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Developing modulationless measuring of magnetic fields and differential velocities at Sayan observatory(*)

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Summary. — In this paper we consider the possibility of modulationless measuring the magnetic-field strength and the differential line-of-sight velocity, based on using a diffraction spectrograph and multichannel CCD photodetectors. The optical system for implementing the method is described. Results of trial observations are presented. When measuring the differential velocity, the spectrograph's inherent noise is reduced by factors of 35–40. It becomes possible to measure the longitudinal magnetic-field strength in a single exposure even if the CCD array is used. This can be particularly attractive when reducing the influence of atmospheric instabilities on the result of magnetic-field measurement using CCD arrays.

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1. – Introduction

At the same time, in relation to the observer, the object under investigation can participate in a variety of other motions such as large-scale flows, solar rotation, diurnal rotation of the Earth, and its ecliptic motion. Thus the absolute value of the line-of-sight velocity of the object under investigation is made up of many components which, what is more, are time variable. These problems are grossly dramatized when wave motions are investigated. The element observed can be affected simultaneously by tens and hundreds of oscillatory modes with different periods, propagation directions and spatial scales. Based on the resulting noise-like mixture obtained by conventional methods, it is difficult and sometimes impossible to understand the character of motions of the object under investigation. The differential method makes it possible to extract from this mixture the wave motions with the directions and spatial scales specified. By its nature, this method is best suited to the investigation of wave motions since the observation of the wave

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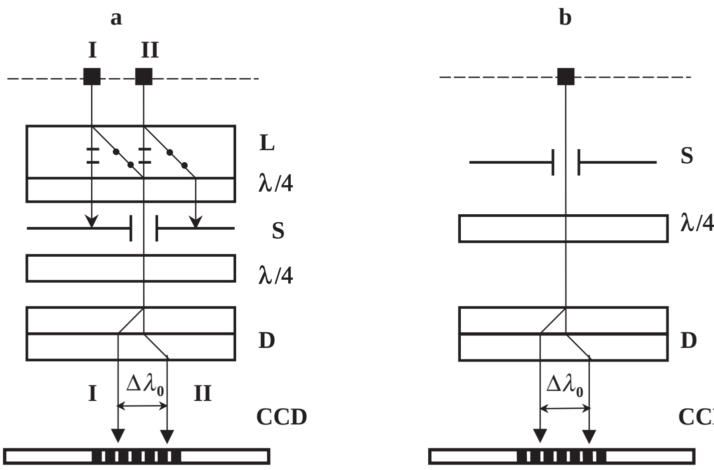


Fig. 1. – Simple optical layout: a) for measurements of differential velocity; b) for measurements of longitudinal magnetic field.

itself intrinsically implies a comparison of the motion at several (two at least) points of space [1, 2].

The differential method can be used most efficiently in the case of a sharply defined directedness of the wave motions along, for example, the longitudinal axis in a prominence filament or in the case of a radial symmetry of the motions in a sunspot. Furthermore, the spectrograph instrumental noise is totally suppressed, and the influence of large-scale atmospheric irregularities is reduced. It should be noted that in differential measurements the spectral line asymmetry effect on the signal is reduced. The total sensitive gain of velocity measurements is by factors from 10 to 100, depending on the contribution to the signal from the diffraction spectrograph noise which is effectively suppressed by this method.

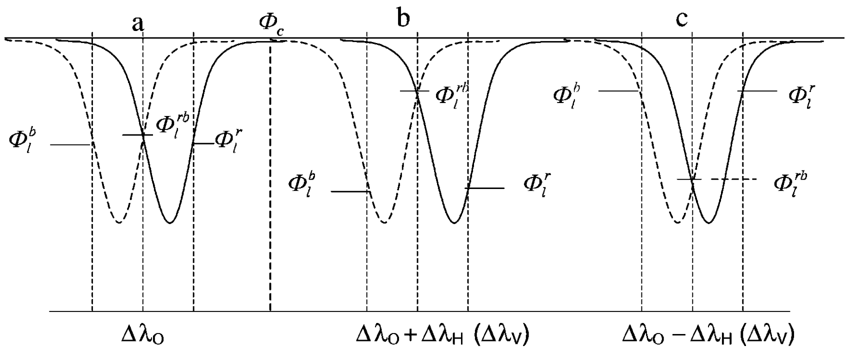


Fig. 2. – Spectral components position as the response to magnetic field or differential velocity.

