Estimation of detection range of single objects and their discrimination against the background surface in observation through scattering media

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We consider estimation of the limiting detection ranges for single objects (in absence of background) and discrimination of such objects against the background surface when they are observed with a help of passive or active optoelectronic systems through scattering and absorbing media. We propose analytical equations, applicable at any optical depth of the medium under conditions of weakly developed scattering processes (small scattering coefficients). The analysis of these equations has shown that the use of optical illumination does not guarantee an increase in limiting detection ranges for objects observed through turbid media.

Efficiency of optoelectronic systems (OES) of detection and recognition of objects in practical applications depends on optical state of atmospheric (hydrologic or atmospheric-hydrologic) channel of optical radiation propagation from an object to observer.

Such dependence can be quite readily taken into account in the case when this channel is weakly turbid in the optical sense. To do this, it is sufficient to control only one characteristic of the channel, namely, the optical path length.

At the same time, if this channel is well turbid, it is usually insufficient to take into account only integral or mean characteristics in the channel (optical path length or depth τ, mean absorption β_{abs} and scattering β_{sct} coefficients). Evidently, in these cases it is necessary to know the distributions $\beta_{abs} = \beta_{abs}(l)$ and $\beta_{sct} = \beta_{sct}(l)$ along the line of sight, as well as the scattering phase function $g(\boldsymbol{\omega}, \boldsymbol{\omega}')$ (here $\boldsymbol{\omega}$ and $\boldsymbol{\omega}'$ are directions of radiation propagation before and after its interaction with a scattering center in the medium).

The theoretical and experimental results are available,[1–5] which show that, for the same scattering phase function and optical depth of the scattering medium, it is possible to obtain the images substantially differing in quality. Therefore, the methods of calculation of detection ranges for single objects (in the absence of the surrounding background) and visual or instrumental discrimination of the objects against the surrounding background must be developed taking into account these external (with respect to OES) factors.

These problems have been considered by many researchers, among which we can mention Ref. 1, where the results of studies of the turbid media influence on limiting detection ranges and contrasts of the object images, observed through these media, are described for different viewing geometries. Most results are obtained through solution of radiative transfer equation in small-angle or small-angle diffusion approximations. Separately, they discuss the asymptotic regime of image formation for optically thick media screening the object from the observer. The expressions by Zege et al.[1] for limiting detection ranges take into account not only the scattering and absorbing properties of the medium, but also the characteristics of the detector (field of view, area of entrance pupil, and level of shot noise) and the illumination source (primarily, the angular divergence of radiation).

In this paper we discuss the construction of such estimates under assumption that the absorption process in the medium dominates over the scattering process. In this case, it is possible to obtain simple analytic expressions relating the mean extinction coefficient in the medium, threshold energy and contrast sensitivity of the detector to intensity of (reflected) radiation propagating from the object and its background surrounding in the direction to the detector. For active observation systems, the radiation reflected from the medium and the intensity of illumination of the object and the background are taken into account.

Passive observation of objects

Suppose that the object is a self-emitting body or is illuminated by an external source of incoherent radiation. Assume that the medium, screening the object from the observer, is characterized by the optical extent τ, stipulated primarily by the absorption process (i.e., $\beta_{abs} \gg \beta_{sct}$, or $\tau_{abs} \gg \tau_{sct}$, here τ_{abs} and τ_{sct} are optical depths of the layer due to absorption and scattering, respectively). In this case, the distortion of the fine spatial structure of the image is absent or insignificant (see formula (5.7) in Ref. 1).

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Then the influence of the medium is reduced to lowering of the object image contrast, which can be quite easily taken into account by the Bouguer law.

Let the intensity of radiation (reflection) from object in the direction to observer be I_t, while that from the background in the object neighborhood be I_f. Then the image contrast of the object's elements against the background in the absence of the medium is

$$k_t = (I_t - I_f)/(I_t + I_f). \tag{1}$$

Attenuation of the optical radiation in the channel connecting the observer and the object is estimated according to the Bouguer law as

$$I = I_0 \exp(-\tau). \tag{2}$$

Here I_0 is the intensity of radiative flux incident on a layer of the medium.

