# Zones of the visibility of a noctilucent cloud

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ABSTRACT

For a noctilucent cloud (NLC) with its typical features the brightness contrast $k$ of such a cloud against the sky is computed as observed from any point within a circle of more than 800 km. This contrast is compared with the contrast threshold $\varepsilon$ of the eye. The quotient $|k|:\varepsilon$ is a measure of the degree of visibility. Its distribution over the earth's surface in the vicinity of an NLC at 5 different times during twilight reveals zones of differential visibility (Figs. 4*a–e*).

## Problem

In recent years systematic observations of noctilucent clouds (NLC) have made remarkable progress, which is mainly due to a number of countries having organized a watch of the occurences of NLC utilizing observational networks and now gradually standardizing their observations on the basis of international rules. The results will in such a way be comparable, permitting appropriate statistical treatment.

Statistics of the time and spatial distribution of the occurrences of NLC permit conclusions to be drawn on the conditions of their formation and, hence, on properties of the very high atmosphere.

There are, however, further parameters modifying the time and spatial distribution of the NLC phenomena. With their influence being known, it will be easier to draw conclusions on the conditions in the very high atmosphere.

Such a factor is the observer's visual faculty. The ability of the human eye to perceive an optical phenomenon is limited. This applied to the visibility of NLC means that, for instance, an observer might not be able to recognize, though rather alert, a trace of an NLC, inspite of the de facto presence of such a faint phenomenon, which could possibly be made visible by photographic or any other means.

Hence, the visual faculty of the eye, though as an undesired factor, enters the statistics of the spatial and time distribution of the NLC. There is the further unpleasant property of the eye that its visual faculty is not constant, rather being very much dependent in twilight on the general brightness in the observer's surroundings. For example, one and the same NLC may during some period of twilight be fairly well visible, whereas in another, darker, phase of twilight it might remain unseen, though having not changed and invariably being illuminated by the sun. Such physiological effects on statistics of the NLC should be taken into account.

There is a further factor to be thought of in interpreting the statistical results, namely the optical behaviour of the NLC, which, for instance, leads to an NLC being visible rather infrequently to an observer positioned immediately below it. At a distance of several hundred kilometers there are, however, places from where this NLC is clearly visible.

In order to find out the influence of such factors upon the visibility of NLC the following calculations are made. A selected NLC is chosen to determine for the various twilight phases if and how clearly this NLC is seen from the various places on the earth's surface. In a previous paper (Dietze, 1968*a*) use was made only of observation places situated in the plane of the solar vertical through the NLC.

## Calculations

Recognizing an NLC with clear sky is largely dependent on the contrast to the background sky. Contrast $k$ is by definition the relative

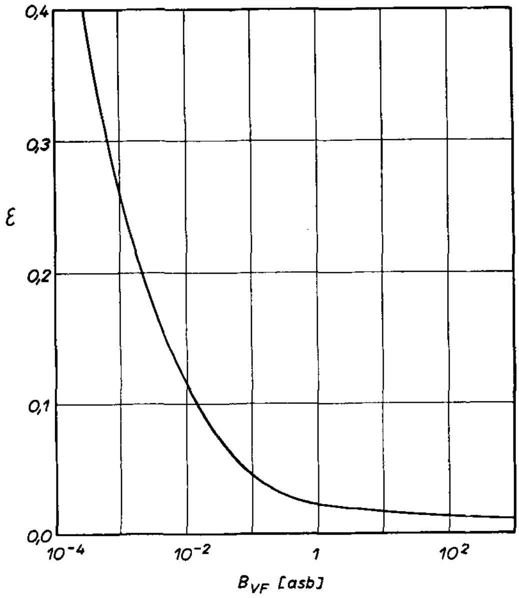



*Fig. 1.* Threshold of brightness-contrast $\varepsilon$ of the human eye for 95 % detection of extended areas.

