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Polarization Characteristics of the Horizontal Automatic Solar Telescope (HAST) at the Sayan Observatory

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Abstract. This paper presents results derived from a theoretical investigation of the polarization properties of the Horizontal Automatic Solar Telescope (HAST) at the Sayan observatory. The behavior of the Stokes vector parameters was calculated depending on the declination and hour angles, as well as on geometrical parameters of the telescopes coelostat.

1. Introduction

When studying the origin of magnetic fields, it is usually necessary to measure the polarization of the light emitted by the concerned area of the solar surface. In this case the degree of measured polarization is frequently relatively small and is therefore strongly affected by a variety of side factors. One of the most meaningful factors of this kind, when mirror telescopes are used, is the instrumental polarization (IP). The situation is further complicated by the fact that the IP depends in a complicated manner on both the solar declination and hour angle. Of course, this introduces a significant error in measurements which behave in a rather complicated way over time. This dictates the necessity of taking a detailed account of the IP when interpreting measurements. Since every stationary telescope has an original optical system, it is necessary to carry out a detailed study of the IP in each particular case. In this paper, a theoretical study is made of the IP of the optical system of the Sayan Solar Observatory's Horizontal Automated Solar telescope (HAST) designed for measuring the magnetic field vector in active regions in the photosphere.

2. The telescopes basic elements

The HAST optical system is schematically illustrated in Fig. 1. The letters "a" and "b" correspond to the top and side views, respectively. Here M1 and M2 designate the coelostat and the auxiliary mirror which sends the beam to the primary parabolic mirror M3 of the telescope. Diagonal mirror M4 directs the beam to the spectrograph slit. Mirrors M1 and M2 can move on rails relative to each other, perpendicular and parallel to the main meridian plane, respectively. The maximum distance between auxiliary mirror M2 and the meridian plane, on which the center of the coelostat mirror lies is $D_{max} = 650$ mm. A is the distance from the center of the coelostat to the vertical plane containing mirror M2 and can vary from 250 mm to 2000 mm. M2, M3 and M4 are arranged in a single

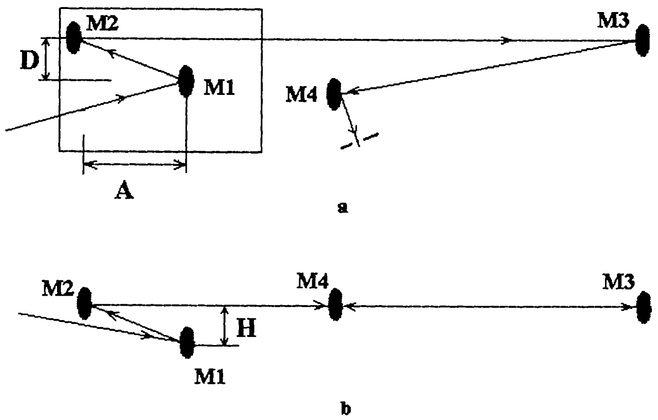

Figure 1. Optical design of the telescope. a - top view; b - side view.

horizontal plane, whereas M1 is lower by a constant value of H=485 mm. The angles of incidence on mirrors M3 and M4 are constant, 5°and 46°, respectively. The optical constants of the mirrors are taken from Demidov (1991).

3. Calculating the influence of the telescopes optical system on the polarization of the incoming beam

First, it is necessary to calculate the values of D and A, with the latitude of the location $\varphi = 51°37'18''$, the solar declination δ_S, and H=485 mm specified. D is taken to be a free parameter which is best to set such that it is minimal in the absence of vignetting of the coelostat beam by the mirror M2. Next, the hour angle of the auxiliary mirror t_0 can be determined using the coelostat formula from Ponomarev (1945). It should be noted that in the process of calculating the above parameters their non-optimality was shown theoretically. Indeed, at the winter solstice when $A_{min} = 250mm$, D must be around zero, but for the diameters d=770 mm of the mirrors of the coelostat group, this will lead to strong mutual vignetting and to a limitation of the rotation angle of the coelostat. In real practice, difficulties emerge already when $\delta = -15°$. To overcome this drawback, it seems appropriate to increase the parameter H to 690 mm as a minimum.

