VISIBILITY RANGE OF AN AIRDROME RUNWAY IN FOG

V.Kh. Brikenshtein, A.S. Drofa, A.A. Shuvalov, and L.I. Yakushkina

Scientific–Production Union "Taifun", Obninsk
Scientific–Research Institute of Aircraft Equipment, Zhukovskii
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Based on the theory of linear systems for solving the problem of image transfer through the scattering media, we present the results of calculations of the brightness of the image of an airdrome runway observed by a pilot when he lands his aircraft in fog. The results show that the visibility range of the airdrome runway in fog is more than twice as large as that predicted on the basis of the vision theory which ignores the additional contribution of light scattered by the observed object to the brightness of its image.

Determination of the visibility range of the objects in the turbid atmosphere is of importance and of current interest for a number of practical needs of the national economy, in particular, for ensuring the safety of the aircraft landing under bad weather conditions. The theory of vision in the turbid atmosphere which is now used cannot ensure the required accuracy of the determination of the visibility range of the observed objects since it takes into account the effect of a scattering medium on the optical image transfer inaccurately. This paper presents the results of calculations of the visibility range of the airdrome runway observed by a pilot when he lands his aircraft in fog. These results are obtained on the basis of the theory of linear systems describing the image transfer through the light scattering medium.

To analyze the visibility of the airdrome runway when landing the aircraft in fog we must know the brightness distribution of the image observed by a pilot on the glide path of the aircraft. Let us assume that the image is formed from the image of the airdrome runway against the background of the earth's surface bordering on the image of sky along the horizon in the field of view of the pilot. The sky brightness is determined by the brightness of the infinitely thick layer of the turbid atmosphere (fog) and is caused by scattering of light of the extraneous sources, for instance, the sun. Let us also assume that the images of sky and the earth's surface are two infinite half–planes with uniform distributions of brightness on both sides of the horizon. Thus, if there is no scattering medium between the observer and the object, the observer percepts the following brightness distribution:

$$B_0(\mathbf{r}) = \begin{cases} B_r \text{ for } \mathbf{r} \in s, \\ B_{bg} \text{ for } \mathbf{r} \in S, \\ B_s \text{ for } \mathbf{r} \notin s \text{ and } S, \end{cases} \quad (1)$$

where $\mathbf{r}$ is the radius vector of the observation point in the image plane; s and S are the areas occupied by the airdrome runway and the earth's surface; B_r, B_{bg}, and B_s are the brightnesses of the airdrome runway, the background of the earth's surface, and the sky, respectively. Under real atmospheric conditions we usually have $B_s > B_r \gg B_{bg}$. Let us determine the contrast of the image of the airdrome runway without fog in the following way:

$$K_0 = (B_r - B_{bg})/B_{bg}. \quad (2)$$

We must elucidate the character of contrast change when there is a scattering medium between the observer and the object. Let us suppose that the scattering medium and illumination conditions remain unchanged over the entire volume of the medium under consideration. In the real atmosphere such assumptions are justified for the day–light observations of the objects under conditions of the surface fog when the observer being in fog views the object against the background of the earth's surface. The effect of nonuniform illumination conditions (depending on the height of the sun above the horizon, the underlying surface albedo, and the vertical stratification of the light scattering medium) on the characteristics of visibility of the objects was studied in Ref. 3. Let us find the brightness distribution of the image observed through the scattering medium. We shall assume that the optical observation system (human eye) does not introduce additional distortions in the image formed with it. Any self–illuminated object or diffuse object reflecting the light can be considered as an ensemble of elementary point sources of light. In linear optical system the image of such object is constructed as a result of superposition of the images of individual point sources.[4,5]

$$B(\mathbf{r}) = \int_{-\infty}^{\infty}\int B_0(\mathbf{r}')\, A(\mathbf{r}, \mathbf{r}')\cdot\delta\mathbf{r}'. \quad (3)$$

Here the function $A(\mathbf{r}, \mathbf{r}')$ which is referred to as the point spread function (PSF) describes the brightness distribution of the image of the diffusely illuminated point source of unit power which is observed through the scattering medium. For the considered viewing geometry the form of the PSF turns out to be dependent of the coordinate $\mathbf{r}'$ of the point source because the viewing line when the pilot observes the airdrome runway is sloped with respect to the image plane and the optical thickness of the scattering medium turns out to be different for different elements of the image. The PSF on the slant paths was studied in Ref. 6.

