ASTRONOMY & ASTROPHYSICS
SUPPLEMENT SERIES

APRIL II **1997**, PAGE 293

Astron. Astrophys. Suppl. Ser. **122,** 293-297 (1997)

Two-band spectral filtering in instruments for measuring solar magnetic fields

V.M. Grigoryev and N.I. Kobanov

Institute of Solar-Terrestrial Physics, P.O. Box 4026, Irkutsk, Russia

Received December 8, 1995; accepted July 10, 1996

Abstract. In this paper we formulate the basic concept of a bichromatic image technique. Specific examples of its application are analyzed in the context of research into solar plasma characteristics by pinpointing its merits and demerits. Specialized requirements to the spectral devices are set forth, which may be summarized as: a) the presence of two nearby identical spectral passbands; b) the mutual orthogonality for the polarization of the light that has passed through neighboring bands; and c) the possibility of controlling the relative position of the bands. Several alternative plausible implementations of the method are considered with the use of Fabry-Perot interferometers (FPI) and magnetooptical filters (MOF) for measuring the longitudinal magnetic field strength and the intensity field. A new design of a filter magnetograph is proposed, based on MOF, with the combination of two optical resonance cells into one.

Key words: filter magnetographic methods

1. Introduction

This paper is primarily concerned with a technique for obtaining longitudinal magnetic field magnetograms, based on two-passband spectral filtering. Longitudinal magnetic field measurements usually use intensity fluctuations measured in the blue and red wings of a spectral line at the frequency of the modulator that consecutively transmits the left and right-handedly circularly polarized radiation. In this case, measurements in the two line wings are made either simultaneously with two photodetectors or sequentially with a single detector (Babcock & Babcock 1952; Beckers 1968; Cacciani 1981), i.e. measurements in each of the spectral bands are separated either spatially or temporally. Note that the identity problem of dynamic characteristics of several photodetectors is a long-standing complicated challenge in experimental astrophysics. A single photodetector and the modulated signal are increasingly favored by the investigator because these two factors act to improve dramatically the sensitivity of measurement. With the advent of CCD and high-speed computers, the essence of the problem did not alter. As before, achieving a higher sensitivity involves the possibility of using a single photodetector for measuring a particular parameter in each pixel, as well as using the rapid modulation-demodulation. It is by no means accidental that this problem was further addressed in publications devoted to the LEST Project (Povel 1990; Keller et al. 1992; Povel et al. 1994). The above considerations are characteristics both for most one-channel magnetographs and for multichannel instruments based on using filter systems and CCD-receivers; the latter are gaining increasing acceptance. Of course, with the advent of CCD, stokes-polarimeters have been and are being developed (Elmore et al. 1992; Mein 1991; Bendlin et al. 1992; Mickey et al. 1996), which measure the distribution of all Stokes parameters in the line profile at each image point. When using methods for solving inverse problems of radiation transfer in a line, they provide a wealth of information about the magnetic field structure and the velocity through the layer thickness where the line forms. However, such observations do not enjoy reasonably high time resolution, but from 8 min to 70 min (Mickey et al. 1996). Some problems in solar physics that involve the study of shortlived and highly dynamic phenomena (flares, ejections, eruptive prominences) require a time resolution over 1 min. Conventional magnetographs with filter systems and CCD (Hagyard et al. 1982; West 1985; Sakurai et al. 1991) will remain effective for much time to come in such observations to make measurements in fixed spectral bands of the blue and red line wings. It is important and useful to further upgrade such systems with the aim to maximize their time resolution and sensitivity. Moreover, the method under consideration does not rule out the possibility of scanning a line profile. And these issues are covered by the present paper. The central idea is that intensity fluctuations are measured **simultaneously in two spectral bands** λ_1 and λ_2 (in the blue and red wings) **with a single**

Send offprint requests to: N.I. Kobanov

photodetector, without any spatial separation into two images. As applied to filter magnetographs, this technique may be called the method of bichromatic image. The idea of the bichromatic image for measuring $H_{\|}$ was suggested in 1971 by Ramsey for birefringent filters and independently by a group including these authors at SibIZMIR (Lebedev et al. 1972) for the diffraction spectrograph. Subsequently, the Ramsey's idea of obtaning two bands in birefringent filters for measuring all Stokes parameters was implemented by Chinese investigators (Guoxiang 1990). This same concept was used in differential line-of-sight velocity measurements and for measuring $\partial I/\partial\lambda$ the spectral line profile (Kobanov 1983, 1993) with diffraction spectrograph. The goal of this paper is to generalize the concept of the method and demonstrate the possibilities of using it in conjunction with different spectral instruments. It should also be emphasized that using the method of bichromatic image **allows for scanning the spectral line profile** in both conventional and filter magnetographs. This is achieved by varying the amount of the spectral interval between λ_1 and λ_2.

