THE VISIBILITY OF AIRPLANES.*

BY

M. LUCKIESH.

Physicist, Nela Research Laboratory.
National Lamp Works of General Electric Co.

1. FOREWORD.

The object of the investigation described below was to analyze the various aspects of the visibility of airplanes, to ascertain the possibilities of attaining low visibility in various phases of airplane activities, to arrive at specific practical recommendations, and to eliminate guesswork by supplying a scientific foundation consisting of measurements for the solutions of the problems involved in obtaining low visibility. The war closed before some of the many interesting details could be thoroughly unraveled, but the fundamental data upon which the attainment of low visibility for airplanes may be founded, are presented in this paper. The work was conducted primarily for the Science and Research Division of the Bureau of Aircraft Production from whom permission for publication has been granted. The original reports contained a number of illustrations in color which will not be reproduced in this paper. Furthermore, it does not appear profitable to present all the details of the original discussions and recommendations.

2. INTRODUCTION.

We distinguish objects through differences in light, shade, and color, or, in other words, through differences in brightness and color. Form is sometimes included in such a statement, but this is unnecessary inasmuch as form is determined by the distribution of light, shade, and color. If, then, an object is seen and recognized owing to a distribution of brightness and color which is different from that of the surroundings, it follows that it will be invisible if no such differences exist or the object will be of low visibility if these differences are minimized. In striving for low visibility we must strive for distributions of brightness and color in the object similar to that of its environment or the background against which it is viewed.

* Based on a paper presented at a meeting of the Section of Physics and Chemistry held Thursday, January 9, 1919.

Many decades ago we learned lessons from nature in the art of concealing coloration and one of the fundamental precepts of Nature's camouflage is that an object of a uniform brightness and color is not as inconspicuous amid the usual natural environments, in which variety in light, shade, and color is infinite, as an object of broken color and brightness, in which the average hue and the average brightness approximate those of the environment. (See Reference 1.) Hence pattern is nearly always an essential feature of successful camouflage. An exception is such a case as a uniform blue sky for a background.

We have learned this lesson in certain types of camouflage and should apply it in certain types of camouflage for aircraft. Invisibility is the dominant note of land camouflage. Invisibility was for some time the chief aim of marine camouflage but the submarine menace with its short range of effective attack has caused "confusibility" to replace "invisibility" for the protection of many vessels. In the case of a submarine attack, for example, on a vessel a mile distant there is no possibility in ordinary weather for "invisibility" to save the vessel. However, "confusibility," by rendering it difficult or even impossible for the submarine commander to judge the exact course of the intended victim, may result in a miss, which, according to the old adage, "is as good as a mile."

The program of study of airplane camouflage included chiefly two general viewpoints, namely, above and below the airplane for invisibility. Unfortunately the solutions of these two problems are usually more or less opposed to each other. When viewing the craft from underneath, the background is the bright sky and clouds whose aspect changes sometimes from minute to minute, and when looking down upon the airplane the background is usually the much darker earth whose aspect changes from season to season, owing to the variation in the earth's cloak. The sky is a uniform background only on a cloudless day or on a perfectly overcast day. A clear blue sky and a dense overcast sky are of lower brightness than sunlit clouds and hazy or lightly overcast skies. A sunlit cumulus cloud will often be many times brighter than an adjacent patch of blue sky. The greatest difficulty, however, is due to the extremely greater brightness of the sky than that of objects in the air as seen from below.

Obviously the character of camouflage which is predominantly required will depend upon the type of airplane, such as bomber, scout, chasse, patrol, etc.; upon the height at which various aerial operations are carried out, and upon various other characteristics of service.

3. MEASUREMENTS AND OTHER OBSERVATIONS.

It becomes evident early in the consideration of the problem of lowering the visibility of airplanes that various measurements could be readily obtained which would provide a firm basis for the actual work. In all branches of camouflage there has been much time and energy wasted in speculation and experiments which scientific investigation would have eliminated. In fact, the only certainties in some branches of camouflage have been established by scientific investigations. The final steps in reducing the visibility of airplanes must necessarily be compromises as is the case in most practical problems, but the writer feels assured that the data herein recorded provide a definite basis for practical work and successful camouflage. In fact, without such data the final practical steps must rest entirely upon the qualitative data obtained by individual judgment and we could not be assured of having adopted the best procedures within months and even years of cumbersome experiments. Therefore, the writer directed his first efforts toward obtaining measurements and making other observations which would establish:

1. The relative brightness or apparent reflection-factor of various earth areas.

2. The mean relative brightness or apparent reflection-factor of the earth.

3. The mean relative brightness of water areas.

4. The mean hue of the earth areas.

5. The mean hue of water areas.

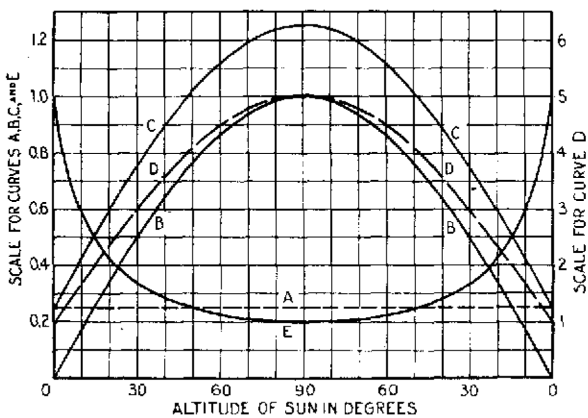
6. The size of pattern for airplane camouflage.