To describe adequately the observed image of the object in the turbid atmosphere under conditions of day–light illumination we must also take into account the fogging brightness which is superposed on the image (3) and is associated with light of the extraneous sources scattered in the layer located between the observer and the object. Because of the fogging effect the brightness of the image observed through the layer increases by an amount which is

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determined by the thickness of the layer and by the conditions of its illumination.[1–3] Substituting Eq. (1) into Eq. (3) and taking the fogging brightness into account we can obtain the brightness distribution of the observed image (see Ref. (7))

$$B(\mathbf{r}) = B_s + (B_{bg} - B_s)\cdot T_{bg}(\mathbf{r})(B_r - B_{bg})\cdot T_r(\mathbf{r}) , \quad (4)$$

where

$$T_{bg}(\mathbf{r}) = \iint\limits_{\mathbf{r}'\in s,S} A(\mathbf{r}, \mathbf{r}')\cdot d\mathbf{r}'. \quad (5)$$

$$T_r(\mathbf{r}) = \iint\limits_{\mathbf{r}'\in s} A(\mathbf{r}, \mathbf{r}')\cdot d\mathbf{r}'. \quad (6)$$

Thus, the image observed through the scattering medium can be represented as the sum of three terms. Each term characterizes the image of the individual self–illuminated object with brightnesses B_s, $B_{bg} - B_s$, and $B_r - B_{bg}$, respectively. The functions $T_{bg}(\mathbf{r})$ and $T_r(\mathbf{r})$ determine the brightness distributions of the image of the earth's surface and the airdrome runway having unit brightnesses. The quantities T_{bg} and T_r take into account the total contribution of the unscattered light of the object attenuated in the scattering medium and of the light of the object scattered by the medium. The value of this contribution depends on the angular dimensions and shape of the observed object as well as on the light scattering properties of the medium.[7] Note that ignoring the contribution of the scattered light to the image of the objects results in $T_{bg} = T_r = \exp(-\tau)$, where τ is the optical thickness of the layer of scattering medium located between the observer and the object. In this case formula (4) takes the form (for $r \in s$)

$$B = B_s\cdot(1 - \exp(-\tau)) + B_r\cdot\exp(-\tau) , \quad (7)$$

which coincides with the formula derived in Ref. 2 for the attenuation of the brightness of the object in the turbid atmosphere ignoring the contribution of the scattered light into the image.

To calculate the brightness of the image of the airdrome runway in fog let us take into account the geometry of the airdrome runway in the field of view of the pilot when he observes it from the glide path. Let us assume that the slope angle of the plane of the glide path with respect to the earth's surface is equal to 2°40′ and the aircraft descents on the straight glide path to the point located 300 m apart from the start of the airdrome runway. The width of the airdrome runway was taken to be equal to 50 m. The coordinates of the observation point in the image plane were described by the viewing angles along two perpendicular axis one of them (the ϖ axis) coincides with the axis of the image of the airdrome runway and another (the φ axis) – with the horizon.

In computer calculations of superposition integrals (5) and (6) the image plane was divided into individual diffusely illuminated elements with small angular dimensions, and within each element the optical thickness of the fog layer located between the observer and the object plane was approximately the same. Taking into account the slope angle of the viewing line of this element, we calculated the brightness of light passed through the layer of fog with given optical thickness in the viewing direction for every element. The brightness of the image of the airdrome runway was found by summing over the contributions of brightnesses from every element of the object plane. The angular dimensions of the elements of the image in the form of a square were taken to be equal to 0.5°× 0.5°. The angular brightness distribution of a scattered light within the individual element was estimated by the Monte Carlo method based on the adjoined trajectory simulation when the unidirectional point source was placed at the point of location of the observer while the scattered light of the source was received by the isotropic receiver which was placed in the object plane and had the dimensions corresponding to the angular dimensions of the element of the image. The calculations were performed with the use of the algorithm described in Refs. 6 and 8 and were based on the method of the adjoined trajectory simulation and local estimating. The error in estimating the brightness was not more than 10%. To describe the light scattering properties of fog we used the scattering phase function for Deirmendjian's C1 cloud model (see Ref. 9).

