METHOD FOR DETERMINING THE TRANSFER AND REFLECTION CHARACTERISTICS OF SCATTERING MEDIA

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Received January 6, 1997

An experimental-calculational procedure has been proposed for determining the transfer and reflection characteristics of scattering media by a relative method with the use of a special test-object in the form of a mira whose brightness is modulated by a linear law. The use of this test-object permits the optical transfer function modulus to be determined in one experiment for several points from the preset range of spatial frequencies as well as the diffuse reflection coefficient of the scattering layer to be calculated from video-signal amplitudes reflected by mira bands. The number of measurements required to obtain sufficient statistic of observations is approximately by an order of magnitude less in comparison with the Foucalt quasiharmonic miras.

Determination of transfer and reflection characteristics of scattering media is a key problem that should be solved to estimate the operational efficiency of opto-electronic devices (OEDs) used for remote monitoring. Thus, to estimate the quality of image formed by the OED from the signal-to-noise ratio perceived by the observer, the initial data necessary for calculations are the optical transfer function (OTF) modulus $S(\nu, \Pi)$ and the diffuse reflection coefficient $R(\Pi)$ of a scattering layer, where ν is the spatial frequency of the examined object and Π are the optical-microphysical parameters (OMPs) of the volume element of the scattering medium.

From the viewpoint of the vision theory, the sought-after characteristics $S(\nu, \Pi)$ and $R(\Pi)$ are a solution of the equation of radiative transfer through scattering media by the well-known numerical or approximate methods.[1,2] However, for most scattering media the data on the optical-microphysical parameters are absent or contradictory. This leads to low reliability of their estimates. These circumstances together with the complexity and large errors of the OMP determination (calculations by the Mie formula or experimental determination) call for experimental-calculational methods of $S(\nu, \Pi)$ and $R(\Pi)$ determination on the basis of comparative estimates of the reflection characteristics of the investigated layer and a certain standard[3] (to determine the reflection coefficient) as well as of contrasts (initial contrast and the contrast in a scattering medium) of images of different test-objects to determine the OTF.[1,4] In this case, test-objects with quasiharmonic brightness variations, namely, the Foucalt miras[4] with spatial frequency of brightness variations $\nu = 1/l_0$, are most commonly used, where l_0 is the spatial period of mira brightness. However, these investigations are very time- and labor-consuming. Thus, to determine the OTF in the predetermined range of spatial frequencies $\Delta\nu = \nu_{max} - \nu_{min}$, a set of the Foucalt miras with different brigthness periods l_0 should be placed in the field of view of an imaging system (IS). In some cases this is impossible because of the narrow field of view of the IS. Moreover, the fact that we obtain the OTF at one point (for a single frequency $\nu_i \in \Delta\nu$) leads to the increase of the number of measurements and hence increases the total expense of the experiment. Methods of reduction of labor consumption based on the use of test-objects with frequency of brightness variations smoothly tuned over the range $\Delta\nu$ for the preset time are also known.[4,5] However, as follows from Refs. 4–5, a unique setup should be constructed to implement these methods. This creates serious technical problems.

These disadvantages have been largely eliminated in the suggested method for determining the transfer and reflection characteristics of scattering media. It is rather simple for technical implementation with the use of commercial devices. It is based on the determination of relative changes in image characteristics of the test object, representing the diffuse-reflection or self-glowing mira with alternating light and dark brightness bands of variable widths Δl_i (Fig. 1), introduced by a scattering medium. In this method, Δl_i is changed so that the dependence of the frequency $\Delta\nu_i = 1/(2\Delta l_i)$ of brightness bands along the mira (for example, along the abscissa) was linear. This mira is the optical analog of a radio chirp and can be described as

$$Z(x) = Z_0 \{1 + K \cos[2\pi\, \nu(x)\, x]\} , \quad (1)$$

$$Z_0 = 0.5\, (Z_{max} + Z_{min}) ,$$

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$$K = (Z_{max} - Z_{min}) / (Z_{max} + Z_{min}) ,$$

$$\nu(x) = \nu_{min} + \Delta\nu \, x / x_0 ,$$

where $Z(x)$ is the dependence of the reflection coefficient or of the brightness of bands of diffuse-reflection or self-glowing mira along the OX axis, $Z_{max(min)}$ is the maximum (minimum) of the function $Z(x)$, and x is the mira size along the OX axis.