As the beam traverses the optical system, it experiences a polarization effect from the four mirrors. In terms of the matrix optics and of the Stokes parameters, this may be expressed by the following formula (Shercliff 1962):

$$S = M_4(i_4)M_3(i_3)R_3(\theta_3)M_2(i_2)R_2(\theta_2)M_1(i_1)R_1(\theta_1)S_0, \qquad (1)$$

where $S = (I, Q, U, V)$ and $S_0 = (I_0, Q_0, U_0, V_0)$, respectively, are the Stokes vectors at the exit and entrance of the optical system; $M_4(i_4)$, $M_3(i_3)$, $M_2(i_2)$ and $M_1(i_1)$ are Mueller's matrices for the respective mirrors; i_1 , i_2 , i_3 and i_4 are the respective angles of incidence of the beam on these mirrors; $R_j(\theta_j)$ are the rotation matrices by angles θ_j, with θ_1 being the angle between the plane of the Sun's hour angle and the plane of incidence of the beam on mirror M1,

θ_2 is the angle between the planes of incidence on M1 and M2, and θ_3 is the angle between the planes of incidence on M2 and M3. Here all rotation angles are measured clockwise along the direction of the beam. Equation (1) does not involve the matrix of rotation between mirrors M3 and M4; this is accounted for by the fact that the planes of incidence for these mirrors lie in a single horizontal plane, and hence the rotation angle is 180°; furthermore, since in the matrix of rotation for the Stokes vector the angle is doubled, the above-mentioned matrix is a unity matrix. The angles i_1 and θ_1 are calculated from formulas of spherical trigonometry, and satisfy the relations:

$$ctg(\theta_1) = ctg(1/2(t_0 - t_S))sin\delta_S, \tag{2}$$

$$cos(i_1) = cos(1/2(t_0 - t_S))cos\delta_S, \tag{3}$$

where t_0 is the hour angle of mirror M2, t_S and δ_S are the hour angle and the declination of the Sun respectively.

The angles θ_2 and i_2 are calculated straightforward from the geometry of the coelostat group by the following equations:

$$cos(\theta_3) = D/\sqrt{H^2 + D^2}, \tag{4}$$

$$cos(2i_2) = A/\sqrt{H^2 + D^2 + A^2}, \tag{5}$$

In equation (4), D should be taken with the "+" sign when t_0 is positive, and vice versa, which will permit the rotation angle to be taken into account when reversing the mirrors. The situation is more complicated with the rotation angle θ_2 between the planes of incidence on coelostat M1 and on auxiliary mirror M2. It may be represented as the sum of the following components:

$$\theta_2 = \theta_2^{|} + \theta_2^{||} + \theta_2^{|||}, \tag{6}$$

where $\theta_2^{|}$ is the angle between the plane of the hour circle of the auxiliary mirror and the plane of incidence of the coelostat, and the formula for calculating it coincides with (2); $\theta_2^{||}$ is the angle between the plane of incidence of the beam on the auxiliary mirror and the vertical plane containing this beam; and $\theta_2^{|||}$ is the angle between the plane of the hour circle of mirror M2 and the above-mentioned vertical plane. The angle $\theta_2^{||}$ is calculated from the geometry of the coelostat group by the formula:

$$sin(\theta_2^{||}) = AD/\sqrt{(H^2 + D^2)(H^2 + A^2)} \tag{7}$$

The rule for D must also be taken into account here, as done in (4). For $\theta_2^{|||}$, it is possible to specify the following relation:

$$tg(\theta_2^{|||}) = -tg(t_0)sin\delta_S \tag{8}$$

The components of Mueller's matrices are calculated by formulas of reflection from absorbing media according to Prishivalko (1963). As has been pointed