7. The shape of pattern for airplane camouflage.

8. Certain brightness measurements in terms of the brightnesses of the sky and of clouds.

The measurements and observations presented in the following may not, in all cases, appear to be of direct interest in solving the problems which have been attacked, but a detailed knowledge of these various aspects is essential for obtaining a full grasp of the possibilities and expedients to be adopted in rendering airplanes of low visibility in general. Thousands of measurements have been made but these will be presented in condensed form. Numerous cross-country flights were made besides many short flights on various types of days and under various natural lighting conditions—a total of 60 hours of flying, or about 5000 miles of air travel having been devoted to the work. Most of the work was carried out at Langley Field, Hampton, Va., but cross-country flights were made from this point to Washington and Richmond, and over the Chesapeake Bay and Atlantic Ocean.

FIG. 1.



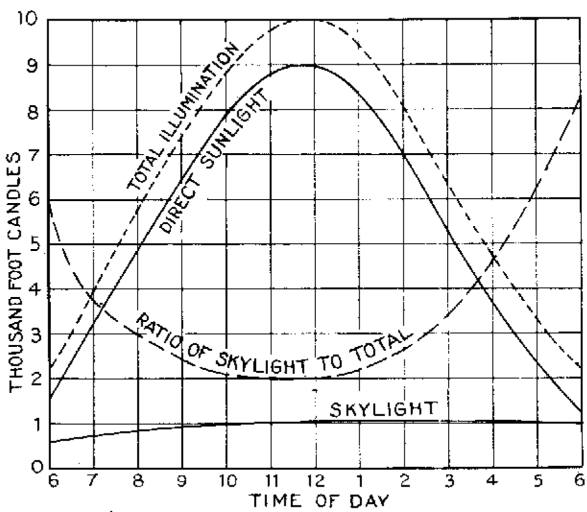
Theoretical relations of the illumination intensities of sunlight and skylight on a horizontal plane.

4. SOME THEORETICAL CONSIDERATIONS.

Before presenting the measurements which have been made and the final discussions of the possibilities of obtaining low visibility a few theoretical and practical aspects will be discussed.

The relation of sunlight to skylight is theoretically considered in Fig. 1 (see Ref. 2). For this purpose the brightnesses of a horizontal white diffusing surface and a shadow upon this surface may be determined. The light from a clear blue sky does not vary greatly in intensity during a considerable portion of the day. However, the amount of direct light from the sun falling upon a horizontal surface varies from zero at sunrise to a maximum at noon and at zero at sunset. For the purpose of discussion the illumination upon a horizontal surface due to direct sunlight at noon is assumed to be four times that due to light from the sky, and for simplicity the amount of light from the sky is assumed to be constant from sunrise to sunset. The illumination intensities due to the sun and sky respectively under the assumed conditions are shown in Fig. 1, curve A being the constant illumination due to the sky and curve B the illumination due to the sun throughout its entire range of altitudes, which is represented on the horizontal scale. Curve C represents the combined illumination from sun and sky. The vertical scale for curves A, B and C is on the left of the figure. The broken curve D represents the ratio of the combined illumination due to the sun and sky to that due to the sky alone; that is, it represents the ratio of the brightness

FIG. 2.

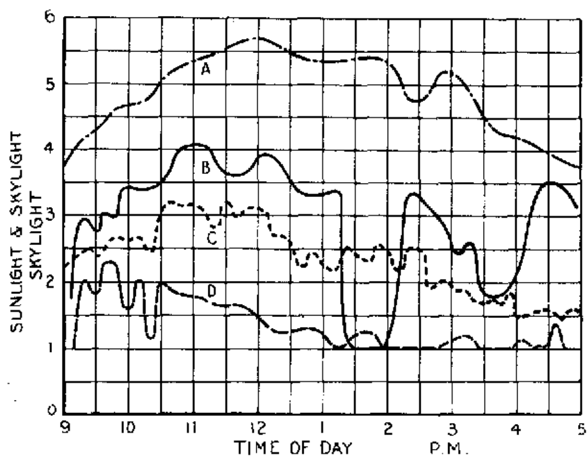


Relations of illumination intensities of sunlight and skylight on a horizontal plane on an extremely clear day.

of the test surface receiving the combined light from the sun and sky to the brightness of a small shadow upon the surface which receives only skylight. In other words, it is obtained by dividing the ordinates of curve C by those of curve A and the values of this ratio are represented on the vertical scale at the right. Curve E is the reciprocal of curve D; that is, it represents the ratio of the brightness of the shadow on the test surface to that of the surrounding portion of the test surface which is illuminated by light from both the sun and the sky. Its vertical scale is on the left of the figure. While natural conditions will not be found to be so uniform throughout an entire day, the data shown in Fig. 1 are interesting and useful for obtaining an idea of the natural lighting conditions on a clear day. The data obtained on clear days do not differ very much from the theoretical curves of Fig. 1. In Fig. 2 are represented the conditions on an extremely clear day.

