Polarization-based devices in solar observations at the Sayan observatory

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ABSTRACT

Several polarization devices for solar observations designed at Sayan observatory are discussed, namely:

1. An electrooptical deflector is used to analyze circular polarization in a spectral line for longitudinal magnetic field measurements. This deflector located after the spectrograph slit incorporates a KD*P crystal and a Savart-plate. In contrast to usual deflectors, it transmits both Zeeman spectral-line components. But it also produces spatial modulation of separation of the Zeeman-split components.

2. An electrooptical deflector of the same type is located in the focal plane of the spectrograph before the photometer slit, to obtain subsequent measurement of the spectral line wings and the line Doppler shift.

3. An electrooptical analyzer is used to measure the magnetic field vector. It incorporates two KD*P crystals and a polarizing prism. The KD*P crystals are controlled by rectangular voltage pulses ($+U_{\lambda/4}, 0, -U_{\lambda/4}$ at frequency f_0 for the first crystal and $\pm U_{\lambda/4}$ at $3f_0$ for the second one). Such an analyzer permits measurement of the Q, U and V Stokes parameters. The properties of the modulator and the control device are discussed.

4. The differential velocity measuring device incorporates an electrooptical deflector and a polarizing beam-splitter located before the spectrograph entrance slit. The device is used to investigate local 5-minute oscillations. The corresponding method of the radial velocity measurements is based on measuring the relative spectral line positions at two different points of the solar image. This method is completely free from spectrograph seeing effects. A modification of this method permits differential solar rotation measurements. The signal calibration methods are also discussed together with their applicability to the determination of the line profile slopness and its variation over the solar image.

Keywords: electrooptical polarization analyzer, electrooptical deflector, method of measuring the solar magnetic filds

1 INTRODUCTION

Astronomy, and solar physics in particular, has always been regarded as the observational science. Nowadays this view stands in need of revision, however. In fact, the term "observations as distinct from the notion of "experiment" implies a passive collection of information about the object. However, electromagnetic radiation of astronomical objects is most seriously affected by researchers. This radiation is resolved into a spectrum; various parts of the spectrum are separated by means of filters; the polarization is measured; interferometry is carried out; etc. This part of the measuring processes and the development of instruments is well worth the name of astrophysical experiment.

In solar physics, the process of measuring magnetic fields and plasma motions in the Sun's atmosphere is best representative of the 'crux' of astrophysical experiment. Instruments for such measurements extensively employ electrooptic crystals and birefringent crystals of Iceland spar (calcite). This latter has such a wide application in astronomy that it is deserving of a special essay.

Below is a description of some polarization instruments based on calcite and electrooptic crystals as developed and used at the Sayan solar observatory.

2 POLARIZATION INSTRUMENTS FOR MEASURING SOLAR MAGNETIC FIELDS AND PLASMA MOTIONS

2.1 General precepts to such measurements

Measurements of solar magnetic fields in astrophysics rely largely on the Zeeman effect. The interaction between emitting atoms and the external magnetic field leads to the fact that the spectral absorption line with frequency ν_o splits into three components in the transverse Zeeman effect. One component with frequency ν_0 is linearly polarized with the electric vector normal to the field. The other two components with frequencies $\nu_0 \pm (e/m)(H/4\pi c)$, where e and m are, respectively, the mass and charge of the electron, and H is the field strength, are linearly polarized with the electric vector parallel to the field.

If one looks along the field, the central component disappears, and the σ-components shows up as a circularly-polarized one. It should be noted that a simple type, triplet splitting, is a special case. In the general case an anomalous Zeeman effect is observed when the line splits into a number of π- and σ-components. The magnitude of splitting of the σ-components is expressed by the formula:

$$\Delta\lambda_H = 4.67 \cdot 10^{-13} g \lambda^2 H \tag{1}$$

where H is in Gauss, and λ in Å. In strong magnetic fields, the value of splitting is comparable to the spectral line width; hence it is possible to measure the value of splitting directly on spectrograms. In the case of weak magnetic fields, split components are strongly blended, and no direct measurement of the splitting is possible. In this case, methods of measurement are based on measuring the polarization in a spectral line.

The state of the radiation field polarization is fully represented by four Stokes parameters: I, Q, U and V.

The distribution of polarization parameters in the spectral line profile is uniquely determined by the value and orientation (with respect to the line of sight) of the magnetic field strength vector.