2. The peculiarities of using the bichromatic image technique in solar research

In experimental research into solar phenomena filtergrams and spectroheliograms have received wide recognition; they represent a solar surface image in a narrow spectral band usually corresponding to a chosen part of the spectral line profile. In some instances it is necessary to have accurate information about the brightness distribution, but when obtaining a filtergram in a single wing of the line, the brightness field will be distorted by the line-of-sight velocity field. In order that one parameter be separated from the other, one more brightness filtergram needs to be obtained in the other wing; after that, it is necessary to perform addition to obtain a brightness filtergram and subtraction to obtain a dopplerogram. This procedure involves unavoidable errors introduced by technical factors when performing these operations. In addition, the atmospheric seeing effect is enhanced in this case, and areas of the image with fast changes in line-of-sight velocity will also make their contribution to the error of measurement. If, however, the bichromatic image mode is employed, then it is possible immediately to obtain in a single frame a brightness filtergram without any distortions caused by Doppler velocity. Also, due regard must be had to the fact that the intensity will be doubled; hence the signal/noise ratio increases, and the exposure time can be further reduced. Errors introduced by the operation of adding up the two frames disappear, and the atmospheric seeing influence is minimized. Unfortunately, information about line-of-sight velocity is lost in this case.

It is, however, possible to combine the merits of both variants. To accomplish this, it is necessary to obtain one frame of the bichromatic image $(I_B + I_R)$ and one frame of

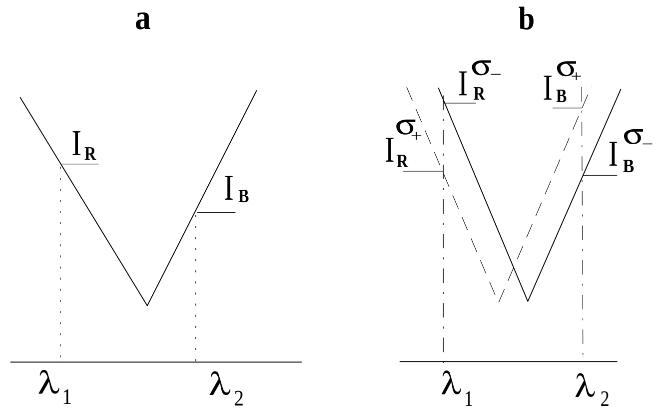

Fig. 1. Principle of signal measurement in two-band filtering mode: **a)** for intensity filtergramm, **b)** for $H_{\|}$ magnetogramm

the monochromatic image I_B or I_R. In this case the subsequent subtraction of twice the second from the first and division by the first gives $(I_B - I_R)\,/\,(I_B + I_R)$, i.e., the line-of-sight velocity. As a result, two frames plus the subtraction/division operation provide a usual dopplerogram and high-quality brightness filtergram with twice the light. It is pertinent to note that the procedure of obtaining a dopplerogram is quite as usual.