Representative data are presented in Fig. 3 for four characteristic days. The measurements were made continually from 9 A.M. until 5 P.M. Curve A represents the ratio of the brightness of the surface receiving both sunlight and skylight to the brightness of a small shadow on the same surface which receives only skylight on a very clear day. The sky was a deep blue and no

FIG. 3.

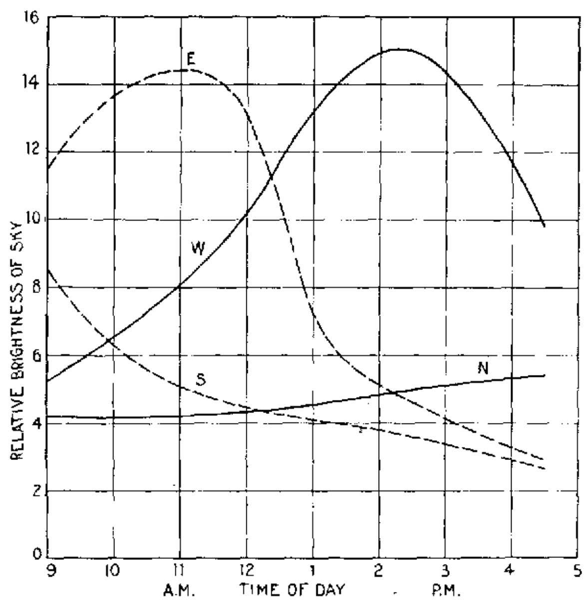


Ratio of total illumination on a horizontal surface outdoors to that due to skylight alone on various days.

definite clouds appeared during the entire period of eight hours—a very rare condition in most localities. It will be noted that during midday the skylight was only one-fifth to one-sixth as intense as the combined intensity of sunlight and skylight. In other words, during midday the sun contributed about four or five times the amount of light that the sky contributed on this clear day. At observatories, high in the mountains, on very clear days it has been found that as little as one-tenth the light which reaches the earth comes from the sky, the remaining nine-tenths coming directly from the sun. The tendency for the ratio to increase toward noon corroborates the conclusions arrived at in the theoretical treatment of the conditions on a clear day, as shown in curve D, Fig. 1, and also in Fig. 2. It should be noted that these observations did not extend from sunrise to sunset, which was the time interval used in the theoretical discussion in Fig. 1. Curve B in Fig. 3 represents data obtained on a day during the morning of which a few large cumulus clouds moved slowly across the sky. The sunlight reflected from these clouds increased the relative amount of diffused light, or light from the sky, with the result that the ratio under consideration was smaller than on a clear day. About 1.30 P.M. massive clouds obscured the sun, so that for a time no shadow was perceptible upon the test surface and the ratio became equal to unity. During the remainder of the afternoon the moving clouds caused considerable variation in the ratio. It should be noted that sunlit cumulus clouds are very much brighter than a clear blue sky. Curve C represents data obtained on a thinly overcast day. The sun was plainly visible, but the sky was overcast with a thin hazy veil and therefore was brighter than a blue sky, with the result that the relative amount of sky-light increased and the ratio under consideration was much smaller than on a clear day. The hazy veil grew thicker and therefore brighter as the day progressed, with the result that the ratio gradually decreased. Curve D represents data obtained on a day during the afternoon of which the sky was quite completely overcast. During the forenoon the sky was covered with broken clouds, but these became welded into a uniform covering about noon, with the results as shown. Thus, results obtained on four distinctly different types of days are shown in Fig 3, and the data give some idea of the tremendous variations in the distribution of natural light outdoors. Absolute intensities of natural light have not been considered in the foregoing, because they are of minor interest.

Inasmuch as the sky is usually a prominent feature, a few facts regarding it may be of interest. Except at altitudes near that of the sun, a clear blue sky is usually considerably brighter at the lower altitudes—near the horizon—than at the zenith, due largely to the greater haziness noticeable at the lower altitudes. This is perhaps always true, excepting when dense clouds, which are not recognized as clouds, are gathering near the horizon. A clear blue sky is darker than an overcast sky except in the extreme cases of the latter. A slight haze or thin veil of clouds increases the brightness of the sky very much and therefore increases the amount of light which illuminates many shadows. The color of the sky when clear is more saturated than under any other condition, varying from this deep blue to the neutral gray of an overcast sky. The extreme non-uniformity of the brightness of clear blue or overcast skies is only revealed by measurement. Often a sky which appears quite uniform will vary in brightness at different points by several hundred per cent. A clear sky is usually brightest at those altitudes near the sun, which becomes

FIG. 4.