Therefore, occurrence of scattering medium of a small optical density (due to scattering) will not lead to a decrease of the contrast coefficient of the object:

$$k_{t(s)} = \exp(-\tau)(I_t - I_f)/\exp(-\tau)\,(I_t + I_f) = k_t, \tag{3}$$

where $k_{t(s)}$ is the coefficient of contrast of the object against the background in observing the body through the scattering medium. Note that in this case we impose no limitations on absorbing properties of the medium. That is, even for large optical depths (caused primarily by the absorption process) the medium exerts no effect on the image quality, if by the image quality only the image contrast is meant. Actually, an increase of absorption in the medium (with the scattering coefficient kept fixed and small) will lead to reduction of illumination in the plane of the object image without changing its contrast, and may substantially change the image's color pattern.

Obviously, for a given sensitivity of the detector, from the energy characteristics of the input signal we can deduce the optical depth τ of the medium, at which the signal from the object will not be detected.

Therefore, for image transfer channels, in which the scattering plays some insignificant role, the limiting detection range R_{lo} of a single object (without surrounding background) is determined only by the detector's energy sensitivity I_{ld}. The limiting range R_{lr}, at which the object can be discriminated against the surrounding background, is controlled by the contrast sensitivity k_{ld} of the detector. Therefore, taking into consideration Eqs. (1)–(3), we can write:

$$R_{lo} = \ln (I_t/I_{ld})/\beta_{ext}, \tag{4}$$

$$R_{lr} = \ln [(I_t(1 - k_{ld}))/(I_{ld}\,(1 + k_{ld}))]/\beta_{ext}. \tag{5}$$

Here $\beta_{ext} = \beta_{abs} + \beta_{sct}$ is the mean extinction coefficient of the medium along the line of sight.

Estimate (5) is obtained in assumption that

a) the intensity emitted (reflected) by the object is higher than the background one (otherwise, it is sufficient to rename the object as background and *vice versa* because, from the viewpoint of image analysis, it does not matter which image region is called the object); and

b) at limiting detection ranges, the intensity of radiation I_t, $I_f \to I_{ld}$, but $I_t > I_f$.

It is easily seen that from Eqs. (4) and (5) the following physically non-contradictory conclusions can be drawn:

– with increasing optical density of the medium, the limiting ranges R_{lo} and R_{lr} decrease;

– at $k_{ld} \to 0$ $R_{lr} \to R_{lo}$ and (5) goes over into Eq. (4);

– at $k_{ld} \to 1$ $R_{lr} \to 0$; and

– at $\beta_{ext} \neq 0$ $R_{lr} < R_{lo}$, i.e., the limiting detection range is greater than the limiting range of discrimination of the object against the background.

Schemes of active observation of objects

Suppose that the observations are made under conditions of optical (laser) illumination. As before, it is assumed that the reception of incoherent optical radiation takes place. We will consider a few main variants of the illumination.

1. Artificial illumination in viewing schemes (general comments)

The illumination may be in the form of wide (or narrow but scanning) optical beam, forming a frame of the image containing both the object and the background, if present.

As before, it is assumed that the intensity of (reflected) radiation from the object in the direction to observer is I_t, while the background intensity in the neighborhood of the object is I_f. Then, the contrast k_t of the image of the object elements or of the object itself against the background *in the absence of the medium* is given by Eq. (1). Let there occur a medium in the channel, and the absorption process in it substantially suppress the scattering process; then

$$k_{t(s)} = \exp(-\tau) \times$$
$$\times (I_t - I_f)/[\exp(-\tau)(I_t + I_f) + 2I_d] \neq k_t, \tag{6}$$

where I_d is the backscattering interference (at a pulsed illumination) or light haze (at a stationary emission of the source).

Thus, in contrast to the passive observation, the occurrence of the scattering medium between the observer and the object leads to image contrast reduction, which increases with growing intensity of the backscattering interference or the light haze.

By the backscattering interference is meant the radiation reflected from the medium during pulsed illumination of the object. Properties of the interference are quite well studied and described.[3,6]

In discussion below we will consider a simpler case of the stationary illumination, i.e., $I_d(t) = I_d$. Dependence of I_d on the medium properties is also described in Refs. 3 and 6.