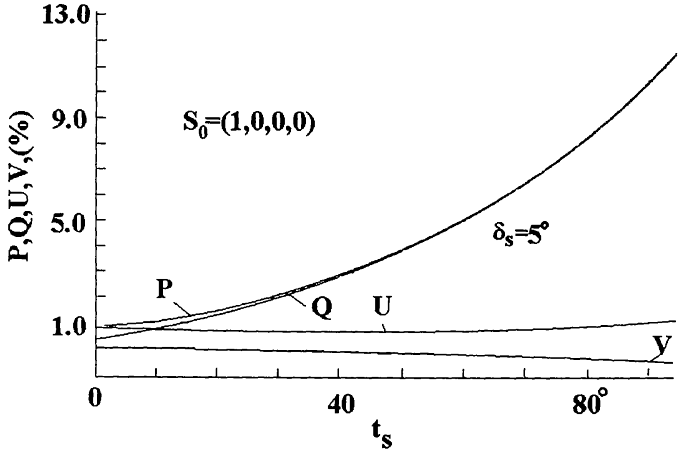

Figure 2. Variation of the Stokes parameters and polarization coefficient depending on the hour angle of the Sun. Mirrors M3 and M4 are not taken into account.

out above, the optical constants were taken from Demidov (1991); this is explained by the fact that the IP in the cited reference is calculated for a telescope located at the same observatory, and the mirrors of the telescopes were coated in the same laboratory. This gives good reason to believe that the mirrors will have identical optical properties. Specifically, the refractive index n is taken in calculations to be 1.21, and the damping factor $\chi = 6.08$.

4. Results and discussion

For calculating the Stokes parameters at the exit of the optical system of the HAST, a program has been developed to operate in the Windows95 operational environment, which provides a convenient interface and graphical display of the dependencies of the Stokes parameters and the degree of polarization P on the Sun's hour angle. The degree of polarization is calculated by the following formula:

$$P = \sqrt{Q^2 + U^2 + V^2}/I \tag{9}$$

Also, the program eases the study of the behavior of these curves by manipulating the optical system's parameters. Provision is made to take into account or to neglect, at the user's will, the contribution from mirrors M3 and M4 in order to estimate this contribution. Thus, Fig. 2 illustrates the behavior of the Stokes parameters and of the degree of polarization P when $\delta_S = 5°$ without taking into account the primary and diagonal mirrors, provided that the natural light is sent to the telescope. Here and in all figures given below, $D = D_{max}$, and t_0 is positive. It must be remarked that the Stokes vector here is normalized to the output intensity. It is seen that all parameters, as would be expected, tend to a minimum when approaching $t_S = 0°$. Of course, this is the result of a minimization of the angle of incidence on the coelostat mirror. The linear po-

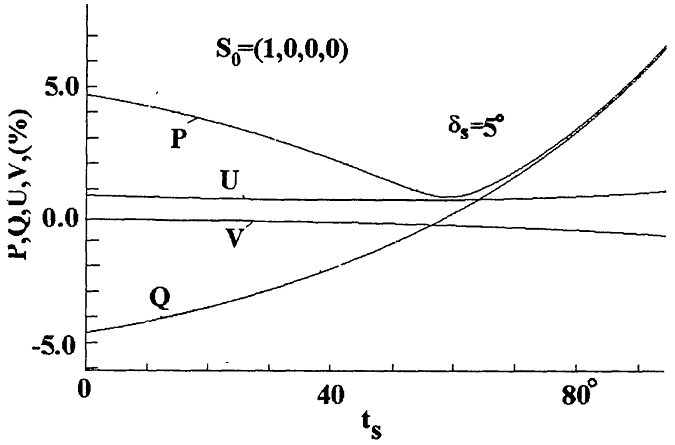

Figure 3. Variation of the Stokes parameters and polarization coefficient depending on the hour angle of the Sun. The influence of mirrors M3 and M4 is taken into account.

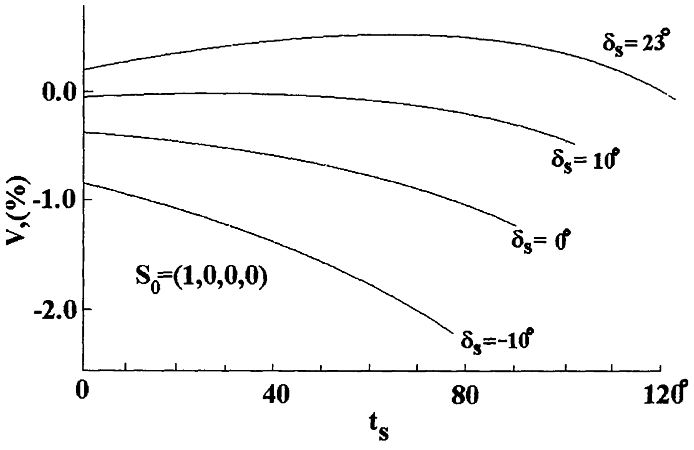

Figure 4. Variation of the V-parameter depending on the hour angle of the Sun. The initial Stokes vector is $S_0 = (1, 0, 0, 0)$.