Expediency of using mira (1) to determine the OTF and the reflection coefficient can be explained by the following reasons.

It is well known[6] that the chirp spectrum is uniform within the limits of $\Delta\nu$ deviation. Then by analogy, the optical spectrum of the signal of chirp-mira $G_{in}(\nu)$ can be represented as

$$G_{in}(\nu) = V^* \sum_{i=1}^{N \to \infty} \delta(\nu - \nu_i) , \quad (2)$$

where V^* is the weighting coefficient independent of ν_i and $\delta(\nu - \nu_i)$ is the delta function.

By the convolution theorem,[7] the brightness of the chirp-mira image formed by an optoelectronic system (OES) on the OX axis in the corresponding plane is the inverse Fourier transform of the signal spectrum at the output from the IS $G_{out}(\nu, \Pi)$, which in the linear-system approximation is equal to

$$G_{out}(\nu, \Pi) = G_{in}(\nu) \, S_c(\nu, \Pi) =$$

$$= V^* \sum_{i=1}^{N} S_c(\nu_i, \Pi) , \quad (3)$$

$$S_c(\nu, \Pi) = S_c(\nu) \, S(\nu, \Pi) , \quad (4)$$

where $S_c(\nu)$ and $S_c(\nu, \Pi)$ are the OTFs of IS in cases of observations through the optically clear atmosphere and the scattering layer, respectively.

From Eq. (3) it follows that aperiodic mira (1) is equivalent to N Foucalt miras by its effect on the IS. This means that the reduction of the contrast of the test-object image (for example, when the OTF of the scattering medium $S(\nu, \Pi)$ changes due to the increase of the thickness of the layer) will not result in the increase of the light band widths of the chirp-mira image at the expence of the decrease in proportion of the dark band widths (analogous blurring occurs when images of aperiodic objects, for example, of a single light line,[8] are formed). In other words, similar to the Foucalt miras, the correspondence between the spatial frequencies of the brightness bands of mira in the object and image planes will be preserved in case of change of the OTF of IS $S_c(\nu, \Pi)$. In this case, the chirp-mira band image brightness variations will be proportional to the IS transfer characteristic (see Fig. 1). Then the sought-after OTF $S(\nu, \Pi)$ of the scattering medium can be easily obtained from signals proportional to the mira image brightness observed through the clear atmosphere and through the aerosol layer.

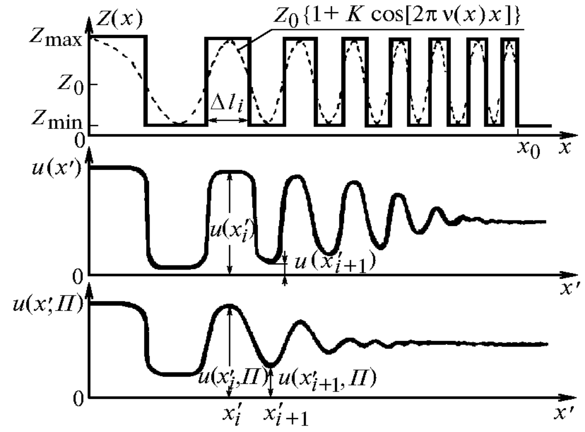


FIG. 1. Dependence $Z(x)$ of the chirp-mira and signals recorded in cases of observations through the optically clear atmosphere, $u(x'_i)$, and scattering medium, $u(x'_i, \Pi)$.

By way of example, let us consider the following situation: the test-object represents the diffuse-reflection chirp-mira having the reflection coefficient $Z(x)$ specified by Eq. (1). The mira image is formed by a television camera. The voltage $u(x')$ in the image plane proportional to $Z(x)$ is determined by way of separation of the video signal of a scanning line that passes through the mira with a special device.