Thus, the problem of measuring the magnetic field reduces experimentally to an exact determination of polarization radiation parameters in a spectral line. Polarized radiation parameters are measured using polarization analyzers that convert data on polarization conditions to an amplitude modulation of the luminous flux recorded by the photodetector. In this case, components that contain data on the Stokes parameters I, Q, U and V, are separated from the amplitude-modulated signal.

2.2 Polarization mosaic

Polarization mosaics have long been used in visual and photographic measurements of spectral Zeeman split lines in the spectrum of sunspots. The mosaic is placed before the spectrograph slit. The mosaic forms at the entrance slit a raster of orthogonal polarizers. The quarter-wave phase plate before the mosaic, whose fast axis makes the angle of 45° to the raster polarization planes, converts the circular polarization of the σ-components of the spectral magneto-split line to mutually-orthogonal linearly-polarized components which successively pass to alternating raster stripes. The spectrograph focal plane shows raster stripes, showing alternatively right- and left-handedly polarized Zeeman split components; the amount of magnetic splitting can be readily measured as the distance between the right- and left-handedly components in neighbouring raster stripes.

Usually, the mosaic of orthogonally polarizing stripes (raster) was made of polaroid film. When cutting stripes of film, this flakes on its edges, so the raster boundaries are not sharp and narrow enough. Moreover, polaroid films are not transparent enough in a wide spectral region; they deform and fade due to heating in the light beam.

We have developed a mosaic that is devoid of these flaws, and its manufacture is a stable production process. It is easy to organize the production for their extensive use by amateur astronomers.

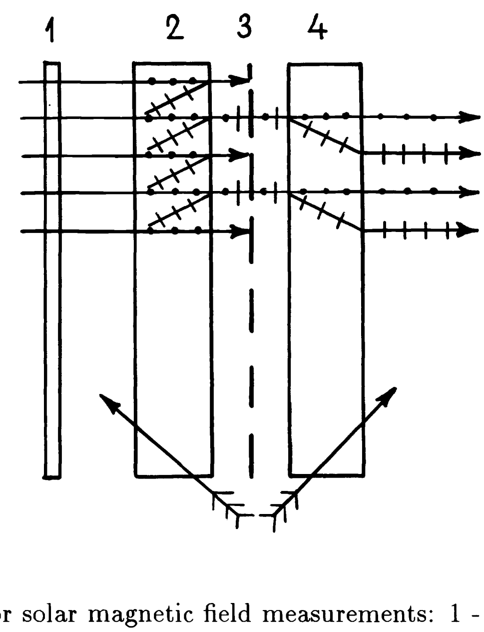

Figure 1: A Scheme of a mosaic for solar magnetic field measurements: 1 - $\lambda/4$ - phase plate; 2 and 4 - calcite plate, 3 - raster stripes.

The new mosaic is schematically shown in Fig. 1. It consists of two calcite plates, rotated by 180° with respect to each other, and a raster of transparent and opaque stripes in between. The bifurcation plane of the calcite plates coincides with the direction of the spectrograph slit. The first spar plate splits each element of the solar image. The plate's thickness is chosen such that the splitting is equal to the raster grid step. Then the light of one polarization passes through the transparent raster stripe, and the light of opposite polarization extinguishes on the opaque stripe. On the whole, each transparent plate lets the light pass from two neighbouring pixels that are superimposed and are oppositely polarized. In the second calcite plate, this superposition is eliminated. Mosaics with 0.2 and 0.4 mm steps have been constructed and are in operation at the Sayan observatory.

2.3 The electrooptic deflector as a circular polarization analyzer in magnetographs for the longitudinal component of field

An element shared by most solar magnetographs is the electro-optic circular-polarization analyzer, composed of an electro-optic KD*P crystal and a polarizer[1]. Such an analyzer transmits either the left- or right-handedly polarized components of a magnetically-split line depending on the voltage applied. Two slits and two photomultipliers, placed in the line wings, produce the signal

$$\delta_{\parallel} \sim 4 I_0 \frac{\partial r}{\partial \lambda} \Delta\lambda_H, \tag{2}$$

where I_0 is the continuum intensity, $\partial r / \partial \lambda$ is the slope of the wing of the absorption line, and $\Delta\lambda_H$ is the Zeeman splitting (i.e. the distance of the σ-component from a normal line position).

