THEORY OF LINEAR SYSTEMS IN DISPERSION MEDIA OPTICS

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This paper reviews the results of investigations into the problems of propagation of optical signals through dispersion media based on the linear system approach. The studies under consideration were conducted at the Institute of Atmospheric Optics of the Siberian Branch of the Russian Academy of Sciences.

The research program into the theory of optical propagation through scattering media was initiated by Academician V.E. Zuev, director of the Institute of Atmospheric Optics (IAO), in the late 1960s. The execution of the program was supported by the development of a unique material and technical foundation and installation of modern computer facilities which were constantly renewed. The major findings of the investigations obtained *prior to* 1975 were covered in the monograph by V.E. Zuev and M.V. Kabanov "Transfer of Optical Signals in the Earth's Atmosphere (Under Noisy Conditions)" (Sov. Radio, Moscow, 1977). Further inquiries into these problems were conducted in the context of the theory of linear systems (TLS). This theory is known to be successfully employed for examination and description of a great variety of physical processes. The results obtained from the electric circuit analysis within the limits of this approach are very popular. The basic concepts and methods used in TLS find application in the analysis and syntheses of optical systems. It will suffice to mention in this connection the well–known monograph by A. Papoulis "Systems and Transforms with Applications in Optics." (McGraw–Hill Book Company, New York, 1968). Recent years have seen intensive investigations to develop and advance optoelectronics for different applications, comprising both active and passive components with illumination from external sources like the Sun, the Moon, or a reflecting surface, etc. These sophisticated complexes include electronic and optical devices can be generally described in terms of the same TLS concepts using in the pulse response, complex transfer functions, amplitude–frequency and phase–frequency characteristics. Finally, it can be readily shown that provided particular conductions are fulfilled, the linear system characteristics can also be used to represent propagation of optical signals through the media which serve to couple the detector to the optical source.[1,2] Attention is drawn to the fairly apparent relationship between the impulse response of the scatter channels and Green's functions. This point has been discussed in close detail elsewhere.[3]

This paper is an overview of the results of investigations into the problem of propagation of optical signals through dispersion media based on TLS. The studies under consideration were conducted at IAO.

STATEMENT OF THE PROBLEM. DEFINITION OF LINEAR SYSTEM CHARACTERISTICS. INVESTIGATION TECHNIQUES

Let us formulate the theory of propagation of optical signals through dispersion media in the same manner as was done in Ref. 3.

Particular cases apart, we will examine the problem of optical propagation, in the most general way and state general methods of attack. A distinction is made between input and output optical signals. By an input signal is meant a signal P_{in} at a point (region) of its emission or incidence on the boundary of a scattering or absorbing medium. An output signal is considered to be signal P_{out} determined at a point (region) of its detection.

Thus signals P_{in} and $P_{\text{out}}(t)$ are taken to be one–dimensional if they are determined for some fixed point (or region) in space as a function of time t. Two–dimensional signals P_{in} and $P_{\text{out}}(x, y)$ are assumed for the steady–state case and three–dimensional signals P_{in} and $P_{\text{out}}(x, y, t)$ will be used for the general case of the space and time dependence. It is evident that the first case is treated in terms of the theory of optical detection and ranging, sensing, and communications, the second case is covered by the theory of vision and the theory of passive sensing of the underlying surface temperature, and the third case is realized under observations on dynamic scenes. The radiation source and detector are assumed to be shielded by a scattering medium whose optical properties are time invariant and determined at each point by the scattering $\beta_{\text{sc}}(\mathbf{r})$, extinction $\beta_{\text{ext}}(\mathbf{r})$, and absorption $\beta_{\text{ab}}(\mathbf{r})$ coefficients and the scattering phase function $g(\mathbf{r}, \omega)$.

Investigations into the process of propagation of optical signals through scattering media are aimed at establishing mechanisms of and relationships between space, time, and energy characteristics, etc., of input and output signals, depending on the optical properties and geometry of propagation channels for short–wavelength radiation. In the most general form these relationships in terms of the radiant intensity are described by the following steady–state

$$(\omega, \text{grad}\, I(\mathbf{r}, \omega)) = -\beta_{\text{ext}}(\lambda, \mathbf{r})\, I(\mathbf{r}, \omega) + \beta_{\text{sc}}(\lambda, \mathbf{r}) \int_{X} I(\mathbf{r}, \omega')\, g(\mathbf{r}, \omega, \omega')\, d\omega' + \Phi_0(\mathbf{r}, \omega) \tag{1}$$

