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VISIBILITY IN THE ATMOSPHERE

by

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Introduction

The study of visibility is a field the basic mission of which is investigation of the laws of visual perceptivity of various natural and artificial objects of the landscape, and of signal lights. With these basic missions, which have broad applied and investigative aspects, there are associated extensive circles of experimental, theoretical, and methodical treatments addressed toward study of the optical properties of the atmosphere and of observed, toward the state of threshold visual functions, toward the creation of special devices, etc.

The present state of the study of visibility is characterized by certain peculiarities which may be summed up briefly as follows.

In the first place, to date it has not been possible to construct any universal, theoretical, methodical, and apparatus complex applicable in constant measure to the resolution of the diversity of applied problems. As practice shows, different branches of the national economy bring forward applied problems which are differentiated as to their content, and correspondingly the resolution of these problems must also be sharply differentiated both as to methods and as to devices used. An obvious example of what we have said is the methods for determining the landing range of visibility at equipped airports.

In the second place, the resolution of each applied problem regarding range of visibility of objects in the atmosphere is possible only in the event that we take into account a series of factors characterizing the properties of the milieu (the transmissivity of the atmosphere), the photometric peculiarities of the objects themselves and of their backgrounds, and the state of threshold visual functions of the observer. The problems cannot be resolved if even one of these factors is an unknown.

In the third place, one is obliged to encounter the specific difficulties of measuring the determining parameters, their changeability in time and in space, and the (generally speaking) low precision of these measurements. These circumstances oblige one to impose reasonable demands both on the precision of determination of range of visibility of objects, and on the main problem of the study of visibility. Relative errors in measurement of the range of visibility amounting to 15-20% are regarded as being acceptable.

Thus, study of visibility is associated with meteorology, in particular with atmospheric optics, and also with the photometry of the landscape, with lighting techniques, with physiological optics, and with the manufacture of special instruments.

Both in the USSR and abroad, in connection with the enormous development of aviation and the lack of methods for blind landing, a great deal of attention is devoted to ways for determining, under complicated weather conditions, the range of visibility of a take-off and landing strip and of the system of signal (landing) lights associated with it. This has become the main problem for the science of visibility. Abroad investigations are also underway as to the problems of visibility of objects on the streets of large cities and on highways, and optimum norms are being worked out for lighting, depending on the degree of visibility of objects on the road. This problem comes up in connection with the catastrophic rise in automobile accidents in the capitalist countries [175, 220].

A characteristic feature of the present-day state of the study of visibility is the increased practical utilization of the integral and spectral transmissivity of the atmosphere in horizontal and non-horizontal directions, and of methods for the measurement thereof.

The transmissivity of the atmosphere, expressed in terms of the meteorological range of visibility, is regarded in certain foreign works as the factor determining the radius of effective radiational contamination in atomic bomb explosions (Figure 1), and as also determining the thermic efficiency of the emanations of lasers at great distances. The transmissivity of the atmosphere conditions the degree of visibility of terrestial objects from circumterrestial cosmic space, and its importance will increase in proportion as satellite and "lunar" meteorology, aero-astronavigation, and photogrammetry from space develop.

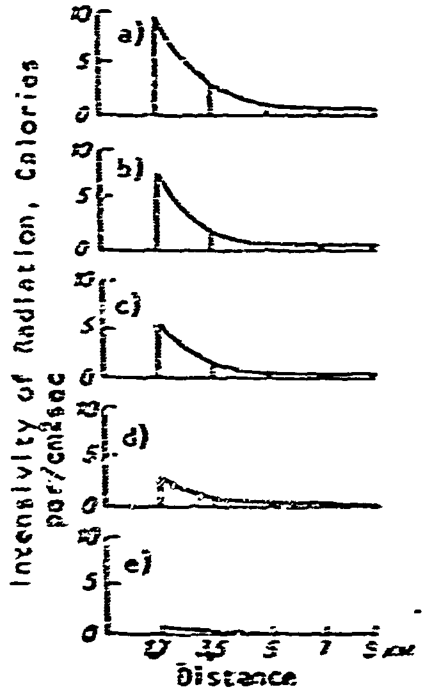

Figure 1. The Radius of Radiation Contamination Upon the Explosion of an Atomic Bomb, as Related to Transmissivity of the Atmosphere [79].
a - absolutely clear; meteorological range of visibility (km); b - 20; c - 10; d - 5; e - 2.5.

The scope of measurements of the transmissivity of the atmosphere (the meteorological range of visibility) has augmented sharply.

Whereas in order to make a safe visual landing with an airplane it is sufficient to measure meteorological range of visibility only up to 10 km, problems having to do with the radiational efficiency of the emanations of a laser require extension of the limit indicated to 100 km. In connection with the problem of measuring the transmissivity of the atmosphere new trends, which have developed rapidly over the last 10-15 years, have made their appearance.

Especially in domestic works we are devoting great attention to study of haze below the cloud level and to the influence of its optical characteristics upon vertical and oblique visibility [68, 95, 205, 210]. The correlational links between the height of the lower limit of clouds and horizontal and oblique visibility are being studied [12, 50, 97, 176, 184, 223]. Works have appeared, abroad and in the USSR, on the climatological aspect of problems of visibility [64, 109, 140].

Considerable attention is being devoted to study of the laws of threshold visual perceptivities of objects and of single and grouped signal lights.

Correct comprehension and utilization of the circumstances of visibility may produce results of exceptional effectiveness in connection with warfare. The operation which the Soviet command carried out in one of the sectors of the Berlin battle in 1945 to bring about mass light-blinding of enemy forces with the help of a great number of projectors is widely familiar. This operation contributed in important measure to the successful outcome of the conflict in that sector.

During the time of the battle of Stalingrad a number of important crossings of the Don were accomplished beneath the surface of the water. This circumstance, as is acknowledged by G. Dörr[1], entirely escaped the attention of enemy air reconnaissance and contributed to ensuring tactical surprise during the changing over of Soviet forces to the counter-attack before Stalingrad.

One could cite a great many such examples. All of them show that special training of the armed forces with respect to the fundamentals of the science of visibility would be decidedly useful.

There is a comparatively large number of articles on various problems of visibility, as may be seen from the attached bibliography. But there are few general monographs. The first and the most complete study of this sort was the widely known monograph of V. V. Sharonov [118]. Although it appeared as early as 1944, the wealth of factual material presented in it and the exceptional clarity of the exposition of the principles of the science of visibility cause it even now to continue being the guide for anyone who works in the field of atmospheric optics and visibility.

We are also familiar with the monograph of Middleton [200], but it falls considerably behind the study of V. V. Sharonov referred to above, as regards the scope and objectivity of the problems discussed. The numerous theoretical, experimental, and methodical works of Soviet specialists find almost no reflection in it.

In a small monograph of Löhle [198] there are statements of common questions of the science of visibility, specifically to its climatological aspects.

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[1]G. Dörr, "The March on Stalingrad," Voyenizdat Publishing House, 1957.

The long article of Linke [197] gives an interesting survey of the development of visibility problems in their methodical and climatological aspects.

A number of interesting articles on methods of calculating the visibility of objects at sea, the metrics of visual receptivity, and the like, are to be found in the single-volume edition of the works of A. A. Gershun [40].

A. I. Gribanov has published a short monograph [52] on the methods of calculating the visibility of objects in the beam of a projector. A series of theoretical and experimental studies are devoted to problems of the passage of a projector beam through the atmosphere in the symposium "The Projector Beam in the Atmosphere," edited by G. V. Rozenberg [99, 100].

Theoretical and experimental problems associated with the science of visibility are examined in studies of E. S. Kuznetsov [76], V. V. Meshkov [86, 87], E. V. Piaskovaya-Fesenkova [96], G. V. Rozenberg [99, 100], I. A. Khvostikov [155, 116, 117], and K. S. Shifrin [127, 128].

Methodical and instrumental treatments associated with the measurement of the horizontal transmissivity of the atmosphere have been published in the works of V. F. Belov [7], V. A. Beryozkin [9, 11], N. G. Boldyryov and O. D. Barteneva [14, 15], L. V. Gulnitsky [53-55], L. L. Dashkievitch [56-60] and I. A. Savikovski [101-103].

A series of photoelectrical assemblies for registration of the transmissivity of the atmosphere have been worked out, published, and introduced into airport practice by V. I. Goryshin [44-49].

The author of the present monograph has set himself the purpose of examining some experimental and methodical treatments applicable to the solution of a series of practical problems that face the science of visibility in its present phase.

The fourth, fifth and sixth chapters are devoted to methodical, experimental and instrumental treatments associated with the determination of range of visibility of real objects and signal lights. Considerable attention is paid in these chapters to the problems of determining landing visibility at times of light and darkness, and also to analysis of photoelectrical gauges for atmospheric transmissivity.

In chapter seven we examine a new method for measurement of horizontal and non-horizontal transmissivity - the method of reverse light diffusion - and an assembly based upon this principle is described. We demonstrate that the method of reverse light diffusion, supplemented by shadow zones, makes it possible to solve a number of problems having to do with the optics of the surface layer.

The eighth and ninth chapters are devoted to instrumental-visual methods of measuring horizontal transmissivity, suitable for use by networks of hydrometeorological stations. Here we describe in detail methods for measuring the meteorological range of visibility in times of light and darkness, and we estimate the errors of measurement and the value of one group of methods as compared with another.

In this monograph there are set forth some results secured by the author over almost 20 years of his work on various problems in the science of visibility.

Bearing in mind the fact that thousands of workers in the Hydrometeorological Service of the USSR, in aviation and in marine and land transport, have to do with problems of visibility, the author has sought to make his exposition as simple as possible. Basic attention has been paid to the physical treatment of the problems examined, with some introduction of simple mathematical apparatus.

At the author's request, the fifth chapter of the monograph has been written by Yu. V. Frid, a leading Soviet specialist on phototechnical equipment for airport use. Paragraphs 41-43 of chapter six were written by V. A. Kovalev.

N. M. Suderevskaya, B. N. Fedorov and L. G. Kuzmin have been the author's collaborators and helpers in his experimental and methodical activities over many years.

The manuscript of the monograph has been examined by V. V. Sharonov, who has furnished valuable advice which the author has made use of with appreciation.

The manuscript of the monograph has been examined by N. P. Rusin, G. M. Zabrodski, V. F. Belov, V. L. Gaevski, V. I. Goryshin, and Yu. D. Yanishevski.

The author wishes to express his sincere gratitude to all the persons named, who have offered valuable critical comments.

The author is profoundly obliged to N. A. Petrov, the responsible editor of the book.

CHAPTER I

FUNDAMENTAL CONCEPTS OF THE STUDY OF VISIBILITY

§ 1. History of the Problem. Visual Scales of Visibility.

The problem of the need for systematic measurements of visibility arose for the first time after the naval Battle of Jutland in May, 1916 between the German High Seas Fleet and the British Grand Fleet. In the opinion of students of this titanic battle, the heavy losses suffered by the British fleet were occasioned by various visibility circumstances, favorable for the German fleet and unfavorable for the British.

After the Battle of Jutland and certain other operations of the First World War, problems of the visibility of objects in the atmosphere and of the transmissivity of the latter came to attract more and more attention in a number of countries. In order to meet the demands of the navies, there were worked out almost simultaneously in England and in Germany scales for the visual evaluation of visibility without any particular requirements being imposed upon the objectives and the conditions of observation. The first scales of visibility are set forth in Table 1.

TABLE 1

Old British Scale of Visibility		Old German Scale of Visibility	
Point	Extent of Point (km)	Point	Extent of Point (km)
X	<0,025		
A	0,025—0,050		
B	0,05—0,10		
C	0,1—0,2		
D	0,2—0,5	1	0,0—0,5
E	0,5—1,0	2	0,5—1,0
F	1—2	3	1—2
G	2—4	4	2—4
H	4—7	5	4—7
I	7—10	6	7—12
J	10—20	7	12—20
K	20—30	8	20—50
L	30—50		
M	>50	9	>50

Each gradation, both of the British and of the German scale, indicates limits of visibility: visible - not visible. Although both scales were set up taking only practical requirements as their basis and although they have no theoretical base, they were the first to reflect the matured need for determination of a threshold visibility of objects, that at which they are barely discernable: the upper limit of each point corresponds to invisibility of the object, the lower to its barely perceptible registering.

Since the gradation of these scales was selected rather arbitrarily, in the 20's and 30's of the 20th Century, other scales of visibility were proposed, having the course of the interval between points based on certain mathematical relationships. Thus, Tetens worked out in 1920 a visual scale in which the extent of each point corresponded to the natural logarithm base e = 2.718. But the intervals of such a scale proved to be too great. The scale was not applied in practice. In 1922 Laing (Whipple) proposed a scale in which for visibility of more than 1 km, the extent of a point was taken as being 1.33 km, and for visibility of less than 1 km it was taken as being 300 m. This scale also failed to find any practical use.

In 1938, Löhle worked out a visibility scale with a point extent equal to e/2 = 1.36. Löhle called this scale, consisting of 30 points, the natural scale. Löhle then proposed an abbreviated, coarser scale, consisting of the 15 even-numbered gradations of the previous scale.

Other scales of visibility, with other definitions of the extent of a point, were also proposed.

At the International Meteorological Conference in 1929 at Copenhagen a 10-point scale of visibility was adopted which was based upon the use of objects on the terrain and which was recommended for application in all countries of the world (Table 2).

TABLE 2. INTERNATIONAL VISIBILITY SCALE OF 1929

Point	Visibility	Point	Visibility
0	50 M	5	4 KM
1	200	6	10
2	500	7	20
3	1000	8	50
4	2 KM	9	>50

When this scale was used in practice, it was at once discovered that there were disagreements as to how to understand the concept "point."

In Europe, in harmony with the note underneath the visibility point, the point was taken as being the distance to the closest object which was not visible. In America, on the other hand, the visibility point was taken as being the distance to the most remote object that was still visible.

Thus, with the same atmospheric blur the "European" visibility differed from the "American" by one point.

The source of the disagreement referred to was a differing approach on the part of investigators to the concept of threshold contrast perception.

In order to eliminate this disagreement, at the International Meteorological Conference of 1935 at Warsaw the following version of a 10-point visibility scale was adopted (Table 3).

TABLE 3. INTERNATIONAL VISIBILITY SCALE OF 1935

Point	Objects visible at distance.......	...but not visible at distance	Point	Objects visible at distance.......	...but not visible at distance
0	—	50 м	5	2 км	4 км
1	50 м	200	6	4	10
2	200	500	7	10	20
3	500	1000	8	20	50
4	1 км	2 км	9	50	>50

This scale is in effect in all countries, including USSR, to this very date.

If one contrasts the international 10-point scale of visibility of 1935 with the old British and German scales (see Table 1), it is easy to see that points 2, 3, 4, 5, 7, 8 and 9 of the international scale represent the corresponding gradations of the British or the German scale.

The 1935 international visibility scale established a single principle of observation based upon determination of the fork "visible - not visible," and eliminated the disagreement which had been occasioned by different ways of understanding the concept "threshold perception" which existed under the 1929 visibility scale.

In Table 4 we compare various scales of visibility borrowed from study [198]. All of them, with the exception of the 1935 international scale, failed to find application.

TABLE 4. COMPARISON OF VARIOUS VISIBILITY SCALES

Testens Scale, 1920 (point interval e = 2,718)		Laing Scale, 1922 (point interval 1,33)		Lohle Scale, Complete 1938 (point interval e/2 = 1,36)		Lohle Scale, Abbreviated (Coarse), 1938		1935 International 10-Point Scale	
Point	Extent of Point (km)	Point	Extent of Point (km)	Point	Extent of Point (km)	Point	Extent of Point (km)	Point	Extent of Point (km)
0	0,0 -0,050	0	0,000--0,150	0	0,000--0,050	0	0,000--0,050	0	0,0--0,05
1	0,050--0,135	1	0,150--0,300	1	0,050—0,075			1	0,05--0,20
2	0,135--0,368	2	—0,600	2	—0,100	2	0,050--0,100	2	0,2—0,5
3	0,368--1,000	3	—0,900	3	—0,125			3	0,5—1,0
4	1,000--2,720	4	—1,20	4	—0,175	4	0,100--0,175	4	1—2
5	2,720--7,340	5	—1,69	5	—0,225			5	2—4
6	7,34--20,1	10	—2,25	6	—0,300	6	0,175—0,300	6	4—10
7	20,1--51,6	15	—3,00	7	—0,450			7	10—20
8	51,6--148,4	20	—4,00	8	—0,600	8	0,300--0,600	8	20--50
9	148,4—403	25	—5,34	9	—0,800			9	>50
		30	—7,1	10	—1,1	10	0,600--1,1		
		35	—9,5	11	—1,5				
		40	—12,7	12	—2,0	12	1,1—2,0		
		45	—16,9	13	—3				
		50	—22,5	14	—4	14	2,0—4		
		55	—30,0	15	—5				
		60	—40,0	16	—7	16	4—7		
		65	—53,4	17	—9				
		70	—71	18	—13	18	7—13		
		75	—95	19	—17				
		80	—127	20	—23	20	13—23		
		85	—169	21	—32				
		90	—225	22	—43	22	23—43		
		95	—300	23	—60				
		100	—400	24	—80	24	43—80		
				25	—110				
				26	—150	26	80—150		
				27	—200				
				28	—275	28	150—275		
				29	—375				
				30	—500	30	275—500		

Commas indicate decimal points.

In 1964 the International Meteorological Conference at Paris adopted two new visibility scales: 1) a complete scale, consisting of 90 points and computed on the basis of precise instrumental measurements, and 2) an abbreviated scale for approximate or naked-eye determination of visibility (Table 5).

TABLE 5. COMPLETE AND ABBREVIATED (POINTS 90-99) INTERNATIONAL VISIBILITY SCALES OF 1964

Pt.	range of visibility (km)	Pt.	range of visibility (km)	Pt.	range of visibility (km)	Pt.	range of visibility (km)
00	<0.010	25	0.350	50	2.00	75	15
01	0.010	26	0.380	51	2.30	76	16
02	0.020	27	0.410	52	2.60	77	17
03	0.030	28	0.440	53	2.90	78	18
04	0,040	29	0,470	54	3.20	79	19
05	0,050	30	0.500	55	3.50	80	20
06	0.060	31	0.550	56	3.80	81	25
07	0.070	32	0.600	57	4.10	82	30
08	0.080	33	0.650	58	4.40	83	40
09	0.090	34	0,700	59	4.70	84	50
10	0.100	35	0.750	60	5.00	85	70
11	0.110	36	0.800	61	5.50	86	100
12	0,120	37	0.850	62	6.00	87	200
13	0.130	38	0.900	63	6.50	88	300
14	0.140	39	0.950	64	7.00	89	500
15	0.130	40	1.001	65	7.50	90	0.0—0.1
16	0,160	41	1.10	66	8.00	91	0.1—0.2
17	0,140	42	1.20	67	8.50	92	0.2—0.5
18	0.180	43	1,30	68	9.00	93	0.5—1.0
19	0.190	44	1.40	69	9.50	94	1.0—1.5
20	0,200	45	1.50	70	10	95	1.5—2.0
21	0,230	46	1.60	71	11	96	2.0—4.0
22	0,250	47	1.70	72	12	97	4.0—10.0
23	0,280	48	1.80	73	13	98	10—20
24	0,330	49	1.90	74	14	99	>20

Commas indicate decimal points.

Regarding these scales we may make the following remarks.

The complete scale has reduced point visibility limits, the practical need for which is questionable and the measurement of which calls for great precision such as cannot be achieved at the present time. Points 88 and 89 are superfluous, inasmuch as the range of visibility in an ideally pure atmosphere (Rayleigh atmosphere) comes to 350 km. In real atmospheres a range of visibility greater than 200-250 km is observed only in rare cases. The determination of such high transmissivity is possible only on the basis of special methods of measurement. As regards the determination of visibility in accordance with the abbreviated scale upon objects on the terrain, in this case, just as with use of the 1935 international scale, one is obliged to encounter numerous complications, difficult to surmount, that will be examined below.

§ 2. Inadequacies of Point (Visual) Determinations of Visibility, and Need for Shifting to Instrumental Methods.

When recommendations were drawn up in 1929 and 1935 for the organization of the determination of visibility on the international 10-point scale in the network of hydrometeorological stations, it was probably not considered to what extent the recommendations in question could be carried out in practice.

At the same time, the carrying out in a network of hydrometeorological stations of measurements of visibility by the "visible - not visible" fork method, despite its apparent outward simplicity, at once ran up against a number of serious difficulties.

In the first place, it was not every hydrometeorological station that had on its premises the indispensable "set" of natural or artificial objects, located at set distances in a single azimuth, of sufficiently great angular dimensions, and projected against a homogeneous background. In the majority of cases, points 8 and 9 cannot be determined, since ordinary natural objects at distances corresponding to these points are as a rule not visible or have excessively small angular dimensions.

During the winter and with snow or frost on the objects the visibility points will be different from what they are upon observations on these same objects, but without snow and frost.

In the second place, in steppe and desert regions, by reason of the absence of objects, observations of this sort are quite out of the question. The setting up of artificial objects - screens - and keeping them in useful shape is impractical, on account of their great size and high cost.

In the third place, a visibility point determined in twilight does not correspond to visibility by day (under the same meteorological conditions), on account of the changing properties of the observer's vision.

In the fourth place, the measurement of visibility in points does not satisfy aviation, regional climatology, and other branches of knowledge as regards its precision.

In the fifth place, the determination of visibility in points is impossible during the dark hours of the 24. The supplementary recommendations in the international 10-point scale as to the setting up at the locality of incandescent lamps corresponding to the limits of the points cannot be carried out in practice on account of the high cost of constructing such a line of lights and the complicated nature of its utilization.

What has been set forth above makes it possible to conclude that universal non-instrumental empirical determinations of visibility by the method of visually fixing the "visible - not visible" fork have proved to be impossible to achieve.

Empirical experimental methods for determining the visibility of objects, as worked out by the outstanding German geophysicist Wiegand, did not give the desired results. A detailed analysis and criticism of the work of Wiegand appear in the familiar monographs of V. V. Sharonov [118, 120].

The problem of measuring the range of visibility for objects has turned out to be considerably more complicated than was anticipated to begin with.

Empirical trials have yielded place to profound theoretical and experimental investigations and to various sorts of methodical treatments.

The numerous investigations with respect to various problems having to do with the visibility of objects that have been carried out by V. V. Sharonov, A. A. Gershuk, V. A. Faas, I. A. Khvostikovski, Koshmider, Foitzik, Löhle, and others, have created the foundation upon which the further study of the properties of atmospheric haze, the photometric properties of terrain objects, and the peculiarities of vision, etc., have been based.

These theoretical and experimental treatments have transferred the problem of visibility from a position of empiricism to a solid scientific foundation. The science of visibility has come into being. Its principle subject matter is the problem of determining the limit distance which is called visibility range, at which terrain objects of various sorts and signal lights are at the threshold of perception, i.e., are either just barely visible, or are quite invisible. The dependence of this problem upon the properties of the objects and lights themselves, the transmissivity of the atmosphere, and the laws of threshold visual perception, demonstrates its complicated character, and shows that it is necessary to take into account the most variegated factors.

So as to get a clear idea of the subject matter of the science of visibility and the methods for solving its varied problems, one must become acquainted in summary form with the basic propositions of principle which constitute its foundation.

§ 3. The Weber - Fechner Law and the Concept of Contrast Luminance

The Weber-Fechner law and its sequelia establish general laws for visual perception of the objects and light sources that surround us[1]. These general laws, associated with threshold and non-threshold visual perception and defining the concept "range of visibility," constitute the basis of the science of visibility.

Let us examine the major content of the Weber-Fechner law and the consequences which flow from it.

Let us suppose that on an absolutely black background we observe a single light source having a luminance B and producing a visual sensation of intensivity E. The problem is posed as follows: by what amount must the observed luminance of this light source be changed so as to produce the first barely perceptible (threshold) subjective alteration in the level of the original sensation E by an amount dE?

According to the Weber treatment, alteration in a given level of sensation (light, sound or other) is proportionate not to the absolute value of the objective alteration in the strength of the exterior excitation, but to the ratio between the objective alteration of the exterior signal and the amplitude of the signal itself. On this account if one assumes that the luminance B_1 of the observed single light source is changed by an amount dB_1 and this increment of luminance has produced a minimum perceptible threshold alteration in sensation E_1 to an extent dE_1, then according to Weber's treatment the magnitude of the threshold alteration in light sensation dE_1 is proportionate to the ratio of the objective change in photometric luminance of the observed source dB_1 to the magnitude of the luminance itself, B_i; i.e.:

$$dE_1 = k \frac{dB_1}{B_1}, \qquad (1.1)$$

where k is the coefficient of proportionality.

Equation (1.1) constitutes the differential form of the Weber-Fechner law, signifying that equal absolute changes in levels of sensation correspond to equal relative changes in luminance of light source.

As we shall see further on, the principle of operation of devices of a

[1]The law which is called the Weber-Fechner law unites the views of the physiologist Weber as regards the process of visual reception, and the mathematical treatment of these views which was produced by Fechner.

special class - visibility gages - is taken as being in conformity with the differential form of the Weber-Fechner law.

Integrating differential equation (1.1) we get

$$E_1 = k \ln B_1 + C. \tag{1.2}$$

Formula (1.2) signifies that light sensation, or intensity of receptivity, is proportionate to the logarithm of the luminance of the light source.

In order to establish the general relationship between light sensations (perceptions) and luminance of source we shall assume that the single light source successively changes it luminance from B_1 to B_2, B_3, ..., B_n, producing levels of light sensation E_1, E_2, E_3, ..., E_n respectively. In this process we assume that the luminance indicated are not selected arbitrarily, but in such fashion that the sensation levels E_1, E_2, E_3, ..., E_n constitute an uninterrupted graduated threshold series. Then it is apparent that changes of luminance B_1, B_2, B_3, ..., B_n by amounts dB_1, dB_2, dB_e, ..., dB_n will produce corresponding changes in sensation levels E_1, E_2, E_3, ..., E_n by threshold amounts dE_1, dE_2, dE_3, ..., dE_n.

Applying equation (1.1) to correspond values dB_2, dB_3, ..., dB_n and dE_2, dE_3, ..., dE_n, we get the n of ordinary differential equations, over and above the one secured above (1.1):

$$\left.\begin{aligned} dE_2 &= k\frac{dB_2}{B_2} \\ dE_3 &= k\frac{dB_3}{B_3} \\ &\cdots\cdots \\ dE_n &= k\frac{dB_n}{B_n} \end{aligned}\right\} \tag{1.3}$$

Solving (1.3) through successive integration of each equation, we secure analogoisly to (1.2):

$$\left.\begin{aligned} E_2 &= k\ln B_2 + C \\ E_3 &= k\ln B_3 + C \\ &\cdots\cdots\cdots \\ E_n &= k\ln B_n + C \end{aligned}\right\} \tag{1.4}$$

Assuming that the levels of sensation rise from E_1 to E_n (i.e., assuming that E_2 is greater than E_1), and subtracting successively $E_2 - E_1$, $E_3 - E_2$, etc., we shall have:

$$E_2 - E_1 = k(\ln B_2 - \ln B_1).$$

$$E_S - E_2 = k(\ln B_3 - \ln B_2).$$

$$\cdots\cdots\cdots\cdots$$

$$E_n - E_{n-1} = k(\ln B_n - \ln B_{n-1}),$$

whence we secure the following relations:

$$\left.\begin{aligned} &\frac{B_2}{B_1} = e^{\frac{1}{k}(E_2 - E_1)} = A^{E_2 - E_1} \\ &\frac{B_3}{B_2} = A^{E_3 - E_2} \\ &\cdots\cdots\cdots\cdots \\ &\frac{B_n}{B_{n-1}} = A^{E_n - E_{n-1}} \end{aligned}\right\} \quad (1.5)$$

Inasmuch as the sequence of differences $E_2 - E_1$, $E_3 - E_2$, etc., is regarded as being the stages of minimum distinguishable differences of sensations arranged in increasing (or diminishing) order, we can advance the proposition that within the limits of successive changes in luminance from the value B_1 to B_n there may be contained 1, 2, 3, ..., n values of minimally distinguishable differences of sensation.

Then in the general case, on the basis of (1.5), we can write:

$$\frac{B_2}{B_1} = A, \quad \frac{B_3}{B_1} = A^2, \quad \frac{B_4}{B_1} = A^3, \quad \ldots, \quad \frac{B_n}{B_1} = A^{n-1}. \quad (1.6)$$

The expression (1.6) constitutes the integral form of the Weber-Fechner law, which reads to the effect that changes in sensation (perception) which change in arithmetical progression correspond to relative objective alterations in the luminance of a light source which change in geometrical progression.

The integral form of the Weber-Fechner law means that the subjective sensation of changes in luminance is not a linear function of the objective alteration in luminance, and that the sensitivity of the eye to the reception of relative alterations in the luminance of a single source is not great.

This conclusion fully explains the fact, very familiar in visual astrometry, that the so-called stellar magnitudes of luminance do in fact constitute gradations, or thresholds, distinguishing the luminance of one set of stars from the minimum differenciable luminances of other stars. The unaided eye distributes all distinguishingable stars into six gradations, or thresholds, of brilliance, although the actual differences between stars as regards brillance are infinitely numerous.

As a great number of experiments have shown, the ratio between the brillances of two stars which are distinguished within a single visual threshold interval, is a constant quantity equal to approximately 2.5. In other words, all stars, as well as points of light, are noted by the eye as being minimally differentiable as regards brilliance if one source is 2.5 times stronger than the other.

In this fashion a star of the first magnitude is 2.5^6, or approximately 250, times more brilliant than the faintest star.

The non-linearity of the linkage between sens··ons and excitations finds its explanation in most recent experiments on th· ·trophysiology of vision, from which it is learned that the frequency of · ·ulses of electrical current in the tissues of the visual nerve increas ·on-linearity as brilliance increases.

The non-linear relationship between sensations and relative alterations in the brilliance of individual sources of light means that if we construct upon this relationship a system of quantitative evaluation of the intensivity of visual sensation, it would suffer through being excessively coarse and could not be used for the evaluation of the intensivity of reception of the objects that surround us.

Experience shows that the eye of a man senses with great delicacy not relative changes in the luminance of individual point-sources of light, but the difference in the luminance of two luminous or non-luminous surfaces of large angular dimensions that are set close to each other. For this case we can secure the necessary relationships by using a line of reasoning analogous to the foregoing.

Let two surfaces (two non-point sources of light) have luminance B_1 and B_2, which are differentiated by such a small amount that they excite only a barely perceptible threshold sensation ε.

Let us assume that the reception of these two surfaces is also subject to the general Weber treatment, i.e., that a given livel of minimally perceptible threshold excitation is proportionate to the ratio of the object difference in luminance between two sources of light to the luminance of one of them, specifically

$$\varepsilon = \frac{\Delta B}{B} = \frac{B_1 - B_2}{B_{1,2}}. \tag{1.7}$$

Although there is an external similarity between (1.7) and (1.1) the physical meanings of these expressions differ substantially. Equation (1.7) can also be regarded as the differential form of the Weber-Fechner law, but this time as applied to the reception not of the changing luminance of a single light, but to the relative difference between two simultaneously observed luminances. On this account equation (1.7) is frequently called the difference threshold, by which we understand the relative threshold difference of luminance of two extended sources of light.

As experience shows, the minimally sensed relative threshold difference of luminance ε remains a constant over a relatively great range of absolute values of B_1 and B_2, so that

$$\frac{B_1 - B_2}{B_{1,2}} = \varepsilon = \text{const}, \tag{1.8}$$

in which connection B_1 is little to be distinguished from B_2.

The quantity ε is called the threshold contrast of luminance and is a very important characteristic of the threshold sensitivity of vision. On this account (1.7) is ordinarily regarded, by analogy with (1.1), as the threshold intensivity of sensation as applicable to two observed extended sources of light.

If the luminance B_1 and B_2 differ considerably, i.e., if they lie beyond the limits of threshold excitation, then the conditions of (1.7) are not applicable to such luminance, and one must take instead of them a quantity characterizing the final, rather than the threshold, intensivity of perception. By analogy with (1.7) and by virtue of the correctness of (1.8), this final intensivity of perception, designated by K, can be written in the form

$$K = \frac{B_1 - B_2}{B_{1,2}}. \tag{1.9}$$

The quantity K is called the constant luminance, in which connection B_i may be considerably differentiated from B_2.

The concept of contrast luminance is one of the most important there is in the science of visibility.

In contradistinction to threshold contrast in (1.7), the significance of final contrast in (1.9), i.e., the relative difference as to luminance between two sources being observed, can serve as a measurement for the numerical expression of the intensivity of visual perception.

Although we must very frequently encounter the concept of luminance contrast in the science of visibility, we must note that the quantity K is far from being always convenient as a characteristic for the intensivity of visual perception. It characterizes only luminance difference, and has nothing to say about the effect upon intensivity of perception of the color of fields, the structure of their surface, angular dimensions, etc. In this there is inherent one of the deficiencies of the differential form of the Weber-Fechner law. To anticipate a little, we may note that there is a more convenient method for determining the intensivity of visual perception through the use of a coefficient of visibility, or of the degree of visibility, of the object. We shall discuss this further on (see § 13).

§ 4. Basis for the Selection of the Initial Contrast Ratio

In equation (1.9) there is one substantial vague point which greatly complicates the practical utilization of this apparently simple relationship. This vague point consists of the fact that in equation (1.9), as also in (1.7), it is not indicated which of two observed luminances ought to stand in the denominator, and between what luminances one should take the difference for the numerator. The differential form of the Weber-Fechner law does not indicate which source of light ought to be the first, and which source ought to be the second.

For threshold contrast (1.7) this circumstance is of no substantial significance, inasmuch as luminance B_1 is little to be distinguished from luminance B_2. Fut for final, non-threshold contrast (1.9), when luminances B_1 and B_2 may have any values differing the one from the other, it is far from being a matter of indifference which of two sources (or surfaces) shall be taken to be the first, and which the second.

There is no common opinion on this matter to date, a circumstance which leads to the following complications.

Some authors treat (1.9) from the photometric point of view, differentiating luminances B_1 and B_2 into a "greater luminance" (B_g) and a "lesser luminance (B_L), indifferently as to whether the more brilliant one is the object or the background. This gives rise to four concepts of contrast, and consequently also to four ways of expressing quantitatively the intensivity of visual perception:

$$\left.\begin{aligned} K_1 &= \frac{B_g - B_l}{B_g} = 1 - \frac{B_l}{B_g} \\ K_2 &= \frac{B_g - B_l}{B_l} = \frac{B_g}{B_l} - 1 \\ K_3 &= \frac{B_l - B_g}{B_l} = 1 - \frac{B_g}{B_l} \\ K_4 &= \frac{B_l - B_g}{B_g} = \frac{B_l}{B_g} - 1 \end{aligned}\right\} \qquad (1.10)$$

Other authors approach (1.9) from the geometrical point of view, differentiating B_1 and B_2 as "luminance of object" (B_{ob}) and "luminance of background" (B_b) and fixing, as it were, a place in the relation (1.9) for each of these luminances. This leads to four further concepts of contrast, and consequently to four further ways of evaluating quantitatively the intensivity of visual perception:

$$\left.\begin{aligned}
K_5 &= \frac{B_{ob} - B_b}{B_{ob}} = 1 - \frac{B_b}{B_{ob}} \\
K_6 &= \frac{B_b - B_{ob}}{B_b} = 1 - \frac{B_{ob}}{B_b} \\
K_7 &= \frac{B_b - B_{ob}}{B_{ob}} = \frac{B_b}{B_{ob}} - 1 \\
K_8 &= \frac{B_{ob} - B_b}{B_b} = \frac{B_{ob}}{B_b} - 1
\end{aligned}\right\} \qquad (1.11)$$

Thus depending on the meaning one gives to the luminances B_1 and B_2, and also on the order of their placement in the numerator and the denominator of equation (1.9), there is not one way of treating the concept of contrast, but instead eight, and obviously there are eight ways of expressing the intensivity of visual perception. Such are the undesirable consequences of the vagueness of the differential form of the Weber-Fechner law that we have been discussing above.

The lack of any agreed standard determination of contrast leads to a state of affairs where all eight ways of expressing it are being used in our literature. Such a multiplicity of concepts of contrast is decidedly inconvenient. It complicates the solution of many applied problems, particularly geophotometric ones, and it even makes it difficult to understand many studies that have been published.

The need for standardization of the concept of contrast has long since become pressing. In the Hydrometeorological Service of the USSR alone we have worked out, on the basis of the concept of luminance, contrast methods for determining the transmissivity of the atmosphere, methods for determining landing visibility, and the range of visibility of real objects, etc.

For out purposes it is indispensable to select a single, most suitable definition of contrast, which we can use in all cases.

In the symposium "Terminology for Phototechnics" (published by the Academy of Sciences of the USSR, 1958), the authors understand by contrast "the ratio of the difference between luminance of objective and of background to the luminance of the background," i.e., they award their preference to contrast K_8.

For reasons which we shall set forth further on, the choice of the relationship K_8 as the standard gives rise to a number of objections. In order to provide a basis for the selection of a contrast relationship, let us analyze Table 6, which affords a clear idea of the magnitudes of contrasts in accordance with (1.10) and (1.11), depending on the characteristics of the luminances of contrasting surfaces.

TABLE 6. COMPARISON OF SOME LIMIT VALUES OF CONTRASTS IN ACCORDANCE WITH (1.10) AND (1.11).

Characteristics of luminance of contrasting surfaces	K_1	K_2	K_3	K_4	K_5	K_6	K_7	K_8
White object on black background	1	∞	$-\infty$	-1	1	$-\infty$	-1	∞
Black object on white background	1	∞	$-\infty$	-1	$-\infty$	1	∞	-1
One luminance twice as great as the other..	0,5	1	-1	$-0,5$	0,5 or -1	-1 or 0,5	$-0,5$ or 1	1 or $-0,5$
Luminance of object and of background the same..........	0	0	0	0	0	0	0	0

As may be seen from Table 6, with a given set of luminance characteristics of contrasting surfaces each of the eight ways of expression contrast produces a substantially different numerical result, with the exception of the case where the luminances are equal.

In our opinion, a substantial deficiency of the "geometrical" contrasts (from K_5 to K_3) is the fact that one and the same intensivity of visual perception (for example, white on black or the reverse) is characterized not by one, but by two differing numerical values, of which one is necessarily negative.

One should note that if one regards contrasts as a measure of the intensivity of visual perception, then negative values of contrasts, particularly those having values of minus infinity, have only a formal meaning and do not permit physical interpretation. This circumstance makes it possible to eliminate from further consideration the contrasts from K_3 to K_8 respectively.

Thus, there remain two "photometric" contrasts - K_1 and K_2.

The relation K_1 is more convenient in practice than K_2. For all possible relations of luminances the value of K_1 ranges between 0 and 1. This is convenient in practice, and the physical treatment of it is clear.

The value of K_2 ranges from 0, when the luminances observed are equal, to plus infinity when maximum contrast is observed. This is what constitutes the practical inconvenience of making use of the K_2 contrast and the difficulty of presenting it in clearly apparent form.

Thus, of the eight contrast relationships examined, we give out perference to contrast K_1, written in the form:

$$K = \frac{B_g - B_1}{B_g}, \qquad (1.12)$$

in which connection the greater luminance of the less luminance may relate either to the object or to the background. Relationship (1.12) approaches the physical sense of the differential form of the Weber-Fechner law to the greatest extent. It is the one which has received the greatest practical application.

In using (1.12) one assumes that the contrasting surfaces possess the following qualities:

a) the surfaces of observation are photometrically without structure and have .arply defined borders (an evident incongruence with the majority of real objects on the terrain);

b) colored objects are considered only from the standpoint of their luminance; the effect of color upon perception is not taken into account (an evident incongruence with real objects on the terrain);

c) the line of contact of fields is even and not jagged (incongruence with the majority of real objects on the terrain).

When we solve problems having to do with the range of visibility of real objects it will be shown to what extent actual conditions diverge from those for which (1.12) holds true.

§ 5. Threshold Visual Perceptivities

As has already been shown, the problem of the range of visibility of objects is linked with the problem of threshold visual perceptivities. Roughly speaking, threshold perceptivities are the perceptivities of very low-visibility objects barely distinguishable by the eye. It is precisely relationship (1.7) in its general form that characterizes the conditions of threshold perceptivity. But threshold contrast (1.7) in the aspect in which it is derived from the differential form of the Weber-Fechner law admits of two interpretations instead of just one:

1) if luminances B_1 and B_2 are close to each other, but the eye can note a distinction between them, then (1.7) characterizes the minimum distinguishable threshold contrast of luminances, called for short, the contrast detection threshold and designated by ε_{det};

2) if luminances B_1 and B_2 are so close to each other that the eye does not detect a difference between them, then (1.7) characterizes the indistinguishable threshold contrast, called the threshold of loss of visibility or more frequently the contrast disappearance threshold, and indicated by ε_{dis}.

The quantities ε_{det} and ε_{dis} are determined by the sensitivity of the eye to the reception of a given threshold contrast under given circumstances of observation.

From the definition it is clear that numerically ε_{det} is greater than ε_{dis}.

"Threshold detection" as it applies to concrete objects means that the object is perceived in the form of a hardly distinguishable silhouette; the surface structure of the object is not made out.

The requirements of practice have given rise to still another concept of the threshold, one associated with a minimal relative difference in luminances B_1 and B_2 such that the form of an object is recognized or its detailed structure is distinguished. This threshold is called the recognition threshold and is designated by ε_{rec}. In the numerical sense ε_{rec} is greater than ε_{det}.

The differentiation between the concepts of thresholds and the numerical difference between ε_{dis}, ε_{det} and ε_{rec} mean that we cannot speak of thresholds in general terms. For example, the statement "a threshold is equal to such-and-such a quantity" is insufficient, since one must indicate what contrast threshold one is talking about.

In studying threshold functions one must also indicate what threshold or thresholds are being investigated.

At the usual (day) level of illumination the eye of man has high sensitivity to the perception of the luminance difference between two contrasting surfaces. The threshold values for objects of sufficiently large dimensions (not less than 30 minutes of angle) come to unit percentages (1-5%) (Table 7).

TABLE 7. VALUES FOR THRESHOLDS
OF CONTRAST SENSITIVITY OF VISION (%)

Author	ε_{dis}	ε_{det}	ε_{rec}	Conditions of Investigation
Under Fixed Observation				
V. V. Sharonov	1.5	—	—	laboratory and field
N. N. Sytinskaya	1.5	—	—	ditto
L. L. Dashkievitch	1.8	—	—	laboratory
N. G. Boldyryov and O. D. Barteneva	—	5	—	field
V. A. Gavrilov	1.9	2.5	3.5	"
Foitzik	1.8	4	—	laboratory and field
Middleton	—	3.1	—	
Blackwell	—	0.8–1.4	—	laboratory
Schoenwald	1.4	—	—	"
Siedentopf	1	—	—	"
König-Brodchun	—	2	—	"
Howell	—	3.2	—	
Halbert	2	—	—	field
International Illumination Commission	—	4	—	
Under Non-Fixed Observation (time of search 15 seconds)				
Tasseei and Oliver	—	—	~7	field
V. A. Gavrilov	—	—	from 5 - 9 (average 7)	"

The differentiation of threshold perceptivities which has been referred to above nevertheless, proves to be insufficient for the purpose of fully reflecting the heterogeneity of real conditions of threshold visual observation.

On the basis of investigations of threshold perceptivities that have been carried out over many years, the author of the present monograph has come to the conclusion that the numerical value of one and the same threshold depends essentially upon whether the observer does know, or does not know, where the object is [25].

If the eye is directed precisely at the object sought, the threshold contrast has one value. If the location of the object is not precisely known and it must be sought over a certain area of space, the contrast has another value, in which connection this value is always a greater one than in the preceding case. Such a way of looking at matters obviously leads to a need for dividing up all the aspects of thresholds referred to above into two classes:

1) visual thresholds with fixed observation, when the eye is constantly following the object;

2) visual thresholds with non-fixed observation, when the location of the object (having a contrast close to the threshold value) is not precisely known and it has to be sought within the limits of a certain space.

With fixed observation all three of the aspects of thresholds referred to above come into play: ε_{dis}, ε_{det}, and ε_{rec}.

With non-fixed observation only two thresholds are sharply detected: ε_{det} and ε_{rec}. With non-fixed observation the ε_{dis} threshold is an indefinite concept. If the object is detected after a certain period of observation, this will obviously be either ε_{det} or ε_{rec}. But if during the course of the given time the object is not detected, then its actual contrast in the given case can be arbitrarily taken as being ε_{dis}.

Thus, non-fixed thresholds are essentially temporal since their magnitudes depend substantially on the time of search. It is meaningless to speak of a non-fixed threshold without indicating the time of search.

On the other hand, fixed thresholds are practically not linked at all with time of search.

The distinction between fixed and non-fixed thresholds can be explained on the basis of an example taken from the practice of aerological observations. It is well known that an aerologist observer who is following a pilot ball can see it for a long time, even if the ball is at an extremely faint perceptivity level. But if the observer even for a moment turns his observation aside, the ball, passing beyond the limits of the fixation cross-lines, is lost from sight, and the observer is no longer in a position to detect it; the "lost" pilot ball is not detected again.

In the light of the considerations set forth one may propose the following classification of threshold relationships, which we shall use from now on:

1) fixed thresholds of the contrast sensitivity of the eye, not linked with time of search, inasmuch as the visual axis of the eye is directed right at the object: ε_{dis}, ε_{det}, ε_{rec};

2) non-fixed thresholds of the contrast sensitivity of the eye, depending on time of search, since the visual axis of the eye lies to one side of the object: ε_{det}, ε_{rec}, (ε_{dis} is nominal).

We may add to what has been said, the statement that the ε_{rec} threshold, whether fixed or non-fixed, is entirely conventional in its meaning and is determined wholly by the character of the problem posed. For example, in one case it is sufficient to determine the object qualitatively - to determine, let us say, whether the object is a house or a hill. In a second case, a need may arise for determination of quantitative relationships as well: if it is a house, how many storeys does it have; if it is a ship, just what sort of a ship, etc. It is clear that in all concrete circumstances ε_{rec} values may differ substantially.

The results of experimental determinations of the numerical values of threshold visual functions are set forth in Table 7. With illumination from 200 to 20,000 lux and with angular dimensions of the object not less than 0.3°, thresholds of contrast sensitivity have minimal values. To either side of the limits of illumination indicated and with angular dimensions of less than 0.3° the thresholds mount rapidly (Table 8 and Figure 2).

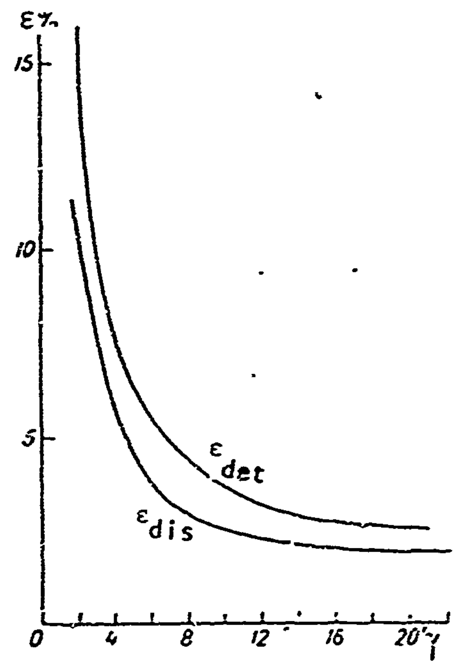

Figure 2. Alteration of Fixed Thresholds ε_{dis} and ε_{det} Depending on Angular Dimensions of Objects γ.

TABLE 8. ALTERATION OF FIXED THRESHOLDS ε_{dis} AND ε_{det} DEPENDING ON ANGULAR DIMENSIONS OF OBJECTS (AUTHOR's DATA).

Angular diameter of object	ε_{dis} %	ε_{det} %
>20'	1.90	2.50
15	2.05	2.80
12	2,30	3.30
9	2,75	4.20
6	3,70	5.60
3	7,50	10.30
2	11,40	16.60

Commas indicate decimal points.

The problem of the range of visibility of objects is to be solved in harmony with the statement of the question of threshold functions set forth above. Just as there is no sense in talking of threshold contrast in general terms, there is no sense in talking of range of visibility in general terms. The concept "range of visibility" must be linked in each concrete case with a definite type of threshold. Since there are three thresholds instead of one, one must speak of three concepts of range of visibility:

1) range of disappearance of an object, corresponding to the threshold of disappearance, and equal to the distance at which the object is not to be distinguished in luminance from the background and ceases to be perceived;

2) range of detection of an object, corresponding to the t' shold of detection, and equal to the distance at which the object is alm not to be distinguished from the background as regards luminance, but wit he eye still being in a position to detect it at the extreme limit of ceptivity in the form of an extremely faint, barely contrasting spot;

3) the range of recognition of an object, corresponding to the threshold of recognition and equal to the distance at which the content of an object or its detailed structure is recognized, depending on the character of the problem posed.

To anticipate a little, we shall show that the range of detection with fixed observation is approximately 20% less than the range of disappearance. The range of recognition may be less than the range of disappearance by some tens of percentage points. With non-fixed observation the distinctions may be considerably greater.

§ 6. The Light-Atmosphere Equation

The relations secured above (1.12) for luminance contrast and (1.7) for the threshold of contrast sensitivity are still insufficient for determination of the range of visibility of objects in the atmosphere. To solve problems one must know in accordance with what law the observed contrast of a distant object changes under the operation of the veiling effect of atmospheric haze. For this purpose it is necessary first of all to establish the regularity of the change in the luminance β of the layer of atmospheric haze as the distance L between the object and the observer increases. This regularity is described by the so-called light-atmosphere equation.

Let us look at Figure 3. We shall show how the luminance β_L of the layer L of the atmosphere which lies between limits A and B changes, assuming that over its entire length the layer L is optically homogeneous.

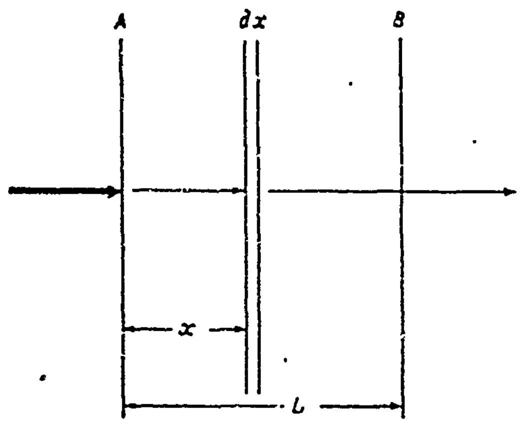

Figure 3. For Derivation of the Light-Atmosphere Equation.

Let a light flow of given density fall upon the A edge of the layer. At a distance x from the A edge we shall isolate the unit layer dx.

Let us assume to start with that the light flow has traversed the course from A to dx without absorption or diffusion. In this event the luminance $d\beta'$ of the layer dx would be proportionate to the illumination E of this layer and to the intensivity of the diffusion of light $\rho(\theta)$, i.e.

$$d\beta' = \rho(\theta) E\, dx = \varkappa\, dx, \tag{1.13}$$

where $\rho(\theta)$ is a function depending on the quantity and dimensions of the particles suspended in the layer dx and on the direction of the sighting upon this layer.

But actually, on the course from A to dx the light flow is weakened by virtue of diffusion and absorption in the medium, and the true luminance $d\beta$ of layer dx will be less than according to (1.13).

The weakening of the light flow over the section of its course referred to is subject to the Buger exponential law, a fundamental law of physical optics running to the effect that over a course x light energy, as a result of diffusion and absorption in the medium, suffers a weakening proportionate to e^{-ax}, where e is the natural logarithm base and a is the index of weakening. In other words, the true luminance $d\beta$ of layer dx is equal not to (1.13), but to

$$d\beta = \varkappa e^{-\alpha x}\, dx. \qquad (1.14)$$

Obviously, the luminance $d\beta_i$ of any other unit layer located in the layer L at a distance x_i from the A edge can be described in analogous fashion.

The complete luminance β_L of layer L, which is the result of the aggregate operation of the unit luminance $d\beta_i$, can be determined through integration of (1.14) within the limits of the entire Layer L, i.e.:

$$\beta_L = \int_0^L d\beta = \varkappa \int_0^L e^{-\alpha x}\, dx = -\frac{\varkappa}{\alpha}\left(e^{-\alpha L} - 1\right) = \frac{\varkappa}{\alpha}\left(1 - e^{-\alpha L}\right).$$

Specifying that

$$\frac{\varkappa}{\alpha} = \frac{\rho(\theta) E}{\alpha} = D,$$ [1]

we have finally

$$\beta_L = D\left(1 - e^{-\alpha L}\right). \qquad (1.15)$$

The expression (1.15) is in fact the light-atmosphere equation we have been seeking, the one that characterizes the change in atmospheric haze depending on the extent of the L layer. It was secured by Löhle in 1922, and in 1924 by Koshmider on the basis of somewhat different reasoning.

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[1] Editors note: in foreign test this symbol is cyrillic Б and has been transliterated throughout this book as D to avoid possible confusion with the English B or the Greek β.

Let us dwell in more detail on the physical meaning of the light-atmosphere equation and let us show to what extent it corresponds to the real conditions which exist in the earth's atmosphere.

Equation (1.15) was derived on the assumption that the layerL is optically homogeneous. Such an assumption, for obvious reasons, at once excludes the applicability of (1.15) to oblique directions directions which embrace optically heterogeneous layers, and allows us to speak of its applicability only to a horizontal direction. But experience shows that optical blurring in the horizontal surface layers of the real atmosphere is frequently heterogeneous and inconstant both in time and in space. If we add to this the fact that "mottled" clouding creates heterogeneous illumination in more orless extensive layers, it becomes clear that the light-atmosphere equation is far from being always valid under the circumstances of the real atmosphere. The physical meaning of the coefficient of the light atmosphere equation also calls for elucidation.

If we take a more and more extensive layer L, then as follows from (1.15), the luminance B_L of the layer initially rises rapidly, but later gradually approaches the value D as a limit. In Figure 4 we set forth diagrammatically the dependence of B_L upon the length L of the layer at various transmissivities of the atmosphere. It is obvious that, no matter how great the length of layer L may become, the value of B_L cannot exceed a certain limit characterized by the magnitude of the coefficient D of equation (1.15).

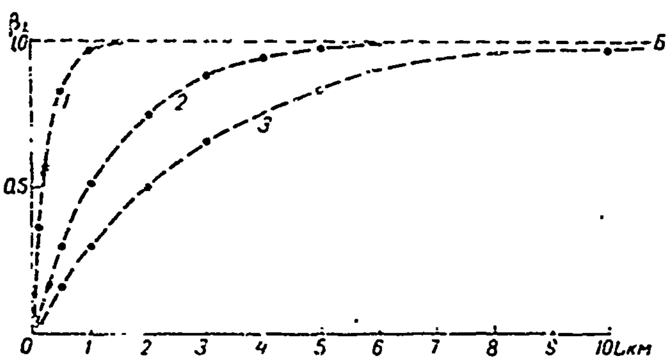

Figure 4. Changes in the Luminance B_L of Atmospheric Haze Depending on the Length of the Layer, with Meteorological Ranges of Visibility of 1 km.

Thus, in its physical meaning the coefficient D characterizes, as it were, the state of luminance "saturation" of the layer L. In other words, the luminance B_L of layer L, after a· ·eving a certain maximum value, does not increase further, no matter how much layer L may become extended.

But such sharp deductions as these as regards the properties of coefficient D of the light-atmosphere equation should be applied only with caution to the real atmosphere.

With considerable blurring of the atmosphere (in the presence of fog or thick haze) the luminance of the surface layer in the horizontal direction does, as experience shows, actually reach a state of saturation over an expanse of some kilometers, and it remains practically constant when the layer is extended further. This means that the luminance β_L of an "infinitely extended" layer of atmospheric haze may be identified with the luminance of the sky at the horizon. In this case it may even occur that a state of luminance saturation may be attained in some oblique directions as well.

The case examined is characterized also by the special quality of atmospheric haze: the color of the haze, as a rule, is white.

The matter stands altogether otherwise with high transmissivity of atmosphere, when the observer can "see through" layers of the atmosphere removed from him by many tens of kilometers and located above a spot which is far below the line of the horizon. For example, with great transmissivity there are frequently visible beyond the horizon the tops of clouds 100-200 km and more from the observer.

In this case, the horizontal line of sighting runs through relatively homogeneous surface layers only for 20-30 km and thereafter rises into layers which are more and more elevated above the corresponding terrain and which consequently, have less and less optical density. The optical homogeneity of layer L is broken down starting at a certain distance, and the relative increment of luminance on the part of layers equal in extent starts to become less and less. The luminance of atmospheric haze does not reach that state of saturation that it would possess if the optical blurring were everywhere just as homogeneous as at the start of the course. The luminance of the haze now changes in harmony with another law, and it does not reach a state of saturation even in a horizontal direction. On this account, with high transmissivity of the atmosphere equation (1.15) is strictly speaking, not applicable, not only to any direction, but even to a horizontal direction, in the real atmosphere.

Thus, in the real atmosphere a range of blurrings exist for which equation (1.15) holds good with sufficient accuracy, and a range for which (1.15) is fulfilled with an error which is the greater, the higher the transmissivity of the atmosphere.

As a limit dividing the ranges referred to one make take, in our view, an atmospheric blurring such that luminance saturation (or meteorological range of visibility; see § 7) is reached in a layer of 50 km long. At such a transmissivity of atmosphere, haze at the horizon still has a white color, and a spot 50 km away from the observer will be below the horizon line by a total of 200 m, i.e., the line of sighting intersects at this distance layers which are almost not to be distinguished as regards luminance from the surface layer.

Summing up, we can conclude that the light-atmosphere equation, while one of the most important theoretical propositions of the science of visibility, is nevertheless, far from describing all the properties of the real atmosphere and is far from being unconditionally applicable to every state thereof. This constitutes a lag in the science of visibility which has not been overcome to date and which makes the solution of applied problems more difficult in a whole swarm of cases.

§ 7. The Equation for the Visibility Range of Real Objects

The general concepts set forth in preceding paragraphs make it possible for one to secure one of the most important relationships of the science of visibility of a real object. By the latter we mean any object on the terrain for which any real object or section of the sky at the horizon serves as a background.

The theory of the range of visibility of objects was worked out for the first time by the German geophysicist Koschmider in 1925 and was developed in the works of V. V. Sharonov, A. A. Gershun, and other Soviet specialists.

Let us assume that we are observing some real object the range of visibility of which must be determined.

The derivation of the appropriate expression is based upon the following premises:

a) the intensivity of visual receptivity of the object is determined by the contrast of luminance between it and the surrounding background;

b) atmospheric blurring under corresponding conditions reduces this contrast to a threshold value;

c) atmospheric blurring, and also the conditions of illumination, are homogeneous from the point of observation to the distance at which loss of visibility of the object occurs;

d) the object has angular dimensions of not less than 0.3° (at the distance of the range of visibility).

Let us first establish the law for diminution of contrast of the observed object under the operation of haze up to the threshold value.

The true luminance B_o of the object, i.e., that not distorted by haze, as observed from a short distance, at once starts to change as we move away from the object. This change takes place in accordance with two principles.

In the first place, as a consequence of the diffusion of light in the layer between the object and the observer the true luminance of the object diminishes from B_o to $B_o e^{-\alpha L}$, where L is the distance from the observer to the object and α is the index of weakening per unit length.

In the second place, by reason of the veiling effect of atmospheric haze, a seeming conversion of a colored object into an achromatic one takes place, and also an increase in the luminance of an object which is proportionate to the luminance of a layer of air of length L (in accordance with the light-atmosphere equation), i.e., proportionate to the quantity

Thus, it at a short distance the observed object has a true luminance, not distorted by haze, of B_o, then at a sufficiently great distance L the luminance of the object B_o' under the joint action of the two factors referred to above will become distinguished from B_o and will assume the value

$$B_o' = B_o e^{-\alpha L} + D(1 - e^{-\alpha L}). \tag{1.16}$$

Luminance B_o' bears the appelation of the observed or apparent luminance.

Through entirely analogous reasoning we can secure an expression for apparent luminance B_ϕ' of any real background:

$$B_\phi' = B_\phi e^{-\alpha L} + D(1 - e^{-\alpha L}). \tag{1.17}$$

We should note that the second term in (1.16) and (1.17) distorts the luminance possessed by the object and by the background considerably more than the first term does. Worsening of the visibility of an object takes place, as Wiegand and Schmaus have emphasized, not so much as a result of weakening of the rays passing from object to observer, as by virtue of the masking effect of haze in the layer between the object and the observer. The masking effect of haze is precisely what is determined by the second term in (1.16) and (1.17).

Let us also note that in the general case, the distance between the object and the background can differ, as a result of which the value of L, forming part of B_o' and of B_ϕ', can also differ. But for this case, which leads to clumsy expressions, the course of further reasoning remains the same as for the case of so-called plane contrast (which is what we are examining here), when the distance between object and background is not great and the indicated differences in L can be disregarded.

Now (1.16) and (1.17) must be substituted in (1.12). But the latter, when one substitutes into in concrete values for the luminance of an object and a background, may have a double form:

$$K(B_o, B_\Phi) = \frac{B_\Phi - B_o}{B_\Phi} = 1 - \frac{B_o}{B_\Phi}, \quad \text{if} \quad B_\Phi > B_o; \qquad (1.18)$$

$$K(B_o, B_\Phi) = \frac{B_o - B_\Phi}{B_o} = 1 - \frac{B_\Phi}{B_o}, \quad \text{if} \quad B_o > B_\Phi. \qquad (1.19)$$

Let us assume that in our case the luminance of the background is greater than the luminance of the object (this is the case for the majority of the problems examined from here on). Then the substitution of (1.16) and (1.17) into (1.18) produces

$$K(B_o, B_\Phi) = \frac{B_\Phi e^{-\alpha L} + D(1 - e^{-\alpha L}) - B_o e^{-\alpha L} - D(1 - e^{-\alpha L})}{B_\Phi e^{-\alpha L} + D(1 - e^{-\alpha L})}$$

Dividing the fraction by $B_\Phi e^{-\alpha L}$ and taking (1.18) into account, we secure

$$K(B_o, B_\Phi) = \frac{1 - \frac{B_o}{B_\Phi}}{1 + \frac{D}{B_\Phi}\frac{1 - e^{-\alpha L}}{e^{-\alpha L}}} = \frac{K_0}{1 + \frac{D}{B_\Phi}(e^{\alpha L} - 1)}, \qquad (1.20)$$

where K_0 is the initial contrast, not distorted by haze, between the object and the background.

The expression secured describes the regularity of change of contrast as distance L between the object and the observer increases, or as blurring of the atmosphere (indicator α) increases with L being fixed.

If the object is brighter than the background, then (1.16) and (1.17) must be substituted into (1.19). In this case in the numerator of (1.20) D/B_0 will stand in the place of the relation D/B_Φ. From (1.20) it follows that the value of the contrast K of the object diminishes until with corresponding values for L (with a given α) the threshold value ε is attained.

This critical value of L is called the range of visibility of a real object and is designated by S_p. Adapting (1.20) to the value of the threshold of contrast sensitivity ε and replacing L with S_p, we secure after simple transformations

$$\varepsilon = \frac{K_0}{1 + \frac{D}{B_\phi}\left(e^{\alpha S_p} - 1\right)},$$

or

$$\frac{D}{B_\phi} e^{\alpha S_p} = \frac{K_0}{\varepsilon} + \frac{D}{B_\phi} - 1.$$

Hence, after logging to the base e, we secure

$$S_p = \frac{1}{\alpha} \ln \frac{\frac{K_0}{\varepsilon} + \frac{D}{B_\phi} - 1}{\frac{D}{B_\phi}}. \tag{1.21}$$

Expression (1.21) is the equation for the range of visibility of any real object projected against any real background.

From (1.21) it is apparent that the range of visibility of a real object is a compound function of five parameters: α, K_0, ε, D, B_ϕ. If even one of these five parameters is unknown it is impossible to solve a problem involving determination of S_p.

Equation (1.21) is examined in greater detail in Chapter IV, where some methodical considerations arising upon the solution of a number of applied problems (in particular, upon determining the so-called landing visibility) are set forth.

Let us turn now to an important particular case, arising from (1.21) when a real object is projected against a background of sky at the horizon. In this case the luminance B_ϕ in (1.21) indicates not the luminance of any arbitrary background, but the luminance of the sky at the horizon. The latter, however, as has been remarked in § 6, can be identified with the value of the coefficinet D, of the light-atmosphere equation when the atmosphere is not very transparent and when the sky at the horizon has no bluish tinge perceptible to the eye.

In that case, inasmuch as a section of the sky at the horizon serves as background for the object, one can consider $B_\phi = D$. Substituting this equality in (1.21), we secure an expression for range of visibility $S_{p\Delta}$ of a real object examined against a background of haze or of sky at the horizon:

$$S_{p.\Delta}=\frac{1}{\alpha}\ln\frac{K_0}{\varepsilon}. \tag{1.22}$$

When there is high transparency of the atmosphere all of the qualifications affecting the physical meaning of the coefficient D (see § 6) hold good for equation (1.22). But at small values for range of visibility (in fog and with heavy hazes) the equality $B_\phi = D$ and consequently correctness of (1.22) may hold good not only in a horizontal direction but also, as has been shown earlier, in oblique ones (at an angle up to some degrees).

The problem of determining the range of visibility of objects against a background of sky at the horizon has been pretty well worked out. It will be examined in detail in Chapter IV.

§ 8. The Meteorological Range of Visibility

Still another decidedly important special case arises from (1.22), that in which an absolutely black surface the inherent luminance of which, $B_0 = 0$, is the object against a sky background. Then we have from (1.18)

$$K_0 = 1 - \frac{B_0}{B_\phi} = 1.$$

The substitution of this value in (1.22) produces, instead of the range of visibility of a real object $S_{p.\Delta}$, the range of visibility of an absolutely black object against a sky background. Designating the latter as S_m, we secure

$$S_м = \frac{1}{\alpha}\ln\frac{1}{\varepsilon}. \tag{1.23}$$

As a concrete value for the threshold of contrast sensitivity of vision ε there is generally taken a value determined comparatively long ago by Koenig-Brodchun in laboratory experiments. According to these experiments, if one understands by ε a relative difference, not distinguishable by the eye, between the luminance of a sufficiently large object and the background, then $\varepsilon = 0.02$ (or 2%). Substitution of this value in (1.23) gives

$$S_{\text{м}} = \frac{1}{a} \ln 50,$$

or finally

$$S_{\text{м}} = \frac{3.91}{a}. \tag{1.24}$$

Expression (1.24) or (1.23) constitutes the familiar Koschmider formula establishing the single-valued relation between the range of visibility of an absolutely black object against a sky background at the horizon, and the degree of optical blurring (transmissivity) of the atmosphere expressed by the index of weakening a.

The range of visibility of an absolutely black surface determined via (1.24) and providing a single-value characterization of atmospheric blurring through the index of weakening a is called the meteorological range of visibility in all countries.[1]

If we compare (1.22) and (1.23) with each other, we can easily see that the range of visibility $S_{p.\Delta}$ of sufficiently dark terrain objects (for example, coniferous forests, for which K is about 0.9) is close to the range of visibility of a theoretically absolutely black surface (the difference between $S_{p.\Delta}$ and S_m does not exceed 10-15%; see Table 18).

In other words the range of visibility of dark real terrain objects on a sky (haze) background at the horizon may also serve as a convenient characterization of the transmissivity of the atmosphere. This is the sense of the measurements which were used as the basis for the 10-point visibility scale of 1935.

As ensues from (1.23) and (1.24), the magnitude of the meteorological range of visibility when there is homogeneous atmospheric blurring should be the same in all directions. A difference in atmospheric transmissivity in various directions, frequently observed, is explained not by error in (1.23) and (1.24), but by actual provision of the real atmosphere.

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[1]At the suggestion of Foitzik, in the German Democratic Republic the term "normal range of visibility" is used instead of the term "meteorological range of visibility" (cf. note on page 329).

1

Thus *the meteorological range of visibility is an arbitrary expression of the transmissivity of the atmosphere over a distance at which, through the operation of atmospheric haze, the visibility of an absolutely black surface, having at that distance angular dimensions not less than 0.3° and projected against a sky (haze) background at the horizon, is lost.*

The relation (1.23) furnished the impetus for various sorts of methodical treatments in order to measure S_{m}, for investigation of threshold functions, etc.

Let us note that the use of the natural logarithm to the base 2.7 in equations (1.21)-(1.23) is less convenient than is that of decimal logarithms. Sometimes the natural logarithm is replaced with the decimal one, and in those cases, upon shifting from one set of logarithms to the other in (1.21)-(1.23), 2.3 must appear in place of 1, i.e., instead of (1.22) we must have

$$S_{p.\Delta}=\frac{2,3}{\alpha}\lg\frac{K_0}{\varepsilon}.$$

Sometimes another procedure is used. In the light-atmosphere equation (1.15) the exponential function $e^{-\alpha L}$ is changed to $10^{-\alpha L}$. But since α in the one case differs from α in the other on the module of the shift from natural logarithms to decimal ones, in order to avoid confusion the index 10 is inserted in the exponential of weakening with the base 10; i.e., $e^{-\alpha L}$ is replaced by $10^{-\alpha_{10}L}$. In other words, one may write

$$e^{-\alpha L}=10^{-\alpha_{10}L}.$$

Hence, logging to the base 2.7, we secure

$$\alpha=2,3\alpha_{10}.$$

Furthermore $e^{-\alpha L}=\tau^L$ or $\alpha=-\ln\tau$, or $\alpha_{10}=\lg\tau$,

$$e^{-\alpha L}=\tau^L \text{ or } \alpha=-\ln\tau, \text{ or } \alpha_{10}=\log\tau,$$

where τ is the transmissivity of the layer L.

Presenting the light-atmosphere equation in the form

$$B_L = D\left(1 - 10^{-\alpha_m L}\right),$$

we can easily secure in place of (1.21) the analogous expression

$$S_p = \frac{1}{\alpha_m} \lg \frac{\frac{K_0}{\varepsilon} + \frac{D}{B_\phi} - 1}{\frac{D}{B_\phi}}, \qquad (1.25)$$

in place of (1.22)

$$S_{p.\Delta} = \frac{1}{\alpha_m} \lg \frac{K_0}{\varepsilon}, \qquad (1.26)$$

and in place of (1.23)

$$S_m = \frac{1}{\alpha_m} \lg \frac{1}{\varepsilon}. \qquad (1.27)$$

It is indispensable for the reader to bear in mind these peculiarities of all the relationships set forth above.

From the content of the paragraph in question it ensues that one cannot speak of visibility in general terms. When one speaks of range of visibility determined at a network of meteorological stations, one has in mind the range of visibility of an absolutely black surface at the horizon, i.e., one has in mind the meteorological range of visibility or the transmissivity of the atmosphere. But if one speaks of range of visibility at airports, let us say, then hear what is involved is the range of visibility of the landing strip, determined in accordance with (1.25) or (1.21) -- i.e., what is involved is the range of visibility of a real object.

One must not confuse the meteorological range of visibility S_m with the range of visibility of a real object S_p or $S_{p.\Delta}$. Although the difference between them is plainly evident from the expressions derived above, even today we run up against cases where these two differing concepts are confused.

In § 5 it was demonstrated that range of visibility should be determined in accordance with the differentiation of threshold functions. Both the meteorological range of visibility and the range of visibility of real objects may be treated as the range of disappearance or of detection, or as that of recognition.

The difference between them can be substantial. Alteration of the threshold of contrast sensitivity by 1% changes the range of visibility of an object by approximately 10%. Expression (1.24) has been derived for $\varepsilon = 0.02$. With $\varepsilon = 0.05$ there would be 3.0 in the numerator, i.e., the difference in S_m in the two cases would be around 30%.

The presence of a threshold of contrast sensitivity in the ratio K_0/ε in expressions (1.21) or (1.25) is natural, inasmuch as we are dealing with the range of visibility of objects. But the presence of a threshold of contrast sensitivity of vision in expression (1.23) for meteorological range of visibility is thus a fault, inasmuch as a subjective threshold factor is injected into a sharply-defined physical concept, "atmospheric transmissivity." This brings it about that in place of the objectively existing concrete value of the transmissivity of the atmosphere there is substituted a multiple value corresponding to the value of ε that may be inserted into the formula for meteorological range of visibility. There is as yet no single opinion as regards the value of ε which ought to be utilized in (1.23). This circumstance has moved the author of the present work to carry out experimental investigations as regards determination of a most-reliable value for ε which should be used in (1.23) or (1.27). From the result of this investigation, which is set forth in § 66, it transpires that the most-reliable value for ε is close to 0.03 (or 3%). If this value is inserted into (1.23), then instead of (1.24) we get

$$S_м = \frac{3{,}5}{\alpha} \qquad (1.28)$$

and instead of (1.27)

$$S_м = \frac{1{,}5}{\alpha_{10}}. \qquad (1.29)$$

The relationships among α, α_{10}, τ and S_m for various values of ε are set forth in Figure 5.

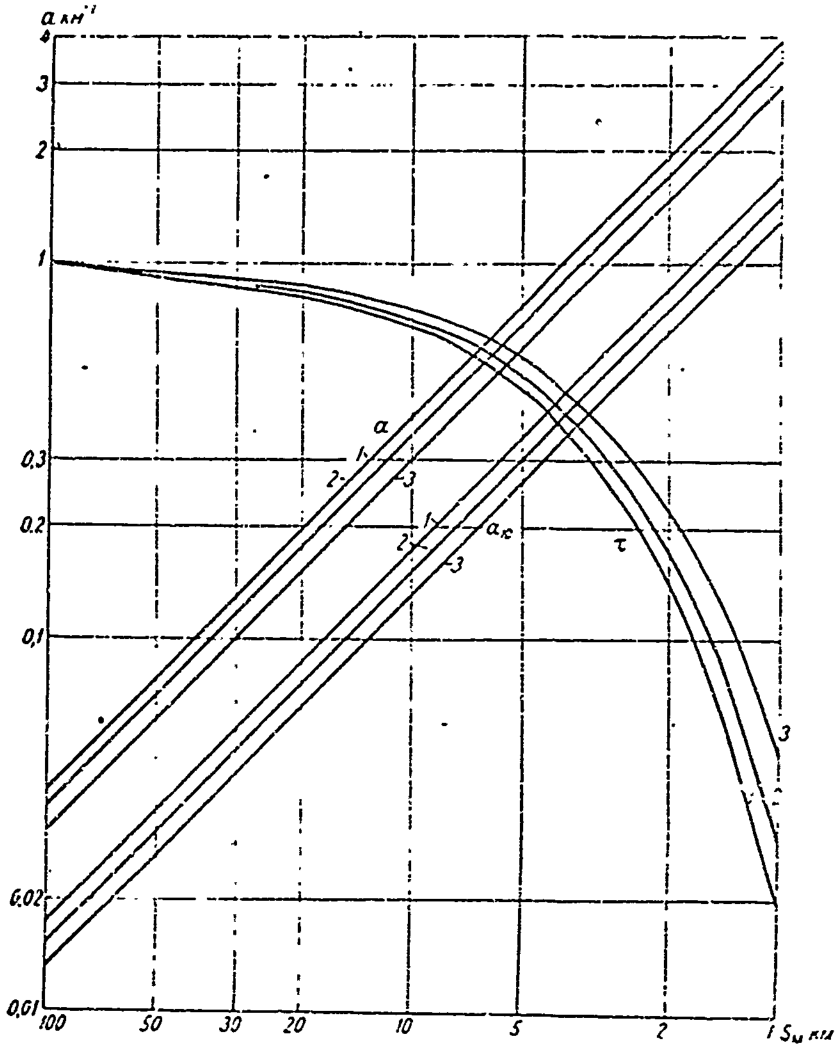


Figure 5. Relationships Among α, α_{10}, τ and S_m for Various Values of ε. Values for ε (%): 1) 2%; 2) 3%; 3) 5%.

We shall in fact make use of expressions (1.28) and (1.29) for meteorological range of visibility, m.r.v. from this point onward, remembering that the angular dimensions at a distance S_m must not be less than 0.3% (about 20' of angle). The way the range of visibility of a black object of less angular dimensions changes is evident from Table 9, drawn up in accordance with (1.23) with the data in Table 6 being taken into account.

TABLE 9. ALTERATIONS IN RANGE OF VISIBILITY OF AN ABSOLUTELY BLACK OBJECT DEPENDING ON ITS ANGULAR DIMENSIONS (% RELATIVE TO AN OBJECT OF LARGE ANGULAR DIMENSIONS)

Angular Diameter of Object	Range: Of Disappearance	Range: Of Detection
⩾20'	100	100
15	97	94
12	94	90
9	89	84
6	82	77
3	64	60
2	54	50

§ 9. The Concept of the Range of Visibility of Signal Lights

The Koschmider theory and expressions (1.21)-(1.28) which ensue from it describe the so-called daylight visibility of non-luminous extended objects. In the dark hours of the 24, the range of real non-luminous objects is likewise fully described by expression (1.21) and (1.22). The small values for the range of visibility of objects at night are brought about, other circumstances being the same, only by a greater value for ε, which attains some tens of percentage points. But the practical activity of man is associated with the visual receptivities (including threshold ones) of objects of a second extensive class -- signal lights in the form of incandescent lamps of various powers and colors, beacon lights, searchlight projectors, etc. If these sources are observed from such close distances that their angular dimensions considerably exceed the threshold of acuity of vision of man, taken as being equal to 1' of angle, then the Koschmider theory and all the relationships of § 5 and 6 are fully applicable to such luminous objects with the provision that the objects are white and that expression (1.19) is used for determination of the contrast of luminance. For colored luminous objects of large dimensions, as experience shows, the Koschmider theory does not hold good. No theory for the range of visibility of such objects has yet been set up. But in the enormous majority of cases, luminous objects are observed from such great distances that their angular dimensions become less than the threshold of acuity of vision and they are perceived as points.

The Koschmider theory is likewise inapplicable to point-sources of light; their range of visibility is determined by other laws.

Let us examine what conditions determine the range of visibility of point-sources of light.

Let us suppose that we are looking at a distance point of light. When we speak of a point-source we refer not to a luminance, but to flash. The flash of a point-source is determined by the sensation which it creates upon the pupil of the eye of the observer.

If from a point-source, having power I_0 and located at a distance L from the observer, a flow of light has traversed a path in the atmosphere without loss through diffusion and absorption, then illumination E upon the pupil of the eye would be determined by the law

$$E = \frac{I_0}{L^2}.$$

But in the real atmosphere the light flow undergoes weakening, as has already been indicated above, in accordance with the Buger exponential law. For this reason the real illumination upon the pupil of the eye, analogously to what was the case with the luminance of an object (cf. § 6), will be equal to

$$E = \frac{I_0}{L^2} e^{-\alpha L}, \tag{1.30}$$

where α is the index of weakening per unit of length.

As is apparent from (1.30), in the real atmosphere illumination E from a point-source diminishes extremely rapidly not only by reason of the spatial redistribution of light energy in accordance with the law of squares of distance, but also in consequence of its simultaneous weakening in accordance with the Buger law.

At a certain distance L_c, called the range of visibility of a signal light, illumination upon the pupil of the eye reaches a minimum at which the eye ceases to see the light in question. This minimum illumination is called the threshold of light sensitivity of the eye with respect to a point-source, and is designated by E_{th}. More briefly E_{th} is called threshold sensitivity to the pupil, it being understood that the signal light is of point dimensions.

Thus for a range of visibility L_c of a point signal light we shall have in place of (1.30)

$$E_{th} = \frac{I_0}{L_c^2} e^{-\alpha L_c}. \qquad (1.31)$$

Threshold illumination has to be classified in just the same way as thresholds of contrast sensitivity. In the first place, the value of E_{th} depends essentially upon whether it refers to fixed or to non-fixed observation. In the second place, threshold illumination is divided into E_{th} upon loss of visibility of light, E_{th} at the moment of detection of the light, and finally E_{th} upon recognition of the light (by E_{th} upon recognition of the light we mean the minimum illumination upon the pupil at which recognition of the color of the light takes place). With this classification of threshold illumination we must associate also the range of visibility of light.

One must note that the eye of man possesses an extremely high sensitivity to the reception of a single distant light after a prolonged stay in darkness.

As S. I. Vavilov's tests have shown [17], after prolonged stay (some hours) in absolute darkness the eye of man acquires a sensitivity which makes it possible for him to perceive a few quanta of light, and even individual quanta of light. With such sensitivity as this the eye would be able, as S. I. Vavilov demonstrates, to see a lighted candle at a distance of 200 km! Thus the limit light sensitivity of the eye that is possible is limited by the very nature of light. But under real conditions the eye of man never acquires such high sensitivity: even though E_{th} may be very small (microluxes and even tens of microluxes), it is nevertheless two or three orders greater than the absolute threshold of sensitivity.

The value of E_{th} rises sharply even when there is an inconsiderable increase in the general illumination or luminance of the background. With transition from the dark to the light part of the 24 hours, the threshold of illumination changes within broad limits -- from 10^{-8} to 10^{-3} lux, i.e., approximately by five orders.

It is important to note that the v· ue E_{th} is different for colored lights observed under identical conditions. On this account, in solving practical problems having to do with determination of the range of visibility of signal lights one must use not one value for E_{th}, but several depending on the level of general illumination, the color of the light, the duration of stay (adaptation) of the observer at a given level of illumination, etc. Study of the threshold receptivity of colored lights has revealed still a further complicating circumstance. It proves to be the case that if the level of illumination upon the eye that is created by the source is close to the threshold level, then colored light sources are perceived as white or almost white sources. The achromatic interval of circum-threshold values of illumination is particularly great for green lights. But for red lights the achromatic interval is absent: at threshold disappearance or detection they are apprehended as being red.

All of what has been set forth above decidedly complicates the solution of problems having to do with determination of the range of visibility of signal lights; many questions remain unexplained and in dispute.

It is impossible to determine the value of L_c directly from (1.30). It can be found either from tables or from a nomogram. To construct the latter, in place of α in (1.31) there is substituted the expression from (1.28) which corresponds to it:

$$\alpha = \frac{3{,}5}{S_м},$$

and (1.31) is presented in the form

$$\ln L_c + \frac{3.5}{2S_m} L_c = \frac{1}{2} \ln \frac{I_o}{E_{th}} . \tag{1.32}$$

Some practical problems relating to the visibility of signal lights are examined in Chapter V. There we present nomograms constructed in accordance with (1.32) and we set forth questions linked with the apprehension of powerful grouped lights.

Some Conclusions

From expressions (1.25), (1.26), and (1.32) it transpires that in order to determine the range of visibility of objects and signal lights it is indispensable to know the factors which characterize the optical properties of the atmosphere (the meteorological range of visibility), the photometric properties of objects, backgrounds, and signal lights, and also the threshold visual functions.

If even one of the factors referred to is unknown, it is not possible to determine the range of visibility of objects or lights.