The disadvantage to such devices is the use of two photoreceivers that have different characteristics, as well as the need to balance them before each observation. A variety of magnetograph designs featuring a single photomultiplier were suggested, but they included a large number of additional optical elements, and they did not gain acceptance because of serious light losses. We have proposed an electrooptic deflector design as the circular polarization modulator where the luminous flux of both σ-components is incident on the photomultiplier simultaneously, but their spatial position is modulated. The principle of operation of such an electrooptic deflector is shown schematically in Fig. 2.

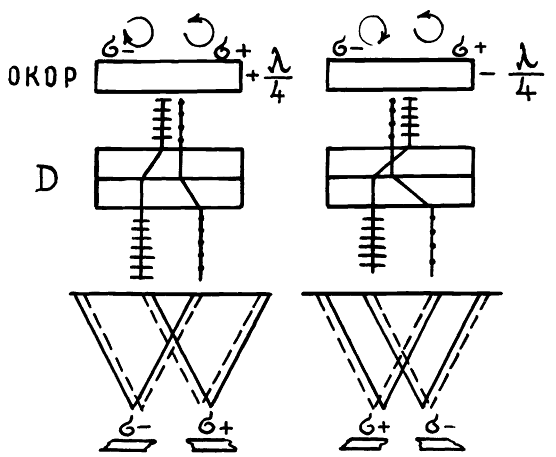

Figure 2: A Scheme of the electro-optical deflector as a circular polarization analyzer in longitudinal field magnetograph.

The deflector consists of an electrooptic crystal to which the AC electric voltage is applied, and a system of two calcite D plates that splits the spectral line image along the direction of the spectrograph dispersion. When the crystal is a $+\lambda/4$-plate, the σ-components that have passed through it, become plane-polarized perpendicularly to each other. The system of the calcite D plates transmits the σ_--component to the left and the σ_+-component to the right, so in the spectrum we obtain the image of two σ-components separated by $\Delta\lambda_0 + 2\Delta\lambda_H$, where $\Delta\lambda_0$ is the amount by which the system separates the calcite plates, and $\Delta\lambda_H$ is magnetic splitting. When the crystal becomes a $-\lambda/4$-plate, the state of polarization of the σ-components that have passed through the crystal, is reversed, and the system of the calcite plates makes the σ_+-component deflect to the left and the σ_--component to the right. In the spectrum, we obtain the image of the σ_+- and σ_--components separated by $\Delta\lambda_0 - 2\Delta\lambda_H$. The exit slit and the photoreceiver that lie between the images of the σ-components, provide the signal at the modulation frequency proportionate to $4\lambda_H$. In designs with a conventional modulator, such a signal is obtained by the combination of the signals from two photomultipliers in the line wings.

2.4 The electrooptic polarization analyzer of the Sayan observatory vector-magnetograph

In the general case the electrooptic polarization analyzer is the combination of two variable plates, M_1 and M_2 (or one constant and one variable), and polarizer P (Fig. 3). The action of the whole system on the polarized light is described by the Muller matrix $M = P(\alpha)M_2(\delta, 0)M_1(\delta, \beta)$, with the initial frame of reference coinciding with the axes of crystal M_2. By taking different values of the angles α and β of phase shifts $\delta_1(t)$ and $\delta_2(t)$ as a function of time, it is possible to consider the various polarization analyzer designs currently in use in solar magnetographs.

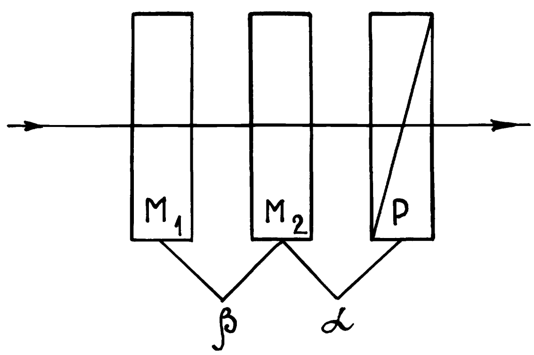

Figure 3: General case of an electrooptical polarization analyzer.

The feature common to most magnetographs was the use of the control sine voltage on electrooptic crystals ($\delta = \delta_0 \sin\omega t$) when information about the Stokes parameters Q, U and V is contained in signal harmonics at ω and 2ω frequencies.

To separate the signals, the property of evenness of the parameters Q and V and the property of oddness of the parameter V with respect to the spectral line are used. By adding and subtracting the signals from two wings of the line, it is possible to single out the three parameters. This procedure applies for the case of a symmetric line and a symmetric position of the slits with respect to the line center. Otherwise, the V-parameter would penetrate into the Q-parameter signal, and vice versa. This introduces errors into magnetic field vector measurements.