2. – Method and instrument

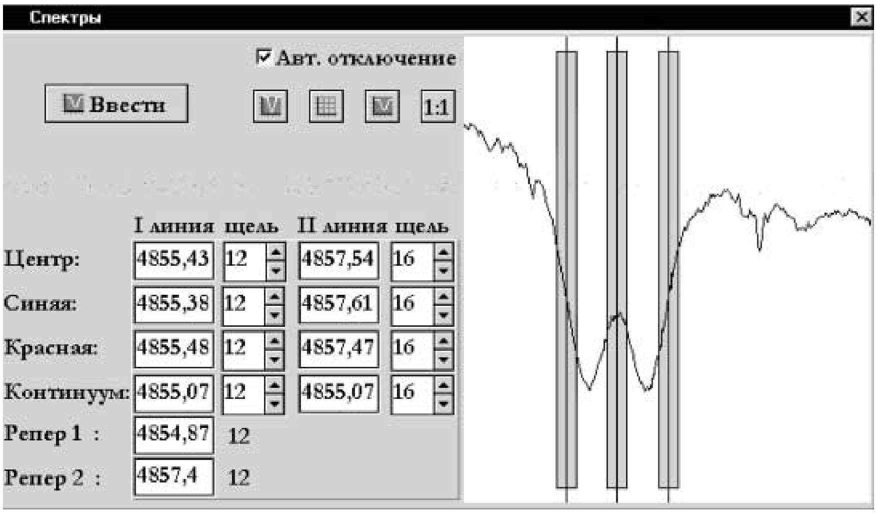
This paper gives an account of a new method for measuring the differential line-of-sight velocity and the longitudinal magnetic-field strength in the modulation-free mode using CCD devices. Figure 1 presents a simplified optical design for performing such measurements.

Orthogonal polarized beams will pass from elements I and II through the spectrograph entrance slit, thanks to polarization prism L. Polarization prism D in fig. 1 is used to accomplish a displacement of these beams in inverse direction along the spectrograph dispersion to a distance equivalent to the half-width (the width at the half-intensity level) of the working spectral line. In our case the directions of polarization of the beams make up 45° with the direction of the grooves of the diffraction grating.

In their simplest version, polarization prisms L and D represent calcite plates. In their more sophisticated version, these plates consist of the combination of two elements permitting the linear separation of the polarized beams to be varied over the required range. When investigating the propagation direction of waves, it is frequently necessary to change the direction of image splitting, which leads to a change in the position of the plane of polarization. In order for the polarization of the beams to be matched to the angular position of prism D, irrespective of the angular position of prism L, two achromatic quarter-wave phase plates are added to the optical system. One of them is oriented with its axes at 45° to the polarization direction of the beams within the prism, and is rigidly attached to prism L. This quarter-wave plate converts the linear polarization of the beams to the circular polarization where the mutual orientation of polarization prism L and deflector D may be arbitrary. The axis of the second quarter-wave plate, that is placed behind the spectrograph entrance slit, is oriented parallel to the dispersion direction of the spectrograph. At the spectrograph output, in this case, two identical images of the spectrum are produced, which are shifted with respect to one another along the dispersion by a small amount $\Delta\lambda_0$ which is determined by prism D. Spectral line images will be superimposed in the plane of the light-sensitive surface of the CCD array. By separating the spectral components by the line half-width, it becomes possible to use in measurements the steepest and linear portions of the line profile, which, on the one hand, ensures a maximum sensitivity to changes in the distance between the components, and, on the other, an independence from the signal from common shifts of the components within the linear part of the profile.

It is remarkable that if all polarization optics placed in front of the spectrograph entrance slit is removed from the system (fig. 1b), then we get an instrument suitable for modulation-free measurements of the longitudinal component (projection onto the line of sight) of the magnetic-field strength $H_{\parallel}$.