We assume that observations are made in sunlight through the optically clear atmosphere (the optical signal attenuation on the path from the examined object to the receiver is insignificant) and that the scattering layer represents a local artificial aerosol formation. In this case for linear section of the modulation (light signal) transfer characteristic of the IS the amplitude of video signal coming from the ith mira band (for example, light band having the reflection coefficient Z_{max}) will be equal to

$$u(x'_i) = a \, Z_{max} \, S_c(\nu_i) , \quad a = \alpha \, E / \pi , \quad (5)$$

where E is the illuminance in the object plane, α is the parameter proportional to the tangent of the slope of the modulation transfer characteristic (considering that α = const, that is, the automatic gain control (AGC) of the television camera is switched off).

For observations through the scattering layer having the OMPs Π, considering reflection of radiation from the layer, we obtain

$$u(x'_i, \Pi) = a \, Z_{max} \, S_c(\nu_i, \Pi) \, S_c(\nu \to 0, \Pi) + a \, R(\Pi) . \quad (6)$$

The differences between the amplitudes of signals coming from the ith mira band and from band $(i + 1)$ (dark band with the reflection coefficient Z_{min}) will be approximately equal to the spread of signals coming from the equivalent Foucalt mira whose brightness varies with the spatial frequency $\nu_* = (\nu_i + \nu_{i+1})/2$

$$u(x'_i) - u(x'_{i+1}) \approx \Delta u(\nu_*) \ ,$$

$$u(x'_i, \Pi) - u(x'_{i+1}, \Pi) \approx \Delta u(\nu_*, \Pi) \ .$$

Dividing $\Delta u(\nu_*, \Pi)$ by $\Delta u(\nu_*)$ and considering Eq. (4) and the obvious relation

$$[\Delta u(\nu_* \to 0, \Pi)/\Delta u(\nu_* \to 0)] \approx [S(\nu_* \to 0, \Pi)]^2,$$

we derive

$$S(\nu_*, \Pi) = \frac{\Delta u(\nu_*, \Pi)}{\Delta u(\nu_*)} \sqrt{\frac{\Delta u(\nu_* \to 0)}{(\nu_* \to 0, \Pi)}} \ . \qquad (7)$$

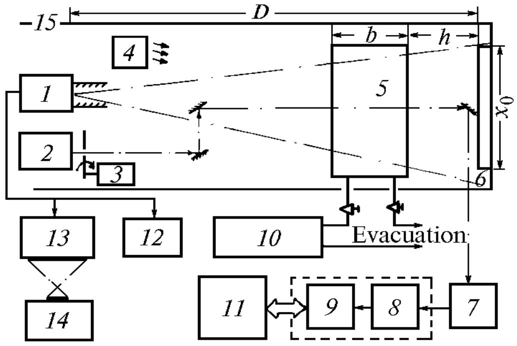
A systematic error of determining OTF is $\sigma = \{[S(\nu_*, \Pi) - S_*]/S_*\} \cdot 100\%$,
where $S_* = \min \{S(\nu_i, \Pi); S(\nu_{i+1}, \Pi)\}$.

To determine $R(\Pi)$, we consider a signal coming from an arbitrary band (let it be light band with the reflection coefficient $Z_{\max}$) whose width is such that $S_c(\nu_i) \approx 1$. Denoting the signal amplitudes $u(\nu_i \to 0) = u(x'_i \to 0)$ and $u(\nu_i \to 0, \Pi)$ and solving Eq. (6) for $R(\Pi)$ considering that $a = u(\nu_i \to 0)/Z_{\max}$, we can easily derive

