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ASTRONOMY AND ASTROPHYSICS

Line-of-sight velocity measurements using a dissector-tube

I. An instrument description

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Abstract. A description of an electronic device for solar Doppler velocity measurements based on a TV dissector-tube is given. As to the principle of measurements, this instrument is the electronic analog of the magnetograph Doppler compensator. The advantages of this device over existing Doppler compensators using a tilting glass plate are the absence of moving parts, the flexibility of the scan parameters, and the high speed. The instrument provides quasi-simultaneous measurements of (a) the shifts of two neighbouring spectral lines, (b) the shifts in a single spectral line at two intensity levels (nearer to the core and the wings), and (c) the spectral line shifts at two points spaced along spectrum height.

The non-uniformity of the photocathode sensitivity must be regarded as the disadvantage of the device. The functional principles of this instrument are described, and some specific errors of measurements are considered. We discuss the influence of: (a) the non-uniformity of photocathode sensitivity, (b) spectral-line inclination in the spectrum, (c) the illumination non-uniformity of the spectrograph entrance slit, and (d) interference and stray light.

Key words: instruments – data analysis

1. Introduction

In 1980, during the process of upgrading the Doppler compensator of the Sayan observatory solar magnetograph (Grigoryev et al. 1985) one of the authors developed an instrument for measuring line-of-sight velocities based on a TV dissector-tube. Subsequently, this instrument was used for observations of oscillations in sunspot umbrae and for investigations of the Evershed effect and velocity oscillations in prominences. In a series of three papers we present some results of these investigations. Paper I gives a brief description of the instrument and discusses possible errors of velocity measurements. In Paper II a description of the photoelectric guider for sunspots is given, and the results of observations of the tangential velocity component variation in the Evershed effect and line-of-sight velocity oscillations in a sunspot are presented. In Paper III we discuss observations of oscillatory processes in prominences.

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2. Description of the instrument

2.1. Principle of operation of the Doppler compensator

Let us remember, at first, the principle of operation of the TV dissector-tube. The optical image, projected onto photocathode 1 (Fig. 1), causes the emission of photoelectrons which are accelerated toward diaphragm 4, under the action of the electric field between photocathode and diaphragm. The magnetic field of the focusing coil 2 contributes to transferring the electronic image to the diaphragm. Electrons that have passed through the opening of the diaphragm 4 to the multiplier 5, correspond to a particular photocathode element. The magnetic field of the deflecting coil 3 deflects electrons in two mutually perpendicular directions. By specifying the form of variation of the deflecting magnetic field, the electronic image can be scanned according to a chosen law. This property of the dissector-tube is employed in the Doppler analyzer (DA) described here.

The DA embodies the compensation principle of measurement. The intensity in the wings of the spectral line are measured by scanning in the direction of dispersion. For this purpose, a square current is fed to the deflecting coil (Fig. 2c). The amplitude of this deflection signal is set so that electrons enter the diaphragm from those areas of the photocathode which receive the light from the chosen sections of the spectral line. If the spectral line is symmetric about the middle of the scanning interval (Fig. 2a, left), the DA output is constant (Fig. 2a, right). In the case of line shift (Fig. 2b, left) an AC-signal at the modulation frequency will appear at the DA output (Fig. 2b, right).

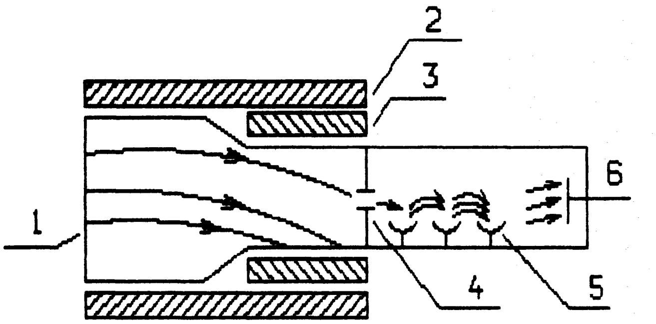

Fig. 1. Circuit of the dissector-tube. Numerals denote. 1: photocathode, 2: focusing coil, 3: deflecting coil, 4: diaphragm with hole, 5: dynode system, 6: anode. Arrows indicate trajectories of photoelectrons

