Interferometric investigation of the atmospheric turbulence using sunlight

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The technique of remote measurement was developed of some parameters of optical instability and atmospheric turbulence at daytime based on the use of a coherence interferometer with a small angular aperture. Measurements of the degree of spatial coherence were carried out during observations of direct sunlight and solar aureole with the following interpretation of interferograms. It was shown experimentally that the light scattered by solar aureole possessed partial spatial coherence. Measurements of the atmospheric coherence diameter by Fried method were conducted. A criterion of optical instability was proposed based on the measurement of the light coherence scattered by solar aureole. The interferometer can be applied to investigation of light scattering in the turbulent atmosphere.

Introduction

The atmospheric turbulence at daytime is commonly studied by sun photometers[1,2] or other specialized instruments.[3,4] When solving these problems, the coherence interferometers have considerable advantages; however, these instruments are mainly used at nighttime.[5,6] At daytime the interferometers were not used. The Fabry-Perot interferometer application is known in the problems on increasing the contrast of spectral lines.[7] This has motivated a series of applications typical of coherence interferometers because data on the atmospheric turbulence at daytime are of interest for atmospheric optics, adaptive optics, and astronomy. Some interest is being shown in the solar aureole.[1]

The problem on the scattering light coherence is quite urgent in studying the interaction of light and the atmosphere. The theory of coherence of multiple wave scattering in randomly inhomogeneous media was developed.[8] In many theories of light scattering[9,10] the presence of partially coherent scattered light is assumed, although the conditions of observation of such light in the atmosphere are not given. This paper describes the technique, which enables one to measure the degree of coherence at remote sensing of the atmosphere using both the direct sunlight and the scattered light of the solar aureole. The technique uses the solar coherence interferometer with a small angular aperture. It is shown that the light of solar aureole is partially coherent.

1. Instrument and observation technology

For the change of the degree of spatial coherence the Young's optical system, shown in Fig. 1, is used. The light from the source of size 2ρ comes through a changeable input aperture of $2b$ diameter in the screen E_1 and arrives at a screen E_2 with two small apertures P_1 and P_2, each of the diameter 0.12 mm at a distance $d = 0.4$ mm between them. Changeable apertures in E_1 are necessary for obtaining small angles of field of view.

Figure 1 shows the edge beams arriving at the interferometer, by which the angle of field of view θ is determined. The interference pattern at the output plane E_3 is scanned with a 0.2-mm-diameter pinhole and a photomultiplier located at this plane, which at measurements move jointly along the axis x perpendicular to the bands of the interference pattern.

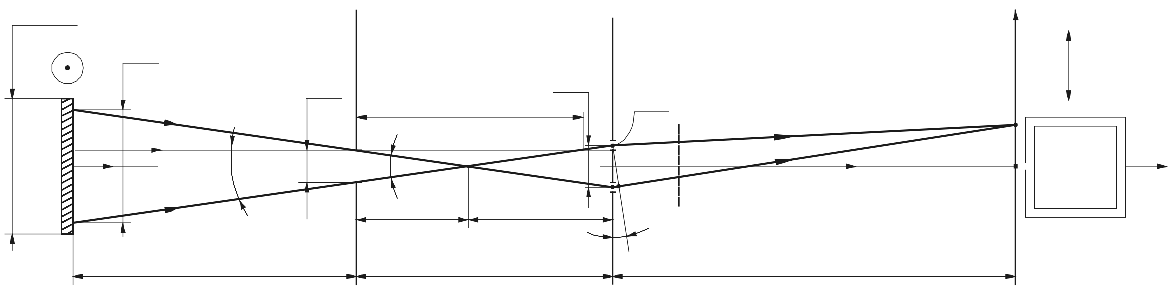

Fig. 1. Optical arrangement of the interferometer.