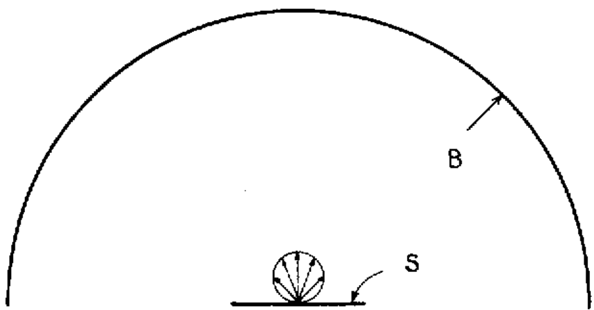
Variation of the brightness of the sky throughout a clear day.

more marked on hazy days when the atmosphere contains more reflecting particles. This is illustrated by means of Fig. 4, the data shown having been obtained on a clear day when the sky was very slightly hazy. The letters on the four curves stand for east, west, north, and south respectively. The brightness of portions of the sky, about 20 degrees above the horizon and approximately at the four points of the compass, were measured during a day in August from 9 A.M. to 5 P.M. at a point near 40 degrees north latitude. No definite clouds were visible during the period of observation. It will be noted that the brightness of the sky was greatest in the east in the morning and greatest in the west during the afternoon. On a perfectly clear day when the sky was a deep blue, the variations of sky brightness were not so great. The recognized constancy of north skylight is also shown in this illustration.

In dealing with the problems of lighting it is necessary to distinguish between illumination and brightness (cause and effect respectively); to appreciate the difference between the conditions and effects on sunny and overcast days; and to be familiar with certain characteristics of reflecting and transmitting media.

If a hemisphere (Fig. 5) of uniform brightness B is solely responsible for the illumination of the surface S, the brightness of S will equal B if S is perfectly reflecting. Furthermore, this

FIG. 5.



Diffusely reflecting surface S illuminated by hemisphere of brightness B.

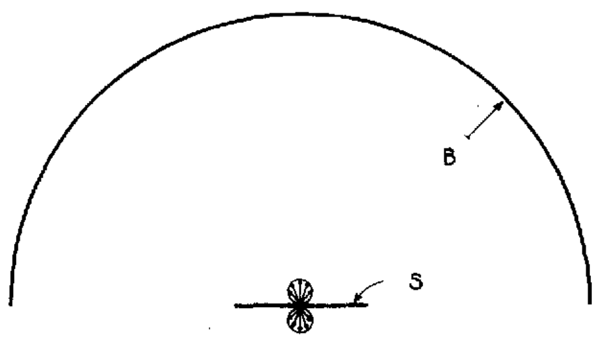
would hold if S were either a polished or a diffusing surface. Inasmuch as the reflection-factor R of a surface is never unity, the brightness of the surface S under the above conditions is equal to RB. If the object were perfectly transparent, obviously the brightness B would be seen through the object, but if it had a transmission-factor of T then the brightness as seen through the object would be reduced to TB.

If the object were perfectly diffusely transmitting, its brightness would be only 0.5 B because one-half the incident light is diffused back toward the hemisphere as indicated in Fig. 6. The foregoing condition is representative of that on a perfectly overcast day or before sunrise and after sunset. Obviously the upper limit of brightness in the case of diffusely transmitting media is only one-half that of reflecting media.

At noon on clear days the illumination of a horizontal surface is due chiefly to direct sunlight. Of course the ratio of direct sunlight to skylight at the earth's surface varies considerably owing to clouds, haze, etc., but of the total light reaching the earth's surface at noon the direct sunlight constitutes as much as 0.9 on extremely clear days. A common value is in the neighborhood of 0.8. This has an intimate bearing upon the visibility of airplanes as viewed from below.

In Fig. 7 we have reproduced the conditions of Fig. 5 with the superposition of direct sunlight at midday. The hemisphere may be considered to represent the sky of brightness B. If the surface S is perfectly diffusely reflecting, its brightness due to the skylight alone is B. Its brightness due to the direct sunlight alone

FIG. 6.