In addition, small distortions of the sine voltage shape on the electrooptic crystal lead to a marked harmonic power redistribution and to a possible appearance of spurious signals. Since the voltage amplitude on electrooptic crystals reaches 3 or 4 kV, nonlinear distortions of about 5-7% are nearly inevitable.

The above limitations led us to conclude that the sine modulation should be rejected and that the best solution should be sought in the application of impulse square-wave voltages. There also exist general theoretical arguments in favour of the square-wave modulation in optical instruments.

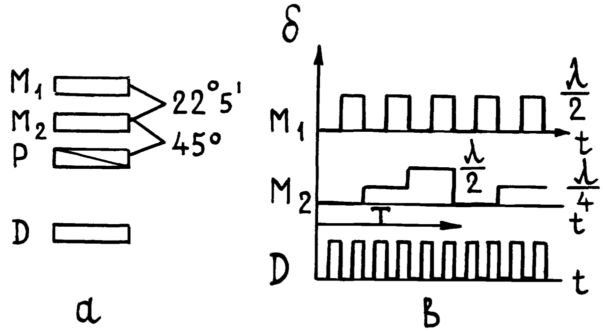

Figure 4: a) The optical system of the polarization analyzer of Sayan observatory vector magnetograph.
b) The fine history of phase shifts produced by electrooptical crystals in such a system.

The optical system of the analyzer which we are using, is shown in Fig. 4a. Crystal M_1 is aligned at the angle $\beta = 22.5°$ to the axes of crystal M_2, and polarizer P is aligned at the angle $\alpha = 45°$. Fig. 4b shows the time diagram of phase shifts between the ordinary and extraordinary rays in crystals M_1 and M_2. One period of modulation contains six states of the electrooptic analyzer. Photoreceiver outputs, corresponding to these states, are proportionate to $I + U$, $I + Q$, $I + V$, $I - U$ and $I - Q$. The pairwise subtraction of signals in appropriate analyzer states ensures an independent recording of the parameters Q, U and V in a certain part of the spectral line. Measurements in two wings of the line can be made to obtain signals of the line-of-sight velocity and its compensation, as well as it is possible to combine the signals of the corresponding parameters Q, U and V from two wings of the line in order to improve the signal/noise ratio and reduce the instrumental polarization effect. Measurements in two wings of the line with two photoreceivers require balancing them in the continuum spectrum prior to the observation. The sensitivity drift of one photoreceiver with respect to the other will introduce an error into the determination of the line position. A balancing error of 0.1% will give an error in the Doppler velocity determination as large as several tens of meters per second.

Such errors are missing from the design with one photoreceiver which uses the electrooptic deflector to switch the photoreceiver from one line wing to the other.

The photometer design with the electrooptic deflector is shown in Fig. 5. The electrooptic deflector consists of the electrooptic crystal and two calcite plates, whose axes are mutually perpendicular and make angles of $\pm 45°$ with the crystal axes. The deflector is placed in front of the photometer slit in the spectrograph's focal plane. The radiation incident on the deflector from the electrooptic analyzer is linearly polarized. The modulating voltage that produces a phase difference on crystal 0, $\lambda/2$, is fed to the deflector. With phase 0 on the deflector, the light from one line wing passes through the slit; with phase $\lambda/2$, the light comes from the other wing. The distance between the parts of the line wings that correspond to the photometer slit, is determined by the thickness of the calcite plates. The difference of signals measured in the right- and left-hand line wing during the modulation period is proportionate to the amount of the line Doppler shift.