A photomultiplier signal was recorded with an H-307 plotter. The time of interferogram recording was 13 s. The scanning and recording system was described in Ref. 11. Angles of field of view of 220, 620, and 1020″ correspond to the diameters of the aperture in E_1 screen of 0.25, 1.62, and 3.0 mm. The field of view angle in the approximation of geometric optics is calculated by the formula:

$$\theta = 2b/z_1, \quad (1)$$

where $z_1 = 2bl_1/[(2a + d) + 2b]$; where l_1 is the distance between E_1 and E_2. It is equal to 0.71 m. The distance l_2 between the screens E_2 and E_3 is equal to 1 m. The first part of the interferometer between E_1 and E_2 is the imaging one. The input aperture in E_1 is used for constructing a source image on the plane E_2. For an average wavelength $\lambda = 0.63$ μm of the filter Φ, intended for light monochromatization, the calculation of the wave parameter $D = \lambda l_1/[\pi\ (2b)]$ shows that at the input aperture of 0.25-mm diameter in the plane E_2 the Fraunhofer diffraction is observed. In this case for an average wavelength of 0.63 μm the calculation gives for the diameter of the first dark fringe of the Airy circle the value of 4.4 mm. By this it is meant that both apertures, P_1 and P_2, are practically at the central spot of this Airy circle because $d = 0.4$ mm. The images at E_2 from the input apertures of 3.0 mm and 1.62 mm in diameter correspond to the shadow approximation. The apertures P_1 and P_2 are located symmetrically about the optical axis of the interferometer; these apertures are always oriented so that the line P_1P_2, connecting their centers, coincides with the direction of the sun motion.

Now we consider in detail the angular characteristics of the interferometer since it is important for interpreting the measurements of the scattered light coherence. The input aperture in E_1 screen in pairs with each of the pinholes P_1 and P_2 forms two smaller fields of view. The field of view angle ϑ for each channel in the geometric approximation can be calculated by the formula:

$$\vartheta = 2b/z_\rho, \quad (2)$$

where $z_\rho = bl_1/(a + b)$. For input apertures with the diameters: 0.25, 1.62, and 3.0 mm the angles are 107, 505, and 906″. From this it follows that for the input aperture of 0.25 mm diameter the light pencils in space before the interferometer are simply adjacent, whereas for input apertures of 1.62 mm and 3.0 mm in diameter the fields of view are overlapped in space by 77 and 90%, respectively.

The interferometer, as an independent instrument, was installed at the mount of the Cassegrainian telescope with the primary mirror of 0.5-m diameter at the Observatory of Simferopol University. The telescope itself was not used. Only its systems of control and tracking were used. The interferometer axis was located parallel to the guide axis that has made it possible to control the sun position visually. The adjustment of the interferometer axis to the solar limb center gave the reference point for measurements. From this position the interferometer, using a timer, was led to the aureole either to the right of the sun (by an accelerated telescope tracking) or to the left of the sun (by switching off the telescope tracking).

Let us assess the errors of optical measurements. The error of the photomultiplier noise within the limits of the operating range did not exceed $\delta_1 = 0.5\%$. Deviations from the linearity of light characteristic did not exceed $\delta_2 = 1\%$. The H-307 plotter error, according to specifications is $\delta_3 = 0.5\%$. The total relative error of the optical signal recorded is

$$\delta = \sqrt{\delta_1^2 + \delta_2^2 + \delta_3^2} \sim 1.3\% .$$

2. Design equations

Interference formula from Ref. 12 used is as follows:

$$I(P) = I(P_1) + I(P_2) + $$
$$+ 2\sqrt{I(P_1)\, I(P_2)}\, \gamma_{12} \cos(\delta - \beta_{12}), \quad (3)$$

where β_{12} is the argument of γ_{12}, $I(P_1)$ and $I(P_2)$ are the intensities of light penetrated through the pinholes; γ_{12} is the module of the function of degree of coherence; δ is the optical phase shift, which is equal to

$$\delta = \frac{2\pi P_2 N}{\lambda} = \frac{2\pi d \sin\varphi}{\lambda}.$$

Formula (3) shows that the third term is the function of coherence of the interfering fluctuations. The degree of coherence γ_{12} is determined by the contrast of the interference fringe

$$\gamma_{12} = (I_{\max} - I_{\min})/(I_{\max} + I_{\min}), \quad (4)$$

The degree of coherence can also be calculated by the theorem of coherence[9]:

$$\gamma = 2J_1(v)/v, \quad (5)$$

where $v = 2\pi RD/(\bar{\lambda} l)$, R is the radius of the light source, l is the distance to the light source. As applied to the problems of atmospheric turbulence,[10] the modulation transfer function (MTF) of the atmosphere M in the model atmosphere–representing instrument can be found from the relation:

$$\langle T(f_x, f_y)\rangle = M(\bar{\lambda}, l_1, f_x; \bar{\lambda}, l_1, f_y; L)\, T_1(f_x, f_y), \quad (6)$$

where T is the optical transfer function of the entire system, T_1 is the optical transfer function of the instrument; l_1 is the focal length; L is the depth of turbulent layer; $f_x = x/(\bar{\lambda} l_1)$; $f_y = y/(\bar{\lambda} l_1)$ denote spatial frequencies. According to our measurement data we have for the interferometer that in the output plane $T_1(f_x, f_y) \sim 1$ in case of spatially coherent laser light. Consequently, according to Eq. (6)

$$\langle T(f_x, f_y)\rangle = M(\bar{\lambda}, l_1, f_x; \bar{\lambda}, l_1, f_y; L),$$

i.e., the coherence function measured with the interferometer.[5] To analyze the experimental results of MTF, the formulae of MTF obtained theoretically are also important. D. Fried[14] has derived, using a single-parametric model, the MTF formula of the atmosphere expressed in terms of the diameter r_0 of atmospheric turbulence:

$$\gamma = e^{-3.44(r/r_0)^{5/3}}, \quad (7)$$

where r is the coordinate in the input plane. Equation (7) can easily be used for the approximation of the experimental MTF to derive the value of r_0.

3. Results of observations

The observations were made during 2001 under different weather conditions. The most favorable were winter, summer, and early fall. Observations were carried out at 12.00–14.00 (local time). For the physical analysis to be performed of interest are the data obtained during the passage of anticyclones.

Interferograms with odd number of bands are obtained at the argument value v, satisfying the condition $0 \le v \le 3.83$. With even numbers of bands the interferograms are obtained under condition $3.83 < v < 7.02$. This is connected with the sign of the function $J_1(v)$ in Eq. (5).

The type of interferograms depends on the diameter of the input aperture in E_1 screen. Now we consider the results of observations at sighting the interferometer axis at the center of the solar limb. Interferograms of such observations are shown in Fig. 2. Measurements were performed on October 8–11 during the period of anticyclone, the wind speed was 7–12 m/s; the pressure was 752 mm Hg, temperature was 22°C, the sky was blue and clear.

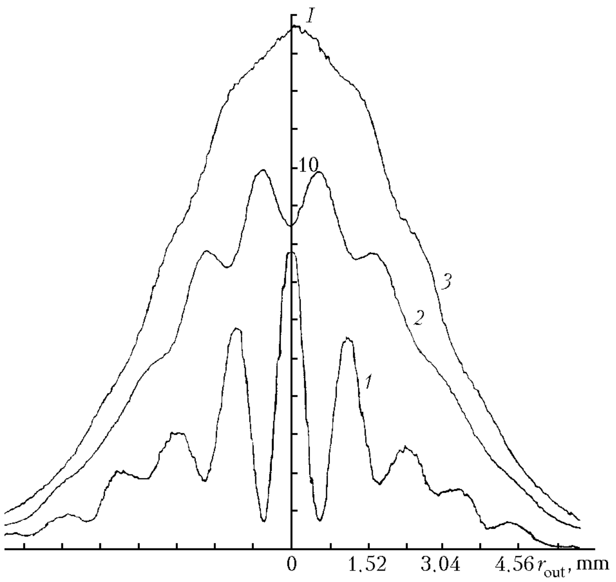

Fig. 2. Interferograms when aiming the interferometer axis at the solar center. For curves *1*, *2*, and *3* the entrance apertures had diameters of 0.25, 1.62, and 3.0 mm, respectively. The scale values of the vertical axis for curves *1*, *2*, and *3* are equal to 0.25, 1, and 2.13 V/div.