Direct measurement of the factors referred to above, especially the transmissivity of the atmosphere, is a pretty difficult problem, calling for the working out of special methods and apparatus and the acquisition of a certain practice in the carrying out of measurements. In this connection one must bear in mind the fact that these factors are not stable, but are subject to considerable changes depending on meteorological and climatic conditions. For example the true contrast K_0, not distorted by atmospheric haze, may vary for the majority of objects of the terrain, as conditions of illumination change, by 10-20% or more. Variations in the color of objects from season to season (wetting with rain, presence upon them of snow or frost) change K_0, and also D/B_ϕ (or D/B_0), by some tens of percentage points.

But what complicates the problem of determining range of visibility of objects and lights most of all is the enormous changes, in time and over space, in the transmissivity of the atmosphere.

The real scope of alterations in the meteorological range of visibility amounts, as experience has shown, to hundreds of thousands, even millions, of percentage points. These alterations very frequently take place over a very brief interval of time: some hours or even minutes. This constitutes the reason why the working out of methods and apparatus for determination of the transmissivity of the atmosphere has come to be the central problem of the science of visibility. From subsequent chapters it will become plain what difficulties have stood and even now stand in the way of solution of this main problem.

The need for systematic measurements of the transmissivity of the atmosphere (in any direction and at any hour of the day), for determination of the photometric properties of various objects of the terrain, for study of threshold visual functions, etc., has contributed to the working out of special methods of measurement and of the complex of apparatus and devices associated therewith. The measurement principles utilized can be divided into two sharply distinguished groups:

I. Visual instrumental methods (the eye of the observer is the indicator), Figure 6.

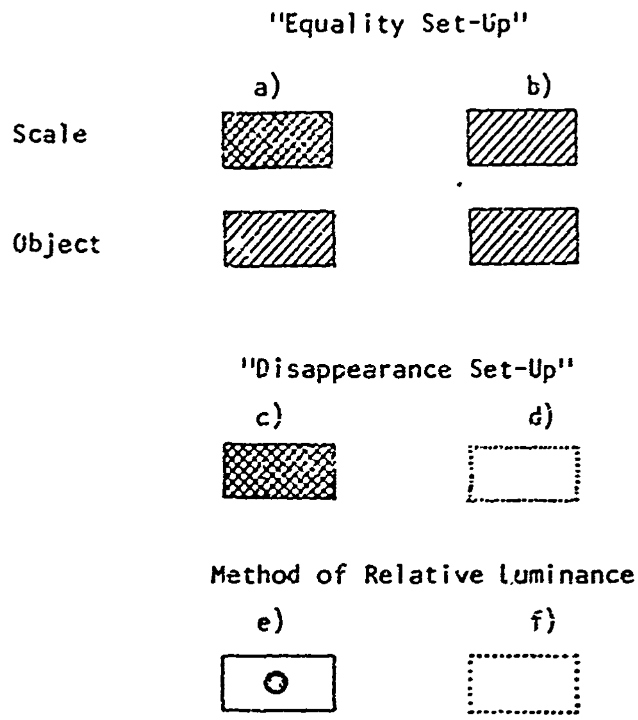


Figure 6. Photometric Principles Utilized in the Science of Visibility in Visual Instrumental Measurements.
a) Initial moment: luminance of scale and of object are different; b) Final moment: luminance of scale and object are the same; c) Initial moment: the object is visible; d) Final moment: the object is invisible (has been brought to threshold perceptivity); e) Initial moment: the black scale mark is visible against the background of the object; f) Final moment: the black scale mark is not visible against the background of the object, but the object is visible.

1) The method of photometric comparison, or "equality set-up";

2) The method of photometric extinction, or "disappearance set-up;"

3) The method of relative luminance (cf. Chapter III).

II. Objective methods (a photoelement is the indicator), Figure 7:

1) The basis method, consisting in direct measurement of the index of weakening, α, over a section of given length;

2) The method of return light diffusion, consisting in measurement of α via the intensitivity of light diffused at an angle of 180° or at an angle close to this, relative to the direction of falling light (cf. Chapter VIII);

3) Objective nephelometers (cf. Chapter IX).

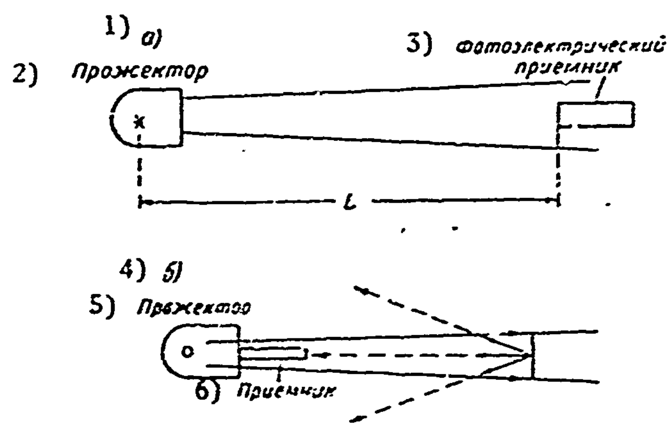


Figure 7. Principles of Objective Photometry Applied in the Science of Visibility in Measuring the Transmissivity of the Atmosphere.
a) The basis method; b) The method of return light diffusion.
Key: 1, a); 2, Projector; 3, Photoelectric collector; 4, b) 5, Projector; 6, Collector.

The objective methods are intended primarily for the measurement of the main parameter -- the index of weakening, α -- and of the value of S_m which is unequivocally linked with it (in accordance with formula (1.25) or (1.27).

By the method of photometric comparison one can determine only the S_m parameter (by the method of contrasts of objects on the terrain, and here only with a limited class of these objects). Measurement of other parameters by this method is difficult and may even be impossible by reason of the color of objects.

The method of photometric extinction and the method of relative luminance, which may be regarded as being a more refined variant of the method of extinction, are more universal. They make it possible to measure all parameters forming part of the equations for the range of visibility of real objects. The defects of these methods are the more difficult process of measurement and the need for acquisition of practice in making observations.

CHAPTER II

NON-ADAPTATIONAL VISIBILITY GAGES

§ 10. Photometric Peculiarities of Visibility Gages, and Field of Their Use

In order to solve various sorts of measurement problems in the optics of the terrain, including determination of the transmissivity of the atmosphere at a network of hydrometeorological stations, a special class of visual devices based upon the method of photometric extinction and called visibility gages is widely utilized.

Examination of the principle of operation of visibility gages as multiple-purpose devices, exposition of their optico-photometric system, and the like, constitute the content of the present chapter.

Visibility gages possess one quality which sharply distinguishes them from any other visual photometry device: they directly measure a certain quantity which can in its physical sense be interpreted as a measure of the intensity of visual perceptivity (sensation) of an object, or as its degree of visibility. This measure of intensivity of perceptivity of an object is expressed in the form of a certain number, V, of thresholds of contrast sensitivity of vision ε, contained in a given contrast K.

Analytically this relation has the form (see derivation in § 13)

$$V = \frac{K}{\varepsilon}. \tag{2.1}$$

As is shown farther on, the initial measured quantity of any visibility gage in making observations of any character is in fact not the magnitude of contrast, but the V value, determined from a graduated table for the given reading. How we get from V to the contrast K is shown farther on.

By intensivity of receptivity, or degree of visibility, of a given object we shall agree to mean a certain amount of visual excitation, characteristic for given conditions of observation, which is determined by the state of the visual analyzer and by the sum total of the photometric, colorimetric, and geometrical differences between the object and the background which surrounds it.

Observations based upon measurement of the degree of visibility V of a given object make it possible to solve a variety of photometric, phototechnical, psychophysiological, and other problems, which as a rule cannot be solved by the comparison method, the "equality set-up." In this connection it is in place to recall the statement of the most outstanding Soviet phototechnical expert A. A. Gershun, to the effect that a need has long since matured for the working out of a simple device which is able to measure the degree of visibility of an object, i.e., the intensivity of its visual receptivity, "as simply as a thermometer measures temperature or a luxometer measures illumination" [40].

Present-day visibility gages are in fact such devices. No other device of visual photometry possesses such qualities.

The field of the varied applications of visibility gages is examined by V. V. Sharonov [118] and L. L. Dashkievitch [56]. We shall dwell upon this question again, after having made a number of supplementary remarks.

Visibility gages are used:

1. In meteorology and atmospheric optics

a) Measurement of contrasts of terrain objects of any color, any angular dimensions and configurations; the objects are projected against a background of any color or luminance;

b) Measurement of the parameter K_o/ϵ in the equation for range of visibility of objects;

c) Measurement of the parameter D/B_ϕ (or D/B_o) in the equation for the range of visibility of objects;

d) Measurement of transmissivity of the atmosphere by daylight through measurement of contrasts or through the degree of visibility of objects;

e) Measurement of transmissivity of the atmosphere by night;

f) Various investigations on the optical properties of atmospheric haze;

2. In phototechnics:

a) Determination of the degree of visibility (intensivity of perceptivity) of landmarks, navigation and highway signs under various atmospheric and optical conditions, in air, sea, railway, and automotive transport;

b) Determination of the degree of visibility of various industrial objects, depending on established norms or on the level of luminance they possess;

c) Comparison with each other as between various lighting apparatus and the way they are placed, as reflected in the degree of visibility of objects that they create (for example, the efficiency of a given placement of projectors at an airfield, etc.);

3. In camouflaging:

a) Measurement of the effectiveness of camouflaging media depending on the level of illumination, the character of the relief of a locality, etc.;

b) Measurement of the concealment effectiveness of artificial smoke screens in accordance with the degree of deterioration of visibility of objects;

c) Investigation of the appearances of buildings, weapons, ships, and establishment of the effectiveness of means of camouflaging them;

4. In radiolocation and television:

a) Measurement of the degree of visibility of a signal under examination, depending on the characteristics of the receiving apparatus and the character of the illumination of the receiver screen by oblique light;

b) Investigation of the degree of reproductivity of the picture tube of the television set of the object image being transmitted;

5. In physiological optics and aviation medicine:

a) Investigation of thresholds of contrast sensitivity of vision depending on the level of illumination, the angular dimensions of objects, their color, the character of contours, and the rapidity of movement; study of the effect of vision fatigue upon the value of threshold functions;

b) Investigation of threshold functions depending on pathological changes in the visual apparatus;

6. In psychophysiology:

a) Investigation of the suitability, and the limits of applicability, of the Weber-Fechner law;

7. In optical technology:

a) Investigation of the effect of light filters on improvement of the visibility of objects (observed through instruments), including also terrain objects;

/6

8. In aeroastrophotograph and microphotography:

a) Comparison of the visibility of objects and their detailed structure as secured in shots made by various cameras and objective lenses, or through the use of various photofilters;

b) Comparison of the visibility of objects secured from various negative or positive materials;

9. In cartography:

a) Numerical determination of the degree of visibility of various scripts, legends, etc.

Only a few of the problems enumerated above can be solved by means of the "equality set-up."

But let us note that the optical-photometrical lay-out of modern visibility gages makes it possible to apply with these devices the method of photometric comparison. Thus modern visibility gages are universal devices of visual photometry, capable of solving problems by the "equality set-up," the "disappearance set-up," and also by the "detection set-up" and the "recognition set-up", and finally, by the method of relative luminance.

Unfortunately, we have to note that in visual photometry insufficient attention is paid to visibility gages. To date there is no theory for the extinction method which would make it possible to point out new fields for its application. It is characteristic that in courses of physical optics and photometry there is not even any mention of the extinction method or of visibility gages. In the Great Soviet Encyclopedia only a few lines are devoted to them. The sole exception is the well-known text on phototechnics of V. V. Meshkov [86, 87], where some visibility gages are described, the method of their use is examined, and great attention is paid to threshold visual perceptivities.

Considering that during the last 20 years the working-out both of visibility gages and of the actual principle of extinction have progressed a great deal, we shall dwell in a little more detail upon the exposition of the rational system of visibility gages, their theory, and the description of present-day examples.

§ 11. Adaptation Effect, and Exposition of the Rational Optico-Photometric System of Visibility Gages

Observations by means of visibility gages are based on a peculiar artificial deterioration of the image of the object which is being examined, and on its being brought by degrees to threshold perceptivity. The latter is achieved by means of the superposition (composition), upon the image being examined, of a supplementary veiling luminance (artificial instrumental haze), which is altogether analogous in its optical effect to fog or heavy haze. The principle for the constitution and operation of the masking luminance is examined in § 12.

Variations in masking luminance which are brought about by the photometrical apparatus of the device make it possible to change within broad limits the degree of visibility of the image being examined, all the way down to complete loss of its visibility (i.e., to threshold perceptivity) against the background of this masking luminance.

In such a process of observation one condition which is important in principle must be met; it was formulated by V. V. Sharonov, and it runs to the effect that as the image of an object diminishes to threshold perceptivity the threshold of contrast perceptivity of the eye must remain a constant, the same as it was prior to the start of observation by means of the device.

To anticipate a little, we shall show that if the condition of V. V. Sharonov fails to be met this leads to the appearance of an adaptation effect which obstructs the taking of precise measurements. The substance of this effect is explained below.

The history of the creation of visibility gages has shown that meeting the condition of V. V. Sharonov is made more complicated through the fact that in order to bring the image under observation to threshold perceptivity one must reduce its initial contrast, as a rule, by some tens of times. For example, if we suppose that the contrast of the object under examination comes to 80%, and the threshold of contrast sensitivity, ε, is 2%, then in order to bring the contrast in question to threshold contrast it must be reduced to one-fortieth.

In the first designs of visibility gages such a considerable reduction of the observed contrast was secured by virtue of sharp diminution of the overall luminance of the field of vision by introducing into the path of the light beams photometric neutral-gray or cloudy dispersion prisms, by diaphragming, etc. It was thought that no matter how markedly the overall luminance of the field of vision of the device might diminish, the eye of the observer would be working under circumstances where the conditions of the differential form of the Weber-Fechner law would be met -- i.e., under circumstances where constancy of the threshold of contrast sensitivity would be maintained.

It was only a comparatively short while ago that it became plain that application of these methods of reducing observed contrast to the threshold value in visibility gages was impossible under any circumstances.

Experience has shown that extinction photometry measurements based upon reduction of overall luminance of the field of vision are accompanied by a new, previously unknown phenomenon -- light (or more precisely darkness) trans-adaptation of the eye, associated with a more or less profound violation of the initial threshold sensitivity, something which leads to a great spread in readings and to unsatisfactory results of measurements.

Externally, light trans-adaptation consists in the following. An object, just extinguished, after some seconds is again observed by the eye, and continues to be observed for a certain time with increasing distinctness. The observer again extinguishes the image which has appeared, still further reducing the overall luminance of the field of vision, but within some seconds the eye once more perceives the object at this still greater level of luminance, etc.

Observations with some examples of the first visibility gages have shown that on a bright sunny day the image of the object may be noted again each time after a number (3-5) of successive extinctions thereof.

Thus what we call an adaptation effect is inherent to visibility gages having a diminishing overall luminance of the field of vision. The effect becomes manifest in the capacity of the eye for adapting itself to the diminished level of illumination which is attained at each successive stage of the bringing of the image of the object to threshold receptivity.

The origin of the adaptation effect may be explained as follows.

The diminishing luminance of the field of vision gives rise to a brief darkness-blinding of the eye, analogous to the blinding observed upon going into a darkened room from brilliant sunlight. In this case the eye requires some time to build up again its original contrast threshold sensitivity; having fallen off sharply in the first moment of darkness-blinding, it then commences to mount, at a given lower level of illumination. If this new level of illumination does not exceed the limits of the applicability of the differential form of the Weber-Fechner law, when there is sufficiently prolonged adaptation the eye would be able to build up again its former threshold sensitivity and would be able to see the object with the former visual intensivity. But since the process of observation with "long-term set-ups" is not possible in practice, repeated extinction of the observed object commences earlier than reconstitution of the sensitivity of the eye becomes complete.

Thus the factual level of the threshold sensitivity at the attainment of which measurements commence at each successive stage of darkness-blindness departs more and more from its original sensitivity level.

The effect of trans-adaptation of the eye as overall luminance of the field of vision diminishes boils down in the last analysis to the fact that by reason of individual differences in the recovery properties in the threshold sensitivities of a number of observers, the readings made by members of the group will diverge sharply from one another, which renders the results of the measurements entirely worthless.

It is obvious that visibility gages having diminishing overall luminance of the field of vision and possessing the adaptation effect do not satisfy the requirement of V. V. Sharonov as to constancy of the threshold of contrast sensitivity, and are unsuitable for any sort of measurement purposes.

In the light of what has been set forth above, it is truly astonishing that the majority of proposed designs of visibility gages are based upon diminishing luminance of the field of vision, with all the consequences which the adaptation effect gives rise to. This is plainly to be seen from a brief survey of the principles of operation of some "adaptation" devices, which is set forth below

Visibility Gages Without Masking Luminance

1. *The Lekish and Moss (1935) binocular visibility gage.* The device consists of two round neutral-gray prisms fastened in a frame like a pair of glasses and mounted before the eyes of the observer. Bringing the object to extinction is achieved by synchronously turning these prisms and by sharp reduction of the overall luminance of the field of vision. Adaptation effect must make its appearance in this device in the sharpest imaginable manner. The device is nevertheless used in the United States and in Great Britain for approximate evaluation of illumination norms under industrial conditions, especially in mines.

2. *The Zukler binocular visibility gage, 1953.* This device is analogous to the Lekish and Moss device, but the course of alteration of the density of the round photometrical prisms is different. It is strange, to say the least, that in 1953 a device was created having the same drawback as the Lekish and Moss device.

Visibility gages Having Masking Luminance

1. *The V. V. Sharonov haze meter (1934).* The observer examines the object through the tube 2 and 4 (Figure 8), in the main focal plane of which a glass plate 3 inclined at an angle of 45° is fastened, plus a photometric prism 1, set up ahead of the objective of the tube. Upon the picture observed there is superimposed a masking luminance which is formed by a milky plate 5 (or ball), fastened above the glass plate. According to the idea the presence of the masking luminance, the operation of which is analogous to that of haze, ought to eliminate the adaptation effect.

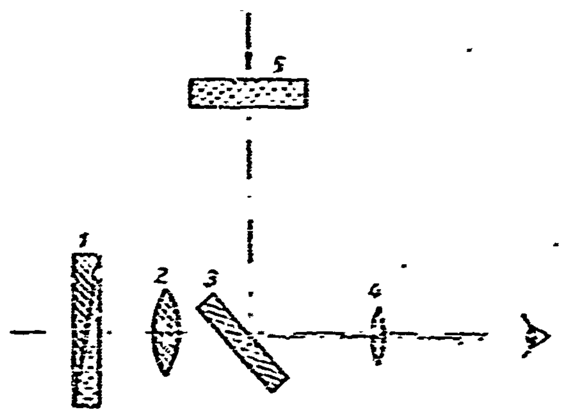


Figure 8. Optical Photometric Circuit of the V. V. Sharonov Haze Meter.

Further extinction of the object observed down to threshold perceptivity was brought about by considerable reduction of the overall luminance of the field of vision by means of the introduction of the thick sections of the photometric prism.

With such an extinction system it was not possible to eliminate the adaptation effect: the object was observed each time after 3-4 successive extinctions thereof. The precision of measurements proved to be unsatisfactory. But the original idea as to the part played by a natural masking luminance in eliminating adaptation effect proved fruitful. It determined the sole correct optical-photometric system for a visibility gage, one which has been put into practice in a series of more recent treatments.

2. *The V. F. Piskun visibility gage (1939-1940).* These devices constitute a refinement of the design of the V. V. Sharonov haze meter. For the

first time the image of a section of the sky at the horizon was used as a masking luminance instead of the middle spherical illumination as in the haze meter. Making the image of the section of sky at the horizon coincide with the observed image of the object was done by effecting an appropriate inclination of a mirror. Bringing the object observed to threshold receptivity was achieved by reducing the luminance of the field of vision through the use of a circular photometric prism.

Observations have shown that the V. F. Piskun device had a substantial indeterminacy of the read-off point by reason of adaptation effect. The results of the observations were unsatisfactory.

3. *The Cottrell visibility gage for mine use (1951)* [149]. As we have remarked above, in mines of the United States, Great Britain, and Belgium visibility gages are used to evaluate the norm of mine illumination in accordance with the degree of visibility of objects at the faces. One of these devices is Cottrell visibility gage (Figure 9). The object, 1, is examined through a semi-transparent plate 3 and a photometric prism 2. An incandescent lamp 8, a plate of milky glass 7, a mirror 5, and an optical system 6 create a constant masking luminance imposed upon the image being examined by the eye, 4. As the prism 2 is rotated the object moves toward extinction against the background of the imposed masking luminance. The indications of the device are referred arbitrarily to the initial value of the masking luminance.

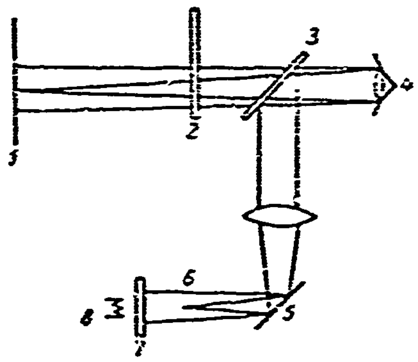


Figure 9. The Optical and Photometric System of the Cottrell Visibility Gage for Mine Use.

Although Cottrell indicates that in his device the degree of adaptation of the eye is taken into account, in reality an adaptation effect must take place, since the total luminance of the field is reduced, by reason of the extinction of the object, to the value of the masking luminance.

4. *The Roberts visibility gage for mine use (1955)* [212, 213]. The device (Figure 10) is intended for mine use. In the Roberts visibility gage both the masking luminance and the luminance of the image of the object being observed can be varied. Light from a lamp 6, passing through a system of absorbers and filters 9 and 10, falls upon a mirror 11 and then upon a semi-transparent plate 5 or 2, creating a masking luminance.

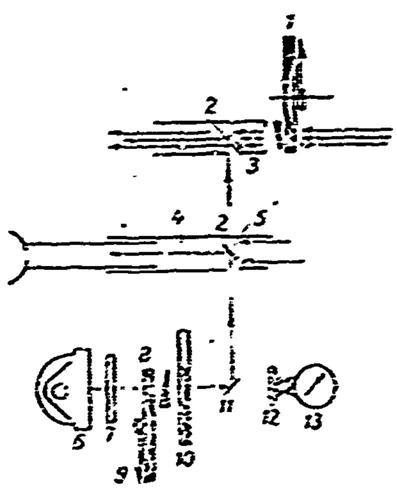


Figure 10. The Optical and Photometric System of the Roberts Visibility Gage for Mine Use.

The image of the object is extinguished by means of a photometric prism 1, i.e., by virtue of reduction of the luminance of the field of vision.

Variations of filters 7 and of the position of the photometric prisms 8 and 9 equalize the comparison fields. In the event of need, data regarding the luminances of objects observed can be registered by the photoelement 12 and the microamperometer 13 connected into its system. For visual observations a tube 4 with a semi-transparent plate 5 is attached; rays 3 pass through it from the object of observation.

Roberts indicates that his device is being used successfully in British mines to characterize the conditions of illumination.

5. *The V. A. Faas visibility gage (1939-1941).* Developing the idea of V. V. Sharonov as to the significance of a masking luminance for elimination of adaptation effect, V. A. Faas came very close to comprehension of the negative consequences of measurements made with devices based upon diminishing luminances of the field of vision.

V. A. Faas worked out some variants of devices having a very simple optical and photometric system, characterized by considerable strengthening of the masking luminance and of the general luminance of the field of vision. The devices were formed in the shape of attachments to a field glass, ball-pilot theodolite, or any other sort of telescopic system. A negative lens was fastened inside the attachment (Figure 11); it had a small aperture at its center, covered by a "cat's eye" movable diaphragm. Upon looking into the eyepiece the eye saw an image of a section of the terrain composed of rays which had passed through the central aperture of the negative lense. This image was examined against a bright luminous background (a masking luminance) created by the negativelens. As the object was being observed, even before the start of the measurement the masking luminance was substantially reducing its contrast. Then the visibility of the object was reduced to threshold value via the diaphragming of the central aperture of the negative lens with the petals of the "cat's eye" diaphragm. With this sort of optical and photometric system V. A. Faas proposed to escape adaptation effect entirely, inasmuch as the overall luminance of the field of vision of the device changed very little. But this proposal of V. A. Faas did not work out. Despite the insignificant reduction in the overall luminance of the field of vision, a non-readaptation effect took place in this case as well, and it had a negative effect upon the securing of stable observation results.

Tests of the V. A. Faas devices made it possible to determine definitively that upon observation of near-threshold contrasts the eye of man is decidedly sensitive to dark-blindness even at slight reductions of the overall luminance of the field of vision.

Thus prolonged experience accumulated while working out and testing visibility gages has made it possible to take cognizance of a general principle for the rational optical and photometric system of devices of this class: the process of extinguishing the image observed must not be accompanied by diminution of the overall luminance of the field of vision. Only on this basis can one create a visibility gage free from adaptation effect, i.e., one which will satisfy V. V. Sharonov's requirement as to constancy of threshold sensitivity of the eye.

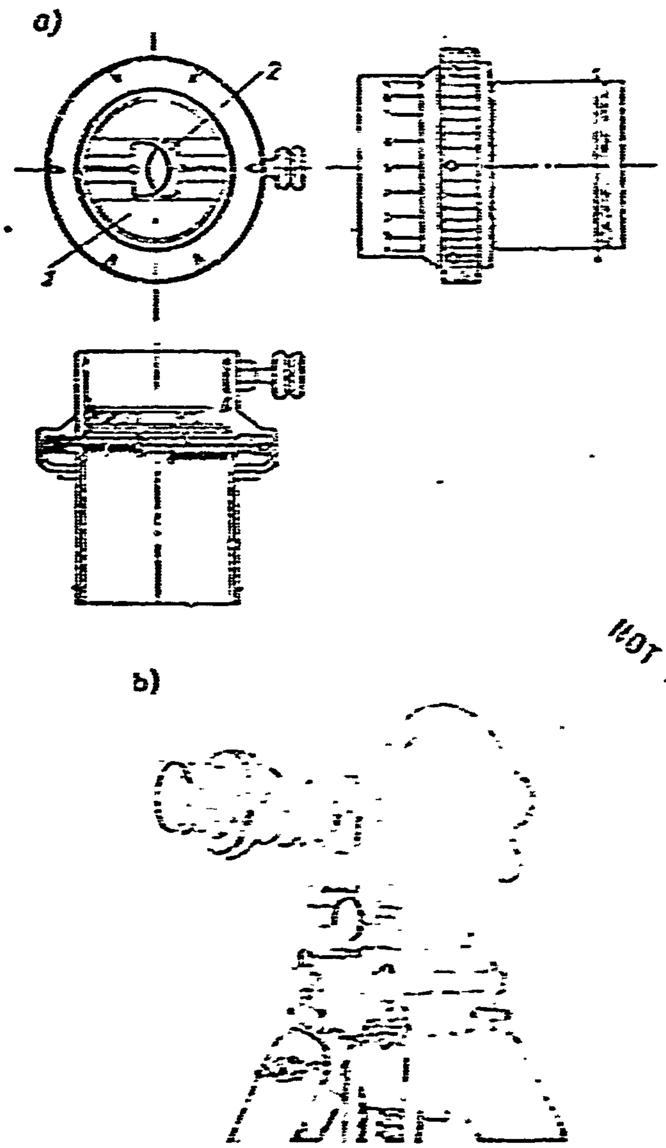


Figure 11. Optical and Photometric System (a) and General Appearance (b) of V. A. Faas' Visibility Gage
1, Optical Lens; 2, Diaphragm.

At present we have for the moment only two types of visibility gages which fully satisfy the non-adaptation requirement. These non-adaptation devices are:

1. The polarization visibility gage (PIV) with constant overall luminance of the field of vision according to the L. L. Dashkievitch system (index M-53A);

2. The visibility gage having augmenting overall luminance of the field of vision, worked out by the author of this monograph (index IDV - "Range of Vision Gage").

Both of the devices referred to are capable of solving a variety of measurement problems (see § 10) by the methods of extinction, relative luminance, and comparison.

§ 12. The Principle of Constituting a Masking Luminance in Present-Day Non-Adaptational Visibility Gages

The PIV and IDV visibility gages have a certain similarity to each other both in the principle for producing a masking luminance and in the peculiarities of photometry via extinction.

The masking luminance in these devices is produced by doubling the image observed in the field of vision and subsequent combining of the object examined and a corresponding section of the second image. For example, if a forest is being examined against a background of sky, two completely identical images are visible (at corresponding readings) in the field of vision of the visibility gage, each blended at a certain angle relative to the other.

By turning the device around its optical axis one can see how both images change position relative to each other in the field of vision, now approaching, now moving away. With a certain position of the device the forest referred to above can easily be combined with the sky background of the second image, which will in fact constitute the masking luminance for the forest. The luminance of these two divided images can change within broad limits, something which makes it possible to carry out extinction of the object observed against the selected background of the second image (in our case, the forest against the sky background). In the PIV the doubling of the image is done with the help of a Wollaston polarizing prism, out of which there emerge two light beams linearly polarized at an angle of 90° and blended relative to each other at an angle of about 1° (Figure 12, a).

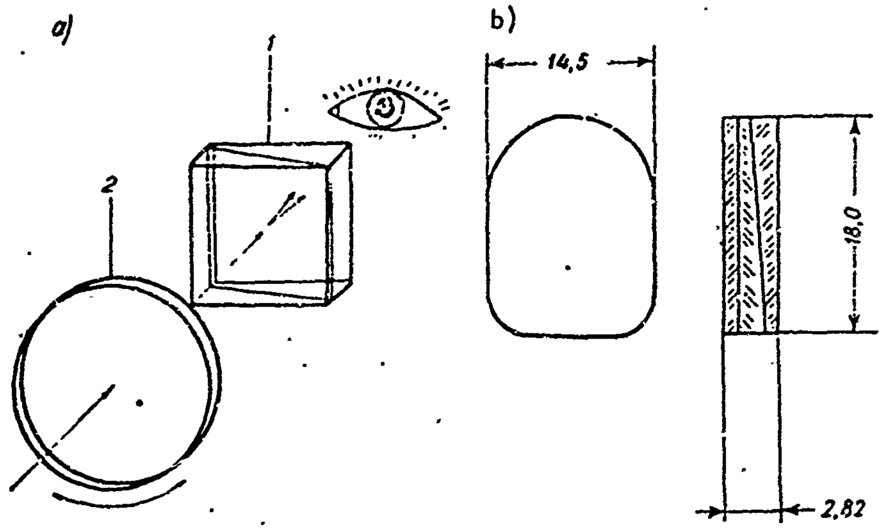


Figure 12. Optical and Photometric System, in Principle, of PIV M-53A (a) and System of Optical Achromatic Prism of the IDV (b). 1, Wollaston polarization prism; 2, Polaroid.

In the IDV doubling of the image is ensured via an optical achromatic prism having a refractive angle of 1.5° and set up ahead of the objective of a telescope of 7X magnification (Figure 12, b).

Variation of the luminance of the two blended images in the PIV is brought about by turning the polaroid, in the IDV by drawing the prism out of the plane of the entrance mount of the objective of the telescope (the plane of the entrance pupil).

A more detailed examination of the process of measurement on both devices, and conclusions as to their corresponding relationships, are given below.

Now we must speak of certain peculiarities of photometry through extinction. Its central shortcoming is the absence of control over the fixing of the moment of reading.

Independently of whether observation is being carried out according to the method of the "disappearance set-up" or according to the method of relative luminance, the observer does not know precisely when he ought to take the reading. Experience shows that the reception of threshold and even near-threshold contrasts is always accompanied by a sensation of uncertainty. The observer carrying out the measurement is at a loss to say whether he has brought the image under examination precisely to the point of disappearance or whether it is still just barely visible; or perhaps it has already long since disappeared and the photometric apparatus is "screwy." In consequence of this the spread in readings, particularly with the "disappearance set-up", may be rather considerable, and the error in measurments, particularly with inexperienced observers, may be greater than the permissible amount.

The cause for the appearance of a sensation of uncertainty during observation of near-threshold and threshold contrasts consists of the following, in our opinion.

When the object being examined in the device is brought to a near-threshold contrast and becomes barely perceptible against the given background, a hardly visible outline, a disorganization in accomodation occurs: the barely contrasting image of the object is slightly better perceived at one moment, slightly worse at another.

This sort of loss of constancy in sharpness of perception is of an individual character. This circumstance is, in our opinion, the reason why a relatively large error is inherent in measurements by the "disappearance set-up," so that broader application of this method in making measurements of all sorts is handicapped. But the error of the "disappearance set-up" can in a certain measure be reduced and the disorganization in accomodation diminished if the extinguished image is shifted slightly in position within the field of vision. This shifting is easily carried out if the visibility gage is rotated around its optical axis to one angle or another simultaneously with the process of extinguishing the object. In this case the spread in readings carried out at the same time by various observers becomes smaller and the precision of measurements increases somewhat.

The application of this method of observation in connection with the solution of certain practical problems is examined below.

We should note that measurements of relative luminance cannot be carried out, in the majority of cases, with this sort of joggling of the image.

§ 13. The Theory of the Visibility Gage Having Increasing Luminance of the Field of Vision [20, 26]

Let us look at Figure 13. Say the optical prism completely covers the objective of the glass. In this case there will be visible in the field of vision of the device only a single image of the picture being observed, displaced relative to the optical axis of the glass. This image is the basic one.

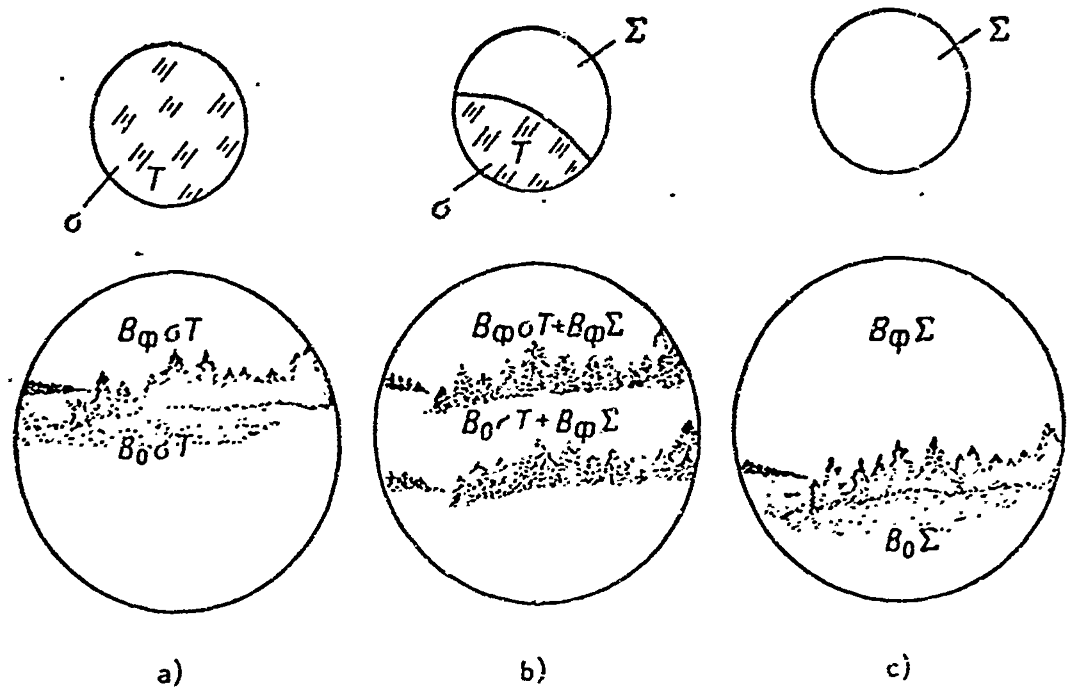


Figure 13. For Derivation of the Basic IDV Equation. What is seen in the field of vision of the IDV on making extinction measurements on the object (the "extinction set-up"): a, Start; b, Part-way; c, Final. Above: diagram of positions of optical prism (with transmission T) relative to the entrance mount of the objective of the glass.

If the prism occupies an intermediary position, i.e., is partially covering the objective of the glass, then the flows of light falling upon it are divided and one will no longer observe in the focal plane of the telescope merely a single picture, but instead two identical images of the same picture (Figure 13, b), combined in a single plane. One of them, as is obvious, is composed of rays which have passed through the optical prism and which have been bent to one side from the optical axis by it; the other image, the supplementary image, is composed of rays which have passed through the par of the objective which is not covered by the prism.

Both of these images in the field of vision of the device are displaced relative to each other by an amount which is proportionate to the refractive angle of the prism, 1.5°, and to the magnification of the glass (7X), i.e., approximately by 10° (the angular displacement in space of the objects is equal to 1.5°).

Obviously, upon gradual withdrawal of the prism beyond the limits of the frame of the objective (of the entrance pupil) the luminance of the basic, bent image will diminish, and the luminance of the second, unbent image imposed upon it will at the same time increase.

In the IDV device the prism has a transmission, T, of 0.35 to 0.40. It is made that way so that the masking luminance changes approximately three times faster than the corresponding diminution in the luminance of the blended image. Thus the extinction of the object being observed is brought about not only by virtue of reduction of its luminance, but also, and principally, by virtue of a rapid rise in the masking luminance as the prism is withdrawn.

This is what constitutes the essence of the method of increasing luminance of the field of vision as one of the ways of combatting the adaptation effect.

Let us designate the effective area of the prism as σ (Figure 13, a), and its transmission as T. The luminance B_o', observed in the field of vision, of the bent image of the object will be proportionate to its true luminance (that outside the device), B_o, multiplied by the amount of the effective area of the prism σ and the coefficient of its transmission T, i.e.,

$$B_o' = B_o \sigma T.$$

We can write analogously an equation for the luminance B_ϕ', as observed in the device, of the background of the bent image:

$$B_\phi' = B_\phi \sigma T.$$

If the prism is completely withdrawn from the limits of the entrance pupil (Figure 13, c), then there will be visible in the field of vision only the unbent image of the same object and background. The luminance, B_o'', of the unbent object will also be proportionate to its true luminance,

B_0, multiplied by the area, Σ, of the free aperture, not covered by the prism, of the objective; i.e.,

$$B_0^{\cdot} = B_0 \Sigma.$$

Analogously, we shall have for the luminance of the background of the unbent image

$$B_\Phi^{\cdot} = B_\Phi \Sigma.$$

Actually, however, at the moment of reading the prism occupies a half-way position and in the field of vision both images -- the bent one and the unbent one -- are visible simultaneously. According to the conditions of the problem, the contrast between the object and the background has to be measured. This can be done with the visibility gage if by rotating the device around its optical axis the bent image is brought to coincide with the unbent image of the background. Then upon a luminance, B_0', of the bent image of the object there is superimposed a luminance, B_ϕ'', of the unbent image of the background. In this event, taking the equations set forth above into account, we get for B_0':

$$B_0^{\cdot} = B_0 \sigma T + B_\Phi \Sigma. \quad (2.2)$$

In just the same way the luminance, B_ϕ', of the bent image of the background is combined with the superimposed luminance, B_ϕ'', of the unbent image of the background; i.e.,

$$B_\Phi^{\cdot} = B_\Phi \sigma T + B_\Phi \Sigma. \quad (2.3)$$

Now we can set up an expression for the contrast in luminance between the object and the background. For contrast in luminance we have adopted expressions (1.18) and (1.19).

For objects projected against a haze background relation (1.18) almost always holds good. § 15 shows how to proceed if the background is darker than the object.

Substituting (2.2) and (2.3) in (1.18) we secure for contrast $K(B_o, B_\phi)$ between the object and the background the following expression:

$$K=\frac{B'_\phi-B'_o}{B'_\phi}=\frac{B_\phi \sigma T+B_\phi \Sigma-B_o \sigma T-B_\phi \Sigma}{B_\phi \sigma T+B_\phi \Sigma}. \tag{2.4}$$

Further dividing the numerator and the denominator by $B_\phi \sigma T$, and taking into account the fact that the contrast observed is brought by masking luminance to a threshold value ε, we secure

$$K=\varepsilon=\frac{1-\frac{B_o}{B_\phi}}{1+\frac{\Sigma}{\sigma T}}. \tag{2.5}$$

As to its significance the numerator of the fraction is nothing other than the starting (initial) value of the contrast according to (1.18). On this account we can write, in place of (2.5),

$$\varepsilon=\frac{K}{1+\frac{\Sigma}{\sigma T}},$$

or

$$\frac{K}{\varepsilon}=1+\frac{\Sigma}{\sigma T}=V. \tag{2.6}$$

Expression (2.6) is the basic formula for the visibility gage having increasing luminance of the field of vision. Its physical meaning consists in the fact that each time an observed contrast is being brought to a threshold value, one gets not the initial value of the contrast, but the magnitude of the contrast as related to a given value for the threshold of contrast sensitivity of the eye. We can also put it this way: the value

$$V=\frac{K}{\varepsilon}$$

represents the quantity of threshold values (threshold intervals) entering into a given contrast under given circumstances of observation. From here on we shall call expression (2.6) the degree of visibility of an object, understanding by this term a certain measure of intensivity of visual receptivity of a given object, which is determined by the level of illumination, the angular dimensions of the object, etc.

The graduation of the visibility gage consists in determining the numerical values of V as functions of readings from the device.

In order to change from values of V to the magnitude of contrast K, from (2.6) we find that

$$K = \varepsilon V. \tag{2.7}$$

Hence it follows that with the help of the visibility gage the contrast of the object is defined as the product of the threshold of contrast sensitivity, ε, times the degree of visibility, V, of the object.

How is ε determined?

From (2.7) it ensues that

$$\varepsilon = \frac{K}{V} = \frac{K}{1 + \frac{\Sigma}{\varepsilon T}}. \tag{2.8}$$

If there is an object with a known contrast value, then its extinction against a given background with the help of the visibility gage gives a value ε, determined through the use of a table of graduations.

V. A. Faas proposed a very simple variant of an object having a known contrast value: a plywood square 3 × 3 cm, covered with black velvet and projected either against a sky background at the horizon or against a white screen as background. The distance from the device to the square is 5-8 meters.

The contrast K of such a square can be taken as being 1, or 100%, for example. In carrying out extinction of this test square against a background, let us say, of white paper and designating by $V_м$ its degree of visibility, we get instead of (2.8)

$$\varepsilon = \frac{1}{V_м}.$$

But practically it is more convenient to express contrasts, including threshold ones, not in digits but in percentage terms. Then we will have

$$\%=\frac{100}{V_{\text{м}}}. \quad (2.9)$$

Substituting (2.9) in (2.7) we secure an expression for luminance contrast:

$$K=\frac{V}{V_{\text{м}}}. \quad (2.10)$$

From (2.10) it is apparent that in comparison with determination of the magnitude of V for an object, finding contrast K for the same object is a more complicated problem, calling for additional measurement of the threshold of contrast sensitivity ε.

Thus, so as to determine contrast with the help of a visibility gage of one design or another, one must carry out two observational procedures:

1. Extinguish ("disappearance set-up") the observed object against the given background and in accordance with the moment of reading find from the graduation table the degree of visibility of the object, i.e., V;

2. Extinguish against a background of white screen (or of sky at the horizon) the black test square, find from the same graduation table for the given moment of reading the degree of visibility of the black square on the background indicated (V_m), and compute K according to (2.10).

It is more convenient to express the contrast which is sought in percentage terms, i.e., in place of (2.10) we should have, by taking (2.9) into account

$$K\%=\frac{V}{V_{\text{м}}}100. \quad (2.11)$$

From what has been set forth it is apparent how much simpler and more convenient it is to make use not of the concept of contrast, but of the concept of the degree of visibility of an object, which is the initial quantity of any given measurement of visibility: the V value of an object is determined by the "disappearance set-up" alone and is directly found from the graduation table. The convenience of utilizing V values, and not

.9

K values, of the object is further shown in a whole series of problems, including the problem of determining the transmissivity of the atmosphere by means of terrain objects. In Table 10 the V values and K values of objects observed under various conditions are compared with each other.

In concluding this section we shall dwell upon the question of the precision of measurements of V and K by the extinction method. Experience over many years has shown that for a trained observer the relative quadratic error $\Delta V/V$ in the carrying out of 3-5 readings upon the object being observed comes to approximately 12%, with a variation of 2-3% in one direction or the other. In other words, the error in measurement of the degree of visibility of an object is

$$\frac{\Delta V}{V} = \delta V = \pm 12\%. \tag{2.12}$$

The error in measurement of contrast of an object is determined, as we may see from (2.11), not only by means of the error δV in the measurement of the degree of visibility of the object, but also by means of the error δV_m in measurement of the degree of visibility of the black test square. These two errors are approximately the same, i.e., each of them comes to 12%.

Thus considering that $\delta V = \delta V_m \approx \pm 12\%$ we get the following expression for the relative quadratic error in measurement of the contrast of an object:

$$\delta K = \sqrt{\delta V^2 + \delta V_m^2} = 17\%. \tag{2.13}$$

§ 16. Theory of the Polarization Visibility Gage with Constant Luminance of Field of Vision

The M-53A polarization visibility gage worked out by L. L. Dashkievitch [57] has no tube, but like the IDV it is based upon the principle of doubling the observed object, with subsequent extinction thereof with the help of a masking luminance. As has been remarked above, one of the sections of the supplementary image, appearing as the polaroid is rotated from its zero position, is used as the masking luminance.

The optical and design system of the polarization visibility gage is shown in principle in Figure 14.

TABLE 10. VALUES FOR DEGREE OF VISIBILITY, V, OF OBJECTS, AND QUALITATIVE CHARACTERISTICS OF INTENSIVITY OF VISUAL PERCEPTION WHICH ACCOMPANY THEM

V	Overall character of Intensivity of Perception	Relationship to Threshold Perceptivity (roughly speaking)	Approximate Value of K (%)
1	Object is invisible (luminance of object and of background perceived as equal).	Corresponds to ε_{dis} with fixed observation	2
1.5-2	Object is barely discerned in the form of a very faint outline and only during fixed observation; during unfixed observation the object is not detected.	Corresponds closely with ε_{det} with fixed observation.	3-4
2.5-3	Very bad visibility -- during fixed observation the object is detected at once. During unfixed observation the object can fail to be detected.	Lower limit of ε_{rec} with fixed observation	5-6
4-5	Very bad visibility. The object is detected during unfixed observation with a search time of 15-20 seconds in the form of a faint silhouette.	Upper limit of ε_{rec} with unfixed observation and search time of 15-20 seconds.	8-10
5-8	Bad visibility without perception of structural details. The object is detected rapidly.	One of the gradations of ε_{rec}.	10-15
10	Satisfactory visibility. Only major details are visible; the color of natural objects is not perceived amid haze.	One of the gradations of ε_{rec}.	20
10-25	Gradations of satisfactory visibility passing into gradations of good visibility; the color of natural objects is distinctly noted at their upper limits.	Relationship outside the threshold zone.	20-50
25-35	Gradations of good visibility.	"	30-70
35-50	Gradations of good and very good visibility; at the limit of acuity of vision all details are visible. Color is fully apprehended.	"	70-100
50-100	Highest gradations of excellent visibility, achieved under exceptionally favorable circumstances.	"	100

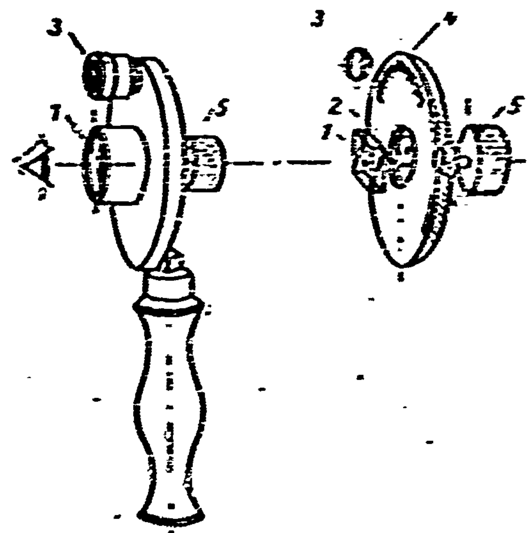


Figure 14. Optical and Design System of Polarization Visibility Gage M-53A. 1, Wollaston prism; 2, Polaroid; 3, Reading lens; 4, Glass dial; 5, Rack and pinion.

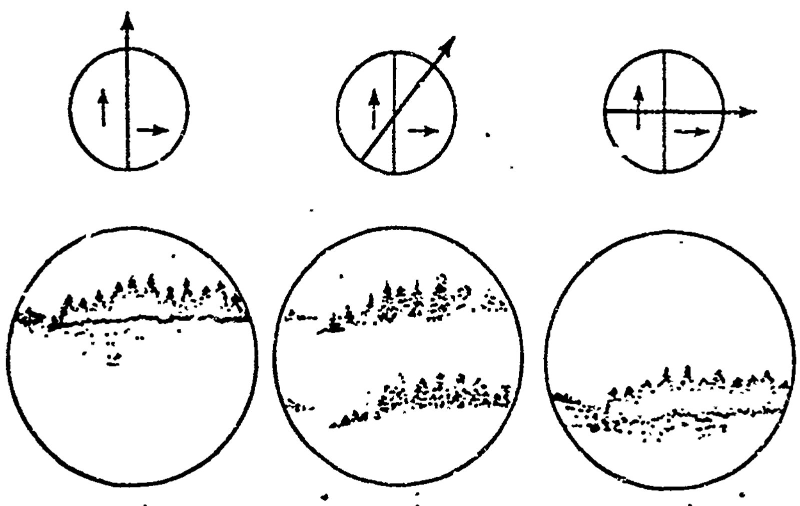
Doubling of the picture observed is brought about, as has already been indicated, by the use of a double-refractive Wollaston prism. The components of the doubled image, polarized in reciprocally perpendicular directions, can change their luminance in opposite directions through rotation of the polaroid -- i.e., if the luminance of one component weakens, the luminance of the other will strengthen, and vice versa.

This course of alteration in the luminance of both components of the image ensues from the Malus law, which reads to the effect that if a natural light of intensivity I_0 passes through two polarizing media placed one behind the other, the planes of polarization of these being turned at an angle ϕ relative to each other, then the intensivity of light I upon issuing from this system will be

$$I = I_0 \cos^2 \phi.$$

Since in the polarization visibility gage the components of the image are polarized in two directions perpendicular to each other, as the polaroid is turned to an angle ϕ the luminance of one image will change proportionately to $\cos^2 \phi$, and the luminance of the other proportionately to $\sin^2 \phi$. On this account, as the polaroid is turned from $\phi = 0°$ to $\phi = 90°$ one image will change its luminance from maximum to zero, and the other from zero to maximum.

Let us turn to Figure 15, with the help of which we can easily explain the principle of operation of the PIV M-53A device.



a) b) c)

Figure 15. For Derivation of the Basic Equation for the M-53A Visibility Gage. What is seen in the field of vision of the M-53A while making measurements via the "extinction set-up": a, Initial position; b, Half-way; c, Final. Above is a diagram of the positions of the planes of polarization of the polaroid (large arrow), relative to the polarizing components of the double-refractive Wollaston prism (small arrows).

The position shown in Figure 15, a (reading "0-0") means that in the field of vision of the PIV only one image of the object and background will be visible, one made up of rays polarized by one of the components of the Wollaston prism parallel to the plane of polarization of the polaroid. Rays polarized perpendicular to the plane of polarization of the polaroid will not pass through the system of the device, as they will be totally extinguished.

Let us consider the image examined above the first or basic one. It is obvious that upon observation in the device the luminance B_ϕ of the background and the luminance B_o of the object in this image are respectively equal, under the Malus law, to $\tau B \cos^2\phi$ and to $\tau B_o \cos^2\phi$, where τ is the coefficient of transparency of the optical system of the device (the prism and the polaroid). For an angle of $\phi = 0°$ these luminances are respectively τB_ϕ and τB_o.

Upon turning the polaroid 90°, i.e., in the second extreme position (Figure 15, c), only a single second, supplementary image of the same object and background will be visible.

The luminances B_ϕ of the background and B_o of the object in the second image are equal to $\tau B_\phi \sin^2\phi$ and $\tau B_o \sin^2\phi$, and for $\phi = 90°$ they are equal to τB_ϕ and τB_o.

In the half-way position of the polaroid, shown at Figure 15, b, both images will be visible, combined at a certain angle relative to each other. In this connection the luminance of the second image will be superimposed upon the luminance of the first image, as a result of which an adding together of luminances will occur. Then in the field of vision of the polarization visibility gage we shall have the following values for the luminances for the basic image:

$$\left.\begin{aligned} &\text{luminance of background:} \quad B'_\phi = \tau B_\phi \cos^2\varphi + \tau B_\phi \sin^2\varphi \\ &\text{luminance of object:} \quad B'_o = \tau B_o \cos^2\varphi + \tau B_\phi \sin^2\varphi \end{aligned}\right\} \qquad (2.14)$$

Substitution of these expressions in the relation (1.18) gives the value of the contrast in luminance between the object and the background observed in the field of vision of the device:

$$K(B_\phi, B_o) = \frac{B'_\phi - B'_o}{B'_\phi} = \frac{\tau B_\phi \cos^2\varphi + \tau B_\phi \sin^2\varphi - \tau B_o \cos^2\varphi - \tau B_\phi \sin^2\varphi}{\tau B_\phi \cos^2\varphi + \tau B_\phi \sin^2\varphi}.$$

Dividing the numerator and the denominator by $\tau B_\phi \cos^2\phi$ and taking into account the fact that the contrast observed is brought to a threshold value, after elementary transformations we secure

$$K(B_\phi, B_o) = \frac{1 - \frac{B_o}{B_\phi}}{1 + \operatorname{tg}^2\varphi} = \frac{1 - \frac{B_o}{B_\phi}}{\frac{1}{\cos^2\varphi}} = \varepsilon. \qquad (2.15)$$

The difference standing in the numerator is nothing other than the real value of the contrast K between the object and the background.

Then (2.15) assumes the form

$$\varepsilon = K\cos^2\varphi,$$

or

$$\frac{K}{\varepsilon} = V = \frac{1}{\cos^2\varphi}. \tag{2.16}$$

Expression (2.16) is the basic formula for the polarization visibility gage, and $1/\cos^2\phi$ is its fundamental instrumental parameter.

The last circumstance is an advantageous one, since it greatly simplifies the process of graduating this device.

If one prefers to measure with a polarization visibility gage the contrast, rather than the degree of visibility V, of the object, then from (2.16) it is easy to derive an expression for contrast, namely

$$K = \frac{\varepsilon}{\cos^2\varphi}.$$

From this it is evident that just as for the IDV, it is necessary to carry out two successive operations:

1. Determine ε, after having extinguished the black test square (K = 1) against the white screen or sky-at-horizon background;

2. Distinguish the object (process of observation is precisely the same as with the IDV). Then upon extinction of the black square we get

$$\left.\begin{array}{c}\varepsilon = 1\cos^2\varphi_{м}, \text{ or } \quad \varepsilon\% = 100\cos^2\varphi_{м}\\ K = \dfrac{\cos^2\varphi_{м}}{\cos^2\varphi}\end{array}\right\} \tag{2.17}$$

in which connection $\phi_m > \phi$.

The relative quadratic errors of measurement of contrast and of the degree of visibility of the object in the polarization device are approximately the same as in the IDV, i.e., for the polarization visibility gage one can consider that $\delta K \approx 17\%$, $\delta V = 12\%$.

§ 15. Derivation of Relationships for the Case Where the Masking Luminance Is Less Than the Luminance of the Object

The principle for measurement of the K or V of objects with the help of visibility gages, set forth in the preceding sections, has contemplated the use of the contrast relationship (1.18), according to which the background used as a masking luminance has always to be brighter than the object.

As E. A. Polyakova has pointed out, if the background is darker than the object, in making use of (1.18) one cannot use such a background as a masking luminance because readings and consequently the values of V and K for objects, will be excessively high. This observation has the character of a principle as regards measurements by the extinction method. It could be avoided by using expression (1.19) in place of (1.18) in cases where the background is darker than the object, and by reconstructing the process of observation so that the object should be utilized as the masking luminance, the extinction against it of the background with which it is combined then being carried out.

In cases where the objects and the backgrounds are of sufficiently great angular dimensions such as alteration of the process of measurement does not give rise to any complications. But if the lighter objects are small in angular dimensions, then the reconstruction of the measurement process referred to above cannot be carried out.

But one can carry out a certain corrective adjustment that makes it possible to secure a correct result while preserving the uniformity of the measurement process, in which adjustment the background is always taken as the masking luminance no matter whether it is lighter or darker than the object.

This corrective adjustment can easily be carried out on the basis of the following reasoning, which applies equally to the IDV device and to the PIB M-53A.

The luminance B_o' of an object observed through the eyepiece of the IDV and combined with the image of a darker background is equal, in accordance with considerations adduced earlier, to

$$B_o' = B_o \sigma T + B_\phi \Sigma. \qquad (2.18')$$

The luminance B_ϕ' of the background in this case is

$$B_\phi' = B_\phi \sigma T + B_\phi \Sigma. \qquad (2.18'')$$

According to (1.19) we should write, taking into account the fact that $B_o' > B_\phi'$,

$$K = \frac{B_o' - B_\phi'}{B_o'} = 1 - \frac{B_\phi'}{B_o'}. \qquad (2.19)$$

Substituting in (2.19) the values B_o' and B_ϕ' from (2.18') and (2.18") and taking into account the fact that through the imposition of haze the observed contrast is brought to the threshold value ε, we secure

$$K_{opt} = \varepsilon = \frac{B_o \sigma T - B_\phi \sigma T}{B_o \sigma T + B_\phi \Sigma}.$$

Hence, dividing the numerator and the denominator by $B_o \sigma T$ and taking into account the fact that $1 - B_\phi/B_o = K$, we shall have

$$\varepsilon = \frac{K}{1 + \frac{B_\phi}{B_o} \frac{\Sigma}{\sigma T}}, \qquad (2.20)$$

in which K designates the given, actually observed contrast of the object.

From (2.20) we find that

$$\frac{B_\phi}{B_o} = \frac{\frac{K}{\varepsilon} - 1}{\frac{\Sigma}{\sigma T}}. \qquad (2.21)$$

But on the other hand, in accordance with the condition of (2.19), we can write

$$\frac{B_\Phi}{B_0} = 1 - K, \tag{2.22}$$

which upon substitution of (2.22) into (2.21) gives

$$1 - K = \frac{K - \varepsilon}{\varepsilon \frac{\Sigma}{\sigma T}}.$$

Hence it follows that

$$\varepsilon \frac{\Sigma}{\sigma T} - K\varepsilon \frac{\Sigma}{\sigma T} = K - \varepsilon,$$

or

$$\varepsilon\left(1 + \frac{\Sigma}{\sigma T}\right) = K\left(1 + \varepsilon \frac{\Sigma}{\sigma T}\right).$$

Recalling that

$$1 + \frac{\Sigma}{\sigma T} = V,$$

we secure finally

$$\frac{K}{\varepsilon} = \frac{V}{1 + \varepsilon(V - 1)} = V^{\bullet}. \tag{2.23}$$

Thus for the degree of visibility of an object under observation with the IDV device we have:

a) if the background is lighter than the object, then in accordance with (2.6)

$$\frac{K}{\varepsilon} = V;$$

b) if the background is darker than the object and this background serves as the masking luminance, then in accordance with (2.23)

$$\frac{K}{\varepsilon} = V^{\bullet}.$$

The value of V, which appears in both relations, is determined from the graduation table for the moment of loss of visibility of the object against the given background. But if the background is darker than the object the value of V will be too high. Still, the corrective multiplier appearing in the denominator of (2.23) eliminates this excess. In order to substitute ε into (2.23) one must extinguish the black square against the white-screen or sky-at-horizon background, but under the same conditions of illumination as the observation of the object was carried out under. Then instead of (2.23) we shall secure (recalling that $\varepsilon = 1/V_m$),

$$V^* = \frac{V}{1 + \frac{V-1}{V_m}}. \qquad (2.24)$$

If the value of V is high (not less than 15, to which a K of about 30% corresponds), then, disregarding an error of some percentage points, we can put V - 1 as more or less equal to V. Then instead of (2.24) we get

$$V^* \approx \frac{V}{1 + \frac{V}{V_m}}. \qquad (2.25)$$

And finally, if the level of illumination is high enough and if the value of V_m can be taken as approximately equal to 50, then we secure in conclusion

$$V^* \approx \frac{V}{1 + 0{,}02V}. \qquad (2.26)$$

If the value of V is low (not more than 15), one cannot use the simplification V - 1 = V, and V* must be determined via the exact formula (2.24).

If one is to shift from V* to contrast, then from (2.24) we secure, assuming that $V^* = K^*/\varepsilon$,

$$K^* = \frac{\varepsilon V}{1 - \frac{V-1}{V_m}}. \qquad (2.27)$$

For the approximate expression (2.26), assuming that ε = 2%, we have

$$K^* \approx \frac{V \cdot 2}{1 + 0{,}02V}. \qquad (2.28)$$

If K is to be determined in figures (decimal fractions), then (2.27) and (2.28) are to be multiplied by 1/100.

Such are the values of the degree of visibility and the contrast of an object as found with the help of the IDV device when the background (the masking luminance) is darker than the object.

Now let us derive an expression for V* applicable to the polarization visibility gage.

Substituting (2.14) into (2.19), we secure

$$K=\frac{\tau B_0\cos^2\varphi+\tau B_\phi\sin^2\varphi-\tau B_\phi\cos^2\varphi-\tau B_\phi\sin^2\varphi}{\tau B_0\cos^2\varphi+\tau B_\phi\sin^2\varphi}.$$

Dividing the numerator and the denominator by $\tau B_0\cos^2\phi$ and recalling that in accordance with (2.19) $1 - B_\phi/B_0 = K$, we secure, upon bringing the contrast observed to threshold value,

$$\varepsilon=\frac{K}{1+\frac{B_\phi}{B_0}\mathrm{tg}^2\varphi}=\frac{K}{1+(1-K)\,\mathrm{tg}^2\varphi}.$$

Hence, after simple transformations

$$K(1+\varepsilon\,\mathrm{tg}^2\varphi)=\varepsilon(1+\mathrm{tg}^2\varphi),$$

or

$$\frac{K}{\varepsilon}=\frac{1+\mathrm{tg}^2\varphi}{1+\varepsilon\,\mathrm{tg}^2\varphi}=V^*. \qquad (2.29)$$

Multiplying the numerator and the denominator of (2.29) by $\cos^2\phi$, we at length secure

$$V^*=\frac{1}{\cos^2\varphi+\varepsilon\sin^2\varphi}. \qquad (2.30)$$

And finally, analogously to (2.26)

$$V^*=\frac{1}{\cos^2\varphi+0{,}02\sin^2\varphi}. \qquad (2.31)$$

Such are the values of the degree of visibility of an object as determined with the polarization device when the background (the masking luminance) is darker than the object.

To shift from V* to contrasts, one proceeds just as in deriving the expressions (2.27) and (2.28).

In conclusion let us point out that the polarization device is to be used with care in determining V or K of surface objects, since the objects themselves and the backgrounds surrounding them contain, in a majority of cases, a considerable polarization component, failure to take which into consideration leads to considerable augmentation of the error of the measurements.

CHAPTER III

THE RELATIVE LUMINANCE METHOD

§ 16. The Essence and Theory of the Relative Luminance Method

Until quite recently visibility gages, as multiple-purpose devices, were used only in the variant providing photometry through extinction, which we call the "object disappearance set-up." As has been pointed out earlier, a relatively high error is inherent in such a measurement process, something which is in our opinion responsible for the scanty extent to which visibility gages have become part of the process of visual photometry.

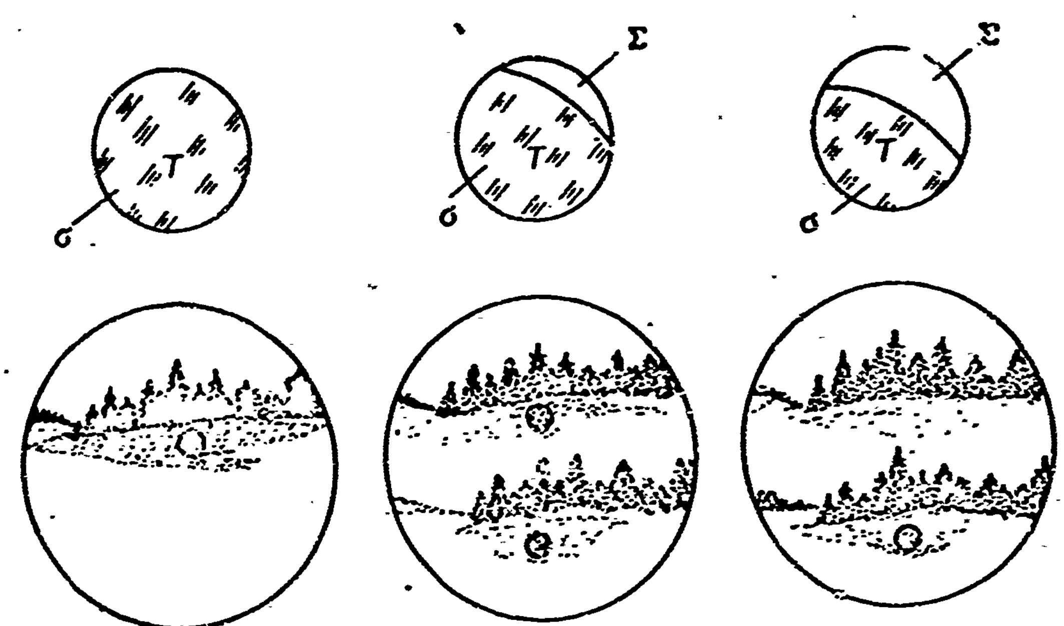
The author of the present monograph has developed a more refined method for extinction photometry, which is approximately one order better, as regards precision of measurement, than the "object disappearance set-up" and which, when applied to the majority of problems to be solved, approaches the accuracy achieved by the "equality set-up" and even exceeds it. For example, over the range of contrasts 70-100% of the relative errors in measurement by the new method (called the method of relative luminance) amount to unit percentages, and even to tenths of one percent [29, 30]. This circumstance will be able to contribute to a more widespread use of the extinction method in visual photometry, particularly in terrain photometry, than has been the case to date.

Observations by the relative luminance method consist in the fact that through the use of a masking luminance (i.e., an unbent image of the background) one extinguishes against a given background not the object, but instead a variable black mark located in the field of vision of the device against the background of the object being observed. In accordance with the moment of extinction of the mark projected against the object one determines the degree of visibility of the object or the contrast between the object and the background. This process of measurement can easily be carried out for a majority of the problems posed in § 10, with the exception of the cases where the objects are of small angular dimensions.

In order that the visibility gage shall operate by the method of relative luminance, its optical and photometric system must be revised in such fashion that an image of a black mark which changes its degree of blackness when the masking luminance is superimposed shall be located in the field of vision. The IDV device referred to above, which is described in § 20, is such a visibility gage.

We shall set forth the theory of the method, first as applicable to the IDV.

Let us imagine that in the field of vision of a visibility gage there is an image of an absolutely black mark in the form of a small disc, which is projected (combined) upon the image of an object having a luminance B_0 (Figure 16, a).



a) b) c)

Figure 16. Re the Theory of Observations According to the Relative Luminance Method.
What is seen in the field of vision of the device: a, Initial position (the mark is projected against the object); b, Halfway; c, Final (the mark is extinguished against the object). Above diagram of the positions of the optical lens of the IDV device relative to the entrance pupil of the objective of the glass.

When the optical prism of the IOV completely covers the entrance pupil (the objective mount of the glass), i.e., when there is no masking haze in the field of vision of the device (Figure 16, a), the luminance B_m' of the mark and B_o' of the object, observed in the device, will be equal.

$B_m' = 0$, since by definition the mark must be absolutely black;

$B_o' = B_o \sigma T$, where σ is the area of the entrance pupil covered by the prism, and T is the transmission of the prism.

With the help of the optical system of the visibility gage, a masking luminance is imposed upon this image of the mark and of the object by withdrawing the optical prism beyond the edges of the entrance pupil of the objective. Then in harmony with the above-described optical system of the visibility gage, a second image of the same object with its mark and of the background surrounding it appears. No attention need be paid to this newly appearing image. But one of the sections of the background of this image can be combined with the first image which is under observation, and this will be the luminance of the masking haze (Figure 16, b). The value of the latter is proportionate to the luminance B_ϕ of the background and to the area Σ of the free aperture of the objective not occupied by the optical prism.

In this way the luminance of the masking haze, equal to $B_\phi \Sigma$, is imposed upon the luminances, examined above, of the first image, and now, with the prism partially withdrawn, the luminances seen in the field of vision will be equal:

$$\left.\begin{aligned} B_m'' &= B_\phi \Sigma \\ B_o'' &= B_o \sigma T + B_\phi \Sigma \end{aligned}\right\} \qquad (3.1)$$

The luminance of superposition, $B_\phi \Sigma$, is increased until the contrast between the mark and the object, as it diminishes, reaches the threshold value ε and the mark ceases to be perceived by the eye (Figure 16, c). This moment is the one at which the reading is taken.

Applying the relation for contrast in the form of (1.18) it is easy to set up, on the basis of (3.1), an expression for contrast $K(B_o, B_m)$ between the object and the mark, brought to threshold receptivity:

$$K(B_o, B_м) = \frac{B'_o - B'_м}{B'_o} = \frac{B_o \sigma T + B_\phi \Sigma - B_\phi \Sigma}{B_o \sigma T + B_\phi \Sigma} =$$

$$= \frac{1}{1 + \frac{B_\phi}{B_0} \frac{\Sigma}{\sigma T}} = \varepsilon. \tag{3.2}$$

In the last analysis what we are interested in is the contrast between the object and the background, and not that between the mark and the object.

The presence in the denominator of (3.2) of the ratio between luminance B_ϕ/B_0 makes it possible to find the contrast that interests us. By analogy with (1.18) we can set up an expression for the luminance contrast between the object B_0 and the background B_ϕ, assuming that $B_\phi > B_0$:

$$K(B_o, B_\phi) = \frac{B_\phi - B_o}{B_\phi} = 1 - \frac{B_o}{B_\phi}; \tag{3.3}$$

Determining from (3.2)

$$\frac{B_\phi}{B_0} = \frac{\frac{1}{\varepsilon} - 1}{\frac{\Sigma}{\sigma T}} \tag{3.4}$$

and substituting (3.4) into (3.3), we shall find the contrast between object and background that we are seeking:

$$K(B_o, B_\phi) = 1 - \frac{\frac{\Sigma}{\sigma T}}{\frac{1}{\varepsilon} - 1}. \tag{3.5}$$

Since from (2.6)

$$\frac{\Sigma}{\sigma T} = V - 1 = V';$$

and

$$\varepsilon=\frac{1}{V_{м}},$$

instead of (3.5) we can write

$$K(B_0,\ B_\Phi)=1-\frac{V-1}{V_м-1}=1-\frac{V'}{V'_м}=1-\varepsilon'V', \tag{3.6}$$

where V' = V - 1, a figure determined from the graduation table in accord-
ance with the moment of extinction of the mark in the device against the object; $V_m' = V_m - 1$ is the same in accordance with the moment of extinction of the mark against the background of sky or a white screen.

Expression (3.5) or (3.6) is the theoretical [illegible] of the relative luminance method.

From the physical meaning of the expressions secured above it ensues that upon extinguishing the mark against the background of the object we secure as a result the contrast between the object and the background which is serving as a masking luminance. For example, if one selects as an object of observation a house, projected (let us say) against a background of forest, and if a section of sky at the horizon serves as a masking luminance, then extinction of the mark against the background of the house gives the contrast between the house and the sky at the horizon. Under the relative luminance method one always gets the contrast between the object and whatever background may be utilized as a masking luminance, within the limits of the angular splitting of images in the field of vision of the IDV.

This real background against which the object is actually projected does not obstruct determination of contrast between the object and the background sought, which may even be located to one side of the object. To anticipate a little, we may point out that this feature is what constitutes the advantage of the relative luminance method over other methods in determining the transmissivity of the atmosphere via terrain objects: the objects of observation can be projected against any real background below the horizon line.

Let us point out the meaning of the distinction between the relative luminance method and object extinction observation as a whole.

In the latter case the contrast $K(B_o, B_\phi)$ between the object and the background is determined, as we are aware, via the relationship

$$K(B_o, B_\phi) = \frac{V}{V_m} = V, \tag{3.7}$$

in which connection the values of V and V_m are determined directly by means of the visibility gage.

With the relative luminance method the quantity measured directly is the contrast, $K(B_o, B_m)$, between the mark and the object, determined in accordance with (3.2), on the basis of which in harmony with (3.6) we compute the contrast $K(B_o, B_\phi)$ between the object and the background which we are seeking.

Thus the distinction between (3.7) and (3.6) consists in the fact that in (3.7) the ratio between the directly measured quantities V and V_m at once gives the value of the contrast sought, while in (3.6) the ratio between the directly measured quantities V' and V_m' has to be subtracted from unity.

The latter circumstance substantially alters the precision of contrast measurements.

§ 17. The Accuracy of Measurements by the Relative Luminance Method

Let us write (3.6) in the form

$$K = \frac{V_m' - V'}{V_m'}. \tag{3.8}$$

Dividing the numerator and the denominator by V' and taking $V_m'/V' = n$, instead of (3.8) we get

$$K = \frac{n-1}{n}. \tag{3.9}$$

Thus the relative luminance contrast can be presented in the form of a function of values of n, these being positive figures, since V_m' is always greater than V'.

After completing logging and differentiation of (3.9), we secure, after obvious transformations

$$\frac{dK}{K} = \frac{dn}{n} \frac{1}{n-1}. \qquad (3.10)$$

But since

$$n = \frac{V_м'}{V'},$$

then

$$\frac{dn}{n} = \frac{dV_м'}{V_м'} - \frac{dV'}{V'}. \qquad (3.11)$$

Substituting (3.11) into (3.10) and shifting to final increments and relative errors $\delta V_m' = \Delta V_m'/V_m'$ and $\delta V' = \Delta V'/V'$, we secure for the quadratic error

$$\delta K = \frac{\sqrt{\delta V_м'^2 + \delta V'^2}}{n-1}. \qquad (3.12)$$

The terms beneath the radical sign are respectively the error of light measurement upon extinction of the black mark against a sky (or white-screen) background or the lighter component of the contrast, and then the error upon extinction of the mark against the background of the object.

Experience shows that for the trained eye the errors of light measurement during observation of the mark against a sky background and of the mark against the background of the object are approximately the same and that, as was shown in § 13, they come to about 12%. Then for the relative quadratic error of measurement of contrast by the relative luminance method we secure in conclusion, in place of (3.12), the following expression:

$$\delta K = \frac{\sqrt{12^2 + 12^2}}{n-1} = \frac{17}{n-1} \%. \qquad (3.13)$$

If (3.13) is compared with (2.13), it is at once apparent that the error in measurement of contrast by relative luminance is $1/(n - 1)$ times less than the error by the "object disappearance set-up."

One can easily determine the numerical values of δK if one finds the values of n depending on the magnitudes of contrasts.

The concrete value of n is easily determined from (3.9): $n = 1/(1 - K)$, upon substitution of arbitrary values of K (in fractions).

The path of values of K according to (3.9) as a function of n-figures, and the magnitude of theoretical errors δK according to (3.13), are set forth in Table 11 and in Figure 17.

TABLE 11. ACCURACY OF THE RELATIVE LUMINANCE METHOD. VALUES OF K AND OF THEORETICAL ERRORS δK AS A FUNCTION OF n-FIGURES

n	K %	δK %	n	K %	δK %
1,00	0	∞	10	90,0	1,9
1,02	2,0	750	11	90,9	1,7
1,03	3,1	570	12	91,7	1,6
1,05	5,0	340	13	92,3	1,4
1,3	23,0	57	14	92,9	1,3
1,5	33,0	34	15	93,3	1,2
2,0	50,0	17	16	93,8	1,1
2,5	60,0	11	20—23	95,0	0,8
3,0	67,0	8,5	24	95,8	0,7
3,5	71,0	6,5	25—30	96,5	0,6
4	75,0	5,7	35	97,0	0,5
5	80,0	4,2	40	97,5	0,44
6	83,0	3,4	50	98,0	0,34
7	85,8	2,8	100 и >100	99,0	0,17
8	87,5	2,4	∞	100	0,00
9	88,9	2,1			

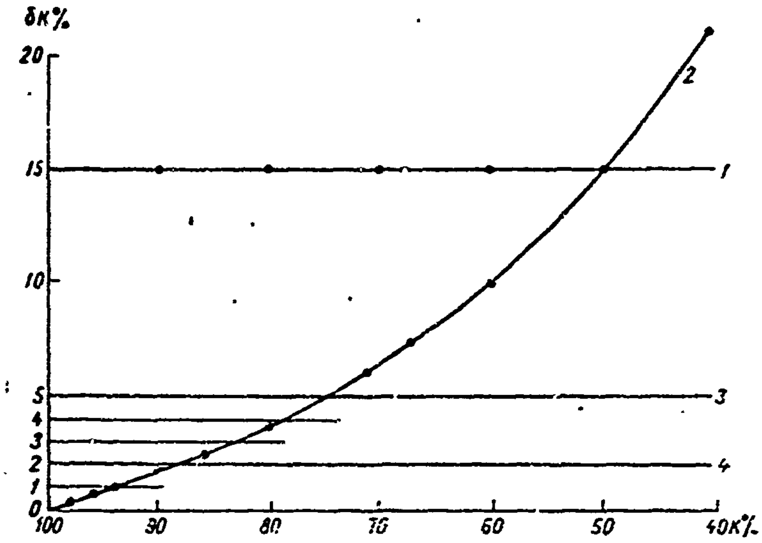


Figure 17. Relative Errors of Measured Contrasts. 1, By extinction of outline of object, or "disappearance set-up;" 2, By relative luminance method; 3, By photometric comparison method, or "equality set-up" when there is a gap between the fields compared; 4, by the moment of disappearance of the dividing line between two fields being compared.

The data in Table 11 and the nomogram in Figure 17 clearly illustrate the unusual path taken by errors when measurements are made by the relative luminance method.

Errors are very great when faint contrasts are measured, and they diminish rapidly as strong contrasts are approached (high degrees of visibility). The greater the contrast or the degree of visibility of the object, the less is the error in measuring it. Over the range of contrasts from 95 to 99% the error, δK, comes to tenths of one percent, which considerably exceeds the accuracy of measurements by the "equality set-up" using monochromatic fields of comparison. In the range of contrasts from 95 to 80% errors come to 1-3%, which still remains back of the accuracy of the "equality set-up" or is comparable with it.

But from the K = 50% value theoretical errors commence to mount rapidly: with K = 0, or more precisely with $K = \varepsilon$, the relative errors come to hundreds of percentage points, passing at the limit (with K = 0) into infinity.

Let us bring to light the physical meaning of the very great theoretical errors of the relative luminance method, and let us demonstrate whether they can make their appearance during practical measurements.

Referring back to § 4 (in the first Chapter), we at once note that contrasts amounting to 2, 3, and even 5% are threshold contrasts, the first two contrasts being perceived only under circumstances of fixed observation. Furthermore, contrasts of 5% and even 7% are still so small that under circumstances of non-fixed observation they are not detected at once and may not be detected even after a 15-second search (cf. Tables 7 and 10).

All these threshold contrasts, and also the near-threshold ones with an upper limit of 10-12%, cannot be sufficiently precisely evaluated in practice without the use of instruments, and on that account they can be left out of consideration.

The greatest errors in measurements of contrasts lie within the range of $20\% < K < 50\%$ with errors δK from 17 to 60%. This is what constitutes the upper limit of the practical error of measurement of contrasts by the relative luminance method.

Thus in practice contrasts of not less than 50% are advantageously measured by the relative luminance method. In the field of greater contrasts δK percentage values rapidly fall off, and in the field of less values (up to 20%) they rapidly mount.

A contrast equal to 50% is the boundary to one side of which the relative luminance method produces a substantial gain in accuracy of measurement; and on the other side of which it offers no advantages as compared with the "object disappearance set-up."

Yet, as one may easily guess, one can by making use of very simple means ensure approximately smooth measurements over the whole range of contrasts from 0 to 100%. To this end it suffices to have in the field of vision, in addition to the black mark, a further two or three light marks having known transmission. When measuring a less pronounced contrast one should extinguish against the object not the black mark, but a correspondingly lighter one.

Thus in making measurements by the relative luminance method one may expect the appearance of errors within the following limits:

Range of Contrast Values (%)	Limits of Quadratic Errors in Measurement of Contrasts, δK, by Relative Luminance (%)
99-94	0.2-0.9
93-85	1-3
80-75	3-5
70-60	6-10
50-40	Error in relative luminance measurements is equal to error of measurements by extinction of object in general, i.e., it comes to about 20%.
40-20	Error of measurements comes to some tens of percentage points. Measurements by relative luminance disadvantageous.
10-2	Objects very faintly visible or not visible at all. No sense in making measurements.

One should emphasize that the indicated accuracy of measurements is retained during the observation of objects of any color. This circumstance opens up possibilities, still very little studied, for the application of the relative luminance method in the solution of certain phototechnical, geophotometric, and psychophysiological problems. In particular, in making light measurements on colored objects it is possible, through a simple procedure and with sufficiently high accuracy, to investigate their luminance contrast, to separate the character of the outlines of an object from its purely luminance- or color-associated characteristics, and the like. By other methods this can be accomplished only by overcoming considerable experimental difficulties.

§ 18. The Relative Luminance Method in Its Application to the Polarization Visibility Gage

The M-53A polarization visibility gage does not have a telescope system, for which reason one cannot set up the variable black mark in the device itself.

So as to be able to carry out measurements by the relative luminance method with this device, one must make use of a removable black mark in the form of a black spot that is set up against the background of the object.

Let us set out the theory of the relative luminance method as it applies to the polarization visibility gage.

Let us imagine (cf. Figure 16) that we are observing through the polarization visibility gage some object against the background of which a removable black spot is projected. A masking luminance is superimposed upon the picture being observed.