Next, we consider the performance of the bichromatic image technique when measuring the Zeeman line splitting. Specifically, it follows from Fig. 1b that in this case the instrument must operate so that one phase of modulation receives the light of intensity $I_1 = I_B^{\sigma-} + I_R^{\sigma+}$ and the other receives $I_2 = I_B^{\sigma+} + I_R^{\sigma-}$. Here $\sigma+$ and $\sigma-$ are the oppositely polarized Zeeman components. In the Ramsey filter magnetograph the $\pm\lambda/4$ modulator is placed ahead of the filter, and the input polarizer is removed from the thickest (most narrow-band) cell of the filter. In one band (λ_1) the filter transmits the horizontally polarized incoming light, and in the other (λ_2) it transmits the vertically polarized light. The polarization of both beams at the cell output is the same. In this manner the required operating conditions are achieved. The principle of operation of a spectrographic analog of such an instrument is very much alike, but its practical implementation is quite different from Ramsey's (Lebedev et al. 1972). Immediately behind the spectrograph entrance slit are the electrooptical modulator $\pm\lambda/4$ and the polarization deflector D. The deflector and modulator are mutually adjusted so that one of the component deviates along the dispersion to the right and the other to the left. The amount of deviation of polarized beams is set approximately equal to the half-width of the spectral line profile. The spectrograph exit slit lies halfway between the splitting spectral components. The intensity of the light that has passed through the entrance slit, varies with the modulation from $I_1 = I_B^{\sigma-} + I_R^{\sigma+}$ to $I_2 = I_B^{\sigma+} + I_R^{\sigma-}$. The polarization deflector is made of one or two calcite plates. If the polarization of one of the beams at the deflector output is normal to the direction of the diffraction grating groovs, then such a deflector should be complemented with a $\lambda/4$-plate in order for the polarization to be transformed to a circular one and to avoid the dissimilar effect of the grating on the intensity of the beams. There exists also a deflector design, in which the polarization of beams makes 45° with the dispersion direction.

Thus, we have considered two essentially different examples illustrating the capabilities of the bichromatic image technique. In connection with the trend today toward the progression of filter magnetographs based on Fabry-Perot interferometers and resonance cells with metal vapours, it would be of interest to explore the prospects for the application of the bichromatic image technique in such instruments.

First we formulate the main requirements that are placed by this problem upon filters used. In this case we will start from the examples considered above by identifying their common properties. These requirements may be summarized as three basic ones.

- The filter is to ensure the formation of a single image simultaneously in two spectral bands.
- Each of spectral bands must transmit the light of a certain polarization only, because it is in this case only that a modulation of the signal becomes possible.
- And finally, there should be a possibility of changing the position of the bands by making them coming closer together or moving apart as required.

3. Analyzing the capabilities of FPI and MOF as filters of the bichromatic image

Fabry-Perot interferometers (FPI) are most attractive for the development of filter magnetographs because of their compact configuration (Rust 1985, 1986). In the case of a solid-state Fabry-Perot etalon the eguation

$$\lambda = \frac{2d}{N}\sqrt{n^2 - \sin^2\varphi} \quad (1)$$

holds, where λ - wavelength corresponding to the middle of the passband; n - refractive index of the etalon material; N - the order of interference; d - thickness of the etalon; and φ -angle between the incoming beams and a normal to the etalon surface.

As follows from the expressions (1), the position of the passband of the etalon depends on several factors. Of them, the angle φ and the refractive index n are most suitable for control. How can an etalon-based bichromatic image filter be created? A first opportunity presents itself when the incoming light beam is divided into two by means of a prism made of birefringent material and constructed in such a manner that the beam of one polarization leaves the prism at a small angle to the beam of a different polarization. Note that the angular path of the beams that have passed through the filter, is readily reconstructed by means of an identical, suitably oriented polarization prism, and there arise no problems with ghosting. For a relative displacement of the bands of the order of 100 mÅ it is sufficient that this angle is about 1°. In this case, by tilting the etalon, it is possible to vary the relative displacement of the passbands $\Delta\lambda_{\rm r}$ over a reasonably wide range. One may achieve, for example, that both beams are let pass in the same spectral band ($\Delta\lambda_{\rm r}= 0$ if $\varphi_1 = \varphi_2$), or it is possible to reverse the position of the passbands. Tilting the etalon is also used for exact tuning to the desired wavelength by producing a quasi-constant displacement. Therefore, to ease the assessments of the modulation of the already tilted etalon, we transform the expression (1). Differentiating (1) with respect to φ and substituting $\cos\varphi \approx 1, \quad \sin\varphi \approx \varphi$ we get

$$\Delta\lambda = -\frac{\lambda}{n^2}\,\varphi\cdot\Delta\varphi \quad (2)$$

For the case with two beams, $\Delta\lambda = \Delta\lambda_{\rm r}$, and $\Delta\varphi$ is the angle between the beams, and φ is the angle between a normal to the etalon and the bisector of the angle formed by two beams. The expression (2) becomes suitable for a direct calculation of $\Delta\lambda_{\rm r}$.