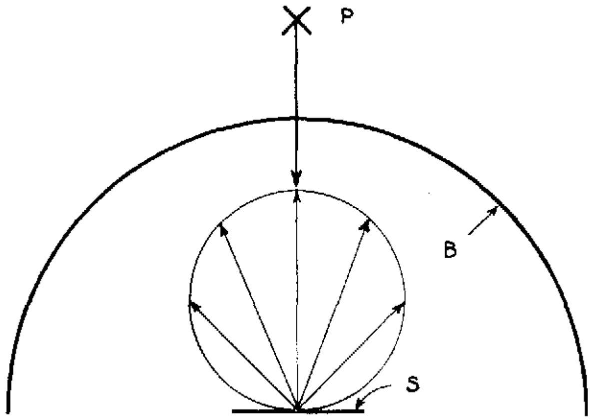
Diffusely transmitting thin object S illuminated by hemisphere of brightness B.

we will assume to be 4 B, which is a fair average. Hence we would have a total brightness of 5 B. If the reflection-factor of the surface is equal to R, then the total brightness is 5 RB.

Assuming the object to be perfectly diffusely transmitting, its brightness would be 2.5 B and, therefore, when viewed against the sky it would appear 2.5 times as bright as the sky. Ordinary translucent media are far from perfectly diffusely transmitting, hence the brightness is 2.5 TB, where T is the transmission-factor. If T were equal to 0.4, under the conditions assumed, we would have the brightness as viewed from below equal to $2.5 \times 0.4 \times B = B$. In other words, if the object were diffusely transmitting with $T = 0.4$ on a clear day when the sun contributed 0.8 of the total light on a horizontal surface at midday, this translucent object, as viewed from beneath, would be of the same brightness as the sky. However, it would not be invisible, because it would appear yellowish in color owing to the fact that most of its brightness is due to sunlight which is yellow in contrast with the blue skylight. The medium may be colored a blue tint to counteract this. (See Ref. 2, Chapter VII, and Ref. 3.)

This discussion is introduced at this point to indicate reasons for obtaining the measurements which are presented in some of the sections which follow. It is resumed again (Secs. 15 and 16) in connection with the practical considerations of low visibility for airplanes which are treated in later sections.

FIG. 7.



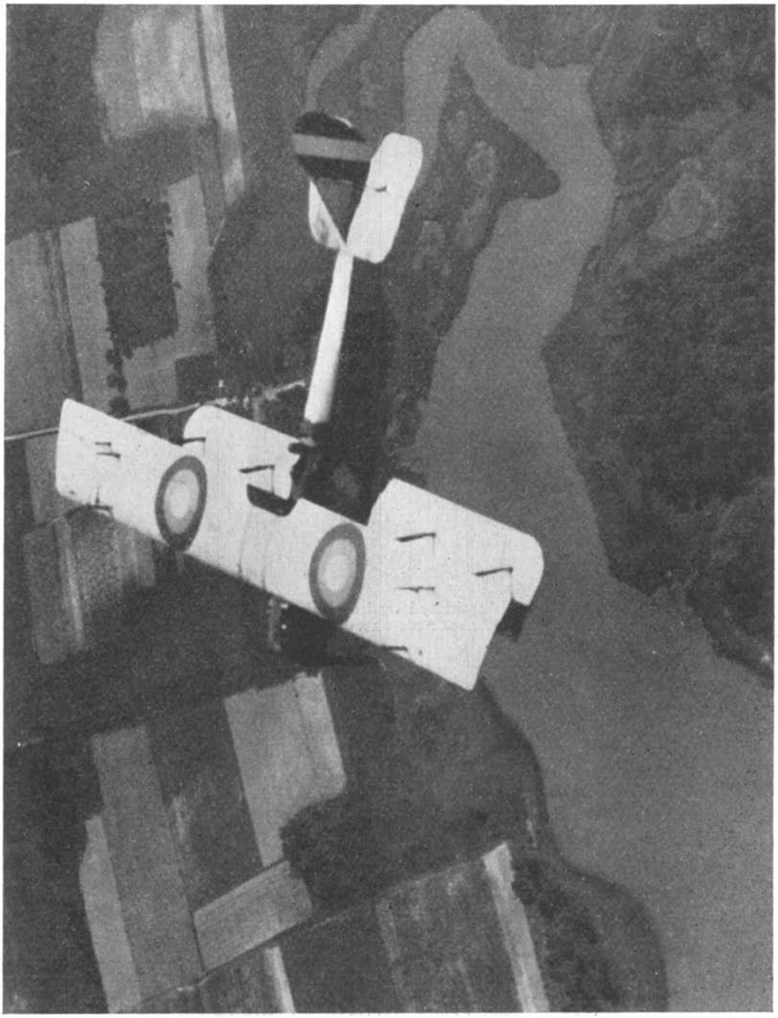
Diffusely reflecting object S illuminated by hemisphere of brightness B and by a point source of light P. Simulating conditions at noon on a perfectly clear day when sun is contributing 0.8 of total light.

5. RELATIVE BRIGHTNESS OR APPARENT REFLECTOR-FACTOR.

To apply the term reflection-factor (commonly called reflection-coefficient) to the earth's surface which has "depth" is somewhat misleading; however, as viewed from an appreciable distance above the earth, this term is not misapplied from a practical standpoint. The term "relative brightness" will be used occasionally and, unless otherwise stated, will mean the brightness relative to a perfectly reflecting and diffusing opaque surface under the same illumination. Obviously the reflection-factor of this theoretical white surface is equal to unity so the values of "relative brightness" may also be considered "apparent" reflection-factors.