At the "0" reading, when the imposed luminance is absent, the luminances observed in the device are equal to the following (cf. § 14):

The luminance of the black spot:

$$B'_м = B_м \tau \cos^2 \varphi = 0;$$

The luminance of the object:

$$B'_o = B_o \tau \cos^2 \varphi.$$

At high readings (more than 50%) there is visible in the field of vision of the polarization visibility gage a second, identical image of the object and of the background surrounding it, but bent at an angle to the first. We need this supplementary image in order to superimpose the masking luminance upon the object being examined and the spot projected upon it. To this end, just as in measurements on the IDV, through appropriate orientation of the polarization device we combine the picture being looked at with the background of the bent supplementary image. The luminance of the background of this supplementary image will be equal, in accordance with the theory of the polarization device, to $B_\phi \tau \sin^2 \phi$. This luminance is added to the luminance of the object and spot being examined, and their total luminances for any intermediary reading will be equal to the following:

The luminance of the removable spot

$$B'_м = B_\varphi \tau \sin^2 \varphi;$$

The luminance of the object

$$B'_o = B_o \tau \cos^2 \varphi + B_\varphi \tau \sin^2 \varphi.$$

Substituting B_m' and B_o' in relation (1.18), and considering that $B_o' > B_m'$, we secure for the moment of extinction of the mark against the background of the object

$$K(B_o, B_м) = \frac{B_o \tau \cos^2 \varphi + B_\varphi \tau \sin^2 \varphi - B_\varphi \tau \sin^2 \varphi}{B_o \tau \cos^2 \varphi + B_\varphi \tau \sin^2 \varphi} = \varepsilon.$$

After elementary transformations we have

$$\varepsilon = \frac{1}{1 + \frac{B_\phi}{B_o}\tan^2\varphi},$$

or

$$\frac{1}{\varepsilon} = 1 + \frac{B_\phi}{B_o}\tan^2\varphi,$$

whence

$$\frac{B_\phi}{B_o} = \frac{\frac{1}{\varepsilon} - 1}{\tan^2\varphi} = n.$$

Since the contrast between an object with luminance B_o and a background with luminance B_ϕ, with $B_\phi > B_o$, is equal to

$$K(B_o, B_\phi) = 1 - \frac{B_o}{B_\phi} = 1 - \frac{1}{n},$$

we secure

$$K(B_o, B_\phi) = 1 - \frac{\tan^2\varphi}{\frac{1}{\varepsilon} - 1}. \tag{3.14}$$

Substitution of this expression into (3.14) at length produces, after simple transformations,

$$K(B_o, B_\phi) = 1 - \frac{\tan^2\varphi}{\tan^2\varphi_m}, \tag{3.15}$$

where ϕ is the angle at which the polaroid is turned when the removable spot disappears against the background of the object; ϕ_m is the same upon the extinction of the removable spot against a white-screen (or sky-at-horizon) background.

This is what represents the value of the contrast of an object when it is measured with the polarization device by the relative luminance method.

The accuracy of measurements by the relative luminance method for the polarization device is approximately the same as for the IDV device. At the same time, the course of alterations in the basic instrumental parameter V in the two devices diverges considerably, as is clearly apparent from Figure 20. The consequences of this divergence are examined in § 20.

§ 19. Intensivity of Perception (Degree of Visibility of an Object) by Relative Luminance

As was pointed out in the first Chapter, the shortcomings of the concept "luminance contrast" keep one from regarding it as a universal yardstick for the intensivity of visual perception; a more acceptable concept is that of "the degree of visibility of an object," which is directly determined by visibility gages.

Inasmuch as the relative luminance method has an error approximately one order less than the error of measurements on extinction of an object in general, it is of interest to secure an analytical expression for the degree of visibility of an object by relative luminance.

Let us once more write down expression (3.9) for contrast by relative luminance:

$$K = \frac{n-1}{n},$$

where

$$n = \frac{V_m'}{V'}.$$

Here V_m' is the degree of visibility of the mark of the device against a given background, which is equivalent to the degree of visibility of a black screen against the same background; V' is the degree of visibility of the mark against the background of the object, which is equivalent to the degree of visibility of the black screen against the background of the object. The quantities V_m' and V' are determined from the graduation table for the moment of the respective extinctions (losses of visibility) of the mark, in which connection $V_m' > V'$.

In order to simplify our further reasoning let us suppose that the background is brighter than the object.

If the degree of visibility V of the object against the given background is written in the form $V = K/\varepsilon$, then in place of (3.9) we shall have

$$V = \frac{1}{\varepsilon}\left(1 - \frac{1}{n}\right).$$

Replacing $1/\varepsilon$ by V_m, and n by the relation written down above, we secure

$$V = V_m\left(1 - \frac{V'}{V_m'}\right).$$

or finally

$$V = V_m - V'\frac{V_m}{V_m'}. \tag{3.16}$$

where V_m is determined in accordance with the moment of extinction of the mark against the background of sky at the horizon (in field investigations) or against the background of a white screen (in laboratory tests). If V_m is more or less equal to V_m', then

$$V = V_m - V'. \tag{3.17}$$

If the luminance of the object and the background, and also the level of illumination, are more or less stable, then the values V_m and V' can be determined with heightened accuracy as means from an extended series of measurements.

Then (3.16) can be written as follows:

$$V = V_{mean} - cV_{mean}', \tag{3.18}$$

where c is a constant equal to $(V_m/V_m')_{mean}$ and determined in advance.

These are the expressions which describe the intensivity of visual perception (the degree of visibility of an object) by relative luminance.

One might get the impression that determining the degree of visibility V of an object by relative luminance is more complicated than by extinction of the object in general, where only one measurement procedure is required. But in actuality one must keep the following in mind:

1. Direct extinction of an object against a given real background, when the panorama observed in the field of vision is as a rule distinguished by an extremely variegated character, is a more complicated character than extinction of a mark against the object and the background;

2. The value V of an object is distinguished by relative luminance approximately by one order more accurately than by extinction of the object in general;

3. The relative luminance V value of an object can be determined not only relative to the background directly adjoining the outline of the object, but also relative to any other surface distant from the object by the amount of the angular splitting of the images in the field of vision of the device. But the value of V by extinction of the object in general can be determined only relative to the background upon which the object is directly projected.

Thanks to the circumstances examined above, the relative luminance method can find widespread application in phototechnology, meteorology (geophotometry), in physiological optics, and in other scientific fields during the solution of various applied and research problems.

§ 20. Description of an Adaptation-Less Visibility Gage Based on the Relative Luminance Method

The working out of the relative luminance method and the possibility of its widespread application in terrain optics, meteorology, phototechnology, and other fields bring up the problem of modernizing in principle the optical and photometric system of the visibility gage to adapt it to the requirements of the method in question.

An adaptation-less visibility gage as a multiple-purpose device satisfying the method of relative luminance must have design and optical-photometric systems which:

1. Shall set up in the field of vision a black mark zeroed as infinity and changing its blackness under the operation of an imposed masking luminance;

2. Shall reduce to the minimum possible the parasitic instrumental luminance;

3. Shall bring about a slower rise in imposed masking luminance than has to be the case in object-extinction observations.

In Figure 18 we set forth the optical and design system of an adaptation-less IDV visibility gage which meets all these requirements[1].

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[1]The IDV device described here, with increasing luminance of the field of vision, is a modernization of earlier patterns of devices in accordance with cr unications of the author [19, 20, 21]. The design system for the collimator was proposed by L. L. Dashkievitch.

The device consists of a visual tube 9 with seven-power magnification; an optical achromatic prism 7 (see Figure 12) set up as close as possible to the objective 8 of the tube and movable relative to the objective via a rack and pinion 5 and 6; a collimator 2 consisting of two identical objectives 1 and 4, between which there is a collective lens 3, on one of the plane-convex components of which there is mounted a round black mark which is seen in the field of vision of the eyepiece 10. The purpose of the collimator is to create in the field of vision of the device an image of this black mark, and at the same time an image of a section of the terrain being examined. In order to bring this about the forward objective of the collimator can be shifted a few millimeters along the longitudinal axis of the device and can bring objects located at from 2 meters to infinity from the observer into clear focus. The collective lens is fastened at the focus of the second, stationary objective of the collimator.

The optical prism 7 is intended to create a masking instrumental "haze", which is achieved by means of a splitting of the observed image, subsequent blending with each other of corresponding parts of both images, and variation of their luminances via the withdrawal of the prism from the objective of the visual tube.

The overall appearance of the IDV device is shown in Figure 19.

In carrying out observations, to begin with one gets a clear image of the mark by focusing the eyepiece. At the eyepiece end its angular dimensions are 30'. Next by focusing the forward objective of the collimator one gets a clear image of the object.

Readings of the IDV device do not depend upon the degree of polarization of the falling rays. Since in reflected or diffuse light the majority of terrain objects have a relatively high polarization component, the IDV device is convenient for carrying out measurements of various sorts and for investigations in the field of terrain optics, including those for determining the transmissivity of the atmosphere. But observations in terrain optics by means of the polarization visibility gage are complicated by reason of the need to struggle with the polarization component of diffused or reflected light.

The system of diaphragms inside the device and the making translucent of all optical units almost completely eliminate parasitic luminance. The weignt of the device is 0.5 kg. Smooth motion of the gear that withdraws the prism beyond the edge of the objective of the tube is ensured by converting linear shifting of the prism into rotatory motion of the dial. Linear shifting of the prism (amounting to 13 mm) is converted into circular motion of the scale to the extent of 330°. In conjunction with the selection of the most advantageous transmission T for the prism, amounting to 0.35, this type of motion ensures decidedly smooth alteration of the instrumental parameter V.

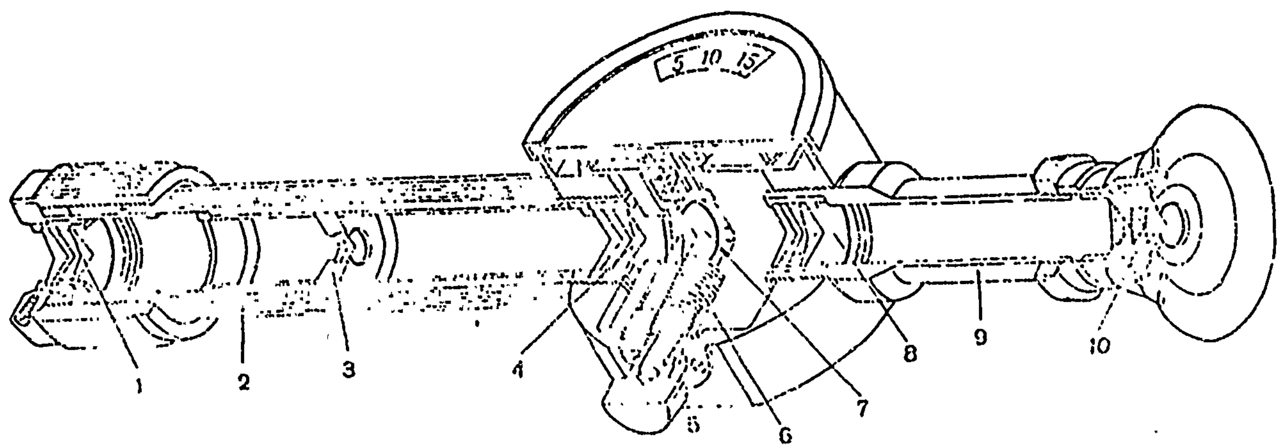

Figure 18. Optical and Design System of IDV Visibility Gage Based Upon Relative Luminance Method.

Figure 19. Overall Appearan~e of IDV Visibility Gage.

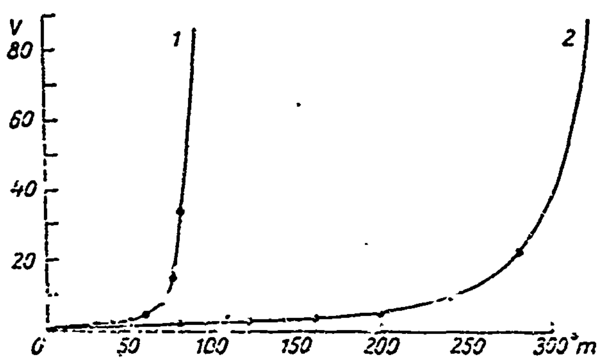

Figure 20. The Comparative Line of the Displacement on the Basis of the Device of Parameter V.
1, the polarization guage of visibility M-53A,
2, the guage of visibility IDV.

In this respect the optical-photometric and mechanical system of the IDV is more advantageous than is that in the polarization device, the bases of which in principle do not permit one to vary the magnitude of alteration in the V parameter per unit of turn ϕ of the polaroid. It has proven to be impossible, both optically and mechanically, to alter the speed of imposition of the masking luminance for identical angles of rotation ϕ of the polaroid.

The comparative characteristics of the displacement of the V parameter for both devices with equal angular rotations of the dial m are set forth in Figure 20. The great steepness of the path followed by V in the polarization device starting from $V > 25$ calls on the observer for heightened visual exertion in determining the correct moment for a reading. Here it is in place to remark that visibility gages having great steepness of alteration of the V parameter are not convenient to use for the determination of large contrasts by the extinction method: reading moments fall at sections of the graduation curve that are very steep, which presupposes a greater error in the measurement of contrast.

The practical application of the relative luminance method and of the IDV device is examined in the fourth and eight Chapters.

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CHAPTER IV

SOME QUESTIONS HAVING TO DO WITH DETERMINATION OF THE VISIBILITY RANGE OF REAL OBJECTS

§ 21. General Observations

Expressions (1.21) and (1.25) derived in our first Chapter in their general form describe, as we have already pointed out, the visibility range S_p of any real object projected against any real background. From these expressions it is apparent that S_p is functionally linked to a series of parameters, specifically

$$S_p = f[S_\gamma, K_0, \varepsilon, D, B_\phi(B_0)] \quad (4.1)$$

(the conventional symbols are the ones used earlier).

The visibility range of lights also depends on a series of factors the meaning of which is clearly apparent from (1.32).

The great number of factors that have an effect on the visibility range of objects; the difficulty of measuring them directly; the lack of agreed definitions; and the arbitrary character of the way some of them are interpreted -- all of these things taken together markedly complicate the solution of applied problems of every sort.

The heterogeneity of the photometric properties of objects; the dependence of the threshold sensitivity of the eye upon the level and circumstances of illumination; the changeability in space and in time of the transmissivity of the atmosphere, etc., set obstacles in the way of developing universal methods for determination of S_p which would be suitable for utilization under any set-up applicable to any concrete problem. For example, detection of a target in the beam of a projector has on the methodological plane nothing in common with the detection, let us say, of a landing strip, although both of these problems are described by one and the same set of theoretical relationships.

Development of the applied side of the science of visibility at its present stage is characterized by sets of specifics of "the given problem," which are sharply expressed in the methodical sense. These sets in the last analysis presuppose the coming into being of a number of important and differentiated directional lines which will be of major significance to our national economy.

Let us turn to some examples.

In connection with the enormous and continuously rising number of automobile accidents on city streets and on highways in all countries, as a result of which every year hundreds of thousands of people perish, and millions of people are hurt, the problem of street and highway visibility has arisen. This directional line studies questions of optimal norms of illumination, and of the degree of visibility of objects on the streets of cities and on highways which are bound up with illumination; questions having to do with the properties of vision and the speed of motor reflexes of man under circumstances of relatively low levels of illumination and low intensivities of visual perception of objects; methods for striving toward heightened efficiency of the operation of the eye under these circumstances, etc.

In connection with the lack of methods for blind-landing airplanes under complicated meteorological circumstances, an evil quite sufficient to its day is the problem of determining the landing range of isibility in all the multiplicity of the meteorological, phototechnica , and visual factors which define it.

Problems of a specific character also spring up in maritime navigation, in railway transport, etc.

It is obvious that in each concrete problem one will have to deal with unique objects and specific apparatus, with unique permissible ranges for the alteration of the parameters that determine the visibility ranges of these objects.

From what has been set forth above it ought to be clear that this Chapter will not contain and cannot contain ready-made recipes for determining the range of visibility of concrete objects or signal lights under the variegated real circumstances of their observation.

This Chapter elucidates some particular questions of a methodical character; it presents data regarding the photometric properties of terrain objects which have been secured with the help of a visibility gage; and it devotes considerable attention to questions having to do with determination of the visibility of objects against a background of haze, as well as to methods for determining landing visibility.

§ 22. Transformation of the Expression for S_p on the Basis of the Theory of the Relative Luminance Method

As transpires from (1.21), S_p is a function of five parameters, and one cannot determine the S_p of an object if even one of these is not known.

Measurement of the parameters V_o and D/B_ϕ by the method of photometric comparison is difficult to accomplish on account of the color of objects and the heterogeneity of their surfaces as regards luminance. These parameters can be determined with relative ease through the help of visibility gages.

As we have shown in the second Chapter, visibility gages directly measure the ratio $V = K/\varepsilon$, which we call the degree of visibility of an object and which can be treated as a measure of the intensivity of visual sensation of an object. As it happens, the quantity V_o is one of the components of (1.21).

With visibility gages one can also determine a second parameter in (1.21), namely the ratio D/B_ϕ (or D/B_o).

Thus if the V of an object and D/B_ϕ are determined with visibility gages, S_p can be examined as a function not of five, but instead only of three parameters:

$$S_p = f\left[S_m,\ V_0,\ \frac{D}{B_\phi}\left(\frac{D}{B_0}\right)\right]. \tag{4.2}$$

Measurement of D/B_ϕ (or D/B_o) is nevertheless a difficult task even for visibility gages. These difficulties are occasioned by the fact that by reason of the relatively low angular furcation of the images in the field of vision of the device, one does not always succeed in superimposing the luminance D of the section of sky at the horizon upon the luminance B_ϕ of B_o, undistorted by haze, of the more luminous component of "surface" contrast that is being observed.

But even if the imposition of luminance D upon the picture being observed is in fact possible, then difficulties arise as regards the determination of the moment of extinction of the surface under observation, on account of its outlines as a rule being indistinct. It becomes necessary to extinguish on the basis of the "texture" of the surface, and even this is possible only when the instrument is joggled, a matter that was referred to in § 12. All of these things, taken together, have led to great errors in measurement of the parameter D/B_ϕ, and consequently to great errors in the determination of S_p.

Only with the development of the relative luminance method was this situation altered.

With the help of this method it became possible to replace the parameter D/B_ϕ with a different parameter, equivalent to it but simpler and susceptible of more accurate measurement. It is precisely this replacement of one parameter by another that constitutes the essence of the transformation that is being explained.

For the sake of practical convenience, it is well to replace the natural logarithm in (1.21) by the decimal one. Then instead of (1.21) we shall have

$$S_p = \frac{2.3}{\alpha}\log\frac{\frac{K_0}{\varepsilon} + \frac{D}{B_\varphi} - 1}{\frac{D}{B_\varphi}}. \tag{4.3}$$

In (4.3) we replace K_0/ε with V_0, and α by a synonymous expression in accordance with the Koschmider formula (1.23), i.e.:

$$\alpha = \frac{\ln\frac{1}{\varepsilon}}{S_0}.$$

Then we secure

$$S_p = \frac{2.3}{\ln\frac{1}{\varepsilon}} S_0 \log\frac{V_0 + \frac{D}{B_\varphi} - 1}{\frac{D}{B_\varphi}}. \tag{4.4}$$

In solving problems having to do with the visibility range of objects, i.e., in perceiving threshold or near-threshold contrasts, there are actually never conditions providing observation in a strictly fixed direction. Actual conditions of observation of threshold or near-threshold contrasts involve a need to search for the object within the limits of some small space, even if the location of the object is known in advance. Experience shows that during such observation the value of ε_{dis}, which corresponds to the losing of an object from sight, mounts somewhat in comparison with ε_{dis} when there is strictly fixed perception.

From our experiments on investigation of threshold functions, carried out under conditions close to fixed perception (see § 66), it transpires that the most reliable value for ε_{dis} for these conditions is 0.026 (2.6%).

If this value for ε_{dis} is substituted into (4.4), we secure

$$S_p = 0.62 S_v \log \frac{V_0 + \frac{D}{B_\sigma} - 1}{\frac{D}{B_\sigma}}. \tag{4.5}$$

But if in (4.4) we substitute a value for ε_{dis} rounded off to 0.03, which we use in the formula for meteorological visibility range (see (1.28)), then in place of the coefficient 0.62 in (4.5) we secure a coefficient 0.62 which, when the more precise value for ε_{dis} is used, gives a difference in value for S_p that is equal to approximately 5%.

Let us now pass on to exposition of the idea of transforming (4.5).

The expression for contrast

$$K = 1 - \frac{B_m}{B_\sigma},$$

where B_m in the less luminance and B_σ is the greater luminance, is easily applied to the ratio for D/B_σ, when one is examining some "surface" contrast and on the assumption that D is the luminance of haze at the horizon and B_σ is the more luminous component of the "surface" contrast being observed, in which connection D must be greater than B_σ.

By analogy with the ratio

$$\frac{B_m}{B_\sigma} = 1 - K$$

one can write the following expressions for the component of luminances of D and B_σ:

$$\frac{B_\sigma}{D} = 1 - K_0(D, B_\sigma), \quad \text{or} \quad \frac{D}{B_\sigma} = \frac{1}{1 - K_0(D, B_\sigma)}. \tag{4.6}$$

But we are already acquainted with one peculiarity of the relative luminance method upon which the transformation being explained is based: in order to find the contrast between the luminosity D of haze at the horizon and the luminance B_σ of the observed component of "surface" contrast it is indispensable that the latter be projected against a background of sky at the horizon having luminance D.

In accordance with relative luminance one can find the contrast between any real object and the sky at the horizon, even if the object is not projected against a sky background. The only thing that is important is that the angular furcation of the images in the field of vision of the visibility gage should make it possible to utilize the luminance of a section of sky at the horizon as a masking luminance. Then, in harmony with expression (3.6), the desired contrast $K_0(D, B_\sigma)$ between the luminance D of haze of the horizon and the lighter component of the observed "surface" contrast B_σ will be equal to

$$K_0(D, B_\sigma) = 1 - \frac{V'_\sigma}{V'_M}. \tag{4.7}$$

Here V_σ' is the degree of visibility (minus one) of the black mark of the device against the background of the lighter component of "surface" contrast, determined in accordance with the moment of extinction of the mark; V_M' is the degree of visibility (minus one) of the mark against the sky background, determined in analogous fashion. In both cases the image of the section of sky at the horizon having a luminance D is to serve as a masking luminance.

Substitution of (4.7) into relation (4.6) gives

$$K_0(D, B_\sigma) = 1 - \frac{B_\sigma}{D} = 1 - \frac{V'_\sigma}{V'_M}.$$

whence

$$\frac{D}{B_\sigma} = \frac{V'_x}{V'_\sigma}.$$

Replacing the parameter $D/B_\phi = D/B'_\sigma$ in (4.5) by the last relation, we secure

$$S_p = 0.625 S_m \log \frac{V_\phi + \frac{V'_M}{V'_\sigma} - 1}{\frac{V'_x}{V'_\sigma}}. \quad (4.8)$$

One can simplify (4.8) if one substitutes a mean value for V_M' secured in accordance with the results of a prolonged series of measurements. This mean value for V_M', determined with the help of the IDV device from some hundreds of series of measurements on the extinction of the mark of the device against a background of sky at the horizon, proved to be equal to 45 with a relative error of 7%. The substitution of this value into (4.8) gives

$$S_p = 0.625 S_m \log \frac{V_\phi + \frac{45}{V'_\sigma} - 1}{\frac{D}{V'_\sigma}}, \quad (4.9)$$

or

$$S_p = 0.625 S_m \log \left(\frac{V_\phi - 1}{\frac{D}{V'_\sigma}} - 1 \right). \quad (4.10)$$

Comparison of the initial expression for S_p (4.5) with the ones transformed in accordance with the method of relative luminance, (4.10) or (4.8), demonstrates the advantage produced by this transformation.

If, as has been pointed out above, direct determination of the D/B_σ ratio presents a difficult task that cannot always be carried out, on the other hand measurement of the equivalent ratio V_M'/V_σ' is altogether simple and can always be accomplished, inasmuch as it is associated with separate extinction of the mark against the "surface" object and against the sky-at-horizon background.

But if one starts with expression (4.10), then the need for extinction of the mark against the sky background falls away, and the entire measurement procedure consists only of extinguishing the mark against the lighter component of the observed "surface" contrast, in which connection the masking luminance is to be the section of sky at the horizon.

It is the simplification of the method system for the determination of D/B_σ which constitutes the essence of the transformation which has been explained.

Let us recall that V_o in (4.10) represents the degree of visibility, not distorted by atmospheric haze, of the object against a given "surface" background, in which connection this background itself is to serve as the masking luminance when V_o is measured.

If the angular dimensions of the object are small, then in (4.10) and in other relations for S_p one should substitute a value $V_{o\gamma}$ for the object which is attained at a given visibility range S_p of the object.

The methods for determining the $V_{o\gamma}$ of the objects having small angular dimensions are examined below.

The correctness of the expression (4.10) can be checked in the following way.

Let us suppose that a black object is being observed on the ground against a white background. The degree of visibility V_o of such an object is equal to 45 as a mean, since this is equivalent to the degree of visibility of a black screen (or the mark of the device) against a sky background, which is also equal to 45.

The quantity V_σ', however, must be determined in accordance with the moment of extinction of the black mark of the device against the background of the lighter surface, i.e., in our case against the white background surface. This, again, is equivalent to observation of the black mark against a sky background, which gives for V_σ' a value which is also close to 45. Substituting all these values into (4.10) or (4.?) converts S_p into S_M, which is what should occur.

§ 23. Table for Coefficients of Transfer from Transparency of Atmosphere to Visibility Range of Terrain Objects

In order to get around the computation of the rather clumsy expression for S_p, A. A. Gershun [40], N. G. Boldyryov [13], Duntley [156], Foitzik [160], and others have proposed various nomograms which make it possible to find the value of S_p in accordance with known values of S_M, V_0 and D/B_σ.

Beside the nomogram method one may propose, it seems to us, a still simpler method for determining S_p. It consists in determining in accordance with given values of V_0 and D/B_σ (or V_M'/V_σ') a certain coefficient which when multiplied by S_M gives the desired S_p.

The idea of determining such correctional coefficients consists in the following.

In (4.10) let us isolate the multiplier

$$0{,}62\log\left(\frac{V_0-1}{\frac{45}{V_\sigma'}}+1\right)=\frac{S_p}{S_M}=q, \tag{4.11}$$

which we shall call the coefficient of transfer from meteorological visibility range to visibility range of real objects.

Guiding oneself via the values of V_0 and V_σ' one can set up a table, convenient for practical use, of the values of the coefficient, q, for transfer from S_M to S_p (Table 12).

Knowing the values V_0 and V_σ' for the object of interest to us, we shall find at the intersection of the corresponding rows and columns of the table the coefficient q. Upon multiplying it by the value of S_M, determined by one method or another for the given moment, we at once secure the quantity S_p for the given real object. Nomographic determination of S_p becomes superfulous.

Table 12 shows what part of the value S_M constitutes the quantity S_p under certain circumstances of observation. In accordance with the data of the table one can follow the laws governing change of S_p at various values of the parameters V_o and $45/V_\sigma' = D/B_\sigma$. It is convenient to make use of the table in constructing nomograms for the solution of various particular problems. Thus we make use of it when we construct nomograms for the determination of landing visibility.

TABLE 12. VALUES OF COEFFICIENT q FOR TRANSFER FROM S_M TO S_p

$V_0 = K_0$	$45/V_\sigma' = D/B_\sigma$											
	1	1.5	2	2.5	3	4	5	6	7	8	9	10
45	1	0.92	[illegible]	[illegible]	[illegible]	0.67	0.61	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
40	[illegible]	0.87	[illegible]	[illegible]	0.71	[illegible]	[illegible]	[illegible]	0.51	[illegible]	[illegible]	[illegible]
35	0.96	[illegible]	0.78	0.72	0.67	0.60	[illegible]	0.51	[illegible]	[illegible]	[illegible]	[illegible]
30	[illegible]	[illegible]	0.71	[illegible]	[illegible]	0.57	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
25	0.87	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
20	0.81	[illegible]	0.61	0.58	[illegible]	[illegible]	[illegible]	0.35	[illegible]	[illegible]	[illegible]	[illegible]
15	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
10	0.62	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.21	0.22	[illegible]	[illegible]	[illegible]
5	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.19	0.16	0.12	0.12	[illegible]	0.10	[illegible]
3	0.30	0.21	0.19	0.16	0.14	0.11	0.09	0.05	0.07	0.06	[illegible]	0.05

§ 24. Determination of V_o of Terrain Objects With the Help of Visibility Gages. Table of V_o Values of Certain Terrain Objects

As was pointed out in the second Chapter, the measurement procedure for determining the V_o (or K_o) of objects consists in making the bent image of the object being examined in the visual field of the visibility gage coincide with the unbent image of the background surrounding this object. The image of this same background is to be the masking luminance.

For example, by making the bent image of a river coincide with the unbent image of one of its shores, and then extinguishing the image of the river to complete loss of its visibility, one at once finds from the table of graduations the V_o of the river against the shore background. In this connection it is important to recall that if the background is lighter than the object, then the table of graduations at once gives V_o for this reading. But if the background is darker than the object (this is determined by visual estimate), then one must introduce into the graduation data a correction in accordance with formula (2.26) or (2.24). It is obvious that if the background is darker than the object, readings on the device and V_0 values will be greater than when the lighter object is used as the masking luminance. Correction in accordance with (2.26) or (2.24) eliminates this excess.

For example, the moment of extinction of a road against the background of a meadow does not coincide with the moment of extinction of the meadow against the background of the road. In this case the V_0 values will differ from each other by a certain amount. The correction referred to evens off both of these values.

One should note that observations of this sort with the visibility gage possess a great degree of individual character.

The structure of the surfaces of observed real objects and backgrounds is decidedly lacking in homogeneity as regards luminance and color. These surfaces consist of individual microelements or micro objects. For example, the shore of a river constitutes an alternation of sandy shelves, grassy or bushy sections, plus various buildings, boats, etc. The river itself has a surface covered with waves, a different luminance depending on depth; boats, ships, etc. may be moving on the river.

When making the images of such real objects and backgrounds coincide the picture which one is observing in the visual field of the device is as a rule exceedingly variegated, and the very river is extinguished not as a whole when masking luminance is intensified, but by sections; against some sections of the background it may be visible, against others not. For this reason it is sometimes difficult to set definitely the moment for a reading. It will be correct if the object observed is extinguished in such fashion that it is in the main not visible against a given variegated background, while at the same time individual elements of the object may still be faintly perceptible against individual small and secondary details of the background.

Experience shows that in making measurements of this character, as practice is acquired by the observer his intuition as to the selection of the proper moment for a reading develops.

Although measurements of this sort are not characterized by high precision and are not simple, they can be carried out only with the help of visibility gages. It is not possible to get such measurements so simply either by means of visual comparison photometries, or by the methods of objective photometry.

In the "A. I. Voyeikov" Main Geophysical Observatory, by using the method set forth and one of the early models of the IDV device, V_0 measurements for various real objects of the terrain projected against various "surface" backgrounds were carried out.

A considerable part of the data were secured from the air, in which connection airplanes and free balloons were used as lifting media.

Efforts to organize analogous observations from a helicopter did not meet with success, as a consequence of the non-adaptability of the cabin of the machine for such measurements (subject to closed fields of vision, etc.).

Airplane observations were carried out through the opened entrance door, the indispensable safety precautions having been observed. E. N. Dovgiallo, A. K. Donskoi, L. S. Yudina, and others took part in these observations.

All V_0 measurements from the air were carried out at low altitudes in order to exclude the influence of haze upon object observations.

Endeavors to make use of the polarization visibility gage for the measurements in question proved unsuccessful. The majority of natural objects, particularly when observed from the air, possess a considerable polarization component, as a consequence of which the moments of readings depend heavily upon the orientation of the device relative to the objects observed. On this account it was necessary to cut short observations with the polarization device.

In Table 13 we set forth V_0 quantities and δV_0 errors for those objects upon which no less than five series of measurements at different times were carried out.

If the V_0 values show in the table are multiplied by 2, we secure the approximate amounts of contrasts K_0 of the corresponding objects. The V_0 values of objects Nos. 5, 7-13, 36-39, 41, and 44 were computed by the formula (2.26).

What deductions of a general character may be made from an analysis of Table 13?

The objects shown in this table can be divided into three groups by degree of visibility (for comparison, see Table 10):

Group 1 - V_o values less than 10, which corresponds to bad visibility;

Group 2 - V_o values lie between limits of 10-20, which can be evaluated qualitatively as satisfactory visibility, although it is in general still far from good visibility;

Group 3 - V_o values comprised within limits of 20-50, which corresponds to good and to excellent visibility.

On the basis of these gradations we can reach the conclusion that the majority of terrain objects projected against "surface" backgrounds should be referred, as regards degree of visibility, to the "poorly visible" and "satisfactorily visible" groups. One should recall that what is involved here is the degree of visibility of objects without haze upon them, and that the latter still further worsens visibility.

Thus the majority of objects placed in Table 13 under numbers 1-35 are little suited, or not at all suited, for visibility landmarks for aviation.

The following are easily and even outstandingly visible from the air against a water background: concrete dams, islands, railway bridges, ships lit up by the sun, and also structures (such as factory chimneys) against a snow background, highways when lit up by the sun against a grass background, etc. These objects can serve as landmarks for aviation even at reduced oblique transmissivity. Good landmarks are rivers, lakes (under certain circumstances of lighting), and the shore of the sea.

The question of the visibility of objects during the winter season is a special one. Visibility from the air of population centers, all sorts of structures, and the like, is bad on account of snow on roofs. An exception is offered by bridges, chimneys, painted buildings, for which V_o is as a rule greater than 25.

"Vegetable" objects, not covered by snow, are easily visible from the air, but if there is snow or frost upon them there is little to distinguish them from the background. But even with good visibility, forests, woods, trees, and other "vegetable" objects are little suited for use as landmarks for aviation.

TABLE 13. MEAN V_0 VALUES OF TERRAIN OBJECTS PROJECTED AGAINST VARIOUS BACKGROUNDS AND HAVING ANGULAR DIMENSIONS OF NOT LESS THAN 20' (CONTRAST $K_0\% \approx 2V_0$)

No. of objects	Character of object and background	Mean V_0	$\delta V_0 = \frac{\Delta V_0}{V_0}\%$	Illumination	Character of observ.
	Objects against an earth surface background				
1	Factory-type buildings on variegated dark background.	7	20	R	From air
2	State regional electric power plant building against dark variegated background	6.5	20	R	Same
3	Wooden cottages against background of stripped earth.	7	--	R	
4	Same against background of brown grass.	6	--	R	
5	Reinforced concrete warehouses against grass background.	15	--	P	
6	Asphalt highway against grass background.	10.5	--	R	
7	Reinforced concrete buildings of hydrostation against grass background.	9	--	P	
8	Same, lightened up by sun.	26	--	D	
9	Dirt road against grass background.	16	20	P	
10	Same, lightened by the sun.	38	--	D	
11	Gray houses (brick or wood) against grass or forest background.	20	--	P	
12	Slate roofs against grass background	16	--	P	
13	Same, against earth background.	19	--	P	
14	Red brick structures against grass background.	9.5	--	P	
15	Railway station against varied background.	8	--	R	
16	Railway bridge against grass background.	5	--	P	
17	Wooden highway bridge against grass background.	13	--	P	
18	Railway against grass background.	8	--	R	
19	Train against forest background.	8	--	R	
20	Evergreen forest against grass background.	8.5	--	P	
21	Individual evergreen trees against earth background.	16	--	R	Ground
22	Young evergreens against grass background.	19	--	R	Same

TABLE 13.* (Continued)

No. of objects	Character of object and background	Mean V_0	$\delta V_0 = \frac{\Delta V_0}{V_0}$ %	Illumination	Character of observ.
23	Individual evergreen trees against snow background.	36	--	P	
24	Leafless bushes against earth background.	10	--	R	
25	Leafy bushes against grass background.	14	--	R	Ground
26	Bare bushes against snow background	24	--	P	Same
27	Pine against brown grass background	15	--	P	
28	Pine against snow background.	25	--	P	
29	Old wooden shed against earth background.	13	--	R	
30	Same, against grass background.	17	--	R	
31	Same, against snow background.	34	--	R	
32	Log houses against earth background	17	15	R	
33	Same, against snow background.	29	25	R	
34	Red brick staructures against earth background.	16	--	R	
35	Same, against grass background.	13	15	R	
36	Concrete runways against brown grass background.	18	15	R	From air
37	Same, against same.	23	15	R	Ground
38	Same, against green grass background.	27	15	R	Same
39	Same.	27	15	D	
	Objects against background of surface of water, and the like.				
40	Concrete dam against water background.	42	--	P	From air
41	Same, agianst water background lit up by sun.	55	--	D	Same
42	Hydroelectric station building, dark against water background.	15	--	P	
43	Same, against water background lit up by sun.	36	--	D	
44	Wooded island against dark water background.	11	± 15	P	
45	Same, against bright water background.	22	± 20	P	
46	Same.	20	± 20	R	
47	Sandy island in river Oka.	35	± 20	P	
48	Sandy island in Lake Ladoga.	33	± 20	P	
49	Same, lit up by sun.	44	± 20	D	

TABLE 13. (Continued)

No. of Objects	Character of Object and Background	Mean V_0		Illumination	Character of Observ.
50	Railway bridge on river Neva against background of bright water.	42	± 25	B	
51	Same from shady side.	15	20	B	
52	Same against dark water background.	15	25	P	
53	Steamer on river against dark water background.	45	--	B	
54	Same against light water background.	15		R	From air
55	Island under snow against background of snow.	5	--	P	Same
56	Railway bridges against background of frozen river.	25	--	P	
57	Painted buildings against snow background.	40	--	P	
58	Wooded island without snow against background of snow.	40	--	P	
59	River under snow against background of bank under snow.	4	--	P	
60	River against green meadow background, dark point in river.	11	--	R	
61	Same, light point in river.	25	--	R	
62	Lake against forest background.	30	--	R	

NOTE: P = Overcast; R = Diffused lighting; B = Cloudless.

The V_o values of objects set forth in Table 13 can be utilized in the practical determination of S_p, but only on the condition that the angular dimensions of the objects at this distance are not less than 20'. If one accedes to a certain insignificant heightening of error in the determination of S_p, one may adopt 15' as the limit permissible angular dimension of the object. Beyond this limit the degree of visibility, V_o, of the object rapidly diminishes (the threshold contrast rapidly mounts), and without this circumstance being taken into account the value S_p, all other conditions being equal, will be considerably exaggerated.

§ 25. The Method for Determining the Degree of Visibility, V_{oY}, of Objects Having Small Angular Dimensions

The initial expressions (4.5) or (4.8) and (4.10) are correct also for objects having small angular dimensions, but the degree of visibility V_o in them must be replaced by V_{oY}.

There are various ways of taking into account the alteration in the degree of visibility or contrast of an object if its angular dimensions at distance S_p fall to less than the permissible limit. The majority of these methods, based upon various propositions as to the laws for alteration of the threshold of contrast sensitivity and of the threshold of visual acuity, are nevertheless pretty complicated for practical use.

If we are not striving for exceedingly high accuracies in the determination of the S_p of small objects, we can propose a decidedly simple method for determination of the dependence of V_{oY} upon the angular dimensions of the object. The basis of this method consists of the experimentally determined law governing the alteration of the V_{oY} of a black body against a sky background and the concept of a "critical distance" at which the angular dimensions of the object reach 15'.

To begin with let us elucidate in a little more detail the meaning of the concept "critical distance."

The angular dimension of 15' X 15' is taken as being the minimum amount beyond the limits of which perception of the object substantially worsens and the value of V_o falls off. For any real object there is a critical distance L_{cr} at which the dimensions 15' X 15' are reached. To determine the L_{cr} value for a given object is extremely easy if one follows the rule to the effect that an angular dimension of 1 meter at a distance of one kilometer, upon observation with the naked eye, comes to about 3.6'.

If any large building, like a grain elevator, has a height of 25 meters, let us say, then at a distance of 1 kilometer its angular height comes to 3.6' times 25, or to 90', i.e., it exceeds by six times the critical dimension. On this account the L_{cr} of such a building is approximately equal to 6 km.

Such an evaluation of L_{cr} is suitable for objects the shape of which is close to the square and rectangular, if only these objects are not very markedly drawn out either in length or in height.

For elongated objects of the type of forests, factory chimneys, television masts, and the like evaluation of L_{cr} becomes somewhat more complicated. As tests carried out with adaptation-less visibility gages show, elongated objects are considerably better visible than is a square having a side equal to the least height (or breadth) of an elongated object. Of course, differing elongation relative to different least dimensions presupposes a differentiation in the intensivity of visual perception of the elongated object.

From the results of investigations of the perception of elongated objects carried out by the author [25], one may take it (without going into detailed proofs here) that for the type of elongated articles mentioned above L_{cr} ought to be increased approximately by 2.5-3 times relative to the distance at which the least dimension of the elongated object attains an angular dimension of 15'.

Let us elucidate the sense of what we have said.

If, for example, a mature forest has a height of 15 m., then its angular height at a distance of 1 km. will come to 3.6'·15 = 54', and therefore for the forest L_{cr} should be equal to 3.5 km. But if one takes into account the fact that the forest should be regarded as an elongated object, this distance should be multiplied by 2.5-3 times, i.e., L_{cr} for the forest is equal approximately to 8.5-10 km.

Through analogous reasoning one can find that for a water tower (or a beacon) having a base about 5 meters in diameter L_{cr} is about 3-4 kilometers.

The method described makes it possible to find approximate values of L_{cr} for some typical objects of the terrain (Table 14).

From Table 14 one can see, among other things, how desirable it is to make use of even a small optical system in order to magnify the angular dimensions observed: for the range of visibility S_p of the majority of terrain objects it eliminates the need for taking angular dimensions into account.

TABLE 14. APPROXIMATE VALUES OF CRITICAL DISTANCE L_{cr} AT WHICH THE ANGULAR DIMENSIONS OF TERRAIN OBJECT ARE NOT LESS THAN 15' X 15'

Object	L_{cr}, km.	
	Observed with Naked Eye	Observed with 8-Power Binocular
Mature forests of all sorts.	8.5-10	50-60
Individual mature groves of all sorts.	4-5	35-40
Large hillocks.	10-12	80-100
Individual mature trees.	1.5-2.0	12-15
Substantial buildings (elevators, houses, etc.)	6	40-50
Large railway bridges.	2-3	15-20
Factory chimneys	4	25-30
Beacon structure	3-4	25-30
Television masts.	6-8	80
Triangulation station.	2-3	25
Log house.	1-1.5	8-12
Man.	0.2	1.5
Truck.	0.5	4.0
Artificial screen 4 X 4 m.	1	8
Artificial screen 2 X 2 m.	0.5	4.0
Large ship.	5	40

If the meteorological range of visibility is less than the critical distance L_{cr} it is not necessary to introduce corrections in the angular dimension of the object, as the object is not visible at a distance less than the meteorological range of visibility.

But if the meteorological range of visibility considerably exceeds L_{cr}, then the situation changes radically: beyond the limits of the critical distance the degree of visibility of the object deteriorates not only as a consequence of the reduction of the angular dimensions, but also by virtue of the masking effect of atmospheric haze. Under these circumstances the range of visibility of a small object observed with the naked eye may be considerably less than S_m.

What has been said above is valid only for the light hours of the 24, both as regards the limit angular dimension of 15' and as regards L_{cr}.

In twilight and, naturally enough, in darkness the laws of visual perceptivity of objects take on an altogether different character. In twilight the degree of visibility of objects deteriorates steadily as the general level of illumination falls off.

Each level of illumination has its own, considerably greater, maximum-permissible angular dimension for an object, and its own critical distance L_{cr}. In the dark, with illuminations at hundredths and thousandths of a lux, the limit angular dimension of an object rises to some degrees, and L_{cr} diminishes correspondingly.

In methodic respects all these questions have been little worked out, and on this account there is no point in dwelling on them in greater detail.

Now let us pass on to examination of the question of the degree of visibility, $V_{o\gamma}$, of objects depending upon their angular dimensions.

The experimental base for this question has been created by field measurements of the degree of visibility of a black body made in the form of a thin-walled hollow brass cylinder having a ratio of length to diameter of opening amounting to 10:1, and blackened inside. The cylinder was set up against a sky background at the horizon; variations of the angular dimensions γ of the black hollow were secured by altering the distance to it. As an instrument one of the early variations of the IDV device was used. The image of a section of sky at the horizon served as the masking luminosity. The value of $V_{o\gamma}$ was determined via the graduated table of the device through reading at the moment of extinction of the image of the black body (observations were carried out without "joggling" the image). The results of the measurements are set forth in Table 15.

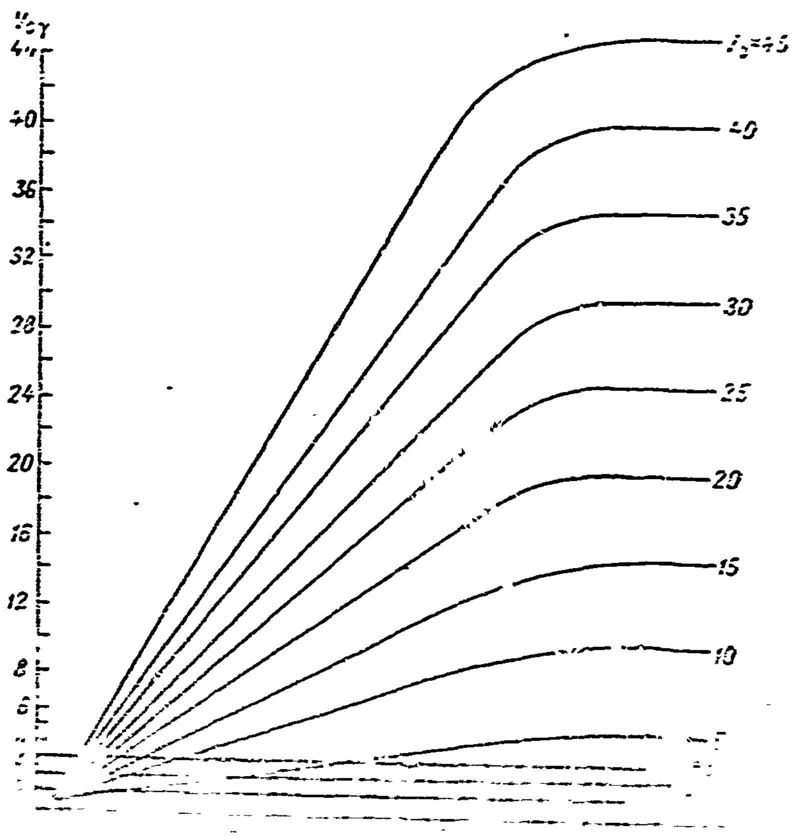
It is apparent, although not stated, that the hollow brass cylinder must have been closed at the end farthest from the observer-translator.

TABLE 15. CHANGE IN DEGREE OF VISIBILITY $V_{o\gamma}$ OF AN ABSOLUTELY BLACK SURFACE PROJECTED AGAINST A BACKGROUND OF SKY AT THE HORIZON, AND DEPENDENCES UPON ITS ANGULAR DIMENSIONS (FOR FIXED OBSERVATION)

γ'	20	15	12	9	6	3	2
$V_{o\gamma}$ (mean).	45	44	38	29	19	8	4

Some tens of series of measurements were carried out for each angular dimension.

The graphic data of Table 15 are presented in Figure 21 in the form of the upper curve.



[illegible]

[illegible] stantial diminution of $V_{0\gamma}$ starts with an angular dimension of [illegible].

In the range of angular dimensions from 15' to 2' change of $V_{0\gamma}$ relative to γ, as may be seen from Figure 21, is of a sharply defined linear character. This linear relationship and the "critical distance" concept which has been introduced make it possible to determine that at least for an absolutely black surface the change in $V_{0\gamma}$ depending on γ follows almost precisely the empirical relationship

$$V_{0\gamma} = V_0 \frac{L_{cr}}{S_M}. \tag{4.12}$$

where V_0 is the initial degree of visibility for the limit angular dimension $\gamma = 15'$.

As regards (4.12) one must make the following reservations. The L_{cr}/S_M relationship can be used only when S_M is greater than L_{cr}. The magnitude of the L_{cr}/S_M ratio characterizes the angular magnitude of an object beyond the limits of the initial value 15'. For example, if $S_M = 2\,L_{cr}$, then $\gamma = 1/2\ 15' = 7.5'$; for this angular dimension we find on the upper curve of the nomogram the $V_{0\gamma}$ values of the black surface which is equal to 22.5 (with initial $V_0 = 45$). If $S_M = 5\,L_{cr}$, we find correspondingly that $\gamma = 0.2 \cdot 15' = 3'$, and $V_{0\gamma} = 9$.

Of course $V_{0\gamma}$ can be determined at once from (4.12) by substituting into that equation known values for V_0 and L_{cr}/S_M. Such a course does not give the concrete angular dimension γ for an object. But this dimension, as we see from the above example, can easily be found.

The upper curve in Figure 21, constructed on the basis of the experimental data of Table 25, may be regarded as a guide one for the construction of the course of change of the $V_{0\gamma}$ of real objects which have a different initial value V_0. There are no grounds for supposing that $V_{0\gamma}$ for pronounced contrast (i.e., for an absolutely black surface) takes one course, and that $V_{0\gamma}$ for a weaker contrast takes another.

The less V_0 value of real objects may be regarded as a correspondingly reduced V_0 value for an absolutely black surface.

Taking this as the point of departure, on the basis of (4.12) values of $V_{0\gamma}$ for a series of other initial values of V_0 were computed. As a result the family of curves which is set out on the same Figure 21 was secured.

The correctness of the course of $V_{o\gamma}$ for any given initial value V_o as thus secured is fully confirmed by analogous curves published in one of the studies of A. A. Gershun [40, page 429], from which Figure 22 has been borrowed. In this drawing the discriminability of $V_{o\gamma}$, corresponding in our case to the degree of visibility, $V_{o\gamma}$, of an object, has been set forth on the ordinate axis, and on the abscissa axis the angular dimension, γ, of the object. The curves illustrated in Figure 22 are constructed for contrast values of 80, 60 and 30%. These curves correspond to the curves in Figure 21 constructed for degrees of visibility V_o of approximately 40, 30 and 15. The splendid coincidence of the paths taken by these curves, secured in independent investigations, carried out on different methodic bases, serves as a confirmation of the method set forth here for determining the relationship of $V_{o\gamma}$ to γ, and of the formula (4.12)

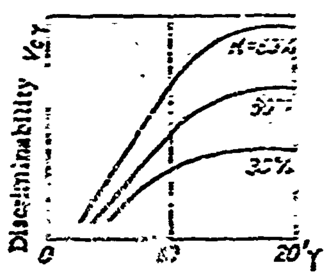


Figure 22. Dependence of the $V_{o\gamma}$ of Objects Upon Angular Dimensions, γ (According to A. A. Gershun).

The family of curves in Figure 21 possesses some interesting peculiarities.

It is obvious that when any object is brought to the threshold of perception, with its contrast K declining to the value ε and with the object becoming invisible, the degree of visibility $V = K/\varepsilon$ of such an object is equal to one. This object will be invisible even under fixed observation (cf. for comparison Table 10). Nor will small objects be visible if their $V_{o\gamma} = 1$. In harmony with the nomogram set forth in Figure 21, no objects having a V_o from 45 to 15, the curves of which intersect a straight line corresponding to $V_{o\gamma} = 1$ and parallel to the abscissa axis, will be visible.

Loss of visibility of all these objects (occasioned, let us recall, only by the small size of the angular dimensions, and not by the action of haze) takes place, as the nomogram shows, when their angular dimension $\gamma = 1'$. This corresponds very well with the generally accepted value for the threshold of acuity of vision, and once more serves as an indirect confirmation of the correctness of the linear dependence of $V_{O\gamma}$ upon γ that has been secured, and of the (4.12) relationship.

The considerations set forth above are based upon the proposition that fixed observation occurs. But under real circumstances one is obliged to deal with unfixed observation, for which a $V_{O\gamma} = 1$ is too small. On this account, for real circumstances of threshold perceptivity $V_{O\gamma}$ must be taken as larger.

If for orientation purposes one takes a value $V_{O\gamma} = 2$ (the second line from the bottom, parallel to the abscissa axis), then, as ensures from Table 10, detection of the object does already correspond to this value for $V_{O\gamma}$, but again only with fixed observation. With unfixed observation objects having $V_{O\gamma} = 2$ can fail to be detected. In these cases the angular dimensions of objects (having the limit initiation value of V_O that are indicated above), come, as is apparent from the nomogram, to 1 - 2'.

Thus with unfixed observation, which is the most typical for practical conditions, one must use $V_{O\gamma} = 3$ for orientation purposes; it corresponds (see Table 10) to detection of the object with unfixed observation. One can see from the nomogram what will be the angular dimensions of objects under these circumstances for various initiation V_O values.

Here one should note that the V_O quantities of real objects projected on a sky background at the horizon never attain a value less than 10 ($K_O \approx 20\%$) This is correct even in the winter time when the object is completely covered with snow.

Evidently, as ensues from observations of the author extending over many years, $V_O = 10$ is a lower limit beyond which no real object projected against a sky background at the horizon falls.

Such is one of the possible methods for determining the degree of visibility, $V_{O\gamma}$, of objects having small angular dimensions, if means of optical magnification are not used in observing them. In expressions (4.9) or (4.10) the parameter V_o must be replaced by $V_{o\gamma}$; i.e., we shall have

$$S_\gamma = 0.625 \log \frac{V_{o\gamma} - \frac{D}{V_\varepsilon} - 1}{\frac{D}{V_\varepsilon}}. \tag{4.13}$$

§ 26. Use of Visibility Gages to Determine the Parameter D/B_ϕ or (D/B_o)

In its general features the principle for measurement of the parameter D/B_ϕ (or D/B_o) has been set forth at the beginning of the present Chapter, where we have spoken of the transformation of the equation for the range of visibility of real objects.

Let us dwell in a little more detail upon some of the details of the principal for measurement as applied to the IDV device.

The idea of measurement is based upon the relative luminance method. The basic image is a bent (mixed) image. The black mark of the device is placed upon the lighter component of the observed "ground surface" contrast, i.e., if the background is lighter than the object then the mark is placed upon the background, and vice versa. The image of a section of sky at the horizon is to serve as the masking luminance.

The point of optical coincidence of the mark with the surface being observed must be selected at such a distance from the point of observation that this section is not under haze and that it will be possible to place upon it, by means of the proper aiming of the visibility gage, the masking luminance in the form of an unbent image of the section of sky at the horizon, the luminance of which is taken as being equal to the D coefficient of the light-atmosphere equation.

All the reasoning applied in Chapter III in the derivation of the basic relationships stands up completely in the present case as well. But in them, in place of the luminance B_ϕ of the background there should stand the luminance D of the second of sky at the horizon; and in place of the luminance B_o of the object, the more luminous component of the observed "ground surface" contrast B_σ.

Without repeating the derivation, we shall write a few obvious final relationships. In place of (3.4) we shall have

$$\frac{D}{B_\sigma} = \frac{\frac{1}{\varepsilon} - 1}{\frac{\varepsilon}{\varepsilon_\gamma}}.$$

Here $1/\varepsilon$ is the degree of visibility V_M of an absolutely black object on a background of sky at the horizon (in our case it is replaced by the black mark of the device); $\Sigma/\sigma T$ is numerically equal to the degree of visibility V_G (minus one) of the black mark against the background of the lighter component of "ground surface" contrast.

In both cases the masking luminance is to be the luminance of the sky at the horizon, i.e., the luminance D.

Thus we can write

$$\frac{D}{B_G} \approx \frac{V_M - 1}{V_G - 1} \approx \frac{V_M'}{V_G'}. \tag{4.14}$$

Taking $V_M' = 45$, which is close enough for practical purposes, we have finally, corresponding to what we got earlier,

$$\frac{D}{B_G} \approx \frac{45}{V_G'}. \tag{4.15}$$

In Table 16, values for D/B_G in accordance with (4.15) are set forth for some terrain objects measured with the IDV device in the manner indicated.

§ 27. Range of Visibility of Objects Against Background of Sky (Haze) At Horizon

Various sorts of threshold or near-threshold observations of objects against a sky background form an important part of the general science of the visibility of real terrain objects. It comprises all cases of visibility of objects at sea and the greater part of cases of the visibility of objects on land. Inasmuch as in these cases the background is haze at the horizon which characterizes by a state of luminance saturation D, they are very simple in theoretical respects, since the luminance B_ϕ of the background (sky at horizon) can be identified (with the reservations set forth in Chapter I) with the D coefficient of the light-atmosphere equation, which gives $D/B_\phi = 1$. Then in place of (4.5) we secured for the range of visibility of an object projected against a background of haze (sky at horizon) and having at that distance angular dimensions not less than 15' × 15'

$$S_{\lambda\,\Delta}=0.62S_{\Delta}\log V_{0} \tag{4.16}$$

or with small angular dimensions

$$S_{p\,\Delta}=0.62S\log V_{0Y} \tag{4.17}$$

TABLE 16. MEAN VALUES $/B_{\sigma} = 45/V_{\sigma}'$ FOR SOME OBJECTS OF THE TERRAIN, MEASURED BY THE RELATIVE LUMINANCE METHOD

Object	Illumi-nation	V_{σ}'	$45/V_{\sigma}'$
Black screen	P	1.0	45
	B	1.3	35
Pine Forest	P	4.0	11.2
	B	8.6	5.2
Deciduous forest	P	2.2	20.5
	B	3.0	15.0
Bushes	P	5.5	8.2
	R	8.6	6.2
	B	12.0	3.8
Grassy hillock	P	9.2	4.9
	R	11.5	3.9
	B	13.8	3.2
Dirt road	R	10.0	4.5
Weathered Wooden Building	P	3.6	12
	B	8.0	5.6
Slate roof	P	27.8	1.6
Concrete Landing Strip	R	30	1.5

NOTE: P - cloudy; R - Diffused illumination; B - Cloudless, objects lit up by sun.

Generally speaking, (4.16) and (4.17) are correct for bright, dull, and dark times of day on the condition that the V_{0} or V_{0Y} of the objects is determined as it applies to the given level of illumination.

As the expressions we have introduced above show, the $S_{p\cdot\delta}$ of an object against a background of haze depends upon two parameters, i.e.,

$$S_{p\cdot\delta} = f(S_M, V_o).$$

The principle for the use of visibility gages in order to determine the V_o of objects and the methods for reading V_{oY} are examined in detail in foregoing chapters.

The methods of measurement of the meteorological range of visibility are set forth in Chapters VI, VIII, and IX.

If the value S_M and the degree of visibility V_o (or V_{oY}) are known for an object, then the amount of $S_{p\cdot\delta}$ is computed according to (4.16) or (4.17), or according to Table 12 (second graph from left) one finds the coefficient of transfer q, and then one computes according to the formula

$$S_{p\cdot\delta} = S_M q.$$

In Table 17 we set forth amounts for the V_o of some typical terrain objects against a haze background, secured from prolonged series of observations with the help of one of the models of the IDV visibility gage. On the basis of the data in this Table, the values for the relative range of visibility of some objects against a haze background are computed (4.16), and these are set forth in Table 18.

From Table 18 it follows that in the light hours of the 24 the range of visibility of the majority of real terrain objects projected against a background of haze and having sufficiently large angular dimensions, corresponds approximately to the meteorological range of visibility.

It is precisely this peculiarity of the real objects in question that makes it possible to identify their range of visibility with the meteorological range of visibility, i.e., with the state of transmissivity of the atmosphere, and that constitutes the foundation for any visual scale of visibility, including the international 10-point scale of 1935.

TABLE 17. MEAN VALUES V_o AND lg V_o OF SOME TERRAIN OBJECTS PROJECTED AGAINST A SKY (HAZE) BACKGROUND AT THE HORIZON DURING THE LIGHT HOURS OF THE 24 (MEASUREMENTS WITHOUT JOGGLING IMAGE) AND HAVING ANGULAR DIMENSIONS NOT LESS THAN 15 × 15'

Object	Period	With sharply defined, even outline		With broken, jagged outline	
		V_o	lg V_o	V_o	lg V_o
Absolutely black body.		45	1.65	--	--
Mature coniferous forests and groves.	Year-Round	40	1.60	34	1.53
Mature deciduous forests and groves:					
With leaves	Spring, Summer and Autumn	34	1.53	28	1.45
Without leaves	Autumn and Winter	24	1.38	20	1.30
Mixed forest.	Year-Round	37	1.57	30	1.48
Individual coniferous tree (not further than 2.5 km):	"	37	1.57	30	1.48
Individual deciduous tree (not further than 2.5 km):					
With leaves	Spring, Summer and Autumn	--	----	28	1.45
Without leaves	Autumn and Winter	23	1.35	20	1.30
Grassy hillocks.	Summer	33	1.52	--	----
Objects under frost or snow (Forests, hillocks, trees, buildings, etc.):					
Gray background	Winter	25	1.40	--	----
Light gray background	"	14	1.15	--	----
Buildings of gray brick and reinforced concrete	Year-Round	23	1.36	--	----
Buildings of red brick	"	40	1.60	--	----
Dark gray steeples, old weather log buildings.	"	40	1.60	--	----
[illegible] poles (not farther than [illegible] km)	"	40	1.60	--	----

TABLE 18. RANGE OF VISIBILITY, DURING DAYLIGHT, OF SOME TERRAIN OBJECTS, PROJECTED AGAINST A HAZE BACKGROUND AND HAVING ANGULAR DIMENSIONS (AT RANGE $S_{p \cdot \Delta}$) not less than 15' X 15' (RELATIVE TO METEOROLOGICAL RANGE OF VISIBILITY S_M)

Object	V_o	lg V_o	Range of Visibility Relative to S_M
Absolutely balck body.	45	1.65	1.00
Coniferous forest with even outline.	40	1.60	0.99
Same with broken outline.	34	1.53	0.95
Deciduous forest with even outline.	34	1.53	0.95
Same with broken outline.	28	1.45	0.90
Same without leaves, with broken outline.	20	1.80	0.80
Mixed forest with even outline.	37	1.57	0.97
Same with broken outline.	30	1.48	0.92
Grassy hillocks with even outline.	33	1.52	0.94
Individual coniferous tree with even outline (not farther than 2.5 km).	37	1.57	0.97
Individual deciduous tree with broken outline, no leaves.	20	1.30	0.80
Same, with leaves.	28	1.45	0.90
Substantial structures of red brick (chimneys, buildings, etc.).	40	1.60	0.99
Dark gray steeples, old weathered log structures, etc.	40	1.60	0.99
Large objects (forests, structures, etc.) under snow and frost (light background).	14	1.15	0.71
Structures of light gray brick.	20	1.30	0.80
Large railway bridges.	30	1.48	0.92
Triangulation signals.	25	1.40	0.91
Old telephone posts.	40	1.60	0.99

Thus if an object is located at a distance less than L_{cr}, and if $S_M < L_{cr}$, then $S_{p \cdot \Delta}$ is determined according to (4.16) or through the q coefficient (Table 12) without any corrections for angular dimensions.

With $S_M > L_{cr}$ it is necessary to find $V_{o\gamma}$ via (4.12) to start with, and then to compute $S_{p \cdot \Delta}$ in accordance with (4.17), with the condition that S_M must be known.

For example, let us determine the $S_{p\cdot\Delta}$ of a factory chimney with S_M = 15 km and V_0 = 40. From Table 14 we find that for the chimney L_{cr} = 4 km. From (4.12) we compute $V_{0\gamma}$ at distance S_M, i.e.,

$$V_{0\gamma} = 40 \cdot \frac{4}{15} = 10,5.$$

Finally in accordance with (4.17)

$$S_{p\cdot\Delta} = 0,62 \cdot 15 \log 10,5 = 9,5 \text{ км},$$

i.e., $S_{p\cdot\Delta}$ is approximately two-thirds as great as S_M. This diminution is occasioned by the aggregate operation of two factors: the reduction of the V_0 value on account of small angular dimensions (at distance $S_{p\cdot\Delta}$) and the masking effect of haze characterized by the magnitude of S_M.

Let us note that actually the magnitude of S_M in the example being examined will be somewhat larger than the one secured, since $V_{0\gamma}$ must be determined relative to the range $S_{p\cdot\Delta}$ which is being sought, and not relative to S_M. But although this point does constitute a chortcoming of the method for getting $V_{0\gamma}$ that has been set forth, the distinction between the actual and the computed values of $S_{p\cdot\Delta}$ is not great, and this is acceptable for practical purposes. Moreover, even the other, more accurate ways of calculating $V_{0\gamma}$ also contain a series of imprecisions, and the value $S_{p\cdot\Delta}$ of a small object is also secured in approximate form.

The approximated method for getting the $V_{0\gamma}$ of objects relative to γ with the help of the introduced concept of "critical distance", as just set forth by us, is readily applicable to elucidating the problem: at what values of S_M is the visibility range of a small object against a sky background basically determined by diminution of its angular dimensions? For this purpose we must find from (4.12): at what value for S_M and the given value for L_{cr} does $V_{0\gamma}$ = 3? (see Figure 21).

For the case of the factory chimney we have from (4.12)

$$S_M = \frac{V_0 L_{cr}}{V_{0\gamma}} = \frac{40 \cdot 4}{3} = 53 \text{ км}.$$

In accordance with (4.17) we determine the maximum range of detection of the chimney

$$S_{p\cdot\Delta\cdot max} = 0.62 \cdot 53^{\log 3} = 16 \text{ км.}$$

At this distance the chimney will be barely visible, on account of the aggregate effect of atmospheric haze and its diminishing angular dimensions. But if from this distance one looks at the chimney with an 8-power binocular, thanks to the augmentation of the angular dimensions it will be a great deal more readily visible.

Thus the maximum range of visibility of a small object, observed against a sky background with the naked eye, depends on the ratio $(L_{cr}/S_M)\cdot 15$ at which the value $V_{OY} = 3$ is attained.

If one takes into account the fact that the threshold range of disappearance is approximately 30% greater than the threshold range of detection, then in our case with the factory chimney (with $S_M = 15$ km) the range of disappearance of the chimney will be equal to 13 km, and in place of the maximum range of 16 km at which the chimney is barely visible, we shall secure a range of disappearance equal to 20 km.

It ought to be remarked that pronouncedly elongated objects on the lines of antennae, or high electric transmission lines, are visible at very great distances. This takes place for two reasons: first, such objects can be projected against a background of blue sky, rather than of haze, which increases their degree of visibility; in the second place, the threshold of sharpness of such objects declines from 1' to 10-20", which changes the initial relationships.

The procedures set forth can easily be applied to any object and for any value of S_M. We repeat, these procedures do not pretend to great precision and give the $S_{p\cdot\Delta}$ value for objects with an error of 25-30%. But as we see it, the attainment of high degrees of accuracy is hardly sensible or susceptible of achievement, if one takes into account the fact that the contrast sensitivity and particularly the acuity of vision in different people are subject to considerable variations; the transparency of the atmosphere may be heterogeneous along a beam of vision, the properties of the objects themselves (character of outlines, etc.) change with distance, etc. A striving toward unjustifiably high precisions leads to making the observation more complicated, to a need for calling to mind a great many rules, to prolongation of the time for solution of the problem, all of which taken together scares the user away from such methods.

In the practical determination of $S_{p \cdot \Delta}$ it is perfectly possible to rest satisfied with an error of 25-30%.

Our method for the determination of the $S_{p \cdot \Delta}$ of objects, based upon the "critical distance" concept and the existence of a linear dependence of $V_{0\gamma}$ upon γ, is precisely the one that offers the degree of accuracy referred to.

§ 28. Landing Range of Visibility, Posing the Problem

The present-day aerial radio navigation complex completely solves the problem of blind flight, as we are aware, at times when no ground orientation points are visible, but at the same time it is still too incompletely refined to ensure blind landing on a runway with 100% guarantee of successful results.

The absence of methods for blind landing makes the regularity of flights depend directly upon meteorological conditions and inflicts enormous losses not only upon aviation, but upon the national economy as a whole.

The working out of blind landing methods under a complicated set of meteorological circumstances is among the most difficult of scientific and technological problems. Prolonged efforts in this direction both in the USSR and abroad have not yet led to solution of the problem. Endeavors to apply television to blind landing, which have been made in many countries, have been recognized to be unsuccessful.

The insufficient contrast sensitivity, the absence of stereoscopic vision, the small resolving capacity, and other shortcomings of present-day television images, lead to distortion of spatial perception and to a lack of correspondence between the scale of the television image and the scale of the picture actually observed. For example, according to experimental data in Belgium, the difference between a visual estimate of the range of visibility up to the beginning of the runway (in the lower part of the approach glide) and its estimate according to a television image comes to tens of meters. Investigations on the application of television for determination of the range of visibility on a runway have not passed beyond the experimental stage.

Tests carried out in England on controlling a blind landing from the control tower with the help of a radio-location apparatus have shown that this method is also unable to guarantee a successful landing in 100% of cases.

The radio-technological principle of so called equi-signal zones appeared very promising; it was supposed to ensure the indispensable precision in guiding the airplane along the axis of the runway and in determining its height above the ground. Experience in use showed that this system ensures a blind approach to the runway only to a distance of about 0.5 km to the beginning of the strip, after which the aviator is once more obliged to shift to visual piloting. Thus the equi-signal zone method also failed to solve fully the problem of the blind landing.

The absence of blind landing methods makes it necessary, at some final stage of the approach glide, to shift to visual piloting and visual landing. In this concluding stage of the flight the visual functions of man estimate altitude and direction of flight more accurately than do present-day aerial navigation devices.

In order to get a clear idea what factors affect visual landing under complicated meteorological conditions, let us follow the trajectory movement of an airplane in the concluding stage of a flight.

Let us turn to Figure 23 (see also Figures 30 and 31).

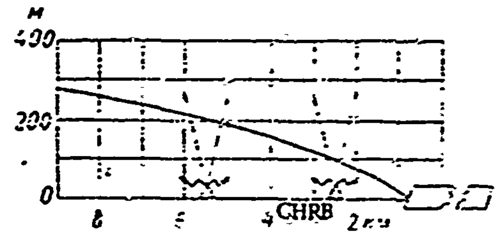


Figure 23. Diagram of Trajectory of Motion of Airplane Going in to Land.

The gradual approach of the airplane (on instruments) commences some tens of kilometers from the point of landing. The flight trajectory of the plane from the start of its loss of altitude to the point of landing is called the approach glide. The landing of contemporary heavy aircraft weighing tens and hundreds of tons is carried out on special concrete landing and take-off strips, equipped with a system of lighting and radio devices intended to ensure a successful visual landing.

With general high transmissivity of atmosphere and with absence of cloudiness the problem of determining landing visibility does not arise, since in the light hours of the 24 the landing strip itself, and by night the system of signal lights associated with it, are readily visible from a distance of some tens of kilometers.

The situation changes radically when heavy atmospheric turbidity and low cloud are observed. In the complete absence of visibility of ground surface objects, piloting of an airplane is carried out by instruments all the way to the close-in homing radio beacon (BPRM) (Figure 23), after passing which the pilot shifts to visual piloting. In this first stage of visual landing there must be communicated to the pilot the so-called vertical altitude -- the height at which, upon coming through the cloud cover, he will see the ground in daylight or signal lights in darkness.

To jump ahead, we shall show that in the first stage complications frequently arise as to the determination of vertical altitude, these being occasioned by the complicated structure of the lower limit of cloud cover.

Simultaneously with vertical visibility the pilot must be told the distance at which, looking along the incline below the approach glide, he will see the beginning of the runway or the system of signal lights at even a very faint (threshold) perceptivity. This determines the so-called oblique visibility range.

Visual landing is not possible at every value for vertical and oblique visibility.

The inertia of the visual and motor functions of man, combined with the great speeds of an airplane in its approach glide and with its inertia, determines for each type of airplane (and also for the class of polit) some specific permissible minimum of vertical and oblique visibility, passing beyond the limits of which is associated with the possibility of an accident. This minimum is determined through landing norms effective in the Civil Aviation System of the USSR. In particular, at present the norms for vertical visibility come to amounts ranging from 50 meters for piston aircraft to 120 meters for jet airplanes of TU-104 type. The norm for oblique visibility runs from 500 meters for piston airplanes to 1,200 meters and more for jet airplanes.

It is obvious that range of visibility on an incline along the glide in any given case cannot be less than the vertical visibility, for which reason the basic factor limiting the visual landing is the oblique visibility.

The inexorable shift to visual piloting immediately before landing has made it necessary to work out scientifically well-grounded operative methods for determining landing visibility. One may give the following definition of the concept of these:

The landing range of visibility (S_{ld}) *is the name given to the maximum distance, on an incline along the approach glide, at which, with worsened visibility, the pilot of a landing airplane, upon shifting from instrument to visual piloting, can detect at the threshold of perceptivity, and recognize, the beginning of the runway and the system of signal lights associated with it.*

With good transmissivity of atmosphere and absence of cloudiness, both in daylight and in darkness the need for determination of landing visibility diminishes, since the runway by day, and the system of signal lights by night, are visible, as has already been pointed out, from a great distance.

With poor transmissivity, in daylight the visibility of the beginning of the runway on an incline along the glide may be worse or better than the visibility of the signal lights, depending on the density of fog or heavy haze and the level of general illumination.

The pilot carrying out the landing must be told both the range of visibility of the beginning of the runway, and the range of visibility of the signal lights.

With heightened turbidity of atmosphere in darkness the range of visibility of the beginning of the runway is very low (considerably less than the meteorological range of visibility), but under the same circumstances range of visibility of high-intensivity signal lights is always greater than the meteorological range of visibility (Figure 24).

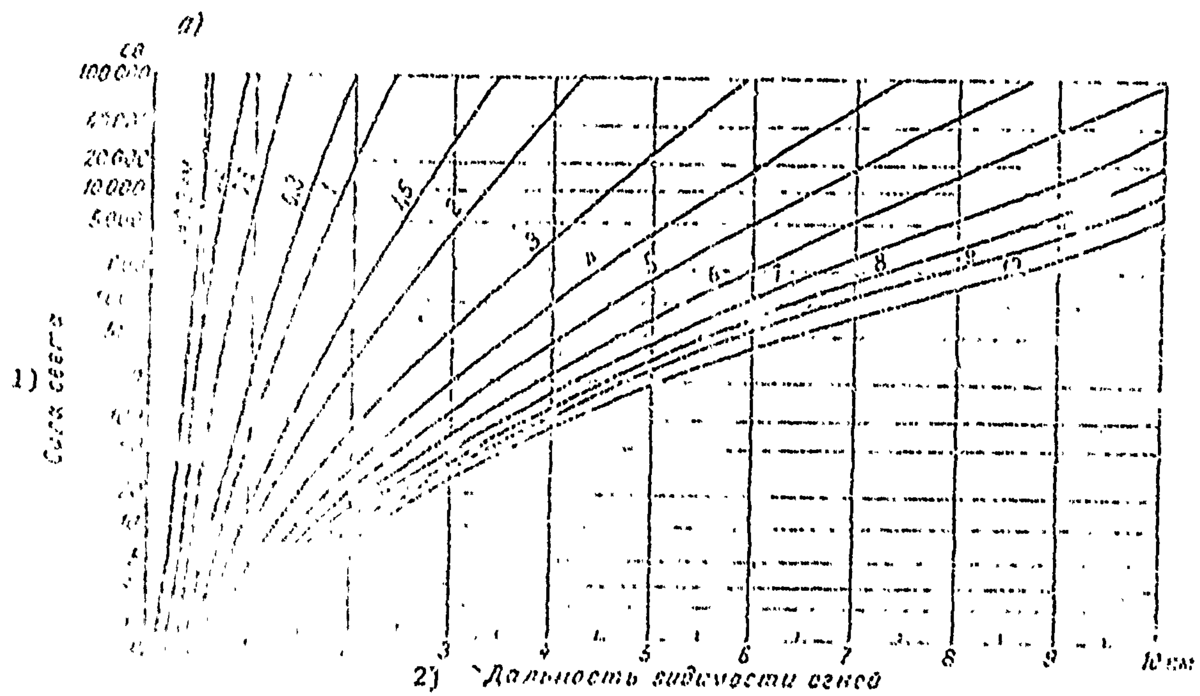
It would seem that the need for determining range of visibility of signal lights at airfields would fall away even when there is dense fog. But a series of complicating factors (aureole effect, etc.), which are examined in detail in the next chapter, shows the lack of justification for any such supposition.

Thus even in darkness an aviator, carrying out a landing with bad transmissivity c. [illegible]osphere, should receive information regarding the range of visibility, [illegible] incline along the approach glide, both of the signal lights and of [illegible] [illegible]ning of the runway.

§ 29. Some Pecul[illegible]arities of Meteorological Factors Determining Landing Visibility

The state [illegible] [illegible]eorological circumstances associated with weather minima for landi[illegible]gs is characterized by heterogeneity and great changeability in time and in space. It is clear from the following examples how greatly this circumstance hampers the determination of landing visibility.

To begin with let us examine the question of the height of the lower limit of low clouds, which determines vertical visibility.



... Range of Visibility of Signal Lights of Varying ... in Darkness and in Daylight.
a) Darkness, $E_{nor} = 10^{-6}$ lux; b) Daylight, $E_{nor} = 10^{-3}$ lux.

Key: 1) Strength of Light; 2) Range of visibility of lights.

If the lower limit of low clouds constituted a shrply defined plane of division between clouds and "pure" atmosphere (Figure 25), determination of vertical visibility would not be difficult, inasmuch as present-day triangulation [12] and photolocation cloud meters measure the height of such a lower limit with sufficient accuracy.

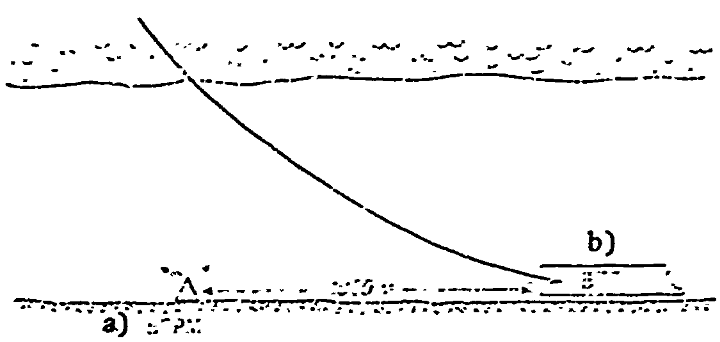


Figure 25. Landing Conditions With Sharply Defined Lower Limit of Clouds
BPRM -- close-in homing radio beacon; VPP -- landing and take-off strip.
Key: a) BPRM; b) VPP.

But as observations show, the lower limit of a cloud height greater than or equal to 200-250 meters is almost never clear-cut. The most widespread structure for the lower limit of such clouds is an alternation of sections of cloud sharply distinguished as to height, at some points passing over into formless strips of cloud hanging all the way down to the earth's surface (Figure 26). Such a cloud is as a rule moving rapidly in one direction or another. What is one to call the height of the lower limit of such a cloud? To what extent does it correspond to vertical visibility for an aviator who is carrying out a landing? Here we run up against disparities between the height of the lower limit of cloud as determined instrumentally through measurements from the ground, and the actual height of "detection" of the ground, determined visually by a pilot ...ing in for a landing; these disparities are constant, and they have not been overcome to date.

One also runs up against another type of structure of the lower limit ... clouds. It is characterized by the fact that there is no real boundary as such, but instead a gradual transition takes place from an optically less dense sub-cloud haze which is also optically variable with height (Figure 27). In many cases the sub-cloud haze reaches the surface of the earth or hangs above it at one inconsiderable altitude or another.

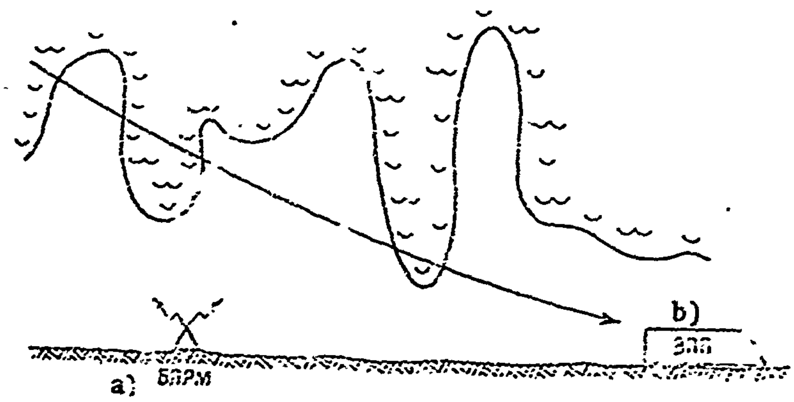


Figure 26. Landing Conditions Amid Complicated Structure of Lower Limit of Clouds
Key: a) BPRM; b) VPP

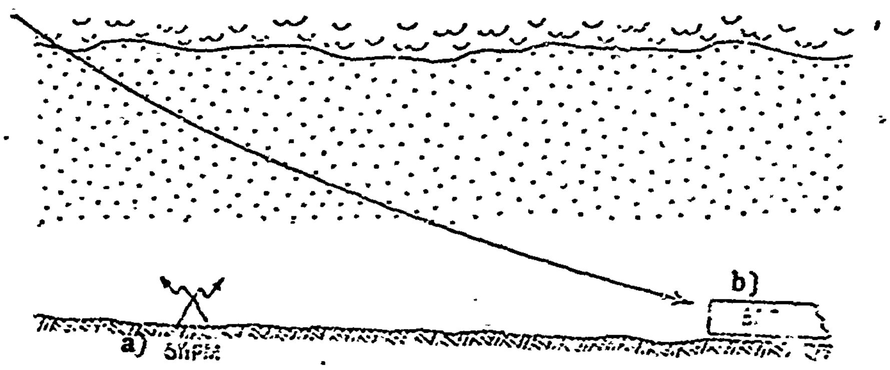


Figure 27. Landing Conditions When Sub-Cloud Haze Is Present.
Key: a) BPRM; b) VPP

What is one to call the height of the lower limit of clouds in this event? Here, as in the preceding case, one encounters discrepancies affecting both the very concept of "the height of the lower limit of clouds," and the data which must be communicated to the pilot who is coming in for a landing.

Such are the difficulties in the way of determining vertical visibility; they arise by reason of the complicated character of the meteorological phenomenon under observation, and of the fact too little study has been devoted to it.

One encounters complications that are no less considerable in connection with the question of measuring the transmissivity of the atmosphere.

The transmissivity of the atmosphere, in an oblique direction and within the limits of landing norms, can change in the sharpest and most unexpected fashion. But to date neither apparatus nor methods have been worked out for measuring the transmissivity of the atmosphere in an oblique direction, such as might be used in practice. Existing treatments have still not emerged from the stage of experimental work and testing (see Chapter VII). This circumstance is a serious obstable to correct determination of landing visibility.

The well-developed basis method (see Chapter VI) makes it possible to measure and register the meteorological range of visibility only in a horizontal direction. But fog, and marked turbidity of the atmosphere in general, are characterized by a considerable spatial heterogeneity and by rapid changes with time both in inclined and in horizontal directions. Methods for measuring and figuring this spatial and temporal heterogeneity have not been worked out to date, something which is sometimes the cause of serious accidents.

Still a further phenomenon of a meteorological character complicates the solution of the question of landing visibility.

A system of airport signal lights is a group combination of constant or flashing lights of high intensivity (power extending up to 500,000 candlepower). Such group lights possess in darkness, when there is pronounced turbidity of the atmosphere, a considerable aureole effect, thanks to which there comes into being a luminous curtain extending some hundreds of meters in width and some tens of meters high. The presence of the luminous curtain increases the importance of threshold illumination E_{th} for the group lights (the light sensitivity of the eye falls off), in which connection this takes place the more, the greater is the atmosphere turbidity. It is striking that despite the urgency of the question there is not a single investigation on the values of E_{th} for group lights in the presence of aureole effect.

If to this one adds the absence of studies on the effect upon E_{th} (as well as on the threshold of contrast sensitivity ε) of such factors as pilot fatigue, dirtying of the sight glasses of the cabin, etc., one may conclude that inadequacy of studies on the threshold visual functions also obstructs any high-quality optical determination of landing visibility.