To reduce the volume of computer calculations of the brightness of the image of the airdrome runway, the databank incorporating the angular profiles of the brightnesses of the images of the individual elements observed through the fog with different optical thickness at different slope angles of the viewing path was preliminary created. The databank incorporated the tabulated profiles of the parameters for the range of variations in these parameters required for calculations of the brightness of the image of the airdrome runway. The increment of the parameters was chosen small in order to ensure the satisfactory accuracy of the interpolation of the data available. The databank which was stored in the computer memory contained 168 perpendicular angular profiles of the images. In calculating the brightness of the image of the airdrome runway at the given altitude of an aircraft and for the given value of the light scattering coefficient s in fog for the chosen viewing line the optical thickness of the fog layer for every element of the image and the slope angle of the viewing line of this element were calculated. Then we seek for the image profile with the closest (smaller and larger) values of the parameters in the tabulated databank. With the help of linear interpolation of these profiles we determined the contribution of each individual element into the brightness of the image of the airdrome runway for the chosen viewing line. The spot check showed that the calculational errors caused by interpolation did not exceed the errors of calculations performed with the help of the Monte Carlo method. The program for calculating the brightness of the image of the airdrome runway was implemented with the help of an ES–1065 computer. The time of calculations of the elements of the image comprising 50 points was about 2–3 minutes.

The example of brightness of the image of the airdrome runway calculated in this way when viewing from the altitude of 15 m through the fog with σ = 10 km^{-1} is shown in Fig. 1. The calculated results were obtained for the contrast $K_0 = 0.6$ and $B_s/B_r = 2$. The plots show the transverse profiles of the brightness of the image of the airdrome runway scaled to B_s (on one side of the axis of the airdrome runway) as a function of the viewing angle φ. Curves *1* and *2* show the change in the brightness of the image on the axis and on the edge of the image of the airdrome runway vs the viewing angle φ while curve *3* shows the change in the brightness of the earth's surface. As can be seen from Fig. 1, the contrast of the image of the airdrome runway against the background of the earth's surface decreases because of both decreasing the difference between the brightnesses of the airdrome runway and the background and increasing the background brightness due to the fogging effect caused by the light scattered in fog.

Determining the distance to the airdrome runway for which the observer cannot separate the brightness of the airdrome runway against the brightness of the background we can determine the visibility range of the airdrome runway at the given altitude.

Let us determine the contrast of the image of the airdrome runway observed through the fog as follows:

$$K(\psi) = (B_r(\psi) - B_{bg}(\psi))/B_r(\psi) , \quad (8)$$

where $B_r(\psi)$ and $B_{bg}(\psi)$ are the brightnesses of the image of the airdrome runway and the earth's surface observed at the same viewing angles ψ. Using Eq. (4) for calculation of the contrast we can obtain the following expression:

$$K(\psi) = \frac{K_0 \cdot T_r(\psi)}{K_0 \cdot T_r(\psi)} + \frac{B_s}{B_r}(1 - T_{bg}(\psi)) + (1 - K_0) \cdot T_{bg}(\psi))),(9)$$

where K_0 is the apparent contrast which is not distorted by the scattering medium and is given by formula (2). If we ignore the contribution of the scattered light in forming the image and assume that $T_{bg} = T_r = \exp(-\tau)$ then the formula for the contrast takes the form

$$K = \frac{K_0}{1 + \frac{B_s}{B_r}(\exp(-\tau) - 1)} . \quad (10)$$

Relation (10) coincides with the formula for calculating the contrast derived in Ref. 2 neglecting the contribution of light of the observed object scattered by the medium to the brightness of the image of the object. Assuming that the threshold visibility conditions of the airdrome runway are realized for $K = K_{th}$ where K_{th} is the threshold contrast for a human eye we can obtain from Eqs. (9) or (10) the visibility range of the airdrome runway, e.g., the distance L for which the apparent contrast of the observed image becomes equal to the threshold and the image of the airdrome runway becomes invisible against the background of the earth's surface. As to the conditions of the airdrome runway observation from the aircraft cockpit, let us set the threshold contrast $K_{th} = 0.04$ (Ref. 2). It then follows from Ref. 2 that for concrete airdrome runway the ratio of the brightness of the turbid sky to the brightness of the airdrome runway depends weakly on the illumination conditions and is equal to 1.5 for the dry airdrome runway. The contrast K_0 for ordinary conditions of landing is usually equal to 0.3–0.6 (see Ref. 2).