In the following table the individual values are means of many observations, and a sufficient number of these are presented to show the consistency of the results. All were made within 150 miles of Langley Field. Further comment on these various types

FIG. 8.



Illustrating character and approximate relative brightness of typical earth areas.

of areas will be found in following sections. Measurements, unless otherwise stated, were made vertically downward from the airplane and usually at altitudes from 1000 to 5000 feet. The brightness measurements were made with different types of instruments in terms of the brightness of a white diffusely reflecting (or transmitting) surface receiving the same illumination. These

TABLE I.

Relative Brightnesses or Apparent Reflection-Factor of Various Types of Earth Areas in Per Cent.

(These were determined in eastern Virginia within 150 miles of Hampton. In all cases the surfaces were viewed from points directly above them, varying from an altitude of 1,000 feet upward. The individual values in the following table are means of numerous measurements. In some cases hundreds of measurements were made during a single flight.)

		Fields	Barren Land	Woods	Inland Water
Aug. 30, 11 to 12.	Generally clear	7.4	10.4	4.9	5.7
Aug. 30, 2 to 3.	Sunny with large clouds scattered	9.3	10.3	4.9	9.0
Aug. 31, 11 to 12.	Generally clear, some thin hazy clouds	6.1	10.1	4.4	6.7
Aug. 31, 1 to 2.	Fairly clear, some clouds	5.8	11.1	3.8	6.2
Sept. 3, 11 to 12.	Sunny, with large scattered clouds	7.9	15.9	3.9	6.3
Sept. 3, 1 to 2.	Generally clear	7.0	19.0	4.6	7.1
Sept. 3, 3 to 4:30.	125-mile trip across country east and south	6.8	17.1	5.0	6.2
Sept. 4, 11 to 12.	175-mile trip to Richmond, Petersburg and return	6.5	13.8	4.5	7.4
Sept. 6, 11 to 12.	Overcast sky	6.7	13.6	4.4	9.1
Sept. 7, 1 to 2.	Clear day	6.3	...	...	7.6
Sept. 9, 11 to 12.	Clear day	...	11.2	3.6	6.7
Sept. 9, 2 to 3.	Clear day	6.7	14.2	3.9	4.4
Sept. 10.	On trip to Washington and return	5.2	8.7	3.5	5.2
	Mean	6.8	1.30	4.3	6.8

Shadow of cloud on earth's surface is less than 1 per cent. Dense clouds up to 78 per cent.

values were then reduced to values in terms of a perfect white. Obviously such measurements had to be made below the clouds when the latter were present. Many measurements were made at various altitudes up to 20,000 feet, although for earth measurements the effect of the low-lying haze was reduced to a minimum by making the measurements vertically downward and at low altitudes. Most of the measurements were made during the middle of the day because instrumental errors were less at this time. However, no extensive differences were obtained in the results at various times of the day or even on sunny and overcast days. In Fig. 8 is seen a fairly satisfactory photographic reproduction of the relative brightnesses of the various types of areas represented in Table I. A close study of this photograph with the mean values of the Table I in mind is quite interesting.

6. LANDSCAPE.

During the period in which the foregoing observations were made the landscape was still predominantly green, although in some areas there was a slight tinge of yellow common to late summer. It seems reasonable to assume that this season of the year represents a fair mean of the conditions during the chief period of active warfare in this zone. There were many ploughed fields barren of vegetation and others which were not entirely covered by green foliage. In the territory of eastern Virginia there is a great deal of wooded country including wooded swamps, so it appeared, among other reasons, best to keep separate records for the different types of earth areas. Furthermore, there are various kinds of soil, so that the variations in the values in Table I are to be expected. However, the consistency of the observations on woods and fields covered with crops and also on water was surprising. The greatest variations were found for barren land.

The mean relative brightness or apparent reflection-factor for a landscape will depend upon the proportions occupied by the various types of areas. This is another reason for obtaining mean values for the various types of areas. It may be of interest at this point to refer to some of the photographs of landscapes which are included in this paper.

Attempts were made to estimate the proportions of different types of areas present in the landscapes studied. This could be fairly accurately determined for any given part of the country by cross-country flights, during which a record of time in passing over the various types of areas could be kept. If the airplane speed were approximately constant this would give a fairly satisfactory mean value for the relative brightness or the apparent reflection-factor of the terraine. This was done a number of times. For example, the mean value obtained during a 175-mile trip from Langley Field to Richmond to Petersburg and return was about 7 per cent. However, it should be noted that this portion of the country contained much wooded area, although the course was generally maintained over the more cultivated regions.