As is seen from Fig. 2, the type of interferograms depends on the diameter of the input aperture. Curve *1* was obtained using the aperture of 0.25 mm in diameter, it contains the odd number of bands. The degree of coherence retrieved from curve *1* measured using the central band is $\gamma_{12} = 0.82$, calculated by Eq. (5) $\gamma = 0.9$ that agrees with the experimental value. Note that high degree of spatial coherence can be obtained due to small angle of the interferometer field of view.

Curve *2* in Fig. 2 was obtained using the aperture of 1.62 mm in diameter. Figure 2 shows minimum at the center and even number of bands. The degree of coherence, measured at the center, is equal to 0.1. The calculated argument $v = 5.82$ and the degree of coherence 0.11 support the type of the interferogram. Curve *3* in Fig. 2 was obtained using the input aperture of 3.0 mm in diameter, which does not show spatial coherence of sunlight. The reason is that the observation region on the sun is large in size – about 1000″. The calculated argument and degree of coherence $\gamma = 0.02$ confirm these conclusions.

The MTF of the atmosphere can be obtained for curve *1* in Fig. 2. The mean value of $r_{0\,out}$ found using MTF of the atmosphere by Eq. (7) $r_{0\,out\,mean} =$ = 11 mm. The result of recalculation in the input plane by the formula: $r_0 = mMr_{0\,out\,mean}$ gives the value for $r_0 = 10$ cm. In the recalculation formula $m = 0.343$ is the scale factor of coordinate transformation in passing from the plane E_3 to the plane E_2 obtained by the scale theorem of the Fourier transform, and $M = l_1R/lb = 26.4$ is the scale factor of the coordinate transform in passing from E_2 to E_1. The factor M for the aperture 0.25 mm is found using the formula of the coherence circle diameter[12] $\delta = 0.16\lambda l/R$, where $\lambda = 0.63$ μm, l is the distance to the sun, R is the sun radius, b is the radius of the input aperture. The value for r_0 agrees with the results of daytime observation of the sun using an astronomical pipe.[4] When the weather is different (strong wind, low pressure), the values of r_0 are less than 10 cm.

4. Spatial coherence in the region of solar aureole

As discussed earlier, the input apertures give the property of directed light reception to the sun interferometer. In this interferometer the maximum angle of the field of view is for the input aperture of 3 mm in diameter. This angle is equal to 1020″ that is close to the angular radius of the Sun. Consequently, if we adjust the interferometer axis to the left or to the right, from the solar center, at a distance of its angular diameter (this position is called the near aureole) the interferometer will not receive the direct sun rays, but will receive only the scattered light of solar aureole directed to the interferometer within the solid angle of the field of view. When the distance between the interferometer axis and the solar limb center is equal to the double angular diameter of the sun, the aureole is called distant.

As can be seen from Fig. 3, all curves give the availability of partial spatial coherence with the degree of coherence for the curve *3* at the center 0.22 and in the range of the first band 0.29. Interferograms were obtained on October 8, 2001 under fine weather conditions, they contain odd number of bands and differ from the interferogram at direct sunlight (Fig. 2, curve *2*), first, by the shape (since the aureole is different light source), second, by a great value of the degree of coherence (0.29 as compared to 0.1). This indicates that the spatial coherence occurred at light scattering in solar aureole.

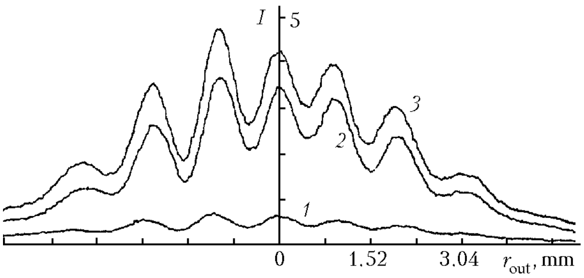

Fig. 3. Interferograms for solar aureole in the Earth's atmosphere at the input aperture of 1.62 mm in diameter; the distant aureole (*1*); at the intermediate position of the interferometer axis (*2*); the near aureole (*3*). The scale value of the vertical axis is 0.05 V/div.