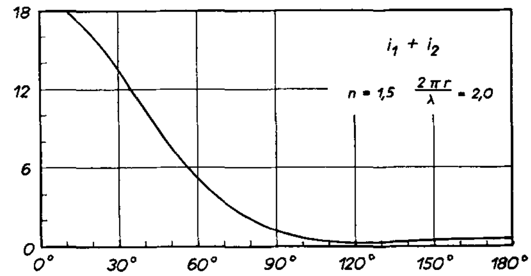



*Fig. 3.* Scattering function used for NLC particles.

difference between the luminance of the objective and that of its surroundings (cf. e.g. Dietze, 1957). The luminance of the vicinity is the luminance $B_S$ of the sky near the NLC. The luminance of the NLC is $B_{NLC} + B_S$, as it is formed by two components, i.e. the sun light $B_{NLC}$ scattered by the NLC particles and the skylight $B_S$. Hence, the contrast therefore is

$$k = \frac{B_S - (B_{NLC} + B_S)}{B_S} = \frac{-B_{NLC}}{B_S} \tag{1}$$

The NLC is visible when the absolute value of the contrast, $|k|$, is greater than the contrast threshold $\varepsilon$ of the eye. As a physiological parameter $\varepsilon$ has the unpleasant property not to be constant, but rather to be changing with the luminance $B_{VF}$ of the visual field, as is shown in Fig. 1. Looking, for instance, towards the sky at daylight the eye can still recognize a contrast of little more than 0.01. Under clear-sky conditions at night ($2 \cdot 10^{-3}$ asb) a contrast of as much as 0.2 is required. These values vary somewhat from person to person, and there are other conditions which are of some influence, too. The relations shown in Fig. 1 based upon studies by Blackwell (1946) are most suitably applicable to the conditions prevailing with the observation of NLC, provided, however, the NLC's angular extent is of some degrees. With the absolute value of contrast $k$ of the NLC equal to $\varepsilon$ the probability to perceive an NLC is 95%.

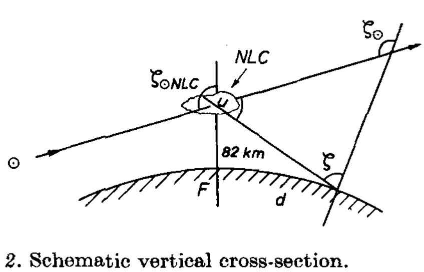



*Fig. 2.* Schematic vertical cross-section.

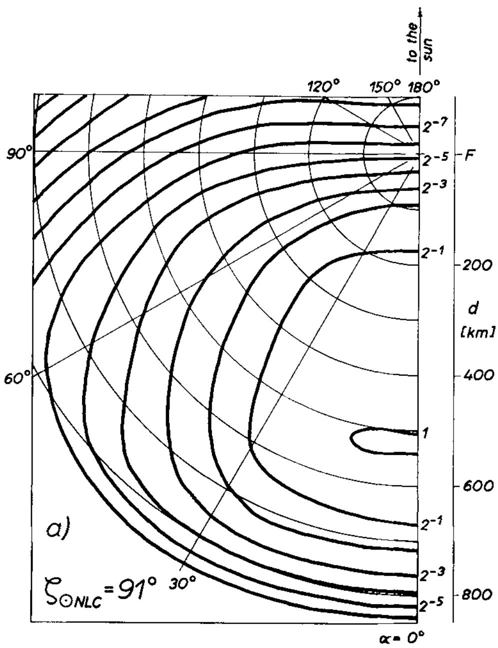
Let us now consider one selected NLC assumed to be at an altitude of 82 km. An observer, to whom the sun is at a true zenith angle of $\zeta_{\odot}^* = 100°$, should see this NLC above the sun at a zenith angle of $\zeta^* = 82°$ at a contrast $k^* = -B_{NLC}^*/B_S^* = -1$. These are data observed most frequently, i.e. they are typical. We call this situation the "basic situation".

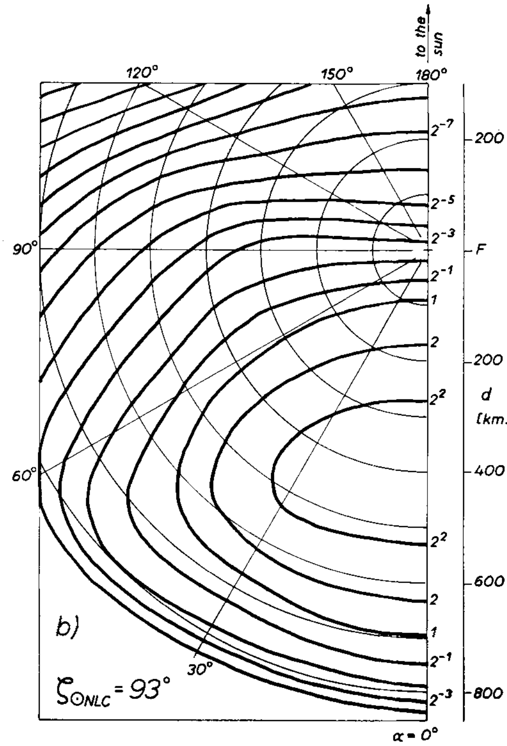
The contrast of this NLC at any other time and observed from any other point of observation is