The principle of V and H measurements is explained in fig. 2, showing the position of the spectral components relative to the center of the conventional “electronic slits” of the CCD detector. Identical groups of pixels produce “electronic slits”, in each of which measurements are made of the integral light flux from a portion of the line wing “cut out” by a corresponding “electronic slit”. It is evident from fig. 2 that, depending on the sign of the measured magnetic field or on the differential line-of-sight velocity, the initial distance between the spectral components $\Delta\lambda_0$ either decreases or increases thus causing corresponding changes of the light flux intensity in the “electronic slits”. Furthermore, an increase in intensity in the central “slit” (between the components) is accompanied by its decrease in the lateral ”slits” (wings), and vice versa. Besides, an additional, “electronic slit” is placed for recording the intensity of the continuous spectrum. This



☑ Авт. отключение

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Центр:	4855,43	12	4857,54	16
Синяя:	4855,38	12	4857,61	16
Красная:	4855,48	12	4857,47	16
Континуум:	4855,07	12	4855,07	16
Репер 1 :	4854,87	12		
Репер 2 :	4857,4	12		

Fig. 3. – The interface window (Russian version) that shows a part of real spectrum near Ni I, 4857.

makes it possible to perform a calculation of signals simultaneously by several formulas, and to compare results. A comparison of the integral fluxes at the center and in the blue and red wings can be accomplished with a very high accuracy. With a 12-digit analog-to-digital converter, for example, the sensitivity of measurements reaches 10^{-4} of the measured light flux. The values of the longitudinal magnetic-field strength and of the differential and line-of-sight velocity are calculated by simplified formulas:

$$H_{\|} = \frac{\Phi_l^{rb} - (\Phi_l^b + \Phi_l^r)}{\Phi_l^{rb} + (\Phi_l^b + \Phi_l^r)} k_H \,, \tag{1a}$$

$$V_d = \frac{\Phi_l^{rb} - (\Phi_l^b + \Phi_l^r)}{\Phi_l^{rb} + (\Phi_l^b + \Phi_l^r)} k_V \,, \tag{1b}$$

$$V = \frac{\Phi_l^b - \Phi_l^r}{\Phi_l^b + \Phi_l^r} k_V \,, \tag{1c}$$

where Φ_l^r , Φ_l^b , and Φ_l^{rb} are the light fluxes integral by the respective electronic slits; and k_H and k_V are the calibration coefficients.

For comparison purposes, use was also made of the formula

$$H_{\|}(V_d) = \left(\frac{\Phi_l^{rb}}{\Phi_\mathrm{c}} - b_0) k_H (k_V \right) \,, \tag{2}$$

where Φ_c is the intensity of the continuous spectrum, and b_0 is the coefficient of zero setting of the scale which is determined experimentally or calculated.

It should be noted that by using “electronic slits”, it is possible to easily simulate the operating mode of the Doppler compensator [3]. In this mode, the “electronic slits” that are placed in the blue and red wings, are shifted in such a way as to maintain the zero

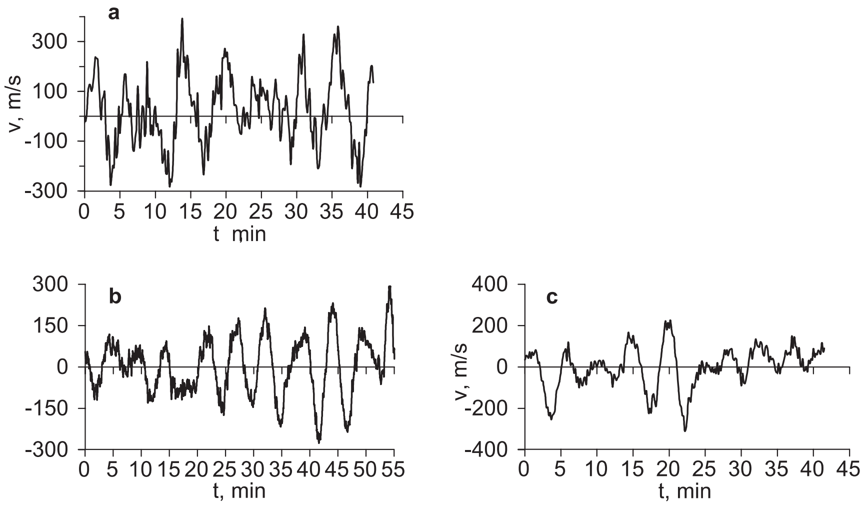

Fig. 4. – Time series of the line-of-sight velocity in disk center (Fe I, $\lambda = 525$ nm): a) Doppler compensator mode; b), c) differential method.

value of the difference signal. Results of measurements in this case are independent of the profile slope, and the calibration procedure is maximally simplified. The sensitivity to line-of-sight velocity changes in the last case is slightly reduced since the "electronic slit" changes its position, and different sets of elements always participate in the measurement. Internal errors are added as a consequence of the different sensitivity of pixels.

