THE STUDY OF VELOCITY OSCILLATIONS IN THE SOLAR PHOTOSPHERE USING THE VELOCITY SUBSTRACTION TECHNIQUE*

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Abstract. A method of measurement of local line-of-sight velocities in the solar atmosphere by means of polarization optics is described. No spurious signals due to instrumental displacements of the spectrum arise with this method. The sensitivity of the method obtained is 0.3 m s^{-1}, with a time constant $\tau = 5$ s and input aperture $1.4'' \times 4.5''$. Some preliminary results of the assessment of spatial characteristics of 5-min oscillations are included. Data are given to illustrate a center-to-limb variation of the spectrum of 5-min oscillations.

The past few years have witnessed an increasing interest in the study of line-of-sight velocities in the solar atmosphere. However, sensitivity of measurements is frequently not sufficient. For instance, when a conventional diffraction-grating spectrograph is used, due to accidental displacements of the spectrum caused by air turbulence within the spectrograph, and by thermal deformations, spurious signals reach 150–250 m s^{-1} (Dittmeyr, 1977; Brandt *et al.*, 1978). Such noise is absent when differential methods are employed (Kalinyak and Vasilyeva, 1971; Kotov *et al.*, 1978; Dittmeyr, 1977). This paper develops the differential method for the investigation of local quasi-periodic motions of the gas.

A scheme illustrating the passage of optical rays is presented in Figure 1. At the entrance slit of the spectrograph is a calcite plate and a phase plate $\lambda/4$. In calcite, each beam splits into two beams with orthogonal directions of the linear polarization. Points A and B of the original image correspond to points a, a' and b, b' at the output of the calcite. The $\lambda/4$ plate, oriented at 45° with respect to the linear polarization

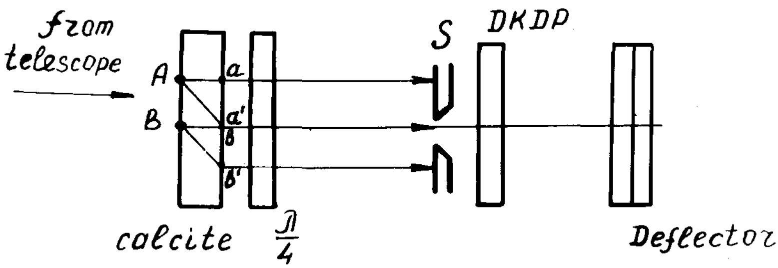

Fig. 1. Optical scheme of the device as used by the author.

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directions of calcite, converts the linear polarization into a circular one. The entrance slit of the spectrograph from point A of the original image receives a beam with a right-hand circular polarization, and from point B, a beam with a left-hand circular polarization. If the line-of-sight velocities from the A and B elements are different, each spectral line will consist of two components which are circularly polarized in mutually opposite directions (Figure 2a). The distance between the components in Figure 2a is $\Delta\lambda_v \sim v_A - v_B$, where v_A, v_B are the line-of-sight velocities of the A and B elements, respectively. In its outward appearance, the picture resembles Zeeman spectral line splitting, with the exception that, in this case, we have 100% polarization of the components. Further measurements can be made by any method usually applied in recording the longitudinal component of the magnetic-field strength. In this treatment, we have used a scheme containing a deflector and a single photomultiplier (Lebedev and Grigoryev, 1976). The deflector consists of two calcite plates oriented so that a beam being ordinary for one plate becomes extraordinary for the other, and vice versa. The plates have the same thickness which is chosen so that the total deviation of beams along the dispersion of the spectrograph $\Delta\lambda_0$ is approximately equal to half the width of the spectral line in which the observations are being made. The polarization directions of the beams at the deflector output make an angle of 45° with the direction of grooves of the diffraction grating.