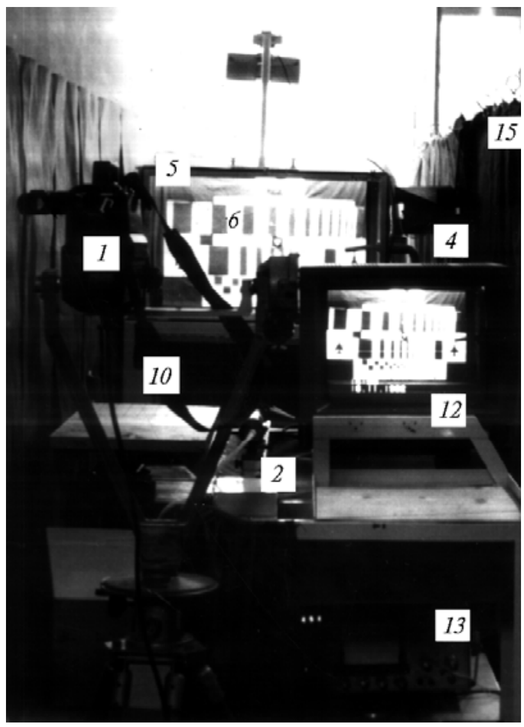
$$R(\Pi) = Z_{\max}\left[\frac{u(\nu_i \to 0, \Pi)}{u(\nu_i \to 0)} - \frac{\Delta u(\nu_i \to 0, \Pi)}{\Delta u(\nu_i \to 0)}\right] . \qquad (8)$$

Thus, the suggested method can be used to determine the modulus of the OTF of scattering medium in several points ν_* and the reflection coefficient by way of rather simple measurements and calculations during one experiment.

To test the outlined approach and to estimate quantitatively the decrease in the number of the experiments (in comparison with the use of the Foucalt mira), a laboratory experiment was carried out on determination of the transfer functions of artificial aerosol formations comprising pirotechnical ammoniac-anthracene compounds of white or blue smoke whose optical and microphysical parameters were *a priori* known (they were determined experimentally). Our investigations were carried out with the use of a model setup (Fig. 2) including the National NV–M5 television camera *1* and the BK40B60 monitor *12*, the test-object *6*, two aerosol chambers (the auxiliary chamber *10* and the main chamber *5* with adjustable pumping-evacuation of the aerosol), a system for measuring the optical thickness of aerosol formation including a source of radiation at $\lambda = 0.63$ μm modulated with the frequency $f_{\rm m} = 166$ Hz (the LGN–2076 laser *2* and the modulator *3*), the detector *7* on the basis of the FD–24K photodiode and a recording system (the narrow-band filter *8* with the central frequency $f_0 = f_{\rm m}$ and the 8-bit ADC *9*) interfaced with the computer *11*. The amplitudes $u(x'_i)$ and $u(x'_i, \Pi)$ were found from the waveforms of video signals (photographed by the camera *14*) of the scanning line passing through the mira center, which were selected with the use of the S1–81 oscillograph *13*. The observational conditions were modeled by illumination of the mira fields by the extended source *4* built around the KGM–1000 quartz lamps. To eliminate glint reflections from the glass walls of the aerosol chamber *5* toward the television camera objective, the axis of the camera *5* was at an angle of 85° relative to the viewing line. In addition, the antiglitter *15* was placed on the model setup perimeter to eliminate signals reflected from external objects and coming to the glass of the chamber *5*.



a



b

FIG. 2. Block-diagram (a) and external view (b) of the laboratory setup.

A diffuse-reflection chirp mira whose brightness is described by Eq. (1) and whose brightness band width is determined by the formula
$$\Delta l_i = D/(2F_{\rm m}\, \nu_i) \ , \qquad (9)$$

where D is the distance between the observation system and the test-object and F_m is the focal distance of the objective of the television camera, was used as a test object.

To perform investigations for spatial frequencies in the range $\Delta\nu = [0.1; 10]$ mm^{-1} for $D = 5.5$ m, $F_m = 54$ mm, and the maximum size of the test-object $x_0 = 1.5$ m, a set of three chirp-miras with deviations 0.1...1.25; 1...4; 3...10 mm^{-1}, respectively, was used.