§ 30. Factors Which Determine Landing Visibility

To sum up what we have said in the two preceding sections, let us make a list of the meteorological, phototechnical, and psycho-physiological factors that determine landing visibility during daylight and during darkness:

I. Meteorological factors:

1) Height and character of structure of lower limit of clouds;
2) Vertical amount of sub-cloud haze and vertical gradient of its optical density;
3) Average transmissivity of atmosphere (mean value of meteorological range of visibility) on an incline along the final section of the approach glide;
4) Transmissivity of atmosphere (meteorological range of visibility) in a horizontal direction close to the beginning of the runway;
5) Changeability of the factors indicated, in time and in space;

II. Phototechnical factors:

1) Photometrical characteristics of the runway and the background surrounding it (parameters $V_o = K_o/\varepsilon$, S/B_c, or $4S/V_c$'

2) Photometric characteristics of the runway signal lights (I_o):

III. Psycho-physiological factors:

1) Characteristics and condition of the threshold visual functions of pilots coming in for landing (ε and E_{th} for group lights).

From what we have said it follows that the meteorological safeguarding of aviation which is associated with determination of landing visibility during daylight and darkness calls for study of the optics of the ground-surface layer, creation of apparatus for measurement of transmissivity of the atmosphere in horizontal and non-horizontal directions, the development of methods for measuring and figuring spatial and temporal changeability of meteorological factors, and the study of threshold visual functions.

§ 31. Methods Systems for Determining Landing Visibility in Daylight. Experimental Values of Basic Parameters

In this section we examine the methods for determining in daylight the range of visibility of the beginning of the runway as an object which forms a "ground-level" contrast with the background that surrounds it. The question of the range of visibility of the signal light system is examined in the next chapter.

Since under complicated meteorological conditions the shift to visual piloting is made at a relatively short distance from the beginning of the runway, the latter can be regarded as an object having large angular dimensions and thus one to which the relationship (4.5) is applicable. But since the light-gray concrete surface of the runway is as a rule more luminous than the background which surrounds it, with the exception of winter conditions, instead of the ratio D/B_σ one can take D/B_{runway} or the equivalent ratio $45/V'_{run}$, where V'_{run} is a quantity determined in accordance with the moment of extinction of the mark of the visibility gage against the runway background.

Thus the determining expressions for S_{land} applicable to the beginning of the runway will be the equations

$$S_{land} = 0{,}62 S_M \log \frac{V_0 + \frac{D}{B_{run}} - 1}{\frac{D}{B_{run}}} \tag{4.18a}$$

or

$$S_{land} = 0.62 S_M \log \frac{V_0 + \frac{45}{V_{run}} - 1}{\frac{45}{V_{run}}}. \tag{4.18b}$$

From these expressions the invalidity of the frequently applied procedure under which S_{land} is determined as the value of the meteorological range of visibility S_M with a certain constant empirical correction, and without taking the parameters V_0 and D/B_{run} into account, is clearly apparent. To this end, in expression (1.23) for S_M the value of ε is increased. For example, in the United States in graduating Douglas transmissivity registers (see § 42) the quantity ε is taken as being equal to 0.055, and S_M as being equal to $\frac{2.9}{\alpha}$ or to $\frac{1.26}{\alpha_{10}}$. In France the value of S_M, measured with an instrument, is simply reduced by 30% or even 60%, and is taken as being the S_{1and} of the beginning of the runway in daylight [226].

Such empirical corrections, and constant ones at that, cannot take into account the seasonal alterations of contrast between the runway and the background surrounding it, nor variations in depending on circumstances of illumination and other factors. The magnitude of S_{1and} for the beginning of a runway is correctly determined only with parameters V_o and D/B_{run} being taken into account.

Here we shall not touch upon steps for measuring S_M with application to the problem of determining S_{1and}, since this question, which has a long history, is examined independently in Chapter VI.

Let us pass on to determination of the parameters V_o and D/B_{run} in their application to the problem of the visual landing of airplanes.

The parameter V_o of concrete runways has been investigated in detail in accordance with the seasons of the year. The measurement procedure is set forth in § 24. The basic ground observations were carried out at Leningrad airport, and the check ones were carried out at Vnukovo airport, Gorkii, and others. The observations were basically carried out by A. K. Donskoi.

The observations on a concrete runway from the air (from airplanes and from free balloons) were carried out at the Leningrad, Kiev, Minsk, and Tula airports. The basic observations were made by E. N. Dovgiallo and the author of the present monograph.

As a result of observations carried out at all seasons of the year, about 250 series of measurements were secured, which made it possible to establish reliable seasonal values for the V_o of concrete runways by daylight under various meteorological conditions. Resultant data are set forth in Tables 19 and 20.

One should note that the deviations (not errors) of actual values of V_o from the mean for various runways and backgrounds and for more detailed lighting conditions do not exceed 25%, and that this figure only slightly exceeds the usual error of photometry by extinction. Inasmuch as V_0 forms part of the value of S_{1and} not directly, but via a logarithm, the averaging indicated is altogether permissible.

TABLE 19. MEAN VALUES FOR V_0 OF CONCRETE RUNWAYS BY SEASONS OF THE YEAR AND UNDER VARIOUS METEOROLOGICAL CONDITIONS (GROUND OBSERVATIONS AND OBSERVATIONS FROM THE AIR)

Season	Background	Cloudless	Diffused Lighting	Cloudy
Spring	Yellow-brown grass from last year.	18 (9)	23 (10)	17 (3)
Summer	Bright green grass.	27 (51)	27 (23)	26 (12)
Fall	Yellow-green or browning grass.	20 (30)	20 (37)	21 (15)

NOTES: 1. In the summer after a rain (with runway wet) and under any lighting conditions the value for V_0 is 21 (six series of measurements).
2. In the Fall after a rain (with runway wet) and for any conditions of illumination the mean value of V_0 is 18 (10 series of measurements).
3. The number of series of measurements is given within parentheses.

During the winter, ground measurements of V_0 become difficult, since the dividing line between the runway and the snow background surrounding it is very far from clear. On this account for the winter (and in part for the spring) period measurements of the V_0 of the runway were carried out from the air (see Table 20).

In accordance with the data of Tables 19 and 20 it is possible to determine the mean quantities for the V_0 of concrete runways for various seasons of the year and various meteorological conditions (Table 21).

Operative utilization of the mean values for V_0 set forth in Table 21 in determining landing visibility is examined in the next section..

Let us now set forth the results of measurements of the parameter D/B_{run} or $4S/V'_{run}$, as they apply to the airports indicated above. The principle for measurement has been examined in detail in § 26. It was impossible to carry out measurements of this sort from the air, as a consequence of limited splitting of the images in the field of vision of the visibility gage.

TABLE 20. MEAN VALUES FOR V_o OF CONCRETE RUNWAYS

Airport	Type of Flight	Background	Condition of runway	Lighting Conditions	V_o	No. of Series of Measurem.
			Winter			
Leningrad	Airplane	Snow	Partly snowed over.	Diffused lighting	8.0	4
"	"	"	Same	Cloudy	6.5	5
Gorkii	Free balloon	"	"	"	8.1	1
Leningrad	Airplane	"	Snowed over	"	6.0	7
			Spring			
Tula	Free balloon	Camouflaged	Without snow, dry	Cloudy	16	5
"	Same	Last year's grass	Partly snowed over	"	15	4

TABLE 21. MEAN VALUES OF V_o OF CONCRETE RUNWAYS FOR VARIOUS SEASONS OF THE YEAR AND VARIOUS METEOROLOGICAL CONDITIONS

Background	Lighting Conditions	Condition of Runway	
		Dry	Wet
Yellow-brown (last year's grass, without snow.	Any	20	--
Bright green young grass.	"	27	21
Yellow-green grass turned brown in spots, and subsequently all turning yellow.	"	20	18
Snow of varying whitenesses (background and runway under snow)	Predominantly cloudy	8	--
Camouflaged (snow patches).	Same	16	--

With application to concrete runways about 100 series of ground measurements of D/B_{run} were carried out; they were executed for the most part by A. K. Donskoi. It proved to be the case that as it relates to a runway the value of this parameter depends but little on the magnitude of the meteorological range of visibility and on the lighting conditions.

In 86% of all measurements carried out for a dry runway in the spring, summer, and fall, the mean value of D/B_{run} came to 1.5 with individual deviations (not errors) from the mean amounting to plus or minus 30%. In 14% of cases (12 series), which were rejected for various reasons, the deviations were greater than ± 30%.

For a wet runway (after rain) the mean value of D/B_{run} came to 2 (16 series of measurements), with deviations of plus or minus 25% from the mean.

In order to determine landing visibility the following final values were selected:

1) for a dry runway D/B_{run} is equal to 1.5 the year round;
2) for a wet runway D/B_{run} is equal to 2.0;

During the winter season, as we are aware, snow is thawed through the use of special machines and concrete runways are always maintained in a dry state, for which $D/B_{run} = 1.5$.

The use of the measured magnitudes of D/B_{run} for operative determination of S_{land} is examined in the next section.

§ 32. Nomograms for Range of Visibility of the Beginning of the Runway During Daylight. Marking the Runway.

The determination of landing visibility range which was set forth in § 28 shows that S_{land} should be based upon the concept of threshold detection.

In France they take as the basis for the norm of landing visibility the criterion of threshold recognition [226, 227], in accordance with which S_{land} is approximately 30% less than the range of visibility in accordance with the threshold of detection.

In our view, to base minima of landing visibility upon the criterion of threshold recognition is unreasonable, since in conditions of bad visibility it would become necessary to prohibit landing a good deal more frequently, something which would without special need inflict a great economic loss.

In the same fashion it is impossible to base landing norms on the criterion of threshold disappearance, at which S_{land} would be approximately 20% greater than the range of threshold detection. To compute the range of landing visibility in accordance with invisibility of the runway is in our view impossible.

Taking as point of departure the circumstance that landing visibility ought to be determined in accordance with the criterion of threshold detection, one should introduce threshold contrast ε_{det} into (4.18a). It is clear that ε_{det} should be applicable not to the value of S_M, but to the parameter V_o, inasmuch as it determines the degree of visibility of a runway against a given background.

The values of V_o for a runway, set forth in Table 21, contain the quantity ε_{dis} in harmony with the procedure for measurement -- i.e., $V_o = K_o/\varepsilon_{dis}$. This means that it is necessary to introduce a correction into the tables referred to above, before one can use them for operative purposes. Without pausing on details, we may note at once that as applied to the landing of airplanes, when observation takes place through dust-obscured slightly yellowish glasses of a pilot's cabin, ε_{det} is approximately twice as large as ε_{dis}, in harmony with which the values for V_o in Tables 19 and 20 should be cut in half. But if the landing takes place in rain or a snowfall, this proves to be insufficient.

Raindrops striking a sight glass that is moving at great speed form something like a curtain of watered dust, which considerably worsens and distorts the perception of objects.

The perception of objects is also considerably worsened during a fall of snow, when snowflakes stick to the sight glass, and partially melt upon it. In these cases, as observations carried out right in the pilot cabin show, threshold contrast of detection rises up to 7%, in harmony with which the value for V_o in Tables 19, 20 and 21 should be reduced approximately by 3.5 times.

Particularly important distortions are introduced, under such circumstances, by sight glasses of the pilot's cabin which are markedly inclined to the line of sight, as in an airplane of TU-104 type.

The V_o values for a runway from Tables 19 and 20, after the introduction of the corrections examined above, are set forth in Table 22.

TABLE 22. SEASONAL MEAN VALUES FOR V_o OF CONCRETE RUNWAYS, SUITABLE FOR NOMOGRAPHING IN THE PRACTICAL DETERMINATION OF S_{land} (FOR DAYLIGHT AND UNDER ANY LIGHTING CONDITIONS)

Background	Condition of runway	Upon Landing of Airplane	
		Without Precipitation	With Precipitation
Bright-green young grass.	Dry	14.0	8.0
Same	Wet	10.0	6.0
Yellowish-green grass, or grass turned brown or yellow.	Dry	10.0	6.0
Same	Wet	9.0	5.7
Yellowish-brown (last year's) grass.	Dry	10.0	5.7
Patches of snow.	Without snow	8.0	5.0
Snow of various degrees of whiteness, patches of snow (overcast lighting).	Patches of snow.	4.0	2.0

According to the data of Table 22 and the values for D/B_{run} set forth above, we construct two nomograms for the operative determination of S_{land}. For this purpose, in the expression for the coefficient of transfer, q, from S_M to S_p (see Table 12)

$$q = 0{,}62 \lg \frac{V_0 + \frac{D}{B_{run}} - 1}{\frac{D}{B_{run}}}$$

we substitute the corresponding values of V_o and an amount for D/B_{run} equal to 2 or 1.5 depending on the state of the runway. The value secured for the coefficient is then multiplied by several arbitrary values for S_M, getting each time the quantity S_{land}. In the rectangular system of coordinates the S_M values are set off on the ordinate axis, and on the abscissa axis the

S_{land} amounts. The products of the arbitrary values for S_M times the given coefficient of transfer q form a straight line in this system of coordinates. For a series of values of the coefficients of transfer associated with the effect of the season of the year and the state of the runway we get a family of straight lines (Figure 28).

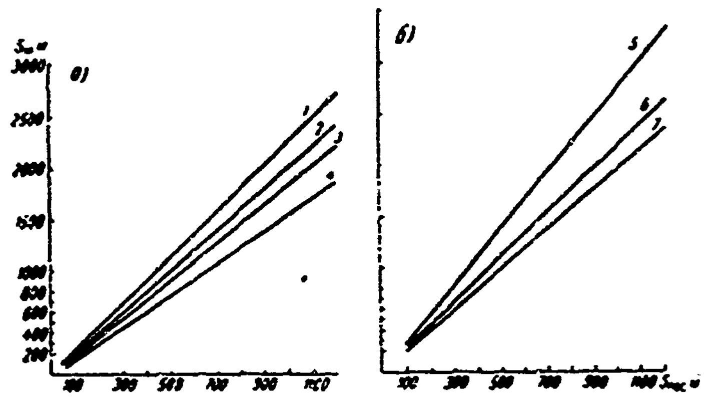


Figure 28. Nomograms For Determination of Landing Visibility S_{land} of the Beginning of the Runway in Daylight Without Precipitation (a) and With Precipitation (b).
1, Runway with patches of snow, background clean snow; 2, Runway wet, background grass of various shades; 3, Runway dry, background greenish-yellow and brown grass; 4, Runway dry, background bright-green grass; 5, Runway with patches of snow or wet, background clean snow; 6, Runway dry, background yellowish-brown grass; 7, Runway dry, background bright-green grass.

The nomogram in Figure 28 a is constructed for a dry sight glass in the pilot's cabin, the nomogram in Figure 28 b for a wet one.

The nomogram is to be used as follows. Knowing S_M, measured on an incline along the glide, we find on the ordinate axis the point that corresponds to this value of S_M. Joining it with the straight line which corresponds to the background that surrounds the runway at the given moment, and then dropping a perpendicular to the abscissa axis we find on it the value for S_{land}.

This is the most correct course for the determination of S_{land}. We may note that up to the present methods and set-ups have not been developed for measuring transmissivity recording systems, for example the M-37 set-up, note turbidity of the atmosphere only in a horizontal direction. In many cases one has to do with a lack of correspondence between transmissivity of the atmosphere on an incline along the approach glide and transmissivity of the atmosphere in a horizontal direction as noted by the M-37 recorder. This lack of correspondence can lead to a divergence between the range of visibility of the runway as determined by the nomogram referred to above, and the range of visibility of the runway on the incline along the glide set by the pilot who is coming in for a landing.

One has to reconcile oneself to this shortcoming until methods and devices for measurement of oblique transmissivity are developed. One of such possible methods is examined in Chapter VII.

In conclusion of the present section, let us pause upon the question of marking the runway as a method for reducing the meteorological range of visibility to the landing range in daylight, and partially twilight hours.

The nomographic determination of S_{land} contemplated in the present section is pretty simple and convenient when S_M values are stable or change but little. The situation becomes considerably more complicated if frequent, non-periodic, and sharp changes in S_M take place, something which is almost always observed when there are marked atmospheric turbidities. In this case the nomographic determination of S_{land} becomes of little operative value, because the person in charge of landing at high-load airports does not have a chance to devote his attention to landing visibility alone nor to follow its alterations continuously via nomograms.

But a simple method does exist which makes it possible to reduce the registered meteorological range of visibility to visual landing visibility of the beginning of the runway without transfer nomograms (or computers). This method consists in marking the beginning of the runway in the form of a system of stripes of one color or another, applied directly to the concrete surface of the runway at its beginning.

The idea of marking consists in principle in creating a constant artificial contrast of the beginning of the runway, which shall at the same time be as high as possible, so as to make the coefficient of transfer, q, from S_M to S_{land} (see Table 12), approximately equal to one. Then the range of visibility of the beginning of the runway will be determined not in accordance with the contrast between the runway and the background surrounding it (variable depending on the seasons of the year), but by the constant contrast between the system of applied stripes and the concrete surface of the runway that surrounds them.

According to the author's measurement data, the highest degree of visibility by day on a light-gray surface of a concrete runway is that possessed by a bright red covering (paint, ceramic tiles, etc.). The V_o value for such coverings is close to 40. Since the D/B_{run} parameter lies within limits 1.5-2, for the worst conditions we find from (4.18a)

$$q = \lg \frac{V_0 + \frac{D}{B_{run}} - 1}{\frac{D}{B_{run}}} = 20.$$

Then

$$S_{land} = 0{,}62 S_{м} q = 0{,}8 S_{м}.$$

For medium conditions, assuming $D/B_{run} = 1.5$, we find analogously

$$S_{land} = 0{,}62 S_{м} \log 30 = 0{,}9 S_{м}.$$

This means that if one determines S_{land} relative to the marking system applied to the surface of the runway, the transmissivity recorder (horizontal or oblique) will, when the corresponding constant correction is introduced, directly indicate the value of the landing visibility of the beginning of the runway. No transfer nomograms or computer apparatus are required.

Marking the beginning of the runway can be carried out in the following fashion (Figure 29):

1) at both ends of the runway an entering zig-zag-shape (or some other sort) of "zebra" of red or another color having the highest V_o value relative to the runway; the zig-zag shaped "zebra" is recognized from a much greater distance than is a rectilinear one; in addition, a rectilinear "zebra" may create an undesirable illusion of nearness;

2) the end and the flanks of the beginning of the runway are edged with lines of red or yellow color;

3) a runway axis is applied along its entire length (red, yellow, or orange paint);

4) sharply-contrasting single or double red or yellow lines are applied to the right and to the left of the axial line, with an interval of 35-50 meters, and over an extent of 250-300 meters from the end of the runway.

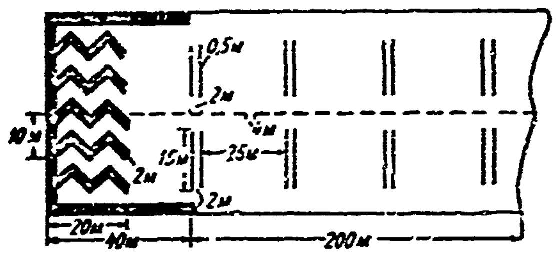


Figure 29. Diagram of Marking for Beginning of Runway.

Marking with white paint does not afford a heightening of visibility of the runway that is to any degree substantial in the winter time, although at other seasons, as it appears from investigations carried out not long ago, white paint affords the greatest contrast. The use of black paint is also disadvantageous, since the V_0 value of this paint against the background of the runway is about 20-25 (contrasts 40-50%) with dry concrete, and it falls to 10-15 with wet concrete, when the concrete darkens considerably.

Marking the beginning of the runway, beside simplifying determination of S_{land}, would heighten the visibility of the beginning of the runway under complicated meteorological conditions, something which would contribute to heightening the regularity of flights at all equipped airports. In addition, marking would facilitate the approach to landing for the pilots, and would simplify the work of airport personnel who service the landings of airplanes.

CHAPTER V

SOME QUESTIONS HAVING TO DO WITH DETERMINING THE VISIBILITY RANGE OF AIRPORT SIGNAL LIGHTS

§ 33. Present-Day Airport Light-Signal Media

Successful and safe landing of an airplane under conditions of bad visibility is possible only when radiotechnical and phototechnical media are utilized as a complex. Both of these forms of landing media reciprocaly complement each other and are of decisive importance at various stages of the landing process.

Phototechnical landing media afford the pilot the more help, the farther they are detected from the runway, i.e., the greater the distqnces from the runway at which the transfer from flight by instruments and radio media to visual orientation in accordance with light-signal media can be made. Since under circumstances of bad visibility phototechnical media cannot be observed from considerable distances, they are extended beyond the limits of the runway in the direction from which the plane will come in for a landing.

Setting up of lighting equipment beyond the limits of the airfield -- in a prolongation of the runway -- is a distinguishing peculiarity of the lighting equipment of all modern airports.

Flight practice shows that for safe and confident landing of airplanes the distance of transfer to visual flight for airplanes having turbo-jet and turbo-propeller engines should come to about 2,500 meters, and for airplanes with piston engines to about 1,000 meters, from the beginning of the runway.

Consequently the shift to visual flight for airplanes with piston engines takes place at the close-in homing radio beacon, which stands at a distance of 1 km from the beginning of the runway, and for airplanes with turbo-jet and turbo-propeller engines, between the close-in and outer marker beacons. The latter is located at a distance of 4 km from the runway. On this account, at first-class airports phototechnical equipment is set up along the margins of the runway and beyond the airstrip at a distance of about 2,500 meters from its start.

In order that signals set up on an airfield shall facilitate the landing of an airplane they must be set in a predetermined fixed sequence, the color of the light flow radiated by them being taken into account, as also the quantity and shape of the lights, the distance between them, etc.

The most widespread design for arrangement of lights intended to facilitate landing of airplanes under circumstances of bad visibility is that shown in Figure 30.

At a distance of 1,500 to 1,600 meters from the closer radio-marker point in the direction of the farther radio-marker point there are set up along a line prolonging the axis of the runway 30 to 36 impulse lights at a distance of 50-55 meters from each other.

The approach lights having flasher light sources are intended to render easier the lining-up of an airplane along the axis of the runway from remote distances as the airplane loses altitude for a landing.

The flash energy of the flashers comes to 150-400 Joules.

The approach flashers operate on a "chain lightning" regime, i.e., in the form of a succession of flashes moving in the direction of the runway. In accordance with the direction of the flashes of "chain lightning" the pilot confidently determines the direction toward the runway as he comes down for a landing.

The time between flashes of two lights falls within limits of 20-30 milliseconds. The frequency of the flashes of each light, and consequently of the whole line of flashers (30-36 units) is 45 in one minute, which corresponds to a flash period of 1.3 seconds.

For better detection of the lights the frequency of flashes is raised to 90-120 in one minute.

Depending on the transmissivity of the atmosphere, the approach flashers are switched in on two levels of brilliance corresponding to flash energy 100% and 30% of their nominal designation.

Between the close-in radio beacon and the beginning of the runway constant-beam approach lights and light-horizon lights are set up.

Constant-beam approach lights are intended to show direction along the axis of the runway and form marking the individual sections between the runway and the close-in radio beacon.

Constant-beam approach lights are set up on a line prolonging the axis of the runway.

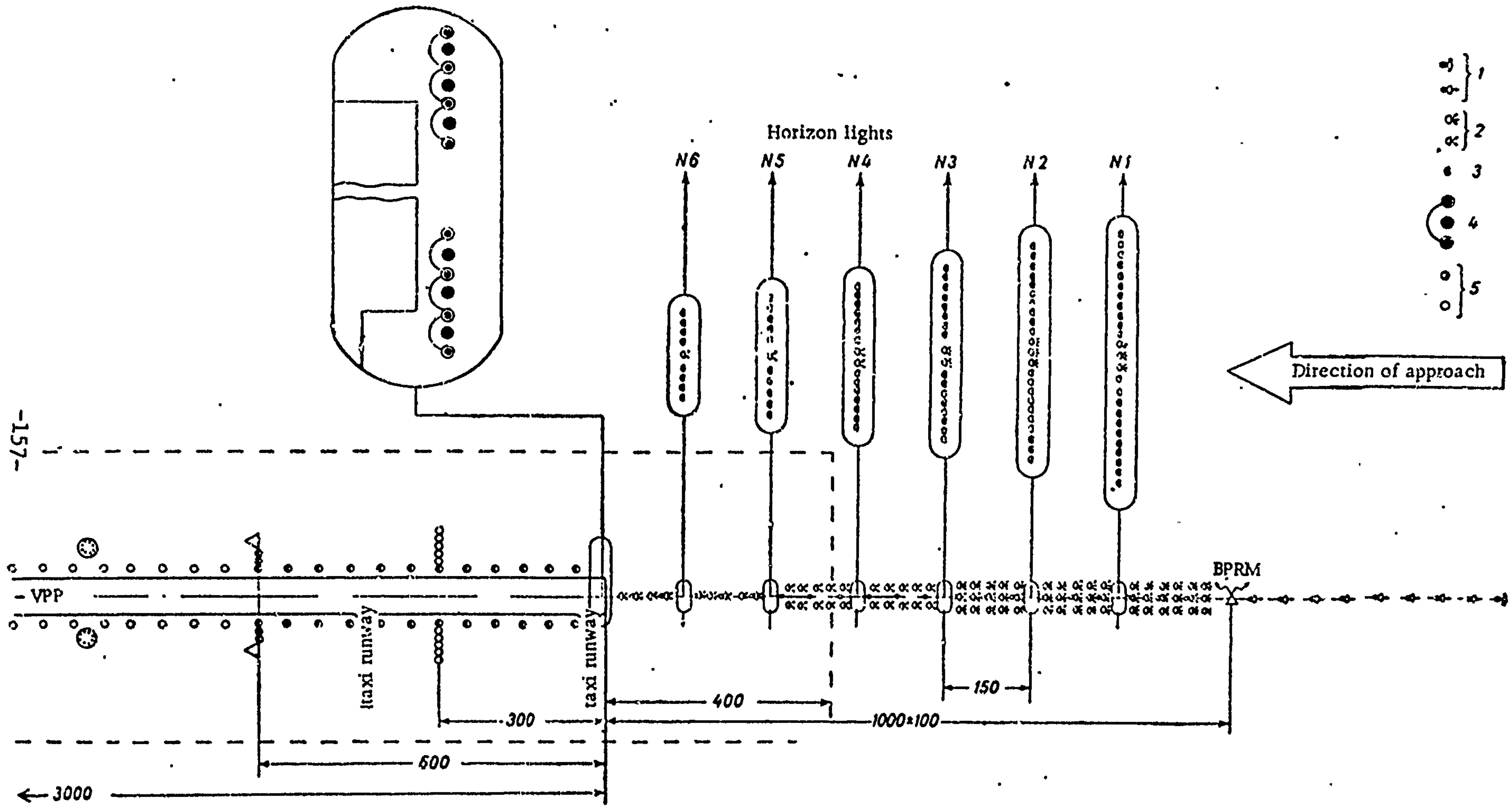


Figure 30. Diagram of Arrangement of Lights to Facilitate Visual Landing of Airplanes Under Bad Visibility Conditions. 1, Flasher approach lights, operating on a "chain lightning" schedule; 2, Constant approach lights; 3, Lights of light horizon; 4, Entrance border lights; 5, Landing lights.

So that the pilot may rapidly determine the location of the plane relative to the beginning of the runway, even in the event that he sees only a part of the lights of the central row, the sections of this row of lights are coded. At a distance of 300 meters from the beginning of the runway single approach lights are set up; at a distance of 300-600 meters doubled ones; and at 600 meters up to the close-in radio beacon, tripled ones.

The doubled and tripled lights are set up on lines perpendicular to the axis of the runway, at a distance of 1.75 m from each other.

The distance between approach lights along the line extending the axis of the runway comes to 25 meters.

Light-horizon lights are intended to form artificial horizons of lights in accordance with which the pilot can judge the horizontal position of the airplane in space.

The light-horizon lights are set up in six rows on lines perpendicular to the prolongation of the runway axis, at distances of 150, 300, 450, 600, 750, and 900 meters from the beginning of the runway. These lights cast an orange beam.

The light-horizon lights are disposed symmetrically relative to the line of approach lights. The distance between light-horizon lights in each row comes to 3.5 meters, and the distance from the line of prolongation of the runway axis to the first light rightward and leftward from this line is equal to 5.5 and 7 meters respectively.

All the light centers of the lights of each light horizon are disposed upon a single line parallel to the horizon.

At the third (from the runway) of the light horizons six projectors with red light filters are set up, with their color apertures aimed in the direction of the runway. These projectors serve as take-off lights, which are intended to show an airplane which is taking off the outer boundary of the end safety strip and the direction of take-off.

Take-off lights are used upon taking off; they are distributed symmetrically relative to the line prolonging the axis of the runway, at a distance of 7 meters from one another.

The constant-beam approach lights and the light-horizon lights have four or five steps regulating the strength of the light, depending on the transmissivity of the atmosphere. These steps correspond to 1, 5, 25, and

100% or (for a second system of lights) to 1, 3, 10, 30, and 100% of the nominal power of these lights.

In order to improve the field of view upon the landing of airplanes under circumstances of good visibility, so-called circuit vision lights, red in color, are set up on the approach lights at a distance of 50 meters from each other and on the take-off lights. The same sort of lights, but of orange color, are set up on the lights of the second and fourth (from the runway) of the light horizons.

Entering, boundary, and landing lights serve to delimit the runway.

There are two variants for setting up the lights of a runway:

1) Two landing lights and a circuit vision light are mounted at the runway in the form of three armatures not connected to each other;

2) All three elements are mounted in a single housing, which is set up at the runway in the form of a single three-lamp armature.

As runway marking lights, combined lights consisting of two landing lights the beams of which are directed along the runway in opposite directions are used, plus a circuit vision light, which sends out light into the entire upper hemisphere.

The landing lights are put to use under circumstances of deteriorated and poor visibility, and the circuit vision light under circumstances of good and deteriorated visibility.

Entering lights are used to mark the beginning of the runway, boundary lights to mark its end. Entering lights emit green light, and boundary ones red light.

At the end of the runway, at each of its corners, there is a single row of seven entering and boundary lights. The distance between lights is 5 meters.

Along the side edges of the runway, at a distance of 50 meters from each other, landing lights are positioned. In the first and last 600 meters of the runway the landing lights have orange filters in the projectors aimed at the center of the strip; but in the projectors aimed in the opposite direction there are no filters. Thanks to this, the landing lights at the last 600 meters of the runway are always emitting an orange light which warns of the end of the runway.

At a distance of 150-300 meters from the start of the runway in each direction, to the left and to the right of the strip, sets of five lights are installed which emit white light and each of which has a single directional beam and a circuit vision mounting. These are called landing indication lights, and they serve to mark off the zones for the landing of airplanes.

The runway lights also have four (sometimes five) adjustable stages of brilliance: 0.3, 2, 15, and 100%; or 1, 5, 25, and 100% of the nominal power of the light.

Along the flank edges of the taxiing lanes, at a distance of 50 meters from each other, taxiing lights are installed. At the points where the taxiing lanes join the runway, light signals are installed that signal permission for the airplane to enter the runway, or prohibition thereof.

Analysis of the system of arrangement of the lights used at airports abroad shows that the lights of the landing zones and the quick-exit lights will become highly developed in the future.

The landing zone lights (white) are intended to mark the runway and facilitate the landing of high-speed airplanes under bad visibility conditions. They are set in concrete over a stretch of 600 meters from the beginning of the strip.

The quick-exit lights (white) are intended to ensure the possibility of taxiing at high speed and of exiting into the closest taxiing lane. These lights are installed at the points where the runway adjoins the taxiing lane, along the central line of the latter. The landing zone lights and the quick-exit lights are not shown in Figure 30.

On the basis of what has been set forth above one can note the following characteristic features of light-signal installations used at airports, from the standpoint of their visibility.

1. In the field of vision of the pilot as an airplane comes down for a landing there is not one signal light, but a large group simultaneously. No method for computing the visibility of a group of point lights has been worked out to date. Until such a methods system is developed one can, in calculating the visibility of airfield light-signal installations, approximately reckon the effect of a group of lights with the help of a specially established coefficient of safety which forms part of the amount of threshold illumination.

2. Light-signalling installations are used in darkness at any values for the meteorological range of visibility, but by day only under bad

visibility conditions. Consequently the range of luminances of the background against which the lights are viewed is very broad. Calculating the visibility of signal lights on an airfield should be carried out over a wide variety of background luminances, all the way up to the maximum luminance values created by natural lighting.

3. In fog one can (with sufficient accuracy for practical pruposes) reduce the action of the atmosphere on the light beam to light scattering alone.

The physical essence of the scattering of light by air consists in the following. A light beam, falling upon some simple object, is scattered by it in all directions. This light diffused by a simple object is what constitutes the primary scattering of the beam of a light falling on suspended particles which exist in the atmosphere. The light flow diffused by the first particle falls upon a second particle, as a consequence of which it receives a secondary scattering. It is in the same way that light scattering of higher orders occurs.

Light signals are always seen against some sort of background (snow, grass, concrete, etc.) illuminated by natural or artificial light. Under circumstances of deteriorated or bad visibility a scattered light flow builds up on the natural background, creating a light envelope having a certain luminance which depends on the state of the atmosphere and the strength of the light. This additional luminance of the background develops as a result of the primary, the secondary, and higher orders of scattering of light by air.

The heightened luminance of the background diminishes the sensitivity of the observer's eye, and consequently diminishes the range of visibility of lights.

On the other hand, a light flow diffused by air creates supplementary components of illumination upon the eye of the beholder (as a result of primary, secondary, and higher orders of diffusion), which facilitate the recognition of lights. Thus the scattering of light during fog leads, on the one hand, to a heightening of illumination upon the eye of the observer, and consequently to improvement of the visibility of signal lights, but on the other hand to deterioration of the visibility of signal lights as a consequence of heightening of the luminance of the background, which reduces the sensitivity of the eye.

It is considered that both of the factors referred to -- increase of illumination and increase of the luminance of the background as a consequence of the scattering of light in fog -- complement each other reciprocally, on which account when the visibility range of signal lights is being calculated these factors are not taken into account.

But as more precise calculations of the author and tests of lights under real circumstances of bad visibility have shown, the influence of the scattering of light in fog upon the range at which signal lights are visible is of substantial importance. By reason of the complicated character of allowing for the scattering of light in fog when one is calculating the visibility of lights, this question is not examined here.

4. In signal lights various colored filters are used: red, green, yellow, and blue. On this account calculation of the visibility of lights should be carried out not only for white light, but for lights of the colors indicated above as well.

5. In phototechnical landing media systems, flasher approach lights of brief duration and of high flash frequency find widespread application. Calculation of the visibility of signal lights should be carried out also for flasher lights.

In order to secure the indispensable range of visibility of signal lights both with good and with bad visibility, they must be of very great power. Such lights are called high-intensivity lights (OVI). For example, a flasher approach light has a power in the flash amounting to about $240 \cdot 10^6$ candlepower; the maximum power of a constant-beam approach light is $150 \cdot 10^3$ to $250 \cdot 10^3$ candlepower; and a runway light has up to $400 \cdot 10^3$ candlepower. When observed at close distances under circumstances of good visibility these lights may provoke dazzling of the pilot, which is inadmissible. On this account as the transmissivity of the atmosphere changes the intensivity of t' e beams of lights is regulated within broad limits. The visibility of lights must be calculated for various values of the intensivity of the beam.

§ 34. Bases for the Calculation of Curves of Light Distribution for Airfield Lights

An airfield signal lighting system meets its prupose if its lights are easily visible to a pilot during the descent of an airplane for a landing under meteorological conditions which correspond to the weather minimum[1] or above. In order that lights may be easily visible to the pilot upon the airplane's descent for a landing, the distributing of their lighting power must be precisely calculated.

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[1] The weather minimum is the name for minimum values of landing visibility range, and height of lower level of cloud, at which the landing of a given type of airplane at a given airfield is permitted.

In order to calculate curves of light distribution for lights one must find that part (zone) of space in which the pilot, at the time of his final descent for a landing, during actual landing, and during taxiing on the runway, must take advantage of phototechnical media. The pilot guides the airplane in this zone for the most part visually, in accordance with the visibility of phototechnical media.

The dimensions of the zone referred to depend first and foremost upon the maneuverability of the airplane itself during the last phase of the descent for landing, and upon the accuracy of the airplane's being drawn in for a landing by the radio devices in the region of shift to visual flight.

Analysis of the parameters of maneuverability of airplanes and of radio device systems in use shows that the zone in which a plane may find itself when a landing is being carried out in accordance with phototechnical media under circumstances of bad visibility must correspond to the geometrical figure set forth in Figure 31. This figure is made up of the following elements:

Inclined planes 3 and 7, produced through the upper and lower planing glides (corresponding to the section at a distance of 600 meters from the beginning of the runway);

Vertical planes 9, 10, and 12, produced through the close-in radio homing beacon point and a point distance from the beginning of the runway by 2,500 meters (the place of shift to visual flight for airplanes having turbo-jet and turbo-prop engines); these planes are perpendicular to the line prolonging the axis of the runway;

Vertical planes 4 and 6, produced through the line of landing lights;

Vertical planes 2 and 8, contacting planes 4 and 6 at the beginning of the runway, and contacting plane 9;

Vertical planes 1 and 11, contacting planes 9 and 12;

Horizontal plane 5, parallel to the runway and distance from it of 60 meters.

Figure 31 also shows the light-signal media.

The dimensions of the visual piloting zone of an airplane when landing under bad visibility conditions are not constant. They depend upon the system of radio landing devices used and on the maneuverability of the airplanes in use. The place where light signals are installed, and their phototechnical parameters, should be calculated so that the illumination from the lights on the outer edges of the visual piloting zone of an airplane landing under bad visibility conditions shall be no less than threshold illumination.

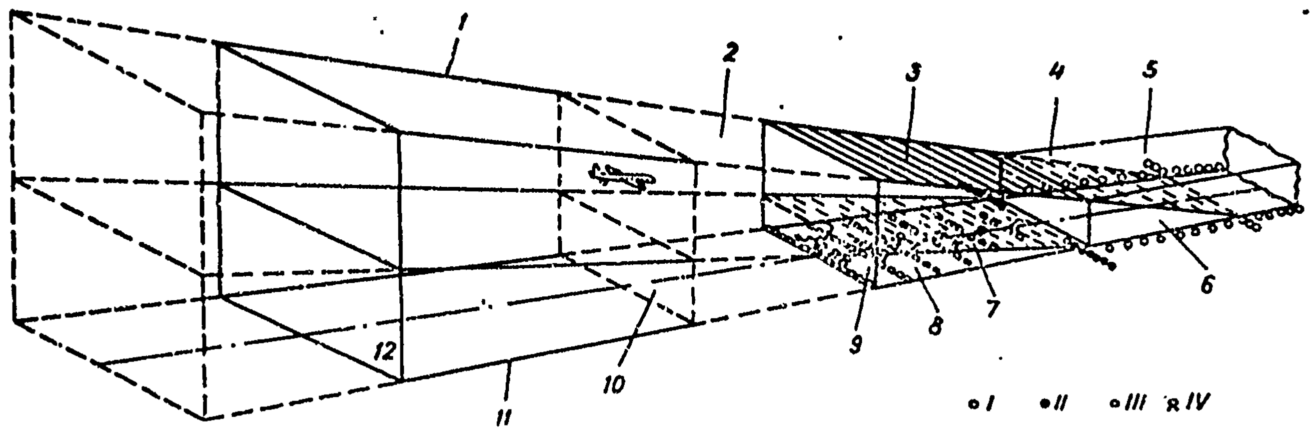

Figure 31. Zone of Visual Piloting of an Airplane and Zone of Effect of Light Signals During Landing Under Bad Visibility Conditions. I, Boundary lights; II, Entering landing lights; III, Light-horizon lights; IV, Approach lights.

Safe landing of an airplane under bad visibility conditions is possible if the pilot sees the lights of the system at a distance (minimum visibility range) sufficient so that he can take the proper steps necessary for the correction of errors. The minimum visibility range of lights, necessary for landing with the accepted system of radio devices, depends in the main on the type (maneuverability) of airplane and the skill of the pilot, and is established on the basis of test flights.

Experimental flights and flight practice in the USSR and abroad have shown that in order to carry out a confident, safe landing of piston airplanes with a landing speed of 140-150 km per hour the minimum visibility range of lights for a pilot of average skill should be equal to 600 meters. For airplanes with other landing speed figures the minimum visibility range of lights is re-calculated accordingly.

Naturally the lights should be visible at a distance no less than the minimum visibility range of the lights. This visibility range of lights, necessary for calculating the curves of light power, is indicated in dotted outline on Figure 31.

For complete calculation of curves of lighting power one must determine the distance to the point of installation of the light being figured, and the angle between a line from the point being viewed to the light on the one hand, and the optical axis of the light on the other hand. For this distance one must determine the necessary lighting power for given values of the meteorological range of visibility and of threshold illumination.

§ 35. Threshold Illumination

If we confidently observe light signals at a certain distance, then as we move farther away from this light source the illumination upon the retina of our eye will diminish, and the signals will be observed less distinctly and confidently.

At a certain distance from the light source we cease to see it, despite the fact that some amount of light flow -- to be sure, very insignificant -- will still fall upon our eye. This is explained by the fact that by virtue of the physiological structure of the eye of man a very insignificant light flow cannot produce a visual impression.

A light signal is visible at a given distance because at that distance it creates illumination upon the pupil of the observer, sufficient to produce a visual impression. The lowest value of illumination upon the pupil of the observer at which a light signal, although decidedly faint, is nevertheless still visible is called the threshold illumination and is designated by E_{th}.

Three sorts of threshold illumination are distinguished:

1) Threshold illumination upon appearance, when the observer is to see a light signal in a direction, known to him, toward the point where the signal is located; i.e., when the observer knows in what direction the light signal is to appear (fixed E_{th} threshold);

2) Threshold illumination upon disappearance, when the distance between the light signal and the observer, with fixed observation, goes on increasing until the signal is lost from sight;

3) Threshold illumination upon detection, when the point where the light signal is located is unknown to the observer and he must detect the appearance of the light signal[1].

The minimum value for threshold illumination corresponds to the case where the visibility of a light signal gradually declines until it disappears. The maximum value for threshold illumination corresponds to the case of detection of the light signal.

In our further examination of this question, when a variant of distinguishing a light signal is not mentioned we are talking about distinguishing the light signal upon appearance.

Threshold illumination depends upon the color of the signal beam, the luminance of the background against which the signal is observed, and the condition of the observer's eye.

Threshold illumination is ordinarily somewhat different for various observers under identical conditions. But if one takes into account data for a great number of observers and introduces some coefficient of safety, one can secure mean values for threshold illumination which are in fact adopted as the bases for calculation of the range of visibility of light signals.

The least threshold illumination is that noted upon observing a light signal against an absolutely dark background corresponding to a luminance of

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[1] The threshold illuminations upon appearance and upon disappearance, described here, may be regarded (see Chapter I) as fixed detection and disappearance thresholds. Threshold illumination upon detection corresponds to a non-fixed detection threshold.

less than 10^{-6} nits[1]. The magnitude of the threshold illumination secured under these conditions is called the absolute light threshold. According to the data of different investigators the absolute light threshold runs from $0.85 \cdot 10^{-9}$ to $8.5 \cdot 10^{-9}$ lux. As the luminance of the background is increased the magnitude of threshold illumination rises (sensitivity of the eye declines), and the range of visibility of light signals diminishes.

Analysis of studies made under laboratory conditions as regards the relationship of the light threshold to luminance of the background when a point light source is under observation show that this dependence is described by the curve set forth in Figure 22.

The visibility range of light signals used in aviation by night, and by day under circumstances of bad visibility, is usually calculated for the most unfavorable conditions of observation -- with greatest luminance of background. At night such conditions occur when the signal is observed under a full moon against a background of snow cover and in the absence of clouds. In this case the luminance of the background comes to $5 \cdot 10^{-2}$ nt. As is evident from Figure 32, the threshold illumination with this luminance of background comes, as determined under laboratory conditions, to $5 \cdot 10^{-8}$ lux.

By day with fog, the luminance of the background comes, according to the author's measurements, to about 10^{4} nt, and the corresponding threshold illumination secured under laboratory conditions is equal to $0.25 \cdot 10^{-4}$ lux.

In measuring threshold illumination under laboratory conditions a series of factors observed under real conditions of flight are not taken into account. These factors are of substantial importance in light signaling in air transport. Among them are:

a) insignificant time that a light signal is observed;
b) ignorance of direction in which appearance of signals should be expected;
c) extraneous lights or bright surfaces located in the pilot's field of vision;

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[1] The nit (nt.) is a unit of luminance equal to the luminance of an evenly shining plane surface emitting in a direction perpendicular to itself a light beam of 1 candlepower per square meter. The luminance of a plane surface emitting in a perpendicular direction light of 1 candlepower per square centimeter was called a stilb under the old standard (sb): 1 nt = 10^{-4} sb; 10^{-6} nt = 10^{-10} sb.

d) observation of signals through protective goggles or the glass of the pilot's cabin;

e) noise of engines, vibration, and oxygen deficiency;

f) physical and nervous fatigue of observers, etc.

To take all these factors into account a safety coefficient or reliability coefficient is introduced. Consequently the calculated threshold illumination is equal to threshold illumination measured under laboratory conditions with the observer adapted to complete darkness, then multiplied by the safety coefficient.

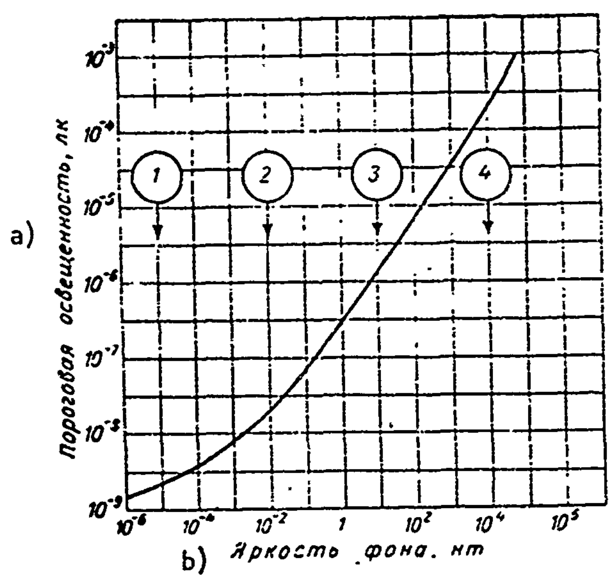

Figure 32. Threshold Illumination of a White Point Light Source Depending on Luminance of Background, As Secured Under Laboratory Conditions.
1, Grass, during moonlight night; 2, Snow under moonlight; 3, Snow in twilight, with fog; 4, Snow at noon, with fog.
Key: a) Threshold illumination, luxes; b) Luminance of background, nt.

At present, with application to the conditions of night signalling in aviation and ocean navigation, we take as the calculated threshold illumination the E_{th} magnitude of a white light equal to $0.2 \cdot 10^{-6}$ lux. Consequently for a background luminance of $5 \cdot 10^{-2}$ nt the safety coefficient is equal to

$$\frac{0.2 \cdot 10^{-6}}{5 \cdot 10^{-8}} = 4.$$

With a safety coefficient of 4 taken into account, for conditions where light signals are observed by day in fog the calculated threshold of illumination E_{th} for a white light is taken as being equal to 10^{-3} lux.

But one should note that for a large number of the factors referred to as influencing the visibility of signals a safety coefficient of 4 is insufficient. In foreign technical literature they are taking as the threshold illumination for night conditions of observation of light signals the magnitude of E_{th} for a white light equal to $1 \cdot 10^{6}$ lux. In this case the safety coefficient comes to 20.

In calculating the visibility of colored light signals one should distinguish between the light and the color thresholds. The least value of illumination upon the pupil of the observer at which one begins to perceive confidently the color of a signal is called the color threshold.

In Figure 33 we set forth magnitudes of light and color thresholds for a point source of light in complete darkness according to the data of L. I. Demkina, which are the fullest and most reliable.

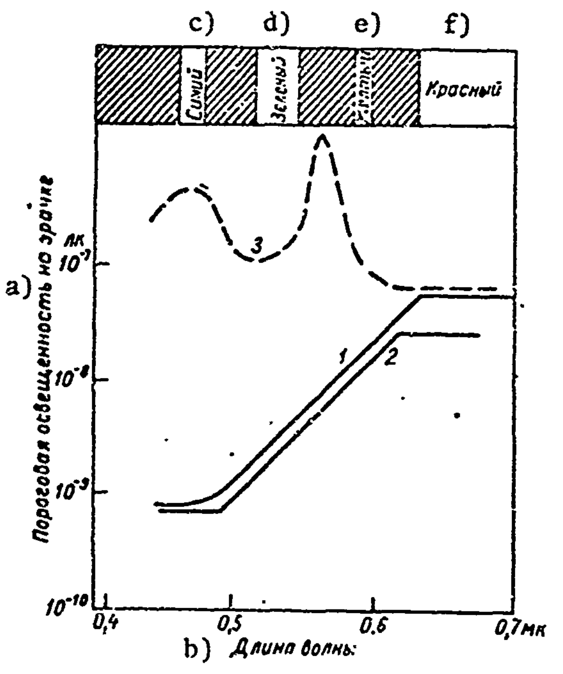

Figure 33. Light Thresholds Upon Appearance (1) and Upon Disappearance (2), and Color Thresholds (3), for a Point Light Source in Complete Darkness (According to data of L. I. Demkina)
Key: a) Threshold illumination upon eye; b) Length of wave; c) Blue; d) Green; e) Yellow; f) Red.

Curve 1 in Figure 33 shows the alteration of threshold illumination E_{th} upon appearance, and curve 2 upon disappearance, depending on wave length. Curve 3 is the limit above which the color of a signal is distinguished (threshold recognition of signal). The area between the curves of light (1) and color (3) thresholds corresponds to the colorless (achromatic) interval. The colorless interval is decidedly considerable for blue and green light, less so for yellow, and is quite absent for red light. This is explained by the fact that the night vision apparatus is not sensitive to the extreme red end of the spectrum. Consequently a red signal is detected and recognized only with the day vision appparatus. The colorless range (the achromatic interval) for red light emanation (having a wave length of 640 microns) is practically equal to zero.

As may be seen from Figure 33, with the exception of red signals the value of color thresholds exceeds the value of light thresholds by many times. For a red signal light and color thresholds coincides, i.e., the moment one perceives the signal one recognizes its color.

Calculated values of threshold illumination of single point color signals, depending on the luminance of the background, are set forth in Figure 34.

Calculated values of threshold illumination for basic point colored-light signals for the backgrounds that are of most interest to us (most unfavorable conditions of observation by night and by day) -- snow, lit up by moonlight ($B_\phi = 5 \cdot 10^{-2}$ nt), and snow at noon amid fog ($B_\phi = 10^4$ nt) -- are set forth in Table 23.

TABLE 23. CALCULATED VALUES OF THRESHOLD ILLUMINATION OF BASIC POINT COLORED LIGHT SIGNALS

Color of Signal	Color Threshold (lux) with Luminosity of Background	
	$5 \cdot 10^{-2}$ nt (snow cover under moonlight)	10^4 nt (snow cover at midday amid fog)
White	$0.2 \cdot 10^{-6}$	$1 \cdot 10^{-3}$
Red	0.45	$1.7 \cdot 10^{-4}$
Yellow	1.1	7
Green	0.55	3.5
Blue	0.5	

From Figure 34 it is apparent that with a luminance of background exceeding 7 nt the threshold illumination of a white signal is greater than that of colored signals. This is explained by the fact that with great luminance of background colored signals have a greater contrast between the object and the background than does a white signal. With a background luminance of 0.75 nt the E_{th} of a white light is equal to the E_{th} of a red light. With background luminances less than 0.75 nt, the E_{th} of a white light becomes considerably less than the E_{th} of a colored light.

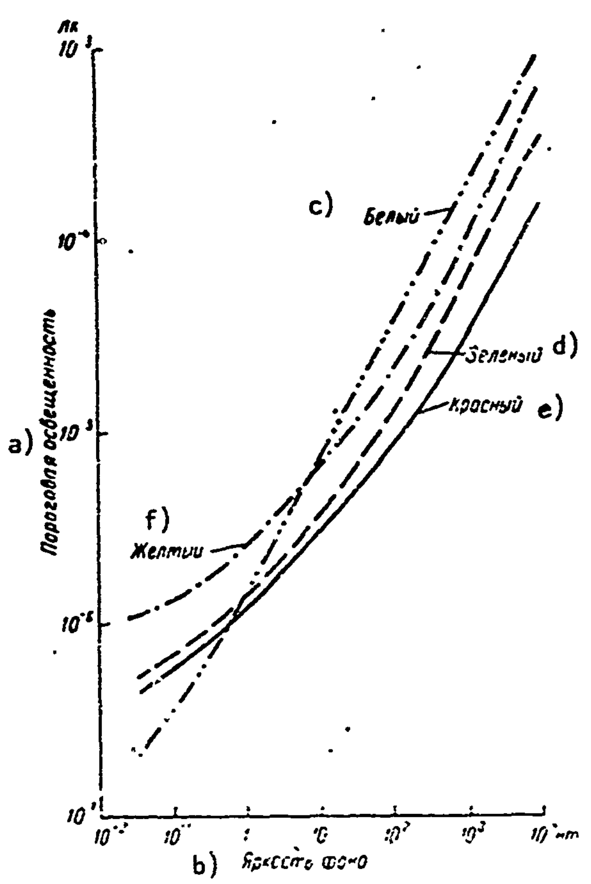

Figure 34. Calculated Values of Threshold Illumination of Point Colored-Light Signals Depending on Luminosity of Background
Key: a) Threshold illumination; b) Luminosity of background; c) White; d) Green; e) Red; f) Yellow.

In calculating the visibility range of lights of a light-signal system, as is plain from what has been said, one must take as point of departure the condition that the pilot must see simultaneously several lights (a group).

Investigations on visual perceptions of group lights are lacking to date.

Considering the great importance of the problem of visibility of group lights in aviation, it is indispensable to expand investigations in this field.

With simultaneous observation of a number of lights, each of them creates a certain illumination upon the eye pupil of the observer. The overall illumination created by these lights is greater than the illumination created by a single light. From this standpoint a group of lights is more visible, and is detected farther off, than a single light.

On the other hand, when a group of lights arranged on an airfield is being observed, the last light at maximum distance from a pilot creates upon his pupil an illumination equal to threshold illumination, while the first lights may create an enhanced illumination worsening the visibility of the remaining lights.

This is particularly noticeable if lights are being observed under conditions of deteriorated or bad visibility, when aureoles develop around lights amid haze or fog, and these worsen the visibility of other lights.

Investigations carried out at the Moscow Power Institute to determine the visibility and distinguishability of signals when sources the luminance of which is considerably higher than the luminance of the background are present in the field of vision have shown that threshold illumination rises sharply in this case, i.e., signals are less visible. Threshold illumination relative to the presence of extraneous sources in the field of vision was determined in the following fashion. With a given luminance of background the eye of an observer was lit for three seconds with one source of blinding light, or with a group, after which the 0.5-1 sec the threshold illumination was determined. The group of blinding light sources was made of signal lights which were brought closer to the observer in the way that this takes place under the real conditions of an airplane landing. The change in threshold illumination relative to the illumination created by a single dazzling source and a group of approaching lights, at the end of one second after dazzling, is shown in Figure 35. Data secured under laboratory conditions as regards alteration of threshold illumination relative to the illumination created by a group of lights approaching the observer are shown in Figure 36.

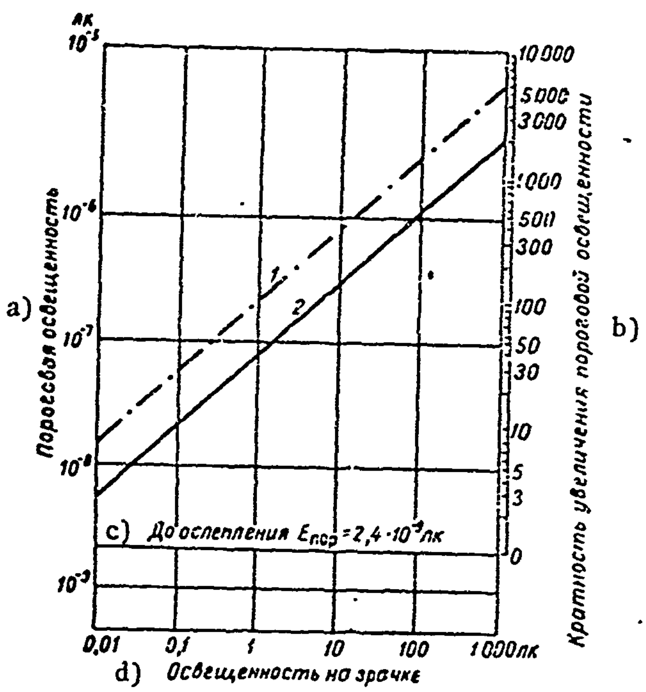

Figure 35. Augmentation of Threshold Illumination at 1 Second After Observation of Signal Lights With a Luminance of Background $B_{\phi} = 10^{-5}$ nt. 1, Group of lights; 2, Single light.
Key: a) Threshold illumination; b) Number of times threshold illumination is amplified; c) Prior to dazzling, $E_{th} = 2.4 \cdot 10^{-9}$ lux; d) Illumination upon the pupil.

Threshold illumination at one second after observation of dazzling lights also depends on their color. During the investigations at the Moscow Power Institute it was determined that the threshold value for sensitivity of the eye at one second after observing the lights comes for red color to 64%, for yellow to 78%, and for green to 156% (threshold illumination of white light taken as 100%).

From the data set forth in Figures 35 and 36 one can conclude that the threshold illumination at one second after dazzling depends in pronounced measure upon the illumination on the pupil of the observer, E_{daz}. Thus, for example, for a single light when E_{daz} = 0.1 lux the threshold illumination mounts approximately 10 times as compared with the amount at which it stood prior to dazzling; with E_{daz} = 10 lux the threshold illumination increases approximately 100 times, etc. With illumination of 0.1 lux created by an extraneous single source of light upon the pupil of the observer the minimum threshold illumination increases from $2.4 \cdot 10^{-9}$ to $3.5 \cdot 10^{-8}$ lux, and with observation of approaching lights the threshold illumination of the eye increases from $2.4 \cdot 10^{-9}$ to $8 \cdot 10^{-8}$ lux.

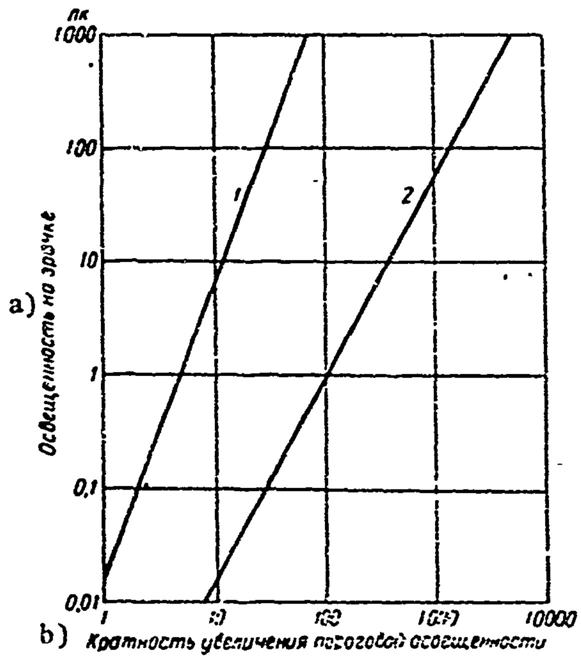

Figure 36. Augmentation of Threshold Illumination at 1 Second After Observation of Approaching Group of Lights.
1) $B_\phi = 5 \cdot 10^{-2}$ nt; 2) $B_\phi = 10^{-5}$ nt.
Key: a) Illumination upon the pupil; b) Number of times threshold illumination is amplified.

§ 36. Weakening of Light by the Atmosphere

Weakening of light by the atmosphere is of considerable importance for light signalling systems.

The light flow emitted by a light or reflected by an object to one side of the observer is partially absorbed, as has been shown above, on its path to the observer by molecules of the air and liquid and solid particles suspended in it (droplets of water, ice crystals, dust particles, etc.), or is diffused upon them. Thanks to the scattering of light, a certain stratum of the atmosphere takes on a specific degree of luminance in any direction.

The scattering of light consists of an alteration of the direction of a light flow after its encounter with particles of the medium, or in other words the totality of phenomena produced by reflection, refraction, diffraction, and intervention of the light rays.

When a light flow is scattered light energy is preserved; in this case there takes place only an alteration of the direction of individual rays, whereas in absorption light-energy is converted into another form of energy.

A light flow is weakened in passing through the atmosphere mainly as a consequence of scattering, and to a slight extent as a result of absorption (the relationship between scattering of light-energy and the transmissivity of the atmosphere was examined in Chapter I).

For our purposes determination of the weakening, by the atmosphere, of a light flow of varied color (i.e., various wave lengths) is of great importance. Numerous theoretical and experimental investigations have shown that the transmission by the atmosphere of a light flow of given wave length, and consequently also of given color composition, depends on the quantity and dimensions of the minuscule particles suspended in the air. If the dimensions of these particles are less than the wave length of the light rays (380-760 microns), then light having shorter wave lengths is strongly scattered in the atmosphere, and light having longer wave lengths (the red light) passes through the atmosphere with less scattering. In an absolutely pure (Rayleigh) atmosphere the spectral index of weakening, α_λ, is inversely proportionate to the fourth power of the wave length λ, i.e.

$$\alpha_\lambda = \frac{C}{\lambda^4}, \qquad (5.1)$$

where C is a constant quantity.

With faint haze and good visibility one can take

$$\alpha_\lambda = \frac{C}{\lambda^{2.5}}. \qquad (5.2)$$

In this case, too, the atmosphere lets the longer-wave rays through better than the shorter-wave ones. But in fog in which water droplets of dimensions greater than the wave length of light rays prevail, a light flow of various color is scattered neutrally (non-selectively).

One can consider that with heavy haze and with fog the spectral index of weakening is inversely proportional to the length of the wave, i.e.

$$\varkappa_{\lambda}=\frac{c}{\lambda}. \qquad (5.3)$$

The somewhat better transmission through the atmosphere of the long-wave section of the visible spectrum, which is observed in individual cases, takes place when there is haze, but not in fog.

The luminance of the stratum of air located between the observer and the object or light being observed is a phenomenon which is ordinarily called atmospheric haze.

At night atmospheric haze creates a supplementary background and as a result of its increasing threshold illumination it worsens the visibility of lights.

On the other hand, by reason of the scattering of light upon suspended particles, bright aureoles at night form which are easily visible against a background of sky or of ground surface. They facilitate determining the location of a light signal, something which is of great importance in landing an airplane under bad visibility conditions.

Reckoning the luminance of the aureole while determining the visibility of lights constitutes a very complicated problem, this phenomenon is not examined here.

By day the luminance of atmospheric haze is many times greater than the luminance of the aureole from artificial sources of light, for which reason in calculating the visibility of lights by day the aureole effect is not taken into account.

It is convenient to use the amounts of the specific transmissivity of the atmosphere and the index for atmospheric weakening when studying the theory of the passage of light through the atmosphere and when carrying out corresponding calculations regarding the range of visibility of light signals, but measurement of these quantities under real conditions is associated with certain difficulties. In addition, it is not possible to get a clear idea of the visibility range of objects and lights by using the concepts "coefficient of transmissivity" or "weakening index."

At meteorological stations in the Soviet Union and abroad the specific transmissivity of the atmosphere is not measured, but instead observations are carried out on the meteorological range of visibility.

As we said in Chapter I, the meteorological range of visibility can be expressed by the weakening index α and α_{10}:

$$S_{м} = \frac{3,5}{\alpha}, \qquad (5.4)$$

$$S_{м} = \frac{1,5}{\alpha_{10}}. \qquad (5.5)$$

§ 37. The Range of Visibility of Constant-Beam Light Signals

The visibility range of light signals depends in the main upon their power, the distance from the light to the observer, the magnitude of threshold illumination, the luminance of the background against which the signal is observed, and the weakening of the light flow by the atmosphere. In addition to these basic factors, the following affect the visibility of light signals: preliminary adaptation of the eye of the observer, noise, the presence of dazzling luminances in the field of vision, oxygen deficiency, vibration, limited time for observation of signals, insufficient transmissivity of glass in window of pilot's cabin, which may be covered with moisture, dust, frost, etc. at the moment of the airplane's descent, physical and nervous exhaustion of the pilot which also reduces the sensitivity of the eye. But the effect of these secondary factors on the visibility of light signals is much less than the effect of the basic factors.

On this account in determining the visibility range of light signals the effect of the secondary factors is taken into account when the magnitude of threshold visibility is determined. The basic problem of light signaling consists in establishing the relationship between the visibility range of the light signals and the basic factors referred to above.

In calculating visibility of light signals three cases must be distinguished.

Case 1. Angular dimension of light signal at distance of observation is so small that the signal may be considered a point-source of light.

Case 2. Light signal at distance of observation has such large dimensions that its visibility is determined only by luminance.

Case 3. Light signal at distance of observation has dimensions such that on the one hand it cannot be considered a point, and that on the other hand its visibility is not determined only by luminance.

Let us examine these three cases in greater detail.

In Case 1 the visibility of the light signal is conditioned by the illumination created by this signal upon the pupil of the observer's eye and determined by the Allard equation (1.31), which we shall transcribe in the form

$$E_{th} = \frac{I}{L^2} 10^{-\frac{1.5L}{S_M}} = \frac{I}{L^2} e^{-\frac{3.5L}{S_M}}. \qquad (5.6)$$

If the illumination on the observer's eye created by the signal is greater than threshold illumination, then the light signal is visible; if it is less than threshold, then the signal is not visible.

From equation (5.6) it follows that a light signal is visible to an observer if its power is not less than

$$I = E_{th}\, L^2 10^{\frac{1.5L}{S_M}} = E_{th}\, L^2 e^{\frac{3.5L}{S_M}}. \qquad (5.7)$$

Expression (5.7) is fundamental. Through its help, knowing the power of the source, the threshold illumination, and the meteorological range of visibility, we can determine the visibility range of the light signal. Solution of equation (5.7) relative to L is algebraically impossible, since L forms part of the equation as an index of degree. This equation can be solved through successive approximations or graphically.

In Figure 57 we set forth curves for visibility range of light signals depending on power and the state of the atmosphere. These curves are constructed for white light with a background luminance of $5 \cdot 10^{-2}$ nt. The curves are constructed for various values of meteorological visibility range and correspondingly for various values of specific transmissivity of atmosphere. With the help of the curves set forth in Figure 57 one can determine:

1) the distance at which a white light will be visible by night with a given transmissivity of atmosphere;

2) the power a white light ought to have so that it may be visible at a given distance on a bright night;

3) the meteorological range of visibility at which a white light of given strength will be visible at a given distance.

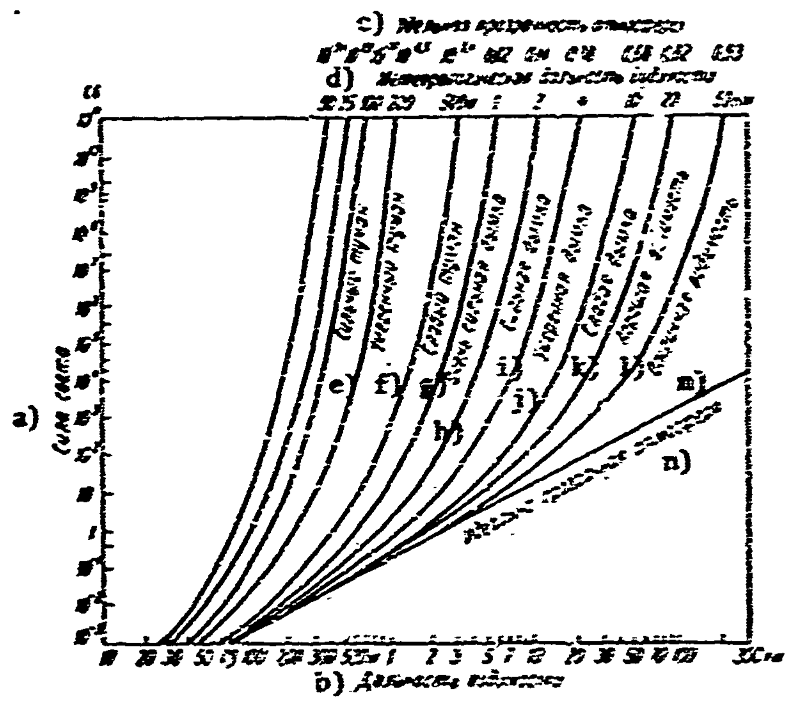

Figure 37. Visibility Range of Constant White Light by Night ($B_{\phi} = 5\cdot10^{-2}$ nt, $E_{th} = 0.2\cdot10^{-6}$ lux)

Key: a) Power of light; b) Range of Visibility; c) Specific transmissivity of atmosphere; d) Meteorological range of visibility; e) Heavy fog; f) Medium fog; g) Light fog; h) Very heavy haze; i) Heavy haze; j) Medium haze; k) Light haze; l) Good visibility; m) Excellent visibility; n) Ideally transmissive atmosphere.

The curves in Figure 37 can be utilized not only when threshold illumination is $0.2\cdot10^{-6}$ lux, the figure for which they are constructed, but also for any value threof. In this event it is necessary only to increase or reduce the given power of the light according to the indicated magnitude of the threshold illumination. As an example let us determine the visibility range of a light emitting a red beam of 20,000 candlepower, with a meteorological visibility range of 50 km and a background luminance of $5\cdot10^{-5}$ lux. For such a background luminance the threshold illumination for red light is, according to the data in Table 23, $0.45 \cdot 10^{-6}$ lux. This threshold illumination is 2.25 times greater than the threshold illumination for white light which was adopted in constructing the curves in Figure 37. Consequently, for the calculation the given power of the light should be arbitrarily reduced to the extent where it will come to 8888 candlepower. A visibility range of 40 km for the light corresponds to this value for power of light on the curve for a meteorological visibility range of 50 km.

Below we set forth the values for the power of a light that are necessary for its being visible at a distance of 2 km with various values for the meteorological visibility range:

Meteorological visibility range (km)	50	20	10	4	2	1	0.5	0.2	0.1
Power of light (candlepower).	1	1.18	1.75	10	40	200	10^7	$8 \cdot 10^{17}$	$8 \cdot 10^{34}$

As may be seen from these data, the power necessary for a light to be visible at a distance of 2 km with a meteorological visibility range up to 2 km is low (40 candlepower); after that, as the meteorological range of visibility declines, it rises sharply and reaches colossal magnitude. It is interesting to note that even the most powerful zenith projectors with parabolic reflectors 1.5 meters in diameter, having $7 \cdot 10^8$ candlepower, will be visible at a distance of 2 km when the meteorological visibility range is 0.4 km. It is technically impossible to create projectors of 10^{34} candlepower, or even of 10^{17} candlepower.

From the data set forth it follows that under bad meteorological conditions it is impossible to observe lights at considerable distances. For this reason, in fog lights of medium power are frequently used, but ones arranged at relatively short distances one from another.

Formula (5.7) can be used for determination of meteorological visibility range at night. For this one must have artificial light sources arranged at a known distance from the observer. Knowing the power of the source, the limit distance at which this light source is visible, and the threshold illumination, with the help of formula (5.7) one can determine the night-time meteorological visibility range.

In Table 24 we set forth data for determination of meteorological visibility range in points (in harmony with the international visibility scale) in accordance with the visibility range of lights by night. As ensues from this table, for example, visibility point 4 means that a light of 3.5 candlepower is visible at a distance of more than 0.826 km and is not visible from a distance of 1.24 km, and that a light of 100 candlepower is visible at a distance greater than 1.42 km but is not visible at a distance of 2.32 km, etc.

TABLE 24. METEOROLOGICAL RANGE OF VISIBILITY DETERMINED ACCORDING TO VISIBILITY RANGE OF LIGHTS BY NIGHT

a) Балл видимости	b) Если при наблюдении огонь	c) Сила света огня (св)								
		3,5	8,5	50	100	200	300	400	500	1000
		d) Дальность видимости огней								
		e) Метры								
0	g) Не виден на расстоянии . . .	97	105	123	132	139	143	146	149	156
1	h) Виден на расстоянии	97	105	123	132	139	143	146	149	156
	g) Не виден на расстоянии . . .	277	310	383	409	437	455	468	475	507
2	h) Виден на расстоянии	277	310	383	409	437	455	468	475	507
	g) Не виден на расстоянии . . .	530	601	771	838	905	948	977	1000	1067
		f) Километры								
3	h) Виден на расстоянии	0,530	0,601	0,771	0,838	0,905	0,948	0,977	1	1,07
	g) Не виден на расстоянии . . .	0,826	0,907	1,28	1,42	1,54	1,63	1,68	1,72	1,86
4	h) Виден на расстоянии	0,826	0,907	1,28	1,42	1,54	1,63	1,68	1,72	1,86
	g) Не виден на расстоянии . . .	1,24	1,5	2,06	2,32	2,56	2,71	2,82	2,90	3,16
5	h) Виден на расстоянии	1,24	1,5	2,06	2,32	2,56	2,71	2,82	2,90	3,16
	g) Не виден на расстоянии . . .	1,77	2,19	3,24	3,66	4,12	4,41	4,62	4,79	5,27
6	h) Виден на расстоянии	1,77	2,19	3,24	3,66	4,12	4,41	4,62	4,79	5,27
	g) Не виден на расстоянии . . .	2,53	3,35	5,43	6,37	6,98	8,04	8,43	9,88	10,0
7	h) Виден на расстоянии	2,53	3,35	5,43	6,37	6,98	8,04	7,43	9,88	10,0
	g) Не виден на расстоянии . . .	3,09	4,3	7,55	9,12	10,8	12,0	12,7	13,4	15,5
8	h) Виден на расстоянии	3,09	4,3	7,55	9,12	10,8	12,0	12,7	13,4	15,5
	g) Не виден на расстоянии . . .	4,22	5,3	10,4	13,3	16,4	18,6	20,2	21,5	25,8
9	h) Виден на расстоянии	4,22	5,3	10,4	13,3	16,4	18,6	20,2	21,5	25,8

Key: a) Visibility point; b) If upon observation the light; c) Candlepower of light; d) Visibility range of lights; e) Meters; f) kilometers; g) Not visible at a distance of; h) Visible at a distance of.

Let us examine Case 2, where the light source at the range of observation is of large dimensions. In this case its visible luminance is reduced only in consequence of weakening of atmospheric light. The visibility range L of such a terminal light source may be defined as the distance at which this source will have a visible luminance equal to the threshold luminance B_{th}, i.e.,

$$B_{th} = B\tau^{L} = Be^{-\alpha L}. \quad (5.8)$$

Hence

$$L = \frac{\lg B_{th} - \lg B}{\lg \tau}. \quad (5.9)$$

If the luminance of the background is greater than zero, then the visibility of the signal in Case 2 is determined not by the absolute value of the sensitivity of the eye, but by the circumstances of contrast. The minimum difference between the luminance of the object and the luminance of the background against which the object is first noted is called the threshold difference of luminance ΔB, and the ratio of this quantity to the background luminance B is called the differential threshold ΔB/B.

The differential threshold depends on the luminance of the background. The relationship of the differential threshold to the luminance of the background is shown in Figure 38.

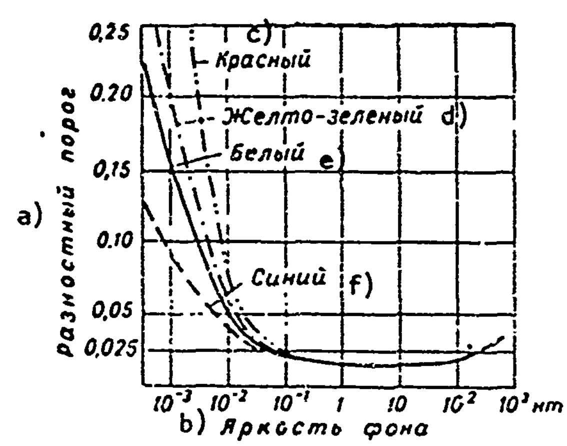

Figure 38. Relationship Between Differential Threshold and Luminance Background
Key: a) Differential threshold; b) Luminance of background; c) Red; d) Yellowish-green; e) White; f) Blue.

In Case 3, where the dimensions of the light signal are intermediate, i.e., neither point nor terminal, one can use neither the regime of constancy of the luminance threshold, nor the regime of constancy of the threshold of illumination. In this case one can use in practical computations formula (5.9), assuming that the threshold luminance B_{th} changes depending on the angular dimensions of the signal.

Mean values for threshold luminance B_{th}, in accorance with the experimental data of many authors, are set forth in Figure 39 in their relationship to the angular dimension d of a light signal (i.e., $B_{th} = f(d)$). From this diagram it follows that the absolute value of a threshold luminance $B_{\infty} = B_{th}$, with d more or less equal to 50°, is approximately equal to $1 \cdot 10^{-6}$ nt for a white beam.

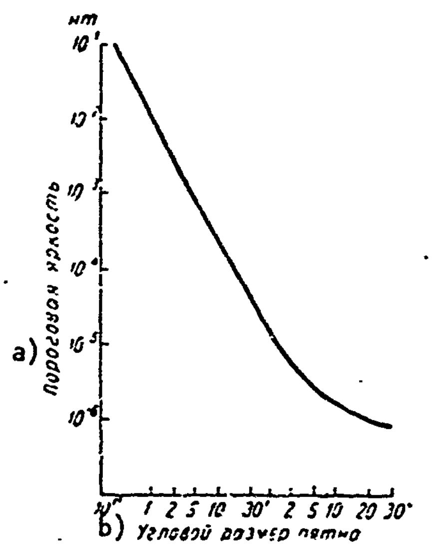

Figure 39. Relationship of Threshold Luminance to Angular Dimensions of Spot of Light
Key: a) Threshold luminance; b) Angular Dimensions of spot.

Moon and Spencer, generalizing the results of measuring absolute threshold luminance, have suggested an empirical equation which describes the dependence of threshold luminance upon the solid angle of a round spot of light:

$$B_{th}\omega = B_{\infty}(0.047 + \sqrt{\omega})^2, \qquad (5.10)$$

where B_{th} is the threshold luminance of a spot having a solid angle ω; B_{∞} is an absolute threshold luminance numerically equal to the threshold luminance for $\omega \to \infty$.

From analysis of formula (5.10) one may draw the following conclusions:

1) threshold luminance depends practically not at all upon the dimensions of the spot of light when $\omega \geqslant 0.1$ steradian, which corresponds to an angular dimension of the signal in the form of a circle with $d \geqslant 50°$;

2) for a signal with small angular dimensions ($d \leqslant 15°$) the threshold illumination E_{th} of a "pseudo-point" light source does not depend on the dimensions of the signal, i.e.,

$$E'_{th} = B_{th}\omega \approx 2.2 \cdot 10^{-3} B_{\infty}. \qquad (5.11)$$

The dependence of threshold illumination upon the pupil on the angular dimension of the spot of light is shown in Figure 40. One can take the magnitude of the absolute threshold illumination created by a "pseudo-point" light source as being equal to $2 \cdot 10^{-9}$ lux.

From the curve in Figure 40 one can reach a judgment as to the angular dimension of light source up to which one can consider the light to be a point-source.

For a black background the threshold of receptivity of a light spot having an angular dimension not greater than 15' is determined by the illumination upon the eye of the observer. With any other background luminance, the magnitude of that angular dimension for the spot at which one can carry out a replacement of the spot of light with an equivalent point light source diminishes.

§ 38. Visibility Range of Flashing Light Signals

The flashing lights used in signalling have substantial advantages over constant-beam lights. White constant-beam lights can easily be confused with random light signals strewn about within a given area. It is easy to distinguish a flashing signal light from constant-beam lights which may fall into the observer's field of vision. In addition, thanks to the fixed frequency of flashes or the combination of long and short flashes, i.e., thanks to the operation of the signal under a coded regime, it is possible to distinguish one signal light from another. Ordinarily during a flight the place where a flashing light will appear to the observer is unknown. On this account the signal appears not in the central part of the aviator's field of vision, but in the peripheral part. Even a faint flashing light which appears on the periphery of the field of vision draws the observer's attention more strongly than a constant-beam light.

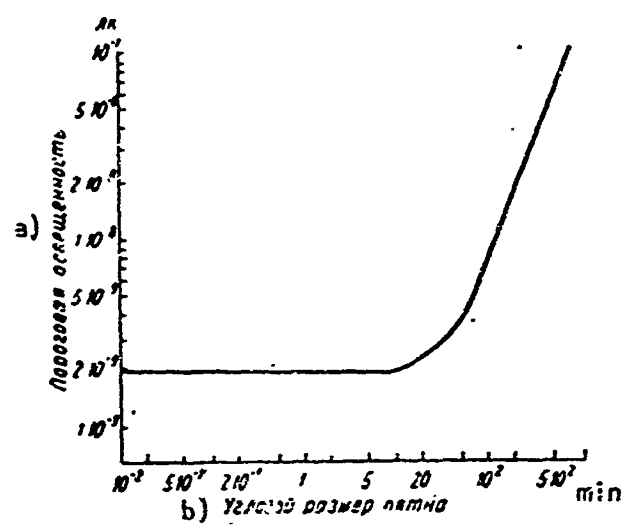

Figure 40. Dependence of Threshold Illumination on Angular Dimensions of Spot of Light.
Key: a) Threshold illumination; b) Angular dimensions of spot.

At short distances, when illumination upon the pupil of the observer is many times greater than threshold illumination, flashing lights are more easily observed than are constant-beam lights; they attract the attention and are readily made out against a background of other lights. But at the limit of the visibility range, when the illumination upon the pupil of the observer is close to threshold illumination, the visibility of flashing lights is worse than the visibility of constant lights. The range of detection of a flashing light depends on the duration of the flash. This is explained by the fact that the sensation of light does not arise instantaneously after the light has fallen upon the eye.

It has been established experimentally that if an observer, after a stay in darkness, observes a white surface having an insignificant luminance close to the threshold value, the sensation will attain its full development only after 1-1.5 seconds (Figure 41). If we limit the duration of observation of this surface to 0.2 seconds, it will seem to us considerably darker (this corresponds to the hatched area in Figure 41) than under prolonged observation. In order to determine the visibility range of flashing lights one must introduce the concept of "effective power."

By the effective power of a flashing light we mean the power of a constant-beam light which has an identical visibility range with it.

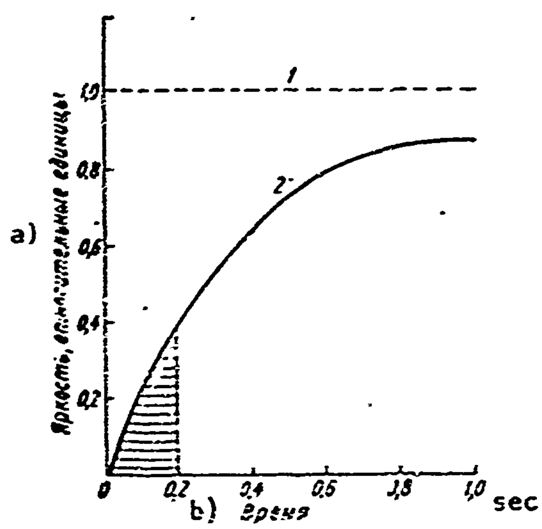

Figure 41. Development of the Sensation of Light Over a Period of Time When Excitation is Faint.
1, True luminance; 2, Apparent luminance.
Key: a) Luminance, relative units; b) Time.