2.5 Electrooptic deflectors in instruments for measuring the differencial line-of-sight velocity

The advent of these methods is associated largely with the awareness of the fact of relativity of a large group of motions on the Sun studied. In fact, when studying movements in any solar feature (sunspot, filament, spicule, plage, prominence), the observer is primarily interested in the direction, the velocity and the character of variation of these parameters relative to the surrounding medium. But with respect to the observer the object under investigation can participate simultaneously in several motions. Let us mention some of them: solar rotation, diurnal rotation of the Earth, motion of the Earth in circumsolar orbit, and large-scale motions of whole active regions. Thus, an absolute value of line-of-sight velocity of the object under study comprises many components and depends on the object's heliographic location, the time of year and the time of day of the observation, and the observatory's geographic location[2]. Based on absolute measurements it is difficult and sometimes impossible to understand the character of the motion, especially if very small changes of parameters observed are the subject for study. As is known, both the solar rotation and the Earth's rotation and, all the more, large-scale motions in the solar atmosphere themselves undergo fluctuations over a reasonably wide time range. In addition, when using the diffraction spectrograph, the sensitivity of line-of-sight velocity measurements is limited by the spectrograph intrinsic noise manifested as chaotic spectral line displacements equivalent to a line-of-sight velocity as high as 200 ms^{-1} [3–5]. By measuring the Doppler shift difference between two spectral line components produced by the light from two regions on the solar surface, it is possible to fully eliminate the resulting influence of measurements of the rotation of the Earth and its orbital motion. Quite importantly, such methods which we will call the spatially-differential methods in what follows, almost totally compensate the spectrograph intrinsic noise[6–8]. Relative measurements are particularly suitable for investigating of the wave processes because the definition of the wave alone implies the relativity of the motion at different points of space (wave phase).

At our Institute, the spatially-differential method was further developed for investigating local parameters of quasiperiodic motions in the solar plasma[8]. A simplified optical system is presented in Fig. 6. The system embodies the principle of simultaneous illumination of the spectrograph entrance slit with the differently-polarized light coming from elements A and B of the solar image equal in their area. These elements are spaced some variable distance L apart. This procedure is achieved by means of an ensemble, composed of the calcite plate and the quarter-wave phase plate, placed immediately in front of the spectrograph entrance slit. With a line-of-sight velocity difference in elements A and B, each spectral line will turn out to consist of two components that differ in the direction of the circular polarization. Measurements are made by means of the electrooptic deflector and a single-slit photometer used by us as described previously for measuring the magnetic field strength. Through suppression of the spectrograph intrinsic noise, the method ensures a sensitivity of measurement of about 0.2 ms^{-1} and dispenses with the need for complicated and expensive procedures for spectrograph stabilization. Another merit of the method is its selectivity to solar oscillation modes of a different degree l and the possibility of controlling it, again by means of the calcite plate[9–11].

Currently the Sayan observatory is doing research on the solar surface rotation rate using a method also based on differential line-of-sight velocity measurements[12]. The method involves direct measurement of the line-of-sight velocity difference of two regions symmetric about the central meridian. The measured line-of-sight velocity difference is converted to the rotation rate at a given heliographic latitude. The principle of measurement is explained by Fig. 7.

It is easy to see that, when passing from a spectral line to the continuum spectrum, the spatially-differential method of line-of- sight velocity measurement is transformed into a high-sensitivity method of measuring the contrast of solar surface details.

It is interesting to note that, if the above-mentioned combination of calcite and the $\lambda/4$-plate is placed immediately behind rather than before the spectrograph entrance slit so that the direction of separation of the rays in calcite coincides with the dispersion direction, we get new possibilities for the calibration of magnetographic measurements and investigating fluctuations of the spectral line profile slope[13]. Taken together this can do not mere than confirm the broadest potentialities afforded by the use of calcite in astrophysical experiment.

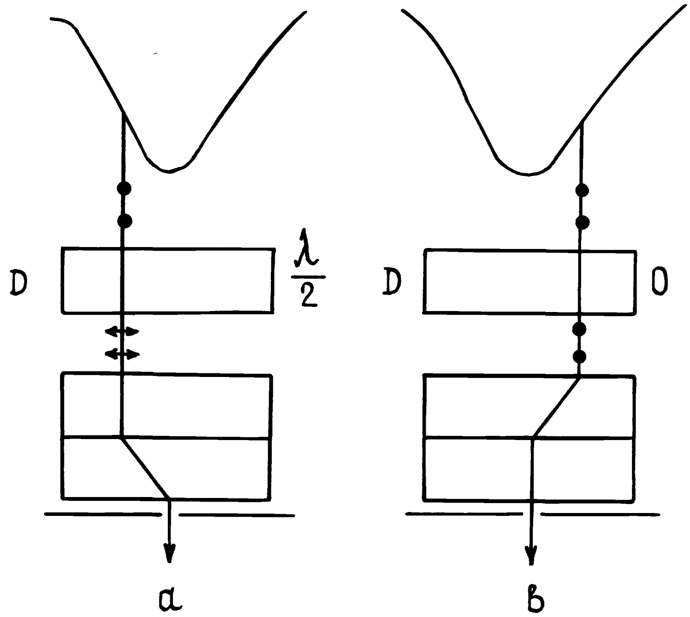

Figure 5: A Scheme of a photometer with an electrooptical deflector for line-of-sight velocities measurement.