Notwithstanding the writer's familiarity with brightness measurements of landscapes, the generally low values obtained in this investigation were surprising. However, these may be accounted for by considering the earth's surface more in detail. On looking down upon such areas as fields, woods, etc., one sees a mixture of highlights and shadows. Much of the area receives only skylight which is only a small part of the total light reaching the earth on sunny days. Even on overcast days the shadows receive only a small portion of the total light reaching the earth's surface. For example, a grass area possesses "depth" similar to velvet. Black velvet has a very low reflection-factor (about 0.4 per cent.), but ordinary blotting paper colored with the same dye will possess a diffuse reflection-factor of about 2 per cent. The depth of the velvet fibre provides light traps and shadows with the result that the reflection-factor as a whole is much lower than that of a single fibre. In a similar manner grass plots, corn-fields, ploughed ground and woods provide light traps and shadows so that the mean brightness or apparent reflection-factor is materially reduced.

For example, let us assume that the reflection-factor of a blade of grass is 0.16; that the sun contributes 0.8 of the total light; and that the normal aspect of the grass plot is one-half shadow and one-half highlight. If the brightness of the sky is equal to B, then the brightness of a perfectly white horizontal reflecting surface will equal B, due to skylight alone, and equal to $5\ B$, due to sunlight and skylight. The brightness of the blades of grass receiving both skylight and sunlight will be $5\ B \times 0.16 = 0.8\ B$. The brightness of the grass in shadow, assuming the shadows to receive full skylight (they actually receive much less), will equal $0.16\ B$. The mean apparent brightness will be equal to $\frac{1}{2}$ $(0.8 + 0.16\ B)$. The mean apparent reflection-factor would then equal $\frac{0.48\ B}{5\ B}$, or 0.1 approximately. Thus it is seen, with these assumptions, the apparent reflection-factor of the grass plot as a whole is much less than that of individual blade which was assumed to be 0.16. It will also be noted that the trapping of light by virtue of the "depth" of such a surface was not considered in the foregoing analysis. Woods are strikingly dark owing to these reasons, and on the whole these considerations prepare us to expect a surprisingly low mean apparent reflection-factor of the earth. Bare earth which has been packed by rain and baked by the sun is conspicuously brighter than the same soil freshly ploughed even after the latter has dried. It is commonly noted that wet dirt is darker than the same dirt when dry. For example, a blotting paper which, when dry, reflected 0.74 of the incident light, reflected only 0.54 of the incident light when wet. The brightness of all earth areas does not vary much with the angle at which they are viewed. This is not strictly the case with the surface of water as will be noted later.

Although an overwhelming number of the values of apparent reflection-factor or relative brightness are included within a range from 3.5 per cent. to 10 per cent., the following ranges include practically all the values obtained for the different types of areas:

Ploughed and barren ground	0.10–0.20
Grass, fields	0.05–0.10
Woods	0.03–0.05
Inland water	0.05–0.10

The values for water are included here for the sake of interest, but owing to the special character of its surface reflection it is discussed at length in Section 9.

The change in Nature's cloak during the various seasons must be considered, but the most intensive activities in warfare are carried on from spring to fall usually and, therefore, the summer garb of Nature is here considered of chief importance. The reflection-factor of snow can be assumed to be equal to that of commercial white pigments and the values for barren ground in Table I will hold for winter. It would not be difficult to make a fairly accurate estimate of the apparent reflection-factors of various types of areas for late autumn after the experience accumulated in the present investigation. From such values fairly successful camouflage could be developed for these seasons.

A number of flights were made during the middle of October in order to obtain certain measurements of apparent reflection-factor of earth areas and observations of the hues of the autumn landscape. These observations were not as exhaustive as those recorded in Table I and on other pages, because as has been stated, we are concerned primarily with the summer landscape. The results obtained for the apparent reflection-factors or the brightnesses relative to a perfectly white surface are:

Fields	6.0 per cent.
Barren land	11.3 per cent.
Woods	4.3 per cent.
Inland water	5.5 per cent.

The landscape was decided brownish and generally dull in character. Few green areas were present and the woods displayed a variety of tints. It is noteworthy that the landscape in general appeared more dull and dead from high altitudes than was expected. Although the number of observations was limited to hundreds instead of thousands, as in the investigation conducted during midsummer, it will be noted that the results are not widely different. To obtain low visibility for airplanes viewed from above the brightness would be about the same for late autumn as for summer, but obviously the color would be changed from a very dark olive green to a dark brown or dark greenish-brown. It does not appear practicable to alter the camouflage for airplanes for the autumn season which is relatively short with the possible exception of a relatively few craft. The dark olive green craft would still be of fairly low visibility as viewed from above during the autumn.

7. CLOUDS.

Sunlit clouds are often several times brighter than an adjacent patch of blue sky. This increases the difficulty of realizing low visibility when viewing the airplane from below against the clouds. When the clouds are below the observer they are of course many times brighter than the earth background when they are illuminated by both the sun and the sky. Some measurements were made in the course of these investigations in order to establish the magnitude of the relative brightness or apparent reflection-factor. These values vary considerably with the character of the cloud and the lighting conditions.