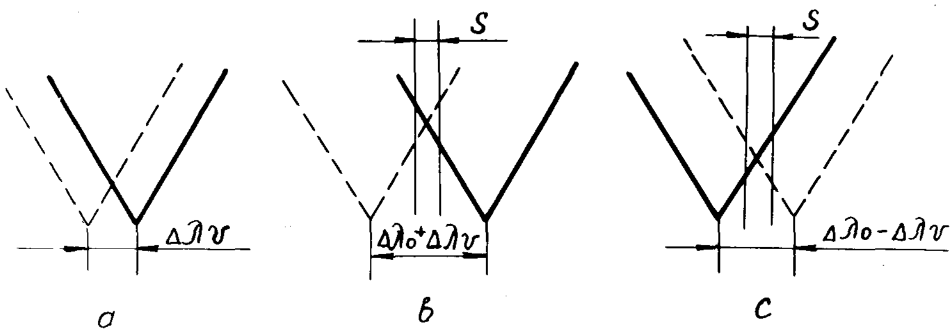

Fig. 2. Position of spectral components in the entrance slit plane of photometer. The spectral line contour is depicted simplified. (a) Original position (without deflector). (b, c) Positions of the components in the DKDP phase $+\lambda/4$ and $-\lambda/4$, respectively.

The spatial arrangement of the spectral components is changed by DKDP and the deflector, as shown in Figures 2b, c. If the phase is $+\lambda/4$, the components 'go away', and light of intensity $I_1 \sim \Delta\lambda_0 + \Delta\lambda_v$ passes through the input slit of the spectrograph. If the phase is $-\lambda/4$, the components displace to meet each other, and $I_2 \sim \Delta\lambda_0 - \Delta\lambda_v$. The difference in intensity for the modulation period is $\Delta I \sim 2\Delta\lambda_v$ and the output current of the multiplier is a variable signal at a frequency of modulation. Figures 2b, c clearly shows that simultaneous displacements of the two components due to instrumental factors would not have any appreciable influence upon the signal. One would think that there is no need for any Doppler compensator. However, this is not the case. In order to significantly decrease the possible influence due to instrumental polarization or to the difference in brightness of the A and B elements, it is desirable to provide a symmetrical arrangement of the spectral components with respect to the photometer slit. Otherwise, the simultaneous effect to these factors and instrumental displacements of the spectrum may give rise to a noise-like signal.

The instrumental polarization effect can be completely eliminated by means of a polaroid, placed in front of the calcite and oriented at an angle of 45° with respect to the directions of linear polarization of the beams in calcite. However, in this case the light intensity is decreased twice. Therefore, the polaroid cannot be used whenever the intensity of the original beam of the telescope is small. The use of a depolarizer composed of a stack of crystal plates or a $\lambda/2$ plate oriented at a definite angle, may turn out to be more advantageous in certain applications.

The calibration procedure is performed in the same way as for magnetographic measurements. A polaroid is placed before the calcite plate such that its main direction coincides with one of the directions of linear polarization in calcite. In this case, bifurcation of image is absent and only one of the circular components remains in the spectrum. By rotating the plane-parallel plate of the Doppler compensator through a fixed angle, the estimated displacement $\Delta\lambda_K$ of the spectral line is assigned and the amplitude of calibration is recorded. Then, the polaroid is removed, DKDP voltage de-energized and the noise, the mean square value of the amplitude of which is assumed to be the sensitivity, is registered. In order to rule out the effect of local velocities on the accuracy of calibration, this is carried out with a substantially defocussed image.

In the summer of 1980 and the spring of 1981, this method was used in observations with the telescope of the Sayan Observatory of SibIZMIR. Figure 3 is a photograph of