or time–dependent

$$\frac{1}{c}\frac{\partial I(\mathbf{r}, \mathbf{w})}{\partial t} + (\omega, \text{grad}\, I(\mathbf{r}, \omega, t)) = -\beta_{\text{ext}}(\lambda, \mathbf{r})\, I(\mathbf{r}, \omega) + \beta_{\text{sc}}(\lambda, \mathbf{r}) \int_{X} I(\mathbf{r}, \omega')\, g(\mathbf{r}, \omega, \omega')\, d\omega' + \Phi_0(\mathbf{r}, \omega) \tag{2}$$

integro–differential radiation transfer equations, where $I(\mathbf{r}, \omega, t)$ is the intensity at a point $\mathbf{r}$ directed towards ω at

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the instant of time t. Any problem of the theory of optical signal transfer through scattering media can be reduced to a solution of Eq. (1) or Eq. (2) under appropriate boundary and initial (in the time–dependent case) conditions.

Let us leave aside the peculiarities inherent in the physical nature of the propagation channels and those physical processes attendant on the energy transfer from the radiation source to the detector. In such an event, a well–known tool of the theory of the linear system analysis can be nominally used to examine distributed scatter channels (the linearity of atmospheric optical channels follows from the linearity of Eqs. (1) and (2) with respect to the intensity). For linear systems invariant under the space or time shift of the source, fundamental propositions of this approach to the solution of problems treated by the theory of optical signal transfer through scattering media are reduced to the following expressions, as applied to the problems of laser detection, ranging, sensing, and communications:

$$P_{out}(t) = \int\limits_0^{\infty} P_{in}(t')\, h(t - t')\, \mathrm{d}\, t',$$

$$\dot{K}_{out}(\gamma) = \dot{K}_{in}(\gamma)\, \dot{H}(\gamma),$$

Here $h(t)$ is the impulse response of the sensing, detection, and ranging or communications channel to $\delta(t)$ and $\dot{K}_{out}(\gamma)$, $\dot{K}_{in}(\gamma)$ and $\dot{H}(\gamma)$ are the respective complex spectral representations of the signals $P_{out}(t)$, $P_{in}(t)$, and $h(t)$. In this case

$$h(t) = F^{-1}[\dot{H}(\gamma)], \quad \dot{H}(\gamma) = F[h(t)]$$

where F and F^{-1} are direct and inverse Fourier transforms and $\dot{H}(\gamma)$ is commonly referred to as the transfer function of the system.

When applied to the theory of vision,

$$P_{out}(x, y) = \int\limits_{-\infty}^{\infty}\int P_{in}(x - x', y - y')\, h(x', y')\, \mathrm{d}\, x'\, \mathrm{d}\, y',$$

$$h(x, y) = F^{-2}[\dot{H}(\gamma, \omega)], \quad \dot{H}(\gamma, \omega) = F^{2}[h(x, y)],$$

Here $h(x, y)$ is the response of the vision channel at a point (x, y) at the image plane to the source $\delta(x, y)$ at the object plane, and F^2 and F^{-2} are the two–dimensional direct and inverse Fourier transforms. The fundamental propositions of the linear system approach to the solution of problems of atmospheric optics are written in a similar manner for observations of dynamic scenes through scattering media.

By the impulse response is meant

a) in the one–dimensional case

$$h(t) = I(\mathbf{r}^{**}, \boldsymbol{\omega}^{**}, t; \mathbf{r}^{*}, \boldsymbol{\omega}^{*}, \delta(t)),$$

i.e. Green's function determined at a point $\mathbf{r}^{**}$ in the direction $\boldsymbol{\omega}^{**}$ subject to the condition that the signal is emitted in the form of the pulse $\delta(t)$ from a point $\mathbf{r}^{*}$ in the direction $\boldsymbol{\omega}^{*}$ or

$$h(t) = P_{out}(\mathbf{r}^{**}, t; \mathbf{r}^{*}, \delta(t)) = \int\limits_{\Omega^{**}} I(\mathbf{r}^{**}, \boldsymbol{\omega}^{**}, t; \mathbf{r}^{*}, \delta(t))\, \mathrm{d}\, \boldsymbol{\omega}^{**};$$

b) in the two–dimensional case

$$h(\mathbf{r}^{**}, \boldsymbol{\omega}^{**}) = I(\mathbf{r}^{**}, \boldsymbol{\omega}^{**}; \delta(x - x^{*})\, \delta(y - y^{*}), \boldsymbol{\omega}^{*}),$$