During our experiment we recorded and processed near 300 signal waveforms. From each waveform we obtained the data to determine the OTF at 6...12 points ν_*. From this it follows that the transfer characteristic of scattering media can be determined by the suggested method and the number of experiments required to obtain a sample with sufficient statistics can be decreased by about an order of magnitude in comparison with the Foucalt miras. The normalized OTFs $S_{\text{exp.n}}(\nu_*, \Pi) = S(\nu_*, \Pi)/S(\nu_{\min}, \Pi)$ of aerosol formations were calculated by Eq. (8) for fixed values of optical thicknesses of the layer $\tau = 0.3, \ldots, 2.1$. The systematic error in determining the OTF did not exceed 18%. An example of $S_{\text{exp.n}}(\nu_*, \Pi)$ is shown in Fig. 3. To compare $S_{\text{exp.n}}(\nu_*, \Pi)$ with the results of theoretical calculations of the transfer characteristics, Fig. 3 shows the normalized OTF $S_{\text{calc.n}}(\nu, \Pi) = S_{\text{calc.}}(\nu, \Pi)/S_{\text{calc}}(\nu = 0, \Pi)$ calculated by the formula

$$S_{\text{calc.n}}(\nu, \Pi) = \exp\left\{-\omega\tau + 0.5\,\omega\tau \sum_{m=1}^{5} \frac{D_m/d_m^2}{b} \times \right.$$

$$\left. \times \left[\frac{b+h}{\{1 + (b+h)^2\nu^2/d_m^2\}^{0.5}} - \frac{h}{\{1 + h^2\nu^2/d_m^2\}^{0.5}}\right]\right\}, \quad (10)$$

where ω is the photon survival probability for the investigated composition, b is the geometric thickness of the layer, h is the distance between the layer and the image plane, and D_m and d_m are the parameters specifying the shape of the scattering phase function of the scattering layer.

Equation (10) is a particular case of the well-known radiative transfer equation in the small-angle approximation for arbitrary location of the scattering layer between the object and the detector[1] when scattering phase function is approximated by the series

$$\varkappa(\gamma) = \sum_{m=1}^{5} D_m \exp[-\gamma\, d_m] . \quad (11)$$

The error of approximation (11) does not exceed 8%.

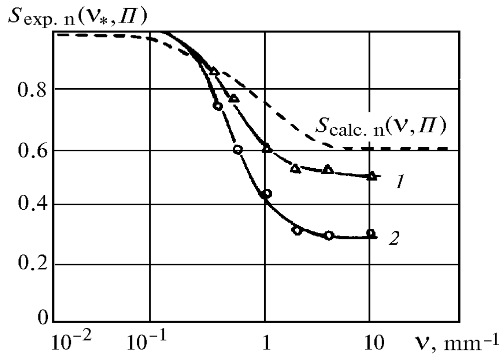


FIG. 3. Normalized optical transfer characteristics of artificial aerosol formations comprising black (curve 1) and white (curve 2) smoke for $\tau = 1.6$, $b = 0.6$ m; *and* $h = 1.2$ m: *the solid curves are for the experimental dependences* $S_{\text{exp.n}}(\nu_*, \Pi)$ *and dashed curve is for* $S_{\text{calc.n}}(\nu, \Pi)$ *calculated by Eq. (10) for an aerosol formation comprising black smoke.*

Comparing the experimental ($S_{\text{exp.n}}(\nu_*, \Pi)$) and theoretical ($S_{\text{calc.n}}(\nu, \Pi)$) dependences, we have found that the spread of the estimates of the OTF modulus does not exceed 15%, that is, the errors of calculations by Eq. (10) for the known OMPs of the aerosol are comparable with the errors of experimental determination of the transfer characteristics of scattering media.

Thus, this method can be used to determine the transfer characteristics of scattering media, whose optical and microphysical parameters are unknown or are determined with insufficient reliability, with accuracy sufficient for practical applications and reasonably low expenditure of labor as well as to estimate the reflection characteristics of the aerosol layer. In addition, our investigations provide a basis for the development of indirect method for determining the optical and microphysical parameters of scattering media.

ACKNOWLEDGMENT

We would like to acknowledge V.I. Klikin for his help in performance of the experiment and data processing.

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