2. Illumination of the object

Let the laser beam illuminate *only the object* of observation and not the surrounding background.

From here on, we omit in formulas the superscripts; the subscripts t and f refer to the object and background, respectively, while parenthesized subscripts indicate the presence of the medium between the observer and the target (index s) and the laser illumination (index l).

Assume that the medium is absent. Then, obviously, for intensities we can write

$$I_{t(l)} = I_t + \Delta I_{t(l)},\ I_{f(l)} = I_f, \qquad (7)$$

and for the contrast coefficient

$$k_{t(l)} = (I_t + \Delta I_{t(l)} - I_f)/(I_t + \Delta I_{t(l)} + I_f). \qquad (8)$$

Comparing Eq. (8) with Eq. (3) in the absence of laser illumination, we found that the use of laser illumination in this case leads to improvement of the image contrast:

$$k_{t(l)} - k_t =$$
$$= 2I_t\, \Delta I_{(l)t}\, I_f /[(I_t + I_f)(I_t + I_t\, \Delta I_{t(l)} + I_f)] > 0.$$

Suppose that there occurs a scattering and absorbing medium between the object and the observer, which does not damage a fine spatial structure in the object image, i.e., a turbid medium in which the absorption process dominates.

Consider two possible cases of influence of I_d on the image of the scene object/background.

(a) The scattering phase function $g(\omega, \omega')$ and parameters of the viewing geometry are such that the reflected radiation in the image is concentrated within the object and does not influence the background image, i.e.,

$$I_{t(s,l)} = I_{t(s)} + \Delta I_{t(l)} + I_d,\ I_{f(s,l)} = I_{f(s)}. \qquad (9)$$

Write down the contrast coefficient of the image for this case in the form

$$k_{t(s,l)} = [(I_{t(s)} + \Delta I_{t(l)}) \exp(-\tau) + I_d - I_{f(s)} \exp(-\tau)] \times$$
$$\times [(I_{t(s)} + \Delta I_{t(l)})\exp(-\tau) + I_d + I_{f(s)} \exp(-\tau)]^{-1}. \qquad (10)$$

It is possible to show that

$$k_{t(l)} - k_{t(l,s)} < 0,$$

i.e., the occurrence of the scattering medium can lead to an improvement of the object image contrast relative to the case free of medium between the image and the object. This is possible in the case that laser illumination radiation, reflected by the medium, additively amplifies the signal from the object (such is the case of the incoherent reception). We assume therewith that the image of light haze does not go outside the boundaries of the object image and remains uniform within its limits. The latter is possible if the scattering medium is uniform in the planes perpendicular to direction of the laser beam propagation.

Hence, the R_{lo} estimate in this case takes the form

$$R_{lo} = \ln\, [(I_{ld} + \Delta I_{t(l)})/(I_{ld} - I_d)]/\beta_{ext}, \qquad (11)$$

and the limiting range of discrimination of the object (or its elements) against the background is

$$R_{lr} = \ln\, \{(I_{t(s)} + \Delta I_{t(l)})\, (1- k_{ld}) \times$$
$$\times [I_{ld}\, (1 + k_{ld}) - I_d\, (1- k_{ld})]^{-1}\}/\beta_{ext}. \qquad (12)$$

(b) Let conditions (a) be not fulfilled and

$$I_{t(s,l)} = I_{t(s)} + \Delta I_{t(l)} + I_d,\ I_{f(s,l)} = I_{f(s)} + I_d. \qquad (13)$$

In this case

$$k_{t(s,l)} = \exp(-\tau)\, (I_{t(s)} + \Delta I_{t(l)} - I_{f(s)}) \times$$
$$\times [(I_{t(s)} + \Delta I_{t(l)} + I_{f(s)}) \exp(-\tau) + 2I_d]^{-1}. \qquad (14)$$

Then

$$k_{t(l)} - k_{t(l,s)} = 4I_d \Delta I_{t(l)} \exp(-\tau)/[\exp(-2\tau) \times$$
$$\times (I_{t(s)} + \Delta I_{t(l)} + I_{f(s)})(I_{t(s)} + \Delta I_{t(l)} + I_{f(s)}) + 2I_d] > 0,$$

that is, the occurrence of the scattering medium in this case leads to decrease of the contrast coefficient of the object image.