i.e. Green's function determined at a point $\mathbf{r}^{**}$ in the direction $\boldsymbol{\omega}^{**}$ subject to the condition that the signal from a monodirectional source is emitted from a point $\mathbf{r}^{*}(x, y)$ or

$$h(\mathbf{r}^{**}, \boldsymbol{\omega}^{**}) = \int\limits_{\mathbf{X}^{**}} I(\mathbf{r}^{**}, \boldsymbol{\omega}^{**}; \delta(x - x^{*})\, \delta(y - y^{*})\, G(\mathbf{r}^{*}, \boldsymbol{\omega}^{*})\, \mathrm{d}\, \boldsymbol{\omega}^{*}.$$

Thus the problem of the optical propagation is solved provided the impulse responses of the external propagation channel and optoelectronic detection circuit have been determined. Then we can write for the spectral region that

$$\dot{K}_{out} = \dot{K}_{in}\, \dot{H}_{dc}\, \dot{H}_{ou}\, \dot{H}_{el}\,, \qquad (3)$$

where $\dot{H}_{dc}$ is the optical transfer function of the dispersion channel, $\dot{H}_{ou}$ is the transfer function of the optical unit and $\dot{H}_{el}$ is the transfer function of the electronic unit of the detection circuit. Ref. 13 discusses the conditions wherein it is possible to consider two separate problems within the framework of the problem of accounting for the effects of the dispersion medium and detection optics on the output signal. An observation made in Ref. 13 restricts the applicability of Eq. (3) to the description of the signal propagation from the source through the scattering medium and detection optoelectronics. It is associated with the finite depth–of–focus of optical systems and probable formation of aberration disks at the image plane.[4]

We used the following basic investigative techniques to examine the linear system characteristics, primarily the impulse response of dispersion channels of optical propagation:

– Monte Carlo method,[2,4–10]

– approximate methods for the radiation transfer equation (RTE),[7–10]

– laboratory experiments with test beds, using model dispersion media placed in cells,[1,7,11,12]

– laboratory experiments on the basis of a big aerosol chamber at IOA.[9,10,13]

LASER SENSING AND COMMUNICATION. ONE–DIMENSIONAL LINEAR SYSTEM CHARACTERISTICS

We have used Monte Carlo method to evaluate the linear system characteristics $h(t)$ and $\dot{K}(\boldsymbol{\omega})$ of the channels for sensing the scattering layers away from the radiation source (in the reflection scheme). The dominant properties of the probe channels are described in Refs. 14 and 15. It has been found that these characteristics are most heavily dependent on geometric factors, like the angle of vision of the detection system (ν), the distance to the layer boundary (z_0) next to the radiation source and the optical density of the medium (τ). Their build–up is responsible for the system impulse response broadening (bandwidth narrowing $\Delta\boldsymbol{\omega}$).

For scattering media with a blurred boundary remote from the radiation source the amplitude and frequency characteristics (AFC) of the channels are monotonic functions of frequency. For scattering media with a well–defined far boundary, AFC of the probe channels may be oscillating in the "high" modulation frequency range. This peculiarity of AFC behavior can be used in estimating the geometric thickness of optical inhomogeneities located in a reasonably transparent sounding path.[14] An illustrative example of AFC is given in Fig. 1. It describes transfer properties of a laser sensing channel for a remote scattering layer with the optical thickness $\tau = 2$, 4 and optical density increasing toward the far boundary.

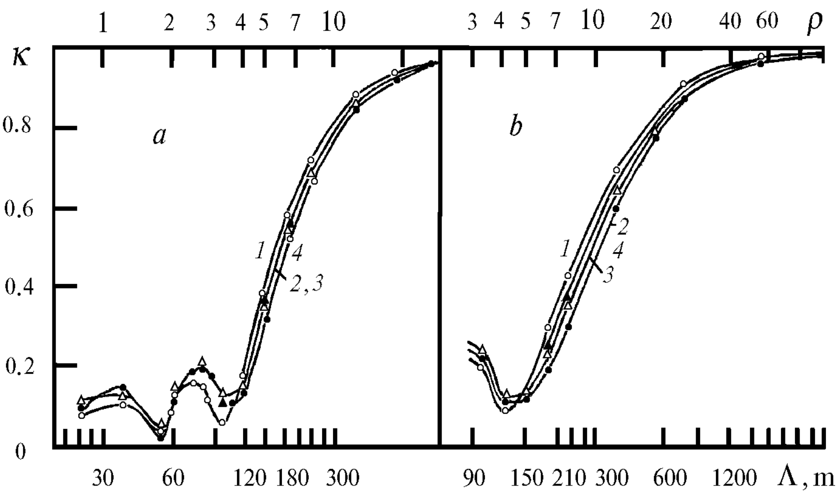

FIG. 1. A sample calculation of AFC of the laser sensing channel for a remote cloud layer with the optical density increasing along the probing direction. The optical thickness of the cloud layer $\tau = 2$ (a) and 4 (b). The curve numbers correspond to the detector angles of vision in the 3′–3° range.