Another way of developing a two-bandpass filter based on a Fabry-Perot etalon is to use a birefringent material as the gap within the Fabry-Perot etalon. Traditionally, birefringence of the material in the Fabry-Perot presents an objectionable property in so far as it gives rise to the appearance of additional transmission bands. By way of example, such is the case for the manufacture of a Fabry-Perot etalon with the gap made of artificial fluorophlogopite. The difference of refractive indices $\Delta n = 4.29 \div 10^{-4}$, or is lower than in natural mica. This can be gor rid of by choosing the plate thickness such that the path difference be $\lambda/2$. This is not always possible, hence it is customary to use a Fabry-Perot etalon in the plane-polarized light beam. For our purposes, however, this property proves to be useful.

Intresting possibility of creating two-band filters arises when we use the control over the refractive index of some crystals suitable for manufacturing FPI. The possible uses of lithium niobate plates as a tunable Fabry-Perot etalon were considered by Rust & Bonaccini (Rust 1986; Bonaccini 1988). For tunable FPI, lithium niobate plates of both Z-cut and Y-cut are used. The latter, even without any voltage applied, transmit the light in two spectrally separated and orthogonally polarized beams (Bonaccini 1988) i.e., they satisfy the two above-formulated main requirements imposed upon bichromatic image filters. The refractive index of an extraordinary ray $n_{\rm e}$ depends little on the voltage applied to the etalon, while the refractive index of an ordinary ray $n_{\rm o}$ is related to the voltage by a linear relationship. Hence it becomes possible to vary (with a fixed position of one spectral band) the position of another as required. However, using directly such a crystal for our problem is complicated by the fact that, with no voltage applied, $\Delta\lambda_{\rm r}$ exceeds significantly the requisite values. To compensate for this displacement, a sufficiently high voltage should be applied there to, which in turn will cause a marked piezoelectric effect, and this must be taken into account. The functional scheme of FPI's filter magnetograph in the bichromatic mode is shown in Fig. 2.

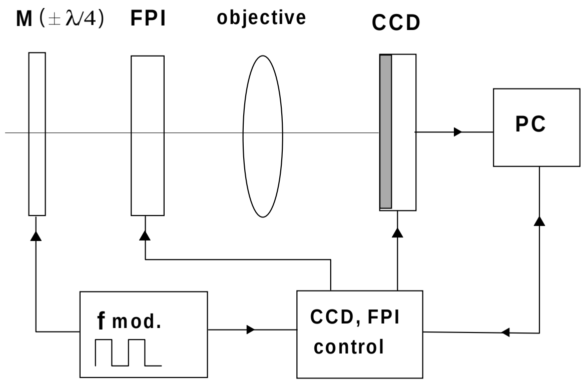

Fig. 2. A simplified block-scheme of FPI-based filter magnetograph in the bichromatic mode

Next we consider the possibilities afforded by magnetooptical filters (MOF). It is well known (Agnelli et al. 1975; Cacciani & Fofi 1978; Cacciani 1981; Rhodes et al. 1984; Cacciani et al. 1991) that, when placed in a longitudinal magnetic field, cells with vapours of some metals have the remarkable properties:

- the cell absorbs the right-handedly circularly polarized light at the wavelength λ_1 and the left-handedly polarized light at λ_2, i.e., it behaves as if there were two narrow-band circular polarizers;

-$\Delta\lambda = \lambda_1 - \lambda_2$ depends not only on H, but also on the density of vapours in the cell specified by the evaporator's current (Rhodes et al. 1984).