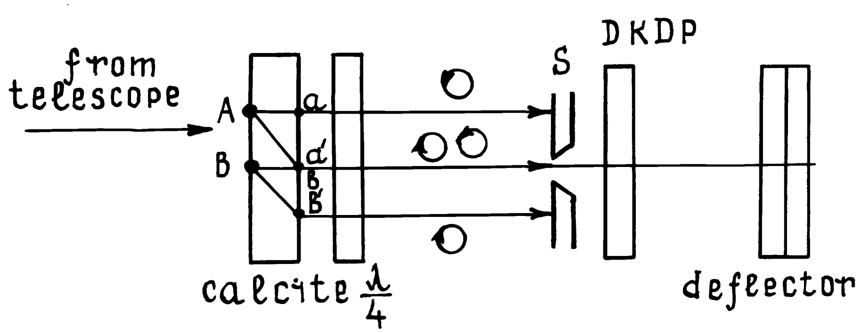

Figure 6: A block-scheme of the spatial-differential method.

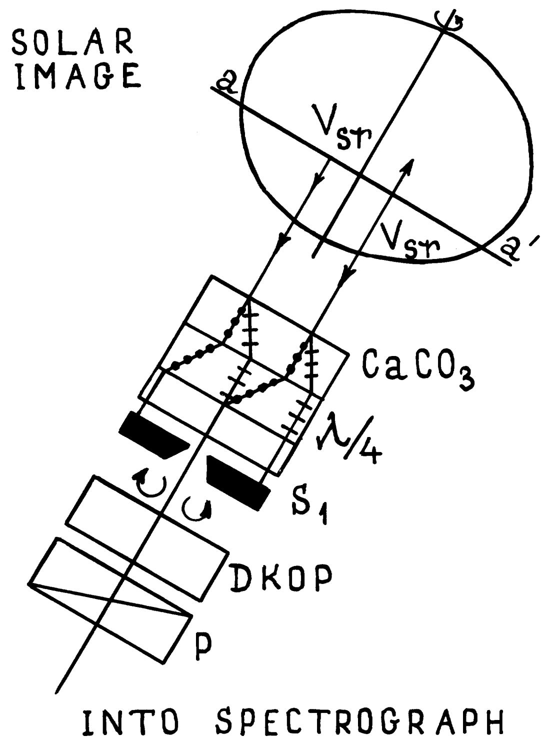

Figure 7: Scheme of device used for measuring the solar rotation velocity. The solar image is 50 mm in diameter. **aa′** is the line of divergence of rays in the calcite crystal. The arrows on the disk indicate the direction of the line-of-sight component of rotation velocity V_{sr}. S_1 - entrance slit of the spectrograph. The KD*P crystal and Glan prism P form the circular polarization analyzer.

2.6 On the accuracy of adjustment of the electrooptic crystal with respect to the spectrograph's optical axis

In optical systems of telescopes and spectrographs, electro- optic polarization analyzers are usually placed in convergent or divergent light beams with the angular aperture of up to 3°. Therefore, angular field effects take on great significance. The point is that the electrooptic crystal is not exactly a $\lambda/4$ - or $\lambda/2$-plate for off-axis rays. In polar coordinates, equal phase delay curves are represented by Cassini ovals, with bands at exit point of the crystal optical axes. When the electrooptic field in the crystal is reversed, the plane in which the optical axes lie, rotates by 90°, and the pattern of equal phase delay curves corotates with it. Also, if the axis of the ray cone is tilted to the crystal, the phase delay integrated over all rays will be different for different modulation states. This will lead to mutual penetration of linear and circular polarization signals. Similar errors arise when the cross-section of the light beam cone in the spectrograph deviates from a circular shape. This may be attributed to a very oblique incidence of rays on the coelostat mount mirror during the morning and evening hours, or when the light beam cross-section is not inscribed in the diffraction grating but circumscribes it. These effects were addressed in papers[4,14], with the formulation of the following requirements:

1. electrooptic KD*P crystals must be as thick as 1-2 mm;
2. the optical system of the telescope and the spectrograph must ensure a circular cross-section of the light ray cone inscribed in the diffraction grating dimensions;
3. the adjustment error of the electrooptic crystal z-axis must not exceed 1/10 of the angular aperture of the light beam.

3 ACKNOWLEDGMENT

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