Using the geometrical similarity law and introducing the non–dimensional parameters $\tau_0 = \overline{\beta}_{ext}\, z_0 \tan \nu_0$ (where $\overline{\beta}_{ext}$ is the mean extinction coefficient throughout the thickness of the scattering medium and ν_0 is the divergence angle of the probe beam) we were able to generalize the investigative results obtained by the numerical method for particular optical and geometrical parameters of probing scenarios.[15]

We will dwell now on a less known result obtained from our investigation into the effect of the inhomogeneous optical density of the scattering layer along the probing direction on the time structure of the multiple–scattering component of lidar returns. Some interest is being shown in this issue in connection with recent attempts to solve inverse problems pertaining to optics of dispersion media with allowance made for multiple–scattering effects.

Let us examine secondary scattering background (i.e. scattering orders higher than the first order) in a lidar return in terms of the impulse response $h_m(t)$. We have estimated this characteristic[16] for a single–ended system of vertical sensing of a remote scattering layer with an optical thickness in the range $0.5 \le \tau \le 6$, and three different profiles of the extinction coefficient throughout the layer thickness (along z–coordinate):

a) $\beta_{ext}(z) = \text{const};$ (4)

b) $\beta_{ext}(z) = \alpha_1(L - z)\, z;$ (5)

c) $\beta_{ext}(z) = \alpha_2(z),$ (6)

where L is the geometrical thickness of the scattering layer, $\alpha_1,\ \alpha_2 > 0$.

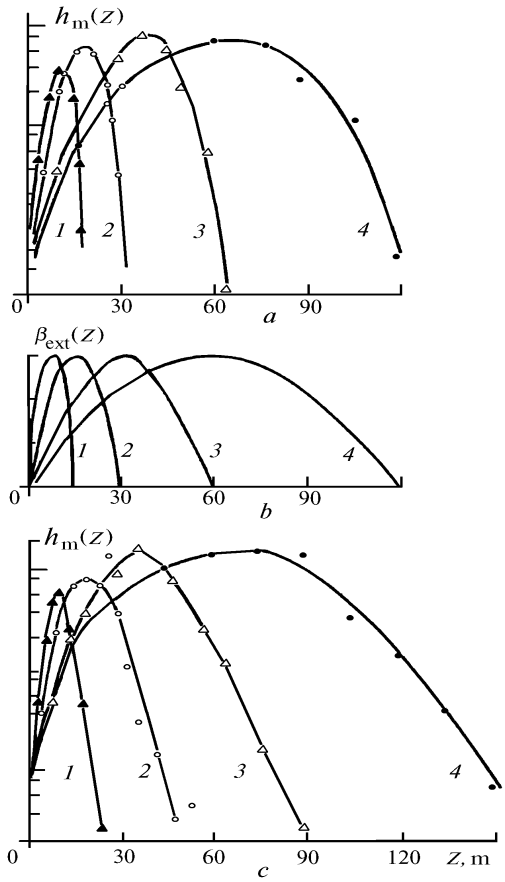

FIG. 2. The results of simulations of the impulse response $h_m(z)$ for sensing a remote cloud layer with a parabolic distribution of the extinction coefficient (b). The curve numbers in Fig. 2a corresponds to those of Fig. 2b. The detector of vision are 3′ (a) and 3° (b).

Figure 2 depicts results of Monte Carlo calculations of the functions $h_m(t)$ for a scattering layer with a parabolic profile of $\beta_{ext}(z)$. To facilitate comparison between $\beta_{ext}(z)$ and $h_m(t)$, the latter function is represented on the coordinates $z = 2\,t\,c$, where c is the velocity of light. The characteristics of $h_m(z)$ are normalized:

$$h_m(z) = h_m(z)/h_{max}\,,$$

where h_{max} is the maximum value of $h_m(z)$ at an angle of vision $\nu = 3°$. As expected, $h_m(z)$ essentially depends on the detector angle of vision. This dependence is most conspicuous at large τ in the case of the homogeneous and parabolic models for $\beta_{ext}(z)$. In addition, it has been found that

a) the multiple scattering background increases as the beam penetrates into a cloud depth $z = z_m \le L$ where it peaks and then rolls off at $z > z_m$;

b) the characteristics of the maximum secondary scattering background, like its peak value h_{max} and position z_m in z–axis, depend on the detector angle of vision and optical properties of the medium.