Obviously, the limiting range R_{lo} of detection of a single object (in the absence of the background) can be estimated in this case from Eq. (11), while

$$R_{lr} = \ln\{[(I_{t(s)} + \Delta I_{t(l)}) \times$$
$$\times (1 - k_{ld})]/[I_{ld}\, (1 + k_{ld}) - 2k_{ld}I_d]\}/\beta_{ext}. \qquad (15)$$

3. Illumination of object and background

Let a stationary artificial source of optical radiation illuminate simultaneously the object and the surrounding background and creates the light haze I_d. Then, the intensity of the object- and background-reflected radiation in the direction to detector is

$$I_{t(s,l)} = I_{t(s)} + \Delta I_{t(l)} + I_d,$$
$$I_{f(s,l)} = I_{f(s)} + \Delta I_{f(l)} + I_d. \qquad (16)$$

Obviously, the limiting range of detection of a single object can be estimated using Eq. (11). Also, it is easy to obtain the estimate of the limiting range of the object discrimination from the surrounding background:

$$R_{lr} = \ln\{[(1 - k_{ld})\, (I_{t(s)} + \Delta I_{t(l)}) - (1 + k_{ld})\Delta I_{f(l)}] \times$$
$$\times [(1 + k_{ld})\, I_{ld} + 2k_{ld}I_d]^{-1}\}/\beta_{ext}. \qquad (17)$$

Let us compare the limiting ranges R_{lo} for passive Eq. (4) (denoted by ${}^{(4)}R_{lo}$) and active Eq. (11) (denoted by ${}^{(11)}R_{lo}$) observation schemes. To do this, consider the difference between them:

$${}^{(4)}R_{lo} - {}^{(11)}R_{lo} = \ln\, (I_t/I_{ld})/\beta_{ext} -$$
$$- \ln\, [(I_{ld} + \Delta I_{t(l)})/(I_{ld} - I_d)]/\beta_{ext}. \qquad (18)$$

Multiplying Eq. (18) by β_{ext}, we obtain

$${}^{(4)}\tau_{lo} - {}^{(11)}\tau_{lo} = \ln\, \{I_{t(s)}(I_{ld} - I_d)/[I_{ld}(I_{ld} + \Delta I_{t(l)})]\}, \qquad (19)$$

where ${}^{(4)}\tau_{lo}$ and ${}^{(11)}\tau_{lo}$ are optical lengths of the paths ${}^{(4)}R_{lo}$ and ${}^{(11)}R_{lo}$, respectively.

The difference (19) can either be positive or negative, depending on characteristics of the optical detector (I_{ld}), illumination source, properties of the medium ($\Delta I_{t(l)}$), as well as emission and reflection characteristics of the object ($I_{t(s)}$). That is, the use of illumination not only fails to increase the limiting range of detection of a single object, but even can decrease it, primarily because of the light haze or interfering side illumination. To eliminate this effect on the efficiency of the instrumental vision systems, the pulsed illumination and gated (controlled) operation of detector is used.[7]

From the comparison of Eqs. (5) and (12) we conclude that the use of illumination increases the limiting range, at which the object can be distinguished against the surrounding background. However, the condition, under which the image of the light haze is concentrated within the object image (or its elements), must be fulfilled. If this is not the case, the use of illumination (under certain conditions) may lead to worsening the efficiency of the optoelectronic system. The same result follows from simultaneous illumination of the object and the background.

Thus, for media with any optical depth τ (characterized by a low scattering coefficient, at which their optical depth due to scattering $\tau_{sct} \ll 1$), formulas (4) and (5) can be suggested for estimation of the detection range and discrimination of objects against a noisy background in passive observation schemes. For active observation schemes, these parameters can be estimated using Eqs. (11) and (12) or (11) and (15) (depending on the scattering phase function) when only the object is illuminated, and using Eq. (11) and (17) when the entire scene, including the object and the surrounding background, is illuminated.

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