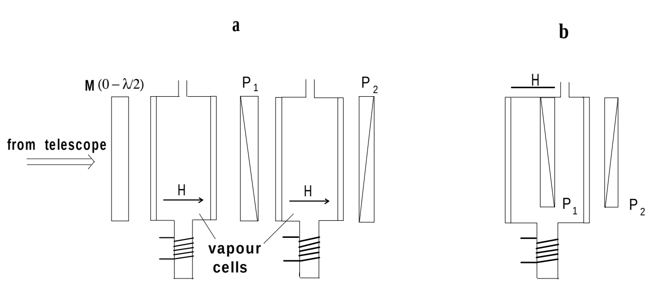

Fig. 3. Examples of functional schems of a MOF-based magnetographs in the bichromatic image mode: **a)** with two optical resonance cells **b)** optimum version with a single cell

To obtain a bichromatic image, it is sufficient to place the cell between two crossed polarizers. The cell output in this case will receive the linearly polarized light in two spectral bands corresponding to λ_1 and λ_2. If exactly the same cell is placed ahead, but without polarizers and with the modulator $0 - \lambda/2$ at the input, then we get an instrument for measuring the longitudinal magnetic field strength, Fig. 3a. In fact, if to the zero phase of the modulator there will correspond a value of intensity $I_1 = 1/8\left(I_B^{\sigma-} + I_R^{\sigma+}\right)$, then with the phase $\lambda/2$ the circular polarization of the Zeeman components changes sign, and the intensity takes on the value of $I_2 = 1/8\left(I_B^{\sigma+} + I_R^{\sigma-}\right)$. As has been pointed out previously, these two frames will suffice for obtaining an $H_{\|}$-magnetogram, with the elimination of the dependence on the line-of-sight velocity and brightness.

Note that if the first cell is placed in a variable magnetic field $\pm H_{\|}$, then there is no need for a polarization modulator at the cell input. And if it is taken into consideration that for the second cell the field reversal is unimportant, then both cells can be placed in a common alternating field. In this case a simplified hypothetical design of a filter magnetograph $H_{\|}$ would appear as one in Fig. 3b wher both cells are combined into one, whose communicating space is separated by the polarizer into two equal parts. Obviously, in this case the shape and position of the bands will coincide best, and this will favorably influence the accuracy of the magnetograph. Such a coincidence is difficult to expect for the design in Fig. 3a. The magnetic field of the combined cell may also be constant; in this case the filter input has to incorporate a circular polarization modulator such as in the design of Fig. 3a. Some technical difficulties associated with the placing of the polarizer inside the cell, do not seem to be insurmountable. Instead, the identity of temperature, pressure and magnetic field inside each of the parts of the cell will ensure an ideal matching of their spectral characteristics.

The posibility of working with reasonably large angular apertures of incoming beams is an important merit of MOF. There are no problems whatsoever when working with the image of the full solar disk or when using short-focus optical systems. Obviously, however, limited possibilities of choosing optical wavelengths should be recognized as the most serious disadvantage of MOF.

4. Discussion

Let us briefly summarize the results of our treatment. First we must mention the advisability of employing the bichromatic image technique in experimental solar research. As shown earlier in the text, the technique has a number of merits. The main of them are: doubling of the light, reduction of the number of frames from one-fourth to half, reduction of the exposure time and, consequently, decrease in the atmospheric seeing effects. The technique is applicable in conjunction with various spectral instruments, from the spectrograph to MOF. The bichromatic method allows for scanning the spectral line profile in both conventional and filter magnetographs.

When handling diffraction spectrograms of solar telescopes, the technique makes it possible to eliminate the influence of internal noise of the spectrograph at low modulation frequencies, upon magnetic field strength measurements. The solar spectroheliograph operated in the bichromatic image mode provides spectroheliograms free from the influence of spectrograph noise and line-of-sight velocities.

Magnetooptical filters satisfy best all requirements imposed upon spectral instruments when using the bichromatic image technique. Conceptually, such filters are two-banded, with a different polarization of the bands and with a possibility for their relative displacement. The angular aperture of MOF is virtually unlimited. There is possibility simultaneously to measure the general magnetic field of the Sun with utilization the scattered light. Unfortunately, spectral lines, with which modern MOF can operate, are far short of optimum for measuring the magnetic field strength. This factor sets serious limits on the fields of application.

Lyot birefringent filters currently in use to obtain the bichromatic image, have a small angular field, a bulky design, large light losses, and a complicated control of the band position. However, because of the wide use at solar observatories and the ease to switch over to the two-band mode of operation (by eliminating the input polarizer of one of the stages), they can gain widespread acceptance in this mode. It is particularly simple and proficient to obtain a bichromatic filtergram of intensities in the spectral line wings.