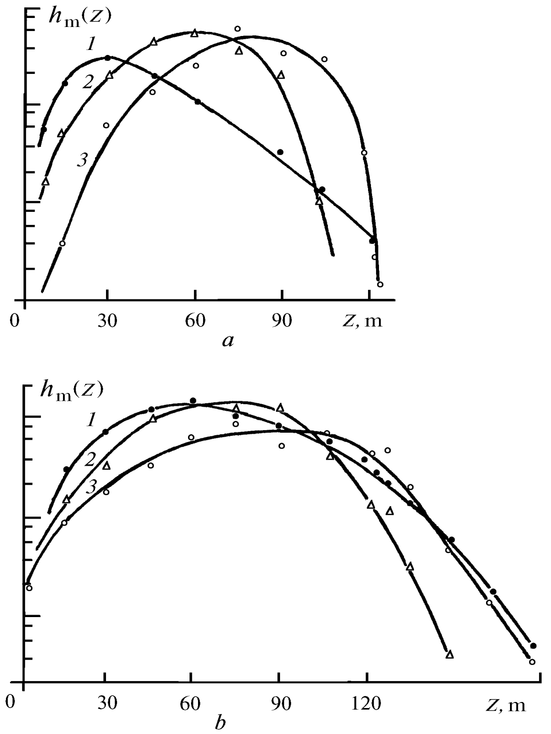

FIG. 3. The effect of $\beta_{ext}(z)$ *on the structure of the multiple scattering background. The optical thickness of the medium* $\tau = 4$*, the angles of vision are 3′ (a) and 3° (b). Curves 1, 2, and 3 correspond to the distributions of* $\beta_{ext}(z)$ *as given by Eqs. (4), (5), and (6).*

Figure 3 presents results of calculations for $h_m(z)$ at $\tau = 4$ and with different models of the vertical profile of $\beta_{ext}(z)$, illustrating special features inherent inherent in the formation of the multiple scattering background under different model conditions. The estimates show that, for a uniform profile of $\beta_{ext}(z)$, the values of max $h_m(z, \tau, \nu_1)$ and z_m (where the secondary scattering intensity is found to peak) tend to build up early in the rise of τ. Moreover, the larger is the detection angle ν_1, the higher are the values of $\max_z h_m(z;\,\tau,\,\nu_1)$ and z_m. Further increase in the optical (geometrical) thickness of the scattering layer (starting with some values of τ depending on ν_1) leaves the characteristics of $\max_z h_m(z;\,\tau,\,\nu_1)$ unaltered.

It can be asserted that at small detection angles $\nu_1 < 10'$ ($\tau_1 < 0.0264$) the peak intensity of the multiple scattering background is saturated for $\tau = 1$, whereas at large detection angles $\nu_1 \approx 3°$ ($\tau_1 = 1.58$) the saturation occurs for $\tau \approx 2$.

The tendency for the intensity saturation of the secondary scattering background with increase in τ is also observed at $z > z_m$, which occurs for $\tau \approx 8$–10.

The most essential result obtained from the simulation of the secondary scattering background is that it revealed a persistent response of the component $h_m(z)$ to the profile of $\beta_{ext}(z)$ for all the values of τ and $\overline{\beta}_{ext}(z)$ studied which tends to fall off somewhat at large values of these parameters.

As for the dependence of $h_m(z)$ on the profile of $\beta_{ext}(z)$ we have failed to find general quantitative relations (for instance, in the form of approximate expressions) between $h_m(z)$ and integrated or mean optical characteristics of the scattering layer (such as τ or $\overline{\beta}_{ext}(z)$) and geometrical parameters of the aperture used in the probing system (for example, ν_0, ν_1 or τ_0, τ_1).

Hence the secondary scattering background appears to be quite sensitive to variations in the optical and geometrical parameters of probing schemes. Efforts to provide adequate elimination of the multiple scattering background from lidar returns are made difficult, if not vain, without knowledge of the optical characteristics of the probed medium. These results, however, provide reason enough to develop techniques for retrieval of information on probed media from lidar returns, taking into account the multiple scattering component.