Interestingly, the proposed optical design (fig. 1) is also suitable for measuring $H_{\parallel}$ in the mode of a so-called λ-meter [4]. For this purpose, it will suffice (using two pairs of "electronic slits") to keep track of the position of the center of gravity of each of the spectral components. The difference of the measured shifts is proportional to the magnetic-field strength, and the semi-sum is proportional to the line-of-sight velocity. The initial splitting of the spectrum, that is ensured by deflector D, can in this case be increased for the sake of convenience. In doing so, it should be remembered that the immediate vicinities of the spectral line must not contain any fine-structured features (which is especially hard to do in a sunspot). Otherwise one will have to increase the width of the "electronic slits", which will result in a certain decrease in the sensitivity of measurements as the process of measurements will involve portions of the line profile with a smaller slope. The result of measurements with such a method is not affected by changes in the profile brightness and slope from pixel to pixel, which is an obvious advantage. The calibration procedure for different spectral lines is substantially simplified since in this case, it is sufficient to know the Lande factor of a given line. In the IR spectral range, such measurements are easier to realize when compared with the visible.

The interface that has been developed in the form of dialog windows eases also the on-line control process of observations, and calculations in the on-line mode leads to a substantial reduction of the memory used on a hard disk to record results of measurements.

To realize observations with the line-array (firm Toshiba, TCD 1301 D, array length 29 mm: 3700 pixels, pixel height 200 μm, and width 8 μm), a program was developed to operate in the Delphi programming environment for the Windows 95/98 operational

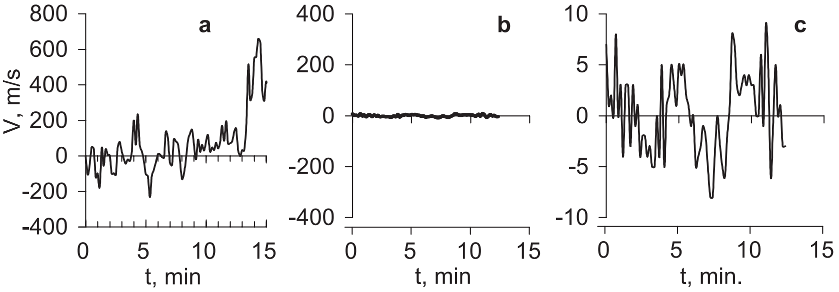

Fig. 5. – Telluric line ($\lambda = 687.4$ nm): a) line-of-sight velocity measured by Doppler compensator mode; b) differential velocity measured by differential method; c) the same on b (other scale).

system. All the control parameters for the operation with the array described below are specified in the program interface, which simplifies the conduct of observations by the user, and makes it possible to promptly change the observing modes. The data accumulation time and the write-in file name for calculated signals are specified in one of the windows. A "live" spectrum is displayed in the other window, which is renewed 30 times per second; the position and width of the "electronic slits" are also displayed there. Figure 3 shows this program interface window where the display shows the working portion of the spectrum near the line of Ni 485.7 nm (in the area of overlapping of the spectral components), and the arrangement of three "electronic slits" in the line: central in the core, and lateral ("red" and "blue"), respectively, in the red and blue wings of the line. Amongst several modes of viewing the "working" spectrum, there is a zooming capability, which improves the accuracy of accommodation of the "electronic slits". In the other dialog window, it is possible to determine the formulas, by which the signal is to be calculated in the "on-line" mode, and results of a calculation rather than raw data will be written in to the file.

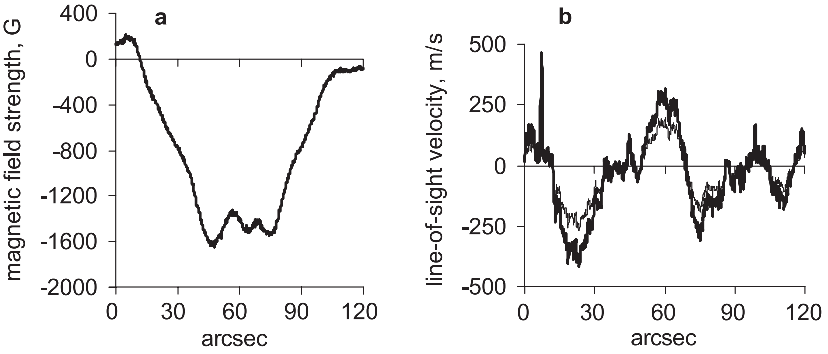

Fig. 6. – A slice through the spot of active area NOAA 9169 (21.09.2000), in a line $\lambda = 5250,02$ nm: a) magnetic-field strength; b) line-of-sight velocity; signals calculated with formula (2)—thick and (1)—thin.