Of well-known filter techniques, the method of choice seems to be FPI based on a solid-state etalon made, where possible, of a material with a controlled refractive index. These instruments are compact, durable and readily adjustable, and have high spectral resolution. In some cases, even the demerit of such a filter, namely the high sensitivity to the angle of incidence of the incoming radiation, may be turned into a merit. For instance, for producing two spectral bands or controlling their position, as has been suggested above, or for compensating the band displacement as a consequence of solar rotation on full disk filtergrams (Rust 1984). This same disadvantage dictates the need to look for ways of reconciling with the feed optical system. It is best to mount such a filter in systems with telecentric ray path. However, in this case the influence of the FPI's spatial inhomogeneouses is increased. Possibly, recent holographic filters (Rakuljic & Leyva 1993) that feature a large angular field and a narrower spectral band, will supersede FPI. In any event it would be well to look for ways of using such filters in the bichromatic image mode.

Furthermore, as may well be noted above, $H_{\|}$-measurements using the bichromatic image technique are made with a push-pull modulation. Recent reports on the use of CCD as a push-pull detector of optical signals (Povel et al. 1990, 1994) will improve significantly the signal/noise ratio. In conjunction with other advantages of the technique described here, this may well lead to a significant improvement of the sensitivity of filter magnetographs.

Acknowledgements. We are grateful to Mr. V.G. Mikhalkovsky for his assistance in preparing the English version of the manuscript.

References

Agnelli G., Cacciani A., Fofi M., 1975, Solar Phys. 44, 509
Babcock H.D., Babcock H.W., 1952, PASP 64, 282
Beckers J.M., 1968, Solar Phys. 3, 258
Bendlin C., Volkmer R., Kneer F., 1992, A&A 257, 817
Bonaccini D., 1988, Infrared Imaging Filter With Lithium Niobate Double Channel Fabry Perot Interferometer, NOAO Preprint, No. 179
Cacciani A., Fofi M., 1978, Solar Phys. 59, 179
Cacciani A., 1981, Space Sci. Rev. 29, 403
Cacciani A., Paverani E., Smith E., Zirin H., 1991, in Solar Polarimetry, November L. (ed.). Progress Toward an Advanced Imaging Vector Magnetograph, U.S.A., p. 133
Elmore D.F., Lites B.W., Tomcryk S., et al., 1992, in Polarization Analysis and Measurement, SPIE, 1746, 22
Guoxiang A., Fear R.J., Peiwen J., 1990, Acta Astrophys. Sin. 10, 2, 180-187
Hagyard M.J., Cumings N.R., West E.A., Smith J.E., 1982, Solar Phys. 80, 33
Keller C.U., Aebersold F., Egger U., et al., 1992, LEST Technical Report No. 53
Kobanov N.I., 1983, Solar Phys. 82, 237
Kobanov N.I.,1983, Solar Phys. 145, 11
Lebedev N.N., Grigoryev V.M., Klochek N.V., Kobanov N.I., 1972, A Method of Measuring the Magnetic Field Strength, Author's Certificate USSR No. 335562. Bull. Izobr., No. 13
Mein P., 1991, A&A 248, 669
Mickey D.L., Canfield R.C., La Bonte B.J., et al., 1996, Solar Phys. (submitted)
Povel H.P., Aebersold H., Stenflo J.O., 1990, Appl. Opt. 29, 1186
Povel H.P., Keller C.U., Yadigaroglu I.A., 1994, Appl. Opt. 33, 19, 4254
Rakuljic G.A., Leyva V., 1993, Opt. Lett. 18, 6, 459-461
Ramsey H.E., 1971, Solar Phys. 21, 54
Rhodes E.J.Jr., Cacciani A., Tomczyk S., et al., 1984, Adv. Space Res. 4, 103-112
Rust D.M., 1984, Some Design Considerations for a solar magnetograph, Preprint APL/IHU 84-27
Rust D.M., 1985, Austr. J. Phys. 38, 781
Rust D.M., 1986, Instrum. Astron. SPIE 627, 39
Sakurai T., Ichimoto K., Hiel E., Miyazaki H., 1991, Solar Terrestr. Environ. Res. Jap. 15, 11
West E.A., 1985, NASA Conf. Publ. 2374, 160