The effective power I_{eff} of flashing lights can be determined from the expression

$$I_{eff} = I_{\phi}\frac{t}{v + t}, \qquad (5.12)$$

where I_{ϕ} is the photometric (true) power of the light (candlepower); t is the duration of the flash (seconds); and v is a constant.

Equation (5.12) is called the Blondell and Ray formula.

The magnitude of v varies within very broad limits and depends on the level of the illumination on the eye of the observer.

For an illumination on the eye of the observer which is practically equal to the threshold value the quantity v is equal to 0.1. This value is in fact adopted at present in making calculations to determine the visibility range of flashing (impulse) lights.

The visibility range of flashing lights is also calculated via formula (5.7), or is determined from the curves in Figure 37.

If the power of a signal light is constant over time, then its photometric power at any moment may be adopted for figuring out the effective power of the light. With changing power of the light, during flash, from zero to maximum (axial light power) and then to zero, as for example in a rotating light beacon (Figure 42), its effective power can be computed in the following manner. In accordance with the curve for the distribution of light by the beacon in the horizontal plane and in accordance with its rapidity of rotation, one constructs a curve for the variation of the power of the beacon in a given direction. With a rotational speed of

$$n \text{ rev/min} = n/60 \text{ rev/sec},$$

a light beacon will turn by 1° in a time of

$$t = \frac{60}{n \cdot 360} = \frac{1}{6n} \text{ sec}.$$

Knowing this ratio, we can recalculate the curve for the light distribution by the beacon by setting off on the abscissa axis the time in fractions of a second instead of the angles in degrees. This is what is done in Figure 42 a for a light beacon having an angle of diffusion in the horizontal plane amounting to 3°, and a rotational speed of n = 12 r.p.m. Let us suppose that the power of the beacon is close to maximum, but that the beacon flashes only for a period t_1 = 0.035 seconds. Then the curve for power of the beacon over time will take the form of a narrow rectangle with peaks 1-1. For a given light power and duration of flash t_1 we calculate according to formula (5.12) the effective light power. We lay off on Figure 43 b the power value that we get (point 1'). Then we suppose that the light power of the beacon is a little less, but that the beacon flashes for a time t_2 = 0.007 seconds. In this case the curve for the power of the beacon's light over time assumes the form of a rectangle having peaks 2-2 (Figure 43 a). The effective light power calculated in this case is marked off on Figure 43 b with the digit 2'.

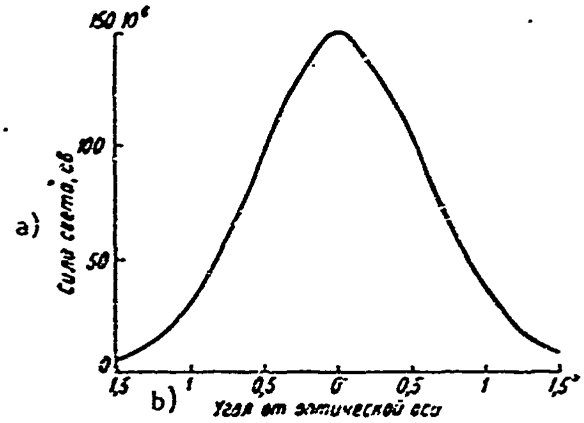

Figure 42. Distribution of Power of Light Beacon in Horizontal Plane.
Key: a) Candlepower; b) Angle from optical axis

Continuing calculations like this, we note that the effective light power achieves a certain maximum and then commences to fall off again. Through points 1', 2', 3', etc., in Figure 43 b we draw a smooth curve. The maximum of this curve (in the given example having $I_{eff} = 12.35 \cdot 10^6$ candlepower) is taken as being the effective light power of the beacon for the given speed of rotation. We take as the duration of the flash the value of 0.017 seconds, which corresponds to this maximum in the curve of Figure 43 b.

The method which has been set forth for calculating the effective light power of flashing signals has been proposed by N. A. Karyakin and V. V. Kuznetsov, and has found widespread application in aviation phototechnics.

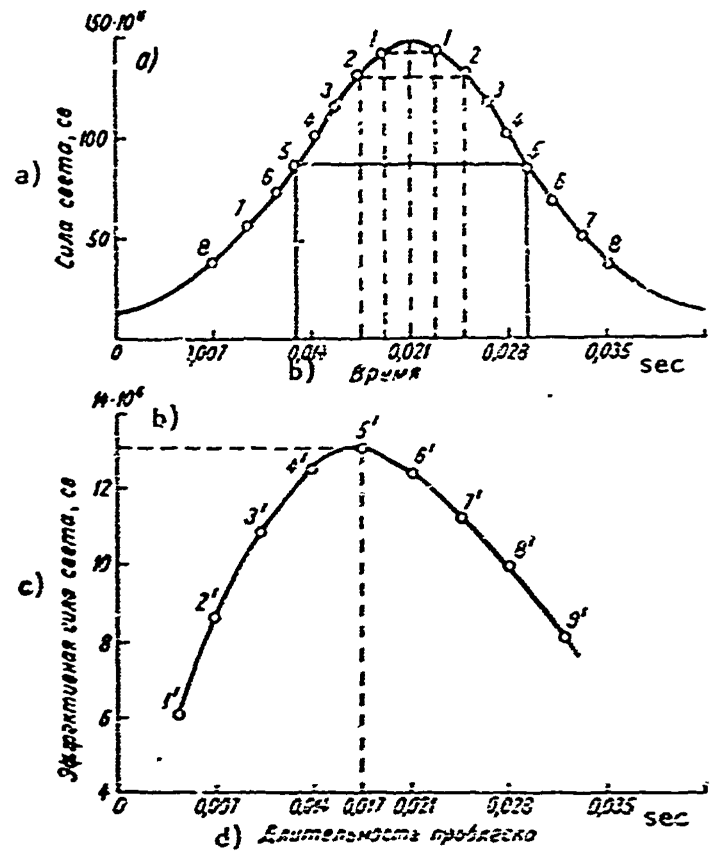

Figure 43. For Calculation of Effective Power of Rotating Light Beacon.
Key: a) Candlepower; b) Time, seconds; c) Effective candlepower; d) Duration of flash, seconds.

CHAPTER VI

THE PHOTOELECTRICAL BASE METHOD FOR MEASUREMENT OF THE HORIZONTAL TRANSPARENCY OF THE ATMOSPHERE

§ 39. General Observations

The parameters V_o, D/B_ϕ, I_o, ε, E_{th} which enter into the expressions for the range of visibility of objects and signal lights change within considerably narrower limits than does the meteorological range of vision S_M.

Changes of V_o and D/B_ϕ from season to season come to some tens of percentage points. The quantity S_M may vary, independently of the season of the year and the time of day, over a brief interval of time by tens and hundreds of thousands of percentage points, and in some cases even by millions of percentage points.

We are still unable to predict such enormous changes in atmospheric transmissivity, and this continues even today to be an unsurmounted barrier in the way of creating computational methods for determining the visibility range of objects and signal lights, and for prognosis regarding visibility range.

Without knowing the current value for S_M, measured directly in the neighborhood of the objects that are of interest to us, we cannot determine their visibility range even approximately, and even if the photometric properties of the objects and the state of the threshold visual functions of the observer are known to us in advance.

This is what constitutes the reason for the fact that the development of methods and apparatus for measuring the transmissivity of the atmosphere in light and in darkness has become the central methodological problem of the science of visibility.

The problem of measuring the transmissivity of the atmosphere in the presence of such an enormous range of changes thereof at any network of meteorological stations has proved to be decidedly difficult in many respects. It has required almost 30 years of effort on the part of scientists of the USSR, the USA, the GDR, France, and other countries, in order at length to create a series of instrumental-visual and objective methods for measuring the transmissivity of the atmosphere, but only in a horizontal direction.

9

The problem of measuring the transmissivity of the atmosphere in a non-horizontal direction has not yet emerged from the stage of experiments and research. One of the possible methods is examined in the following chapter.

The first photoelectric set-ups of field type intended for measurement of the horizontal transmissivity of the atmosphere appeared in the 30's of the 20th century, when the problem of the mass production of photoelements was solved.

From the creation of the first photoelectric set-up in 1934 to the development of present-day transmissivity recorders produced in large runs and measuring a limited range of atmospheric turbidity (with application to the problem of safe landings for airplanes) more than 20 years elapsed.

The expenditure of so long a time as this on the development of objective apparatus is explained by the fact that for a long time the paths to overcoming the difficulties of a design and exploitational character with which the work of the apparatus in question is associated were not clear. These difficulties are linked with the need for meeting the following fundamental conditions:

1) uninterrupted, stable, and reliable operation of the apparatus under circumstances of aging of the photoelectric indicators, inconstancy of the luminance of light sources, instability of the feed sources, etc., must be ensured, the apparatus must work reliably and stably over the course of a prolonged time without frequent regulation and adjustment.

2) the apparatus must be sturdy in operation and must ensure reliability of measurements in daylight, when the parasitic radiation from diffused daylight may be some orders higher than the useful (measurable) light flow;

3) over and above the ordinary requirements imposed upon apparatus operating under field conditions, transmissivity recorders must contain anticipatory measures against sweating, dust, the freezing of accumulated snow, and other forms of dirtying of the exposed optical parts of the apparatus.

One readily understands how serious is each point of these requirements, to say nothing of their totality. And at the same time failure to meet even one point of the list indicated brings to naught the function of the apparatus in its entirety.

A brief survey of the development of objective methods for measuring horizontal transmissivity, set forth below, shows how difficulties have been overcome step by step, and how complicated this problem has proved to be as a whole.

§ 40 Basis of the Photoelectric Base Method in Principle

The photoelectric apparatus examined in the present chapter, which are intended for measurement and recording of horizontal transmissivity of the atmosphere, are based on a single general principle: in a stratum of given length (the so-called measurement base) an index of attenuation α, calculated for a unit length of one kilometer, which is then converted in accordance with the Koschmider formula (1.28) into meteorological range of visibility, S_M. This method of measuring transmissivity has received the name of photoelectric base method.

We should note that photoelectric base methods, and also the instrumental-visual ones which are examined below, for determination of atmospheric transmissivity are extrapolational ones. This means that α is determined for the section constituted by the relatively short measurement base, and then, on the basis of the hypothesis of the homogeneity of the horizontal transmissivity of the atmosphere, is extended to greater distances.

The extrapolational possibilities of any method of measuring S_M are characterized by the dimensionless parameter

$$z=\frac{S_M}{L},$$

where L is the magnitude of the measurement base or the distance to the object (in instrumental-visual methods).[1]

It is obvious that where there is spatial (horizontal) heterogeneity of atmospheric turbidity extrapolational methods cannot give correct results.

The photoelectric base method of measuring transmissivity is carried out in the form of two stations located at the ends of the measurement base: a stabilized source of light at one end, and a photoelectric detector at the other.

When photoelectric set-ups that are based on a differential system are used, the light source and the detector, mounted in a single aggregate, are placed at one end of the measurement base, and at the other end a reflector system which sends back to the detector the light which falls upon it

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[1] The parameter z shows what amount of base distances or of measurement sections L must be contained in a given value for S_M so that a specified or permissible error in the measurement of δS_M shall be ensured).

Let us examine the elementary theory of the photoelectric base method (Figure 44).

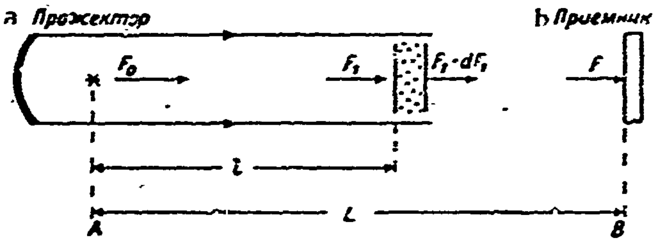

Figure 44. In Connection With the Theory of the Photoelectric Base Method for Measuring S_M.

Key: a) Projector; b) Detector.

Let a photoelectric detector stand at point B (at one end of the measurement base of length L), and at point A (at the other end of the base) a projector emitting a parallel non-monochromatic light beam F_0 of constant intensity.

The theory of the base method is founded upon the assumption that the transmissivity of the stratum L is the same as the transmissivity of the atmosphere away from the base.

At a certain distance from the projector the beam of light, after having passed through stratum l and having become attenuated (by reason of the scattering of light upon suspended particles) to a value F_1, encounters an elementary, optically turbid stratum dl. Upon emerging from it the beam will have a value $F_1 - dF_1$, where $-dF_1$ is the amount of the light beam which has been scattered and absorbed in stratum dl. It is obvious that the value $-dF_1$ is proportionate to the thickness of the stratum dl, the magnitude of the beam F_1 which enters stratum dl, and the intensivity of attenuation (scattering and absorption) α in the stratum dl, characterizing the optical properties of the medium.

In other words, the amount of reduction of the light beam $-dF_1$ in the stratum dl is described by the differential equation

$$-dF_1 = F_1 \alpha \, dl. \tag{6.1}$$

Distributing the variables and integrating along the entire stratum of length L and within the limits of the values for the light beam from F_0 to F arriving at the detecter, we secure

$$\int_{F_0}^{F} \frac{1}{F_1} dF_1 = -\int_0^L \alpha \, dl,$$

whence

$$\frac{F}{F_0} = e^{-\alpha L},$$

or

$$F = F_0 e^{-\alpha L}. \tag{6.2}$$

This is the way the magnitude of the light beam which has transversed the course L from the projector to the detector changes. Expression (6.2) constitutes the Buger law which we referred to in § 5. This law runs to the effect that attenuation of a light flow in a homogeneously turbidized stratum takes place in accordance with an exponential regime.

It is in fact expression (6.2) that constitutes the foundation for the photoelectric base method.

Let us examine the theoretical accuracy of the base method and the conclusions arising therefrom.

Logging and differentiating (1.29) we secure

$$\frac{\Delta S_M}{S_M} = -\frac{\Delta \alpha}{\alpha}. \tag{6.3}$$

From expression (6.3) it is obvious that the relative error of measuring the meteorological range of visibility is equal to the relative error of measuring the index of attenuation.

Applying (6.3) to the base method, we secure from (6.2)

$$\alpha = -\frac{1}{L}\ln\frac{F}{F_0} = -\frac{1}{L}(\ln F - \ln F_0).$$

Differentiating the last expression and then replacing the differentials with increments, we secure

$$\Delta\alpha = -\frac{1}{L}\left(\frac{\Delta F}{F} + \frac{\Delta F_0}{F_0}\right). \qquad (6.4)$$

But since from (1.28)

$$\alpha = \frac{3{,}5}{S_M}, \qquad (6.5)$$

from (6.4) and (6.5) it follows that

$$\frac{\Delta\alpha}{\alpha} = -\frac{1}{3{,}5}\frac{S_M}{L}\left(\frac{\Delta F}{F} + \frac{\Delta F_0}{F_0}\right). \qquad (6.6)$$

Substituting equation (6.6) in (6.3) and designating S_M/L by z we secure the expression for the relative quadratic error

$$\frac{\Delta S_M}{S_M} = 0{,}29z\sqrt{\left(\frac{\Delta F}{F}\right)^2 + \left(\frac{\Delta F_0}{F_0}\right)^2}. \qquad (6.7)$$

Expression is the relative error of measuring the meteorological range of visibility by means of the photoelectric base method that we have been seeking.

The ratio $\Delta F_0/F_0$ represents the error of photometering the light beam at such high transmissivity that the attenuation of light on the section of the measurement base may be disregarded. This error, for a well-tuned apparatus and with application of a stabilized light source, is not great -- ordinarily less than 1%, on which account from here on we need not take it into consideration. Then, designating δF as equal to $\Delta F/F$ and δS_M as equal to $\Delta S_M/S_M$ for brevity's sake, we secure finally

$$\delta S_M = 0{,}29z\delta F. \qquad (6.8)$$

As (6.8) shows, the relative error of measuring the meteorological range of visibility by the base method is a linear function of two factors: 1) the extrapolational parameter z; 2) the relative error δF of measurement of a light beam attenuated by the atmosphere over the section of the measurement base. This error is determined by the accuracy of photometering the light beam falling upon the detector that is possessed by an apparatus of given design during the course of its prolonged utilization.

The error of measurement δF over a rather broad range of variation of light flow proves to be, in first approximation, a constant quantity.

At very low values of light flow the error δF commences to mount. For not very powerful projectors (which are those ordinarily used in the set-ups described below) this moment occurs with a value for S_M close to the amount of L, i.e., with $z \approx 1$. Thus constancy of the error of photometering a light flow under the circumstances operative in accordance with the base method may be taken as running from z more or less equal to 1.5, and upward.

The considerations enunciated make it possible to draw a conclusion regarding the limits of applicability of the photoelectric base method for measurement of the transmissivity of the atmosphere. This conclusion may be represented in visual form if on the basis of (6.8) we set up a table (Table 25) and construct a nomogram of theoretical errors of the method under examination, guiding ourselves by values for z and δF.

TABLE 25. THEORETICAL RELATIVE ERRORS δS_M (%) IN MEASURING S_M BY THE PHOTOELECTRIC BASE METHOD, DEPENDING ON VALUES OF z AND δF

z	δF%				
	1	2	3	4	5
5	1.4	2.8	4.2	5.6	7.0
10	2.9	5.8	8.7	11.6	15.0
20	5.8	11.6	17.5	23.2	29.0
30	8.7	17.5	26.1	35.0	43.5
40	11.6	23.2	35.0	46.5	55.0
50	14.5	29.0	43.5	58.0	72.9
100	29.0	58.0	87.0	116.0	145.0

From Table 25 and the nomogram constructed on the basis thereof (Figure 45) there transpire those requirements which must be imposed upon the design of a photoelectric set-up if one is to get concrete values for accuracy of determination of S_M. A figure of 25% is universally taken as being the upper limit of the still permissible error in the measurement of S_M. Depending on the quantity δF, this error is attained with z more or less equal to 80 (when δF = 1%) and with z more or less equal to 20 (when δF = 5%).

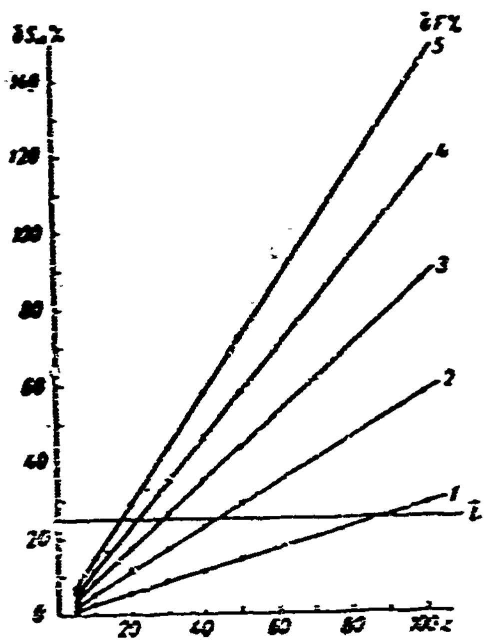

Figure 45. Theoretical Relative Errors of Measuring S_M by the Photoelectric Base Method.
l, Limit of permissible error.

These measurement (extrapolational) possibilities depend on the incline of the straight lines in Figure 45, which is determined by the magnitude of the error of δF of a given photoelectric set-up. The measurement possibilities of the method mount rapidly as the error of δF diminishes.

In order to establish the accuracy of the photometry of a given set-up one must either compare its indications with the indications of some standard set-up or, if the latter is not available, carry out protracted measurements and then contrast the quantities secured with the value for the visibility of dark objects on the terrain that are projected against a sky background at the horizon and that are observed at the threshold of receptivity; or else by bringing in for comparison purposes other methods of measurement.

Augmentation of the accuracy of measurements of S_M by the base method can be achieved through one of two courses: 1) reduction of S_M/L ratios by virtue of prolongation of the measurement base; 2) reduction of the exploitational photometry error of δF.

The first course is not always advantageous, since measurement of small values for S_M becomes impossible.

The second course is more readily applicable, and at present photoelectric apparatus are manufactured having a photometry error of δF amounting to about 1%, which offers the possibility of measuring S_M with values of z running up to 80-90, with a relative error δS_M of not more than 25%.

We should note that formula (6.8) takes on a somewhat different form if in the expression for meteorological range of visibility we use other values for the threshold of contrast sensitivity. If we assume, for example, that $\varepsilon = 0.05$ (i.e., 5%), then in the denominator of the numerical fraction of (6.6) we shall have 3.0 in place of 3.5, and in place of (6.8) we shall get

$$\delta S_м = 0{,}33z\delta F.$$

Analogously, with $\varepsilon = 0.02$

$$\delta S_м = 0{,}26z\delta F.$$

The theoretical error δS_M at one and the same value for z depends on the selection of the magnitude of the threshold ε. In reality, however, with different values of ε one should take various values of z; then δS_M will be identical for all three magnitudes of ε. The question of the most reliable value for ε is considered in § 66.

The base method has a serious shortcoming in use, brought about by the necessity in principle for the existence of a measurement base. This limits the possibilities of the method, making it possible to carry out measurements only in one azimuth and only in a horizontal direction. The base method is almost inapplicable on the open sea, in free air, in mountains, and under other similar circumstances where there is no possibility of placing both stations of the base method at the necessary distances apart.

§ 41. Photoelectric Set-Ups of the Initial Period (1934-1940)

The Bergman Apparatus

In 1936 Bergman constructed the first photoelectric atmospheric transmissivity gage, based on the zero-compensation method. The apparatus became widely known and entered into the history of meteorological instrument-making as an apparatus having a zero-compensation system and as a device in which for the first time the idea of modulating light beams in order to combat the parasitic irradiation of photoelectric indicators by scattered daylight.

The system of the Bergman apparatus is represented in Figure 46. The apparatus works as follows.

A beam of light from a lamp L, passing through a condenser K, is modulated by a disk MD having a frequency of f = 500 Hz. After this, passing through a filter F, the beam is divided by a semi-transparent mirror Z into two parts: one part, passing through the objective O and the regulating diaphragm D, avoiding the atmosphere, falls upon photoelement FE_1; the other part via the objective O_1 passes through the stratum (base) which is under investigation in the atmosphere and, having been reflected from a flat mirror located at a distance of 50 meters from the apparatus, falls via objective O_3 on the second photoelement FE_2.

The photoelements are connected to the primary windings of two identical sections of a transformer T in such fashion that the photocurrents from FE_1 and FE_2, induced in the second winding, run toward each other.

In the event of inequality of light flows, a differential current arising in the secondary winding enters the amplifier Y, is rectified after amplification, and is fed into galvanometer G, provoking a deviation of the arrow.

At the basis of the measurement process thre lies the zero-compensation method, consisting in the circumstance that through change in the aperture of the diaphragm D the flows are made equal, the arrow of the galvanometer being brought to zero -- which, generally speaking, should correspond to equality of the light flows falling upon the photoelements.

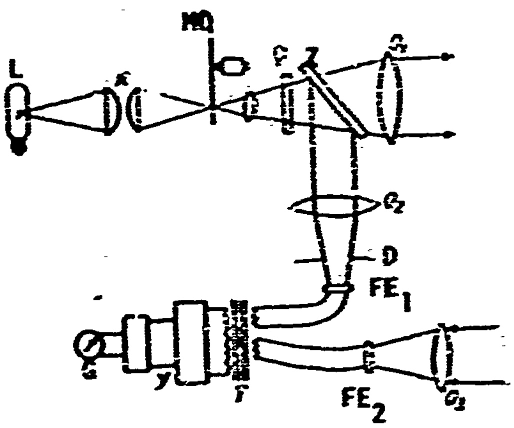

Figure 46. Diagram of the Principle of the Bergman Photoelectric Apparatus.

Reading of indications is carried out in accordance with the position of a diaphragm graduated in values for meteorological range of visibility. It was supposed that such a system would exclude the effect of scattered daylight, and also the effect of fluctuations in the luminance of the light source, instability of amplification of the amplifier, etc. But it soon became apparent that the apparatus had a number of shortcomings, among which the most important were the following:

1) the use of two photoelements does not provide the necessary precision of measurement, inasmuch as each of them has a different rate of aging with time; this circumstance proved to be the source of considerable errors in measurement;

2) it was supposed that at exit from the photoelements the electrical impulses of the signals would be identical in form, co-phasal in time, and of equal duration, since only such conditions would ensure the necessary precision of measurement and any deviation from them would lead to a sharp rise in error of measurement; actually, as we show below, these conditions cannot be met in the Bergman apparatus.

The Bergman apparatus also had other shortcomings: for example, the evening-off of light flows that was carried out by diaphragming one of them led to a supplementary error by reason of the differing degree of sensitivity of the photoelement at its center and at its edges.

The aggregate of the deficiencies of the apparatus described was such that in this apparatus it is impossible in principle to meet the first point of the requirements upon objective apparatus that were set forth at the end of § 39.

Despite these deficiencies, the idea of applying modulation and a zero-compensation system proved to be viable and underwent further development in subsequent treatments.

The V. A. Faas Extinctometer

A second way of combatting parasitic irradiation of the photoelement was applied in 1940 in the extinctometer of V. A. Faas. The instrument was intended for study of the optical density and heterogeneity of artificial smoke screens, and also of clouds, for which purpose the raising of the instrument on a captive or free balloon was contemplated.

The instrument consisted of two tubes fastened to a metal shaft at a distance of 2 meters from each other. In one tube there was placed a light source and a control photoelement, in the other the measurement photoelement. The ratio of the currents from these photoelements was measured with the help of a logometer. It was expected that the effect of fluctuation of the intensivity of the light source would be eliminated in this way. In order to eliminate the effect of the parasitic irradiation of daylight upon the measurement photoelement, a system consisting of a lens and diaphragm was used which ensured so low an angle of the field of vision that only a light flow from the illuminator fell upon the measurement photoelement, and the surrounding background was eliminated.

The very small measurement base (2 meters), the presence of two photoelements, the use of an inertia device like the logometer for the measurement of the rapid changes in the optical density of smoke screens -- all these things compelled failure in the utilization of the extinctometer.

But the idea of combatting scattered daylight luminance via diaphragming and the selection of low angles of the field of vision[1] found application in later treatments of objective transmissivity recorders. For example, in 1952 at the Le Bourget airport a Tasseel [226] transmissivity recorder was installed; it had a design principle very similar to the design of the Faas extinctometer. The recorder consisted of an illuminator and a collector, mounted in concrete pedestals placed 150 meters apart. The illuminator

[1] This way of combatting scattered daylight luminance was worked out by V. A. Faas jointly with M. S. Sterizat.

consisted of a lens with an incandescent lamp fastened at its focus. A control photoelement was affixed outside the lens and facing the exiting light flow. The collector contained an analogous lens with a limiting diaphragm of 4 mm close to the focus, and an analogous photoelement at a distance of 70 mm from the diaphragm. A change-over switch that turned on the photoelements at the illuminator and collector in succession every 20 seconds was linked up to an automatic recorder. Tasseel, taking into account the shortcoming of his system arising from the use of two photoelements, estimates the error of δF at 5%. For a base of 150 meters this makes it possible to measure visibility within limits of $270 \text{ m} \leq S_M \leq 2{,}400 \text{ m}$, to which a z of 15 corresponds.

The recorder was turned on only at low visibilities. There have been no further publications about it.

The Bradbury and Fryer Registering Apparatus [141]

This apparatus, created in 1940, was the next considerable step in developing zero-compensation devices.

Taking into account the deficiencies of the Bergman system with its two photoelements, Bradbury and Fryer developed and tested an apparatus having a single photoelement. The use of a single photoelement in a zero-compensation system called for the development and carrying into operation of the principle of commutation, i.e., of successive, alternating switching-in of control and measurement light beams on one and the same photoelement.

It was supposed that such a principle of design would ensure stable and accurate measurement of atmospheric transmissivity independently of alteration of the parameters of the apparatus itself (aging of the photoelement, instability of radiation of the light source, etc.).

Let us briefly examine the principle of operation of the apparatus. It consists of a collector-measurement device with a light source and a reflecting mirror set up 50 meters from the recorder.

The principle of the design of the collector-measurement apparatus is shown in Figure 47. The apparatus comprises: 1) a light source RL (mercury gas-diffusion lamp); 2) a modulator, consisting of a motor M_1 and turning screens VZ; 3) a collector apparatus, consisting of a photoelement FE, a filter F, and an alternating-current amplifier; 4) a mirror galvanometer G, a light source IS, and an automatic recorder.

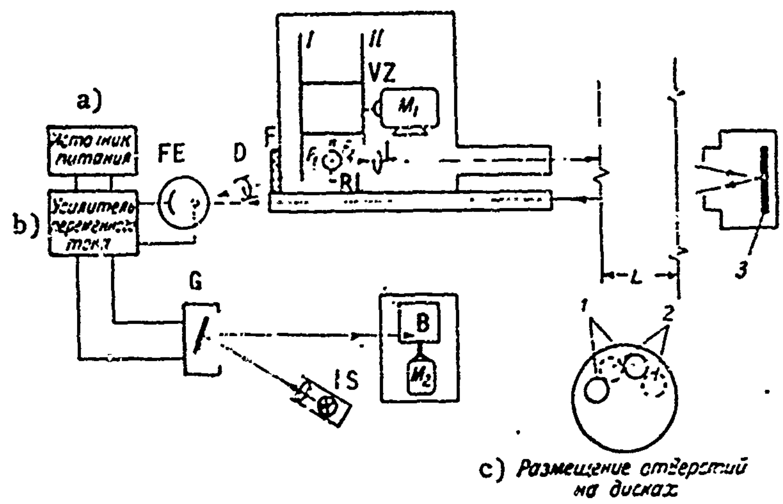

Figure 47. Design Principle of Bradbury and Fryer Photoelectric Apparatus
Key: a) Feed source; b) Alternating-current amplifier; c) Shifting of apertures in disks.

The turning screens VZ are built in the form of two disks I and II, firmly fastened in a fixed relationship to each other, but at a certain distance from each other, and set upon a common axis. The mercury lamp RL is placed between these disks, as is illustrated diagrammatically in the lower right-hand corner of Figure 47 (apertures 1 pertain to disk I, apertures 2 to disk II).

As the disks are rotated a commutation of the light flows F_1 and F_2 takes place. In one half of the period, flow F_1 falls upon photoelement FE. In the other half of the period, flow F_1 is shut off, but during this time the aperture of disk II is opened and light flow F_2 passes through lens L, the measurement base L and, after being reflected from mirror Z, returns and falls upon the same photoelement.

Compensation (evening-up) of light flows F_1 and F_2 is carried out only when there is high transmissivity of the atmosphere, under which circumstances the zero of the system is established. To this end a variable diaphragm D is used; by varying its aperture, minimum deviation of the galvanometer is secured, which should correspond to equality of light flows F_1 and F_2.

Upon reduction of the transmissivity of the atmosphere this equality is broken down as a consequence of reduction of flow F_2. In this event, a variable signal with a frequency equal to the frequency of modulation makes its appearance at exit from the photoelement; it is called the imbalance signal. This signal, fixed in accordance with the deviation of the arrow of the galvanometer from zero position, is a measurable one; i.e., its amount characterizes the degree to which the atmosphere has become turbid.

Inasmuch as compensation of the light flows takes place only at one extreme value for atmospheric turbidity and is absent in all other ranges, periodically -- at intervals of one hour -- the flow F_2 which goes into the atmosph-re is covered with a mechanical interrupter and only the control flow F_1 falls upon the photoelement. In this way the zero of the system in the range of transmissivity being measured is checked, and errors on account of aging of the photoelement, instability of illumination by the lamp, etc., are taken into account.

The indications of the galvanometer are recorded photographically on drum B, activated by a small motor M_2. The signal being measured, i.e., the signal of imbalance, is taken down on a tape, as are the control points.

Although the apparatus described here has substantial advantages over the Bergman set-up (alternating commutation of the light flows used upon one and the same photoelement), new shortcomings were nevertheless discovered in it. The principal one of these was the sum total of the errors occasioned by imperfection of the process of commutating two signals on one photoelement and leading to a state where the moment of balance (zero) of the system did not correspond to a strictly photometric equilibrium of the flows being compared (for a more detailed exposition of the question see § 43).

On account of these deficiencies the Bradbury and Fryer apparatus could not ensure reliable measurements, and work on it was halted.

From what has been set forth above it is apparent that on the applied level, progress was essentially not registered in solving the problem during the first phase in the creating of mass photoelectrical apparatus for the measurement and registration of atmospheric transmissivity, and that this phase should be regarded as a period of ground-work and research.

The main fruit of the period being examined was the application of the principle of modulation in order to combat parasitic radiation of scattered daylight (Bergman) and of the principle of commutation of light beams upon one photoelement as a means of combatting instability of the parameters of the photoelectric apparatus themselves (Bradbury and Fryer). In the process of developing these principles more and more new difficulties came up, which it has only of late become possible to overcome to a certain extent.

§ 42. Non-Compensation Photoelectric Apparatus

Non-compensation photoelectric apparatus constitute the simplest variants of the base method, ones where a projector with stabilized feed is placed at one end of the measurement section and a photoelectric collector and automatic recorder is placed at the other. Such a system of measurements excludes the possibility of uninterrupted checking of the system's zero, and it admits only of episodic checking of the zero on days having high transmissivity or in accordance with dark support objects on the terrain, if they are projected against a sky background at the horizon and are under haze at threshold visual perceptivity.

Two photoelectric apparatus of stationary type, very similar to each other, are built on this principle. One of these is the Doublas apparatus [158], developed in the United States in 1947; its commercial production was undertaken approximately in 1950. The second apparatus -- the V. I. Goryshin transmissivity register -- commenced series production in 1956 under the designation M-37.

Both apparatus are intended for measurement and registration of the meteorological range of visibility S_M at airfields in order to safeguard visual landing of airplanes.

At present many foreign airports are equipped with the Douglas apparatus, and almost all the USSR airports having concrete runways are equipped with the M-37 apparatus.

The apparatus are similar to each other in their principle of operation and in design respects, for which reason there is no point in describing them separately. In neither apparatus is modulation of the light source used. In order to avoid the use of direct-current amplifiers with their constant zero drift, the photoelements of each apparatus are connected to the circuit of the impulse generator in such fashion that the frequency of the impulses produced is proportionate to the illumination upon the photoelement which is produced by the projector. In order to eliminate the effect of parasitic irradiation of the photoelement with scattered daylight, the angle of vision of the collector is made very small with the help of a special long-focus objective and a system of diaphragms.

In the Douglas apparatus the electrical impulses are amplified by a two-cascade alternating current amplifier, and measurements of frequency are fed into the cascade; its outlet is connected to an automatic recorder or to a specially developed electronic-beam tube.

In the V. I. Goryshin M-37 apparatus a multivibrator cascade serves as an impulse generator. In this connection the level of signals proves to be high enough, and subsequent amplification of the impulses is not called for. The impulses, without supplementary amplification, are transformed, and are then fed into the cascade that measures frequency.

The exploitational error of photometering δF for the M-37 apparatus (as apparently also for the Douglas apparatus) has proved to be equal to approximately 3%, to which a value for the z parameter equal to approximately 30 corresponds for both apparatus (for $\delta S_M = 25\%$).

In the range of norms of landing visibility for which the upper limit of values of S_M does not exceed 3 km, and with a measurement base of 250 meters, z comes to 12, and the theoretical error $\delta S_M = 10\%$ (see formula 6.8). This accuracy is completely satisfactory if one considers additionally the fact that the parameters V_0 and D/B_σ are determined with errors approximately twice as great.

But experience in the use of these apparatus has revealed their substantial defects, which have served as a stimulus to the development of more highly refined devices.

One of the defects of the apparatus described is associated with the method of checking the zero for the system. This check has to be carried out at such high transmissivity of the atmosphere that the turbidity of the stratum on the section of the measurement base can be disregarded. With a base length L of 250 meters checking of the zero of the apparatus can be carried out when the value of S_M is not less than 25 km, and if L is 1 km (in the USA), when S_M is 100 km. Obviously if there is a turbidity of the atmosphere to any extent persistent and considerable, lasting some days (and in some regions of Siberia low transmissivity during the fall runs for weeks), checking of the zero cannot be carried out· in this event one can only recheck the functioning of the apparatus, and that only if there are dark objects on the terrain, located at known distances, projected against a sky background, and standing at the limit of visibility.

If objects on the terrain are lacking, the control in question is entirely insusceptible of execution until good visibility makes its appearance.

Another exploitational defect was more serious. It arises from the way of combatting parasitic irradiation of the photoelement with scattered atmospheric light.

Strong diaphragming of the variable light beam in the focal plane of the objective of the collector calls for extremely strict constant coaxiality of the projector and the collector. The slightest displacements of the projector or the collector give rise to total disruption of the work of the apparatus. In order to avoid this and ensure stability of the measurement process, it was found necessary to fasten the projector and the collector on massive bases extending not less than two meters deep. In the United States at Washington airport a six-meter concrete pile, driven into the ground in proximity to the main landing and take-off strip in such fashion that the beam goes past to one side above the runway at an elevation of five meters from the concrete surface, serves as a support for the projector. In Figure 48 we show the placement of the Douglas apparatus at American airports.

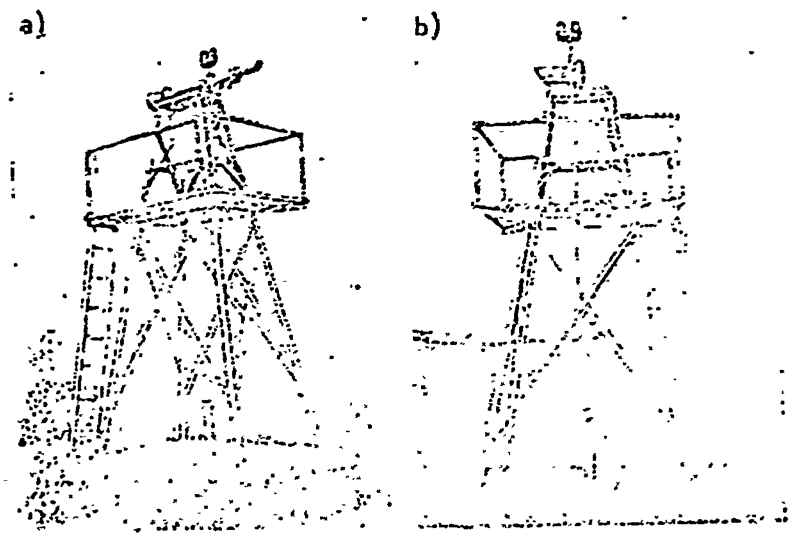

Figure 48. Placement of Douglas Photoelectric Apparatus on Terrain
a) Collector; b) Projector. The distance between collector and projector is up to 1 km, the height of the bridge is 5 m.

Thus the method of combatting scattered light has given rise to a major exploitational shortcoming -- the stationary character of the device, its being confined to the place where the concrete supports are located. Experience has shown that concrete supports, even such massive ones as the ones referred to above, still fail to ensure strict fixity of the position of the collector and the register vis-a-vis each other. In the fall, when the ground freezes, and in the spring, when it thaws, the two stations referred to become displaced relative to their initial position and the system has to be tuned anew.

The confinement of the apparatus to a given place, which excludes the possibility of any moving them about, obliges one to have at each airport a number of apparatus of the type described. Nevertheless, experience in the exploitation of the M-37 apparatus has shown that when regular, skilled supervision is ensured they give perfectly satisfactory results.

We may place the apparatus having high-intensity impulse sources of light developed by Freungel [168, 170, 171] among the number of non-compensation photoelectric devices.

Fruengel developed apparatus for several uses: registers of meteorological range of vision at airports, signal devices to report visibility values dangerous for a given region, including warning devices (sirens, beacons, etc.). Here we shall examine only a device for registration of the meteorological range of visibility. As a light source there was used in the device a small projector of 31 cm diameter, inside which a gas-discharge impulse lamp of a luminance of 10^7 candlepower per square centimeter was placed. This lamp is connected into a special system which provides 72 flashes per minute. The light source is placed at a distance of 150 meters from the collector apparatus. The collector is an antimony-cadmium vacuum photoelement. Electrical impulses from the photoelement are fed to a four-cascade amplifier having a special system for automatic regulation of amplification which operates in such fashion that the amplitude of all impulses remains constant upon exit.

The voltage of the automatic regulation is converted by a special system into a current from 0 to 1 milliampere, which is in fact the measurement current.

The optical part of the collector apparatus consists of a quartz lens of 90 mm diameter and having a focal length of 300 mm, and also of a diaphragm 1.5 mm in diameter, which ensures an angle of vision equal to 10'. A special diaphragm -- honeycombs consisting of 169 tubes 5 mm in diameter and 250 mm long -- is installed ahead of the lens.

Among shortcomings of the system one must list the following:

1) limited number of flashes of the impulse lamp;

2) dependence of amplitude of the light impulses of the lamp upon the parameters of the trigger, voltage on the lamp, etc.;

3) the radiation of the impulse lamp and the maximum spectral transmissivity of the antimony-cadmium photoelement are in the short-wave part of visible radiation and are sharply differentiated from the curve of visual perception of the eye, which may lead to increase of the error of measurement at medium and high transmissivity;

4) the complicated character of the electrical system; the accuracy of measurement is affected by the amplification factor of four amplifiers, the deviation from the logarithmic law on the part of the system for the automatic regulation of amplification, etc.

No details relative to the exploitational quality of the set-up, the errors of measurement, the steadiness of work, have been published.

§ 43. Zero-Compensation Photoelectric Apparatus

After the Second World War, in the USSR, the GDR, and France development compensation photoelectric apparatus commenced again, the principle of design for the majority of them being so similar to one another that there is no need to analyze each design separately. It is sufficient to examine the most highly refined apparatus -- the Foitzik transmissivity register. An analysis of this treatment makes it possible to establish the character of the new and serious shortcomings which are inherent in all treatments of this sort, and which are associated, as we show below, with imperfection of the process of commutating light beams.

Thereafter we shall examine a new principle of commutation developed by V. I. Goryshin and converted into reality by him in a compensation transmissivity register.

The Foitzik Transmissivity Register [163]

The design of the register, developed in 1950, is presented in Figure 49. From an incandescent lamp IL light is divided into two flows:

1) the "measurement" light flows, which is formed by lens L_1 and objective O_1 into a narrow, solid beam and which, after passing through the

stratum of the atmosphere being tested, falls upon a mirror reflector Ref; after which, returning to the device, it falls upon a paraboloid reflector P and then upon the measurement photoelement FE_1;

2) the "compensation" light flow, or the comparison flow, which is brought down upon the same photoelement FE_1 within the device, passing through lens L_2 and prisms PR_1, PR_2, PR_3, PR_4, and two diaphragms D_1 and D_2.

A cylindrical modulator Mod serves for modulation and alternative commutation of these light flows on the photocathode of photoelement FE_1.

The commutation cycle consists of the following processes:

a) only the light flow which has passed over the measurement base in the atmosphere falls upon the photocathode; the control light flow is completely covered over;

b) the measurement light flow commences to become covered over by the hood of the modulator, and the control flow commences to open; toward the end of this stage the first flow will have been covered over completely, and the second will open completely;

c) only the control light-flow falls upon the photocathode; the measurement light-flow is completely covered over;

d) the control light-flow commences to become covered over, and the measurement flow commences to open (reverse commutation of light flows); toward the end of this stage the control flow will have become completely covered over and the measurement flow will have opened completely.

After process d) the whole cycle is repeated.

[illegible] b) and d) determine what is actually the process of commutation [illegible]

[illegible] upon the accuracy of measurement of the transmissivity [illegible] It is precisely when processes [illegible] and d) are running their course [illegible] commutation [illegible] reduce the accuracy of measurements.

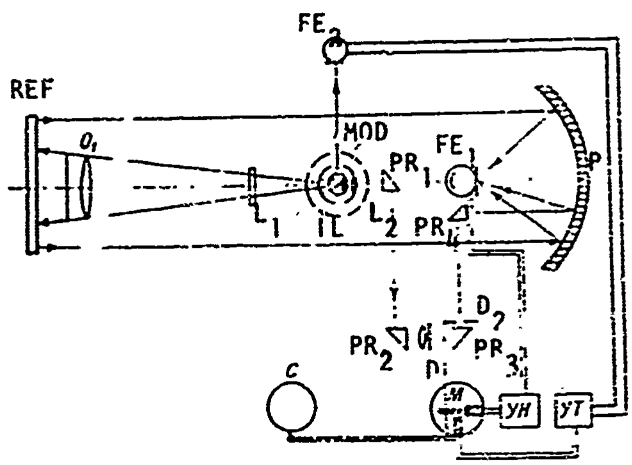

Figure 49. Diagram of Principle of the Foitzik Photoelectric Compensation Transmissivity Register.

As applied to the apparatus described, when the light flows are equal the variable component of the flow in the circuit of the photoelement FE_1 ought to be equal to zero, generally speaking. With reduction in the transmissivity of the atmosphere the measurement light flow becomes weaker and a variable signal component, having a frequency of commutation of 250 Hz makes its appearance in the FE_1 circuit. This signal of imbalance is communicated to voltage amplifier VA, and from its exit to the voltage winding of a small Ferraris phase motor M, the axle of which is connected with a variable diaphragm D_2. As a result of the action of the signal of imbalance, a depletion of the system takes place, during the process of which the motor changes the aperture of the diaphragm to a point where the level of signals from both light flows has been evened off and the signal of imbalance has become zero (or more precisely, has fallen below the threshold at which the motor turns over). A signal, proportionate to the magnitude of the aperture in the diaphragm at that moment, is communicated to the automatic recorder C.

The photoelement FE_2 is the source of a resistance signal communicated via amplifier AT to the secondary winding of the motor.

Such is the design system of the device, which the author intended to be an automatic zero-compensation transmissivity register. But tests of the device have brought to light a series of serious deficiencies in it.

In order to explain them we shall have to analyze what constitutes the imperfection of the process of commutation of the light flows, so often referred to above and characteristic for the majority of compensation photoelectric apparatus, making their functioning unsatisfactory.

As was pointed out above, the b) and d) commutation processes are impossible to make instantaneous in practice. But even under real conditions, when processes b) and d) are of finite duration, it would be possible to eliminate commutation defects if the following could be accomplished: by however much one light flow commutated upon the photoelement is diminished at each given moment of time, the second light flow should increase by just that amount, and vice versa. In this event, in a position of photometric equilibrium, the amplitudes of the impulses from the commutation flows would prove to be equal, there would be no variable component in the entering circuit of the amplifier, and the system would be in balance.

What has been said above in fact constitutes the indispensable conditions of commutation in the absence of which no photoelectric apparatus based upon modulation can measure with any degree of accuracy.

Is a "law" of commutation ensured in the compensation apparatus described above? -- i.e., does a simultaneous, but oppositely-running, equivalent change take place in the two light flows at the moment of their falling on the photocathode of the indicator?

The simplest line of reasoning shows that these conditions are not met in the devices analyzed above, for anumber of reasons.

As far back as 1951 V. F. Belov [7] showed that one of these reasons is the lack of correspondence between the dimensions of the light beam falling upon the reflecting mirror (at the end of the measurement base), and the dimensions of the mirror itself: the diameter of the light beam reaching the reflecting mirror is always larger, in consequence of an inevitable divergence over the measurement base section, than the dimensions of the reflecting mirror.

V. I. Goryshin not only analyzed in detail the consequences of this circumstance, but also showed that it is merely one of the many causes for the emergence of commutation disturbance occasioning the failure of all compensation transmissivity registers that had been worked out up to that time. Let us demonstrate the character of the commutation disturbance occasioned by non-correspondence between the dimensions of the reflecting mirror and the dimensions of the light flow falling upon it.

Let us turn to the upper part of Figure 50. The photometrically evened-off light flows fall in alternation upon the photoelement located close to the modulator hood: flow F_{comp} which has covered a short path from the light source, and flow F_{meas} which has traversed the measurement base in the atmosphere. On the diagram we illustrate the moment when the completely covered comparison flow is to open up, and the completely open measurement flow is at the same time to become covered over. According to the commutation law it is required that an equivalent reduction of flow F_{meas} should precisely correspond to the increase of flow F_{comp}. But this will actually not happen in reality: up to a turning of the hood to an angle α the light flow F_{meas} will not become reduced, since the reflector will not, during the course of this time lapse, commence to be screened by the non-transparent wall of the hood. For this reason, from the time of the start of modulation of the light flows under examination and up to the time when the hood turns to angle α the aggregate light flow will go up, as a result of which a positive ejection of signal will take place (see the diagram at the lower left corner of Figure 50).

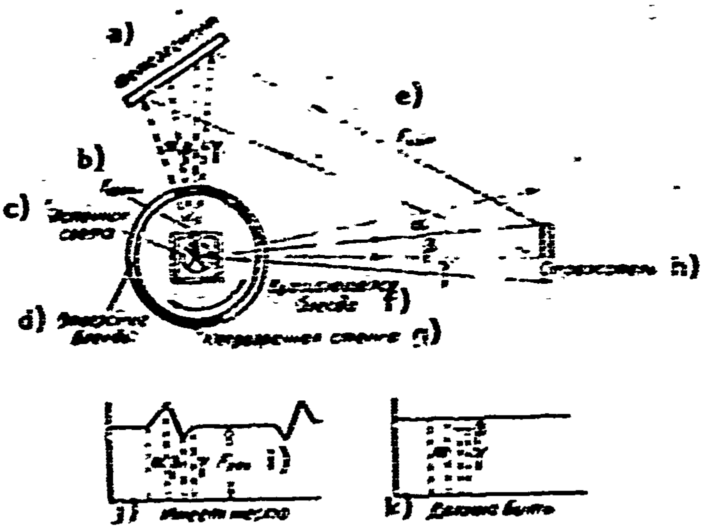

Figure 50. Diagram Explaining How the Basic Commutation Disturbance Arises in Compensation Photometric Apparatus. Key: a) Photoelement; b) F_{comp}; c) Light source; d) Aperture of hood; e) F_{meas}; f) Rotating hood; g) Non-transparent wall; h) Reflector; i) F_{res}; j) What actually occurs; k) What ought to happen.

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Further on the hood will turn to angle β and will completely cover the reflector, and the flow F_{meas} will not fall upon the photoelement. But by that moment the flow F_{comp} will not yet have opened up fully, so that consequently at the given moment the resultant light flow will be less than the mean value. Thereupon a negative ejection of signal will make its appearance.

Then, until the reflector is screened, and the hood turns to angle γ, the flow F_{comp}, gradually increasing, is at length fully opened and is compared with flow F_{meas}. For this moment the resultant flow $F_{res} = F_{meas} = F_{comp}$.

This is the way things stand in the first half of the modulation period.

In the second half of the modulation period, when flow F_{meas} is to open up, and F_{comp} is to close, a non-correspondence of the course of alteration of flows again occurs, but with the reverse sign: F_{comp} starts to diminish at once upon the hood's touching the edge of the flight flow F_{comp}, but flow F_{meas} will not fall upon the photoelement until the hood has turned to angle α. Over this interval of time the resultant flow will be less than the flow which ought to exist when there is correct commutation. The further behavior of the signal in the second half of the modulation period should be plain from the diagram presented in Figure 50.

From what has been set forth it is obvious that, as a consequence of non-correspondence of the dimensions of the reflector and of the light flow falling upon it, the flows F_{comp} and F_{meas} commutated have on the photoelement will not complement each other at the moment of commutation, and the commutation "law" will not be carried out, even through the condition $F_{comp} = F_{meas}$ holds good.

As a result of this, at the moment of photometric equilibrium there makes its appearance at the exit of the photoelement a commutation disturbance having a frequency equal to the frequency of modulation; this disturbance is what creates a false signal. The latter makes the position of photometric equilibrium of the system indeterminate, as a result of which accuracy of measurements deteriorates sharply.

This is only one of the reasons which condition the low exploitational qualities of the apparatus, with flows compared through commutation, that have been examined above.

In his apparatus [94], O. I. Popov sought to eliminate the commutation disturbance occasioned by failure of the dimensions of the reflector and of the light flow F_{meas} falling upon it to correspond, by making the flow slightly divergent and by catching the whole of it in the field of vision of a collector after reflection from a mirror. He managed to accomplish this, but at the cost of setting up the mirror and the collector on substantial foundations, which led to deterioration of the exploitational qualities of the device.

The circumstance which has been examined is not the sole cause for the arising of commutation disturbances. As V. I. Goryshin has shown, these also arise through the following causes:

a) when the modulated flows are differentiated as to the distribution of the density of light energy, i.e., are heterogeneous as regards structure; the character of the commutation disturbances which develop under this set of circumstances is even more complicated than the character of the disturbances examined above;

b) when the modulated flows are different as regards the dimensions of their cross-sections, something which produces a commutation disturbance analogous to that examined above;

c) when the diameters of the apertures on the disk of the modulator and the distances between these apertures are other than strictly equal to each other;

d) when the light flows F_{comp} and F_{meas} do not illuminate one and the same section of the light-sensitive surface of the photoelement.

Impairments to commutation arising in accordance with circumstances a), b), and c), are close to one another in character and provoke the same sort of effect as does the impairment examined above -- the one which is occasioned by different dimensions of the mirror and of the light flow falling upon it

The commutation impairment in accordance with condition d) arises, on all occasions, as a consequence of varying sensitivity of the surface of the photocathode of the indicator at various points. On this account evening-off F_{comp} and F_{meas} via diaphragming of the light flow alone (without use of milky glass or other analogous media) is inadmissible in principle, since in this case the amplitude relationships upon the conversion of light signals into electrical ones are broken down.

V. I. Goryshin has shown that the magnitude of the voltage of the impairment to commutation depends upon the time of commutation and the magnitude of the light flow; that the presence of an impairment to commutation is occasioned by a phase shift between the two signals, depending upon the relationship between the magnitude of the impairment and the magnitude of the frequency difference.

To resume what has been set forth above, we may say that the different design various of zero-compensation set-ups developed in the past and based upon mechanical modulation of light flows are linked with at least five causes which produce violation of the "law" of commutation and which bring to naught all of the merits of the zero method. On this account the principle of commutation which has been embodied in the designs worked out in the past cannot ensure the necessary accuracy of measurements. The causes which evoke impairment to commutation cannot be eliminated in their entirety, as has been shown in [46, 47], and in order to construct apparatus which possess greater accuracy of measurement, the very principle of modulation must be changed in such fashion that the impairments to commutation which arise shall exercise a minimal effect upon the accuracy of measurements.

After having presented a correct diagnosis of the failures which had pursued the earlier treatments, V. I. Goryshin, taking his last deduction as his basis, created a design for a compensation recorder of transmissivity having an altered principle of modulation of light flows.

The V. I. Goryshin Compensation Transmissivity Recorder [47, 49]

The optical system of the compensation recorder is in general constructed on the principle of the usual systems of this type (Figure 51).

The measurement light flow from the incandescent lamp IL is focussed by the condensor L_1-L_2 in the plane of the modulator disk M, and then, with the help of lens L_3, prism Pr_1, and objective L_4, is formed into a small solid angle and goes to the reflector, located 100 meters from the apparatus. The reflected light flow is received by the concave mirror 3 and then falls on the photocathode of the photoelement FE.

The comparison flow is also focussed, via the lens L_5, the prism Pr_2, and the lens L_6, in the plane of the modulator disk M, and then, passing through lens L_7, prism Pr_3, and measurement diaphragm D, it falls on the objective L_8, after which it is focussed on milky glass MG. After having passed through the adjustable photometric wedges (or prisms) AW (necessary for initial regulating) and lens L_9, the flow falls upon the photocathode in the form of a very slightly diverging beam of constant cross-section. The output from the photoelement is connected to the automatic recorder via an alternating current amplifier.

The basic distinction between the compensation recorder described and the compensation devices examined earlier consists in the special system for modulation of the light flows to be compared, which is achieved through an original design of the modulator disk (Figure 52 e). When this modulator is rotated by a motor m (Figure 51), at each half-turn of the disk one of the light beams is completely covered, while the other is at the same time modulated by comb-like teeth.

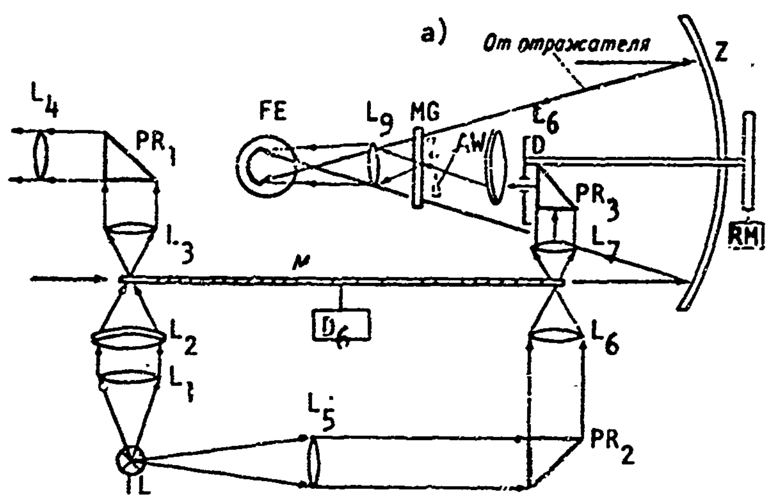

Figure 51. Diagram of the Principle of the Photoelectric Compensation Apparatus of V. I. Goryshin.
Key: a) From reflector.

In Figures 52 a and 52 b we show diagrammatically the character of the impulses from the measurement (F_1) and control (F_2) light beams respectively.

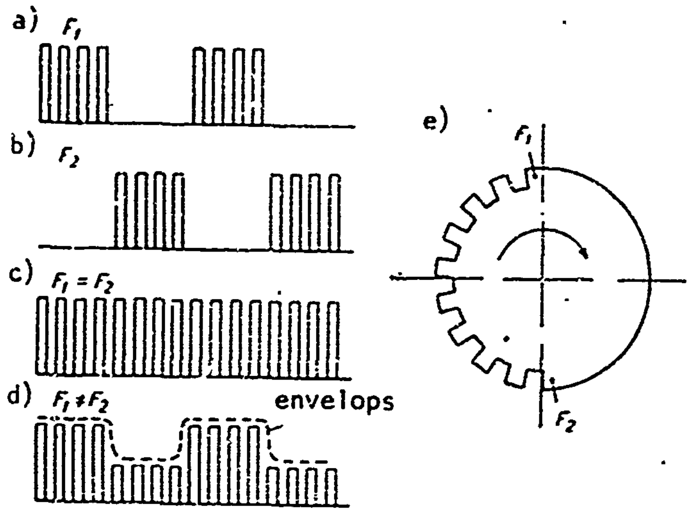

Figure 52. Design of Modulator Disk and Principle for Elimination of Impairments to Compensation of Photoelectric Compensation Devices (After V. I. Goryshin).

The character of the signal resulting when the commutated light beams F_1 and F_2 are equal (balance of system) is shown in Figure 52 c.

The electrical signal which develops proves to be modulated with a frequency which depends on the number of teeth in the comb and the speed of rotation of the disk. For the apparatus described this frequency is equal to 1,700 Hz.

With inequality of commuted flows F_1 and F_2 the character of the signal resulting changes, since a signal of imbalance makes its appearance, as is shown diagrammatically in Figure 52 d.

The resultant signal secured is first amplified to carrier frequency and then, after detection and separation out of the imbalance signal, to the envelope frequency.

When light flows F_1 and F_2 are unequal the imbalance signal that develops reacts upon the reversible motor rm of the automatic recorder (see Figure 51), which, operating upon diaphragm D, brings the system into equilibrium. During equilibrium the signal of imbalance falls out, and at the output of the system only the impulses of the carrier frequency are found.

This principle of modulation, i.e., having commutation and modulation on different frequencies, makes it possible to reduce to a minimum the effect of the commutation impairments which destined the compensation devices developed earlier to be inadequate.

Other considerable design refinements were introduced into the apparatus described, as well (advantageous relationship of dimensions of teeth in the comb to the light circle focused upon the modulator, sensible shape of the sectored measurement diaphragm, etc.), which reduced the photometric error δF to 1%. This makes it possible to evaluate the extrapolational possibilities of the device as running up to a quantity of z equal to more or less 80-90. With a measurement base of 250 meters (distance to reflector 125 meters) it is now possible to register S_M up to 20 km with an error for this value of visibility that does not exceed 20-25%.

Thus in respects having to do with principle the compensation transmissivity recorder of V. I. Goryshin is at present the most highly refined device in its class.

In concluding our brief survey of the development of photoelectrical methods for measuring and recording the horizontal transmissivity of the atmosphere we shall draw up a few basic conclusions.

1. Photoelectric base devices founded upon modulation of light flows and upon the use of two photoelements for differential measurement of flows F_{comp} and F_{meas} have a deficiency in principle, occasioned by the uneven aging of the photoelements over time. These apparatus cannot ensure measurement of atmospheric transmissivity with the necessary accuracy even within the limits of landing visibility norms. Devices of this type are of historical interest only.

2. Photoelectric base apparatus, based upon modulation through the use of a single photoelement, are in a position to ensure the necessary accuracy of measurement only on the condition that the commutation impairments provoked by various causes are eliminated. The numerous design varieties of devices in which this condition is not met are also only of historical interest.

3. The photoelectrical method as a whole has inherent in it a serious deficiency associated with expense, complicated design, frequent need for adjustment, indispensability of skilled supervision, etc. Apparatus requiring massive concrete or stone supports are characterized by a further shortcoming which consists in their being able to measure only in a set azimuth.

CHAPTER VII

MEASUREMENT OF HORIZONTAL AND NON-HORIZONTAL TRANSMISSIVITY OF THE ATMOSPHERE BY THE LIGHT BACK-SCATTER METHOD

§ 44. General Observations

Up to the time that meteorological rockets came into use, the method of projector sounding, developed in the USSR by I. A. Khvostikov and his collaborators [115, 116] and abroad by Hulbert [187] and other investigators, was one of the basic ways of sounding optically the upper strata of the atmosphere.

Through the help of projector sounding success was encountered in establishing many facts of fundamental importance, which have subsequently been confirmed by data secured by sending up rockets. A considerable and uneven aerosol hazing of the entire thickness of the troposphere and a great part of the stratosphere was detected. In these strata, contrary to expectations, a purely Rayleigh scattering does not exist; the hypothesis as to the exponential change of atmospheric transmissivity with altitude was not borne out [66, 100].

A survey of the development of the method of projector sounding of the atmosphere is given by G. V. Rosenberg [99].

In raising here the question of the measurement of non-horizontal transmissivity by the light back-scatter method we have it in mind as our ultimate purpose not to investigate the transmissivity of the upper strata of the atmosphere, but instead to perform a more limited task: that of measuring the transmissivity of a surface stratum having a thickness of 200-300 meters, to the end of determining as reliably as possible landing visibility, i.e., the visibility of objects along the concluding part of the descent glide.

One of the peculiarities of measuring non-horizontal transmissivity is the non-applicability of extrapolational methods, the ones ordinarily used in measurements of horizontal transmissivity. We cannot apply to non-horizontal directions the hypothesis as to the homogeneity of turbidity, as is ordinarily done for horizontal directions. For this reason, in measuring the transmissivity of a limited slice in an inclined direction, one cannot extrapolate a measured quantity into more extended sections in the same direction.

In a non-horizontal direction one can measure the transmissivity only of a limited inclined slice into which a light beam penetrates and within which the intensivity of scattered light is great enough to be measured visually or objectively. This circumstance complicates the problem of determining non-horizontal transmissivity to such an extent that at the present moment no developed, acceptable methods for measurement thereof exist.

This is why our data regarding the optical properties of the surface 200-300 meter stratum are limited. We still know very little about the optical properties of haze under low clouds, about the character of the change in atmospheric transmissivity with altitude, about the vertical density of surface cloud.

Measurement of non-horizontal transmissivity is possible in principle on the basis of projector sounding. But the need for introducing complicated current corrections into each angular altitude, these being called for by the properties of the scattering index; the complications of interpreting given measurements; the complications of the apparatus; and the like -- all these things constitute a serious drawback to bringing this method into a state where it can be exploited.

As G. V. Rosenberg has correctly pointed out [99], back of the simplicity, in principle, of projector sounding there lie concealed considerable difficulties of an apparatus, methodic, and interpretational character.

In order to determine slant visibility an effort has been made to utilize such radical means as sending up a helicopter with an observer on board, and sending up captive balloons with suspended black screens. But the rapidity with which atmospheric process operate, a feature characteristic for weather landing minima, takes all the value out of episodic ascents; for to be sure it is far too risky to keep helicopters or balloons in the air in proximity to runways during the entire period when a complicated state of meteorological affairs exists, particularly at crowded airports.

At present two methods for measurement of non-horizontal transmissivity of the surface atmospheric stratum are being developed; they are substantially differentiated from each other:

1) the method of equal angles, proposed in 1949 by Stewart, Drummeter, and Pearson [224], through which one can measure the averaged transmissivity of a limited inclined stratum (about 100 meters) with a fixed slant angle relative to the horizon;

2) the light back-scattering method [22, 23], which makes it possible to measure a series of optical characteristics of the surface stratum -- the transmissivity of inclined strata up to 250 meters in length and with slant angles from 0 to 90°, horizontal transmissivity stratum by stratum, the altitude of the upper limit of cloud (up to 100 meters above ground), and some others.

§ 45. Formulating the Question of the Measurement of Non-Horizontal Transmissivity by the Light Back-Scattering Method

The method of light back-scattering is proposed for measuring non-horizontal and horizontal transmissivity of the atmosphere over a range extending to some slight extent beyond the limits of presently operative norms for landing visibility.

The physical essence of this method of measurement consists in determining the transmissivity of the atmosphere in accordance with the intensivity of light scattered by a stratum of the atmosphere back to a light source illuminating this stratum. The idea of such a method for measuring atmospheric transmissivity was enunciated for the first time in 1951 [22]. At present this method, which is becoming more and more widespread [58, 134, 152, 203, 204], is called the light back-scatter method or the method of return light-scatter.

The system for measuring the transmissivity of atmosphere via the light back-scatter method consists in the following.

The atmosphere is lighted up by the beam of a projector. The aerosol particles suspended in the air, and also molecules of water vapor and atmospheric gasses, scatter the light rays in all directions, including that back to the projector at an angle of 180° relative to the light beam sent out by it. In this connection it is assumed that the quantity of light energy scattered back to the projector is proportionate to the degree of optical hazing of the atmosphere. This assumption has at this date been substantiated experimentally (see § 49).

An objective or visual collector is set up parallel to the optical axis of the projector or at a slight angle to it.

The magnitudes of light flows scattered back and measured by one means or another are graduated as functions of the transmissivity of a homogeneous atmosphere, i.e., of the meteorological range of visibility, which makes it possible to measure horizontal transmissivity of the atmosphere, too, by the light back-scatter method.

In order to measure non-horizontal transmissivity it is necessary first of all to know the distribution of the intensivity of back-scatter, commencing at the projector and moving outward along the projector beam. The calculation introduced in the following section shows that distribution of the luminance of light back-scatter has a characteristic peculiarity: close to the projector a bright return-illumination extending a total of 20 to 30 meters develops. In this zone more than 90% of the entire light energy of the projector beam which is scattered back is concentrated.

Clearly without elimination of the bright-illumination zone measurement of non-horizontal transmissivity will be impossible, since this zone obstructs the detection and measurement of the fainter light flows which come in from more remote zones of the projector cone. Effective penetration into the atmosphere when a brightly gleaming nearby zone is present is decidedly small -- 20 to 30 meters in all.

Exclusion of the bright illumination zone furnishes, as the calculation introduced below shows, an entirely different distribution of the luminance of light back-scatter, one making it possible to measure the light scattered by sections of the projector cone which lie removed from the projector by tens and hundreds of meters, or even by thousands of meters with suitable light sources.

The brilliantly gleaming column of air in proximity to the projector is eliminated by means of the shadow zones method described farther on.

With the help of shadow zones the effective penetration in a projector beam increases from 20-30 meters by a number of multiples and even by some tens of multiples, something which makes it possible to carry out the measurement of atmospheric transmissivity in any direction.

The principle of measuring non-horizontal transmissivity consists in the fact that in a stratum of the atmosphere, illuminated by a projector beam and inclined at a certain angle to the horizon, two successive effective penetrations, different in magnitude, occur; the difference between them makes it possible to find a mean horizontal transmissivity of a slant slice located at some altitude above the surface of the earth (see Figure 60).

Repetition of such a procedure as this for a number of selected angles of slant of the projector beam makes it possible to carry out a stratum-by-stratum sounding of a transmissivity which has been averaged (for the given stratum). Combining a number of such strata furnishes the possibility of finding the aggregate slant transmissivity of a certain thickness of the surface stratum at any selected angle to the surface of the earth.

This is the general system in principle for the measurement of non-horizontal transmissivity by the light back-scatter method.

In this chapter we shall examine the first steps in the practical carrying into operation of this method.

§ 46. Calculating the Luminance of Light Back-Scatter

Let us carry out an approximate computation of the horizontal stratum-by-stratum luminance of projector haze, commencing at the projector and moving outward, for a sighting direction of 180° ("down the beam," according to G. V. Rosenberg's terminology) and for different gradations of a homogeneous turbidity: from fog to a Rayleigh atmosphere. The basic idea of this computation is developed in studies of A. A. Gershun, V. V. Novikov, A. I. Gribanov, and other Soviet phototechnicians. In general terms we shall keep to the [40 and 52] systems for this computation.

A shortcoming of our computation is the assumption that the luminance of a projector beam close to the projector follows the law of squares, whereas this actually takes place only for the zone of formation. The luminance we calculate will be somewhat less than the actual. This difference plays no substantial part, inasmuch as the principle of measuring a non-horizontal transmissivity is based upon two successive effective penetrations into the projector beam, different in magnitude; and in addition, it is completely taken into account by the method of gradation.

Let us turn to Figure 53. Let us say that a projector is emitting into a homogeneously turbidized atmosphere a beam of very slightly diverging rays. At a distance L from the projector these rays will pass through a unit stratum dL. As a consequence of light scatter, stratum dL may be regarded as a unit light source which has different light power in various directions. The degree of this difference is determined by the indicatrix of light scatter.

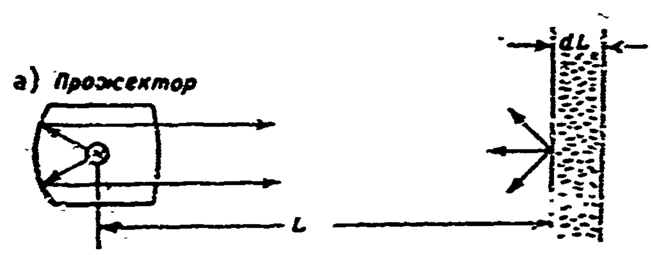

Figure 53. In Connection With Computing the Luminance of Light Back-Scatter.
Key: a) Projector

For any given direction constituting an angle θ with the direction of the falling rays, the strength of light dI(θ) of stratum dL is equal to

$$dI(\theta)=\rho(0)E\,dL, \tag{7.1}$$

where E is the illumination of stratum dL created by the projector; $\rho(\theta)$ is the index of scattering in the direction constituting angle θ with the direction of the projector ray.

If the medium not only scatters but also absorbs light energy, then the general index of attenuation α is made up of a scattered part, ρ, and an absorbed part, ν, i.e., $\alpha = \rho + \nu$. It is ordinarily assumed that the gaseous and aero-colloid components of the atmosphere do not absorb light energy, but merely scatter it, i.e., it is assumed that attenuation boils down to scattering, and that $\alpha = \rho$. Such an assumption cannot be applied to smoke particles, mineral dust, and the like, which have perceptible true absorption.

In order to simplify the calculation we shall take $\alpha = \rho$, assuming that smoke and dust particles are absent.

In the practice of phototechnical calculations the accepted thing is to consider the projector a point source of light. Since up to the formation of the beam a projector is actually a light source having a slight divergence of light rays, the assumption referred to above may be regarded as arbitrary. It is nevertheless used, in the first place because it greatly simplifies calculation, and in the second place because eschewing this assumption and replacing it with a stricter one leads to such clumsy integrals that they can be accepted only on the basis of simplifying assumptions that reduce to naught the severity of the initial formulation. On this account, following the generally accepted practice, we shall consider the projector as being a point source of light. In this case we can apply the Allard relation to it [see (1.31)], in accordance with which illumination E of the unit stratum dL, created by the projector, is equal (with loss of light in stratum L in direction θ taken into account) to

$$E = \frac{I_0}{L^2} e^{-\rho L}, \tag{7.2}$$

where I_0 is the power of the light of the projector, ρ is the index of scatter in stratum L, which is assumed to be homogeneously turbidized.

Substituting (7.2) into (7.1), we secure an expression for the power of the light of the unit stratum dL:

$$dI(\theta) = \rho(\theta) \frac{I_0}{L^2} e^{-\rho L} dL.$$

In the direction back to the light source, i.e., with $\theta = 180°$, the unit stratum dL will create a luminance of "haze" dB, which, taking into account loss of light on the path from dL to the projector, is equal to

$$dB = \rho(\theta)\,dI(\theta)\,e^{-\rho L}.$$

Substituting the value dI(θ) and replacing ρ(θ) by $\rho(\theta_{180})$ (the index of scatter with θ = 180°), we secure

$$dB = \rho(\theta_{180})\frac{I_0}{L^2}e^{-2\rho L}\,dL. \tag{7.3}$$

By reason of the existence of the scatter indicatrix, which changes from one atmospheric turbidity degree to another, the quantity $\rho(\theta_{180})$ has difference values for different turbidities.

As a consequence of insufficient knowledge of the absolute values of $\rho(\theta_{180})$ at different turbidities of the atmosphere, calculation of unit luminance in accordance with (7.3) gives rise to difficulties.

In order to get around this difficulty, A. A. Gershun proposed that instead of the index of scatter ρ(θ) a non-dimensional auxiliary parameter ψ(θ) be introduced, it being equal to the ratio of the index of scatter ρ(θ) to the whole index of scatter ρ, taken as being a unit, i.e.

$$\psi(\theta) = \frac{\rho(\theta)}{\rho}, \tag{7.4}$$

where (see § 68)

$$\rho = \int_0^{2\pi} d\varphi \int_0^{\pi} \overline{\rho(\theta)}\sin\theta\,d\theta = 2\pi\int_0^{\pi}\overline{\rho(\theta)}\sin\theta\,d\theta. \tag{7.5}$$

Here $\overline{\rho(\theta)}$ is the mean value of the function of scatter in direction θ relative to the falling rays. Angle ρ is a solid angle with its apex in the center of the scattering volume.

In accordance with its physical sense the auxiliary parameter ψ(θ) characterizes the form of the indicatrix of scatter.

It is further assumed that for any direction the mean spatial value of ψ(θ) is proportionate to 1/4π. In the event of isotropic light scatter, i.e., in the event of a spherical indicatrix, for any particular direction θ the parameter $\psi(\theta)$ would be equal to $1/4\pi = 0.0796 \approx 0.08$ [sic], and for a solid angle $4\pi\psi(\theta) = 1$.

But in reality, any physical medium possesses anisotropy of scatter. In the simplest case of anisotropic scatter, namely in the case of a Rayleigh (molecular) symmetrical indicatrix, when

$$\frac{\rho(\theta)}{\rho} = \overline{\rho(\theta)} = \frac{3}{4}(1+\cos^2\theta),$$

the parameter $\psi(\theta)$ is equal to

$$\psi(\theta) = \frac{1}{4\pi}\cdot\frac{3}{4}(1+\cos^2\theta) = \frac{3}{16\pi}(1+\cos^2\theta).$$

For the angle $\theta = 180°$ which is of interest to $\psi(\theta_{180}) = 0.12$; for angle $\theta = 90°$, $\psi(\theta_{90}) = 0.063$.

But so simple a definition of the values of $\psi(\theta)$ is possible only for a Rayleigh indicatrix. For a real polydisperse atmosphere, possessing scatter indicatrices diverse in form and magnitude, the definition of $\psi(\theta)$ becomes complicated, since no reliable equations of atmospheric indicatrices exist.

On the basis of an analysis of experimental atmosphere indicatrices of scatter, measured by various investigators, A. A. Gershun recommends the following value for parameter $\psi(\theta)$ for the scatter angle $\theta = 180°$ which is of interest to us:

1) for a Rayleigh atmosphere $\psi(\theta_{180}) = 0.12$;

2) for a fairly transparent, clear atmosphere $\psi(\theta_{180}) = 0.05$;

3) for a polluted, turbidized atmosphere $\psi(\theta_{180}) = 0.03$.

For an ideally pure Rayleigh atmosphere the meteorological range of visibility can be assumed as equal to approximately 350 km. Let us assume further that for a turbidized atmosphere $S_M < 10$ km, and for a pure atmosphere $S_M > 35$ km.

If these values of S_M and the magnitudes of $\psi(\theta_{180})$ that correspond to them are laid off on the axes of a set of coordinates on logarithmic scale, we secure the straight line represented in Figure 54.[1] This straight line makes it possible to get approximate values of $\psi(\theta_{180})$ with values of S_M from 1 to 350 km.

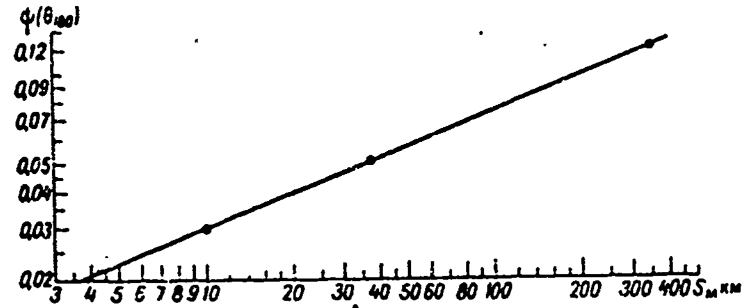

Figure 54. Values of Parameter $\psi(\theta_{180})$ Depending on Magnitude of S_M.

The indicated values of $\psi(\theta_{180})$ were set at the basis of calculation of the luminance of light back-scatter and of the approximated luminance of "projector haze" making observations "down the beam," starting from the projector and moving outward.

Now let us continue the calculation of the luminance of light back-scatter.

In accordance with (7.4) we can write

$$\rho(\theta_{180}) = \psi(\theta_{180})\,\rho. \tag{7.5a}$$

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[1] Thus far there is no single view regarding the value of S_M for a Rayleigh atmosphere. If one assumes with F. Linke [197] that for a Rayleigh atmosphere $\alpha_{Ray} = \rho_{Ray} = 0.0113$ km^{-1}, or with K.S. Shifrin [127] that $\alpha_{Ray} = 0.0095$ km^{-1}, one can secure the following values of $S_M = \ln \frac{I}{\varepsilon} / \alpha$ for a Rayleigh atmosphere:

ε%	2	3	5
S_M, km, (according to Linke)	346	310	266
S_M, km, (according to Shifrin)	412	368	315

Substitution of this expression in (7.3) gives the value for the luminance dB of the unit stratum dL:

$$dB=\psi(\theta_{180})\rho\frac{I_0}{L^2}e^{-2\gamma L}. \tag{7.6}$$

We shall show that the quantity ρ, which figures twice in (7.6), is described by integrals (7.5) or can be given numerically in accordance with the Koschmider relationship (1.28).

Integrating (7.6) for all unit strata located at distances from L_1 to L_2 away from the projector gives the luminance of "projector haze" in the stratum L_1-L_2, occasioned by the scatter of light upon suspended particles (including molecules of atmospheric gasses):

$$B=\int_{L_1}^{L_2}\psi(\theta_{180})\rho\frac{I_0}{L^2}e^{-2\gamma L}dL. \tag{7.7}$$

In the sub-integral function of (7.7) we have justification for taking as constant quantities the strength of the projector's light I_0 and the coefficient, or index, of scatter ρ for the given optical state of the atmosphere. The function $\psi(\theta_{180})$ for a given atmospheric turbidity may also be regarded as a constant quantity.

Thus we have finally

$$B=\psi(\theta_{180})\rho I_0\int_{L_1}^{L_2}\frac{e^{-2\gamma L}}{L^2}dL. \tag{7.8}$$

This is the value of the luminance of a projector ray between stratum L_1 near the projector and a more distance stratum L_2, if one looks at a projector ray from behind along its optical axis.

Now it remains to calculate the integral in (7.8). It might be possible to get it by means of the following procedure.

Let us designate -2ρ by α. Then the integral in (7.8) is reduced to the form:

$$\int \frac{e^{ax}}{x^n} dx = \frac{1}{n-1}\left(-\frac{e^{ax}}{x^{n-1}}\right) + a\int \frac{e^{ax}}{x^{n-1}} dx.$$

Since in our case n = 2, the last integral falls among integrals of the type

$$\int \frac{e^{ax}}{x} dx = \ln x + \frac{ax}{1.1!} + \frac{(ax)^2}{2.2!} + \frac{(ax)^3}{3.3!} + \ldots + \frac{(ax)^m}{m.m!}.$$

Thus the integral in (7.8) which is being sought may be solved in the following way:

$$\int_{L_1}^{L_2} \frac{e^{-2\rho L}}{L^2} = \left\{-\frac{e^{-2\rho L_1}}{L_1} - 2\rho\left[\ln L_1 - 2\rho L_1 + \frac{(2\rho L_1)^2}{2.2!} - \right.\right.$$
$$\left.\left. - \frac{(2\rho L_1)^3}{3.3!} + \ldots\right]\right\} - \left\{-\frac{e^{-2\rho L_2}}{L_2} - 2\rho\left[\ln L_2 - 2\rho L_2 + \right.\right.$$
$$\left.\left. + \frac{(2\rho L_2)^2}{2.2!} - \frac{(2\rho L_2)^3}{3.3!} + \ldots\right]\right\}.$$

Integration of (7.8) through breaking it down into series leads, as we see, to decidedly awkward expressions. But the practice of phototechnical computations shows that the expression secured is not merely awkward, but does not even afford the necessary accuracy of result, particularly when values of ρL are great.

A. A. Gershun has worked out an original and more up-to-date course for calculating the integral in (7.8) through its conversion into integrals of simpler form which are susceptible of being tabulated.

The integral in (7.8) is reduced to the form

$$\int_{L_1}^{L_2} \frac{e^{-2\rho L}}{L^2} dL = 2\rho\left(\int_{2\rho L_1}^{\infty} \frac{e^{-t}}{t^2} dt - \int_{2\rho L_2}^{\infty} \frac{e^{-t}}{t^2} dt\right).$$

Thus instead of (7.8) we shall have

$$B = 2\psi(\theta_{180})\rho^2 I_0\left(\int_{2\rho L_1}^{\infty}\frac{e^{-t}}{t^2}dt - \int_{2\rho L_2}^{\infty}\frac{e^{-t}}{t^2}dt\right).$$

Each integral within the parentheses is expressed by means of the auxiliary function

$$F(2\rho L) = \int_{2\rho L}^{\infty}\frac{e^{-t}}{t^2}dt,$$

which is then integrated by parts:

$$F(2\rho L) = \int_{2\rho L}^{\infty}\frac{e^{-t}}{t^2}dt = \frac{e^{-2\rho L}}{2\rho L} - \int_{2\rho L}^{\infty}\frac{e^{-t}}{t}dt.$$

On the basis of existing tables for values of e^{-x}/x and of tables for the integral $-\int_x^{\infty}\frac{e^{-t}}{t}dt$, A. A. Gershun and G. R. Tsyplyakov worked out a table of values for F(x) with various values of $x = 2\rho L$ (See Table 26).