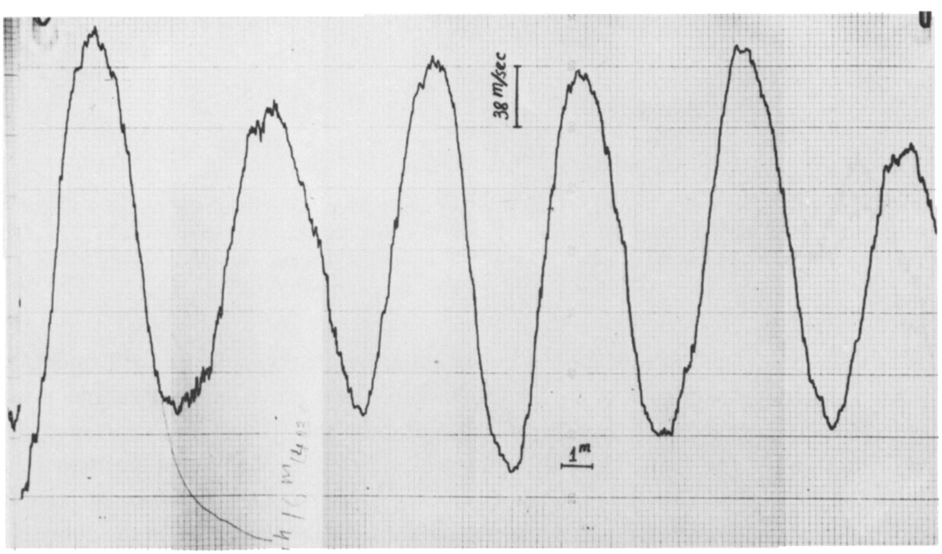

Fig. 3. Fragment of a record of 5-min oscillations of the line-of-sight velocity, as obtained with the differential method for $L = 12''$. Though the value of the velocity is not large on this record (peak to peak 250 m s^{-1}) the signal is very clear because the noise of the spectrograph has been compensated for.

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part of a record of 5-min oscillations of the line-of-sight velocity observed in the quiet photosphere at the center of the disk. The observations were made in the Fe I 5250.2 Å line with a 1.4″ × 4.5″ aperture. The sensitivity of this record, determined as a mean square of the noise amplitude with the DKDP de-energized, is about 0.3 m s^{-1} for a time constant $\tau = 5$ s. This noise is quite inconspicuous on the record, while noise-like deviations reaching 10–15 m s^{-1} observed on some portions of the record, are the real signal due to image motion. Further sensitivity augmentation is possible through an increase in light intensity and signal integration time. For comparison, Figure 4 gives a fragment of a similar record taken using a conventional method with the aid of a Doppler compensator. On this record, the noise amplitude is as high as 250–300 m s^{-1} for $\tau = 1$ s.

The method described herein is primarily intended to measure line-of-sight velocities. However, it is easy to modify it for measurements of brightness relative variations of two elements of the solar surface in a chosen part of the continuum or in white light.

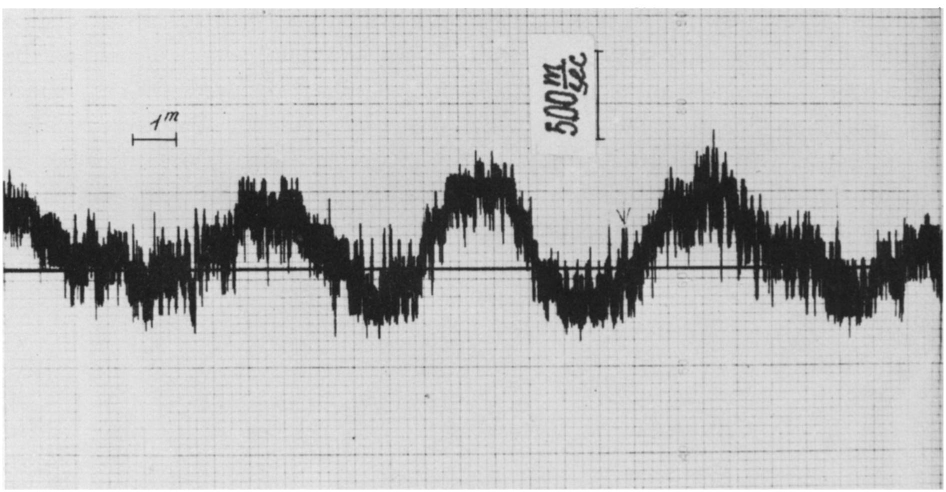

Fig. 4. Fragment of a similar record, as obtained by the author earlier with the aid of a Doppler compensator. A region of the quiet photosphere 1.4″ × 2.5″ at disk center was observed in the Fe I 5250.2 Å line. The velocity (peak to peak) is about 700 m s^{-1}. The noise of the spectrograph is about 250 m s^{-1}.