Let us now consider the results of calculations of the visibility range of the airdrome runway for the given values of the photometric parameters. In calculating the contrast from Eq. (9), we shall choose the brightness of the airdrome runway on its axis for the brightness of the airdrome runway assuming that the smearing of the boundaries of the image observed through the fog effects poorly on the visual perception of the image with a naked human eye (see Ref. 7). Results of calculation of the visibility range of the airdrome runway in fog for different contrasts K_0 are presented in Table I.

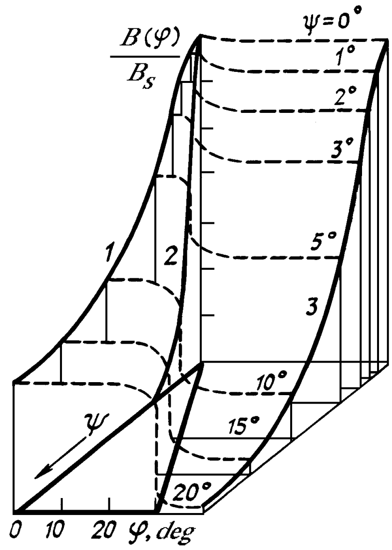

FIG.1

A certain dependence of the visibility range on the altitude of the aircraft above the ground can be explained by the changes in the image of the airdrome runway in the field of view of the pilot when the airplane descends so far as the contribution of the scattered light to the image depends on the shape and angular dimension of the observed object. Note that for the chosen geometry of the glide path the airplane fly over the start of the airdrome runway at an altitude of 14 m and, consequently, the most significant changes in the image observed by a pilot took place around this altitude.

TABLE I. Visibility range of the airdrome runway (in meters) in fog for $\sigma = 5$ km^{-1} at different altitude of the aircraft above the ground.

	L_s, m					
K_0	h, m					
	5	10	15	20	30	Eq. (10)
0.30	617	667	700	634	601	343
0.45	763	782	825	759	685	421
0.60	794	831	958	843	771	478

Table I presents also the values L_s calculated from Eq. (10) disregarding the effect of the scattered light on the image. In this case the value L_s is independent of the altitude of the aircraft above the ground. It can be seen from Table I that the values L_s calculated by us are nearly twice as large as the values calculated from formula (10). This fact can be explained by the different additional contribution of the scattered–in–fog light of the airdrome runway and the earth's surface to the brightness of the image observed by a pilot. This difference increases with increase of the light scattering coefficient in fog. In this connection, as can be seen from the data in Table II, the difference between the visibility range calculated by us and the visibility range calculated by formula (10) increases as well.

TABLE II. Visibility range of the airdrome runway (in meters) from the altitude of 15 m *for different transparency of fog (upper rows correspond to the case when the contrast was determined on the basis of the axial brightness of the airdrome runway, lower rows – on the basis of the brightness on the edges of the airdrome runway.)*

K_0	L_s based on the proposed method			L_s based on Eq. (10)		
	σ, km^{-1}					
	5	10	20	5	10	20
0.30	700 628	425 363	229 193	343	171	86
0.45	825 745	454 406	241 227	421	210	105
0.60	958 848	510 449	275 240	478	239	119

In calculating the contrast, the axial brightness of the airdrome runway was taken for the airdrome runway brightness in the above–discussed data. However, as can be seen from Fig. 1, the brightness distribution of the image of the runway observed through the fog is nonuniform, namely, the brightness of the image is smaller on the edges of the airdrome runway than on the axis. To make the determination of the visibility range more reliable one can take the brightness of the edge of the airdrome runway (for corresponding viewing angle φ) for the airdrome runway brightness in calculating the contrast from formula (9). The results of calculation of L_s for such a determination of the contrast are also presented in Table II. As can be seen from the tabulated data in this case the values L_s are different but this difference (up to 15%) is negligible in comparison with their difference from the results calculated from formula (10) in which the effect of the scattered light on the image in the scattering medium is ignored.

In conclusion it should be noted that the effect of the scattered light of the observed object on its visibility range was demonstrated in this paper by way of a simple (in theoretical sense) example when the scattering medium was homogeneous and its illumination conditions were uniform over the entire space of observation. It is clear, however, that in the inhomogeneous medium as well as for nonuniform illumination conditions (caused by the inhomogeneity of the medium itself, by the effect of underlying surface albedo, by the sun height above the horizon, and so on) the considered factor can also be of great importance and ignoring it in calculating the visibility range can result in highly underestimated data.

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