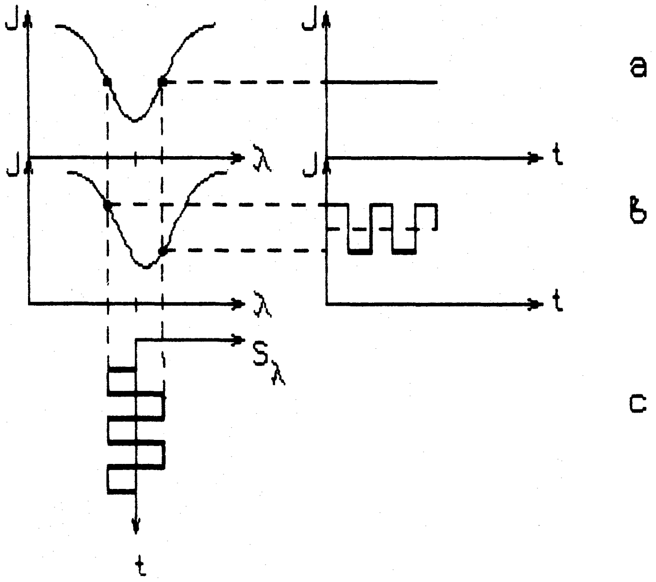

Fig. 2a–c. Diagram explaining operation of the Doppler compensator. At the left: profiles of the nonshifted **a** and shifted **b** spectral lines, and also signal form of interrogation of the spectral line wings **c**. At the right: corresponding dissector outputs

Depending on the direction of line shift, the signal phase varies with respect to the scanning signal. This signal is filtered out, demodulated, amplified and integrated. The integration result in the form of the feedback signal is fed via the voltage-current converter to the deflecting system. The feedback signal plays the role of a compensating action, changing the DC-component of the deflection signal so that the middle of the scanning interval is displaced with the spectral line shift. The displacement occurs until the line is scanned symmetrically again. Incidentally, it should be noted that the DC-signal at the DA output (Fig. 2a, right) characterizes the mean brightness at some intensity level in this line.

Figure 3 presents the functional block-diagram of our Doppler analyzer (DA) which provides a quasi-simultaneous measurement of spectral line shifts by two channels. The output current is converted to voltage by the converter 1 and, through the compensator of the influence of the brightness fluctuations 2, is fed to two measuring channels, each of which consists of a demodulator- filter and an integrator (first channel – devices 3 and 5, and second channel – 4 and 6). The measuring channels operate alternatively. They are connected to the feedback by means of the switch 9. The switching frequency of the channels is a half of the modulation frequency of the spectral line wings. In the case of corresponding deflection signals in X and Y such an analyzer circuit makes it possible to measure either Doppler shifts of two neighbouring spectral lines, or shifts in a single spectral line at two points spaced along the spectrum height, or the spectral line shifts at two levels of intensity (nearer to and farther from the line core).

The amplitude of the AC signal (Fig. 2b) at the DA output depends on the spectrum brightness. That is, in our method of measurement the sensitivity of the measuring channel depends on the brightness. In order to eliminate this, the circuit incorporates the device 2 for compensation of the influence of the brightness fluctuations (Fig. 3) which essentially divides the difference of the signals from the line wings by their sum. Device 2 also makes it possible to equalize the sensitivities of the measuring channels, when simultaneous observations of two spectral lines with different profiles are performed.

The focusing–deflecting system of the dissector makes it possible to interrogate the spectral line wings at the frequency of 600 Hz, without distortion the square form of the scanning signal. With a time constant (τ) of the measuring channels in excess of 1 s, measurements can be considered as quasi-simultaneous.