The investigations into the impulse reactions of optical communication channels were performed by means of Monte Carlo calculations under the small angle and small angle diffusion approximations and laboratory experiments in the aerosol chamber. The unique experimental facilities available at IAO made possible penetration in optical depths $\tau \approx 70$, estimation of the validity range for approximate methods used for solution of RTE and thorough examination of the effects of optical properties of adiabatic fogs and geometrical parameters of the signal detection schemes on the polarization and time structures of the impulse response of optical communication channels. The most essential results obtained from those investigations were reported in Refs. 9, 10, and 13. As part of the research program the peculiarities were elucidated of the formation of polarized and cross–polarized impulse response of optical communication channels, and laws were established that govern their changes depending on the variations in characteristics of artificial fogs resembling cloud features (of C1 type) in the scattering properties. The effect of the variable parameters of observation schemes on the delay in the peak impulse response was studied and conditions for complete depolarization of the detected radiation were determined.

The feasibility of control over the optical properties of the scattering medium like extinction, optical thickness and scattering phase function permitted the use of the results of these experiments for estimating the applicability limits of mathematical models for description of the transfer properties of scatter channels. Specifically, the accuracy of the small angle approximation in the solution of RTE for description of the impulse response $h(t)$ was evaluated. At the same time the dependence of their shape and power characteristics on the variable parameters of observation schemes was considered at length for the range of values where the single–scattering, small angle and diffusion approximations are applicable to the solution of RTE. Beyond this range the form of the impulse response was examined using Monte Carlo method and experiments in the aerosol chamber. The results obtained in the course of the execution of the research program discussed in Refs. 9, 10, and 13 can be summarized in the following way:

– For small values of the optical thickness, where the angular spread of the multiple–scattered beam is not wider than the angular aperture of the detector ($n_0^2 \ll n_1^2$), the pulse width is determined by single scattering in the detector field–of–view and does not depend on the optical thickness. In our simulation conditions $\tau \le 10$.

– For the transition region (τ = 10–70) the temporal pulse shape can be described to a reasonable accuracy by the small angle approximation, assuming that the effective diffusion factor and the photon dwell time in the medium are increased.

– For $\tau > 70$ the dependence of the pulse width on the viewing angle vanishes, allowing of asymptotic solutions.

IMAGE TRANSFER THROUGH SCATTERING MEDIA. TWO–DIMENSIONAL LINEAR SYSTEM CHARACTERISTICS

The process of object image transfer through scattering media can be examined (on the assumption that the object plane is homogeneous) using two impulse responses $h_g(x, y)$ and $h_{gg}(x, y)$ descriptive of the noise due to side illumination and re–reflection, respectively, and two integrated characteristics, like the haze intensity, i.e. radiance of light scattered from the direct sun beam into the sensor's field–of–view without being reflected by the surface, and the illumination intensity of the object plane under observation E_0. In some instances we need only have knowledge of the parameters $\eta_\infty = \int\limits_{-\infty}^{\infty}\int h_g(x, y)\, dx\, dy$ and $\gamma_\infty = \int\limits_{-\infty}^{\infty}\int h_{gg}(x, y)\, dx\, dy$ instead of the impulse responses.

Our investigations pursued the following objectives:

– to develop statistical modeling algorithms and measurement procedures for the linear system characteristics $h_g(x, y)$ and $h_{gg}(x, y)$;

– to establish the major mechanisms for the scattering and reflection noise and its effect on the image quality in the visible and infrared spectral regions;

– to explore the features peculiar to the image transfer through scattering media under pulsed illumination of observable objects;

– to develop hardware and software for correction of image distortions due to scattering and absorption.

Similar investigations were carried out elsewhere.[17–41] Our research program was distinguished by a fairly large set of laboratory experiments combined with numerical simulations by Monte Carlo method. This has enabled us to develop computational algorithms for impulse responses using the statistical modeling technique. The resultant procedures take proper account of special features inherent in the image formation for the objects viewed through scattering media. The investigations were conducted in two steps. In the first stage different measurement procedures for linear system characteristics of vision systems (object–medium–detector) were tried out and compared, and the major mechanisms responsible for the image transfer were studied in laboratory experiments on model physical media, simulating optical properties of clouds, fogs, and dense optical hazes. Numerical calculations by Monte Carlo method, simulating real laboratory experiments, were done concurrently.