The differential method was applied by the author in observations on the refinement of the spatial characteristics of 5-min oscillations. Two kinds of observations were carried out: temporal and spatial. In the former case, the spectrograph entrance slit 'sees' the same image elements in the course of 1.5 to 3 hr. The image position was controlled by a photoelectric guide to an accuracy of 1″. The displacement of the elements due to solar rotation was compensated for by a slow scanning in the direction of rotation. Regions of a quiet photosphere at the disk center without pores, faculae, and strong magnetic fields were usually selected for observation. The temporal series performed differed from each other in distance L between the elements under investi-

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gation. For most observations, the direction was the same as that of the solar equator. A set of calcite plates available to us allowed us to discretely change L from 2″ to 40″. The length of the spectrograph entrance slit was varied from 2″ to 12″, while its width was kept constant, 1.4″. With this method, a minimum amplitude of 5-min oscillations must be observed for the elements, in which both the phase and amplitude of oscillations show the best matching. In this case, using the value of L it is possible to try to determine the spatial wavelength λ. An analysis of 24 observations (each of a 1.5 to 3 hr duration) yields a value of $\lambda \approx 30-32''$. Approximately the same period can be identified from the power spectra, calculated by the FFT method using results of spatial scan processing (Figure 5). Scans of 300–350″ length in the direction L were taken in quiet regions of the photosphere near the disk center, with apertures of 1.4 × 4.5″ and 1.4 × 6.5″.

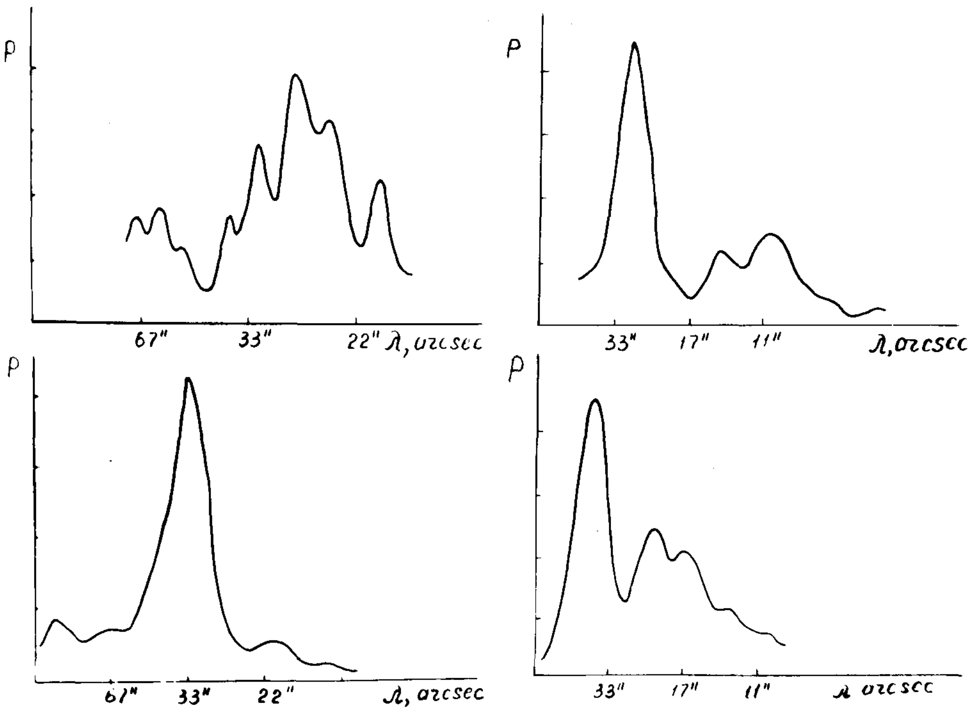

Fig. 5. Power spectra of individual scans. A mean length of one scan is 350″. The scanning rate is 1″ per sec. The scale P is arbitrary.

Of course, the statistic of these observations is insufficient, therefore the estimate we made should be regarded as a preliminary one. Results like ours have been obtained earlier by Fossat and Ricort (1973, 1975) and Deubner (1972).