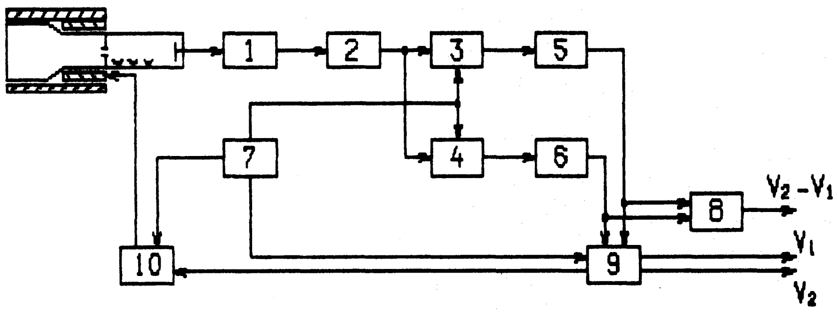

Fig. 3. Functional block diagram of the Doppler analyzer. 1: current–voltage converter; 2: compensator of the influence of the brightness fluctuations; 3, 4: demodulator-filters; 5, 6: integrators; 7: control unit, 8: differential amplifier; 9: switch; 10: voltage–current converter

The idea of a simultaneous operation of two channels implies measurements of the velocity difference at two points. The signals of the first and second channels are subtracted by the device 8 (Fig. 3), or by the subsequent processing. When determining the differential signal, the τ equality of the measuring channels is important. The time constant of each measuring channel is determined by the ratio of the effective τ of the demodulator–filter and the analog integrator (devices 3, 5 and 4, 6), connected in series, to the feedback gain. Before the observation, the time constants are equalized according to the character of their response to an equal input impulsive disturbance (for example, an abrupt spectral line shift).

2.2. *Technical realization*

Two types of dissector-tube with apertures of 0.3×0.3 mm^2 and 0.08×2.3 mm^2 were used in the observations. A subarea of the photocathode with the size equal to the size of the cutting hole of the diaphragm with proper account of the transfer coefficient of the electronic image is called the aperture here. The working area of the photocathode is 16×16 mm^2 in size.

3. Possible errors of line-of-sight velocity measurement

3.1. *Some remarks*

Line-of-sight velocity measurements using the dissector-tube are characterized by the same errors as in other photoelectric observations (let us call them the classical errors). In this section we wish to describe the more specific (nontraditional) errors of Doppler velocity measurement; some of them are typical not only of the DA but also of other instruments measuring spectral line shifts.

All numerical error estimates have been obtained for the line Fe I 5434.5 Å, at a dispersion of 0.45 Å mm^{-1}. The observations were made at the Tashkent horizontal solar telescope (focal length 17 m) with the diffraction spectrograph in the 5th order in the atmospheric line O_2 6874.7 Å, at a dispersion of 0.28 Å mm^{-1}.

3.2. *Non-uniformity of the sensitivity of the dissector-tube photocathode*

When scanning the spectral line, the dissector aperture is displaced along the photocathode, passing the areas with different sensitivity. If the value of sentivity gradient of the photocathode is constant in an area with a larger size than the spectral line width, the error of measurement will have a constant value, independent of the line shift.

If the sensitivity gradient varies gradually from one area to another within the line width, the spurious shift of the spectral line will depend on the measured velocity. In this case (Druzhinin 1984):

$$\Delta V_D = K' \, \Delta\lambda \, c/\{(2\lambda)[1+K(1-3n)]\} \quad (1)$$

where ΔV_D is the value of spurious velocity, $\Delta\lambda$ is the half-width of the spectral line, λ is the wavelength, K is the sensitivity gradient of the photocathode (the intensity ratio of the continuum spectrum near the red and blue wings of the spectral line), c is the light velocity, and n is the residual intensity in the line core. $K' = \Delta K \, \Delta\lambda_0/D$, where ΔK characterizes the variation of K, $\Delta\lambda_0$ is the measured shift of the spectral line, and D is dispersion. When deriving the formula (1), the spectral line profile was approximated by a triangular contour.

For real photocathodes $K \cong 1.01$, and ΔK does not exceed 0.01 per 1 mm. For Fe I λ5434.5 Å $n=0.2$ and $\Delta\lambda = 0.2$ Å. Hence, for example, when measuring the velocity of 2 km s^{-1} ($\Delta\lambda_0 = 0.036$ Å), at a dispersion of 0.45 Å mm^{-1} the error will be 3 m s^{-1} (the relative error of measurement will be 0.16%).