Outside the tabulated field, with values of $x < 0.01$, the function F(x) was figured out according to the formula

$$F(2\rho L) \approx \frac{1}{2\rho L}.$$

On the basis of tables for the values of $F(2\rho L)$ we have the following expression for the luminance of a projector beam calculated in accordance with the principle of light back-scatter from L_1 to L_2 for a homogeneous atmosphere:

$$B_{L_1-L_2} = 2\psi(\theta_{180})\rho^2 I_0[F(2\rho L_1) - F(2\rho L_2)]. \quad (7.9)$$

The functions in brackets are determined in accordance with tables for various values of ρ and L, in which connection $L_1 < L_2$. The difference between these functions is what constitutes the numerical value of the integral in (7.8).

TABLE 26. VALUES FOR FUNCTION F(2ρL) (AFTER A. A. GERSHUN AND G. R. TSYPLYAKOV)

2ρL	F(2ρL)	2ρL	F(2ρL)	2ρL	F(2ρL)	2ρL	F(2ρL)
0,00	∞	0,32	1,41	0,64	0,404	0,96	0,164
0,01	95,0	0,33	1,34	0,65	0,391	0,97	0,160
0,02	45,7	0,34	1,28	0,66	0,379	0,98	0,156
0,03	29,4	0,35	1,22	0,67	0,368	0,99	0,152
0,04	21,3	0,36	1,16	0,68	0,357	1,00	0,149
0,05	16,6	0,37	1,11	0,69	0,346	1,1	0,117
0,06	13,4	0,38	1,063	0,70	0,335	1,2	0,0926
0,07	11,2	0,39	1,017	0,71	0,325	1,3	0,0741
0,08	9,51	0,40	0,974	0,72	0,316	1,4	0,0600
0,09	8,24	0,41	0,933	0,73	0,307	1,5	0,0487
0,10	7,23	0,42	0,894	0,74	0,298	1,6	0,0399
0,11	6,41	0,43	0,858	0,75	0,290	1,7	0,0328
0,12	5,73	0,44	0,824	0,76	0,281	1,8	0,0271
0,13	5,17	0,45	0,792	0,77	0,273	1,9	0,0225
0,14	4,69	0,46	0,761	0,78	0,265	2,0	0,0188
0,15	4,27	0,47	0,732	0,79	0,258	2,1	0,0157
0,16	3,92	0,48	0,704	0,80	0,251	2,2	0,0132
0,17	3,61	0,49	0,678	0,81	0,244	2,3	0,0111
0,18	3,33	0,50	0,653	0,82	0,237	2,4	0,00936
0,19	3,09	0,51	0,630	0,83	0,231	2,5	0,00793
0,20	2,87	0,52	0,607	0,84	0,225	2,6	0,00672
0,21	2,68	0,53	0,586	0,85	0,219	2,7	0,00571
0,22	2,50	0,54	0,565	0,86	0,213	2,8	0,00486
0,23	2,34	0,55	0,546	0,87	0,207	2,9	0,00415
0,24	2,20	0,56	0,527	0,88	0,202	3,0	0,00356
0,25	2,07	0,57	0,509	0,89	0,197	3,1	0,00304
0,26	1,95	0,58	0,492	0,90	0,192	3,2	0,00261
0,27	1,84	0,59	0,476	0,91	0,187	3,3	0,00224
0,28	1,74	0,60	0,461	0,92	0,182	3,4	0,00192
0,29	1,65	0,61	0,446	0,93	0,177	3,5	0,00166
0,30	1,56	0,62	0,431	0,94	0,172		
0,31	1,48	0,63	0,417	0,95	0,168		

Note: The values of F(2ρL) in the interval of values of 2ρL from 0.01 to 0.00 are set forth in Table 27.

In accordance with the Koschmider formula the quantity $\rho = \alpha$ is ordinarily expressed in inverse kilometers. But on the other hand the accepted thing is to express luminance B in stilbs (candlepower per square centimeter). If in expression (7.9) luminance is expressed in stilbs, then ρ must be reduced to inverse centimeters ($1\ cm^{-1} = 10^{-5}\ km^{-1}$).

Thus in (7.9) $\rho^2 = 10^{-1}\ km^{-1}$. Then (7.9) assumes the form

$$B_{L_2-L_1} = 2\psi(\theta_{180})\rho^2 I_0 [F(2\rho L_1) - F(2\rho L_2)]\, 10^{-10}\ \text{sb}, \qquad (7.10)$$

where L is to be expressed in kilometers, and ρ in inverse kilometers.

Expression (7.10) characterizes the luminance (which we have been seeking) of an optically homogeneous column of air, illuminated by a projector and running from L_1 to L_2, sighted "down the beam," i.e., at an angle of 180° relative to the rays issuing from the projector.

§ 47. Depth of Effective Penetration L_{eff} Into a Homogeneous Rayleigh Atmosphere With $\theta = 180°$

Expression (7.10) is the basic one for the light back-scatter method. It enables one to calculate the relative luminance of columns of air of varying lengths, and in this way to solve in principle the important question of the depth of effective penetration L_{eff} into the atmosphere when sighting down a ray at an angle $\theta = 180°$. Let us calculate L_{eff} for an ideally pure Rayleigh atmosphere.

Let us clear up to begin with the meaning we attribute to the concept L_{eff}.

The general luminance $B(\theta_{180})$ of a projector ray of infinite length in a direction $\theta = 180°$ ought theoretically to be taken as being 100%. But for a ray of infinite length the concept L_{eff} is devoid of meaning, since an illuminated stratum remote by any distance you please from the projector participates physically in forming a signal which can be theoretically taken as 100% in calculating. Inasmuch as the sensitivity of the collector is not infinitely great, the collector is not in a position to react to the contribution made by a remotely positioned stratum. If the relative size of the minimum contribution which the collector is still able to detect is designated by n%, then the distance L_{eff} at which "saturation" of luminance is attained for the given collector ought to be calculated for a distance from the projector at which the luminance of the ray amounts to (100-n)%.

If, for example, we take n as being equal to 5%, then by L_{eff} we should mean the distance at which luminance $B(\theta_{180})$ makes up 95% of the full luminance of the ray that is theoretically attained at infinity. Here we may carry out an analogy with the procedure, familiar and already known to the reader, under which the luminance B_ϕ of the sky at the horizon is made equal to the coefficient D of the light-air equation, in which connection a divergence of a few percentage points between B_ϕ and D is allowed.

Thus by depth of effective penetration into the atmosphere (or more precisely, into the projector beam) we understand a distance from the projector such that upon looking "down the beam," i.e., in a direction $\theta = 180°$, we achieve a state of "saturation" of the luminance of the beam scattered backward, in which connection when further removal of the stratum toward infinity takes place no perceptible increment of the signal occurs.

Inasmuch as the depth of effective penetration is a relative quantity, one might calculate it quite simply via computation of the difference between the two functions in brackets (7.10). But it is of interest to determine L_{eff} when there is an approximated calculation of the constant $2\psi(\theta_{180})\rho^2 I_0$, something which makes it possible to offer a few supplementary observations regarding the potentialities of the method.

Since the quantity $\psi(\theta_{180})$ forms part of (7.10) as a constant component, it does not exercise influence upon the depth of effective penetration into the atmosphere at a given turbidity level for the latter. On this account there is no need to complicate the calculation by introducing each time precise values for $\psi(\theta_{180})$. It is sufficient to make use of the three values which were referred to during analysis of the nomogram in Figure 54.

For all cases let us assume that the distance of L_1 from the projector mirror is equal to 1 meter, and that L_2 varies from 1 to infinity.

Now let us calculate L_{eff} for a Rayleigh atmosphere. So as not to overload this book with detailed computations and tables, we shall set forth here only an outline of the computation.

For a Rayleigh atmosphere we assume with F. Linke that $\rho = 0.0113$ km^{-1}, $\rho^2 = 12.8 \cdot 10^{-5} = 1.3 \cdot 10^{-4}$; and further that, as we are aware, $\psi(\theta_{180}) = 0.12$. The light power of the projector, I_0, when a RDSH-250 superpressure gas-discharge mercury lamp having an arc glow luminance of about $2 \cdot 10^4$ stilbs is used, comes to approximately $5 \cdot 10^7$ candlepower (for a mirror of 60 cm diameter).

Thus as applied to a Rayleigh atmosphere the constant in (7.10) is equal to

$$2\psi(\theta_{180})\rho^2 I_0 \cdot 10^{-10} = 2 \cdot 1{,}2 \cdot 10^{-1} \cdot 1{,}3 \cdot 10^{-4} \cdot 5{,}4 \cdot 10^{-7} \cdot 10^{-10} = \\ = 1{,}7 \cdot 10^{-7}.$$

Finally, for a Rayleigh atmosphere we secure from (7.10)

$$B_{L_1-L_2} = 1{,}7 \cdot 10^{-7}[F(2\rho L_1) - F(2\rho L_2)].$$

For determination of the values of the functions in brackets we shall make use of Table 26 drawn up, as we have remarked above, by A. A. Gershun and G. R. Tsyplyakov, and for a Rayleigh atmosphere Table 27, worked out in accordance with the approximated formula

$$F(2\rho L) \approx \frac{1}{2\rho L}.$$

The data secured with applicability to a Rayleigh atmosphere are set forth in Table 28.

From Table 28 it transpires that the intensivity of the light flow scattered back to the projector falls off rapidly as one moves away from the projector. Thus in the 1-5 meter from the projector stratum 80% of the entire back-scattered light energy is contained, and in the 1-10 meter stratum, as we have remarked above, 90%.

As the data in Table 28 show, in a Rayleigh atmosphere at a distance of 25 meters from the projector a state of luminance "saturation" is practically achieved, since the contribution made by all remaining strata comes to little over 5%. This distance may in fact be taken as the depth of effective penetration L_{eff} for a Rayleigh atmosphere, if one looks "down the beam" from a distance of 1 meter from the projector.

TABLE 27. VALUES OF $F(2\rho L) \approx \frac{1}{2\rho L}$ FOR A RAYLEIGH ATMOSPHERE ($\rho = 0.0113\ km^{-1}$, $S_M = 350$ km)

2ρL	F(2ρL)	2ρL	F(2ρL)
0,0000226	44 000	0,00452	221
0,000113	8 800	0,00497	204
0,000226	4 425	0,00542	185
0,000452	2 300	0,00556	175
0,000675	1 475	0,00678	148
0,000904	1 106	0,00904	105
0,00113	885	0,01130	88
0,00136	735	0,01356	74
0,00180	555	0,0158	63
0,00226	442	0,0181	55
0,00271	370	0,0226	40
0,00316	316	0,0271	33
0,00362	276	0,0310	28
0,00407	245	0,0362	24

TABLE 28. STRATUM-BY-STRATUM DISTRIBUTION OF LUMINANCE OF LIGHT BACK-SCATTER IN A HOMOGENEOUS RAYLEIGH ATMOSPHERE (S_M = 350 km)

Distance from Projector, m	Luminance of Stratum	% of Luminance	[Illeg.]	Stratum-by-Stratum Increment of Luminance "Stilbs"	"%"
1—5	$5.49 \cdot 10^{-3}$	80,0	1—5	$5.49 \cdot 10^{-3}$	80
1—10	6.17	89.9	5—10	0,68	9,9
1—20	6,51	94.9	10—20	0,34	5,0
1—30	6,63	96.6	20—30	0,12	1,7
1—40	6,69	97.6	30—40	0,06	1,0
1—50	6,73	98.1	40—50	0,04	0,5
1—60	5,75	98,4	50—60	0,02	0,2
1—∞	6,86	100	50—∞	0,11	1,7

Note: The data regarding luminance relate to the test set-up described below.

In analogous fashion one can determine L_{eff} for any other value of S_M. Below we set forth values, computed in the same manner, for the depth of effective penetration L_{eff} into a homogeneously turbidized atmosphere, with various values of S_M and with observation through a closer zone of brilliant glow (the length of the stratum of luminance "saturation" when sighting "down the beam"):

S_M, km	0.5	1	3	5	10	20	Rayleigh atmosphere
L_{eff}, m	13	18	18	20	20	20	25

From these data it is apparent that L_{eff} diminishes as atmospheric turbidity mounts. For limits of meteorological visibility associated with weather landing minima L_{eff} comes to a total of 15-18 m.

Such are the properties of the light back-scatter method if observation "down the beam" is carried out through the brilliantly glowing stratum of the zone close at hand.

Thus without exclusion of the close brilliant-glow zone the method of light back-scatter would have to be evaluated as a local method making possible the measurement only of horizontal transmissivity over the broad range of its real change. But it is evidently impossible to work out a methods system for measurement of non-horizontal transmissivity without excluding the brilliant-glow zone and with an L_{eff} mounting to 15-20 m.

Can we set aside from the measurement process the intensivity glowing stratum of air in proximity to the projector?

Such a possibility, indeed a sole such possibility, does exist. It consists, as has already been pointed out, in the necessity of supplementing the light back-scatter method by means of the shaded zones method, which makes it possible, as it were, to pass to one side of the intensive-glow zone and to enter the projector beam beyond its boundaries. Through this course we succeed in securing a measurable signal from the strata of the atmosphere which are remote from the projector by tens and hundreds of meters; the local character of the light back-scatter method is eliminated, and it becomes possible to measure the non-horizontal transmissivity of the atmosphere.

§ 48. Augmenting the Depth of Effective Penetration Into the Atmosphere With the Help of Shaded Zones [23]

Let us consider briefly what the idea of shaded zones consists of, and what new measurement possibilities their use opens up.

Let us imagine that on the optical axis of a projector an objective collector apparatus is positioned 5 meters ahead of the mirror.

In this event, back of the collector apparatus there would be a five-meter glowing zone containing more than 80% of all the light energy scattered along the beam back to the projector. If this zone were to be cut out and were not to take part in the formation of the signal, then the collector would be capable of sensing signals from the more remote strata of the atmosphere, where the state of luminance "saturation" would be achieved in stratum of altogether different length. To be sure, the signal would under these circumstances be considerably fainter than without the introduction of the collector apparatus, but it would still be sufficient for its being measured. As calculations in accordance with the system set forth above show, the depth of effective penetration L_{eff} increases substantially even with removal of the collector from the projector by 5 meters. For example, in fog with S_M = 0.5 km, L_{eff} would achieve 50 meters instead of 15 meters, and in a Rayleigh atmosphere L_{eff} would be equal to 130 meters instead of 15. In principle the collector apparatus can be moved even farther from the projector, even farther from the zone of the brilliantly glowing column of the atmosphere, which would make it possible to measure the light scattered back from strata even more remote than in the foregoing case. Calculations show that comparatively insignificant movements of the collector apparatus forward in the direction of the projector beam produce a surging increase in the depth of effective penetration of the ray into the atmosphere.

But the way of increasing the depth of effective penetration that we have explained runs up against mounting technical difficulties in the way of holding the collector apparatus fast as it is moved forward and back along the optical axis of the projector. Instead of this method of excluding the brightly glowing strata, it would be possible to make use of another, consisting in the shading of the zone of brilliant glow with the help of non-transparent diaphragms of one diameter or another, fastened ahead of the projector on its optical axis. If the diaphragms are round, then a readily discernible shadow cone is formed with its base at the diaphragm and its apex on the optical axis at some distance from the projector. In this connection depending on the diameter of the diaphragm, the angle of divergence (emission) of the rays of the projector, and the magnitude of the field of vision of the collector, the depth of the shaded zone may vary from some meters to some tens of meters. The design of a set-up having such shaded zones is shown in Figure 55 in principle. But shading the projector with diaphragms is also disadvantageous, as a consequence of the attenuation of its axial light power.

A more consequential method for creating a shaded zone is the placement of the collector on a bracket at some distance to one side of the projector, and the carrying out of turns of the collector to specified angles relative to the optical axis of the projector (Figure 56). In this case the axis of sighting of the collector at a given angle of aim enters the projector beam at a calculated distance from the projector, cutting out a brilliantly glowing stratum of specified length without reducing the light power of the projector.

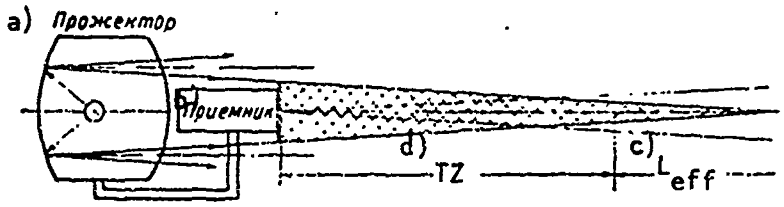


Figure 55. Method of Excluding the Zone of Brilliant Glow: Creation of a Shaded Zone (TZ) by Diaphragming the Projector Beam with a Non-Transparent Diaphragm Having a Central Aperture Equal to the Angle of the Field of Vision of the Collector (From the Photocathode Side).
Key: a) Projector; b) Collector; c) L_{eff}; d) TZ.

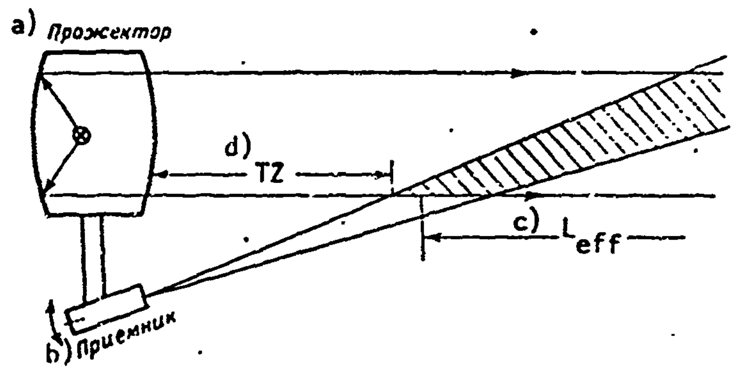


Figure 56. Method of Excluding the Zone of Brilliant Glow: Placement of the Collector to One Side of the Projector and Scanning Along the Projector Beam by Turns of the Collector or a Prism to Specified Angles Relative to the Optical Axis of the Projector. TZ - Shaded zone.
Key: a) Projector; b) Collector; c) L_{eff}; d) TZ.

The results of calculation of change in the luminance of "projector glare" with various shaded zones and values of L_{eff} are set forth in the nomograms of Figure 57.

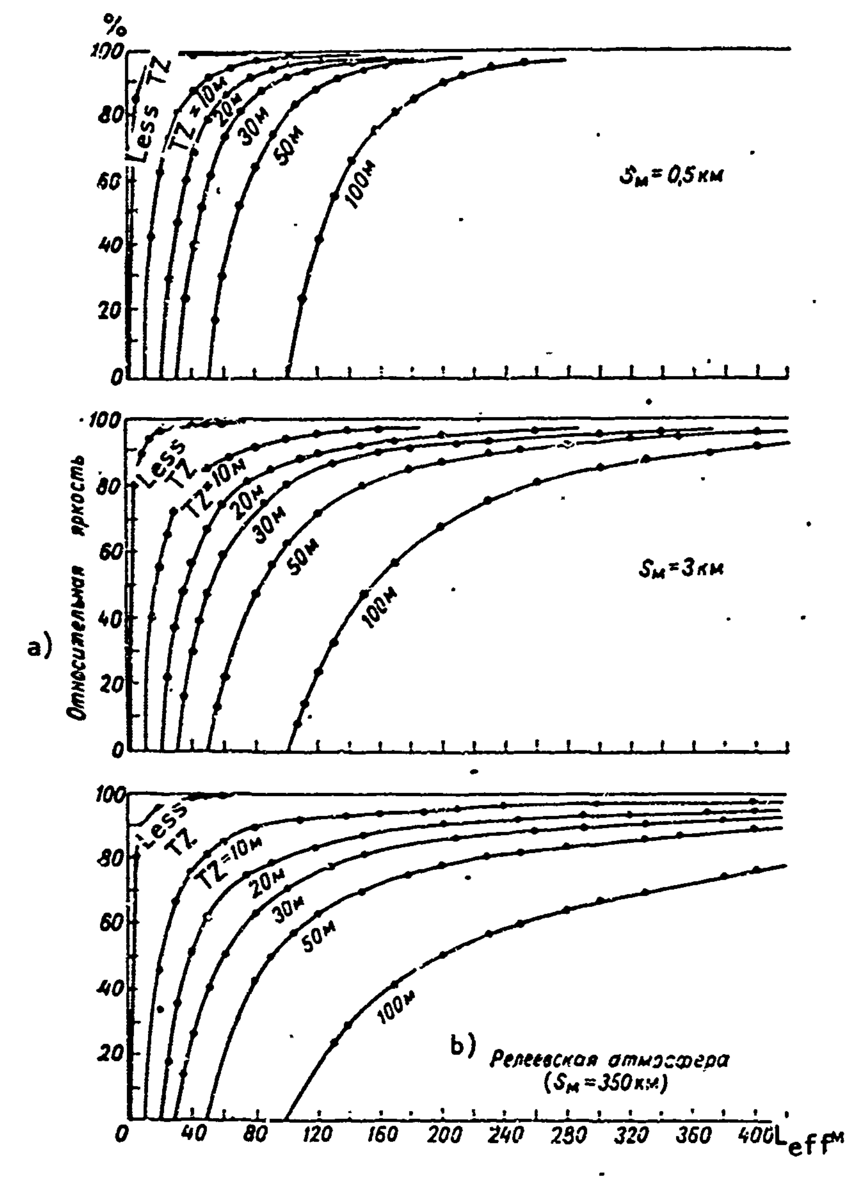


Figure 57. Depth of Effective Penetration L_{eff} Depending on the Magnitude of the Shaded Zone TZ and the Values for S_M.

Key: a) Relative Luminance; b) Rayleigh Atmosphere (S_M = 350 km)

From the curves presented in this figure it is apparent that increase of the shaded zone is accompanied by a characteristic slant, of the curves for the distribution of the luminance of back-scatter, relative to the abscissa; in which connection this slant is the greater, the more transmissive is the atmosphere. Values of L_{eff}, and also the distances from the projector at which a condition of "95% saturation" luminance is achieved, can be determined from the nomograms presented.

Variations of L_{eff} depending on the value of S_M and the magnitude of the shaded zone are the key to the construction of the methods system for measurement of non-horizontal transmissivity and to the carrying out of stratum-by-stratum sounding of the surface strata of the atmosphere.

§ 49. Character of the Correlation Between the Intensivity of Back-Scatter And the Transmissivity of the Atmosphere

Augmenting the depth of effective penetration into the projector beam with the help of shaded zones still does not of itself guarantee the possibility of measuring non-horizontal transmissivity.

In order to reach a final judgment as to the possibility of measuring the transmissivity of the atmosphere through the light back-scatter method it is necessary to elucidate the character of the correlation between the transmissivity of the atmosphere and the magnitude of the signal to be measured, i.e., the intensivity of back-scatter.

Obviously if at one and the same transmissivity of the atmosphere the magnitude of the signal to be measured changes within broad limits and independently of any regular linkages, then the principle of light back-scatter will prove to be inapplicable for measurement not only of non-horizontal, but also of horizontal transmissivity.

Thus establishing the character of the correlation between the transmissivity of the atmosphere and light back-scatter is a matter of importance as regards principle. This question was investigated on a first test model of the "slanting beam" set-up [38] built as far back as 1960 and intended for checking the initial theoretical propositions of the light back-scatter method.

We do not offer a description and diagram of the set-up here.

The set-up, mounted on a photometric range at Voyeikovo, was graduated on days having steady transmissivity relative to values of S_M (in the horizontal direction) in accordance with the indications of a M-37 transmissivity recorder and other devices available at the range. The set-up was graduated for three shaded zones equal respectively to 20, 30, and 40 meters.

For each shaded zone about 200 graduated points were secured over a range of S_M values from 0.35 to 20 km, and for all three zones about 600 points in all. The results of the graduation are set forth graphically in Figure 58. Along the ordinate axis the signal u_c is set forth in logarithmic scale, and on the abscissa axis the S_M values.

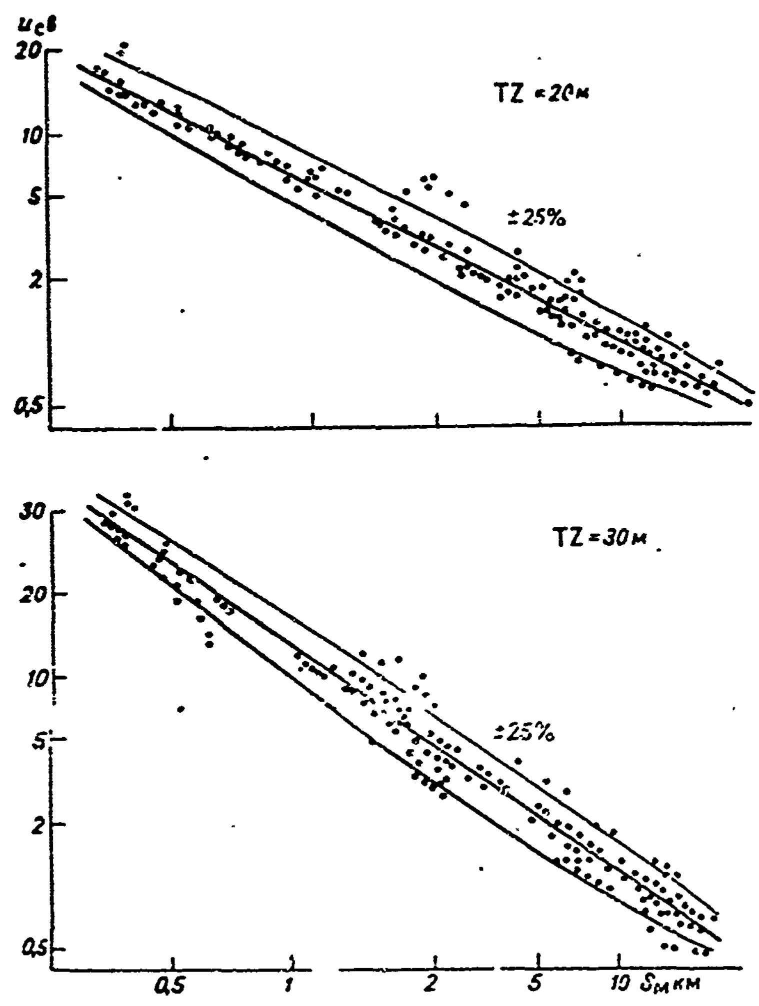


Figure 58. Character of the Correlation Between S_M and the Magnitude of the Signal u_c in the Light Back-Scatter Method, as Secured on the "Slanting Beam" Test Set-Up.

In the graphs presented it transpires quite obviously that in the logarithmic scale of coordinates a linear relationship exists between the intensivity of the light back-scatter and the magnitude of meteorological range of visibility. 70% of all the graduated points were located with deviations of plus or minus 20% from the central straight line, and as much as 90% of them within limits of plus or minus 25%. Irregular, major fluctuations of magnitude of signal measured were not detected at one and the same level of transmissivity.

This circumstance is of decisive significance for the application of the principle of light back-scatter in measuring non-horizontal and horizontal transmissivity, and it substantially simplifies the graduation and interpretation of the results of measurements.

In this connection the study [152] calls for attention; it reports regarding experiments with a test set-up on back-scattering that were carried out in 1956-1957 in the United States in a region where the air is not polluted with industrial smokes.

The results of 200 measurements are set forth in the form of a composite graph (Figure 59).

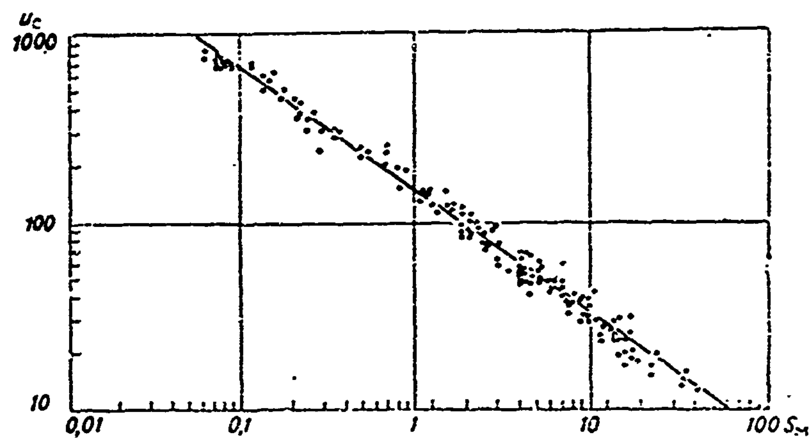


Figure 59. Character of the Correlation Between S_M and the Magnitude of Signal u_c, Secured on an American Back-Scattering Set-Up.

As the graph shows, this study too detected a well-defined linear relationship between S_M and the magnitude of signal u_c. This relationship is expressed by the authors in the following form:

$$S_M = \frac{c}{u_c^{1,5}},$$

where c is a constant.

It is easy to see that the graph in Figure 58 and the graph in Figure 59 coincide.

Investigations on a more up-to-date "slanting ray" set-up with automatic remote control, constructed in 1965 by the author and V. A. Kovalev and described below, once more confirmed the linear correlation between S_M and back-scatter.

The data secured make it possible to conclude that a linear correlation between the intensivity of back-scatter and the transmissivity of the atmosphere (on a logarithmic coordinate scale) is a general property of the back-scatter method. This circumstance permits us to make us of the method explained for measurement of a series of optical characteristics of the surface stratum of the atmosphere. These we examined below.

Let us dwell briefly upon one interesting circumstance which arises both from the results of our measurements and from the data of the American investigators.

Experience has shown that with one and the same level of transmissivity the magnitude of the signal received undergoes fluctuation attaining 20-25% relative to the measured mean value of S_M. This spread considerably exceeds the errors in photometering the scattered light flow reaching the collector. It is decidedly curious that the magnitude of the spread referred to remains the same over a wide range of atmospheric turbidities: from heavy fogs to good transmissivity (15-20 km), something which may be regarded as an objective limit to the accuracy of the back-scatter method.

Neither the magnitude of this spread, nor its constancy over the entire range of atmospheric transmissivity measured in reality, has yet received explanation.

§ 50. The Theory of Measuring Non-Horizontal Transmissivity by the Method of Light Back-Scatter (Theory and Method of Stratum-by-Stratum Sounding of Horizontal Transmissivity)

As we indicated above, a considerable increase in the depth of effective penetration, L_{eff}, into the atmosphere with the help of shaded zones is the key to the construction of a methods system for measurement of non-horizontal transmissivity.

From § 46 it is plain that change in the luminance of back-scatter takes place, generally speaking, in accordance with the Buger exponential law. But in contradistinction to the usual form of that law

$$\tau^L = e^{-\rho L} = \exp\left(-L 2\pi \int_0^\pi \overline{\rho(\theta)} \sin\theta \, d\theta\right),$$

(for the conventional designations see § 8), in the back-scatter method the length of course L should be doubled, i.e., instead of L we should have 2L (inasmuch as a ray covers a double course: from the light source to the scattering stratum and back), and the integral scatter indicator ρ should be replaced by a scatter indicator $\rho(\theta_{180})$. In other words, we would be obliged, formally speaking to write

$$\tau^{2L} = e^{-2L\rho(\theta_{180})}, \quad (7.11)$$

but in our instance 2L is replaced by the equivalent quantity L_{eff}, which takes into account the double course traversed by the ray.

Furthermore, although we are actually measuring a light flow characterized by the scatter index $\rho(\theta_{180})$, it ought to be brought into harmony with general atmospheric turbidity. But the latter is characterized by the integral scatter indicator ρ, which in its turn can be expressed through the meteorological range of visibility in accordance with the Koschmider formula. In other words, in place of $\rho(\theta_{180})$ we should make use of a relationship equivalent to it and analogous to (7.5a), i.e.

$$\rho(\theta_{180}) = c_{180}\rho.$$

where c_{180} is the partial value of the relative indicatrix of scatter when measuring at an angle $\theta = 180°$; this value differs with differing atmospheric transmissivity. The product $c_{180\rho}$ is determined by the conditions of the graduation.

Taking into account what has been said above, we can write in place of (7.11)

$$\tau^{L_{eff}} = e^{-L_{eff} c_{180\rho}}. \quad (7.12)$$

Expression (7.12) constitutes the Buger law as applied to the back-scatter method. Basing oneself on (7.12) it is not difficult to lay out a system for stratum-by-stratum sounding of atmospheric transmissivity on the basis of two successive effective penetrations different as regards amount. The system for such a measurement is set forth in Figure 60. With one and the same angle of elevation ϕ of the projector, i.e., for one and the same slant direction, two different effective penetrations into the projector beam are successively effected by changing the shaded zones. Obviously a greater L_{eff} will correspond to the larger shaded zone. Let us designate the greater effective penetration by L_{eff2} and the lesser one by L_{eff1}.

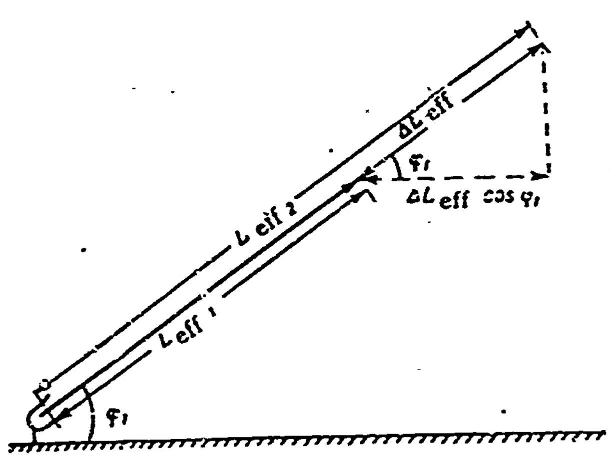


Figure 60. Diagram of the Principle for Measurement of Slant Transmissivity by the Back-Scatter Method (Method of Two Effective Penetrations).

Having received signals for effective penetrations $L_{eff.2}$ and $L_{eff.1}$, we determine in accordance with the calibration nomogram the mean values $S_{M.2}$ and $S_{M.1}$ in the specified slant direction that correspond to these signals (see the nomograms in Figure 58).

It is clear that the values $S_{M.2}$ and $S_{M.1}$ are characterized by a mean slant transmissivity over sections $L_{eff.2}$ and $L_{eff.1}$ respectively.

But this sort of information regarding slant transmissivity is only relatively valuable, inasmuch as the averaging may take place for excessively deep effective penetrations (up to 200-250 meters and more). Most valuable is information regarding the mean transmissivity of the atmosphere stratum that lies between two effective penetrations $L_{eff.2}$ and $L_{eff.1}$, something that would make it possible to reach judgments about the mean transmissivity of a stratum of atmosphere at a specified altitude above the earth's surface. The carrying out of such measurements is precisely what constitutes the basis of the method being set forth.

In order that the course of further reasoning may be more readily understood, let us recall one of the basic propositions of physical optics.

Let us imagine that we have two media of density L_1 and L_x, each of which has a transmissivity τ^{L_1} and τ^{L_x} (see Figure 61).

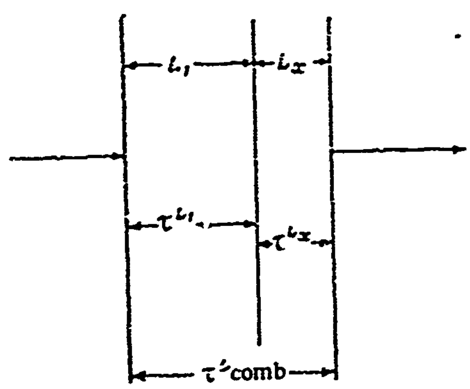


Figure 61. Combined Transmissivity of Two Strata, as Applicable to Determination of Slant Transmissivity of the Atmosphere.

In accordance with a proposition of physical optics, the combined transmissivity $\tau^{L_{comb}}$ of both strata is equal to the product of the transmissivities of both media, i.e.,

$$\tau^{L_{comb}} = \tau^{L_1} \tau^{L_x}. \tag{7.13}$$

This proposition of physical optics is entirely applicable to the method under examination for measurement of stratum-by-stratum transmissivity of the atmosphere. If we turn to Figure 60, it becomes evident that $\tau^{L_{comb}}$ is to be related to $\tau^{L_{eff.2}}$, and further that τ^{L_1} is to be related to $\tau^{L_{eff.1}}$; and finally, that τ^{L_x} is to be related to the value $\tau^{\Delta L_{eff}}$ which we are seeking. In other words, analogously to (7.13), we can write

$$\tau^{L_{eff\,2}} = \tau^{L_{eff\,1}} \tau^{\Delta L_{eff}}. \tag{7.14}$$

From (7.14) we determine the transmissivity of the slant section ΔL_{eff}, specifically

$$\tau^{\Delta L_{eff,slant}} = \frac{\tau^{L_{eff\,2}}}{\tau^{L_{eff\,1}}} = \tau^{L_{eff\,2} - L_{eff\,1}}. \tag{7.15}$$

On the other hand, taking (7.12) into account we can write

$$\tau^{\Delta L_{eff\,slant}} = \frac{e^{-L_{eff\,2} c_{2(180)}\rho}}{e^{-L_{eff\,1} c_{1(180)}\rho}} = e^{-L_{eff\,2} c_{2(180)}\rho + L_{eff\,1} c_{1(180)}\rho}. \tag{7.16}$$

Assuming that

$$c_{2(180)}\rho = \rho_2 \text{ and } c_{1(180)}\rho = \rho_1,$$

we secure in place of (7.16)

$$\tau^{\Delta L_{eff\,slant}} = e^{-\rho_2 L_{eff\,2} + \rho_1 L_{eff\,1}}. \tag{7.17}$$

Replacing the integral scatter indexes ρ_2 and ρ_1 in accordance with the Koschmider formula:

$$\rho_2 = \frac{3,5}{S_{m.2}} \text{ and } \rho_1 = \frac{3,5}{S_{m.1}},$$

we secure in place of (7.17)

$$\tau^{\Delta L_{\text{eff slant}}} = e^{-3,5\left(\frac{L_{\text{eff }2}}{S_{m.2}} - \frac{L_{\text{eff }1}}{S_{m.1}}\right)}, \tag{7.18}$$

whence

$$\Delta L_{\text{eff slant}}(-\ln\tau) = 3,5\left(\frac{L_{\text{eff }2}}{S_{m.2}} - \frac{L_{\text{eff }1}}{S_{m.1}}\right). \tag{7.19}$$

Bearing in mind the fact that

$$S_m = \frac{3,5}{\rho} = \frac{3,5}{-\ln\tau},$$

we finally secure (throwing out the "eff" index of ΔL_{eff})

$$S_{m(\Delta L_{\text{slant}})} = \frac{3,5}{-\ln\tau} = \frac{\Delta L_{\text{slant}}}{\frac{L_{\text{eff }2}}{S_{m.2}} - \frac{L_{\text{eff }1}}{S_{m.1}}}, \tag{7.20}$$

in which connection it is obvious that

$$\Delta L_{\text{slant}} = (L_{\text{eff }2} - L_{\text{eff. }1}) \text{ km}.$$

Expression (7.20) describes the mean transmissivity of the slant section ΔL_{slant}, expressed through meteorological range of visibility (in kolometer unit length), and is the basic formula of the method. We shall show that (7.20) describes also the mean horizontal transmissivity of the stratum ΔL_{hor} which lies between the two effective penetrations $L_{\text{eff.2}}$ and $L_{\text{eff.1}}$.

From Figure 60 we get the obvious equality

$$\Delta L_{hor} = \Delta L_{slant} \cos \varphi_1, \tag{7.21}$$

where ϕ_1 is the angle of incline of the projector beam relative to the horizon.

Hence it follows that

$$\tau^{\Delta L_{hor}} = \tau^{\Delta L_{slant} \cos \varphi_1};$$

on the basis of (7.18) we secure

$$\tau^{\Delta L_{hor}} = \tau^{\Delta L_{slant} \cos \varphi_1} = e^{-3.5\left(\frac{L_{eff.2}}{S_{M.2}} - \frac{L_{eff.1}}{S_{M.1}}\right)\cos \varphi_1}. \tag{7.22}$$

Further, analogously to (7.19) and (7.20), we secure

$$S_{M(\Delta L_{hor})} = \frac{\Delta L_{slant} \cos \varphi_1}{\left(\frac{L_{eff.2}}{S_{M.2}} - \frac{L_{eff.1}}{S_{M.1}}\right)\cos \varphi_1} = \frac{\Delta L_{slant}}{\frac{L_{eff.2}}{S_{M.2}} - \frac{L_{eff.1}}{S_{M.1}}}. \tag{7.23}$$

Thus expressions (7.20) and (7.23), characterizing respectively the mean slant and mean horizontal transmissivity of the stratum $\Delta L = (L_{eff.2} - L_{eff.1})$ km, expressed through the meteorological range of visibility in kilometers, have proved to be identical.

We have deliberately carried out the derivation of (7.21), (7.22), and (7.23) in order to emphasize this last circumstance.

We would also be able to show, by going through an analogous calculation, the identity to (7.20) of the expression for vertical transmissivity $S_{M(\Delta L_{vert})}$ of the stratum $\Delta L_{vert} = \Delta L_{slant} \sin \varphi_1$.

The physical sense of the identity of expressions (7.20) and (7.23) respectively for slant and horizontal (and also vertical transmissivity of stratum ΔL is plain: this is the mean transmissivity of the stratum or the mean meteorological range of visibility in kilometer unit length. The mean transmissivity in the stratum over a kilometer's distance ought, in fact, to be the same in any direction. But in this connection it is only mean transmissivity in the horizontal direction, to which the hypothesis of homogeneity of turbidity is applicable, that is of practical significance.

The practical significance of the mean transmissivity over one kilometer in the vertical and the slant direction is slight, because in a real atmosphere transmissivity changes sharply with altitude and the hypothesis of homogeneous turbidity is not applicable.

Thus after having carried out two successive effective penetrations $L_{eff.2}$ and $L_{eff.1}$ at a specified angle of elevation ϕ_1 of the projector, we at once determine in accordance with formula (7.23) the mean horizontal transmissivity of the stratum $h_2 - h_1$ at a given altitude above the earth's surface, in which connection

$$h_2 = L_{eff.2} \sin \phi_1,$$

$$h_1 = L_{eff.1} \sin \phi_1.$$

By varying the angles of elevation $\phi_1, \phi_2, \ldots, \phi_i$, by carrying out for each of them two successive effective penetrations $L_{(eff.2)\phi i}$ and $L_{(eff.1)\phi_i}$, and knowing for each of the latter the magnitude of S_M, we can achieve stratum-by-stratum sounding for strata of the atmosphere located at a specified altitude above the ground and closely adjoining one another.

In order to ensure successful landing of airplanes under complicated meteorological conditions it suffices to determine the transmissivity of 4-5 strata above the earth's surface (the thickness of each being 20-30 meters).

Calculating the angles of elevation ϕ_i of the projector and the magnitude of the shaded zones in order to get the specified values of L_{eff} is a technical matter on the details of which we need not pause here.

§ 51. The Order of Carrying Out Measurements

The method of stratum-by-stratum sounding of atmospheric transmissivity described in the foregoing section calls for the availability of two initial nomograms without which measurements cannot be accomplished.

These nomograms are:

a) Calibration nomogram I, prepared beforehand with application to the given set-up, on one of the axes of which values of S_M are laid off, and on the other, readings in accordance with the measurement device; in order to determine S_M during the process of calibrating one may make use of any of the set-ups, devices, and methods described above (for the "slanting beam" set-up described below calibration is carried out only once); nomogram I has the form shown in Figure 58;

b) Computation nomogram II, prepared beforehand, for the values of the depth of effective penetration L_{eff} in relation to values of S_M and the magnitude of the shaded zone TZ (Figure 62). The principle for calculating L_{eff} and constructing the nomogram has been examined above.

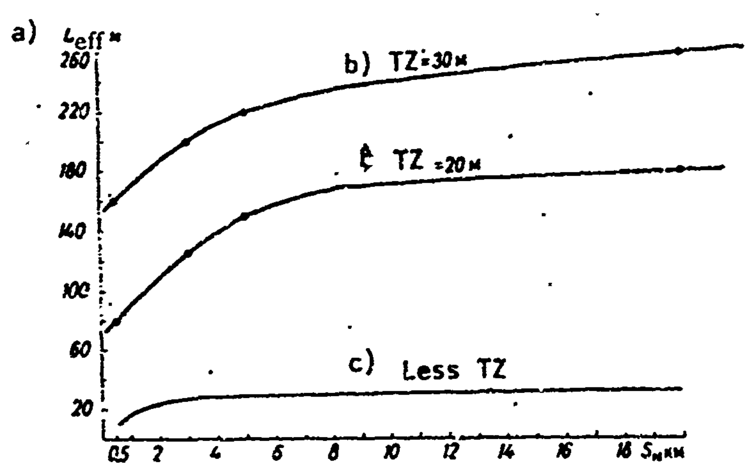


Figure 62. Calculation Nomogram II of Values of L_{eff} In Relation to Measured Values of S_M (Applicable to the "Slanting Beam" Set-Up).
Key: a) L_{eff} m; b) TZ; c) Without TZ.

Measurement of stratum-by-stratum transmissivity should be carried out in the following order.

1. First one measures horizontal transmissivity. For this purpose the projector is given a horizontal direction and the signal is measured for

each (or for one) shaded zone. The magnitude of S_M is determined in accordance with calibration nomogram I from this signal.

2. The projector is given an angle of elevation ϕ_1. The signal is measured separately for each of the two shaded zones used. With these signals we return once more to calibration nomogram I, in accordance with which we determine the mean values $S_{M.2}$ and $S_{M.1}$, but this time in an inclined direction.

3. In accordance with the values secured for $S_{M.2}$ and $S_{M.1}$ we resort to the calculation nomogram II, in accordance with which we find the corresponding values for $L_{(eff.2)\phi_1}$, and $L_{(eff.1)\phi_1}$.

4. In accordance with formula (7.23) we determine the value of the mean horizontal transmissivity $S_{M(hor)\phi_1}$ of a stratum at a given altitude above the earth's surface.

5. The operations under 2 and 3 are repeated for angles of elevation $\phi_2, \ldots, \phi_n$ of the projector.

6. Knowing the transmissivity of a series of strata of the atmosphere at specific altitudes, in accordance with transfer nomograms (on the construction of which we shall not pause here) we determine the mean combined transmissivity of the atmosphere in the direction of the descent glide or for any other angle relative to the earth's surface.

With L_{eff} equal to one kilometer more or less (which cannot yet be achieved) and a marked runway, measurements carried out at the glide angle would at once give values of S_{land} without any nomograms or other measurement procedures.

It is indispensable to note that if there is strong atmospheric turbidity one must introduce a correction for reduction of the magnitude of signal by reason of supplementary attenuation of light flow in the section of the shaded zone. The true magnitude of the signal $u_{c.true}$ will be greater than the measured value $u_{c.meas}$ by an amount $e^{\rho L}$, i.e.,

$$u_{c.true} = u_{c.meas} e^{\rho L},$$

where $\rho = {}^{3.5}/S_M$ (S_M is determined in accordance with calibration nomogram I), and L is the length of the shaded zone.

The correction referred to is easily found from tables for the exponential function e^x to be found in any mathematical handbook.

§ 52. Determination of Altitude of Upper Limit of Fog (Optically Homogeneous Surface Stratum)

Experience in studying working models of apparatus based on the light back-scatter method has shown that when there are angular elevations of the projector beam from the horizontal direction upward signals change not at once, but instead at a certain angular altitude ϕ_i. In this connection experience shows that the stronger the atmospheric turbidity, the greater the angle of elevation ϕ_i at which a sharp change in signal starts.

It is natural to assume that the phenomenon referred to arises because in the surface stratum of the atmosphere a certain optically homogeneous thickness of air exists. The signal does not change so long as effective penetrations $L_{eff.2}$ and $L_{eff.1}$ remain within the zone of homogeneous turbidity. It is only upon a given effective penetration's exiting beyond the limits of the homogeneous stratum for a part of its depth and upon its entering into a stratum having a different transmissivity that the magnitude of the signal changes sharply. This circumstance makes it possible to construct a methods system for determination of the altitude h_0 of the upper limit of fog or, in general, of a homogeneously turbidized stratum.

Let us turn to Figure 63. Measurement of h_0 commences with measurement of S_M in a horizontal direction (as was pointed out above), in which connection it is sufficient to apply the two most remote shaded zones.

For these shades zones we determine in accordance with the magnitude of signal secured S_M (in accordance with gradation nomogram I), and then $L_{eff.2}$ and $L_{eff.1}$ (in accordance with calculation nomogram II). Then, having established the largest shaded zone with the largest $L_{eff.2}$ and giving the projector in succession larger and larger angles of elevation ϕ_i, we continuously follow the magnitude of the signal being measured. As soon as the signal changes sharply, we halt the projector. Knowing L_{eff} along the slant down the direction of sighting in an optically homogeneous stratum, and knowing the angle of elevation ϕ_1 of the projector, we find the altitude $h_{o.2}$ of the stratum:

$$h_{0,2}=L_{eff\ 2}\sin\varphi_1.$$

We switch over to the smaller shaded zone with the smaller $L_{eff.1}$ and we continue raising the projector to angle ϕ_2, at which a sharp change in signal with use of $L_{eff.1}$ takes place.

Analogously to the foregoing we secure

$$h_{0,1}=L_{eff\ 1}\sin\varphi_2.$$

The desired altitude h_o is determined as an arithmetical mean:

$$h_0=\frac{h_{0,2}+h_{0,1}}{2}.$$

The quantity h_o will be somewhat too high, inasmuch as effective penetration by part of the depth (about 10% of L_{eff}) will have to go beyond the limits of the homogeneously turbid stratum for the signal to change sharply enough.

This means that the altitude of the upper limit of fog or of a homogeneously turbid stratum must with 100% reliability be no higher than the value found for h_o.

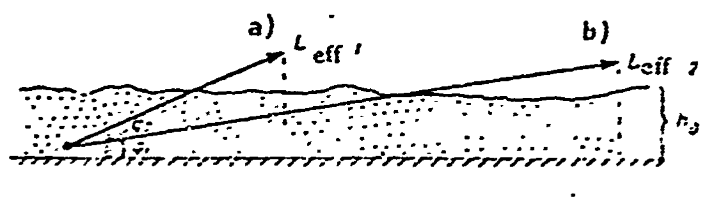


Figure 63. Method for Determining the Altitude of the Upper Limit of Fog or of a Homogeneously Turbid Stratum
Key: a) $L_{eff.1}$; b) $L_{eff.2}$.

§ 53. Theoretical Error of Stratum-by-Stratum Sounding of Atmospheric Transmissivity

Let us evalueate the theoretical error of stratum-by-stratum sounding (see § 50).

In calculating we shall take (7.23) as our point of departure. In order to simplify computations, let us assume an error in the determination of ΔL_{slant} as being equal to zero, and for simplicity of recording we shall write L_2 and L_1 in place of $L_{eff.2}$ and $L_{eff.1}$ respectively, also $S_{M(hor)}$ in place of $S_{M(\Delta L_{hor})}$.

After having differentiated (7.23) through, we secure after simple transformations

$$\frac{dS_{M.2}}{S_{M.2}}=\frac{dS_{M.1}}{S_{M.1}}\approx 20\%. \tag{7.24}$$

Let us examine the expressions within parentheses in the numerator.

As the graduation nomogram (see Figure 58) has a linear character and the spread of values of S_M over the whole range of atmospheric turbidity comes to 20-25%, the spread of values of S_M over the two shaded zones is approximately one and the same. This enables us to consider that the relative errors of the values of $S_{M.2}$ and $S_{M.1}$ are approximately equal to each other, i.e., we can write

$$\frac{dL_2}{L_2}\approx\frac{dL_1}{L_1}\approx 10\div 15\%.$$

The relative errors of effective penetrations dL_2/L_2 and dL_1/L_1 are also close to each other. This is clearly evident from the character of the calculation nomogram in Figure 62, in which the course of changes in L_{eff} for the shaded zone at 20 meters and the course of changes in L_{eff} for the shaded zone at 30 meters are almost parallel to each other. If we assume that for two successive effective penetrations in a given slant direction, $S_{M.2}$ differs by $S_{M.1}$ even by 100% (which cannot take place in practice) then, as ensues from the nomogram, even in this case the relative value of dL_2/L_2 will be distinguished from dL_1/L_1 by no more than 20%.

Taking this as point of departure, one may assume

$$dS_{M\,(hor)} = \Delta L_{slant} \frac{\frac{L_2}{S_{M.2}}\left(\frac{dL_2}{L_2} - \frac{dS_{M.2}}{S_{M.2}}\right) - \frac{L_1}{S_{M.1}}\left(\frac{dL_1}{L_1} - \frac{dS_{M.1}}{S_{M.1}}\right)}{\left(\frac{L_2}{S_{M.2}} - \frac{L_1}{S_{M.1}}\right)^2}.$$

Thus the expressions in parentheses in the numerator of (7.24) are approximately equal to each other. Then, separating out the expressions in parentheses in the character of a common multiplier and carrying out obvious abbreviations, we secure in place of (7.24)

$$dS_{M\,(hor)} = \Delta L_{slant} \frac{\frac{dL_{(1,2)}}{L_{(1,2)}} - \frac{dS_{M\,(1,2)}}{S_{M\,(1,2)}}}{\frac{L_2}{S_{M.2}} - \frac{L_1}{S_{M.1}}}. \qquad (7.25)$$

Dividing (7.25) by (7.23), shifting from differentials to increments, and throwing out the index (1, 2), we secure an expression for the relative error δS_M:

$$\delta S_M = \frac{\Delta S_{M\,(hor)}}{S_{M\,(hor)}} = \frac{\Delta L}{L} + \frac{\Delta S_M}{S_M}. \qquad (7.26)$$

For the quadratic error of stratum-by-stratum sounding of horizontal transmissivity we finally secure, after having exchanged the relations in (7.26) for δ for brevity's sake,

$$\delta S_{M\,(hor)} = \sqrt{\delta L^2 + \delta S_M^2}. \qquad (7.27)$$

Substituting into (7.27) the values set forth above for δL and δS_M (for either of the two values $L_{eff.2}$ and $L_{eff.1}$, and also $S_{M.2}$ and $S_{M.1}$), we secure

$$\delta S_{M\,(hor)} \approx \sqrt{15^2 + 20^2} \approx 25\%.$$

This is the theoretical error in the determination of the horizontal transmissivity of each stratum sounded.

If the magnitude of this error appears to be too great, let us recall that present-day photoelectrical and instrumental-visual methods of measuring the meteorological range of visibilities have an error of 16-20%, and sometimes even 25%.

§ 54. Description of a "Slanting Beam" Set-Up With Automatic Remote Control

The "slanting beam" set-up with automatic remote control has been developed and manufactured for the carrying out of the measurements indicated in foregoing sections, specifically:

a) for determination of mean horizontal transmissivity of the atmosphere at different altitudes above the surface of the earth (from 2 to 250 meters);

b) for measurement of mean transmissivity in a given inclined direction at a distance of 50 to 250 meters along the incline and with angles of elevation from 0 to 90°;

c) for determination of the altitude of the upper limit of fog (stratum having homogeneous turbidity).

For the future determination of the altitude of the lower limit of low clouds will also be possible.

The set-up consists of a projector (diameter of mirror 90 cm) with a measuring attachment and a built-in elevation-angle drive, and also a control panel.

The projector, with the units referred to, is mounted on a truck (Figure 64). The control panel can be mounted to one side of the projector, within the limits imposed by the length of the feed cables.

At the focus of the projector mirror a super-pressure RDSh-250 gas-discharge mercury lamp having a rated luminance of arc of about 20 kilostilbs is installed.

The projector can assume elevation angles of 0, 2.5, 5, 10, 20, 30, 45, 60 and 85%.

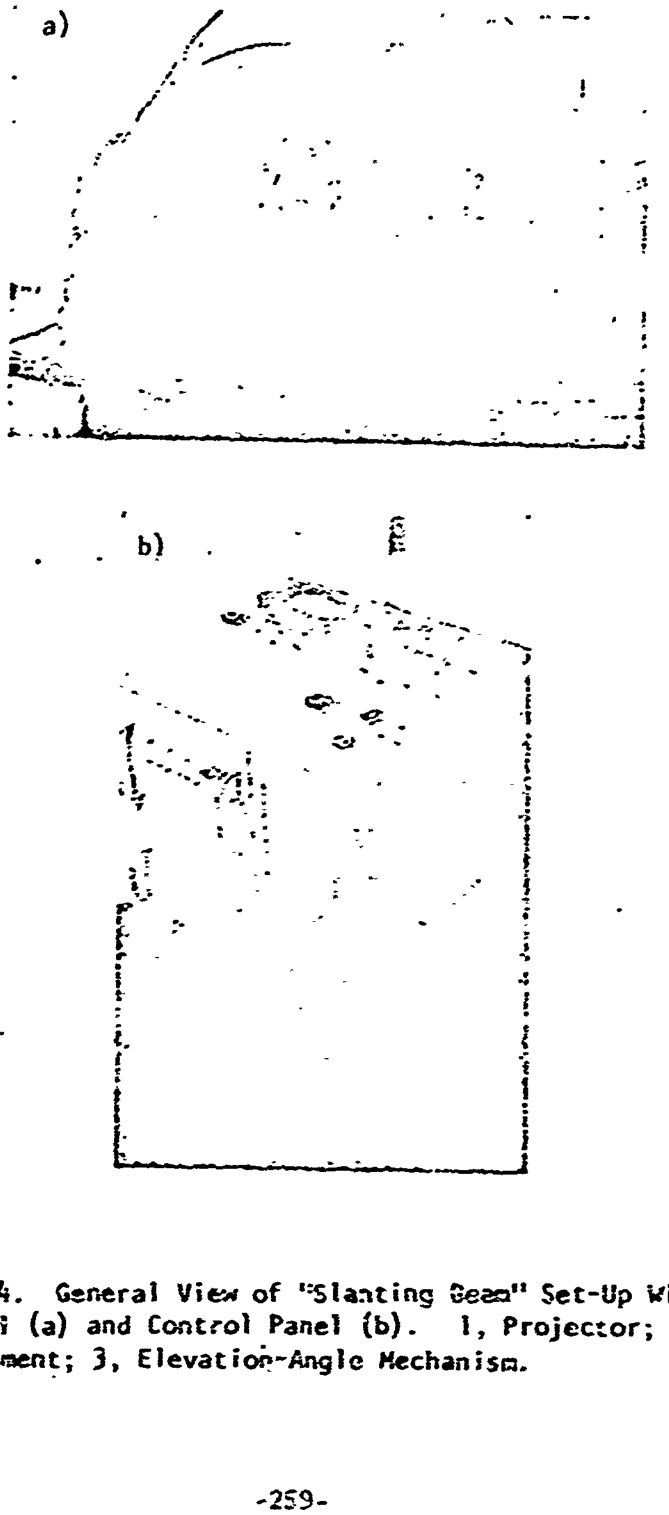
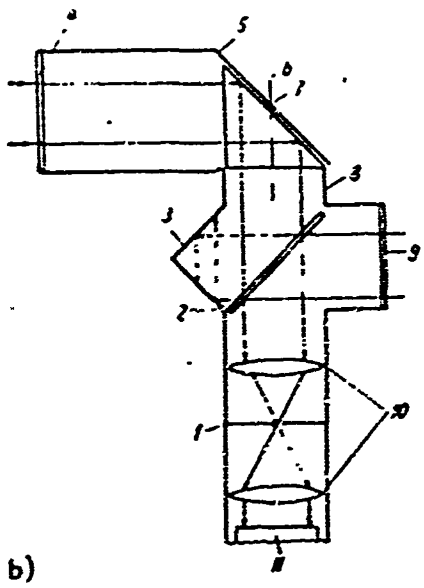


Figure 64. General View of "Slanting Beam" Set-Up With Remote Control (a) and Control Panel (b). 1, Projector; 2, Measuring Attachment; 3, Elevation-Angle Mechanism.

a)



b)

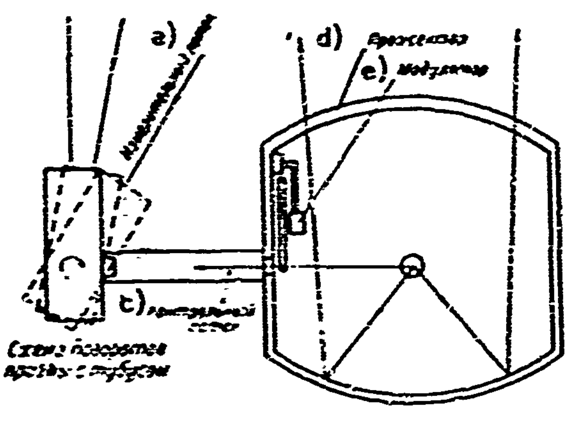


Figure 65. Diagram of Measuring Attachment of "Slanting Beam" Set-Up (a) and Diagram of Stepped Scanning by Full-Interior-Reflection Prism Along the Projector Cone (b). 1, Diaphragm; 2, Reflector plate; 3, Black absorber; 4, Protective glass; 5, Rotating heat; 6, Axis of rotation; 7, Prism; 8, Stationary base; 9, Milky glass; 10, Lenses; 11, FEU-22 photocathode.

Key: a) Measurement flow; b) Diagram of turning of prism with tube; c) Control flow; d) Projector; e) Modulator.

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The measuring attachment (Figure 65) is fastened at 70 cm to one side of the projector drum at the end of a rod which is rigidly attached to the drum housing. It contains: a) a full-interior-reflection prism with tube and mechanism which enable it to carry out stepped scanning along the projector beam; b) an objective; c) a FEU-22 photomultiplier; d) a preliminary amplification cascade.

The optical axis of the collector, which coincides with the axis of the tube, and the projector beam are always located in a single plane at any elevation angle of the projector.

Through the use of a driving mechanism the prism can be turned relative to the projector beam to three fixed angular positions, at which the optical axis of the collector enters the projector beam from one side at distances of 15, 20 and 30 meters from the projector drum. These distances are in fact the shaded zones, for each of which L_{eff} is computed with consideration being given to the geometry both of the projector cone and of the cone of the collector's field of vision.

The measurement flow at any given position of the prism is focused, after passing through the prism and the objective, upon the FEU-22 photocathode. The control flow directly from the light source also falls upon this same photocathode, after having passed through apertures in the wall of the projector drum housing and in the measuring attachment and after having undergone reflection from the glass plate set at a 45° angle. The measurement and control light flows having different frequencies of modulation are commutated on the FEU-22 photocathode.

After passing through the automatic amplification control and detection circuits, the measurement and control signals are fed into corresponding microampere meters mounted on the exterior panel of the control desk.

All commands for angular elevations of the projector, for angular shifts of the prism along the projector beam, for turning the lamp on and keeping it going, for regulating feed to the FEU-22, etc., are carried out from the control panel. A system of signal lamps announces through the help of special relays both the reception of commands (red light) and their execution (green light).

The radiotechnical units of the set-up and the automatic system were developed by V. A. Kovalyov.

The signals received are processed in accordance with the nomograms and formulas set forth in foregoing sections.

In conclusion we shall make a few remarks regarding the method, referred to at the beginning of this Chapter, for measuring slant transmissivity by means of the method of equal angles, and we shall evaluate its measurement potentialities.

A diagram of the equal-angles method in principle is set forth in Figure 66.

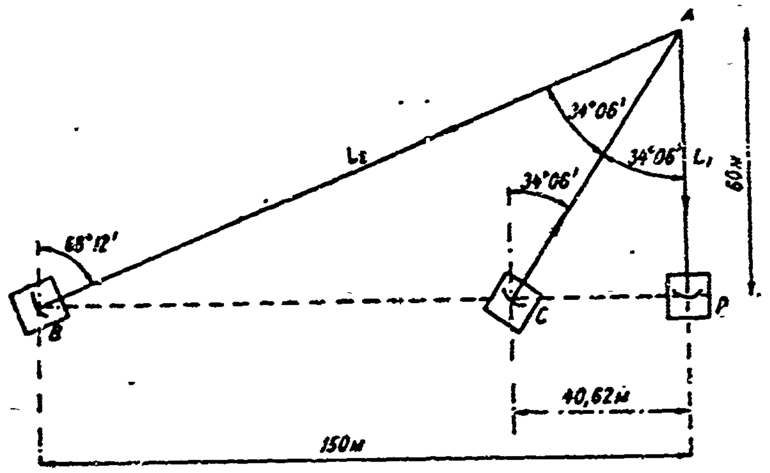

Figure 66. Diagram of the Principle of the Equal-Angles Method.

A projector sends out from point C and at some constant angle to the horizon a modulated light beam. At points B and D two identical collectors are set up, so turned that their optical axes, which intersect at point A, form equal angles with the optical axis of the projector beam. This method of aiming the collectors makes it possible to eliminate the effect of the indicatrix of scatter upon the results of measurements, inasmuch as the index of scatter $\rho(\theta)$ for each collector proves to be the same, as a consequence of the symmetry of their aiming relative to the projector beam. This circumstance considerably simplifies the graduating of the set-up, which is unquestionably a merit of this method. In accordance with the magnitude of the ratio between the signals processed by each collector an averaged slant transmissivity is determined for a sector equal to the difference between the lengths of path L_2 and L_1 (counting from point A).

But the equal-angles method possesses limited measurement potentialities, and it has a series of serious shortcomings.

In the first place, the method of measuring is based upon the use of two collectors (two photoelements). Present-day technology is still not in a position to create photoelements having identical aging characteristics. For this reason the use of two photoelements in the equal-angles method requires the creation of a complicated system for checking and taking into account the aging of each of these, without which the apparatus cannot work reliably.

In the second place, the equal-angles method can measure only a single, partial optical characteristic of the surface stratum, specifically the averaged tansmissivity of a sector at a constant slant, equal, as has already been indicated, to the difference between the lengths L_2 and L_1. But such a limited amount of information satisfies only to a slight extent the requirements of aviation for safety of visual landing.

In the third place, a set-up based on the equal-angles method is a stationary one. Under complicated meteorological conditions, in order to secure full information regarding the optical properties of the atmosphere in the various glide sections from the close-in homing radio beacon to the beginning of the runway, it is necessary to set up a number of such apparatus.

No publications exist dealing with the exploitational qualities of the apparatus based on this method, as demonstrated by its work.

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CHAPTER VIII

DETERMINATION OF THE METEOROLOGICAL RANGE OF VISIBILITY BY INSTRUMENTAL-VISUAL METHODS THROUGH THE USE OF VISIBILITY GAGES

§ 55. General Remarks

The horizontal transmissivity of the atmosphere, expressed through meteorological range of visibility S_M, is one of the characteristics of the physical state of the atmosphere, and as such it is among the basic meteorological elements that are determined at the hydrometeorological station networks of all the world's countries.

The range of atmospheric turbidity which undergoes measurement is covered by the international 10-point visibility scale adopted by the International Meteorological Conference in 1935 (see Table 3), i.e., it is the span of meteorological range of visibility (m.r.v.) running from 0.05 km to 50 km. Measurement of m.r.v. within such broad limits at a hydrometeorological station network is a difficult task in all respects. Endeavors to perform it on the basis of naked-eye estimates of visibility points upon natural objects during daylight and on artificial lights in darkness have proved to be fruitless for reasons examined in Chapter I.

Many years of endeavor to create for station networks objective apparatus simple and reliable in operational respects, and capable of measuring m.r.v. over all 10 points of the international scale, have not yet been crowned with success, and the station network is still not equipped with objective transmissivity gages[1]. Up to the minute m.r.v. at a station network has been determined, and will evidently long continue to be determined, on the basis of instrumental-visual methods.

If today there were to be created an objective apparatus responding in full measure to the problems of the basic station network, time would be required for its introduction at each meteorological station (if in fact that would be appropriate) and to ensure proper care of it.

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[1]It has been suggested recently that observatories under local administration of the Hydrometeorological Service of the USSR, the regional hydrometeorological stations, etc. (except the AMSG network) can be linked by V. I. Goryshen's compensating transmissivity recorder (see § 43) with a measurement range of 0.2 km < S_m < 25 km meteorological range of visibility.

But in addition to this, present-day instrumental-visual methods will be applied for research purposes, in field operations, under expedition conditions, etc., by virtue of their simplicity, the possibility of using them under any conditions, and their measurement principle which is easily accessible to any observer. One must also bear in mind the following circumstance. Some questions having to do with the distribution in the atmosphere of the emanations of quantum generators and the calculation of the range of their radiational effectiveness, the calculation of the radiation contamination of a nuclear weapon, etc., even today bring up the problem of measuring transmissivity of the atmosphere up to 100 kilometers. One can form an idea of the visibility of terrestrial objects from great altitudes and from space around the earth only if methods for determining high-level transmissivity of the atmosphere, running into many dozens of kilometers, are available.

Measurement of such high-level transmissivity by objective photoelectric methods is, as was shown in § 40, still not susceptible of realization in practice, while at the same time it can be achieved even today with the help of instrumental-visual methods.

The development of methods for instrumental-visual measurement of atmospheric transmissivity has an interesting history and is of independent scientific significance. For this reason it is well to examine here the question of instrumental-visual methods for measuring m.r.v.

In this Chapter we examine and evaluate the following fully developed instrumental-visual methods for measuring m.r.v. by daylight:

1) measurement of m.r.v. through the luminance contrasts of terrain objects by the photometric equalization method ("equality set-up");

2) measurement of m.r.v. through the luminance contrasts of terrain objects by the photometric extinction method ("disappearance set-up");

3) measurement of m.r.v. in accordance with the degree of visibility of terrain objects by the photometric extinction method ("disappearance set-up");

4) measurement of m.r.v. through contrasts of natural and artificial objects by the relative luminance method;

5) measurement of m.r.v. through two black bodies by the relative luminance method.

From here on the first two methods will be called contrast methods for short; the third, the degree of visibility method; and the fourth and fifth, relative luminance methods. To anticipate, we shall show that the most highly refined of all these methods is the relative luminance method with the use of two black bodies.

The foundations for instrumental-visual methods of measuring m.r.v. were laid in studies by V. V. Sharonov, V. A. Faas, V. F. Piskun, V. A. Berezkin. Subsequently N. G. Boldyryov [13], V. F. Belov [7], N. G. Boldyryov with O. D. Bartenev and I. Y. Nechayev [15, 85], N. E. Rityn, L. L. Dashkievitch [58, 59], I. A. Savikovski [103], L. V. Gulnitski [53, 54], and other Soviet specialists have worked on these methods.

§ 56. The Foundations of Instrumental-Visual Methods of Horizontal Transmissivity Methods in Principle

Let us return to expression (1.20), which describes the rule for change of the contrast of any object projected against any "terrestial background," as brought about by haze:

$$K=\frac{K_0}{1+\frac{D}{B_\phi}(e^{\sigma L}-1)}. \tag{8.1}$$

The conventional designations are as before.

The theoretical basis of the contrast method is a partial case of this expression, when the object is projected against a background of cloud (haze) in a horizontal direction, where luminance, as we know, in a majority of cases attains a state of "saturation" and can be made equal to coefficient D of the light-air equation. In other words, in the partial case referred to one may put $B_\phi = D$; then the expression written above assumes the form

$$K=\frac{K_0}{1+(e^{\sigma L}-1)},$$

whence

$$K=K_0e^{-\sigma L}. \tag{8.2}$$

This is the rule of change, under the operation of atmospheric haze, in the contrast K of an object projected against a cloud background, in proportion as distance L to the object increases.

Expression (8.2) lies at the foundation of the contrast method. From the sense of (8.2) the main requirement of the method, imposed upon terrain objects, transpires: the objects may have any initial value of true contrast K_0, any color and geometrical characteristics, but they absolutely must be projected against a section of sky at the horizon[1].

If the object is projected against a cloud background, but above the horizon line by more than 1.5-2°, then only on days having considerable atmospheric turbidity is (8.2) applicable to such objects; and it is inapplicable on days having high transmissivity, when the luminance of haze in these directions does not reach a state of "saturation" and equality of B_ϕ to D may not take place.

Objects projected against a background of other more remote objects can also be used, but only on days having atmospheric turbidity such that the remote object is completely masked by haze and is absolutely invisible from the observation point.

From (8.2) we secure

$$e^{\epsilon L}=\frac{K_0}{K}\qquad(8.3)$$

or after logarithming to the base e

$$\epsilon=\frac{1}{L}\ln\frac{K_0}{K}.\qquad(8.4)$$

Substitution of (8.4) into the Koschmider formula for m.r.v. gives

$$S_m=\frac{\ln\frac{1}{\varepsilon}}{\epsilon}=\frac{L\ln\frac{1}{\varepsilon}}{\ln K_0-\ln K}.\qquad(8.5)$$

On the basis of experimental determination of the most reliable value for the threshold of contrast sensitivity ε in the Koschmider formula (see § 66) we assume that ε = 0.03 and ln 1/ε = 3.5. Then in place of (8.5) we shall have

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[1] Meeting this condition is indispensable when m.r.v. is being measured by the relative luminance method (see § 16).

$$S_M = \frac{3.5L}{\ln K_0 - \ln K}, \quad (8.6)$$

or, shifting to decimal logarithms,

$$S_M = \frac{1.5L}{\log K_0 - \log K}. \quad (8.7)$$

As we see from the equivalent relationships (8.6) and (8.7), determination of meteorological range of visibility through contrasts of terrain objects consists in the fact that to begin with, through measurement of the true K_0 and the haze-distorted K of one and the same object, one determines the index of attenuation α (or α_{10}), and that thereafter one calculates in accordance with the Koschmider formula the value of S_M.

Although meteorological range of visibility is dealt with as being the range of visibility of an absolutely black body, still in order to measure it by the contrast method it is not indispensable, as we can see from (8.6) and (8.7), to have on the terrain absolutely black bodies. The attractiveness of the contrast method consists precisely in the fact that theoretically S_M can be determined, as has already been shown, from any real object with any value K_0, any angular dimensions, any shape, and any color.

Let us show the theoretical course of change of the contrast K of various objects projected under a haze background, under the operation of haze. From (8.7) we determine

$$\log K = \log K_0 - 1.5\frac{L}{S_M}, \quad (8.8)$$

or recalling that $S_M/L = z$

$$\log K = \log K_0 - 1.5\frac{1}{z}. \quad (8.9)$$

In accordance with this formula Table 29 has been computed and a nomogram for change of contrast K depending on the initial value of true contrast

K_0 and the magnitude of the extrapolational parameter z has been constructed[1]. The nomogram is set forth in Figure 67.

TABLE 29. COURSE OF CHANGE OF CONTRAST K (%) OF OBJECTS PROJECTED AGAINST A HAZE BACKGROUND, DEPENDING ON THE VALUE z AND THE QUANTITY K_0

z	K_0, %					
	100	90	80	70	60	50
100	96,6	87,0	77,3	67,6	58,0	46,3
80	95,8	86,2	76,6	67,0	57,5	48,0
60	94,4	84,9	75,5	66,1	56,6	47,2
40	91,7	82,5	73,4	64,2	55,0	45,9
20	84,1	75,7	67,3	58,9	50,5	39,3
10	70,8	63,7	56,6	49,6	42,5	33,0
5	50,1	45,1	40,1	35,1	30,1	23,4
2	17,8	16,0	14,2	12,5	10,7	8,3
1	3,2	2,9	2,5	2,2	1,9	1,5

As may be seen from the table and the nomogram, change of contrast K takes place very rapidly at small values of z and slows down sharply starting from z more or less equal to 20, and higher. We may note that this peculiarity of the course of change of the contrast K of objects markedly limits the potentialities of the contrast method in measuring S_H.

It is not difficult to guess that the course of changes in K in Figure 67 reflects the course of change of luminance of atmospheric haze with increase of distance.

§ 57. Errors in Measurement of S_H Through Contrasts of Terrain Objects

Differentiating (8.7) and disregarding errors in determination of L, we secure

$$dS_{\text{м}} = -\frac{0{,}43 \cdot 1{,}5L\left(\frac{dK_0}{K_0} - \frac{dK}{K}\right)}{(\log K_0 - \log K)^2}.$$

[1] Determination of the extrapolational parameter z is given in § 40.

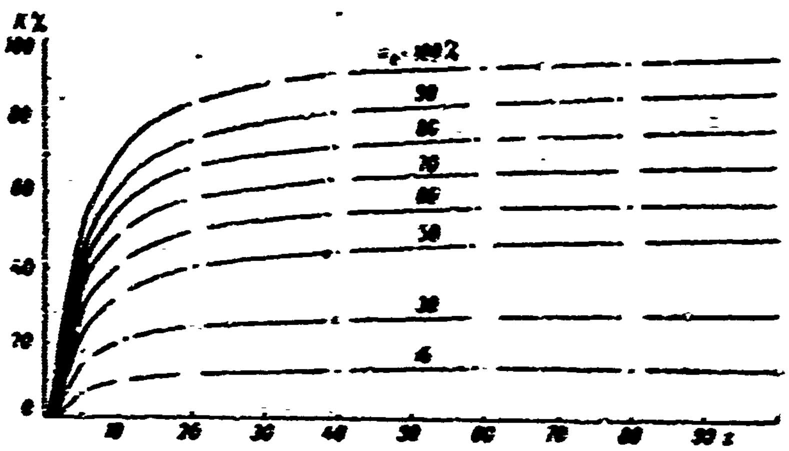

Figure 67. Change of Contrast K of Objects With Distance, Depending on Initial Value of Contrast K_0 and Magnitude of Parameter z.

Dividing this expression by the value of S_M in (8.7) and shifting from differentials to increments, we secure an expression for the relative error:

$$\frac{\Delta S_M}{S_M} = \frac{0{,}43\left(\frac{\Delta K_0}{K_0} + \frac{\Delta K}{K}\right)}{\log K_0 - \log K}. \qquad (8.10)$$

But from (8.9) it follows that

$$\log K_0 - \log K = 1{,}5\frac{1}{z}.$$

Substitution of the last expression in (8.10) and replacing for brevity's sake $\frac{\Delta S_M}{S_M}$ with δS_M, $\frac{\Delta K_0}{K_0}$ and $\frac{\Delta K}{K}$ respectively with δK_0 and δK, gives us for the relative error of separate measurement

$$\delta S_M = 0{,}29z(\delta K_0 + \delta K)$$

and for the quadratic error of separate measurement

$$\delta S_M = \pm 0.29z \sqrt{\delta K_0^2 + \delta K^2}. \tag{8.11}$$

Expression (8.11) furnishes an exhaustive answer to the question regarding the accuracy of measurement of S_M according to the contrasts of terrain objects and regarding the general properties of this method.

Errors of measurement of S_M are delimited by the value of the extrapolational parameter z and by the aggregate relative errors of measurement of the contrasts K_0 and K of terrain objects.

The error of δS_M is the less, the farther off the object of observation is located, i.e., the less z is, all other circumstances being equal.

As regards errors in measurement of contrasts K_0 and K of objects, here we run up against some peculiarities of the contrast method that do not appear in patent guise either in (8.7) or in (8.11). One of these peculiarities is the practical impossibility of simultaneously measuring the contrasts K_0 and K of terrain objects. In practice, at the moment of measurement of S_M only the contrast K of an object under haze can be determined. The contrast K_0 of the objects must, however, be determined in advance, on days with transmissivity so high that haze on the objects is absent. This constitutes a serious drawback of all instrumental-visual methods for determining S_M from natural objects.

This circumstance leads to two consequences.

In the first place, in (8.7) in place of the true value of the contrast K_0 of a given object one must substitute a mean amount $K_{0\ mean}$, secured in advance from a prolonged series of observations. Obviously the real conditions under which determination of S_M takes place are always to some extent different from the "mean" conditions to which $K_{0\ mean}$ relates.

In the second place, the determination of $K_{0\ mean}$ for those objects, most advantageous for the method, that are located at a distance ($L > 10$ km), is difficult, inasmuch as cases of such high transmissivity that no haze is observed upon the objects and that measurement of K_0 is possible are relatively rare. On this account one usually ascribes to remote objects a $K_{0\ mean}$ value determined from closer objects of the same type. This may involve a source of errors difficult to take into account, inasmuch as the photometric properties of monotype natural objects may change with distance. For example, even the darkest natural object -- a coniferous forest -- in the absence of haze appears darker, the farther it is located from the observer. Other, lighter objects in the absence of haze change (darken) with distance more markedly than does a coniferous forest.

Seasonal and inter-seasonal changes in the K_0 of natural objects still farther complicate the contrast method, which again fails to be evident from expressions (8.7) and (8.11). This circumstance makes it necessary to determine for the year-round cycle, and then use, not one value, but a whole series of values for the $K_{0\ mean}$ contrast of one and the same object. Inasmuch as not a single object, but a number of objects, are used for observation, correctly taking $K_{0\ mean}$ into account on all objects is pretty complicated.

Furthermore, measurement of the contrast K_0 of natural objects which have color has proved impossible to carry out with the method of photometric comparison. The eye of man is not capable of equalling-out with any degree of accuracy the luminance of a variable gray marker with the luminance of a colored object of observation. With the photometric comparison method it is possible to measure only the haze-distorted K contrast of a limited group of natural objects. As a matter of necessity a value for the K_0 contrast of objects (even coniferous forests) which has been determined by other methods is used in the comparison method. In particular, measurement of the K_0 of natural leafy objects can be carried out by visibility gages, the extinction method ("disappearance set-up"), and the relative luminance method (measurement of contrasts by these methods is examined in detail in Chapters III and IV).

But when the "disappearance set-up" is applied, the values of K_0 (just as those of K) change substantially depending on the character of the outlines of objects: with a jagged, interrupted outline the object is brought to disappearance earlier, and the measured contrast will be less than the contrast of an object of the same class, but one having a sharp linear outline (Figure 68).

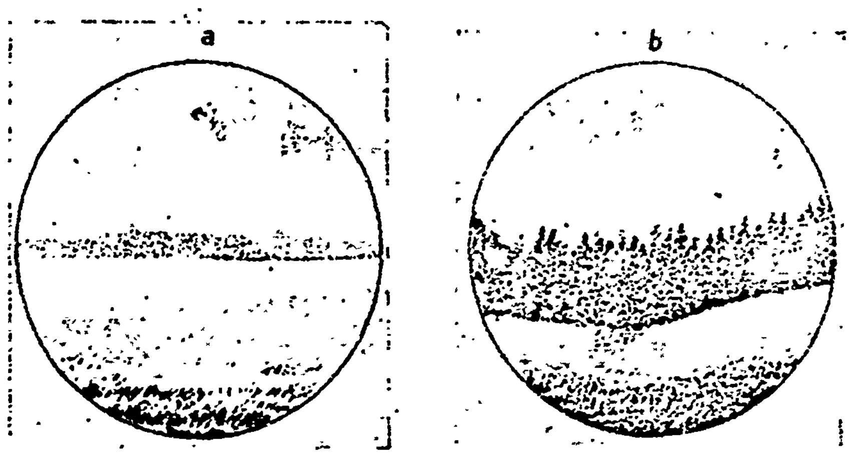

Figure 68. Diagrammatic Representation of Objects Having A Smooth (a) and An Interrupted (b) Outline

The effect of the outlines of objects on the visual perceptivity thereof is such that objects having less contrast but having a sharp outline may be visibile at threshold perceptivity as well as or even better than objects having more contrast but having an interrupted outline. As a consequence of this, even though objects of the type described may possess different K_0 values, their visibility range may be the same.