Results of observations for the 3.0 mm diameter of input aperture are shown in Fig. 4. The observations were made on April 3, 2001 when the weather was characterized by variable cloudiness, wind speed was 9 to 14 m/s, the air pressure was 749 mm Hg, temperature was 12°C. Curve *1* corresponds to the distant aureole, curve *2* corresponds to the near aureole. The degrees of coherence at the center of curves are equal to 0.18 and 0.26, respectively. Interferograms include even number of bands. As was noted above, curve *3* in Fig. 2 for the same aperture does not show coherence in direct sun rays.

Thus, in this experiment the partial spatial coherence of light, scattered within solar aureole is also confirmed. Such a result agrees with an indirect conclusion on the laboratory experiment with light scattering on a possibility of coherent scattering at small angles to the initial direction.[15] Note that the degree of spatial coherence from the solar aureole light depends significantly on the weather conditions. For example, on April 23, 2001 before the passage of a cyclone, when the weather was sunny and fine, the degree of coherence of solar aureole light became zero. Such a curve, as curve *2* in Fig. 4 about one day ahead of the cyclone will lose its interference structure and become a single-maximum curve with slightly noticeable traces of bands. This effect can be explained by the dynamics of the increase of the content of water aerosol forms before the cyclone since the air pressure that day was 731 mm Hg.

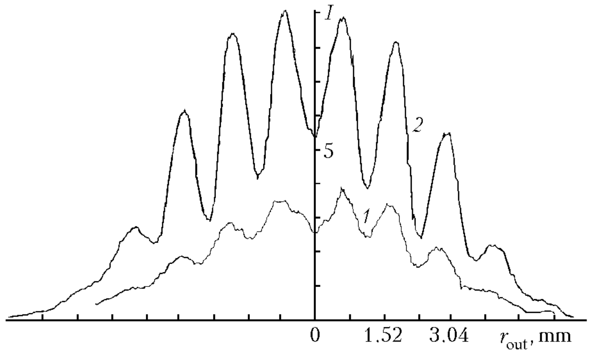

Fig. 4. Interferograms for solar aureole in the Earth's atmosphere at the entrance aperture of 3.0 mm: the distant aureole (*1*); the near aureole (*2*). The scale value of vertical axis is 0.05 V/div.

For the input aperture of 0.25 mm when observing the solar aureole the partial spatial coherence is also detected. The interferogram contains odd number of bands and it is similar to curve *1* in Fig. 2. We present data of such measurements obtained on March 30, 2001 during the period of cold anticyclone with the following weather data: air pressure is 752 mm Hg, night temperature was −10°C; at daytime the temperature was +10°C, the wind speed was 9 m/s, the sky was blue and clear, the aureole is weak. According to the measurement results the degree of coherence at the center of the interference pattern equals 0.87 (for the aureole) and 0.82 (at direct sunlight). The values of r_0 found using MTF, are equal to 12 cm (for the aureole) and 10 cm (for direct sunlight).

Now we consider the question on the possibility of using the degree of coherence for retrieving the characteristics of the optical instability of the atmosphere during daytime. It has been known that the phenomena of coherence[9] and polarization of scattered light are related in a complex way to the molecular motion, aerosols, and atmospheric turbulence. The coherence of scattered light characterizes the correlation of the processes, which are linked to light transmission through the turbulent atmosphere. Experiment showed that the coherence of light of solar aureole reacted readily to the optical state of the atmosphere. The measured value is the coherence degree γ_{12}, which, on the other hand, characterizes the image quality, obtained through the turbulent atmosphere, because this value depends on the quality of the interference pattern. Therefore, as a criterion of the optical instability of the atmosphere during daytime we can use the experimentally measured value γ_{12} – the degree of coherence of light observed in solar aureole if the measurements are made at one and the same location of solar aureole.

Conclusions

1. Experimental procedure of remote sensing of the turbulent atmosphere was developed with the use of the sun interferometer of coherence with a small angular aperture.

2. Spatial coherence of sunlight was investigated; diameters of atmospheric coherence, according to Fried, were calculated using MTF.

3. Spatial coherence of solar aureole light was detected experimentally. A criterion of the optical atmospheric instability was proposed in the form of the value of the degree of coherence of solar aureole light.

4. A possibility was shown of using solar aureole to study the light scattering phenomenon.

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