larization reaches 12%, whereas the circular polarization does not exceed -0.7%. A minimum P is attained when $t_S = 0°$, and makes up 1.1%. The behavior of the curves with the inclusion of the objective M3 and diagonal M4 mirrors is shown in Fig. 3, as well as in all figures given below. The degree of polarization attains a minimum already when t_S is different from 0°, and reaches only 0.8%. The values of the V parameter have also increased significantly - it now reaches about -1%. Such a relatively strong influence is accounted for by a rather large angle of incidence (46°) on diagonal mirror M4, whereas the influence of mirror M3 is negligible because of the small angle (5°). The program can also calculate all Stokes parameters for different initial Stokes vectors and declinations of the Sun. The results for the V-parameter are presented in Fig. 4 and Fig. 5, for Q in Fig. 6 and Fig. 7, and for U in Fig. 8 and Fig. 9.

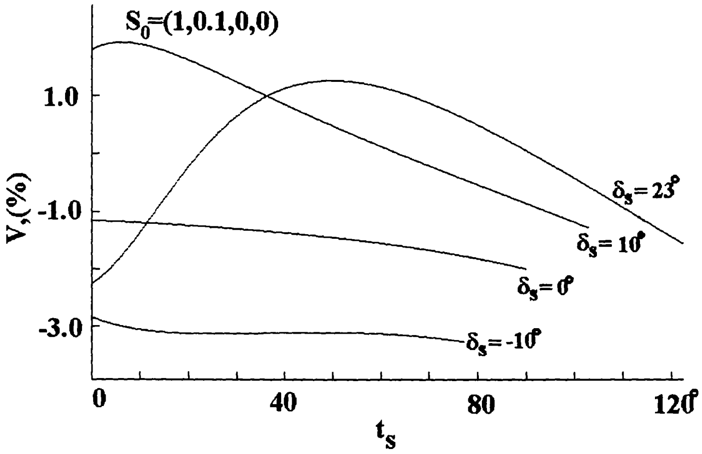

Figure 5. Variation of the V-parameter depending on the hour angle of the Sun. The initial Stokes vector is $S_0 = (1, 0.1, 0, 0)$.

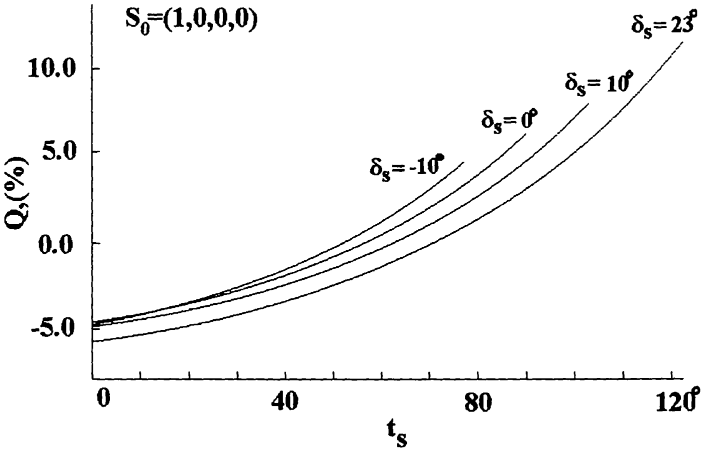

Figure 6. Variation of the Q-parameter depending on the hour angle of the Sun. The initial Stokes vector is $S_0 = (1, 0, 0, 0)$.