The series in Figure 6 visualizes the manner of center-to-limb variation of the spectral composition of 5-min oscillations. The spectra were obtained from numerical treatment of three time series (each of 2.5 to 3 hr) taken in the 5250.2 Å line at L = 12″ and with a 1.4 × 6.5″ spectrograph entrance slit; the first series corresponds to the disk center,

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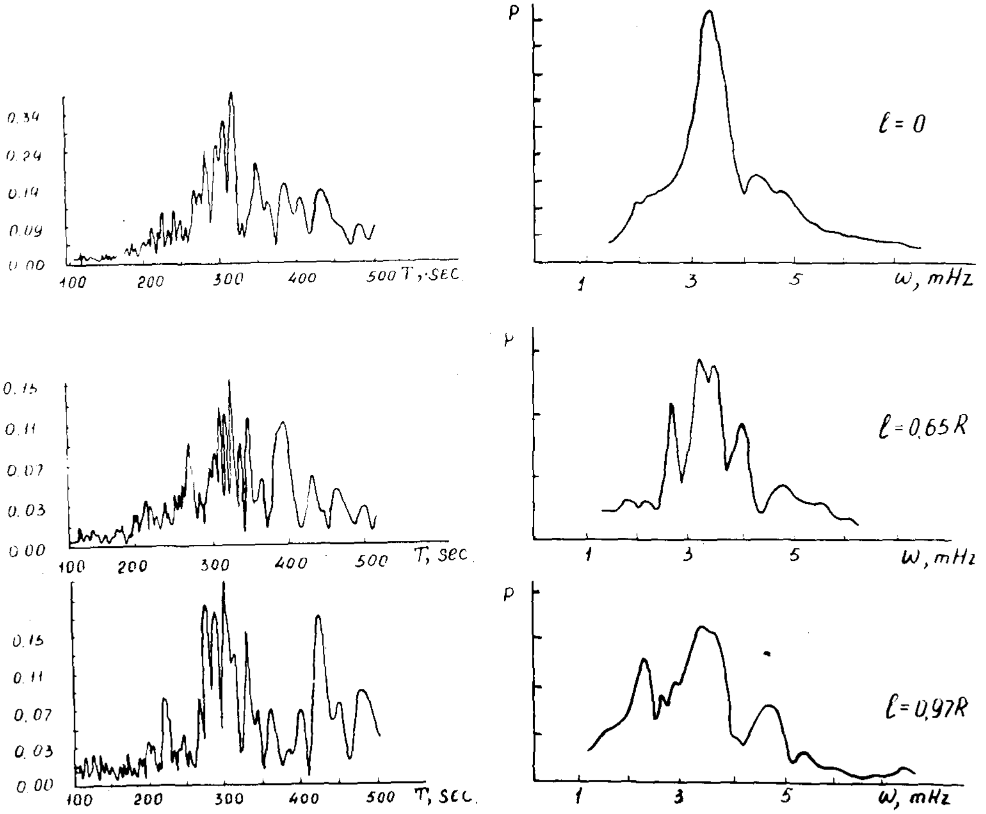

Fig. 6. Center-to-limb variations of the spectrum of 5-min oscillations. On the left are correloperiodograms as calculated by the method of Kopecký and Kuklin (1971); on the right, power spectra. Arbitrary units along the ordinate axis are used for all spectra.

the second to 0.65 R distance between the center and the N-pole, and the third to 0.97 R. Regions for observations were chosen near the central meridian. Typically, with increasing distance from the center there is an increase in side peaks with respect to the main maximum; at the same time, the side peaks are shifted in different directions from their central position, thereby expanding slightly the frequency band. More significant variations refer to the low-frequency region of the spectrum. It is interesting that on some histograms showing the distribution of the number of oscillations with a period, like the one obtained earlier by Howard (1967), a similar behavior of center-to-limb variations can be observed. If these are indeed the real variations of the structure of the spectrum of 5-min oscillations rather than projection effects, for example, then they possibly should be taken into account also in studies on low-frequency global oscillations, being made in integral light with the differential method.

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