The second stage dealt with theoretical investigations based on algorithms and software for simulating the impulse responses of the vision channels. The algorithms and software used had been validated for adequacy of the calculated results in the course of the execution of the first stage. At that point, aerospace conditions were simulated for viewing objects through the cloudy or cloudless atmosphere (assuming plane–parallel or spherical models) in the visible or infrared regions.

Among the most significant results obtained in the course of the execution of the research program we would like to mention the following findings:

– the t–effect and its interpretation[2];

– the estimation of the applicability limits for the angular scanning procedure when measuring the impulse response of vision channels[12];

– the effect of optical and geometrical viewing conditions on the image isoplanatism and space resolution of vision systems[42–44];

– the major mechanisms responsible for the side illumination noise[7];

– software, and hardware to compensate for the distortion effect of scattering media on the image quality[45];

– the effect of scattering and reflection processes on the intensity of upwelling IR radiation fluxes[47];

– development of an information software system for image transfer problems.[46]

Important conclusions were reached from the investigations reported in Refs. 2, 7, 12, 42–44 which can be summarized as follows:

The severe distortion effect of a scattering layer on the image quality (as the medium moves between the observer and the object) can show itself if the dimensions of the inhomogeneous reflectivity (emissivity) zones are comparable with the impulse response width corresponding to the observing conditions. This effect can occur under natural illumination and in viewing selfluminous objects. It is not improbable that the t–effect will recur as the medium moves, except that its severe distortion effect will manifest itself in other portions or details of images.

The scattering medium is shown to have an appreciable effect on the size of the area exhibiting image isoplanatism. The crucial factors determining this dependence are the optical thickness of the medium, the scattering phase function and the inhomogeneity of optical properties of the medium along the observing line. The image isoplanatism zones decrease in size monotonically as the optical thickness increases. An increase in the oblongness of the scattering phase function and build–up of the optical thickness of the medium are accompanied by an expansion of the central image isoplanatism zone, to say the least. The movement of the medium toward the observer likewise causes the area of isoplanatic image regions to increase.

An essential single–valued characteristic of the image quality is the space resolution which is sensitive to variations in optical properties of the viewing scheme parameters and, importantly, is determined by the space pattern of brightness of the observable object. We have succeeded in establishing a link between these characteristics and the contrast sensitivity of the image analyzer (locker) and, on this basis, among other things in giving an insight into the causes of and elucidating the conditions for the occurrence of the t–effect.

Let us take a brief look at the fundamental properties of the impulse responses $h_g(x, y)$ of vision channels in vertical viewing schemes. Their form is found to be mainly affected by the distribution pattern of the extinction coefficient $\beta_{ext}(z)$ along the sight line, rather than the integrated optical thickness of determinate horizontally homogeneous scattering media that shield the object from the observer. If the optical thickness of the medium is kept constant, the shape of the impulse response well change markedly provided that layers with enhanced optical density are concentrated between the object and the observer, with the distance from the observer being variable. On the other hand, the total side illumination power is independent of $\beta_{ext}(z)$, and completely determined by the optical thickness of the medium, its absorptance and the form of the phase scattering function. For an absorbing turbid medium an increase in its optical thickness causes the brightness B_g of the side illumination to increase initially and then to decrease monotonically.

The impulse response $h_{gg}(x, y)$ for the re–reflection noise has distinctive features of its own. Figure 4 illustrates calculations of the impulse responses $h_{gg}(\varphi)$ normalized to their values. The results were obtained for vertical viewing schemes through a scattering layer with the optical thickness $\tau = 1$ and 6 depicted in curves 1 and *2* through 4 respectively. Curve *2* joins the points corresponding to three different distances of the object planes to the closest boundary of the scattering layer (φ is the angle between the vertical direction from the observation point and that toward the illumination point).

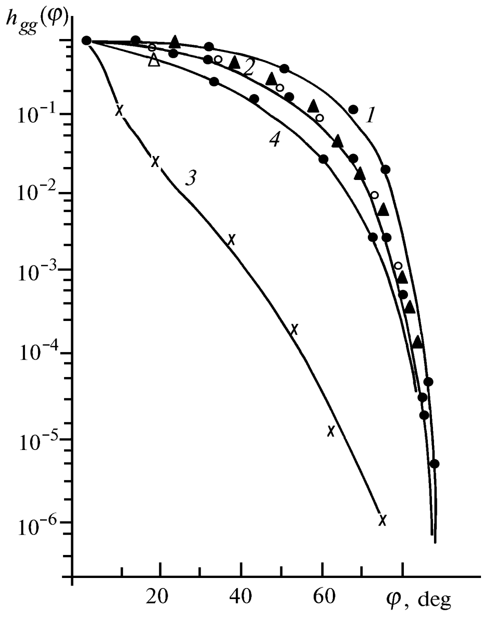

FIG. 4. Monte Carlo calculations for the impulse responses $h_{gg}(\varphi)$ normalized to their maximum values for different optical and geometrical parameters of the viewing scheme.