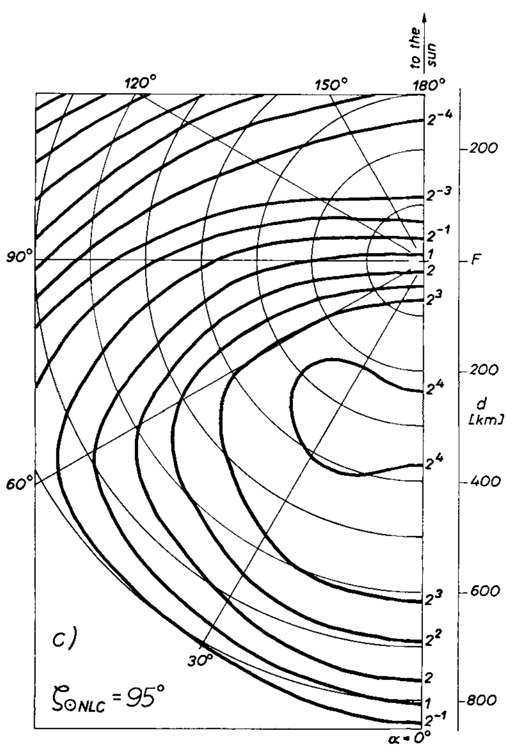
$$k = \frac{-B_{NLC}}{B_S} = k^* \frac{B_S^*}{B_S} \frac{B_{NLC}}{B_{NLC}^*} \tag{2}$$

This equation permits the contrast $k$ to be calculated from the known contrast $k^*$ of the basic situation, provided both the ratios on the right are known.

We are now going to use empirical values for the sky luminances $B_S$ and $B_S^*$. After Bullrich (1948) the zenith luminance is known for any solar depression. We have calculated the relative distribution of the luminance over the sky from the results of Barteneva *et al.* (1967).




*Figs. 4a–e.* Zones of visibility of an NLC situated 82 km above $F$. $F$ is the origin of the polar co-ordinates $d$ ( = distance at the earth's surface) and $\alpha$ ( = azimuth of the line of sight from the observer's point towards the NLC). The curves connect the observing places at the earth's surface of the same value $|k|:\varepsilon$ of visibility, the amounts of which are written by powers of 2 at the right border. The NLC is visible from the zones having $|k|:\varepsilon > 1$. $\zeta_{\odot \mathrm{NLC}}$ = true zenith angle of the sun as seen from the NLC.