3.3. *Inclination of spectral lines*

Errors of line-of-sight velocity measurements associated with the inclination of spectral lines to the direction of the dispersion manifest themselves in the presence of a brightness gradient along the spectrum height on the entrance aperture of the dissector-tube. Figure 4 illustrates the

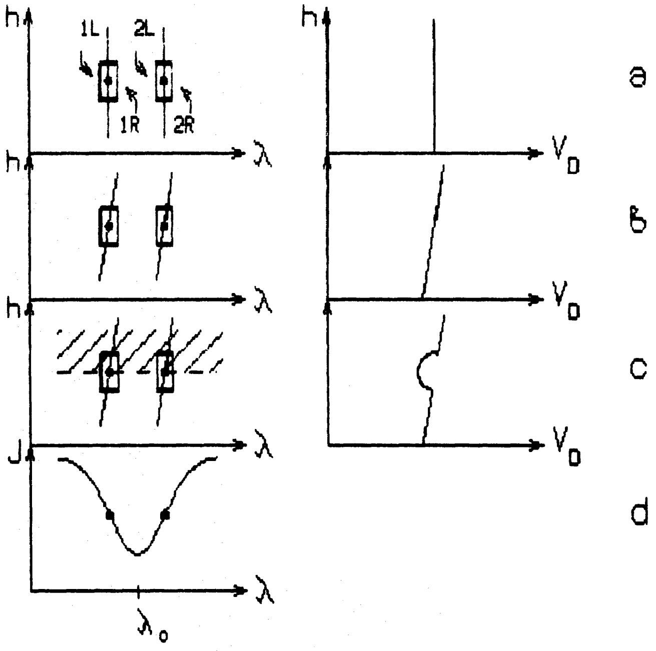

Fig. 4a–d. Schematic representation of the error of line-of-sight velocity measurement in the case of the spectral line inclination to the direction of the dispersion and in the presence of a brightness gradient along the spectrum height. Left: schematic representation of a part of the spectrum: **a, b** with uniform brightness in height h, and **c** in the presence of a contrast boundary in the spectrum. Right: measured line-of-sight velocity profiles along spectrum height. **d** Spectral line profile; squares indicate the entrance apertures of the photometer in the blue and red wings of the spectral line

origin of such errors. Three cases are shown: (a) there is no line inclination, and the brightness along the spectrum height is uniform; (b) the spectral line is inclined, and the brightness is uniform; (c) the line is inclined, and the brightness along the spectrum height is non-uniform. The two squares indicate the entrance apertures of the dissector-tube in the blue and red wings, respectively. Solid lines indicate the positions of the equal intensity levels in the line wings so, as if they were dividing the aperture into two parts. The spectral line contour is given at the bottom of the figure, and the position of the middle of the dissector-tube apertures is marked. When the spectrum is scanned along height (perpendicularly to the dispersion), a different distribution of the line-of-sight velocity (right-hand half of Fig. 4) will be recorded in each of the cases under consideration. In the case of a uniform brightness across the dispersion the spectral line occupies a position such that signal 1L is balanced by 2R, and 2L will be balanced by 1R, irrespectively of the line inclination (Fig. 4a, b). If, however, the brightness is not uniform across the dispersion and the line is inclined, no equality of the signals will occur. In order to attain an equality of the signals from the entire entrance aperture, the spectral line must be shifted. Figure 4c (at the right) shows how the line-of-sight velocity signal will vary when the contrast boundary passes through the entrance aperture of the dissector. Thus, even in the absence of a real solar velocity, a spurious signal occurs.