Figure 5 presents simulation results for the integrated brightness of the side illumination and extra illumination of the observation point by the radiation flux reflected the entire homogeneous object plane (relative units).

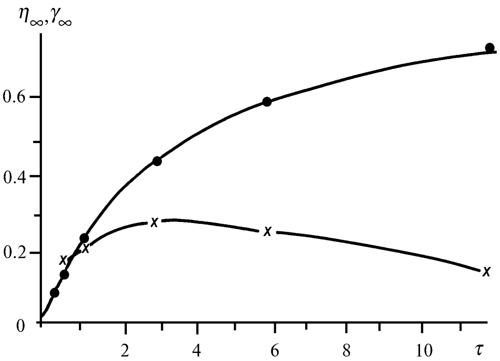

FIG. 5. Integrated characteristics as a function of the optical thickness of the model cloud layer.

Notice that we have examined the behavior of the impulse responses $h_g(x, y)$ and $h_{gg}(x, y)$ and the characteristics of η_∞ and γ_∞ for the visible and infrared spectral regions. The observing conditions have been found in Ref. 47 wherein account must be taken of this noise in the retrieval algorithms for the underlying surface temperature based on the space–borne measurements of the luminosity of the atmosphere0underlying surface system.

A thorough analysis of characteristic properties of the impulse responses $h_{gg}(x, y)$ derived for selfluminous objects as viewed under different observing conditions made feasible the development of new hardware and software to ameliorate the distortion effect of scattering media on the image quality of small–sized isolated objects and groups of objects.

In Ref. 45 we have estimated ranges of values for optical and geometrical observing conditions wherein the use of simple instrumental solutions yields a substantial improvement in the object images shielded from the observer by dense scattering media. It is shown, however, that, in some instances, it is the image processing software for frequency or space ranges which proves to be more efficient than the other means discussed in this paper.

We have integrated the major software products intended for handling problems of the image transfer through scattering media into a computer software package. The latter makes it possible to perform closed numerical simulations allowing of imaging particular objects as generally viewed through an inhomogeneous multicomponent medium of spherical shape at given conditions of illumination and wavelength of the detected radiation. It also permits correction of image distortion on the basis of knowledge of the impulse response $h_g(x, y)$.

SUMMARY

Comprehensive experimental and theoretical investigations into the problems of optical propagation through scattering media were carried out at IAO. The results obtained can be summarized as follows:

1. TLS was consistently extended for the investigation into the process of optical signal transfer through scattering or absorbing media.

2. Algorithms for mathematical modeling of transfer properties of optical propagation channels formed by

scattering media were developed and validated for the adequacy of the resultant calculation data.

3. The validity range for the approximate measurement procedures for the impulse responses of image transfer channels was evaluated theoretically and experimentally.

4. Transfer properties of atmospheric optical sensing (detecting and ranging), communication, and vision channels were studied for the case where the information–bearing characteristics of optical signals propagating through the channels are strongly affected by scattering and reflection processes. The major mechanisms responsible for scattering and reflection noise were established or ascertained. The medium was found to produce a severe distortion effect on the object image. Conditions favoring the occurrence of the effect were elucidated and a qualitative and quantitative interpretation of the phenomenon was given.

5. Factors associated with radiation scattering by the atmosphere or reflection (re–reflection) by the underlying surface, that are generally overlooked or only roughly approximated, were examined. Their effect on the accuracy of retrieval of the underlying surface temperature from passive aerospace IR sensing data was assessed.

6. Hardware and software were proposed to eliminate (ameliorate) the distortion effect of the scattering medium on the image quality for objects viewed through dense scattering media. The investigative results relative to the problem of the optical signal transfer will be detailed in the monograph by V.E. Zuev and V.V. Belov "Transmission of Optical Signals through Scattering and Absorbing Media" which is currently in preparation.

Further investigations into the subjects under discussion to be carried out at IAO will be concerned with the effect of nonorthotropy exhibited by the reflecting (radiating) properties of surfaces on the image quality, imaging peculiarities of viewing systems with active coherent or incoherent illumination (among them viewing through optically dense scattering media) and development of hardware and software for correction of image distortions induced by scattering and absorbing media.

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