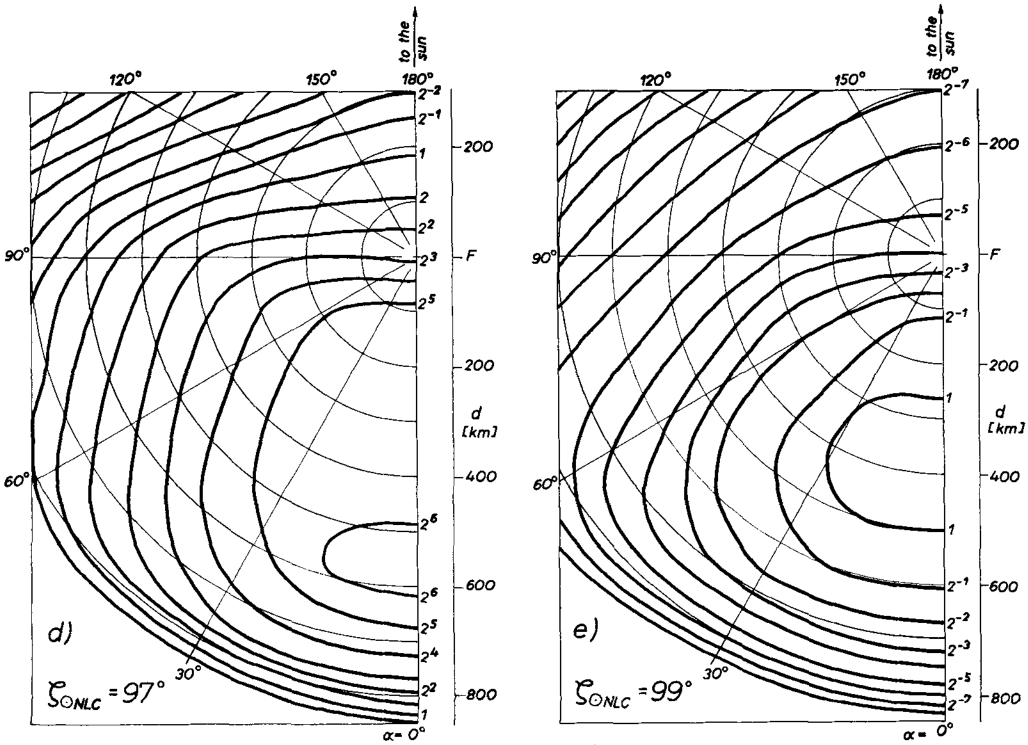
The last ratio in eq. (2) is

$$\frac{B_{\mathrm{NLC}}}{B^*_{\mathrm{NLC}}} = \frac{i_1 + i_2}{i_1^* + i_2^*} \frac{e^{-am}}{e^{-am^*}} \frac{u}{u^*} \tag{3}$$

The first ratio on the right contains the dependence on the scattering function of the solar light scattered by the NLC i.e. on the scattering angle. We describe the light scattering at the NLC particles after the Mie theory. $i_1$, $i_2$, $i_1^*$ and $i_2^*$ are polarized components of the scattered light for each scattering angle $\varphi$, which may be calculated as follows:

$$\cos\varphi = \cos\zeta \cos\zeta_{\odot} + \sin\zeta \sin\zeta_{\odot} \cos\alpha \tag{4}$$

$\zeta_{\odot}$ is the true zenith angle of the sun related to the observational place. $\zeta$ and $\alpha$ are the zenith




angle and the azimuth at which the NLC is visible to the observer (Fig. 2). The azimuth counts from the direction towards the sun, i.e. $\alpha = 0°$ means that the observer sees the NLC in direction of the sun, in other words, he is—as seen from the NLC—opposite to the sun.

The values for $i_1 + i_2$ and $i_1^* + i_2^*$ are available from Tables by Giese *et al.* (1961). We assume the refractive index of the NLC particles to be $n = 1.5$, and an effective particle diameter of $2r = 0.3$ $\mu$m. These values correspond to the results of the polarization measurements made by Witt (1960). For the parameter $2\pi r/\lambda$ we take a value of 2.0 which corresponds to a wavelength of $\lambda = 472$ nm. This corresponds to the bluish colour of the NLC. In Fig. 3 the scattering function is shown.

The second ratio on the right of eq. (3) takes into account the extinction on the way from the NLC to the observer (Fig. 2). This distance varies with the zenith angle $\zeta$ of the NLC. These distances are expressed as optical air mass $m$ or $m^*$, respectively, and are inserted, using *Bemporad's values*, into the calculation. The extinction coefficient is assumed to be 0.4, which corresponds to an atmosphere of moderate turbidity.

$u$ and $u^*$ in the last ratio of eq. (3) are the lengths of the line of sight situated inside the NLC (Fig. 2). To calculate them the curvature of the earth and the atmospheric refraction must be taken into account; hence, we have used the Tables of Link & Sekera (1940) and Link (1947).

The aforementioned values are inserted into eq. (2) to calculate the contrast for observing places within an 800 km radius around the plan position $F$ of the NLC (Fig. 2), i.e. for 5 different times during twilight when the true zenith angles $\zeta_{\odot NLC}$ of the sun for the NLC positions are 91°, 93°, 95°, 97° and 99°.

For any of the solar positions $\zeta_{\odot NLC} = 91°$ tc 97° the illumination of the NLC by the sun is of equal intensity. For, using the results of Dietze (1968*b*) concerning the optical conditions during twilight it follows that at these solar positions the attenuation of the solar beam illuminating the NLC due to absorption in the ozone layer, to scattering in the very high portions of the atmosphere, and to the divergence effect (i.e. refractive divergence) is less than 1%.

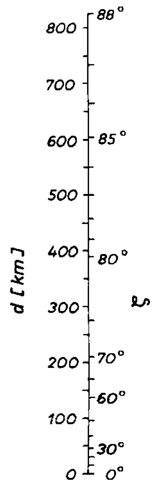



*Fig. 5.* Distance $d$ at the earth's surface from plan position $F$ of an NLC and zenith angle $\zeta$ of this NLC situated 82 km above $F$.