Model calculations have demonstrated that even with

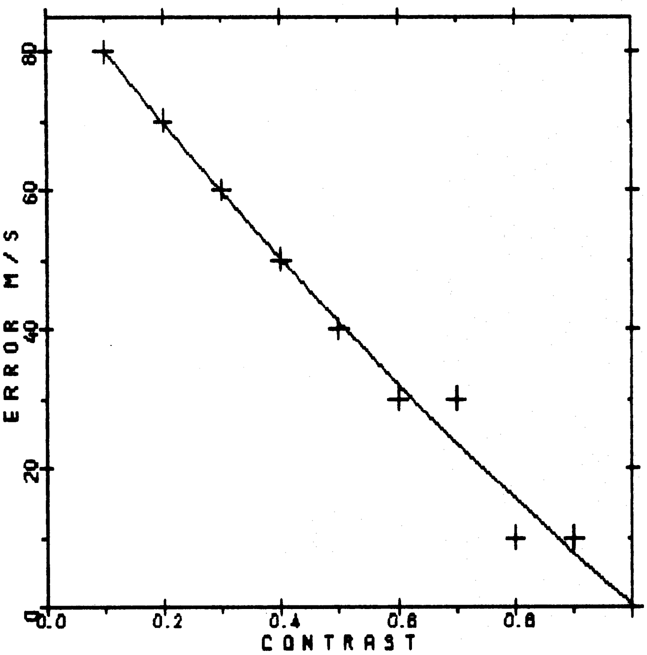

Fig. 5. Dependence of the error of velocity measurement on the magnitude of contrast (brightness gradient) in spectrum height, in the case of 2°-spectral line inclination to the direction of the dispersion. Contrast equal to 1, corresponds to uniform brightness along spectrum height

an inclination of 0.°5 and a contrast of 0.7 (the penumbra-photosphere boundary) perpendicularly to the dispersion, the line-of-sight velocity error reaches 10 m s^{-1}. Figure 5 presents the dependence of the velocity measurement error on the amount of contrast perpendicularly to the dispersion, calculated for the line inclination of 2°. Under contrast we understand the ratio of the brightness at a given point to the mean brightness in the photosphere. The figure gives the calculated values (+) of the error and their approximation by a second-degree polynomial. The error value was calculated in steps of 10 m s^{-1}, as a consequence of which the points for 0.7 and 0.8 contrast deviate from the smoothed curve.

Spectral line inclination is characteristic for spectrographs, in which the spectrum image is constructed below the entrance slit (the spectrograph, at which the observations were carried out, has such disadvantage). The appearance of line inclination is also possible due to poor adjustment of the spectrograph. Besides, an inclination of spectral lines is inevitable when real solar features are observed. If, for example, on the interval of 4″ (along the height of the slit) the line-of-sight velocity changes by 200 m s^{-1}, the spectral line inclination for our observing conditions is about 1°.

3.4. Non-uniformity of illumination of the spectrograph entrance slit

When making photoelectric observations of the Sun, one has often to work with a spectrograph entrance slit of a width larger than normal. In this case, usually, the slit is illuminated nonuniformly because the image with contrast details is projected to it. The resulting spectral line profile in this case will be distorted in accordance with the brightness distribution on the spectrograph slit, and the line asymmetry will appear. Displacements of the image will be accompanied by a change in line asymmetry, which will give rise to a spurious line-of-sight velocity signal.

For evaluating the influence of the velocity gradient over the slit upon the line-of-sight velocity, we used the well-known convolution equation for the spectral line image:

$$I(\lambda')=\int_{-\infty}^{+\infty} W(\lambda)A(\lambda'-\lambda)\,d\lambda \tag{2}$$

where $I(\lambda')$ represents the measured spectral line profile, $A(\lambda'-\lambda)$ is the apparatus function of the spectrograph, and $W(\lambda)$ is the true line profile. The apparatus function was calculated as a superposition of the diffraction profiles:

$$J(\Delta l)=J_0[\sin(R)/R]^2 \tag{3}$$

with the half-width $\Delta l_1=0.02$ Å, and $R=\pi\,\Delta l/\Delta l_1$. For modelling the contrast detail over the aperture, the value of J_0 was varied as $J_0(x)=\sin(Bx+\varphi_0)$, where x is a coordinate along the spectrograph slit width. The sinusoid period equals the slit width. For $W(\lambda)$ we took the Gaussian function:

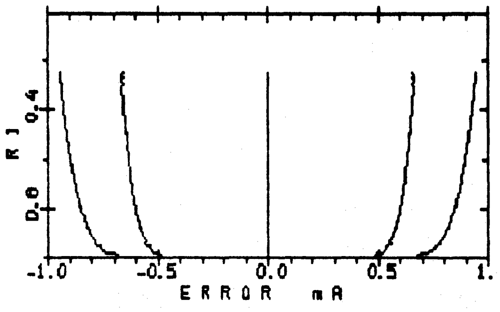

Fig. 6. Variation in the position and shape of the spectral line bisectors in the case of a displacement of the contrast detail across the spectrograph entrance slit. RI – residual intensity

