \Delta y < 60 arcsec$.

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3.3. Efficiency

To estimate the efficiency in double-pass mode E_{DP}, we can start from the efficiency of a single-pass spectrograph E_{SP}. If R_{SP} and R_{DP} are respectively the spectral resolving powers in single pass and double pass, we can write

$$E_{DP} = E_{SP} \times E_G \times E_T \times E_S \times R_{SP}/R_{DP}$$

where E_G is the efficiency of the grating ($\simeq 0.7$), E_T the efficiency of the transfer optics (mirrors, prisms and filter, $\simeq 0.6$), and E_S the efficiency of the multiple slit ($\simeq 0.5$). So, a rough estimate is $E_{DP} \simeq 0.2 \times E_{SP} \times R_{SP}/R_{DP}$.

In fact, since the width of the multiple slit can be adjusted to the strength of the lines under study (without spoiling the spatial resolution), the ratio R_{SP}/R_{DP} is generally greater than 5, so that the MSDP provide generally shorter integration times than single-pass spectroscopy.

4. Solar Results

It is not possible to mention all the results of MSDP observations, since 1977. They can be classified according to 3 items, corresponding to specific capabilities:

- High spatial resolution: dynamical analysis of fine structures in filaments and prominences , quiet chromosphere, spots, granulation (penetration in upper layers, correlation with pressure waves...)

- High speed spectroscopy: fast 2D events (velocity fields in mass ejections, flares and post-flare loops, fast motions preceding flares...)

- Coordinated campaigns, in particular with space probes: many dynamical events have been observed simultaneously in the visible, UV, EUV and X ranges. 3D data are very well suited to superimposition with data from other instruments.

5. Conclusion and Prospects; "Night"Astronomy

In Solar Physics, we have seen that MSDP instruments are especially powerful with respect to

- spectroscopy with high spatial resolution (No slit degrading the images, identical effects of seeing in all wavelengths, possiblity of tracking very small features)
- high speed imaging, well suited to fast events
- 3D-character, very useful in coordinated campaigns

Next advances will consist in the 3D spectro-polarimetry, that is to say, in particular, the accurate analysis of magnetic structures. It will be possible with the solar Rytchey-Chrétien telescope THEMIS, which will also provide high spatial resolution (tilt mirror and correlation tracker).

An other item might be the speckle spectroscopy. Simultaneous observations of high photon flux images (wide band) and MSDP channels (narrow bands), could be used to improve the spatial resolution of imaging spectroscopy by speckle techniques (Keller et al. 1992).

MSDP spectrographs are not used so far in night-time astronomy. However, they should be complementary of other 3D-spectroscopy techniques. Several directions might be investigated:

- Multi-color imaging:

  In the case of wide band spectroscopy, the MSDP can provide large fields with high spatial resolution; all the available photons are used, contrary to filters that must be tuned successively.

- 3D-spectroscopy with limited spectral ranges:

  In the case $N = 20$ and $R = 20000$ for example, with a $4m$ telescope and a typical $6m$ spectrograph (with large blaze angle gratings), it can be seen from results of section 3 that the same kind of beamshifters as in solar physics should provide the field of view $15 \times 60 arcsec$, and the spectral domain equivalent to $150 kms^{-1}$.

  In addition, several spectral ranges can be observed simultaneously.

- MSDP with large number of channels:

  Other sets of characteristics can be chosen, of course, according to the scientific programmes. In particular, if only small square fields of view are needed, other beamshifters can be designed to fill the area of the detectors with other arrangements of the channels ($N \simeq 100$). The spectral ranges should be also extended.

The performances of the MSDP spectrographs can be adjusted, according to the astrophysical problems. Except for the losses due to a few reflections and refractions, all the photons are collected simultaneously in full ranges $x \times y \times \lambda$, which is not the case, neither with "long-slit" spectroscopy, nor with tunable filters. This good efficiency might be appreciated for 3D spectroscopy with high spatial resolution.

Acknowledgments. The images shown in figure 2 were processed by the microdensitometer MAMA of INSU (CNRS).

Discussion

G. Monnet: Besides the possible "night" applications that you suggest, others can possibly be envisaged, such as a correlation velocity spectrograph. As far as I am aware, there is already one application in use, namely the joint development by Kyoto University and the University of Hawai of a low resolution near-infrared spectrograph, where your double-pass subtractive scheme is used to suppress the strong OH airglow lines.

J. Bland-Hawthorn: Solar astronomers seem to have covered all parts of instrumental parameter space presumably because they are overwhelmed by photons.

Is there anything you cannot do at present? What are the likely developments in the coming years?

P. Mein: The modelling of fine magnetic solar structures (subarcsec) needs very high spatial and spectral resolution, so that the flux of photons is not too large, even in the solar case.

As an example of next instrumental advance, I mention again the THEMIS polarization-free telescope, with active optics (tilt mirror), and two long spectrographs (8m), used in additive or subtractive modes. Such capabilities cannot be found simultaneously in any existing telescope.

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