We may see from Table 30 how much the contrasts of objects of one and the same class, but having different outline characters, are distinguished from one another.

If the $K_{0\ mean}$ value is determined for an object with an interrupted outline, and the magnitude of K is measured on an object with a sharp outline, then the difference in the denominator of (8.7) will be reduced, and S_M will be augmented.

Disregard of the character of outlines of an object may serve as a source of supplementary considerable errors in measuring S_M.

From what has been set forth above it is apparent that the contrast method is not so simple and not so exact as expression (8.7) might seem to indicate. The convenience of using natural objects is purchased at the high price of a complicated taking into account of seasonal and other variable variations for K_0, different times for measurement of K_0 and K, and a relatively low accuracy of these measurements.

So in the contrast methods we must make use of the following general expressions:

1) for meteorological range of visibility

$$S_M = \frac{1.5L}{\log K_{0\ mean} - \log K_{tek}} \qquad (8.12)$$

2) for the quadratic error of separate measurement of S_M

$$\delta S_M = \delta S_M = 0.23z\sqrt{\delta K^2_{0\ mean} + \delta K^2_{tek}}, \qquad (8.13)$$

where the index "TEK" furnishes the current (not the mean) contrast of an object under haze.

§ 58. Application of the Photometric Comparison Method in Measuring S_M in Accordance with the Contrasts of Terrain Objects

The method of photometric comparison was applied on a considerable scale at meteorological stations for measurement of S_M by daylight, earlier than were others. This was helped along by the circumstance that V. V. Sharonov developed a simple and inexpensive device called a diaphanoscope, which was introduced into the station network to the number of some hundreds of units shortly after the end of the Great Fatherland War.

Experience in the use of diaphanoscopes, and then the pupillary photometer developed by N. G. Boldyryov and described in [4], made it possible to establish fully the suitability of the photometric comparison method for measurement of S_M in accordance with the contrasts of terrain objects diversified as to shape and color.

V. V. Sharonov's diaphanoscope consists of a simplified stepped comparison photometer, designed as a six-power telescope containing an ocular reticule with 13 gray marks of differing contrast quality (for details on the theory of the device and its construction see [123]). The principle of observation consists in selecting a marker that corresponds most closely in luminance with an object under haze that is being observed and that is projected against a sky background at the horizon. The marks should be placed against the haze background at a certain height above the object.

In the N. G. Boldyryov pupillary photometer, the optical-photometric system of which constitutes a combination of a visibility gage and a comparison photometer (for details see [4]), the idea of measuring the contrasts of objects by means of an "equality set-up" was carried into practice in its most highly refined form.

Just as in present-day visibility gages, in the field of vision of the pupillary photometer one observes a split image of the section of the terrain being examined and a split image of a marker made as a non-transparent plate having a patterned outline imitating the outlines of a natural forest. Through the superposition of a masking luminance analogous to the way this is done in visibility gages, the contrast between the unidsplaced image of the marker and the displaced image of the object projected against a haze background at the horizon is evened off. At the moment of equality of contrasts the reading is taken.

Under suitable circumstances of observation, that is to say when one has shapeless, monochrome comparison fields with sharply defined boundaries, bringing the comparison fields to photometric equality is a relatively easy measurement procedure which can be carried out with high accuracy. The error of measurement in these cases does not exceed 1-2%.

It is precisely these qualities of the comparison method that have served to bring it into use for measurement of S_M.

In creating the pupillary photometer N. G. Boldyryov took as his starting point the idea that the superposition of a masking luminance upon the image of a natural object ought first of all to lead to destruction of the color-character of the object and to convert it into a uniform gray surface, after which further photometering would be reduced to a simple comparison of the luminances of two qualitatively uniform surfaces (the object and the marker), carried out with ease and precision such as are inherent in the comparison method. If this initial idea of N. G. Boldyryov had proven to be justified, then the comparison method would have been ideal not only for the purpose of measuring S_M but also for other problems in terrain photometry.

But the universal tests of the comparison method which were carried out in the Main Geophysical Observatory as regards its suitability for determining S_M revealed a number of peculiarities inherent in its principle which markedly limited its acceptability for these purposes.

In the foregoing section we indicated that the comparison method does not succeed in determining the contrast K_0 of objects having considerable color. As was established in testing the pupillary photometer, the color character of an object is preserved even when a considerable masking luminance, cutting its contrast approximately to one-half, is superposed upon its image. The color disparity between the gray marker and such a colored object obstructs an accurate setting-up of equality. With the comparison method one can measure with the required precision only faint contrasts of colored objects, i.e., objects having color that are masked by considerable haze in the initial position.

The true K_0 contrasts of such objects cannot, as has been indicated above, be determined with the necessary accuracy by the comparison method. Most suitable for the comparison method are low-colored and markedly contrasting objects along the lines of coniferous forests (throughout the year, excluding cases of frost and heavy snow) and dense deciduous forests (in the summer).

The best object in all respects for the comparison method is an artificial black screen with even just its top edge projected against a sky background at the horizon, and inclined toward the sighting line at an angle of 45-60°.

Experience in making use of diaphanoscopes, and subsequently tests on the pupillary photometer, have shown that only such objects as these should be considered in the determination of m.r.v. by the comparison method.

Let us establish the measurement (extrapolational) limits of the method of photometric comparison under the most favorable conditions possible, i.e., when the object and the marker closely correspond to each other as regards color (grayness), shape, and dimensions.

Such conditions were created in a special laboratory apparatus developed by N. G. Boldyryov and described in [4], whence we borrow the results of a few measurements.

This apparatus made it possible to alter the contrasts of the marker and the object within broad limits -- from threshold contrast to 100%. In this connection the marker and the object did not adjoin each other abruptly: a narrow gap was formed between them, as occurs in field determinations of m.r.v. by the comparison method.

Under these circumstances, as N. N. Sytinskaya [106] points out, even a slender gap separating one field of the comparison from the other leads to a heightening of the photometering error from 1-2% to 5%. But if the fields to be compared are separated by a broader interval, then the error of measurements mounts and may attain 15-20%. An error of 1-2% is achieved only in the event that the fields to be compared contact each other without any interval at all, forming a conspicuously perceptible dividing line which disappears at the moment of equality of the luminances being compared.

These deductions of N. N. Sytinskaya were completely confirmed by the data from measurements by O. D. Barteneva [4] and I. A. Savikovski [101]. The error δK in the measurement of contrast with ideally similar marker and object and with a narrow gap present between them proved to be equal to ± 5%. This error is the upper limit of accuracy in the measurement of the contrasts of objects by the photometric comparison method.

By making use of these data one can evaluate the maximum extrapolational potentialities of the comparison method in the measurement of S_M in accordance with black screens.

If we use as an object having K_0 more or less equal to 100% a removable black marker in the form of a shield or a black cavity (as is done with the M-53A device), or a variable black marker located in the field of vision of the device (as takes place in the IDV device), [1] then in place of separated measurement of the contrasts K_0 and K of the black screen one can at once measure the ratio K_0/K by the comparison method. Then in place of (8.12) we secure

$$S_м = \frac{1{,}5L}{\log\left(\frac{K_0}{K}\right)_{\text{current}}},$$

and in place of (8.13)

$$\delta S_м = 0{,}29z\sqrt{\delta\left(\frac{K_0}{K}\right)^2_{\text{current}}} = 0{,}29z\delta\left(\frac{K_0}{K}\right).$$

Since $\delta\left(\frac{K_0}{K}\right) = 5\%$, then

$$\delta S_м \doteq 1{,}45z\%. \tag{8.14}$$

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[1] At the end of this section we discuss the possibility of converting present-day visibility gages into comparison photometers.

As the upper limit of permissible error of measurement we take the quantity $\delta S_M = 25\%$. From (8.14) it is apparent that this value is attained when z = 17.

This is the upper extrapolational limit of measurement of S_M by the comparison method, when the shield or marker and the object are identical to each other as regards color quality (grayness), shape, and dimensions. In this event, for measurement of visibility within the limits of the international 10-point scale on the terrain it is necessary to set up two balck screens: at 200 and at 3,000 meters from the observation point. When this is done, the more distant screen, for the case of a device having ten-power magnification, should have dimensions of not less than 3 X 3 meters (angular dimensions of 30') and should be projected, at least as regards its upper edge, against a sky background at the horizon. For the IDV device, which has seven-power magnification, the dimensions of the screen at this distance would come to 5 X 5 meters, and for the M-53A device, which has no telescopic system, a screen of 30 X 30 meters would be required.

Setting up such screens on terrain and keeping them in useful state are impossible for a meteorological station. During the winter cleaning adhering snow and frost from remote and large screens is a task difficult to carry out. In addition, since the black screens are inclined at an angle of 45° to the line of sight (in order to secure maximum blackness), during the winter (particularly on sunny days) they gleam perceptibly by reason of light from the snow-covered ground surface which they reflect. On this account the value of S_M measured during the winter season from inclined black shield-screens is too low [illegible]. In order to avoid this, during the winter observations should be made from vertical black screens[1].

From what we have set forth above it follows that measurement of visibility by the comparison method over the entire scope of the international 10-point scale via black screens alone is very laborious. It is more logical to measure S_M by the comparison method both via screens and via natural objects (as L. L. Dashkievitch did with the help of the M-53A device), of course if suitable objects exist on the terrain. Let us examine the limits of applicability of the comparison method in measuring S_M from natural objects.

[1] In measuring visibility over a limited span and when the device has a telescopic system the use of a small vertical screen of black velvet is entirely justifiable throughout the year (see § 64 and 65)

The most suitable natural object possessing the least color character is a mature coniferous forest. If there is even a slight haze upon it, it is converted into a sufficiently gray object and is basically distinguished from the marker only through luminance. But now powerful influence is exerted upon the accuracy of evening off the contrasts not only by the presence of a narrow gap, but also by difference in the outlines of the object and the marker. According to data in [4], the error δK in measurement of the contrast of coniferous, and also of dense deciduous (summertime) forests, comes to plus or minus 10%. As has been indicated, we cannot determine the K_0 even of a coniferous forest by the comparison method. We must make use of mean values $K_{0\ mean}$ secured with the help of visibility gages through the extinction method or, something which is considerably more accurate, by the method of relative luminance (in the latter case without taking into account the character of the outline). From prolonged experience in measuring the contrasts K_0 of objects by the extinction method it follows that $\delta K_{0\ mean}$ (seasonal) for a coniferous and for a dense deciduous forest is equal to 7%.

Substituting the values δK and δK_0 indicated into (8.13), we secure for the relative quadratic error of measurement of S_M the following expression:

$$\delta S_M = 0{,}29z\sqrt{7^2+10^2} = 3{,}5z\%.$$

The permissible error $\delta S_M = 25\%$ is attained with $z = 7$, i.e., with a value of z half as great as when black screens are used. This reduction is occasioned only by the effect of the outlines of the object and the use of the mean value $K_{0\ mean}$ (for the given season) on account of the seasonally different measurements of K and K_0.

Now for measurements of S_M over the entire span of the 10-point scale on the terrain there must be a minimum of three objects at distances of 100-300 meters, 1-2 km, and 6-10 km (visibility points 0 and 1 are determined visually).

The extrapolational potentialities of the comparison method become even worse if one uses for observations objects having a sharply pronounced color character, such as autumnal deciduous and mixed forests, bush thickets, or objects having a considerable mottled character of luminance when they are partially covered with snow. In this event even when there is an inconsiderable haze reducing the initial contrast of such objects to 35-40%, photometering for equality is difficult by reason of the difference in color that is preserved between the object and the marker, despite the haze upon the object. The error δK now increases still farther and comes to no less than 20% according to data in [4, 103]. With fainter haze it is impossible to carry out photometering of such colored or mottled objects. It is still more impossible to measure by the comparison method the true K_0 contrast of such objects, and this has to be determined, as has already been indicated, either by the extinction method or by the relative luminance method.

Keeping the value $\delta K_{0\ mean}$ = 7% for colored and mottled objects, for the relative error δS_M we secure:

$$\delta S_м = 0{,}29z\sqrt{7^2+20^2} = 6{,}1z\%.$$

From this it is apparent that in measuring m.r.v. by the comparison method from colored or heterogeneous-luminance objects the extrapolational parameter z is equal to 4 (for δS_M = 25%), which is now but little to be distinguished from the results which were secured in their day through the use of diaphanoscopes.

One should note that in measuring m.r.v. from natural objects with the help of the M-53A polarization visibility gage sources of supplementary error make their appearance in the form of the polarized component of the luminance of haze and of the actual objects of observation. Readings from the device prove to be dependent on its orientation relative to the object of observation.

As I. A. Savikovski has shown [103], in making use of the M-53A device the component of the error δS_M occasioned only by the polarization properties of light natural objects (K_0 more or less equal to 50%) may attain 20%. On this account measurement of m.r.v. with a polarization device should be carried out only on dark terrain objects, the polarized component of the luminance of which is relatively slight.

We shall now show how the visibility gage may be converted into a comparison photometer.

As was indicated in Chapter II, the optical-photometric system of present-day non-adaptation visibility gages is based upon optical splitting of an image observed in the field of vision of the device. On this account at a certain intermediary reading there are visible in the device's field of vision both two images of the object, and two images of the black marker (in the M-53A device a removable black screen set up 3-5 meters from the observation point serves as the black marker). Of these four images one may choose for measurements:

for the M-53A device -- the basic (unbent) image of the screen observed at reading "zero", and the supplementary image of the object appearing at high readings;

for the IDV device -- the basic (bent) image of the variable black marker observed at reading "zero", and the supplementary image of the object appearing at high readings.

Through appropriate orientations of the device or through precise setting up of the movable screen one brings about a situation where the object and the marker (or screen) are located in immediate proximity to each other.

By turning the rack and pinion of the device the observed luminances of the marker and the object are moved to one side or the other until they appear uniform, which is in fact the moment of reading.

Through analogous procedure one can compare light sources, and the like, with each other (see § 67).

Let us formulate some conclusions regarding the use of the comparison method for measurement of S_M from terrain objects projected against a sky (haze) background at the horizon. These measurements, with an upper limit of permissible error δS_M = 25%, are possible in the following cases:

1) when the object and the comparison marker are completely identical as regards color quality, dimensions, and outline, something which makes it possible to determine the K_0/K ratio at once; the extrapolational limits of measurement comes to 2z-17z;

2) when coniferous forests or dense summertime deciduous forests serve as objects of observation; the true contrast K_0 of the object and the contrast K of the same object under haze are determined at different times; the extrapolational limits of measurements are 2z-7z;

3) when using relatively bright objects with perceptible color: deciduous and mixed forests, hillocks in the autumn and spring, etc., and also objects partially covered with snow; the extrapolational limits of measurements are 2z-4z.

Visibility gages based upon splitting the image make it possible to measure . K contrast distorted by haze through the photometric comparison method (with the condition that this measurement shall not be affected by the color quality of the object) and the true contrast K_0 by the extinction method ("disappearance set-up") for practically any objects.

Such are the potentialities in principle of the method of photometric comparison in the measurement of m.r.v. in accordance with the contrasts of terrain objects.

§ 59. Application of the Extinction Method for Measurement of S_M in Accordance with the Contrasts of Terrain Objects

The principle of photometering by extinction (the "disappearance set-up") makes it possible, as has been indicated in Chapter II, to measure the contrasts K_0 and K of objects of any color quality, any angular dimensions, and any configuration of outline. But here it is necessary to make an important observation regarding the difference in the magnitudes of contrasts obtained by the extinction method and by the comparison method.

A contrast determined with the help of a visibility gage in accordance with the moment at which the visibility of the object is lost is called a perceived contrast, inasmuch as its magnitude depends on luminance, color, angularity, shape, and other properties of the object, which affect its visual perceptivity.

A contrast measured by the method of the "equality set-up" is called a luminance contrast, inasmuch as this process of measurement takes into account only the difference in luminance and does not take into account the color, shape, and other distinctions between the object and the marker.

As numerous experimental data have shown, the perceived contrast does not as a rule coincide with the luminance contrast, other things being equal.

If the object of observation has a jagged, interrupted outline (see Figure 68 b), then its perceived contrast is always less than the luminance contrast.

The perceived contrast coincides (within the limits of errors in measurement) with the luminance contrast if the object has a distinct or smoothly varying contour (see Figure 68 a) and sufficiently great angular dimensions.

Failure of the perceived contrast and the luminance contrast of natural objects to correspond is, as has been indicated, a source of supplementary errors in the determination of S_M by the method of photometric comparison, inasmuch as the table values for the contrast $K_{0\ mean}$ of natural objects having a jagged outline, measured by the extinction method, are reduced as compared with the magnitudes of the luminance contrast K_0 if it is possible to determine them by the comparison method.

The magnitude of this reduction may be considerable (see Table 30), in consequence of which the value of S_M when the comparison method is used may be heightened, inasmuch as the difference between the logarithms of the contrasts in the denominator of (8.12) will be less than the value would be with measurement of K_0 and K only by the comparison method.

Let us also note that in determining the range of visibility of real objects one has to deal with seen contrasts, i.e., with actually perceived ones, and not with luminance contrasts.

The procedure for measuring contrasts by the extinction method is examined in detail in Chapter II. Let us recall that the contrast K of an object is defined as the relation

$$K=\frac{V}{V_M},$$

where V is the degree of visibility of the object against a given background (in our case against a sky background); V_M is the degree of visibility of a black square (or the black marker of the instrument) also against a sky background at the horizon.

A section of sky at the horizon (the second supplementary image) is to serve as the masking luminance.

In accordance with (8.12) the expression for K must be applied twice:

1) in measuring the true contrast of the object (mean value)

$$K_{0\ mean}=\left(\frac{V_0}{V_M}\right)_{mean}=\varepsilon_{mean}V_{0\ mean}$$

2) in measuring the current contrast of the same object under haze

$$K_{current}=\left(\frac{V_0}{V_K}\right)_{current}=\varepsilon_{current}V_{distant.current}.$$

The expression of S_M may be written in the form

$$S_M = \frac{1{,}5L}{\log\left(\frac{V_0}{V_r}\right)_{\text{mean}} - \log\left(\frac{V_x}{V_M}\right)_{\text{current}}}, \quad (8.15)$$

or

$$S_M = \frac{1{,}5L}{\log(\varepsilon_{\text{mean}} V_{0\,\text{mean}}) - \log(\varepsilon_{\text{current}} V_{\text{true, current}})} \quad (8.16)$$

From (8.15) and (8.16) it follows that the possibility of determining S_M by the method of extinction in accordance with the contrasts of real objects having any color quality, any angular dimensions, and any shapes is won at the cost of complicating the methods system for measurement; specifically, each determination of S_M calls for knowledge of four quantities: $V_{0\ \text{mean}}$, $V_{M\ \text{mean}}$, V_{current}, and $V_{M\ \text{current}}$.

As has already been indicated, experience in making observations brings to light a divergence between averaged and current quantities. For this reason, aside from a divergence between $V_{0\ \text{mean}}$ and $V_{0\ \text{current}}$, there also exists a divergence between $V_{M\ \text{mean}}$ and $V_{M\ \text{current}}$, in which connection $V_{M\ \text{mean}}$ is obviously determined more accurately than is $V_{M\ \text{current}}$.

Such are the consequences of determining the K_0 and K contrasts of objects at different times; this difference of time is retained also during determination of S_M by the extinction method.

For the quadratic errors of measurement of the contrasts we get:

$$\delta K_{0\ \text{mean}} = \sqrt{\delta V_{0\ \text{mean}}^2 + \delta V_{M.\text{mean}}^2},$$
$$\delta K_{\text{current}} = \sqrt{\delta V_{\text{true, current}}^2 + \delta V_{M.\text{mean}}^2}.$$

Let us evaluate the components of these errors.

In the foregoing section it was shown that in the comparison method $\delta K_{0\ \text{mean}} \approx 7\%$. $\delta V_{0\ \text{mean}}$, too, is determined with approximately the same degree of accuracy. From experience with prolonged observations on the extinction of a black movable screen or the marker of the device against a sky background it transpires that $\delta V_{M\ mean}$ is determined with an error of about 6-8%, i.e., that it also can be taken as being equal to 7%.

Thus for the quadratic error of measurement of the true contrast K_0 by the extinction method we have

$$\delta K_{0\,mean} = \sqrt{7^2 + 7^2} = 10\%$$

in place of δK_0 = 7% according to the comparison method when coniferous and dense deciduous forests are used as objects.

The relative errors of the components for $\delta K_{current}$, as was shown in §13 and 14, are equal to approximately 12% in each case, i.e.,

$$\delta V_{true,\,current} = \delta V_{M.\,current} \approx 12\%.$$

Consequently,

$$\delta K_{current} = \sqrt{12^2 + 12^2} \approx 17\%.$$

For the relative error of measurement δS_M we secure in accordance with (8.13)

$$\delta S_M = 0{,}29z\sqrt{\delta K_{0\,mean}^2 + \delta K_{current}^2} = 0{,}29z \times$$
$$\times \sqrt{\delta V_{\delta\,mean}^2 + \delta V_{M.\,mean}^2 + \delta V_{true,\,current}^2 + \delta V_{M.\,current}^2} = 0{,}29z\sqrt{386}, \tag{8.17}$$

or

$$\delta S_M \approx 0{,}29z \cdot 20 = 5{,}8z\%.$$

In other words, measurement of S_M by perceived contrasts of terrain objects by means of the extinction method is possible with an upper limit of extrapolation z = 4.3 (for δS_M = 25%), which is little to be distinguished from the measurement potentialities of the diaphanoscope and the comparison method using colored natural objects.

These small extrapolational potentialities of the method under examination are occasioned only by the fact that measurement of contrasts by the extinction method calls, every time, for the supplementary determination of the threshold of contrast sensitivity, $\varepsilon = 1/V_M$. With application to $K_{0\ mean}$ and $K_{current}$ one must determine ε_{mean} and $\varepsilon_{current}$ with relative errors of 7 and 12% respectively. These two supplementary measurements not only heighten the error of determination of S_M, but also considerably complicate the measurement methods system. On this account measurement of S_M in accordance with the perceived contrasts of objects by the extinction method is not advisable, and the method has not undergone development and application.

But under the extinction method one can construct a more accurate and simpler way of measuring S_M if one determines not the contrasts, but the degree of visibility, V, of the objects.

Let us examine the foundations in principle of this method.

§ 60. Application of the Extinction Method for Measurement of S_M in Accordance with the Degree of Visibility of Terrain Objects

The conclusion as regards the possibility of measuring S_M by the extinction method with higher accuracy thrusts itself upon one as one examines expression (8.17).

As was shown in Chapter II, visibility gages directly measure not the contrast K of an object, but its degree of visibility $V = K/\varepsilon$, i.e., the relation of the contrast K to the threshold ε. We should recall that the magnitude of V, determined as the quantity of threshold intervals contained in the given contrast, expresses the intensitivity of the visual perception of an object with all the photometric and geometrical properties that pertain to it and when it is observed under specified lighting conditions.

The system of methods of measurement S_M via contrasts, rather than via the degree of visibility of objects, as described in the foregoing section, was a concession to a more expanded concept of contrast, although from the very start it was plain that as a result we would get a more complicated and less exact method, on account of the necessary presence of ε in the expressions for K_0 and K.

Now we shall show that renunciation of contrasts and use of the degree of visibility, V, of objects, as determined directly by visibility gages, simplify measurements and make them more exact.

The initial premise of the method of determining S_M in accordance with the degree of visibility of objects is the proposition to the effect that under the action of haze the degree of visibility V of an object projected against a sky background at the horizon changes in accordance with the same rule as does the contrast K of the object, i.e.,

$$V = V_0 e^{-\alpha L}, \qquad (8.18)$$

where V_0 is the degree of visibility of the object when there is no haze on it; V is the degree of visibility of the same object, but when observed through haze. Potentially arising objections against the replacement of the contrasts K in (8.2) by the degree of visibility V of an object are easily eliminated: both quantities are reciprocally linked, and they arise from the differential form of the Weber-Fechner law; they constitute merely different ways of expressing the intensitivity of visual perception of the object. This has already been discussed at the end of § 13.

After solving (8.18) relative to α and after substituting the value found for α in the expression for S_M, we secure by analogy to (8.7):

$$S_M = \frac{1.5L}{\log V_0 - \log V}. \qquad (8.19)$$

But even the use of the degree of visibility of the object does not eliminate the need for determining the V_0 and the V of the object at different times.

It is impossible in practice to measure the quantities V_0 and V simultaneously, just as is the case with the contrasts K_0 and K. One must necessarily make use of mean tabular values for $V_{0\ mean}$, determined in advance from a prolonged series of measurements and then refined on the spot. But with current determinations of S_M one need measure only the degree of visibility V_{dist} of an object under haze.

Thus in accordance with (8.12) we can write in place of (8.19)

$$S_M = \frac{1.5L}{\log V_{0\,mean} - \log V_{dist.\,current}}. \quad (8.20)$$

The principle for determining V_0 and V_{dist} is the same as the principle of determining K_0 and K: the image is brought to threshold perceptivity by means of a masking luminance (see Chapter II and III).

When (8.20) is compared with (8.15) or (8.16) the advantages of using the degree of visibility of an object become apparent: in (8.20) the threshold of contrast sensitivity ε is absent, in connection with which measurements of the thresholds ε_{mean} and $\varepsilon_{current}$ fall aside.

This is the place to remark that even before the Great Fatherland War V. A. Faas was trying to introduce a radical improvement into the methods system for determining S_M in accordance with natural objects, to which end, in order to measure simultaneously K_0 and K, he made models of such terrain objects as coniferous and dense deciduous forests. The models consisted of small black shields set up in proximity to the observation point, having shapes and outlines that imitated the objects under observation. The same model served also for determination of the threshold ε.

Since the photometric properties of terrain objects had at that time been studied very little, V. A. Faas assumed that observation on such a model could take the place of measurement of the contrast K_0 of the objects indicated. Then in place of $K_{0\,mean}$ it would be possible to substitute in (8.12) $K_{0\,current}$ or even directly to determine the ratio K_0/K for terrain object, which would heighten the accuracy of measurements. But V. A. Faas did not live to complete this work.

Subsequently the author of the present nomograph sought to apply modelling for determination of the visibility V_0 of any real terrain objects. To this end the model was given not only geometrical but also photometric (through appropriate coloration) similarity to the object. In other words, an attempt was made to develop a method of simplified varicolored photometering of variously colored terrain objects. Despite the obvious impossibility of strict geometrical and photometric similarity between the object and the model, it was assumed that divergence between the object and the test model in accordance with the V_0 value was less than the non-correspondence between the tabular and the true values of V_0. Despite persistent endeavors, it was necessary to drop the models method. To prepare a test specimen of satisfactory shape, to color it properly, to change the color and sometimes also the outlines depending on the seasons of the year, proved to be no easy matter. The method of modelling objects proved to be unsuccessful, as there was no success in eliminating through this procedure the need for measuring V_0 and $V_{dist\ current}$ at different times; the use of averaged tabular data is indispensable up to the moment where V_0 quantities are adjusted for accuracy in accordance with selected objects at the point of determination of S_M.

As was indicated in Chapter II, in any measurements by the method of extinguishing an object the error is somewhat reduced if the observation is carried out to the accompaniment of joggling the image being examined (which is achieved by turning the instrument to a certain angle to either side relative to the optical axis). But one should recall that extinction with joggling of the image heightens the readings by the amount of some divisions on the scale of the instrument. Extinction with joggling can be regarded as a procedure which heightens, as it were, the contrast sensitivity of the eye. On this account it is necessary to maintain uniformity in observations, i.e., these should be carried out either only with joggling of the image, which we in fact recommend for all cases, or without any joggling at all.

Let us evaluate the extrapolational potentialities of measuring S_M by the method being examined here.

For the relative quadratic error of separate measurement we can write, having (8.20) in mind

$$\delta S_M = 0.29 z \sqrt{\delta V_{0\,mean}^2 + \delta V_{true.current}^2} \qquad (8.21)$$

From a comparison of (8.21) and (8.17) one sees distinctly the advantages of using the concept "degree of visibility of the object" over using the concept "contrast": under the radical sign in (8.21) we do not have two relative errors of measurement of the threshold of contrast sensitivity ε, specifically

$$\delta\varepsilon_{mean} = \delta V_{M.mean} \approx 7\% \text{ and } \delta\varepsilon_{current} = \delta V_{M.current} \approx 12\%.$$

Assuming, as before, that

$$\delta V_{0\,\text{mean}} \approx 7\% \text{ and } \delta V_{\text{true. current}} \approx 12\%,$$

we secure

$$\delta S_{M} = 0.29z\sqrt{7^2 + 12^2} = 4.02\%. \qquad (8.22)$$

For a permissible error δS_M = 25% extrapolation is possible to a value of z = 6.5, which almost corresponds to the extrapolational potentialities of the comparison method when only coniferous and dense deciduous forests are used.

If one takes into account the fact that use of the degree of objects is not linked with limitations in the selection of the latter, then the advantage of the method expounded over the method of perceived and luminance contrasts becomes even more evident.

In order that measurements of S_M in accordance with the degree of visibility of objects may be commenced, one must have reliable values $V_{0\,\text{mean}}$ for various sorts of terrain objects projected against a sky background at the horizon, applicable to various seasons of the year, various lighting conditions, the character of outlines, etc.

For observations on the determination of $V_{0\,\text{mean}}$ there were recruited not only the observer corps of the photometric range at Voyeikovo, but also the Toksovo, Kovrov, Konotop, Borovichi, and Novgorod-Volynsk weather stations, which furnished for analysis and processing valuable data regarding the visibility V_0 of local objects[1].

As a result of the processing of the extensive material, Table 30 was drawn up, it contains averaged values of V_0 and of the perceived contrasts K_0

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[1] Observations were carried out in accordance with the "disappearance set-up" method with the help of one of the early modifications of the IIV visibility gage. At the time when the measurements indicated were carried out the relative luminance method had not yet been developed.

for the most typical terrain objects, with the character of contours being taken into account, and also the type of observation procedure (with or without joggling of the image).

In light of the high reliability of the data in Table 30, this table is not only of value for determining S_M, but can also be recommended for the solution of other terrain photometry problems.

Somewhat unexpected was the fact that the mean values $V_{0\ mean}$ and $K_{0\ mean}$ of objects proved to be dependent only in slight measure upon the azimuth relative to the sun, and also upon the lighting conditions. Divergences in V_0 values with sun lighting proved to lie within the limits of the quadratic errors of measurement for other lighting conditions. This afforded a possibility of unifying $V_{0\ mean}$ values no matter what the character of the lighting, which considerably cut down the dimensions of the table.

The circumstance that there is only slight dependence of contrast and of the degree of visibility of the object upon the azimuth of the sun is presumably to be explained by the fact that if, for example, the luminance of an object in an azimuth opposite to that of the sun goes up, then a compensating heightening of the luminance of haze takes place as well.

During observations in the winter season on snow-covered objects in overcast weather with low cloud it often seems that the cloud is considerably darker than the objects. One should recall that this is an optical illusion: photometrically the cloud, if it forms an even and continuous background, is brighter than the snow-covered objects. Minnart pointed this out in [88].

For measurements of S_M in accordance with the degree of visibility of objects within the limits of the international 10-point scale on the terrain, one must have at least three objects at distances of 200-1,200 meters, 1.3-7 km, and 8-12 km.

Errors in measurement of δS_M will run from 10% (for $z = 2$) to 25% (for $z = 6.5$). Measurements with z greater than 6.5 are useless, because the errors will exceed 25%.

TABLE 30. MEAN VALUES OF V_0, log V_0, and K_0 OF SOME TYPICAL TERRAIN OBJECTS PROJECTED AGAINST A HAZE BACKGROUND, WITH SUNNY AND OVERCAST LIGHTING (FOR ANGULAR DIMENSIONS OF OBJECT OR ITS IMAGES IN THE FIELD OF VISION OF THE INSTRUMENT NOT LESS THAN 15 X 15')

a) Объект	b) Период	c) Линия контура											
		d) плавная			e) пилообразная			d) плавная			e) пилообразная		
		V_0	lg V_0	K_0 %	V_0	lg V_0	K_0 %	V_0	lg V_0	K_0 %	V_0	lg V_0	K_0 %
		f) При покачивании изображения						g) Без покачивания изображения					
h) Хвойные леса и рощи	o) Круглогодично (зимой без заснеженного контура)	45	1,65	92	38	1,58	75	40	1,60	85	32	1,50	65
i) Лиственные леса и рощи:													
j) с листвой	p) Весна, лето, начало осени	38	1,58	70	32	1,50	58	33	1,52	63	28	1,41	55
k) без листвы	q) Поздняя осень, зима (без инея), ранняя весна	27	1,43	50	22	1,35	40	24	1,38	45	20	1,30	38
l) Смешанные леса	r) Круглогодично	40	1,60	75	34	1,53	60	37	1,57	70	30	1,48	57
m) Отдельное хвойное дерево (не далее 2,5 км)	»	40	1,60	75	34	1,53	60	37	1,57	70	30	1,48	57
n) Отдельное лиственное дерево (не далее 2,5 км):													
j) с листвой	s) Лето, осень	—	—	—	21	1,49	55	—	—	—	28	1,44	52
k) без листвы		25	1,40	45	21	1,32	38	22	1,35	40	19	1,27	35

Key: a) Object; b) Period; c) Outline Contour; d) Smooth; e) Jagged; f) With joggling of image; g) Without joggling of image; h) Coniferous forests and groves; i) Deciduous forests and groves; j) With leaves; k) Without leaves; l) Mixed forests; m) Individual coniferous tree (not farther than 2.5 km); n) Individual deciduous tree (not farther than 2.5 km); o) Throughout the year (in the winter, without snow-covered outline); p) Spring, summer, beginning of autumn; q) Late autumn, winter (without frost), early spring; r) Throughout the year; s) Summer, autumn.

TABLE 30 (continued)

t) Травяной холм	gg) Лето, осень	36	1,56	65	—	—	—	32	1,50	60	—	—	—
	hh) Весна	32	1,30	58	—	—	—	28	1,45	53	—	—	—
u) Леса, холмы, отдельные деревья, крыши зданий с заснеженным или заиндевевшим контуром при различном фоне:	ii) Зима												
v) темно-серым		40	1,60	75	—	—	—	37	1,57	70	—	—	—
w) серым		30	1,47	55	—	—	—	25	1,40	45	—	—	—
x) светло-серым		16	1,20	30	—	—	—	14	1,15	27	—	—	—
y) Строения из красного кирпича (здания, трубы и т. д.)	jj) Круглогодично	45	1,65	93	—	—	—	40	1,60	85	—	—	—
z) Темно-серые шпили зданий, церквей и т. д.	kk) Круглогодично (без заснеженного контура)	50	1,72	93	—	—	—	40	1,60	85	—	—	—
aa) Толевые крыши, а также искусственные черные щиты	ll) То же	50	1,72	100	—	—	—	45	1,65	95	—	—	—
bb) Старые бревенчатые постройки (почерневшие)	mm) Круглогодично	50	1,70	95	—	—	—	40	1,60	85	—	—	—
cc) Старые телефонные столбы (не далее 450 м)	"	50	1,70	95	—	—	—	40	1,60	85	—	—	—
dd) Кустарник:													
ee) без листвы	nn) Осень, зима, весна	—	—	—	21	1,32	38	—	—	—	19	1,27	35
ff) с листвой	oo) Лето	—	—	—	—	1,50	—	—	—	—	—	1,40	—

Key: t) Grassy hillock; u) Forests, hillocks, individual trees, roofs of buildings with snow-covered or frost-covered outline against various backgrounds; v) Dark-gray; w) Gray; x) Light-gray; y) Red brick structures (buildings, chimneys, etc.); z) Dark-gray spires of buildings, churches, etc.; aa) Tar-paper roofs, and also artificial black shields; bb) Old log structures, blackened; cc) Old telephone posts (not farther than 450 meters); dd) Thickets of bushes; ee) With leaves; ff) Without leaves; gg) Summer, autumn; hh) Spring; ii) Winter; jj) Throughout the year; kk) Throughout the year (without snow-covered outline); ll) The same; mm) Throughout the year; nn) Autumn, sinter, spring; oo) Summer.

Instrumental measurements of S_M in cases where S_M is less than 200 meters are undesirable. Such values for visibility are noted very rarely -- cloud of such great density possesses extreme optical inconstancy which makes instrumental measurements pointless; finally, visibility up to 200 meters can be determined by simple visual observations on objects in the locality.

Let us formulate a few conclusions:

1. With the non-adaptable visibility gage (M53A, IDV) method of extinguishing ("moving to disappearance") it is possible to determine S_M for any natural objects of scenery (objects of any color, any perceptible dimensions, with bright heterogeneous surface and any shape). From this two systematic variants are possible.

a) S_M is measured in accordance with the perceived contrasts K_0 and K of objects;

b) S_M is measured in accordance with the degree of visibility $\bar{V}_0$ and V of objects.

Variant a) has little to offer, as it is complicated, calls for two supplementary measurements of the threshold ε, and possesses only slight extrapolational limits (2z-4.5z).

Variant b) is more convenient, since it does not call for the measurement of the threshold ε and it possesses extrapolational limits 2z-6.5z, i.e., approximately the same as the comparison method when only coniferous and dense deciduous forests are used.

2. In the presence upon the terrain of appropriate objects the mean values of $V_{0\ mean}$ can be determined directly in accordance with Table 30, which has a sufficient degree of reliability. Determination of $V_{0\ mean}$ for objects not in Table 30 calls for some dozens of series of measurements in each season, with no haze on the objects.

3. The heterogeneity of the objects selected for observation has its negative side, associated with the complicated character of the taking into account of seasonal variations in the values of V_0, with the subdivision of single-type objects depending on the character of their outlines, and on other individual properties they possess.

§ 61. Determination of S_M by the Relative Luminance Method. Initial Theoretical Correlations

The methods of determining S_M via the contrasts and the degrees of visibility of real terrain objects, examined in foregoing sections, are pretty complicated and possess small extrapolational potentialities (not more than 7z on natural objects and not more than 15z on artificial black screens).

As a consequence of the low accuracy of the measurement of contrast which is inherent in all these methods, on the terrain one has to use only such objects, including artificial ones, as are already masked in their initial position by a considerable atmospheric haze. For measurements of visibility over the span of the international 10-point scale on the terrain one must have a minimum of three objects at different distances, and the variable photometric properties and geometrical peculiarities of these must be taken fully into account.

It would hardly be possible to refine these methods radically as compared with the stage that has been achieved.

Considerable improvement in the state of affairs as regards instrumental-visual determinations of S_M may be expected from the relative luminance method described in Chapter III. As the reader will recall, over the span of contrasts from 95 to 100%, errors in the measurement of δK come to tenths of one percent, rising to individual percentage units in the span of contrasts from 70-90%. This means that the relative luminance method makes it possible to fix the presence on the object, particularly if it is black, of the slightest traces of haze, something which ought to raise substantially the extrapolational limits of measurements, and consequently lead to simplification of the methods system for determining S_M.

As is shown in following sections, on the basis of the relative luminance method the author of this monograph has developed some variants of the measurement of S_M in daylight, the best of which possesses extrapolational limits of z equal to more or less 220, something which makes it possible, over the span of the international 10-point scale, to determine S_M from a single black body at a distance of 200-250 meters from the point of observation.

Without examining afresh the theory of the relative luminance method and the principle of observations, we shall pause here to consider only a few of its features as they apply to the substance of the question being discussed.

Use of the relative luminance method for measurement of S_M consists in determining by this method, in the expression for meteorological range of visibility

$$S_{м} = \frac{1{,}5L}{\log K_0 - \log K}$$

the true K_0 and the haze-distorted K of the contrast between the object being observed and the sky (haze) at the horizon. In this connection for the relative luminance method it is not necessary that the objects be projected against a sky (haze) background at the horizon. They may be projected against any real object at any distance one chooses. But it is important that upon observation in the visibility gage the degree of splitting between the basic, bent and the supplementary, unbent images, determined by the properties of the given design of visibility gage, shall make it possible to superimpose upon the object of observation a masking luminance in the form of a section of sky at the horizon produced by the second, supplementary image.

It is in this point, as has been indicated above, that there resides one of the advantages of the relative luminance method in comparison with the extinction or comparison methods, for which the objects of observation must indispensably be projected against a sky background at the horizon.

In expression (3.3) for the contrast between object and background, luminance B_ϕ of any selected background must be substituted for luminance D of haze at the horizon, i.e., in place of (3.3) one should have

$$K(B_0, D) = 1 - \frac{B_0}{D}, \qquad (8.23)$$

where B_0 is the luminance of the object, in which connection $B_0 < D$.

All the subsequent computations of § 16. leading to the final expression (3.6), are correct also for the present case, but expression (3.6) for contrast should be written in the form

$$K(B_0, D) = 1 - \frac{V-1}{V_м - 1} = 1 - \frac{V'}{V'_м}, \qquad (8.24)$$

where V' = V - 1 -- a quantity determined in accordance with the graduation table of visibility gage by reaching the moment of extinguishing the mark of the device against the background of the object, $V'_M = V_M - 1$ -- a quantity determined in accordance with the extinguishing of the marks against the background of the sky at the horizon. Thus, of course, $V'_M = 1/\varepsilon - 1$, where ε is the baffle contrasting luminance of the eye (the liminance D of the haze on the horizon is due to the sensitivity of the film).

Thus it follows from (8.24), for the degree of contrast of the object, according to the method fo relative luminance as associated with luminance according to the method of extinguishing the object, it is necessary to make two observations:

1) To extinguish the luminance D of the haze on the object so that it gives V';

2) Also to extinguish the luminance of the background haze · horizon so that it gives V'_M.

We notice that there is no contrast according to the method of relative luminance, and that th.. procedure of establishing the range of visibility V of the object becomes independent of the current extinguishing of markers against the sky background.

In correlating the formula (8.24) for the term S_M, the application is used twice: 1) for the measurement of true contrast of the object K_0, and 2) for the measurement of distortion by haze of the object K, and so it is necessary to establish:

$$\left.\begin{aligned} K_c &= 1 - \frac{V'_0}{V'_M} \\ K &= 1 - \frac{V'_\text{д}}{V'_M} \end{aligned}\right\} \tag{8.25}$$

where V'_0 and V'_{dist} are quantities determined in accordance with the graduation table for the moment of extinction of the marker against an object without haze and with haze respectively.

If observations are carried out on natural objects, then their true contrast K_0 cannot be determined at the moment of direct measurement of S_M. Just as in the cases examined above, this must be determined in advance, prior to the start of systematic measurements of S_M, on days when there is no haze on the object.

The relative quadratic errors of measuring S_M by the relative luminance method are determined in accordance with expression (8.11), where the errors δK_0 and δK under the radical sign can be determined via (3.12) or via the graph in Figure 17, or via Table 11.

§ 62. Measurement of S_M in Accordance with Natural Terrain Objects by the Relative Luminance Method. Evaluation of Applicability of the Method

Measurements of meteorological range of visibility by the relative luminance method were commenced for the first time in June 1957 at the photometric range of the Main Geophysical Observatory at Voyeikovo. To begin with a methods system for determination of S_M from natural objects was worked out, in which connection a movable thin-walled hollow cylinder, blackened inside and set up against the background of the object under observation, served as the black marker. In order to carry out the measurements the following objects were used: a coniferous forest, a grassy hillock, a line of bushes, and an individual coniferous tree.

Inasmuch as the relative luminance method measures only luminance contrast of objects without taking into account the character of the outline, it became necessary to determine anew the K_0 of the articles indicated, since the data of Table 30, which contains values for perceived contrast, are inapplicable for the method under examination.

As was to be expected, the very first measurements showed that the K_0 values of the objects indicated, determined by the relative luminance method, were higher than the magnitudes for K_0 measured via extinction of the outline (Table 31).

Let us note that for measurement of transmissivity of the atmosphere the method of measuring the contrasts K_0 and K is in itself of no particular importance, but it is important that K_0 and K be measured by one and the same method.

TABLE 31. VALUES OF K_0 (%) DETERMINED BY THE RELATIVE LUMINANCE METHOD (a) AND BY THE LOSS OF VISIBILITY OF THE OBJECT (b) (DATA OF TABLE 30)

Object	Outline of object	a	b
Individual coniferous tree.	Even	88.5	75
Grassy hillock.	"	75	65
Dense thicket of bushes.	Interrupted	85	70
Coniferous forest.	Even	93	93

Practical measurements of S_M via natural objects by the relative luminance method at once ran up against complications associated with the photometric properties of the natural objects.

It turned out that the K_0 contrasts of darker objects measured via relative luminance do not exceed 93% instead of the 95-96% that had been expected. Although the difference comes to only 2-3%, nevertheless, as will be clearly apparent from what follows, it considerably narrows the measurement potentialities of the method.

Furthermore, the high accuracies of measurements of contrasts by the relative luminance method made it possible to detect a dependence of the value for the true contrast K_0 of an object upon the azimuth of the sun and other lighting circumstances, something which had not been revealed during measurements via loss of visibility of the object, by virtue of their low accuracy. This fluidity of values of K_0 is supplementarily complicated by their seasonal variations, particularly at the change of seasons -- the fall of leaves, the spring emergence of buds, etc.

For measurements of S_M the tables of values of the K_0 of terrain objects, determined via the relative luminance method, become decidedly clumsy by virtue of what has been said, and the actual taking of K_0 into account becomes rather complicated. But this does not exhaust the complications.

By reason of the individuality of the course taken by errors in the measurement of contrasts by the relative luminance method, the use of natural objects with their comparatively low K_0 values affords practically no advantages in comparison with the methods examined in § 58, 59 and 60.

Let us examine the extrapolational potentialities of the relative luminance method and of the error δS_M, taking as an example objects having K_0 values equal to 80, 90, 93% (the darkest natural object) and 100% (an absolutely black body). The theoretical errors δK_0 for these objects when measuring them via relative luminance are respectively equal to 4.2, 1.9, 1.3, and 0% (see Table 11).

In order to determine the error δS_M when an object with a given K_0 value is used, we cannot take the K value of the same object under haze as being in any measure close to the magnitude of K_0, inasmuch as the error δK via the relative luminance method is always greater than the error δK_0. For example, with K_0 = 80%, for which δK_0 = 4.2%, one cannot take the value of K as equal to 76%, since δK in this case comes to 5% and the equally-probable value K may catch up to and even exceed the equally-probable value K_0. For this reason, in order to determine the theoretical error of δS_M when using an object with a given magnitude of K_0 one must take a maximum value of K such that, when the error δK is taken into account, it does not cover the magnitude of K_0, taken with the error δK_0 taken into account.

For an object with K_0 = 80% the closest K value having a "non-covered" error δK comes to 71%.

For objects having K_0 values equal to 90, 93, and 100%, the closest "non-covered" K values are respectively equal to 85, 88, and 99%.

Now, in accordance with the formula

$$\frac{S_M}{L} = z = \frac{1.5}{\log K_0 - \log K}$$

one can establish the value of z in accordance with the magnitude of K_0 and the arbitrary values of K. Making use thereafter of Table 11 and formula (3.12), one can easily determine the values of the theoretical error δS_M. The results of these computations are set forth graphically in Figure 69.

In this figure the values of z are laid off on the abscissa axis, and on the ordinate axis the theoretical errors δS_M. Each curve illustrates the course followed by the errors δS_M depending on the initial K_0 value of the terrain object.

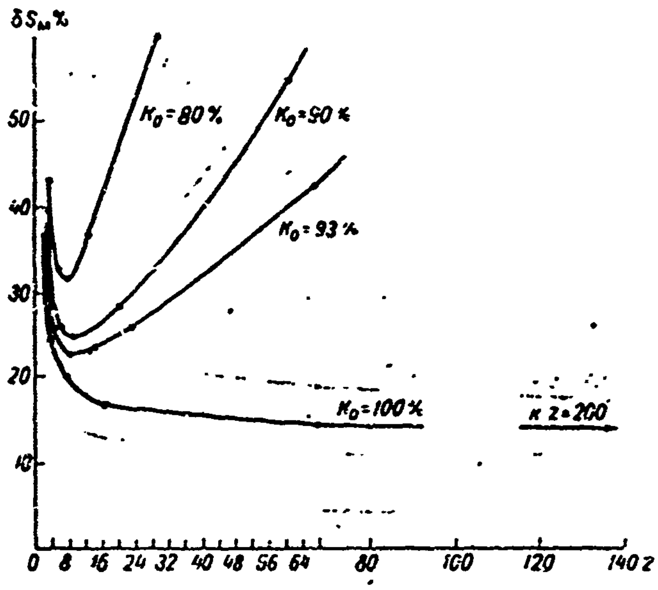

Figure 69. Extrapolational Potentialities of the Relative Luminance Meth-d in Measuring S_M Via Natural Terrain Objects.

From the nomograms in Figure 69 the limits of applicability of the relative luminance method when measuring S_M via the contrasts of natural objects are made graphically apparent.

As the top curve shows, for objects having K_0 = 80% the minimum error of measurement δS_M comes to about 32% with z = 7. To either side of this minimum the errors mount rapidly.

Hence it follows that all terrain objects having K_0 less than or equal to 85% are unsuitable for measurement of S_M via the relative luminance method, inasmuch as the measurement errors δS_M registered are higher than what is permissible (25%). Among such objects are: deciduous forests in the summer, autumn, and spring; individual deciduous trees, bush thickets, grassy hillocks, reinforced concrete and silicate-brick buildings, and all objects in the winter season when covered with snow or frost. Even for objects having K_0 = 90% the minimum error δS_M = 25%, and it is still not possible to carry out measurements of S_M from such objects.

Thus the majority of natural terrain objects are unsuitable for measurement of S_M via the relative luminance method.

The matter stands somewhat better with the darkest terrain objects: coniferous forests, buildings of blackened red brick, etc., for which the mean value of K_0 = 93%. For this group of objects the course followed by errors δS_M is represented by the second curve from the bottom in Figure 69. The minimum error δS_M in this case comes to 23% with z = 8, and it rises relatively slowly to 26% when z = 25. These extrapolational limits of measurement exceed by several times the potentialities of the comparison and extinction methods when natural objects are used, and are almost 1.5 times greater than the potentialities of the comparison method when black screens are used.

Where suitable conditions exist, i.e., where there is a dark strip of coniferous forest projected against any background, it is easy to organize observations in accordance with relative luminance. But one should recall that in this case, as in the comparison method with observation in accordance with coniferous forests, we encounter a "latitude effect" of the placement of such objects predominantly in the northern parts of the USSR, and during the winter by reason of frost or partial or complete coverage with snow these objects, too, become unsuitable for observation, even in the geographical regions referred to.

Control observations carried out at the photometry range of the Main Geophysical Observatory at Voyeikovo in accordance with the four objects mentioned above have completely confirmed the theoretical course of errors in measurement by the method being explained. It was necessary at once to choose such objects as a grassy hillock and a strip of bushes, since the error of group determinations of S_M rarely lay below 25%. Satisfactory data were secured only when observing a coniferous forest.

Thus even bringing in the relative luminance method with its accuracy higher by approximately one order does not afford a substantial gain relative to results secured by the comparison and extinction methods. This makes it possible to draw the general conclusion that to achieve any sort of progress in the measurement of S_M via the contrasts of natural objects, as compared with the present level, is hardly to be deemed possible.

Nevertheless, the relative luminance method incorporates a potentiality, in principle, for radically improving instrumental-visual determination of S_M. This possibility consists in renouncing the use of natural objects, and in the development of methods for measuring S_M which are to be based on the use of artificial black bodies or screens.

§ 63. Determination of S_M by the Relative Luminance Method With the Use of a Single Black Object (Single Black Object Method)

In Figure 69 our attention is drawn by the course taken by the curve of errors δS_M in measurements carried out in accordance with an absolutely black body having K_0 = 100%. It differs sharply from the course of curves for natural objects. The extrapolational potentialities are in this case extraordinarily expanded, in comparison with the ones examined earlier, to z = 150-200.

So high an accuracy of the relative luminance method, in measuring the contrasts of artificial black bodies with values of K_0 that are practically speaking close to 100%, is precisely what makes it possible to construct a process for measuring S_M on a new and more highly refined methodical basis, without having recourse to natural objects.

Let us first pause to consider an initial variant -- the single-black-body method -- in order to examine in the following section a still more perfect variant, the method of two black bodies.

Let us suppose that a black object (body) is set up on the terrain in which connection, as has already been indicated, it may be projected against any "ground" background below the horizon line (within the limits of the angular splitting of images in the field of vision of the visibility gage). In accordance with (8.25) we are to measure by the relative luminance method the true contrast K_0 and the haze-distorted contrast K of the black object.

The procedure for measurements which was examined in § 16 is preserved in this case without any alterations.

The following artificial constructions may be used as the black object: a black shield or screen inclined toward the line of sight at 45-60°; a vertical screen of black velvet; a parallelepiped blackened inside, in which the dimensions of the open cavity are related to the length of its base as 1:3 or 1:2, or even 1:1.5. The true contrast K_0 of such black objects when they are sighted through the device can be taken as 97% for the inclined black shield (painted plywood), 98.7% for the velvet, and 99.0% for the black cavity. These are mean values secured from prolonged tests of various forms of black objects.

For example, the K_0 of the black parallelepiped with a length of its base three times as great as the dimensions of the open cavity comes to 99.2%.

By a control experiment it was established that the K_0 of a special black body the length of which was ten times greater than the open cavity came to 99.3% upon observation through the device, i.e., it failed to achieve 100%. The existence of this incomplete blackness of a black body as viewed through the instrument is occasioned not only by a certain inherent luminance of the black body (particularly in the case of painted shields) and by the luminance of the column of air between the black body and the device, but primarily by parasitic luminance, i.e., by light scattered within the measurement device by the lenses, diaphragm walls, etc.

The linear dimensions of the black object depend on the distance at which it must be set up, and also on the presence in the visibility gage of a telescopic system.

In turn, the distance at which the black object should be set up depends on the optimum value of the extrapolational parameter z pertaining to the given method. The dimensions of black objects applicable to the IDV and M-53A devices are indicated below, after establishment of the z figure for the method being explained. Taking K_0 = 99% for the black hollow and recalling that in accordance with (3.9) K = (n - 1)/n, or n = 1(1 - K), we find that n is more or less equal to 100, whence by (3.12) we determine that δK_0 = 0.17% (inasmuch as $\delta V_{M.current} = \delta V_{M.current} \approx 12\%$).

Thus when the single-black-object method is used in (8.25) one is to measure directly only the K value of the object under haze, i.e.,

$$K = 1 - \frac{V'_{dist.current}}{V'_{M.current}},$$

which is associated with two measurement procedures: 1) extinction of the marker against the background of the object under haze, which gives $V'_{dist.current}$, and 2) extinction of the marker against a sky background at the horizon, which gives $V'_{M.current}$. The relative errors of measurement of these quantities, as has been shown more than once above, are equal in each case to 12%, i.e.,

$$\delta V'_{dist, current} \approx \delta V'_{M, current} \approx 12\%.$$

Substituting the quantities K_0 and K in the formula for S_M makes it possible to find the value of the meteorological range of visibility.

For determination of the extrapolational potentialities of the method being explained one must establish the closest "uncovered" values, for the contrast K of the black object under haze, at which confident measurements may be initiated.

As such a first "working" contrast one should take K = 97%, for which n = 33. The measurement error δK according to (3.12) will be equal to

$$\delta K = \frac{\sqrt{\delta V_{д}'^2 + \delta V_{м}'^2}}{n-1} = \frac{\sqrt{12^2 + 12^2}}{33} = 0{,}51\%.$$

(the index "current" has been dropped out).

For the relative quadratic error of the separate measurement of δS_M, according to (8.13) we get, knowing δK_0 and δK,

$$\delta S_{м} = 0{,}29z\sqrt{\delta K_0^2 + \delta K^2} =$$
$$= 0{,}29z\sqrt{0{,}17^2 + 0{,}51^2} \approx 0{,}16z\%,$$

whence it is apparent that for δS_M = 25%, z = 150.

This is the upper extrapolational limit for the single-black-object method.

But, to anticipate a little, we shall indicate that in consequence of certain shortcomings of the method which will be expounded upon further the true extrapolational limits are somewhat lower than the theoretical ones, and specifically that in practice z = 120. It is precisely this figure that constitutes the upper extrapolational limit for the single-black-object method. We point it out at once so as to establish the minimum dimensions of the black screen and the minimum distance to it.

For measurement of visibility over the span 0.5 km $\leq S_M \leq$ 50 km on the terrain it is sufficient to have a single black object at a distance of 350 to 400 meters from the point of observation.

The minimum dimensions of the black object depend on what visibility gage is being used.

For the IDV device, which has a seven-power telescopic system and in its field of vision a round black marker of 25' diameter, the angular dimensions of the black object should come to a minimum of 1°. At a distance of 350 meters it will be necessary to set up a black object of 1 X 1 meter dimensions, or a shield-screen of 1 X 1.3 meters dimensions (taking into account the inclination of 45° toward the line of sight).

For the M-53A device, which does not have a telescopic system and which uses a movable marker in the form of a shield having a square hole cut out of its center, the minimum dimensions for the shield at a distance of 350 meters should come to 4 X 3 meters (the setting up of black bodies falls aside for the M-53A).

The single-black-body method has passed official tests in the system of the Main Administration of the Hydrometeorological Service and is at present being incorporated into the station network.

The organization of observations, the order of carrying out measurements, and the processing of data are set forth in detail in the accompanying instructions.

Further work on refining measurements of S_M by the relative luminance method has made it possible to bring to light some defects of the single-black-object method.

The main defect of the single-black-object method is the failure to satisfy on the part of the way of measuring $\epsilon_{current}$, which is carried out in the case of each observation through extinction of the marker or the movable shield against a sky background. Here two factors that lower the accuracy of measurements of $\epsilon_{current}$, and consequently also of S_M, come to light:

1) a considerable effect of instrumental error occasioned by the great steepness of the graduation curve of the devices in the sector corresponding to the moment of extinction of the marker (the movable shield) against the sky background (see Figure 20);

2) the effect of difference in the luminance of those sectors of sky against the background of which extinction of the marker or the movable shield is carried out.

Experience has shown that on account of these factors divergences in the value of $\varepsilon_{current}$ as determined by a group of observers do not fall below 10-12%, and may at times reach 15-20%, relative to the quantity ε. But a divergence in the value of ε amounting to n% leads to a divergence in the magnitude of S_M amounting to approximately 2n%. Consequently the divergence in the values of S_M attains 25-30%.

Furthermore, current "observation in accordance with the sky" obstructs measurements of S_M during twilight and even during the time preceding it. This is occasioned by fields of adaptation differing in luminance, when the marker or the movable shield is first extinguished against the background of the black object and the eye adapts itself to the luminance of the twilight landscape, and then they are at once extinguished against the background of the considerably more luminous sky. This produces an exaggerated $\varepsilon_{current}$ value, which sharply raises S_M during twilight. Consequently the single-black-object method excludes measurements of S_M in twilight.

Thus the need for "observations in accordance with the sky" constitutes the principal defect of the single-black-object method. This defect reduces the extrapolational potentialities from z = 150, which is what the theory offers, to z = 100-120 in practical conduct of the method.

§ 64. Determination of S_M by the Relative Luminance Method With the Use of Two Black Objects (Two-Black-Object Method).

In the search for ways of eliminating the defects of the single-black-object method the idea came up that one might use two black objects, identical in angular dimensions and photometrically similar, located at different distances and approximately in a single azimuth. In this connection the closer black object (of smaller linear dimensions) was to be set up at such a short distance from the observation point (5-10 meters) that the luminance of haze upon it might be disregarded under any atmospheric turbidity.

At first glance it might seem that it would be reasonable to determine $K_{0\ current}$ directly by the relative luminance method from a small black object located close at hand and photometrically similar to a more remote one by relating it to the more remote object which would find itself under a haze. But such a conclusion is erroneous, since the determination of $K_{0\ current}$ in accordance with the closer object, or direct determination of the K_0/K ratio would in any event call for carrying out of the extinction of a marker against a sky background (for determination of $\varepsilon_{current}$), something which would afford no advantages in comparison with the single-black-object method.

The problem consists in replacing "observation in accordance with the sky" by observation, equivalent to it, in accordance with the closer black object. Such a replacement proves to be possible.

Let us write (8.25) in an initial form conforming to (3.5):

$$\left.\begin{aligned} K_0 &= 1 - \frac{V'_0}{\frac{1}{\varepsilon} - 1} \\ K &= 1 - \frac{V'}{\frac{1}{\varepsilon} - 1} \end{aligned}\right\} \qquad (8.26)$$

where V'_0 and V' are values determined from the graduation table for the moment of extinction of the marker against the black object without haze and with haze respectively.

But measurement of V'_0 is now carried out in accordance with the closer black object having no haze upon it, and V' in accordance with the remote object under haze. For this reason (8.26) may be written as follows:

$$\left.\begin{aligned} K_0 &= 1 - \frac{V'_{0\,closer}}{\frac{1}{\varepsilon} - 1} \\ K &= 1 - \frac{V'_x}{\frac{1}{\varepsilon} - 1} \end{aligned}\right\} \qquad (8.27)$$

The first expression of (8.27) opens up the way to a new method of determining $1/\varepsilon$, and consequently ε, on the condition that the K_0 value of the object is known. We shall show what sort of a method this is. After elementary transformation of the first expression of (8.27) we secure

$$\frac{1}{\varepsilon} = 1 + \frac{V'_{o\ closer}}{1 - K_o} . \qquad (8.28)$$

It is formally possible to get a value $1/\varepsilon$ in accordance with the second expression of (8.27), but no practical use can be made of it since K is a variable quantity and it is not possible to determine $1/\varepsilon$ from a prolonged series of variations with any reliability.

Expression (8.28) makes it possible to determine in a new way the threshold of contrast sensitivity ε by the relative luminance method. This way is associated with extinction of the marker against the background of the closer black object, the K_0 contrast of which is to be determined in advance with the help of the same device. In this connection, if in accordance with the conditions of the problem it is necessary to know the mean value ε_{mean}, (8.28) should be written in the form

$$\frac{1}{\varepsilon_{mean}} = 1 + \frac{V'_{closer.mean}}{1 - K_{o\ mean}} , \qquad (8.29)$$

where $V'_{closer.mean}$ is the mean value of V'_{closer} upon extinction of the marker against the background of the closer black object, determined from a prolonged series of measurements; $K_{0.mean}$ is the mean contrast of the closer black object, observed in the device and determined in advance, also from a prolonged series of measurements.

If in accordance with the conditions of the problem one must know the current magnitude of $\varepsilon_{current}$, then (8.28) should have the form

$$\frac{1}{\varepsilon_{current}} = 1 + \frac{V'_{closer.current}}{1 - K_{o\ mean}} , \qquad (8.30)$$

where $V'_{closer.current}$ is no longer the mean, but instead the current magnitude, determined on each occasion in accordance with the moment of extinction of the marker against the background of the closer black object. The background relative to which the K_0 of the closer black object (the object does not have to be projected against the background sought) should serve as the masking luminance.

Expression (8.29) furnishes the foundation for the casting aside of "observations according to the sky" and replacement thereof with observation according to the closer black object.

Substituting (8.29) into (8.27) we secure:

$$\begin{aligned} K_{0\,current} &= 1-\left(\frac{1-K_{0\,mean}}{V'_{closer.mean}}\right)V'_{0\,closer.current} \\ K_{current} &= 1-\left(\frac{1-K_{0\,mean}}{V'_{closer.mean}}\right)V'_{dist.current} \end{aligned} \tag{8.31}$$

where $V'_{0\ closer.current}$ and $V'_{distant.current}$ are quantities determined from the graduation table with current determination of S_M in accordance with the moment of extinction of the marker against the background of the closer and more remote black objects respectively.

The expression within parentheses in (8.31) obviously correspond approximately to ε_{mean} in (8.29). Actually, from (8.29) we find

$$\varepsilon_{mean} = \frac{1 - K_{o\ mean}}{1 - K_{o\ mean} + V'_{closer.mean}} \tag{8.32}$$

which is distinguished from the expressions in parentheses in (8.31) only by the difference $1 - K_{0\ mean}$ in the denominator.

Inasmuch as the $K_{0\ mean}$ of the black object is distinguished from unity by not more than 0.03, the difference $1 - K_{0\ mean} \leq 0.03$, whereas the value $V'_{closer.mean}$ is close to unity[1].

---

[1] As was shown in the foregoing section, the loose equality of $K_{0\ mean}$ to unity, revealed only by a method so highly precise for these contrast values as is the relative luminance method, is to be explained mainly by the presence of parasitic luminance of the measurement device.

Thus the approximate value ε_{mean} within parentheses in (8.31) is distinguished from the precise value ε_{mean} according to (8.32) by no more than 3% of the magnitude of ε_{mean}, i.e., one can write

$$\varepsilon_{mean} = \frac{1 - K_{0\,mean}}{1 - K_{0\,mean} \cdot V'_{closer.mean}} \approx \frac{1 - K_{0\,mean}}{V'_{closer.mean}}. \tag{8.33}$$

On the basis of (8.33) the expressions of (8.31) can be transcribed in the following form:

$$\left.\begin{aligned} K_0 &= 1 - \varepsilon_{mean} V'_{0\,closer.current} \\ K &= 1 - \varepsilon_{mean} V'_{dist.current} \end{aligned}\right\} \tag{8.34}$$

with the distinction from (8.26) or (8.27) that now ε_{mean} is determined in accordance with the extinction of the black marker of the device against the closer black object, and not against the sky background at the horizon. But on the other hand, as was indicated above,

$$\varepsilon_{mean} = \frac{1}{V_{M.mean}},$$

where $V_{M.mean}$ is the mean value for the degree of visibility of the black marker of the device (or the movable shield) against a sky background at the horizon. On this account one can write

$$\varepsilon_{mean} \approx \frac{1 - K_{0\,mean}}{V'_{closer.mean}} \approx \frac{1}{V_{M.mean}}. \tag{8.34a}$$

On the basis of (8.34a) expressions (8.34) can be written in the form:

$$\left.\begin{aligned} K_0 &= 1 - \frac{V'_{0\,closer.current}}{V_{M.mean}} \\ K &= 1 - \frac{V'_{dist.current}}{V_{M.mean}} \end{aligned}\right\} \tag{8.35}$$

Within the limits of errors of measurement

$$V_{M.mean} \approx \frac{V'_{closer.mean}}{1-K_{0\,mean}} \approx 45.$$

Expressions (8.34) and (8.35) are the bases for the method of two black objects. For measurement of S_M one must carry out two measurement procedures: 1) extinguish the marker of the device against the background of the closer black object; 2) extinguish the marker of the device against the background of the more distant black object under haze.

The measurement procedure of "observation according to the sky", which is obligatory for all the methods examined above (aside from the determination of S_M by the comparison method and by the degree of visibility of objects), is now excluded. By virtue of this fact one also eliminates all the complications that procedure gave rise to in the single-black-object method, these being indicated at the end of the preceding section.

It is obvious that physically, thanks to the photometric and geometric similarly of the black objects used, observation in accordance with the closer black object would be the equivalent of observation in accordance with the distant object if there were to be no haze upon it. On this account in (8.34) it is actually $K_{0.current}$ and $K_{current}$ that are determined, since the quantities $V'_{0\ closer.current}$ and $V'_{distant.current}$ reflect the current, and at the same time an equivalent, state of both black objects under given conditions of observation (with a given lighting, effect of atmospheric scatter indicatrix, etc.).

Let us evaluate the extrapolational limits of the two-black-objects method.

In accordance with what has been set forth in foregoing sections the relative error of unit measurement of $\delta V_{M.mean}$, as it was performed earlier, can be taken as equal to 7%.

The relative errors of current measurements of $V'_{closer.current}$ and of $V'_{dist.current}$ are equal to 12% in each case, i.e., in correspondence with what has been indicated earlier

$$\delta V'_{closer.current} = \delta V'_{dist.current} \approx 12\%.$$

Assuming, as in the single-black-object method, that K_0 = 99.0%, for which n_1 is more or less equal to 100, and taking as the first "working" contrast (with which measurements may be commenced) K = 97.5%, for which n_2 = 40, we secure according to (3.12)

$$\left.\begin{aligned} \delta K_0 &= \frac{\sqrt{\delta V^2_{\text{M.mean}} + \delta V'^2_{\text{closer. current}}}}{n_1 - 1} = \frac{\sqrt{7^2 + 12^2}}{100} = 0{,}15\% \\ \delta K &= \frac{\sqrt{\delta V^2_{\text{M.mean}} + \delta V'^2_{\text{dist. current}}}}{n_2 - 1} = \frac{\sqrt{7^2 + 12^2}}{40} = 0{,}38\% \end{aligned}\right\} \qquad (8.35a)$$

For the relative quadratic error of separate measurement of S_M for the contrasts K_0 and K indicated, we secure in accordance with (8.13)

$$\delta S_M = 0{,}29z\sqrt{\delta K_0^2 + \delta K^2} = 0{,}29z\sqrt{0{,}15^2 + 0{,}38^2} = \\ = 0{,}29z \cdot 0{,}41 = 0{,}12z\%.$$

From this it follows that for δS_M = 25% the upper extrapolational limit z of measurements of S_M by the two-black-objects method comes to 210, which exceeds by almost twice the extrapolational potentialities of the single-black-object method, under which, practically speaking, z = 100-120.

For measurement of atmospheric turbidity within the limits of the international 10-point scale of visibility on the terrain, it is sufficient to have one black object at a distance of 250 meters from the point of observation. For the IDV device it should have dimensions of 70 X 70 X 90 cm (for the M-53A device the dimensions of the black object should come to 2.5 X 2.5 X 3.0 meters).

But the non-linear course of errors in measurement of contrasts by relative luminance makes measurement of S_M disadvantageous in accordance with only a single black object and within the limits of the international ten-point scale.

The zone disadvantageous for measurement lies within the field of small values of z, which fall respectively to small values of contrasts. As computation of errors shows, starting from small value of z it is more logical to shift to observation of a more proimity located intermediary black object, having a greater contrast, i.e., a greater z quantity for a given S_M. This intermediary black object should be placed at 0.1 of the distance to the distant black object, in a single azimuth with it; the dimensions of the distant object should be reduced approximately 10 times. It is not indispensable that the intermediary object should be projected against a sky background.

So as to find the most advantageous limits of measurements on the distant and the intermediary object, we calculate and construct a nomogram showing the course taken by measurement errors δS_M in accordance with these objects depending on the S_M values and the z parameter.

For calculation we take K_0 as 99% and δK_0 as 0.15%. Then we compute δS_M in accordance with (8.13), K in accordance with (8.9), δK in accordance with (8.35a); finally, $S_M = zL$.

The results of the computation are presented in Figure 70.

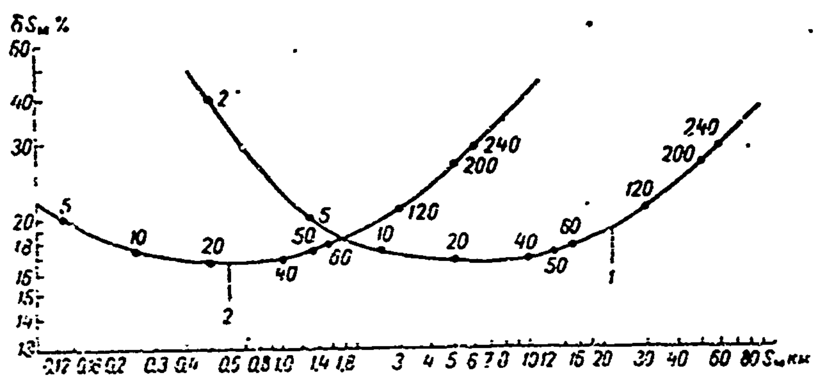

Figure 70. Most Advantageous Limits of Measurements of S_M On The Basic, Remote (1; L = 250 M) and Intermediary (2; L = 25 m) Black Objects in the Relative Luminance Method. Figures by the curves are the values of the z parameter.

From the nomograms one can draw a series of interesting conclusions bearing upon some peculiarities of the two-black-objects methods.

1. The minimum (theoretical) error of measurement δS_M comes to about 16%. With $\delta S_M = 20\%$ the z parameter changes from 5 to 120, and with $\delta S_M = 25\%$ the limits of extrapolation expand from $z = 4$ to $z = 200$.

2. With $S_M \approx 2.5$ km measurement errors δS_M on the distant and intermediary objects are identical and come to 18%. With $S_M < 2.5$ km it is the more advantageous to carry out measurements on the intermediary black object, the less the z value is. On the other hand, with $S_M > 2.5$ km the accuracy of measurements on the distant object becomes higher, and within the limits 2 km $< S_M <$ 30 km the error comes to 17-20%.

3. The lower extrapolational limit in the two-black-objects method proves to be, as is apparent from the nomogram of Figure 70, the value $z \approx 4$, in which connection $\delta S_M = 25\%$. But in practice, for the sake of securing equal-accuracy measurements one should shift to observation in accordance with the intermediary black object in those cases where for the distant object $z \leq 10$. The moment for making the change is indicated in the pertinent instructions.

The expressions (8.34) or (8.35) can be transformed and brought to a simpler form. Let us divide both expressions (8.34) by ε_{mean}:

$$\left.\begin{aligned} \frac{K_0}{\varepsilon_{mean}} &= \frac{1}{\varepsilon_{mean}} - V'_{closer.\,current} \\ \frac{K}{\varepsilon_{mean}} &= \frac{1}{\varepsilon_{mean}} - V'_{dist.\,current} \end{aligned}\right\} \qquad (8.36)$$

But, as we are aware, $1/\varepsilon_{mean} = V_{M.mean}$. Then in place of (8.36) we get:

$$\left.\begin{aligned} \frac{K_0}{\varepsilon_{mean}} &= V_{M.mean} - V'_{closer.\,current} \\ \frac{K}{\varepsilon_{mean}} &= V_{M.mean} - V'_{dist.\,current} \end{aligned}\right\} \qquad (8.37)$$

In (8.37) the physical sense of the two-black-objects method is more clearly disclosed: the quantities $V'_{closer.current}$ and $V'_{dist.current}$ constitute current corrections which must be introduced into the mean quantity $V_{M.mean}$ which has been determined in advance, in order that one may secure, through observations on the two photometrically identical distant and nearby objects, current values $V_{O\ current} = K_O/\varepsilon_{mean}$ and $V_{current} = K/\varepsilon_{mean}$. In this connection $V_{M.mean}$ can be determined either in accordance with the moment of extinction of the marker against the nearby object [see (8.34a)], or via prolonged series of extinctions of the marker against a sky background under various weather conditions (the worse variant). Thus, the physical sense of $V_{M.mean}$ consists in the fact that $V_{M.mean}$ characterizes the degree of visibility of a black object against a sky (haze) background at the horizon.

Consequently, in place of (8.37) we may finally write:

$$\begin{aligned} V_{o\ current} &= V_{M.mean} - V'_{closer.current} \\ V_{dist.current} &= V_{M.mean} - V'_{dist.current} \end{aligned} \qquad (8.38)$$

where $V_{M.mean}$ can be taken as equal to 45, as this is in fact done in the present nomograph.

Substituting these values into the formula for S_M gives the meteorological range of visibility that we are seeking.

Obviously (8.38) is equivalent to (8.34) or (8.35), and all of what has been said above relative to the latter expressions is also true for (8.38).

The corrections $V'_{closer.current}$ and $V'_{dist.current}$ characterize the deviation of the $V_{O\ current}$ and $V_{dist.current}$ of the black object being observed (the distant or the intermediary one) from the degree of visibility of an absolutely black body by reason of the effect of atmospheric haze, the atmospheric indicatrix of scatter, the parasitic luminance of the instrument, etc.

Such are the basic properties and the potentialities in principle of the two-black-objects method.

Let us note that with the M-53A device, which does not have a telescopic system and uses a movable black marker, measurements by the two-black-objects method are laborious. If the movable marker is set up at 3-5 meters from the point of observation, then the closer black object, which plays the part of a "sky substitute," has to be located somewhat farther (at 20-25 meters). But given the sensitivity of the method, which admits of 200 x extrapolation, such a nearby object may be under haze even with S_M = 5 km. Thus measurements by the two-black-objects method with a M-53A can be commenced with an S_M of no less than 7-8 km.

Now we must convince ourselves of the extent to which the practice of measurements confirms the justice of the tenet that dropping "observations according to the sky" and replacing them with observations via the closer black object or shield lead to heightened accuracy of measurements and to expansion of their extrapolational limits.

Let us turn to the results of field tests of the method of two black objects, carried out on the photometric range at Voyeikovo.

In view of the absence of a standard set-up for measurement of S_M, to the end of greater objectivity of the experimental check on the method expounded measurements of S_M were carried out not in accordance with a single black object, but simultaneously in accordance with two, set up approximately in the same azimuth at 200 and 500 m from the observation point and having dimensions of 70 X 70 X 90 cm and 1.4 X 1.4 X 1.8 m respectively. The nearby black object of small dimensions was placed at 7 m. From the object set up at 200 meters the m.r.v. was measured up to 40 km; from the object at 500 meters, that to 100 km.

As a consequence of the closed field of view, all objects were set approximately 1° below the open horizon line. As a measurement device the first working examples of the IDV device, described in detail in Chapter III, were used.

The very first observations showed that elimination from the process of measurements of "observation by the sky" and replacement thereof with observation by the closer shield do in fact afford great advantages: the spread in readings by the group of observers was reduced, the accuracy of measurements S_M was heightened, the extrapolational limits of measurements were extended, and measurements in early twilight became possible.

The results of many months of measuring S_M in different seasons of the year, carried out by the personnel of the photometric range at Voyeikovo, are set forth in Figure 71. In each series of measurements the overall number of which exceeded 200, from two to four observers took part. Measurements carried out by single observers were not included in the processing.

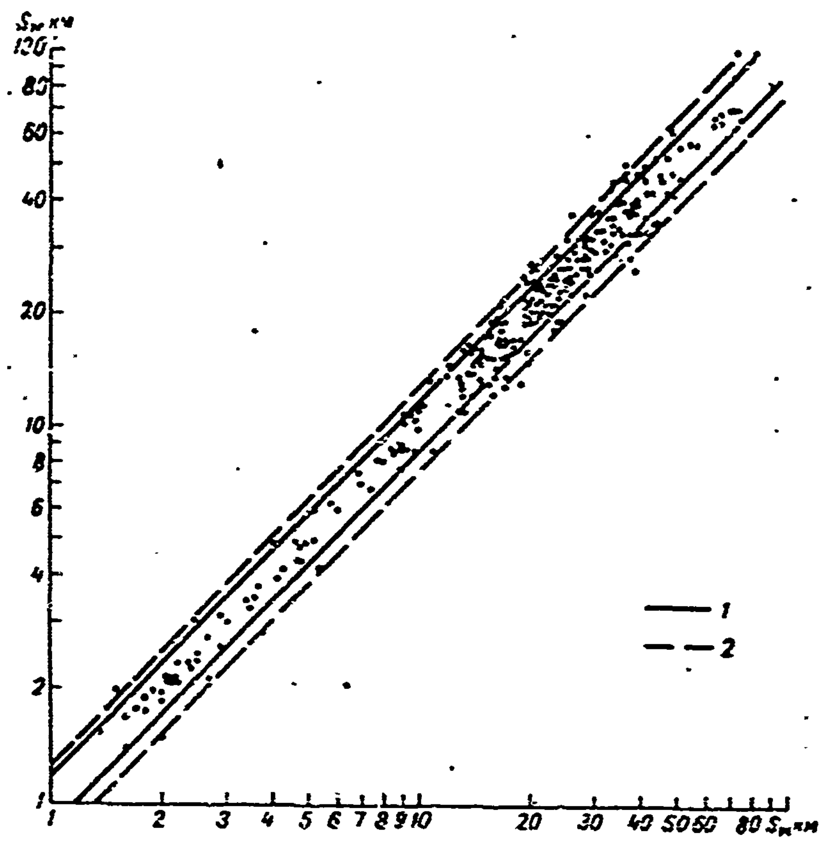

Figure 71. Results of Field Tests of Relative Luminance Method (Two-Black-Objects Method). Convergence of results of measurements of S_M in accordance with black bodies at distances of 200 and 500 meters. 1, Zone of errors of ± 15%; 2, Zone of errors of ± 25%.

In Figure 71 we have laid out on the abscissa axis the "true" values of S_M, being the arithmetical mean from the results secured by the group of observers. With S_M < 10 m, as a standard m.r.v. gage we used the M-37 transmissivity recorder. On the ordinate axis of the nomogram in Figure 71 we have laid out the values of S_M secured by each observer of a given group. Simultaneous observations in accordance with two remote black shields set up at distances of 200 and 500 meters pursued the purpose of clarifying the character of change in the values of S_M with distance to the object (as one often finds occurring in the extinction and comparison methods) when natural objects are used and when their photometric and geometrical properties are not completely taken into account.

As is apparent from Figure 71, the basic mass of observations (more than 80%) falls into the plus or minus 15% error zone; a considerably smaller part of the observations (about 20%) fall into the 15 to 25% error zone. Beyond the limits of permissible error, 25%, there proved to be only a few series of measurements. The same result was secured also by comparing the results of measurements with the indications of the M-37 transmissivity recorder (Figure 72). Thus the experimental check of the two-black-objects method confirmed the correctness of its theoretical bases in principle. What has been set forth renders it possible to conclude that among all the instrumental-visual methods examined above, the two-black-objects relative luminance method is the most exact and the most convenient for measurements during daylight and partial twilight in steppe and polar regions, on terrain with a closed field of view, inasmuch as the setting up of black bodies of relatively small outside dimensions at a slight level above the earth and maintaining them in operational condition present no difficulties. The development of the two-black-bodies method has crowned many years of research upon the creation for meteorological stations of the most acceptable instrumental-visual method of measurement of S_M by daylight.

In Figure 73 we compare with each other the extrapolational potentialities of all the instrumental-visual methods examined in the present chapter, and the accuracy of measurements of S_M by these methods. Errors δS_M are laid off on the ordinate axis, the extrapolational parameter z on the abscissa axis. The highest permissible error of measurement is considered to be $\delta S_M = \pm 25\%$.

From the nomogram of Figure 73 it is apparent that the least extrapolational potentialities are those of the extinction and comparison method with the use of natural objects. Then the method of comparison with observation from a black shield follows. For comparison we also present on the nomogram the extrapolational potentialities of the M-37 transmissivity recorder and of the compensation recorder on V. I. Goryshin's system, which may be regarded as the standard objective instrument at the present stage as regards accuracy of measurements. For all of these methods and apparatus the quantity δS_M proves to be a linear function of z.