At $\zeta_{\odot NLC} = 99°$, however, the total attenuation is 99.6%. Accordingly, we have for $\zeta_{\odot NLC} = 99°$ multiplied the contrast values calculated after eq. (2) by a factor 0.004.

The absolute values of contrast, $|k|$, are to be compared with the eye's contrast threshold $\varepsilon$ in order to be able to state if the NLC is visible and to what degree. We now form the ratio $|k|:\varepsilon$, which is an appropriate measure for the degree of visibility, i.e. how well the NLC stands out against the sky. With $|k|:\varepsilon = 1$ the NLC is just visible; with $|k|:\varepsilon < 1$ the NLC becomes invisible. More precisely, with $|k|:\varepsilon = 1$ the NLC may be detected at a 95% probability, and this probability decreases rapidly with smaller values of $|k|:\varepsilon$ and increases with greater values.

The values for $\varepsilon$ are taken from Fig. 1 which includes the luminance within the visual field $B_{VF}$ of the observer. In general, for $B_{VF}$ the sky's luminance $B_S$ as at the position of the NLC is used. With near-horizon sky positions for $B_{VF}$ values are used which are lower by up to 35% than $B_S$. This is because at these sky positions the visual field is formed not only by the sky but to some extent by the darker earth's surface.

The values $|k|:\varepsilon$ obtained in such a way are used to draw Fig. 4*a–e*; they represent the earth's surface as seen from above. Above $F$ there is at 82 km the NLC, for which the zenith angle of the sun is $\zeta_{\odot NLC}$. The coordinates of the observing places are their distance $d$ from plan position $F$ of the NLC, and the azimuthal direction $\alpha$ towards which the observer sees the NLC. $\alpha = 0°$ means that, as seen from the observer's point, the NLC is in the very same azimuthal direction as is the sun. The curves connect the observing places of the same value $|k|:\varepsilon$. The spacing of the curves corresponds to a factor 2. The curve designated "1" encompasses the area from where the NLC is visible.

Using Fig. 5 the zenith angle $\zeta$ of the NLC is obtained from distance $d$.

## Discussion

Let us now consider what deviations from the assumptions used for the calculations may occur, in order to be able to draw conclusions on the applicability of the results.

The assumed height of the NLC of 82 km is the one most frequently occurring. Within the interval of $82 \pm 3$ km there is half of all the NLC heights measured. The extreme height limits range from 74 km to 92 km (Fogle, 1966). Any change of height can only result in rather insignificant deviations from our results.

The properties of the NLC particles essentially controlling their optical behaviour, such as magnitude, refractive index and shape undergo variations and deviations from the values used here. With it go changes of the scattering function and, hence, of $i_1 + i_2$ and $i_1^* + i_2^*$ in eq. (3). The changes that are really possible can be assessed only with some difficulty since the knowledge on the properties of the NLC particles is rather insufficient. The advantage of the values chosen is that they have been obtained from optical measurements.

The values used for the sky luminance are representative for a station situated outside industrial areas in the absence of clouds and a snow cover. Deviations are caused by changes of the atmospheric turbidity. Disregarding extraordinary cases the sky luminance may be expected to deviate from our values by a factor up to 4 or 1/4. At near-horizon sky positions the deviations might be greater still. The ground cover plays a role only in deep twilight. The sky luminance is increased by snow by a factor of less than 2.

The extinction coefficient $a = 0.4$ likewise corresponds to average conditions. Its influence upon the NLC brightness is with near-horizon NLC much greater than with near-zenith ones.

With the extinction coefficient doubling up to 0.8 the luminance $B_{NLC}$ decreases to less than a half when the cloud is 30° above the horizon. The luminance decreases down to as little as 6% when the NLC is 8° above the horizon. With extinction decreasing by one half to a = 0.2 then the luminance $B_{NLC}$ increases by one half at an elevation angle of 30°, but at 8° the increase is four times.

Scattering of the light changes in the same sense as does extinction, which means that the sky luminance $B_S$, too, is correlated to atmospheric extinction. The multiple scattering of light playing a rather important part, the relationship between extinction and sky luminance during twilight is a rather complex one. Hence, quantitative details cannot be given. It should, however, be stressed that with rather intense atmospheric turbidity, i.e. with some higher rate of extinction, the sky luminance, too, is greater. In other words, atmospheric turbidity very much modifies the contrast of NLC against the sky. For, an increase in turbidity reduces the contrast not only by an attenuation of the NLC's brightness but additionally by an increase of sky brightness.