$$W(\lambda)=W_c\left\{1-D\exp\left[C\left(\frac{\lambda-\lambda_0}{\Delta\lambda_e}\right)^2\right]\right\} \quad (4)$$

with the 1/e – width $\Delta\lambda_e$ = 0.2 Å, and the coefficient $C = -8.71034$; D is the residual intensity of line core. The size of the entrance slit image in the spectrum was chosen to be 0.1 Å, which for our observing conditions corresponds to the aperture of 2″. Figure 6 gives the spectral line bisectors calculated in this way, in the presence of a detail on the spectrograph slit with 10% contrast. The bisector in the form of a straight line corresponds to the case when the contrast detail is at the center of the entrance slit and the phase shift of the sinusoid $\varphi_0 = 90°$, while the outer bisectors correspond to the cases when the detail is about at the edge of the spectrograph entrance slit ($\varphi_0 = 0°$ and 180°, respectively). Errors, caused by the non-uniformity of illumination of the slit, manifest themselves more strongly in the core of the spectral line and, as our model calculations show, can reach 25 m s^{-1} for a displacement of the image by 1″.

3.5. Possible errors due to interference and stray light

Optical elements (filters, the Dove prism, and the entrance window of the dissector-tube), located in the light beam, may give rise to interference on the photocathode of the dissector-tube. Through a suitable tilt of corresponding optical elements one can achieve that interference fringes cease to be observed in the brightness; however, when measuring velocities at different levels in the spectral line, fringes unseen in the brightness, are clearly discerned in the differential signal of velocity. Figure 7 gives an example of the recording of the differential signal (Fig. 7a) and the mean brightness signal (Fig. 7b) as observed in the quiet photosphere at the center of the solar disk. The differential signal was determined as the velocity difference at two intensity levels in the spectral line. In this case the spectrum was scanned along height. Numerical estimations showed that in order for such signals to appear in the differential velocity, the contrast of the interference fringes must reach 1%.

When observing solar features with a complicated structure in the brightness and velocity (sunspots), the stray light is able to affect greatly the measured line-of-sight velocities. The presence of the stray light leads to the appearance of spectral line profile asymmetry because the line profile from the stray light having a different Doppler velocity is superimposed on the line profile from the object. It is difficult to take into account the influence of the stray light because it is necessary to know the scattering function and the distribution of velocities and brightnesses in the object. Our simple estimates (Pevtsov 1987) show that relative errors of velocity measurements in sunspots can reach 10–20% for the sunspot penumbra and 40% for the umbra.

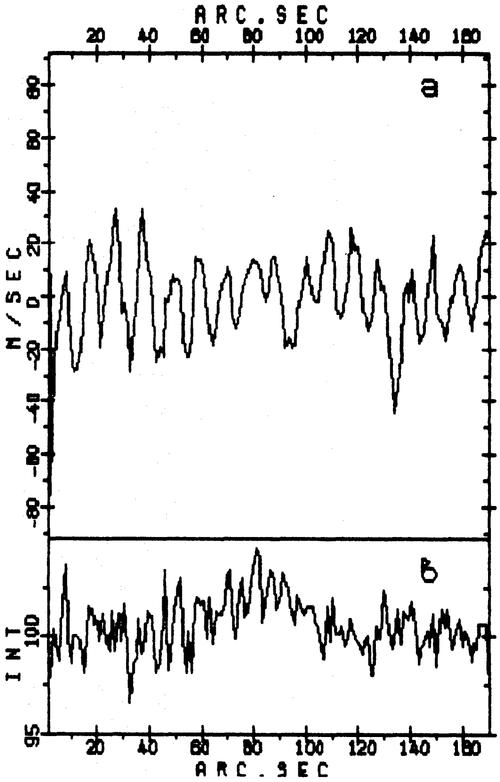

Fig. 7a and b. Interference influence when scanning along spectrum height. **a** Differential velocity signal when measuring at two levels in the spectral line. **b** Brightness signal (in percent of the mean photospheric brightness)

The errors of determining line-of-sight velocities considered above, are rather small; nevertheless, when making measurements to an accuracy of 10–20 m s^{-1}, it is necessary to take into account the possibility of their appearance.

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