3. – Observations

The first observations according to the technique described above were performed in September-October 1999 by using a linear CCD array on a horizontal solar telescope of the Sayan observatory and were continued in 2000 (with a CCD matrix as well). These observations were of testing character and were aimed at studying the main characteristics and features of this method. Observations by using the conventional technique (imitation of the Doppler compensator mode) were performed with the same linear CCD array for comparison. In observations performed in 2000, an RTE/CCD-256-H (Princeton Instruments) CCD matrix was used. The cooler of the matrix operating on the Peltier effect allows for the use of a wide range of operating temperatures. The linear size of the photosensitive window is 0.5×2 cm (256×1024 square pixels), one pixel is $\simeq 20\,\mu$m. The Fe I line ($\lambda = 525.02$ nm) was observed in spectra measured with both a linear CCD array and a CCD matrix. This is a purely photospheric line with an equivalent width of 12 pm and the Lande factor equal to 3. Figures 4b, c present time series of the differential line-of-sight velocity measured at the center of the disk in the undisturbed photosphere in a line of 525.02 nm (obtained with a guide and tracking). The noises in b), c) are real signals of velocity caused by atmospheric motions (about 3–4$'$). Oscillations with a 5-min period (3 mHz), which are characteristic of the solar photosphere, are clearly pronounced in the record. A similar time series obtained with the same CCD array in the mode of Doppler compensator imitation is shown in fig. 4a. A higher noise level in the record of fig. 4a as compared to that in fig. 4b,c is obvious. This is due to the effect of the internal instabilities of an astronomic grating spectrograph (thermal inhomogeneities of the air mass filling the spectrograph's volume, local pressure variations, residual strains of movable mechanical parts, etc.).

In order to determine more precisely the gain achieved upon noise suppression in the differential method, a similar observation was performed in the oxygen line of the Earth atmosphere ($\lambda = 687.4$ nm). As is known, telluric lines can be employed as natural references in measurements of Doppler velocities with an accuracy of up to 5–10 m/s [5, 6]. Figure 5a shows the measurements results of the spectrograph's intrinsic noise recorded by a linear CCD array in the mode of a Doppler compensator following up the position of a telluric line. As we see, the instability amplitudes reach 200–300 m/s at a recording time constant of 10 s over time intervals of tens to hundreds of seconds and may substantially distort the velocities measured. The data in fig. 5 allow us to estimate the degree of spectrograph noise suppression in measurements by the differential method: the contribution of the spectrograph noise decreases by a factor of 30–40. This means theoretically that the sensitivity in differential measurements with a CCD array may exceed the sensitivity in conventional measurements of the Doppler velocity by the same factor.

Figure 6 shows the results of processing a frame obtained by using the CCD matrix. Figure 6b is the line-of-sight velocity distribution calculated with two formulas: thick curve is the ratio of the difference of the lateral components to the continuum (formula (2)), and thin curve is the ratio of the difference of the side components to their sum (formula (1)). The difference between curves in fig. 6b is most likely determined by the fact that, in the second case (thin line), the calculated signal is more exposed to the influence of line profile changes. Figure 6a shows the distribution of the longitudinal magnetic-field strength along the slit. The sensitivity of measurements $H_{\|}$ is roughly estimated at no worse than 10–20 Gauss. A detailed investigation of the errors inherent in this method will be made elsewhere.

4. – Conclusions

The chief merit of the method considered here is that the measured quantities (V_d, $H_{\|}$ or $H_{\|}$ simultaneously with V) can be obtained in no longer than one exposure with the CCD array. But this means in particular that the method can be highly attractive in investigating the fine structure of the magnetic field or of the velocity field. In observations with the CCD matrix, it is possible to reduce the exposure time to 1–5 ms, with such values of exposure, the atmosphere looks like "frozen", and does not introduce any additional errors into measurements. An improvement on the sensitivity of measurements is favored by a significant decrease of the contribution to the signal from the spectrograph internal noise which are inherent in this method. Note that in investigating wave processes, a highly valuable property of the method is the possibility of implementing it using spatial filtering in the direction and wavelength.

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