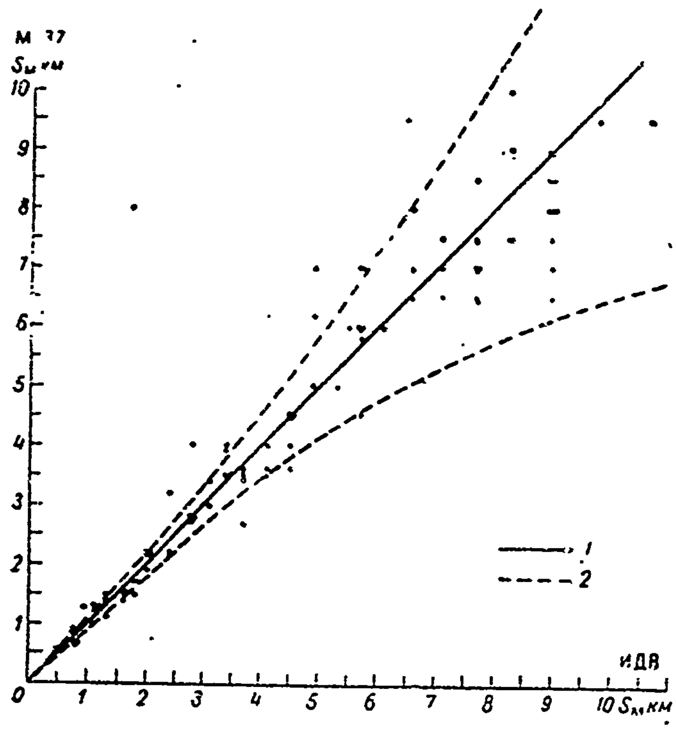

Figure 72. Comparison of Results of Measurement of S_M By The Two-Black-Objects Method and the Indications of The M-37 Photoelectrical Apparatus. 1, Line of equal values; 2, Zone of errors of M-37.

Curves 6 and 7 reflect the course of the error of measurement δS_M under the relative luminance method respectively for a single and for two black objects. The advantages of the two-black-objects method over the extinction and comparison methods are obvious without commentary. Let us recall that with $z \leqslant 10$ one should shift to observations from an intermediary black object, which ensures equal-accuracy measurements of S_M over a span from 200 meters to 50 km.

It is necessary to make a remark on the use of inclined black screens in the wintertime when working with the M-53A.

As has been indicated above, in the wintertime inclined black screens gleam perceptibly in consequence of diffusion scatter of light by the snow cover. On this account in the wintertime observation based on them produces a considerable supplementary error. In order to reduce this error one should carry out observations via vertical shields in the winter. As experience has shown, during winter it is still better to use vertical screens of black velvet. Of course, this is possible only when a visibility gage having a telescopic system is used; thanks to this, the linear dimensions of screens can be reduced proportionately to the magnification of the visual tube. Removable velvet screens are very convenient for winter use, as a means for combatting frost, icing, adherence of snow, etc.

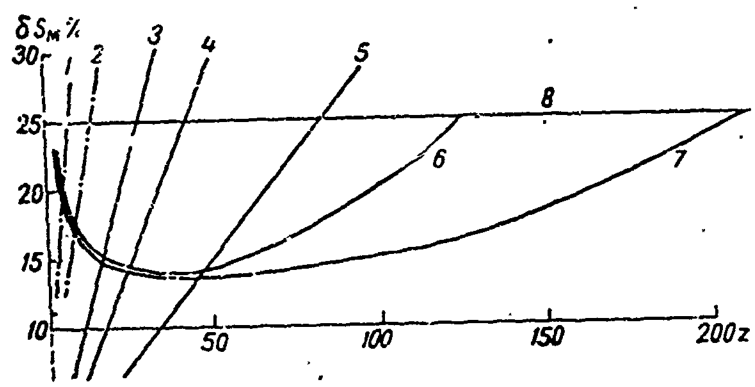

Figure 73. Comparison of Extrapolational Potentialities of Various Methods for Measuring S_M. 1, Extinction and comparison method with use of natural objects; 2, Comparison method with use of black screen (ideal comparison photometer); 3, 4, 5, Photoelectric base method with errors in photometering flow amounting to 3, 2, and 1% respectively; Method of relative luminance; 6, Single-black-object method; 7, Two-black-objects method; 8, Limit of permissible error of measurement under the technical conditions of the Main Administration of the Hydrometeorological Service.

Small screens of black velvet have proven their worth splendidly in one of the methodic treatments set forth in the next section.

General conclusions on the two-black-objects method consist of the following:

1. The two-black-objects method, the development of which was concluded in 1962, has obvious advantages as regards extrapolational potentialities over all other instrumental-visual methods, including the single-black-object

method in use at meteorological stations. In addition, as the results of practical checking show, the two-black-objects method also has advantages relative to the congruence of results of measurements carried out by a group of observers.

2. With permissible variations in the setting up of the black body on the terrain, running from 200 to 250 meters, measurements of meteorological visibility from 1.5 to 40 or 50 km are possible. With $S_M < 2$ km observations should be carried out from an intermediate, identical, small black body set up at 0.1 of the distance from the remote object.

3. The two-black-objects method, and visibility gages based upon the relative luminance method, fully solve the problem of measuring visibility in daylight and partial twilight at meteorological stations with a closed field of view, in steppe and arctic regions, in the complete absence of natural objects, inasmuch as the setting up on the terrain of small-size screens and maintaining them in operational state offer no difficulties.

§ 65. A Simplified Variant of the Relative Luminance Method

The author of the present nomograph has been asked to work out, for expedition conditions, a simplified variant of the instrumental visual method of measuring S_M, on the basis of the relative luminance method, over a span of atmospheric turbidities from 0.5 to 10 km.

To solve the problem the method of relative luminance (the two-black-objects method) and the IDV visibility gage based on that method were used.

Prolonged observations in accordance with the two-black-objects method revealed one peculiarity of that method which in fact lay at the foundation of the simplified variant. This peculiarity consists in the fact that at reduced atmospheric turbidity (with S_M less than about 15-20 km) and predominantly in overcast weather, readings on the nearby black object located 5-10 meters from the observer are little to be distinguished from on another, and the spread in the magnitude of $V'_{close.current}$ which arises has little effect on the value of K_0 in (8.35) or V_0 in (8.38) and, consequently, on the final value of S_M (< 20 km).

There arose the idea of studying in greater detail the change in the magnitude of $V'_{close.current}$ under circumstances of visibility up to 10 km, or a maximum of 20 km, on the basis of taking, at a really small spread of $V'_{close.current}$, instead of that quantity the mean value $V'_{close.mean}$ from prolonged observations, and of cutting short current observations in accordance with the nearby black object when visibility values are low.

Thus when using expressions (8.35) and (8.38) the need for determining $V'_{close.current}$ in accordance with the closer object would fall away, and over a given span of atmospheric turbidity the whole process of measurement would boil down to merely extinguishing the marker of the instrument against the background of the remote object, i.e., to determination of $V'_{dist.current}$ alone.

This was the initial idea for a simplified variant of the two-black-objects method.

In order to make the spread of $V'_{close.current}$ quantities as great as possible, i.e., in the last analysis to secure a value for $V'_{close.current}$ having a low quadratic error, it is important that the close and the remote black objects possess maximum blackness, changing but little under any circumstances of illumination.

Screens of painted plywood are ill suited for the simplified variant, since even when they are inclined toward the line of sight they gleam perceptibly under sunlight, and during the winter whenever there is snow cover. There is no use expecting minimum deviations of $V'_{close.current}$ from the mean value with such screens.

The matter stands considerably better with black bodies of sheet dural in the form of a parallelipiped having an open cavity and with the back wall inclined toward the line of sight. But under expedition conditions even black bodies having small dimensions are hard to transport and are clumsy.

A vertical screen of black velvet proves to be the best black object in all respects.

The blackness of velvet, exceptional in comparison with all other materials, is, as we are aware, not a property of the coloring substance, but a peculiarity of the structure. If one looks at velvet through a 15-25X glass, one can see that it consists of an infinite quantity of narrow and deep black "holes" of various dimensions. Black velvet may be regarded as a black body put together out of a multitude of black honeycombs. A vertical screen of black velvet does not change its blackness in the winter, whereas wooden or metal screens painted black, especially when inclined at an angle of 45°, gleam perceptibly, as was remarked above.

Thus for the simplified variant of the relative luminance method black velvet screens are used as black objects. If one considers that the span of dimensions lies within limits 0.5 km $\leq S_M \leq$ 10 km, which for the two-black-objects method is an extrapolational parameter of $z = 200$, and that the IDV instrument has a 7-power telescopic system, then the dimensions of a screen should be small, since placing it at 50-60 meters from the observer is sufficient.

In order to determine the accuracy of measurement of S_M when the mean value $V'_{close.mean}$ is used one must establish experimentally the quadratic error $\delta V'_{close.mean}$ via prolonged series of measurements, on the basis of which one then finds the error δS_M.

For cases where 1 km < S_M < 20 km, some dozens of series of measurements were carried out to reveal the mean value $V'_{close.mean}$ in accordance with the closer velvet shield. It proved to be 0.73, with a mean quadratic error $\delta V'_{close.mean}$ of about 15%.

We should remark that in accordance with data from observations on the photometric range at Voyeikovo, in overcase weather during the winter the value of S_M fails to exceed 20 km in about 90% of cases.

With 1 km < S_M < 50 km the magnitude of $V'_{close.mean}$ changes but little; but as a consequence of greater spread of individual values for $V'_{close.current}$ the error $V'_{close.current}$ reaches 20%. The heightening of this error and the increase in spread of values for $V'_{close.current}$ are occasioned by the effect of sun lighting.

Thus with 1 km < S_M < 20 km the error $\delta V'_{close.mean} \approx 15\%$, which is greater than the error $\delta V'_{M.mean} = 7\%$ and is only a little higher than the error $\delta V'_{close.current}$ with current extinction of the marker against the background of the closer object, which comes to ± 12%. This is what constitutes the essence of the initial idea for the simplified variant of the two-black-objects relative luminance method: the current value of $V'_{close.current}$ in (8.35) or (8.38) when 1 km < S_M < 20 km can be replaced by the mean value $V'_{close.mean}$ secured in advance, and the measurement process for these conditions can be reduced to a mere two or three readings from the remote (or intermediary) black object.

A substantial methodic gain!

We shall show that use of the mean value $V'_{close.mean}$ in accordance with the velvet shield in place of the current value $V'_{close.current}$ does not worsen the accuracy of the measurement of S_M when 1 km < S_M < 20 km.

In accordance with (8.35a), when the black body is used

$$\delta K_0 = \frac{\sqrt{\delta V'^2_{M.mean} + \delta V'^2_{closer.current}}}{n_1 - 1} = 0.15\%,$$

where $\delta V'_{M.mean}$ = 7%, $\delta V'_{close.current}$ = 15%, n_1 = 100 (for S_M from 0.5 to 50 km). In the simplified variant we have for δK_0: $\delta V'_{M.mean}$ = 7%, $\delta V'_{close.mean}$ = 15%, n_1 = 75 (for S_M from 1 to 20 km), i.e., δK_0 = 0.23%.

The value of δK in the simplified variant obviously remains the same as in (8.35a), i.e., $\delta K \approx 0.40\%$.

Thus the use of $V'_{close.mean}$ in place of current observation in accordance with the closer object changes matters only a little with respect to accuracy and the extrapolational limits of the change of S_M -- only when 1 km < S_M < 20 km, to be sure.

Let us see what will happen if we determine $V'_{close.mean}$ for limits of measurement 1 km < S_M < 50 km. Prolonged observations have shown that in this event, as was remarked above, the error $\delta V'_{close.mean}$ rises to 20%. Then in accordance with (8.35a) we shall have

$$\delta K_0 = \frac{\sqrt{7^2 + 20^2}}{75} = 0{,}28\%,$$

and δK will remain unchanged, i.e, δK = 0.40%. Hence

$$\delta S_M = 0{,}29z\sqrt{\delta K_0^2 + \delta K^2} = 0{,}29z\sqrt{0{,}28^2 + 0{,}40^2} = 0{,}14z\%.$$

For an upper limit of δS_M = 25%, the parameter z = 175. In this case, too, the simplified variant yields ground only a little to the precise method as regards extrapolational potentialities for limits 1 km < S_M < 50 km. But in order to ensure equal-accuracy determinations of S_M within the span referred to, one may recommend the carrying out of measurements in accordance with the simplified variant up to z = 150, but by the precise method with z values from 150 to 500.

Thus the simplified variant of the two-objects method is of equal accuracy, up to z = 150, with the single-black-object method, but it calls for only one measurement procedure instead of two.

What sort of results do practical measurements in accordance with the simplified variant produce?

In Figure 74 we present the results of current measurements of S_M in accordance with the simplified variant for the span 1 km < S_M < 20 km, and also processed prior observations carried out by the precise two-black-objects method at the photometric range of the Main Geophysical Observatory at Voyeikovo (in both cases the same mean value for $V'_{close.mean}$ was used). In the drawing S_M values in accordance with the M-37 transmissivity recorder, or mean quantities of S_M for a group of observers, are laid off on the abscissa axis, and on the ordinate axis, measured values for S_M.

From Figure 74 it is clearly apparent that on the practical plane, too, the replacement of current values $V'_{close.current}$ by the mean magnitude $V'_{close.mean}$ over the span 1 km < S_M < 20 km is entirely justified. This confirms one more time the correctness of the initial premises of the simplified variant of the relative luminance method.

Now let us turn to a description of the methodic side of measuring S_M within the span 0.5 km < S_M < 10 km, which we referred to above.

As a black object we took a screen of black velvet 35 X 35 cm, fastened to special frames which could be set up easily on a pole, a meteorological telescoping mast, a post, etc. The screen can be set up one degree below the horizon line some 50-60 meters from the observer.

Both the two-black-objects method and its simplified variant, possessing high extrapolational potentialities, make it possible to standardize the distance to the remote object depending on the upper limit of S_M which is being subjected to measurement. This standardization of distances and the unity of the method of measurement make it possible to provide on the IDV visibility gage not only the basic scale, but also a supplementary one, on which the S_M value is shown for a given standard distance L to the black body. The need for any sort of gradation tables or for the processing of measurement results falls aside completely when distance L to the black object and limit values of z are selected correctly. But, as was indicated above, in order to maintain accuracy of measurements when z > 150 one should shift from the simplified variant to the precise one, carrying out current observations in accordance with the closer black object, and determining S_M in accordance with the gradation table in accordance with the basic scale.

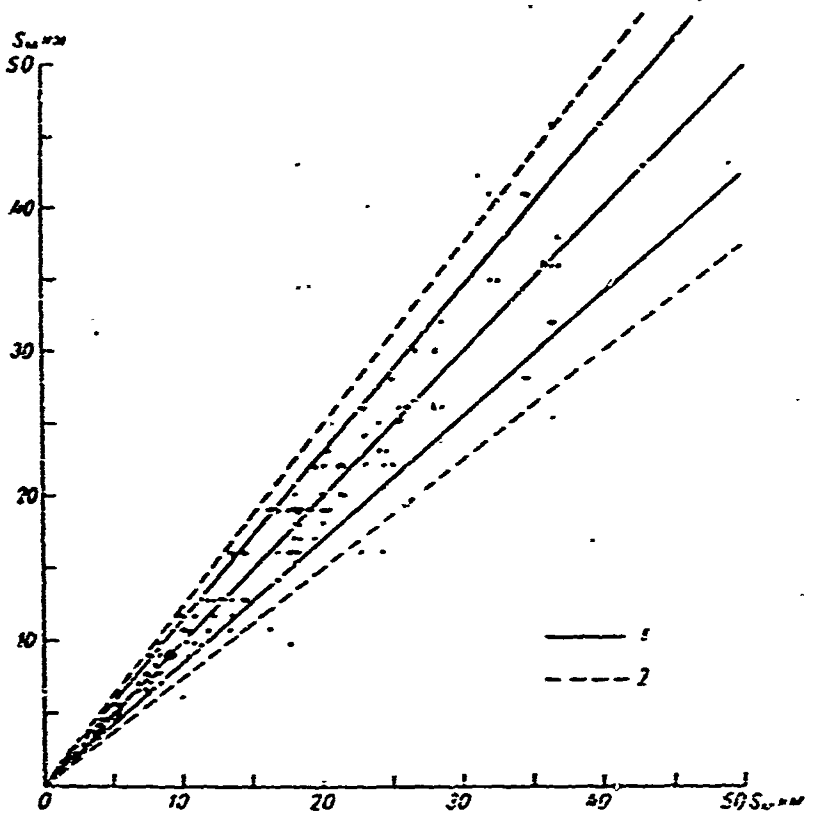

Figure 74. Results of Measurements of S_M in Accordance With The Simplified Variant of The Two-Black-Objects Relative Luminance Method. Observations were not carried out in accordance with the closer object when S_M < 20 km (the mean reading was used); when S_M > 20 km measurements were carried out in accordance with the precise two-black-object method, i.e., via observations in accordance with the closer black object. For legends see Figure 71.

For the frequent case of a measurement of S_M within limits 0.5 km < S_M < 10 km, there is a supplementary scale in the instrument with values of S_M up to 10 km. Obviously one can install in the instrument a scale of S_M values for any span of visibilities, in particular for limits 0.5 km < S_M < 50 km (with L = 250 m).

The simplified variant of the relative luminance method and the IDV visibility gage in a design treatment by G. V. Suvorov were presented at the beginning of 1964 for state performance tests, and they passed them successfully. The IDV instrument has been put into series production.

The most recent series model of the IDV visibility gage is shown in Figure 75. In this model, in contradistinction to the original pattern (see Figure 19), two scales are introduced, of which one, as was remarked above, at once indicates the value of visibility. The angular dimensions of the black marker in the field of vision are increased to 30'. A movable sleeve has been introduced in order to eliminate flanking glare upon the objective from inclined light. Diaphragming within the instrument has been made more powerful in order to obtain maximum attenuation of parasitic luminance. The image of objects in the field of vision is direct, with 7.2X magnification. The weight of the instrument is 450 grams.

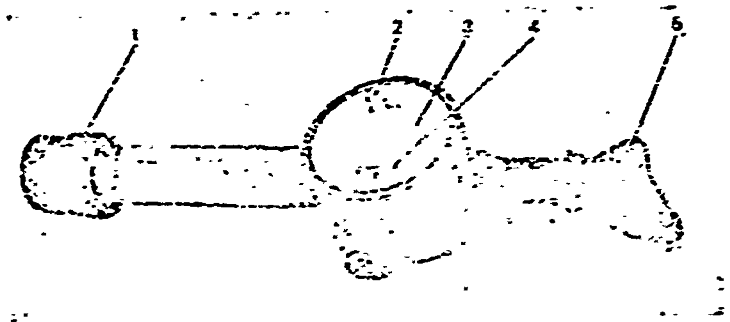

Figure 75. General View of IDV Visibility Gage With Scale of Values of S_M Forming Part of the Device (For a Given Standard Distance to the Remote Black Object). 1, Collimator with movable sleeve; 2, Scale of values of meteorological range of visibility; 3, Measurement platform; 4, Basic scale of instrument; 5, Visual tube and eyepiece with eyeshade.

§ 66. Experimental Determination of Reliable Value of Threshold of Contrast Sensitivity ε in Koschmider Formula.

In the basic Koschmider formula for meteorological range of visibility

$$S_{м} = \frac{1}{\varepsilon} \ln \frac{1}{\varepsilon}$$

the threshold of contrast sensitivity ε appears in general form, without indication of any concrete numerical value.

The great importance of this formula in the study of visibility has served as a stimulus for the setting up of numerous investigations upon the threshold of contrast sensitivity. The distinguishing peculiarities of the many studies carried out in this sense are the heterogeneity and the contradictory character of the results secured.

Numerous disagreements, not overcome to date, have arisen as regards the concept "threshold contrast" and its numerical expression, as a result of which there is even today an absence of any agreed standard definition, accepted by all countries, of meteorological range of visibility[1].

First of all, it occurs to us not without interest to provide a brief survey of the results of investigations on the thresholds of the contrast sensitivity of vision (basically, the fixed thresholds).

Koschmider, taking as his basis laboratory investigations by Koenig and Brodchun, took for the meteorological range of visibility a value ε = 0.02 (or 2%) (ln 1/ε = 3.91 or log 1/ε = 1.7).

Koenig and Brodchun, in harmony with one of the treatments of the differential form of the Weber-Fechner law, regarded ε = 0.02 as hardly

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[1] Disagreements have gone so far that in the United States and some other countries the concept "meteorological range of visibility" has been rejected and the concept "meteorological optical range" is used instead; under this concept atmospheric turbidity is characterized by the length of a stratum of atmosphere such that a parallel beam of rays on passing through it will become attenuated to 5% of its initial intensivity. In Soviet literature this term is translated as "meteorological range of visibility", although the sense of the two terms is obviously different.

constituting an acceptable threshold contrast (a barely perceptible detection of the dividing line of the field of vision of a photometric apparatus). But Koschmider, in harmony with another treatment of that same law, regarded $\varepsilon = 0.02$ as a visually unperceived threshold contrast, and in accordance with this view he understood as range of visibility the distance at which disappearance of the contrast being observed occurs.

At present both in domestic and in foreign studies the value $\varepsilon = 0.02$ is used very frequently, but again in a twofold interpretation: in some cases the unperceived contrast is taken as the indicated value of the threshold, and people speak of the range of disappearance, and in other cases they understand by this term the perceived contrast and what they have in mind is the range of detection.

In their investigations of threshold functions V. V. Sharonov and N. N. Sytinskaya have demonstrated that the values for ε determined under laboratory and field conditions are substantially differentiated from each other even when one and the same method of investigation is used.

Initially V. V. Sharonov proposed that in the formula for S_M $\varepsilon = 0.019$ ($\ln 1/\varepsilon = 3.96$), but later he adopted $\varepsilon = 0.015$, or $\ln 1/\varepsilon = 4.15$, in which connection he related this value to the unperceived contrast and treated the range of visibility as the distance of disappearance.

In accordance with the results of measurements carried out with the help of a polarization visibility gage, L. L. Dashkievitch takes $\varepsilon = 0.018$ and treats it as the unperceived threshold contrast.

Schoenwald [160], as a result of laboratory investigations in artificial fog with observation of a round black object with an angular diameter of 1°, found that $\varepsilon = 0.02$ and that the unperceived contrast corresponds to this threshold. The magnitudes of threshold contrasts found by Siedentopf under laboratory conditions [219], but for objects the angular diameter of which was less than 1°, deviated considerably from the laboratory data of Schoenwald and come to about 0.01 ($\varepsilon = 1\%$).

In accordance with evaluations of the visibility of natural objects at 15 km distance, Hulbert [160] secured mean values for unperceived contrast ε equal to 0.02.

Foitzik [160], after having analyzed the results of extensive observations on natural and artificial terrain objects having angular dimensions of not less than 1°, determined that the mean value is $\varepsilon = 0.02$. For objects of "sharp-boundary" shape and smaller angular diameters (the spires of churches, water-towers, signal towers, etc.) the value of ε increases and may reach 5%.

But it is essential to remark that Foitzik does not indicate to what threshold, the perceived one or the unperceived one, he relates these values. Inasmuch as at the start of his investigations Foitzik refers to Koschmider, one may suppose that he has in mind the unperceived contrast.

Starting from the fact that a whole series of investigators have got $\varepsilon = 0.02$ in a majority of cases, Foitzik proposes that this value be introduced into the equation for S_M as a constant of horizontal range of visibility, and that the quantity

$$S_M = \frac{3.91}{\alpha} \quad \text{or} \quad S_M = \frac{1.7}{\sigma_{10}}$$

applicable to a dark object having angular dimensions of 1° projected against a sky background at the horizon should be called the normal range of visibility. This latter, regarded as a physical unit of atmospheric turbidity, can easily be associated with the range of visibility of real objects.

It is easy to see that the normal range of visibility is the same thing as the illustrative range of visibility. This last term was proposed in 1940 by V. F. Piskun, and it frequently figured in Soviet meteorological literature before the second World War and in the first years after it.

At present the term most widespread in all countries is "meteorological range of visibility," which we are in fact making use of in the present nomograph.

Side by side with data that are in harmony with each other there are studies the results of which diverge sharply.

From the extensive laboratory investigations of the American physicist Blackwell [139] it transpires that threshold detection of contrast lies between limits of 0.008-0.014. We may remark that no investigator has gotten such low threshold contrasts for detection.

But American transmissivity recorders on the Douglas system [158] are graduated not in accordance with Blackwell's data, but for a value $\varepsilon = 0.055$, taken as being the threshold of detection of a black screen against a fog background. The distance corresponding to this detection is taken as the criterion in accordance with which the landing of airplanes at American airfields is permitted or forbidden.

The International Commission on Illumination recommends as a threshold of detection the value ε = 0.04, for which log 1/ε = 3.22.

Middleton [200], upon studying visual thresholds of detection, secured from 1,000 series of observations the distribution of threshold quantities set forth in Figure 76, a. The mean value for the threshold of detection from all of these series is equal to 0.031, and ln 1/ε = 3.50.

Middleton processed the data from investigations of threshold contrasts carried out in the United States by Howell. The results of the processing of 285 series of observations are set forth in Figure 76 b, analogously to 76 a.

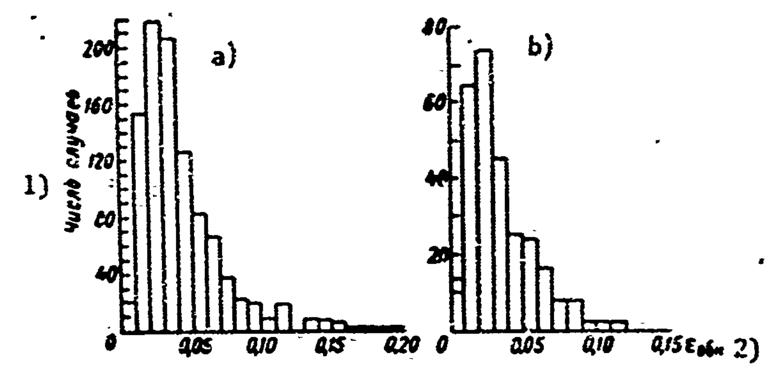

Figure 76. Distribution of Thresholds of Detection ε_{det} According to Middleton (a) and Howell (b)
Key: 1) Number of Cases; 2) ε_{det}.

The frequency of distribution of threshold quantities and the mean value of the threshold of detection amounting to 0.03 coincide with Middleton's data.

N. G. Boldyryov and O. D. Barteneva [15] found, from observations on natural objects carried out via the DM-7 visibility gage, that ε as a threshold of detection is equal to 0.05 (ln 1/ε = 3.0). These authors regard the meteorological range of visibility as being the distance of detection.

M-37 transmissivity recorders of V. I. Goryshin's design, with which almost all equipped airports of the USSR are supplied, are graduated for a value $\varepsilon = 0.035$, and the magnitude of S_M that is recorded is taken as being the range of disappearance.

The observation Instruments and Methods Section of the World Meteorological Organization proposed, at its session in Toronto in 1953, that in the expression for S_M the value $\varepsilon = 0.05$ be used, understanding ε as being the detection threshold.

In France [226], transmissivity recorders are graduated for $\varepsilon = 0.07$ ($\ln 1/\varepsilon = 2.66$), and the value secured for S_M is applied, with the help of empirical correctional multipliers, to the range of visibility of a runway at the threshold of recognition. Thus the French meteorologists are the first to have brought into aviation practice the threshold recognition contrast of an object, with $\varepsilon = 7\%$. But here one should note that the use of large thresholds (7 or 5%) in the formula for S_M under the pretext of ensuring that the requirements of aviation are met is at least unjustified. A linkage between S_M and the landing range of visibility cannot, as was indicated in Chapter IV, be ensured by a mere heightening of the magnitude of threshold contrast in the formula for S_M. In reality, it is necessary to take into account the photometric properties of the runway and of the background surrounding it, and also the luminance characteristics of atmospheric haze.

From the brief survey we have given above it is apparent that expansion of studies on threshold functions has not brought us closer to a uniform approach to the problems of threshold contrast, but has forced us still farther away. The scales of the disagreements and of the divergences in approach lie far beyond the limits of the contradictions in the differential form of the Weber-Fechner law. The roots of the disparities in results secured lie in the heterogeneity of the properties of human vision, which make themselves apparent in the setting up of one sort of visual experiments or another.

The differences of opinion, described above, as regards the selection of a reliable value for the contrast threshold ε in the expression of S_M have led the author of the present nomograph to carry out a special study for the purpose of determining at what value for ε, substituted into the Koschmider formula, the magnitude of S_M coincides to the greatest extent with the actual meteorological range of visibility.

The initial proposition for the investigation may be formulated as follows: the greatest number of coincidences of measured values for the meteorological range of visibility with actual values thereof should indicate the point at which one gets the reliable value for ε.

As a criterion for the actual value of S_M we took a precise visibility furcation, fixed upon the terrain: "visible -- not visible", in accordance with natural and artificial objects projected against a sky background at the horizon. The correctness of the reliable value for ε was interpreted in accordance with the number of times the measured values of S_M fell within the limits of one or another precisely fixed furcation of visibility.

The use of the furcation as a "standard" of visibility is of course associated with a certain amount of imprecision, inasmuch as limits of visibility are indicated, and not the actual value thereof. But we had to reconcile ourselves to this, by reason of the absence of a standard apparatus.

The study was carried out on the photometric range of the Main Geophysical Observatory at Voyeikovo, where natural objects were selected and additional artificial objects were set up in the form of shields projected against a sky background. As a result eight furcations were secured, data regarding which are set forth in Table 32.

TABLE 32. OBJECTS USED FOR DETERMINATION OF THE RELIABLE VALUE FOR ε

No. of Furcation	Limits of Furcation (meters)	Breadth of the Furcation Relative to the mean (% ±)	Character of Objects Forming Furcation
1	100-200	33	Artificial shields.
2	200-300	20	" "
3	300-420	17	" "
4	500-1,000	33	Black shield and coniferous forest with jagged outline.
5	420-1,000	40	Same.
6	1,000-1,400	17	Coniferous forest and individual pine tree.
7	1,700-2,700	23	Grassy hillock and coniferous forest.
8	2,700-4,000[1]	19.4	Coniferous forest.

[1] As the upper limit of the furcation we took the indications of the transmissivity recorder and an evaluation of the degree of haze upon an object located at 2,700 meters. There was no object on the range at a distance of 4,000 meters.

As may be seen from the data in Table 32, the relative breadth of five furcations out of the eight lie within the measurement accuracy limits that are attainable by visibility gages (furcations Nos. 2, 3, 6, 7 and 8).

The eight furcations indicated were broken down into three more or less homogeneous groups, containing furcations having approximately uniform relative breadths: Group 1, furcations Nos. 3, 6 and 8 having relative breadth of ± 17%; Group 2, furcations Nos. 2 and 7 having relative breadths of ± 22%; Group 3, furcations Nos. 1, 4 and 5 having relative breadth of ± 33%, ± 40%.

During the course of a year 261 series of observations were made on the three groups of furcations. Measurements were carried out only on days when proper conditions existed for precise visual fixation of the furcation by the "visible -- not visible" method.

As the final criterion for accuracy of determination of S_M at one value for ε or another we took the number of incidences both within the precise limits of the visually fixed furcation and within the limits of a furcation extended by ± 20% from its upper and lower boundaries.

The magnitude of S_M was measured through the use of one of the early models of the IDV instrument in accordance with the degree of visibility of natural and artificial objects, their photometric and geometrical properties being taken fully into account as is set forth in § 60. The S_M value was calculated according to the formula

$$S_M = \frac{L \log \frac{1}{\varepsilon}}{\log V_{0\,mean} - \log V_{dist.current}},$$

where L is the distance to the object of observations, always less than the lower limit of the fixed furcation; $V_{0\,mean}$ is the true degree of visibility of the object (not distorted by haze), the value of which was taken from Table 30 and was then made more precise in its application to the objects used; $V_{dist.current}$ is the degree of visibility of the same object, distorted by haze and determined via current observations in accordance with the graduation rating.

Each current measurement $V_{dist.current}$ made it possible to determine S_M with substitution of one value of ε or another. For our purposes we selected the three following values for the threshold ε: 0.02, 0.03 and 0.05, for which the log 1/ε magnitudes are respectively equal to 1.7, 1.5 and 1.3. In accordance with these three values for ε, S_M magnitudes were calculated for each of the 261 series of observations.

The results of these observations are set forth in Table 33. In this table, as well as in Tables 34 and 35, we show in parentheses the percentage of the overall number of measurements coming to 261 and taken as being equal to 100%.

Column 6 is introduced so as to reach an objective final judgment regarding the suitability of one value of ε or another, and so as to take into account errors of measurement of S_M coming to 15-20%.

The observations which went beyond the upper and the lower limits of the precise, unextended furcation, together with their plus or minus signs of deviation, are given in columns 7 and 8, in which connection the overall number of observations going beyond the limits of the precise furcation has been taken as 100%.

Analysis of the data in Table 33 makes it possible to draw the following conclusions.

For all eight furcations of visibility the greatest percent of incidences within the precise furcation falls as follows: for ε = 3%, to five furcations; for ε = 2%, to two furcations; for ε = 1%, to one furcation.

Over 261 series of observations, there fall within precise furcations of visibility:

ε, %	2	3	5
Number of cases	154	181	154
% of 261	59	69	59

Into furcations extended by ± 20% there fall:

ε, %	2	3	5
Number of cases	222	237	216
% of 261	85	91	83

TABLE 33. RESULTS OF DETERMINATION OF MOST RELIABLE VALUE c IN THE FORMULA FOR S_M

a) Визуальные границы видимости ("видно—не видно"), м	b) Число измерений S_M	c, м	c) Число измерений S_M, попавших в точную вилку	d) Число измерений S_M, попавших в вилку, расширенную на ±20 % от границ точной вилки	e) Число измерений S_M с отклонением >20% от границ точной вилки (брак)	f) Число измерений S_M, выходящих за верхний предел точной вилки (знак плюс)	g) Число измерений S_M, выходящих за нижний предел точной вилки (знак минус)
1	2	3	4	5	6	7	8
h) 1-я группа вилок с относительной шириной ±17% (91 случай наблюдений)							
300—420	25	2 3 5	18 (72) 19 (76) 13 (52)	23 (92) 24 (96) 23 (92)	2 (8) 1 (4) 2 (8)	6 (86) 2 (33) —	1 (14) 4 (67) 12 (100)
1000—1400	28	2 3 5	13 (46) 8 (29) 1 (4)	24 (86) 20 (71) 7 (25)	4 (14) 8 (29) 21 (70)	— — —	15 (100) 20 (100) 27 (100)
2700—4000	38	2 3 5	14 (37) 21 (63) 23 (60)	25 (70) 35 (92) 35 (92)	15 (30) 3 (8) 3 (8)	24 (100) 12 (86) 7 (46)	— 2 (14) 8 (51)
i) Среднее	91	2 3 5	45 (50) 51 (56) 37 (41)	72 (80) 79 (87) 65 (71)	10 (20) 12 (13) 26 (29)	30 (65) 17 (32) 7 (13)	16 (35) 26 (68) 47 (87)

Key: a) Visual limits of visibility ("visible -- not visible") in meters; b) Number of measurements of S_M; c) Number of measurements of S_M falling within the precise furcation; d) Number of measurements of S_M falling within a furcation extended by ± 20% beyond the boundary of the precise furcation; e) Number of measurements of S_M having a deviation greater than 20% from the boundaries of the precise furcation (failure); f) Number of measurements of S_M passing beyond the upper limit of the precise furcation (plus sign); g) Number of measurements of S_M dropping below the lower limit of the precise furcation (minus sign); h) First group of furcations having relative breadth of ± 17% (91 cases of observations); i) Mean.

TABLE 33 (Continued)

J) 2-я группа вилок с относительной шириной ±22% (97 случаев наблюдений)							
200—300	35	2 3 5	21 (60) 22 (63) 15 (43)	33 (94) 32 (91) 27 (77)	2 (6) 3 (9) 8 (23)	8 (57) 3 (23) 1 (5)	6 (43) 10 (77) 10 (95)
1700—2700	62	2 3 5	25 (40) 42 (68) 45 (73)	44 (71) 53 (85) 54 (87)	18 (29) 9 (15) 8 (13)	35 17 (95) 12 (85) 12 (71)	2 (5) 3 (15) 5 (29)
1) Среднее	97	2 3 5	46 (47) 64 (65) 60 (61)	77 (80) 85 (88) 81 (84)	20 (20) 12 (12) 16 (16)	43 (84) 20 (60) 13 (35)	8 (16) 13 (40) 24 (65)
k) 3-я группа вилок с относительной шириной ±33%, ±40% (73 случая наблюдений)							
100—200	7	2 3 5	5 (71) 7 (100) 6 (86)	7 (100) — 7 (100)	— — —	2 (100) — —	— — 1 (100)
500—1000	24	2 3 5	21 (88) 19 (80) 18 (75)	24 (100) 24 (100) 23 (96)	— — 1 (4)	3 (100) 4 (80) —	— 1 (20) 6 (100)
420—1000	42	2 3 5	37 (88) 40 (95) 33 (78)	42 (100) 42 (100) 40 (95)	— — 2 (5)	3 (60) — —	2 (40) 2 (100) 9 (100)
1) Среднее	73	2 3 5	63 (86) 66 (90) 57 (78)	73 (100) 73 (100) 70 (96)	— — 3 (4)	8 (80) 4 (57) —	2 (20) 3 (43) 16 (100)

Key: 1) Mean; J) Second group of furcations having relative breadth of ± 22% (97 cases of observations); k) Third group of furcations having relative breadth of ± 33%, ± 40% (73 cases of observations).

Note: The sum of plus-sign deviations and minus-sign deviations comes to 100%.

Thus when $\varepsilon = 3\%$ one notes the greatest number of incidences both within the precise furcation and within the extended one.

A second important circumstance which thrusts itself upon one is the number and character of the deviations of the calculated values for S_M from the upper and lower limits of the precise furcations. With $\varepsilon = 5\%$, almost all deviations have a minus sign for six furcations out of the eight.

Inasmuch as the furcation is determined in accordance with the principle "visible -- not visible," the lower limit of the furcation is always noted by the eye; consequently, the prevalence of minus deviations at $\varepsilon = 5\%$ means that this threshold is greater than the minimally-sensed threshold contrast ε_{det}.

The number and signs of deviations of S_M for the three values of ε are set forth in Table 34.

TABLE 34. CHARACTER OF DEVIATIONS OF S_M BEYOND LIMITS OF PRECISE FURCATION, FOR VARIOUS VALUES OF ε

ε, %	Overall number of Deviations Beyond Limits of Precise Furcation	Number of Deviations	
		With plus Sign	With minus Sign
2	107 (41)	81 (75)	26 (25)
3	80 (31)	38 (48)	42 (52)
5	108 (41)	21 (14)	87 (81)

From the data in Table 34 it is apparent that only for $\varepsilon = 3\%$ are both deviation signs equally frequent, whereas for $\varepsilon = 2\%$ and particularly for $\varepsilon = 5\%$ the repetitional character of signs is sharply distinguished. Thus for $\varepsilon = 5\%$, minus deviations predominate. Hence it follows that this value of ε is too high for evaluation of the lower limit of the furcation as the threshold of detection with fixed observation, since observers have perceived a contrast of less than 5% as being the lower limit of the furcation. According to our data a 5% threshold contrast corresponds rather to an unfixed detection threshold than to a fixed one. The preponderance of plus-deviations (75% of all cases) with $\varepsilon = 2\%$ means that this threshold is too small and does not characterize the non-perceived threshold contrast, which ought to be set larger.

The results of the study in question as they affect $\varepsilon = 3\%$ must be confessed to have proved somewhat surprising.

An assumption has arisen to the effect that natural objects, in which capacity we used an individual pine tree (distance 1,400 m), a high hillock (distance 1,700 m), a forest with individual trees that stood out sharply (distance 2,700 m) introduced a certain element of inaccuracy both into the values for the limits of a furcation and into the values for S_M as measured in accordance with one or another of the objects listed. This element of inaccuracy was occasioned by the character of the outlines of natural objects: a jagged, saw-toothed outline lowers the visibility range of the object, and the threshold of perception of such an outline rises. On this account, if one measures the threshold of contrast sensitivity in accordance with the degree of visibility of such objects, its magnitude would in all cases have to come out too high. This means one might expect that studies on objects having an uninterrupted outline, for example on artificial objects -- black shields -- would make it possible to draw more sharply defined conclusions as to the effect of ε upon the reliability of calculated values of S_M.

From the foregoing observations the author of this monograph isolated only those which had been made from shields, and carried out supplementary observations from the shields alone (these supplementary observations are also included in Table 33). In this way we secured five furcations constituted by shields and by one coniferous forest having a relatively smooth outline. The results of these measurements are set forth in Table 35.

The data in this table, covering 133 cases of observations, have in fact made it possible to draw still more sharply defined conclusions regarding the effect of the magnitude of ε upon the value of S_M. For all five furcations, the greatest number of incidences in the precise furcation again falls to $\varepsilon = 3\%$ (80% of all cases of observations). 77% of cases fall to $\varepsilon = 2\%$, and 64% of cases to $\varepsilon = 5\%$. Incidences within the limits of furcations extended by ± 20% come to: 97% for $\varepsilon = 3\%$; and 90% each for $\varepsilon = 2\%$ and $\varepsilon = 5\%$.

The distribution of signs for deviations is even more sharply defined in this case, namely when $\varepsilon = 5\%$ all deviations are minus ones relative to the lower visible boundary of the precise furcation; at $\varepsilon = 2\%$ plus deviations from the upper limit of the furcation again predominate (71%); and only a 3% threshold gives a more balanced distribution of signs.

Inadmissibly great deviations of calculated values for S_M from the boundaries of the extended furcation (failure) in the cases of all eight furcations come to the following (a, number of failed observations; b, percent of total number of observations, i.e., of 261):

ε, %	2	3	5
a	39	24	45
b	15	9	17

TABLE 35. RESULTS OF DETERMINATION OF MOST RELIABLE VALUE OF ε IN THE FORMULA FOR S_{H}, ONLY BLACK SCREENS BEING USED

a)	b)	c)	ε, %	d)	e)	f)	g)	h)
100–200	7	33	2	5 (71)	7 (100)	—	2 (100)	—
			3	7 (100)	—	—	—	—
			5	6 (86)	7 (100)	—	—	1 (100)
200–300	35	20	2	21 (60)	32 (91)	2 (6)	8 (57)	6 (43)
			3	32 (63)	32 (91)	3 (9)	3 (23)	10 (77)
			5	15 (43)	27 (77)	6 (17)	1 (5)	19 (95)
300–400	25	17	2	18 (72)	23 (92)	2 (8)	6 (85)	1 (14)
			3	19 (76)	24 (96)	1 (4)	2 (33)	4 (67)
			5	13 (52)	23 (92)	2 (8)	—	12 (100)
400–1000[1]	42	40	2	37 (88)	42 (100)	—	3 (60)	2 (40)
			3	23 (55)	42 (100)	—	—	2 (100)
			5	33 (79)	40 (95)	2 (5)	—	9 (100)
500–1000	24	33	2	21 (87)	24 (100)	—	3 (100)	—
			3	19 (80)	24 (100)	—	4 (80)	1 (20)
			5	18 (75)	23 (96)	1 (4)	—	6 (100)
Среднее	133	—	2	102 (77)	129 (97)	4 (3)	22 (71)	9 (29)
			3	107 (80)	129 (97)	4 (3)	9 (35)	17 (65)
			5	85 (64)	120 (90)	13 (10)	1 (2)	47 (98)

[1]Coniferous forest having even outline.

Key: a) Visual limits of visibility ("visible -- not visible"), m; b) No. of measurements of S_{H}; c) Breadth of furcation (±, %); d) No. of measurements of S_{H} falling within precise furcation; e) No. of measurements of S_{H} falling within furcation extended by ± 20% beyond boundary of precise furcation; f) No. of measurements of S_{H} with deviations more than 20% beyond boundary sign; h) No. of deviations having minus sign.

From this it is apparent that the quantity of inadmissibly great deviations when $\varepsilon = 3\%$ is little more than half as great when $\varepsilon = 5\%$, and is 60% as great when $\varepsilon = 2\%$.

Thus analysis of the experimental material shows that as regards the number of incidences within the limits of the precise furcation and within the limits of the furcation extended by ±20%; as regards evenness of distributions of the signs for deviations from the boundaries of the precise furcation; and finally, as regards the smallest number of failures, the value of S_M calculated with ε equalling 0.03 has a clear advantage over S_M calculated with ε equalling 0.02, and especially with ε equalling 0.05. In harmony with the data of Tables 33 and 35 the value $\varepsilon = 0.02$ is too small, and S_M is secured too high. In accordance with the same data the quantity $\varepsilon = 0.05$ is too high, and S_M is secured (in 40% of cases) lower than the actual visible lower boundary of the furcation.

In harmony with the experiment carried out we take it that the most reliable value for ε in the Koschmider formula is 0,03, and that $\ln 1/\varepsilon = 3.5$ (or $\log 1/\varepsilon = 1.5$).

As detailed analysis, even more sharply defined conclusions are secured with $\varepsilon = 2.65\%$. Upon being rounded off, this value gives the quantity of $\varepsilon = 3\%$ adopted in the present study.

§ 67. Regarding Determination of the Transmissivity of the Atmosphere in Darkness by Instrumental-Visual Methods

The methods for measurement of atmospheric transmissivity which has been examined in the foregoing sections of this Chapter are applicable only during the light hours of the 24, inasmuch as the basis for these methods consists of one or another way of measuring contrasts (or degrees of visibility) of natural or artificial objects. For measurement of the transmissivity of the atmosphere during darkness these methods are inapplicable, something which is occasioned by a sharp falling-off in the contrast sensitivity of the human eye, even though the value for the actual contrast between the object and the background does not change upon the shift from day illumination to night illumination. This embodies the reason why there has been no success to date in developing a universal instrumental-visual method for determination of S_M which would be suitable both in daylight and in darkness. This problem can only be solved on the basis of photoelectric measurements, although even in this case serious complications arise, these being associated with the need for eliminating parasitic scattered daylight luminance, a matter we examined in detail in Chapter VI. No photoelectric apparatus acceptable for the basic hydrometeorological station network as regards its use qualities has yet been devised.

Measurement of the transmissivity of the atmosphere in darkness is possible in principle with the help of the following visual or instrumental-visual methods:

1) in accordance with the degree of visibility of lights on the terrain (non-instrumental method);

2) the nephelometric method;

3) the "stellar" photometry method;

4) the back-scatter method.

To anticipate, we shall point out at once that the first and third methods are merely of historical interest and that at present only the instrumental-visual variant of the back-scatter method continues to preserve its significance. The nephelometric method continues to be controversial. There are no up-to-date treatments of this method.

Let us pause to consider the side of all these methods that relates to principle.

Determination of m.r.v. in Accordance with the Degree of Visibility of Lights on the Terrain

The first methods for determination of meteorological visibility in darkness were constructed on the basis of non-instrumental methods (analogously to daytime observations from terrain objects) that made use of objects emitting luminance of their own -- lights of known lighting power positioned at known distances on the terrain.

V. A. Beryozkin worked out a nomogram (Figure 77) in accordance with which the value of S_M in points on the international scale of visibility could be determined on the principle of a "visible -- not visible" visibility furcation for lights. To this end there had to be on the terrain as many lights as there were approximately visibility scale-points, and these lights had to be at known distances and had to have known power. The nomogram was constructed in accordance with the Allard formula (1.31) reduced to the form of (1.32) on the assumption that threshold illumination on the pupil of the eye, E_{th}, is equal to $2.7 \cdot 10^{-7}$ lux.

Although such a way of determining S_M in darkness looks simple from the outside, in putting it into operation it proves to be complicated and clumsy.

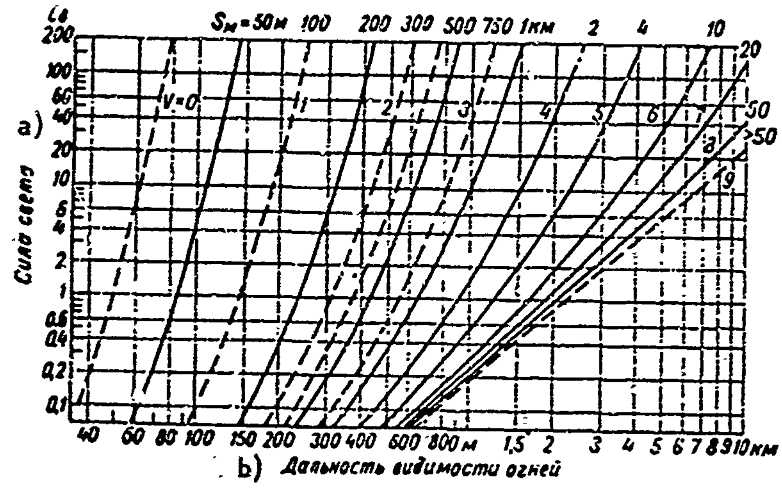

Figure 77. Nomogram of V. A. Beryozkin for Determination of S_M in Terms of International Scale Points, From Lights of Known Power at Given Distances (or For Solution of the Reverse Problem -- For Determination of Range of Visibility of the Lights at a Given S_M Value).

Key: a) Power of light; b) Visibility Range of light.

In the first place, the initial proposition of the nomogram, associated with the value $E_{th} = 2.7 \cdot 10^{-7}$ lux calls for the level of darkness adaptation of the observer's eye being at least approximately in harmony with the indicated value for E_{th}.

The practical impossibility of bringing about universally a standardization of conditions under which the constancy of the value of E_{th} would be ensured, particularly if mass measurements of visibility on the basis of a network of stations are involved, constitutes a weighty fault of the method referred to.

The real heterogeneity of the levels of darkness adaptation of the eyes of observers leads to such variations in the values for E_{th} that the spread in values for S_M may come to hundreds of percentage points; by the method under examination, visibility would be determined with an error not less than one point, plus or minus, on the international scale.

In the second place, in carrying out the method great difficulties arise in determining the light power of the lights observed, these being subject to considerable changes by reason of sputtering of the incandescent coil. Systematic checking of the lights observed with the help of special photometers would be an excessively complicated and clumsy measure for a mass network of stations.

In the third place, some light, or even several lights, may not be present on the terrain. Installing the lights of which one is short, running feed lines out to them even at short distances, are again complicated operations that do not recommend themselves.

On account of the basic shortcomings referred to, the method for measurement of S_M by night which is being described has not become widely distributed and is practically nowhere in use.

But the nomogram of V. A. Beryozkin has not lost its significance: It is very convenient to solve the reverse problem through its use: that of determining, in accordance with a given meteorological range of visibility in points or fractions of a point, the value for the visibility range of a light of known power when $E_{th} = 2.7 \cdot 10^{-7}$ lux.

The Nephelometric Method for Determining S_M

At one time a group of Soviet specialists devoted a great deal of effort to the creation of an original nephelometric method and developed a series of design variants of visual nephelometers. The side of this method which relates to principle, and the conclusions which relate to the merits and shortcomings of individual designs for visual nephelometers, are examined in the next Chapter.

Determination of S_M by "Stellar" Photometry Methods

Measurement of the transmissivity of the atmosphere by "stellar" photometry has a long history, well set forth in the nomographs of V. V. Sharonov [118] and Middleton [200]. Here we shall touch only upon those developments which have been brought to completion since the publication of the monographs referred to.

Let us recall that at the basis of stellar photometry there lies the comparison of the light power of a remote light, observed in the form of a gleaming point, with an artificial gleaming point, or "star" (hence the name of the method), of variable luminance, created by special instruments -- "stellar" comparison photometers. After having measured with such a device the light, altered by haze, of the point-light under observation, and knowing its true lighting power, we determine according to the Allard formula the index of attenuation α, and then, making use of the Koschmider formula, the value for S_M.

There is another variant of the stellar photometry method, in which S_M is determined from two identical (point) lights, one of which is located so close to the observation point that the effect of atmospheric turbidity can be disregarded in all cases. It is more convenient to employ here as an instrument not a special stellar photometer, but instead a visibility gage functioning as a stellar comparison photometer. The comparison star in this case is the light close at hand.

The simplest variant of the stellar photometry method was proposed, shortly after the end of the second World War, by V. V. Sharonov, who described a way for photometering lights of known power with the help of the graduated scale of a diaphanoscope [123]. But the method he proposed found no practical application.

N. G. Boldyryov created an original design of stellar photometer [5], by means of which the flash of a given light on the terrain was compared with the flash of two artificial comparison stars the flashes of which were different from each other.

A series of designs for stellar photometers were developed by N. E. Rityn, Middleton, Gold, et al.

But success was not achieved in creation of an apparatus and method for measuring S_M by the stellar photometry principle which would be suitable for use in the base hydrometeorological station network. The main difficulty of the method was the positioning on the terrain of lights (a minimum of two) having a given lighting power. Installing posts to carry the feed lines, stabilizing the light flow emitted by the lights, and the like -- all these things proved to be beyond the limits of meteorological station capacities.

In addition to this, it proved to be the case that evening-off the flash of two point-lights was associated with a considerable error which did not fall below 12-15%. This brings it about that the extrapolational potentialities of the stellar photometry method are very low: z does not exceed 10. In other words, when a light is placed at a distance of 1 km, the upper limit of measurement of S_M comes to no more than 10 km.

The author of the present monograph has tried to refine the principle of stellar photometry. As terrain sources of light, in place of incandescent lamps, reflectors of special construction were installed.

The reflector consisted of a concave mirror of 12 cm diameter, at the focus of which a small flat mirror was positioned. When such a reflector is lit up by an automobile headlight it appears as a brightly gleaming point. Two reflectors were installed on the terrain: a small one at a distance of 100 meters and a large one at a distance of 500 meters. As an instrument one of the early modifications of the IDV visibility gage was used -- the IV-GGO device which forms part of the M-6 installation complex [71] which was at one time supplied to the station network. The instrument was used as a stellar comparison photometer. In order to heighten the accuracy of photometering, the stationary gleaming points to be compared were converted into Lissajous figures by lightly tapping the instrument. This lowered the error of measurement from 12-15% to 5%. The details of this treatment are published in [24].

But experience in making use of the M-6 installation showed that even a complete replacement of light sources by reflectors and a reduction of error of photometering the points to be compared by half improved matters only to an insignificant extent. The extrapolational parameters of z increased from 10 only to 15. The reflectors were a lot of trouble to set up and cleaning them of dust and snow, etc. was difficult.

Thus stellar photometry, too, with its small extrapolational potentialities and the complications of installing lights on the terrain and maintaining them in operational state, failed to solve the problems of measuring S_M in darkness at a station network.

The state of affairs changed only with the development of new methods for measuring atmospheric transmissivity, in particular, the light backscatter method.

Measurement of S_M by Instrumental-Visual Variants of the Light Back-Scatter Method

L. L. Dashkievitch [58], has developed a visual apparatus, the M-71, based upon the principle of light back-scatter (see Chapter VII) and intended for measurement of S_M in darkness at meteorological stations.

The system for the principle of the apparatus is set forth in Figure 78. A searchlight of about 100,000 candlepower sends out a light beam into the atmosphere. An M-53A polarization visibility gage is pointed "down the beam" at a scatter angle of about 180°; it views the light sheaf from the searchlight through the lower semicircular through-hole apertures of the light box. The upper non-through-hole semicircular aperture is illuminated by the searchlight itself and constitutes a field of vision a diagrammatic view of which is also presented in Figure 78. By turning the polaroid of the M-53A device evening-off of the luminances of the two half-fields of comparison is brought about, and S_M is determined from the reading given.

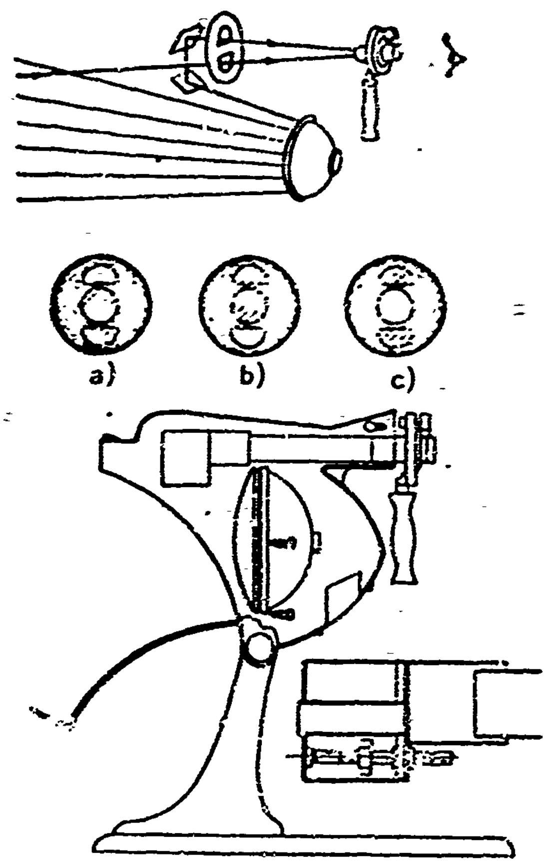

Figure 78. System, in Principle, of the Visual M-71 Apparatus For Measurement of S_M in Darkness at Meteorological Stations.

a) and c) are positions of the comparison field at which readings are not taken; b) is the moment of reading, when the fields to be compared are identical in luminance.

A general view of the installation is shown in Figure 79. The theory of the principle for determining transmissivity of the atmosphere by the light back-scatter method is examined in Chapter VII, and there is no need to repeat it here.

Figure 79. General View of M-71 Installation

Details bearing upon the design of the apparatus, the way of graduating it, the results of tests, methods recommended while carrying out measurements, are set forth in the articles [51, 58].

In 1962 the apparatus described underwent state tests, and at present it is being introduced under the index number M-71 in the network of meteorological stations for determination of S_M in darkness. As experience in the use of this apparatus has shown, measurement of S_M with the help thereof can be started when the sun is about 8° below the horizon.

The span of measurements of S_M is very broad: from 0.5 to 50 km. The error of measurement of S_M lies within the interval of 20-30%.

The author of the present monograph has also worked out, on the basis of the light back-scatter method, a portable visual instrument for determination of S_M in darkness over a span from 0.5 to 10 km, in which observations are carried out very conveniently.

The system of the device is set forth in Figure 80. Near the focus of a concave mirror 12 cm in diameter a light source, 1_c in the form of a small projector is installed. It consists of a 6-volt incandescent lamp located within the focus of a small lens. A slightly de-focussed beam is directed into the atmosphere. Light scattered backward falls upon the collecting concave mirror b and is focussed upon the inner field of a flat annular mirror 3, set up before the focus of the concave mirror (closer to the mirror). The comparison flow passes through a milky glass 4 which is affixed to the transparent part of the annular mirror, and it is controlled by a "cat's-eye" diaphragm, 2, to the point of evening-off with the field being measured. The eye fixes the fields to be photometered through an eyepiece 5, via an aperture in the concave mirror. To feed the lamp one needs only a small storage battery.

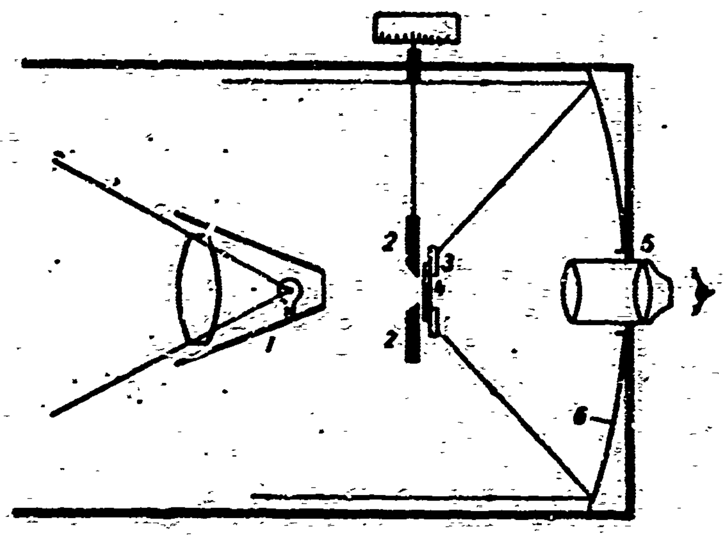

Figure 80. Principle of Design of Portable Visual Instrument Based on the Light Back-Scatter Method, for Measurement of S_M in Darkness.

As observations with a model have shown, measurements can be carried out within the indicated range of visibilities when the sun is 8-10° below the horizon (with cloudless sky).

Measurement of the transmissivity of the atmosphere by the back-scatter method has also some shortcomings. For example, when there is precipitation, especially heavy snow, raindrops or snowflakes falling close to the apparatus cause a strong back-reflection of light and signals are received too high, and the value of S_M is secured too low. On this account when there is precipitation one must introduce into the indications of the device corrections which have been determined experimentally.

But the method as a whole, and its visual modification, have also substantial merits; the absence of a measurement base, the possibility of measuring S_M on shipboard, from a balloon, etc.

CHAPTER IX

THE NEPHELOMETRIC METHOD OF MEASURING THE HORIZONTAL TRANSMISSIVITY OF THE ATMOSPHERE

§ 68. Physical Basis of the Method

At the basis of the nephelometric method lies the phenomenon, familiar in physical optics, to the effect that a beam of light, passing through a turbid medium, undergoes diffusion upon the particles suspended in it, and in consequence of this takes on a perceptible luminance. This luminance changes markedly depending on the degree of turbidity of the medium; measurements of the luminance by one means or another make it possible to judge the degree of transmissivity of that medium.

The application of the nephelometric method to the measurement of transmissivity of the atmosphere is very tempting. This method does not require base sections, is satisfactory for daylight and nighttime, can be widely applied on open terrain, amid mountains, at sea, etc.

The nephelometric principle of measuring transmissivity of the atmosphere was worked out for the first time by A. A. Gershun, M. M. Gurievitch, and H. E. Rityn, who created a series of visual nephelometers [121, 122] that are described below.

A characteristic peculiarity of the nephelometric method in the form in which the investigators named above developed it is the relative scantiness of the illuminated volume of turbid air, a limitation brought about by the practically limited dimensions of the light beam used.

We shall point out at once that this involves a controversial problem, not solved to date, regarding the applicability in principle of nephelometric determinations of atmospheric transmissivity, inasmuch as there exist an opinion to the effect that the light-diffusing properties of a small local volume may differ considerably from the light-diffusing properties of the real atmosphere as a whole.

Let us set out the physical basis for nephelometric measurements of atmospheric transmissivity, basing ourselves upon the study [34].

Inasmuch as the local volume of air being tested in the nephelometer constitutes an optically turbid medium, a light beam passing through it is attenuated as a consequence of partial absorption and diffusion upon colloidal-disperse suspensions of water and dust, and also upon molecules.

of air. The magnitude of this attenuation, expressed by an index of attenuation α, is made up of a diffused and an absorbed part, expressed respectively by an index of diffusion ρ and an index of true absorption ν, i.e.,

$$\alpha = \rho + \nu. \tag{9.1}$$

All the quantities in formula (9.1) have a dimensionality inversely proportionate to length.

According to the Burger law (see (6.2))

$$\frac{F}{F_0} = e^{-\alpha L},$$

where the relationship of the light flow F that has traversed a course within the turbid medium, to the flow F_0 entering that medium is the transmissivity τ of a stratum L of the medium in question.

In other words, we may write

$$\frac{F}{F_0} = \tau^L,$$

whence

$$\tau^L = e^{-\alpha L} \tag{9.1a}$$

or in accordance with (9.1)

$$\tau^L = e^{-(\rho+\nu)L}. \tag{9.2}$$

From physical optics we are aware that absorption of light energy by gas molecules, and also by colloidal-disperse suspensions of water, are negligibly small as compared with its diffusion. In this case the index of true absorption is ordinarily taken as being $\nu = 0$. Then from (9.1) it follows that

(9.3)

$$\alpha = \rho.$$

and instead of (9.2) we secure

$$\tau^L = e^{-\rho L}.$$

For a stratum of unit length

$$\tau = e^{-\rho},$$

whence

$$\rho = -\ln \tau. \qquad (9.4)$$

But from application of (9.3) to the Koschmider formula (1.28) it ensues that

$$S_M = \frac{3.5}{\rho}.$$

Consequently,

$$\rho = \frac{3.5}{S_M}. \qquad (9.5)$$

The expressions (9.4) and (9.5) disclose the physical sense of the nephelometric method for determination of atmospheric transmissivity; the quantity ρ of diffused light observed in the nephelometer is equal to the natural logarithm of the transmissivity τ of the atmosphere taken with an inverse sign, or is inversely proportionate to the meteorological range of visibility S_M.

One must emphasize once more that the relation (9.5) which links the index of diffusion ρ with the meteorological range of visibility S_M has been secured on the assumption that the diffusing medium does not absorb light energy, i.e., that the index of true absorption $\nu = 0$. With application to a real atmosphere this proposition is correct only in the event that in the air there are no aerosol particles possessing perceptible true absorption: dust of mineral origin, smoke particles, and the like. If there are many such particles in the atmosphere, then attenuation of the light beam by reason of true absorption may be considerable and can even prevail over diffusion (for example, in dust storms). Then from the small quantity of diffused light one may make an incorrect conclusion to the effect that the meteorological range of visibility is high.

6

Inasmuch as such particles are almost always present in a real atmosphere, nephelometric measurements based on (9.4) and (9.5) in a certain measure contain an error which is greater, the more such particles there are in the atmosphere.

These constitutes still another shortcoming, involving principle and still not studied to conclusion, of nephelometric measurements of atmospheric transmissivity. Despite this fact, with nephelometric measurements it is always assumed that $\nu = 0$ and $\alpha = \rho$.

The magnitude of the diffused light beam as defined by the index of diffusion ρ, depends markedly upon the direction of sighting at the light beam which has passed through the volume of air being tested. In other words, with identical properties of the turbid medium being measured in the nephelometer, the quantity of diffused light changes depending on the angle of diffusion θ, i.e., on the angle between the direction of sighting and the direction of propagation of the light beam. Thus one should speak of an index of directed diffusion $\rho^{(\theta)}$ rather than of ρ.

The entirety of the particular values of $\rho^{(\theta)}i$ at various spatial angles of diffusion, expressed in vector form, can be presented in the form of a spatial index of diffusion.

For each atmospheric turbidity an indicatrix of diffusion of its own is characteristic, inasmuch as each particular value $\rho^{(\theta)}i$ depends on the quantity and dimensions of the light-diffusing particles in the unit volume.

Literature regarding studies of atmospheric indicatrices of diffusion is decidedly extensive [96], but a lack of space prevents us from dwelling on this problem in greater detail.

The initial relationships (9.[illegible]) and (9.4) do not contain any plain indication of the dependency of the index of diffusion ρ upon the direction of sighting relative to the rays passing within the nephelometer. In order to get a stricter idea of the links between $\rho^{(\theta)}i$, α, and S_M and the circumstances of the gradation of nephelometers, we shall deduce a relation which defines the magnitude of the light flow diffused within a nephelometer at a given atmospheric turbidity.

At the center of the spherical diffusion chamber of a nephelometer (chamber radius R) let there be a light-diffusing particle of volume dU, upon which a light wave of intensivity I falls. We can regard this light-diffusing particle as an elementary source of light of power dI (Figure 81).

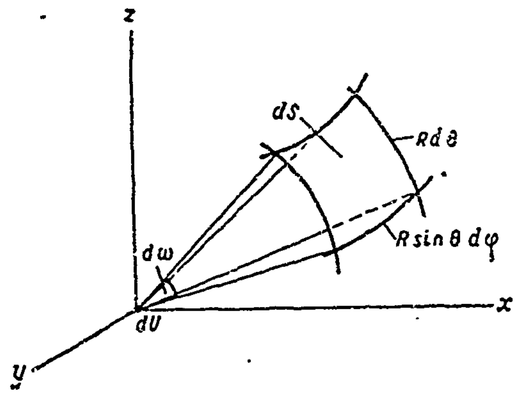

Figure 81. Relates to the Nephelometric Method For Measuring Transmissivity of Atmosphere.

A light flow dF'_{dif}, diffused by the particle and reaching an elementary area dS on the surface of the diffusion chamber, is equal to the product of the power dI of the light source times the magnitude of the solid angle under which the area dS is visible from dU, i.e.,

$$dF'_{dif} = dI\, d\omega.$$

But inasmuch as a light flow, diffused in a given direction and reaching the wall of the diffusion chamber, has different values thanks to the indicatrix, we should write in place of the foregoing expression the following one:

$$dF'_{dif} = \rho'(\theta)\, dI\, d\omega,$$

where $\rho'(\theta)$ is a coefficient depending on the direction of propagation of the diffused flow; i.e., it is an index of diffusion in a direction constituting an angle θ relative to the light falling on dU.

Since the solid angle $d\omega = dS/R^2$, and the area dS on the surface of a sphere is equal to

$$dS = R \sin\theta\, d\varphi R\, d\theta,$$

then, assuming that

$$\rho'(\theta)\, dI = \rho(\theta),$$

we secure for dF'_{dif} $$dF'_{dif} = \rho(\theta) \sin\theta \, d\varphi \, d\theta.$$

This is the magnitude of the light flow arriving at the elementary area dS from the diffusing particle.

The total amount of light energy diffused by a single particle and reaching the walls of the chamber of a nephelometer in all directions is equal to

$$F'_{dif} = \int_0^{2\pi} \int_0^{\pi} \rho(\theta) \sin\theta \, d\theta \, d\varphi = 2\pi \int_0^{\pi} \rho(\theta) \sin(\theta) \, d(\theta). \qquad (9.6)$$

Now we must write an expression defining the total light flow F_{dif} diffused by all particles located in the nephelometer. Formally it is simple to do this if one integrates (9.6) through for all directions within a solid angle 4π from quantity $\rho(\theta)$, assuming that all particles are iso-disperse, i.e., identical in dimensions and diffusing properties.

Then in place of (9.6) we would get

$$F'_{dif} = \int_{4\pi} \rho(\theta) \, d\omega, \qquad (9.7)$$

where $d\omega = 2\pi \sin\theta \, d\theta$ -- the elementary solid angle the apex of which lies at the center of the volume (the chamber) of the nephelometer [40].

But in reality in the diffusion chamber of a nephelometer there are poly-disperse particles with various diffusing properties, to which (9.7) is inapplicable. Each such poly-disperse particle or group of homogeneous particles makes its individual contribution to the total quantity of diffused light energy. At present it is impossible to express this through mathematical relations.

In order to get out of this fix, in (9.6) we introduce in place of $\rho(\theta)$ an "averaged" function of diffusion $\overline{\Gamma(\theta)}$, describing in general form the "averaged" indicatrix of diffusion which comes into being as a result of the aggregate action of all particles located in the nephelometer. Then in place of (9.7) for total diffused light flow

$$F_{dif}=\int_{4\pi}\overline{\Gamma(\theta)}\,d\omega=2\pi\int_{0}^{\pi}\overline{\Gamma(\theta)}\sin\theta\,d\theta. \tag{9.8}$$

As to physical sense, F_{dif} represents an integral form of the index of diffusion ρ, or in the light of the assumption of (9.3), an integral form of the index of attenuation, i.e.,

$$\alpha=\rho=cF_{dif},$$

where c is a constant for the given circumstances of turbidity. On this account we can write in place of (9.8) (see (9.1) ff.):

$$\alpha=\rho=2\pi c\int_{0}^{\pi}\overline{\Gamma(\theta)}\sin\theta\,d\theta, \tag{9.9}$$

in which connection the function $\overline{\Gamma(\theta)}$ can be selected so that the constant c shall be equal to one.

The expression (9.9) furnishes a pointer for the principle of developing a rational design of nephelometer and for the method of graduating them.

Design variant No. 1 is the so-called directed nephelometers which measure the index of diffusion ρ in one direction constituting an angle θ with the direction of the light beam passing through the volume which is being tested. In place of measurement of ρ in accordance with (9.9), we actually determine

$$\rho_{\theta}=cF_{dif}(\theta), \tag{9.10}$$

where $F_{dif}(\theta)$ is the amount of light diffused within the given angle θ by all particles located in the nephelometer.

The transition from (9.10) to (9.5) calls for graduation of the nephelometer in accordance with various actual values of S_M from a standard instrument or from some other one. The graduation can be carried out also from artificial standards of turbidity having known values of ρ. The constant c is determined by the circumstances of the graduation.

Design variant No. 2 is the integral nephelometers, which measure the index of diffusion ρ in accordance with (9.9), i.e., in accordance with the total volume illuminated by the light beam passing through it (or in some single plane in accordance with several directions).

For transition from (9.9) to (9.5), as a result of our not knowing the analytical form of the averaged function of diffusion $\overline{\Gamma(\theta)}$ for various values of atmospheric turbidity, we must carry out a number of supporting graduation measurements at various magnitudes of S_M.

All of the visual and objective nephelometers developed up to the present time fall either under design variant 1 or design variant 2.

§ 69. Design Variants of Directed and Integral Nephelometers, and Some of Their Peculiarities in Use

A. A. Gershun, M. M. Gurievitch, and N. E. Rityn have developed a number of variants of visual nephelometers which fall among the directed nephelometers as regards their design system, i.e., they fall to design variant 1.

A Diagram of the principle of such a nephelometer is shown in Figure 82.

In a ball-shaped or cylindrical cavity 1 which is blackened on the inside and which is called the diffusion chamber, air from outside is sucked in and is lighted up by a brilliant parallel beam of light produced by lamp 4 and condenser 3. A black body, 10, eliminates as far as possible the diffusion reflection of light from the walls of the chamber. The beam of diffused light passes through a Luemmer cube 8 and is examined by the eye via eyepiece 9. The angle β between the direction of sighting and the direction of the light beam is 45°. The light beam being compared, which is directed by mirrors 5, falls on the reflecting plane of the Luemmer cube. Evening-off of the light flows is carried out by diaphragm 7 operated by scaled drum 6. The diffused light is examined against the background of the black body via eyepiece 9.

The scale of the drum should be graduated in values of meteorological range of visibility S_M.

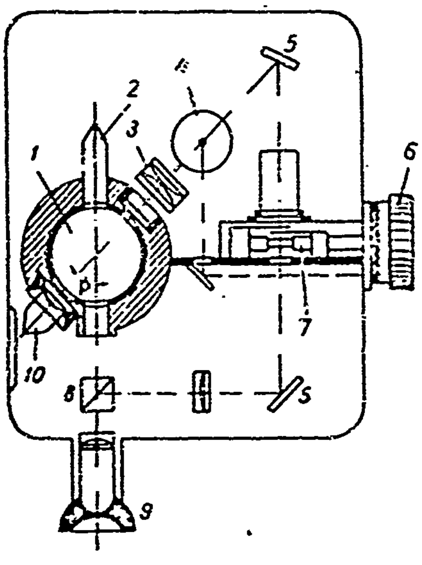

Figure 82. Diagram of Principle of Visual Nephelometer of A. A. Gershun, M. M. Gurievitch and N. E. Rityn.

Many years of testing various variants of directed visual nephelometers, performed by V. V. Sharonov, V. F. Belov, and others, and also by the author of this nomograph, have made it possible to establish the following measurement and use properties of these instruments.

With relatively high transmissivity of atmosphere (S_M > 10 km), the greater part of the indications of the nephelometers coincides well with actual visibility as determined by instrumental-visual methods and with visual observations of good quality.

In the interval of S_M from 3 to 10 km approximately 25% of observations deviated from actual visibility by some tenths of one percent (possible effect of the local character of measurements).

At lower transmissivity of the atmosphere, particularly for observations in fog, indications of nephelometers in the majority of cases diverge sharply from the actual visibility both in the upward direction and in the downward direction. Apparently the basic cause of these divergences is the effect of the local character of measurements by reason of the small volume of the nephelometers, and also in consequence of considerable spatial heterogeneity of the actual atmospheric turbidity.

An exploitational peculiarity of visual directed nephelometers which makes its appearance more markedly at low transmissivities is the frequent non-periodic spurts of luminance of the field of vision when large suspended particles get into the diffusion chamber. The frequency of these spurts, particularly in fogs, but also in the spring on dry terrain devoid of plant growth, can be so great that it sometimes becomes impossible to carry out measurements.

A major defect in use found in visually directed nephelometers is insufficient luminance of the field of vision, occasioned by the small volume of the area subjected to testing.

In daylight, particularly on a bright sunny day and with $S_M > 10$ km, by reason of the low luminance of the field of vision measurements are possible only after a preliminary 10-15 minute darkness adaptation of the eye of the observer; carrying this out under field circumstances is associated with a whole series of exploitational inconveniences and complications. Upon the taking of a test sample of air into the diffusion chamber of the nephelometer, as experience shows, a breakdown of the structure of the aerosol takes place which leads to distortion of the results of measurement.

Thus experience in the use of visual nephelometers for the measurement of S_M has revealed their serious exploitational shortcomings. Further work on these devices was terminated by the authors referred to.

Considering the defects of directed nephelometers, V. F. Belov proposed a new, more highly refined idea of nephelometric determinations of the transmissivity of the atmosphere, based upon measurement of the integral index of diffusion described by expression (0.9) [7, 8]. The integral nephelometer, corresponding in our presentation to design variant No. 2, is made in the form of a hollow ball, whitened inside, having a diameter of 25 cm and consisting of two separable hemispheres 2 and 3 (Figure 83).

The photometric apparatus consists of a photometric cube 4, diaphragms 6, eyepiece 5, and a white barytic comparison surface 7. An incandescent lamp 8 serves as a light source, and it illuminates the walls of the ball evenly. Upon observation through the eyepiece one sees two halves of the field of vision, one of which is directly illuminated by the lamp 8, while diffused light, observed against the background of the black cavity 1, falls upon the other.

Thanks to the spherical form of the chamber the aerosol is evenly illuminated from all sides by light scattered diffusely by the walls of the ball. In its turn the aerosol, too, evenly scatters light in all directions. Thus the intensivity of the scattered light flow F_{dif}, and presumably also the quantity ρ, do not depend on the direction of sighting. Thanks to this circumstance (9.9) carries through in its entirety, i.e., the intensivity of diffusion is proportionate to the quantity and dimensions of the aerosol particles, and is consequently proportionate to the integral index of diffusion ρ which is being sought.

The taking of the aerosol into the chamber is accomplished by simply opening the upper hemisphere and then closing it. Experience in working with a pattern model of the integral nephelometer has shown that the luminance of the comparison field is so great that observations can be carried out in daylight without preliminary darkness adaptation of the eye. In the nephelometer described, provision is made for a variant of the measurement of the index of diffusion ρ with the help of a photoelectric sensor.

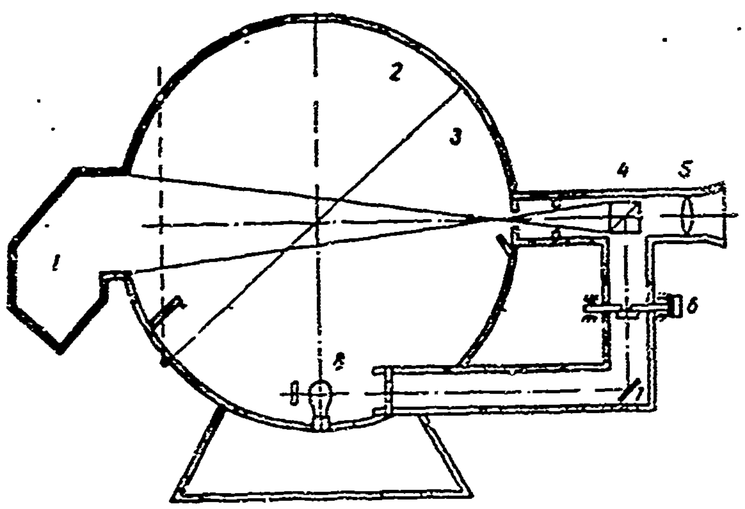

Figure 83. Diagram of the Principle of the Integral Nephelometer of V. F. Belov.

A general view of the V. F. BElov integral nephelometer is presented in Figure 84.

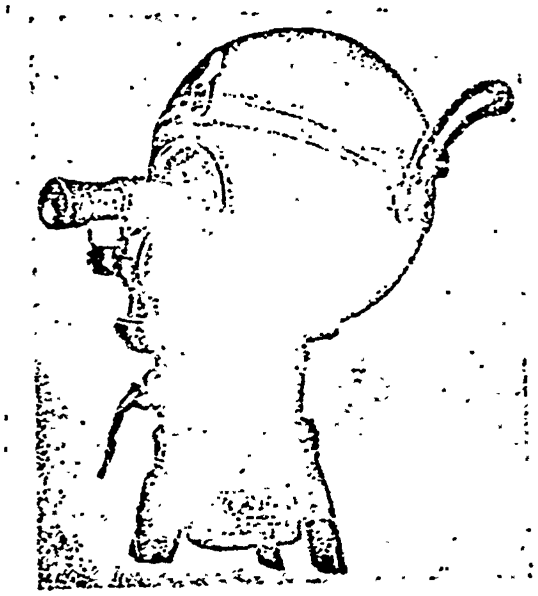

Figure 84. General View of V. F. Belov Integral Nephelometer

Along with this, as V. F. Belov points out, the nephelometer he has developed does have a defect, consisting in the fact that immediately after the closing of the top lid sedimentation of large aerosol particles commences. This can also be regarded as being, in a fashion, a breaking-down of the aerosol structure along the line of sight, bringing about that the test sample of air (along the line of sight) becomes more transmissive, the quantity ρ falls steadily, and S_M rises correspondingly. Thus a breakdown in the structure of the aerosol upon the admission of a test sample of air takes place not only in directed nephelometers, but also in the integral one, despite the considerable volume of the measurement chamber of the latter. This defect, in the opinion of V. F. Belov, is difficult to overcome and can be eliminated only when measurements are carried out directly in the atmosphere.

Work on further refinement of V. F. Belov's integral nephelometer was discontinued, although in our opinion the system proposed by him constitutes the most highly improved form of nephelometric measurements of atmospheric transmissivity.

In the United States in February 1965 a patent [209] was published for an object integral nephelometer having an impulse lamp as a light source and a photoamplifier as a collector. The air test sample is continuously sucked in through the ball-shaped cavity by means of a pump. The design of the principle of this nephelometer precisely reproduces the idea of the V. F. Belov integral nephelometer, but there is no reference to this circumstance.

In study [231] there is a communication regarding a polar objective nephelometer falling within construction variant No. 2.

With this instrument measurements of atmospheric transmissivity have been carried out at various altitudes through the use of balloons. No data of an exploitational character are communicated.

What has been set forth above makes it possible to say in conclusion that experience in the application of nephelometers for the purpose of measuring the meteorological range of visibility has not given favorable results, generally speaking. Evidently the main defect of nephelometric measurements consists in the low representational character of the data at medium and low atmospheric transmissivity. To what extent the "gigantic" extrapolations of nephelometric measurements are valid can only be shown by further improvement of the nephelometric method as a whole.

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13. ABSTRACT

The author gives a description of present-day ways of determining visibility through the atmosphere. He explains how atmospheric transmissivity, the visibility of actual objects, and the range of visibility on landing an aircraft are measured. He emphasizes particularly the methods for determining the level of visibility. In a number of cases he concludes that problems which he regards as being important have not yet been satisfactorily solved.