On consideration of instrumental polarization in monochromator measurements of brightness and polarization of diffuse skylight

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Possible errors in measurements of diffuse skylight by spectral devices free of analyzers are discussed. With a DMR-4 double quartz monochromator taken as an example, it is shown that the degree of instrumental polarization can exceed 0.2, which may result in 20% underestimation of real brightness at unfavorable relation between the skylight and instrument polarization angles. The equations for consideration of instrumental polarization are presented.

Spectral instruments with various spectral resolutions are often required in studying optical phenomena in daytime and twilight skylight. The instruments used in such cases are commonly spectrographs or monochromators with CCD linear arrays or photomultiplier tubes (photodiodes) as radiation detectors. If a high spectral frequency is needed for measurements of some atmospheric parameter, then the best disperser is a double monochromator. Such a quartz monochromator, for example, forms the basis for the Dobson ozonometer used by the Global Atmosphere Watch in total ozone measurements.

Because a light beam experiences several reflections from mirrors and prisms or diffraction gratings on its way between the entrance and exit slits, the instrumental polarization arises in the monochromator. In other words, the radiation detector becomes an imperfect polaroid. This introduces no additional errors into determination of atmospheric parameters, when measuring the direct sunlight, because its linear and elliptic degrees of polarization are zero. This fact was well known as early as in 1930s.[1] The situation becomes quite different, when measuring the diffuse daytime or twilight skylight. The degree of linear polarization of this natural radiation can achieve 0.85 at high atmospheric transparency.[2] If the optical block of the used spectrophotometer does not include an analyzer – nicol or polaroid, then the measurement error can be rather high depending on the polarization degree and the orientation of the light polarization plane in the device for the studied point of the sky, and, what is even more important, this error can be uncertain. This paper is devoted to analysis of its magnitude.

Consider the polarization characteristics of the spectropolarimeter based on a DMR-4 double quartz monochromator.[3] The analyzer in this device is represented by the Glan prism, which linearly polarizes light by more than 99.5%. It is located in front of the DMR-4 entrance slit and can rotate around the optical axis of the objective. The skylight is measured at three positions of the analyzer, rotated through 60°. A FEU-71 photomultiplier tube, having the maximal sensitivity in the shortwave spectral region, serves a detector of light. The brightness, polarization degree, and orientation of the polarization plane are determined by the Fesenkov technique.[4]

Data on the degree of the instrumental polarization $P_{\text{inst}}(\lambda)$ and the orientation of the plane $\beta_{\text{inst}}(\lambda)$ of the light spectral polarization in the polarimeter can be obtained through the following experiment. Substantially diaphragmed objective of the polarimeter is directed to the sun, and the spectral fluxes F_1, F_2, and F_3 are measured (in relative units) at three positions of the analyzer with the step of 60°. If the device did not polarize the light, these fluxes would be equal. Actually, they are different. Calculate $P_{\text{inst}}(\lambda)$ by the equation[4]:

$$P_{\text{inst}} = \frac{2\sqrt{F_1(F_1 - F_2) + F_2(F_2 - F_3) + F_3(F_3 - F_1)}}{F_1 + F_2 + F_3}.$$

The obtained results for DMR-4 are shown in Fig. 1. It is seen that the degree of the instrumental polarization has a complex spectral dependence and equals zero nearby 426 nm. When calculating the angle $\beta_{\text{inst}}(\lambda)$, characterizing the electric vector oscillations about the plane of incidence and reflection of the light beam from the first mirror, as[4]

$$\tan\beta_{\text{inst}} = \frac{\sqrt{3}(F_3 - F_1)}{2F_2 - (F_1 + F_3)},$$

gradual rotation of the instrumental polarization plane with the change of λ is clearly seen, and nearby $\lambda = 426$ nm the angle β_{inst} changes in a jump by 90° (Fig. 2). Obviously, other spectrometers have absolutely different spectral characteristics $Đ_{\text{inst}}(\lambda)$ and $\beta_{\text{inst}}(\lambda)$.