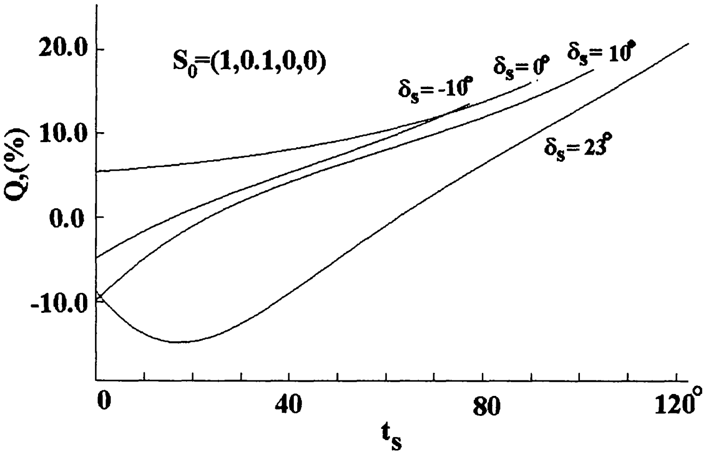

Figure 7. Variation of the Q-parameter depending on the hour angle of the Sun. The initial Stokes vector is $S_0 = (1, 0.1, 0, 0)$.

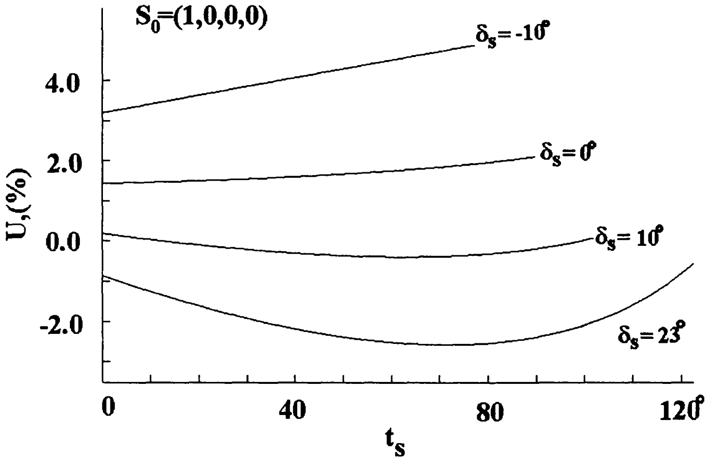

Figure 8. Variation of the U-parameter depending on the hour angle of the Sun. The initial Stokes vector is $S_0 = (1, 0, 0, 0)$.

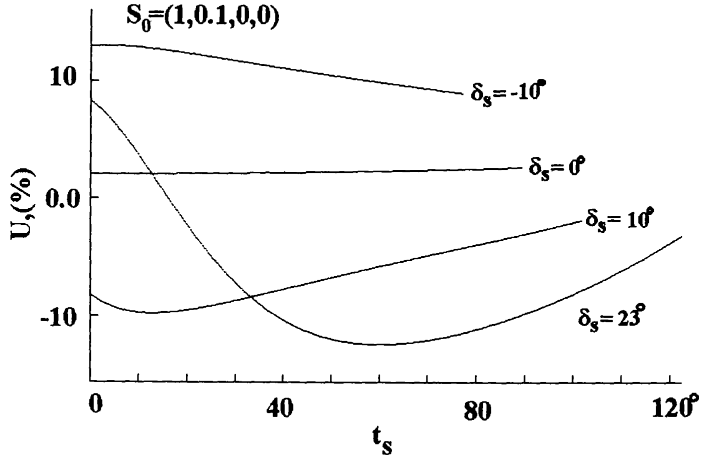

Figure 9. Variation of the U-parameter depending on the hour angle of the Sun. The initial Stokes vector is $S_0 = (1, 0.1, 0, 0)$.

5. Conclusion

A further logical step in this research area will involve experimental verification of the theoretical data directly at the telescope. The primary objective will then be to determine, as accurately as possible, the optical constants of the optical system's mirrors. There are two possible procedures in order to achieve this objective. One implies 'forcing' the above-mentioned parameters from the theoretical model to fit experimental results, as described in Demidov (1991). The other procedure includes measuring the elliptical polarization of the mirror-reflected light using a special-purpose polarimeter, as described in Sankarasubramanian et al. (1999).

It should be noted in conclusion that this research effort is of interest from the methodological point of view, and makes it possible to select most effectively the time of observation and the parameters of the optical system, as well as to more accurately interpret final results.

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