The attenuation of the sunlight illuminating the NLC at $\zeta_{\odot NLC} = 99°$, was assumed to be 99.6%. With different optical conditions there will be a change not only of the illumination of the NLC but even of the sky luminance. At $\zeta_{\odot NLC} = 99°$, it follows, deviations from our results are more probable than at different solar positions.

Atmospheric refraction has always been taken into account when its values were such as to modify the result.

It has already been said under what conditions the values of the contrast threshold $\varepsilon$ of the eye (Fig. 1) are applicable. These values are, however, valid for the adapted eye. It takes the observer when going during the dark phase of twilight from a very bright room out into the open more than half an hour to have his eye entirely adapted. For this period higher values of $\varepsilon$ are relevant. This is the case at many observing stations during deep twilight. Then lower values of $|k|:\varepsilon$ apply. The effect of the non-adapted eye is, no doubt, of a significant influence upon the statistical results of the observed NLC frequency.

## Results

The discussion reveals that the results as shown in Fig. 4*a*–*e*, are representative in reflecting the most frequently occuring case and, at a reasonable approximation, even the average conditions.

In all those cases, when contrast $k$ or the contrast threshold $\varepsilon$ are changing by a factor, the distribution (Fig. 4*a*–*e*) of the zones of visibility is maintained; it is only the degree of visibility ($|k|:\varepsilon$) that changes. This is particularly the case if the NLC's density differs from the one stated in our case.

Frequently occuring structures of NLC are bands and billows which mainly form as a result of NLC consisting of a layer deformed into a wave-like shape rather than being plano-parallel. If the observation is made in the vertical from below the wave-like structure can not be recognized. With, however, the line of sight meeting at a slant angle a slant wave flank, for $u$ in eq. (3) and Fig. 2 much greater values apply. The observer then perceives bands and billows. If they are detectable only with some difficulty these NLC may be expected to be visible merely thanks to their wave-like deformation and then only to observers at favourable observing places. Such an increase of contrast is the more probable the nearer to the horizon the NLC is positioned, i.e. the farther away the observer is from the plan position. This is of some significance to the statistical distribution of NLC over the various elevation angles above the horizon.

The arrangement of the isolines and with it of the zones of visibility bears according to Fig. 4*a*–*e* some similarity whereas the degree of visibility varies with the solar position. Observers who, as seen from the NLC, are on the side opposite to the sun, i.e. to whom the NLC is positioned on the sun's side, have the most favourable chances to detect the NLC.

Let us now proceed to the region of visibility ($|k|:\varepsilon > 1$). With sinking sun this region progressively extends reaching its maximum extent of about $10^6$ km² when the sun is appr. 7° below the horizon of the NLC ($\zeta_{\odot NLC} = 97°$). This means, at this situation each point of our NLC is simultaneously visible from within an area of $10^6$ km² of the earth's surface. Then the area of visibility decreases rather rapidly. It is of an oval shape whose short axis coincides with the azimuthal direction of the sun's rays. With $\zeta_{\odot NLC}$ between 95° and a little over 97° the NLC becomes visible even to some places on the sun's side, i.e. the observer positioned there can detect the cloud in the sky's side opposite to the sun.

With any solar position the area of the most favourable visibility is at the solar vertical opposite to the sun—as seen from the NLC. The distance $d$ of this zone from plan position $F$ varies with the solar depression. On the average $d$ is 400 km, corresponding to a zenith angle of the NLC of 80°.

The comments on the visibility of NLC in the solar vertical, presented in a previous paper (Dietze, 1968*a*), apply in analogy. The results of the quoted paper deviate in some respect a little from the results obtained here. This may be explained by the values for the sky luminance originating from different sources and differing slightly.

For NLC observed by physical radiation meters or photographic methods rather than by visual means, there are quite different patterns of visibility distribution. For, under these circumstances a threshold fitting the specific method is to be used instead of the physiological contrast threshold $\varepsilon$.

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## ЗОНЫ ВИДИМОСТИ СЕРЕБРИСТОГО ОБЛАКА

Вычисляется контраст яркости серебристого облака $k$ с его типичными особенностями по отношению к небу при наблюдении облака из любой точки внутри круга диаметром более 800 *км*. Этот контраст сравнивается с пороговым контрастом $\varepsilon$ человеческого глаза. Отношение $|k|:\varepsilon$ является мерой степени видимости. Распределение этого отношения по поверхности Земли вблизи серебристого облака для пяти различных моментов времени в течение сумерек показывает существование зон различной видимости (см. фиг. 4а–е).