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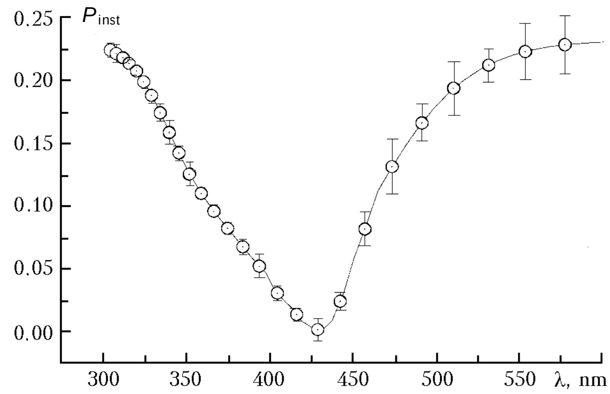

Fig. 1. Wavelength dependence of the instrumental polarization degree.

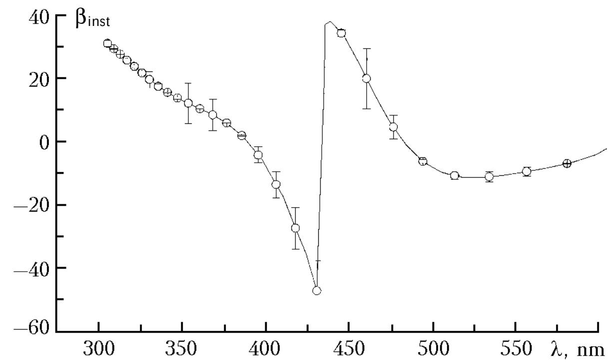

Fig. 2. Wavelength dependence of the instrumental polarization plane.

As follows from Fig. 1, the degree of instrumental polarization at the wavelength of 310 nm is equal to 0.22. According to the mountain measurements, the degree of skylight polarization P at zenith with the sun near the horizon can achieve 0.65 in this spectral region[2,5] and the angle of oscillations of the electric vector β makes up 90° with the plane of solar vertical. If the spectrometer is not equipped with a polaroid, then in the most unfavorable case, that is, at $|\beta - \beta_{inst}| = 90°$, the results of brightness measurement turn out underestimated by 15%. At $\lambda > 600$ nm the error is even greater (21%). At the same time, the measurements of the sky brightness nearby $\lambda = 426$ nm are free of extra errors, because here $Đ_{inst}$ is zero. At other sky points and at other wavelengths, the errors have intermediate values.

Thus, when using spectropolarimeters, it is necessary to introduce corresponding corrections to the data of measurement of the polarized skylight characteristics. As was proposed by G.Sh. Livshits, these corrections can be introduced as factors equalizing the detected fluxes irradiating the polarimeter by the nonpolarized light. They are determined from observations as follows[6]:

$$k_1 = F_2 / F_1;\ k_2 = 1;\ k_3 = F_2 / F_3.$$

Then the sought values of the diffuse light intensity I, the degree of linear polarization $Đ$, and the orientation of the plane of polarization β at any sky point (the last ones are measured with respect to the plane of the corresponding vertical) are equal to:

$$I = k_1 I_1 + I_2 + k_3 I_3;$$

$$P = \frac{2\sqrt{k_1 I_1 (k_1 I_1 - I_2) + I_2 (I_2 - k_3 I_3) + k_3 I_3 (k_3 I_3 - k_1 I_1)}}{k_1 I_1 + I_2 + k_3 I_3};$$

$$\tan\beta = \frac{\sqrt{3}(k_3 I_3 - k_1 I_1)}{2 I_2 - (k_1 I_1 + k_3 I_3)}.$$

Here I_1, I_2, and I_3 are the measured values of the diffuse light intensity at the corresponding positions of the analyzer. Just in this way we can avoid the measurement error discussed above. Naturally, such measurements require a more complex instrumentation.

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