The apparent reflection-factor of cumulus clouds receiving full skylight and sunlight as measured vertically above them on various days, varied with the density of the clouds. The mean values of the upper surface of clouds, determined on different days, were found to be as follows:

Very dense clouds (Fig. 9)	0.78
Dense clouds, quite opaque	.62
Dense clouds, quite opaque	.59
Dense clouds, quite opaque	.55
Dense clouds, nearly opaque	.44
Thin clouds	.40
Thin clouds, (Fig. 20)	.36

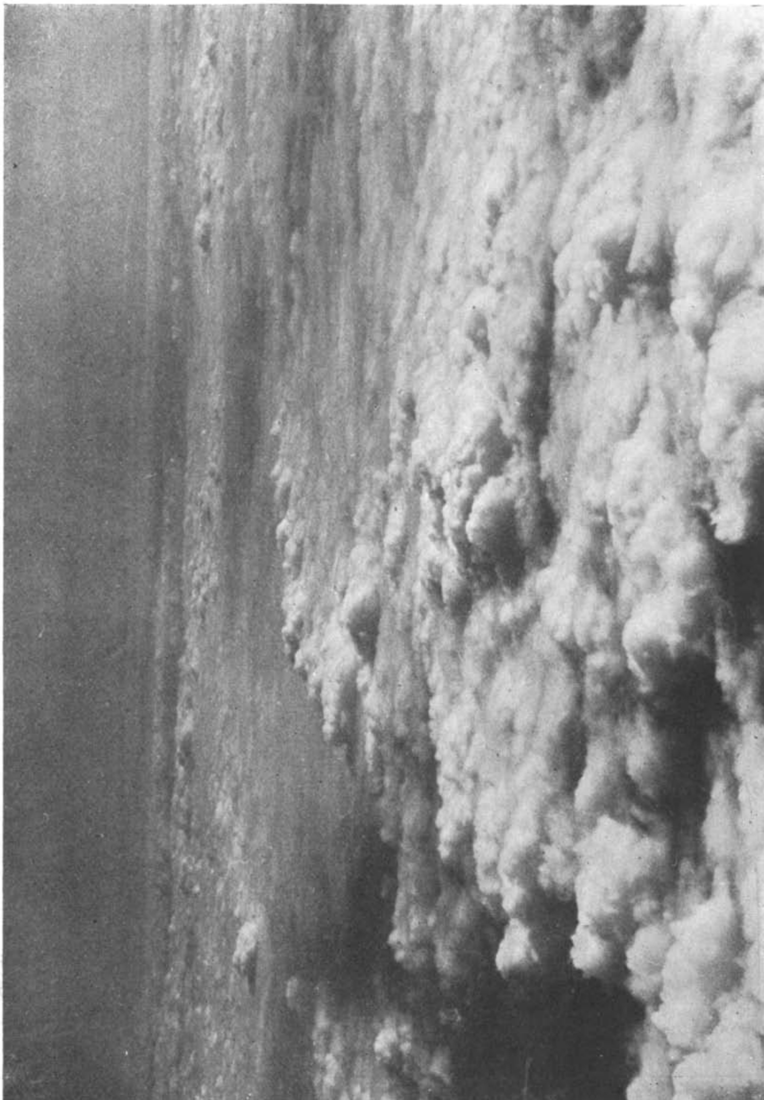
One day when the sky was very heavily overcast, with the exception of a small rift which admitted the airplane with safety to the upper region, a great many measurements of the brightness of the upper surface of the clouds were made. These observations were made near the sunny side of the hole in the extended massive layer of clouds and the values of relative brightness obtained varied from 0.7 to 0.8 with a mean of 0.78. The character of the clouds as seen from above is illustrated in Fig. 9. Inasmuch as the upper side of a cumulus cloud was found to be six times brighter than the lower side, we must conclude that there is a "mass" effect unless we choose to conclude that there is a tremendous absorption. In other words, great masses of clouds can be relatively much brighter than a purely diffusing non-absorbing medium in a thin layer, which theoretically would possess a transmission-factor equal to 0.5 and a reflection-factor of the same value.

The sunlit surfaces of dense clouds were found to be commonly 5 to 10 times the brightness of the adjacent patches of clear blue sky. Ordinary cumulus clouds provide a screen for airplanes as often as they are backgrounds. Cirrus clouds, owing to their great height, are usually backgrounds when they are present. In Fig. 10 a common condition is illustrated. The photograph was taken from an altitude of about 7000 feet, the cumulus clouds being at an altitude of 4500 feet. The effect of the haze is seen by the obscurity of the distant landscape. Some of the other photographs are of interest at this point, especially in showing the high brightness of portions of the clouds and their lack of uniformity in brightness.

8. HAZE.

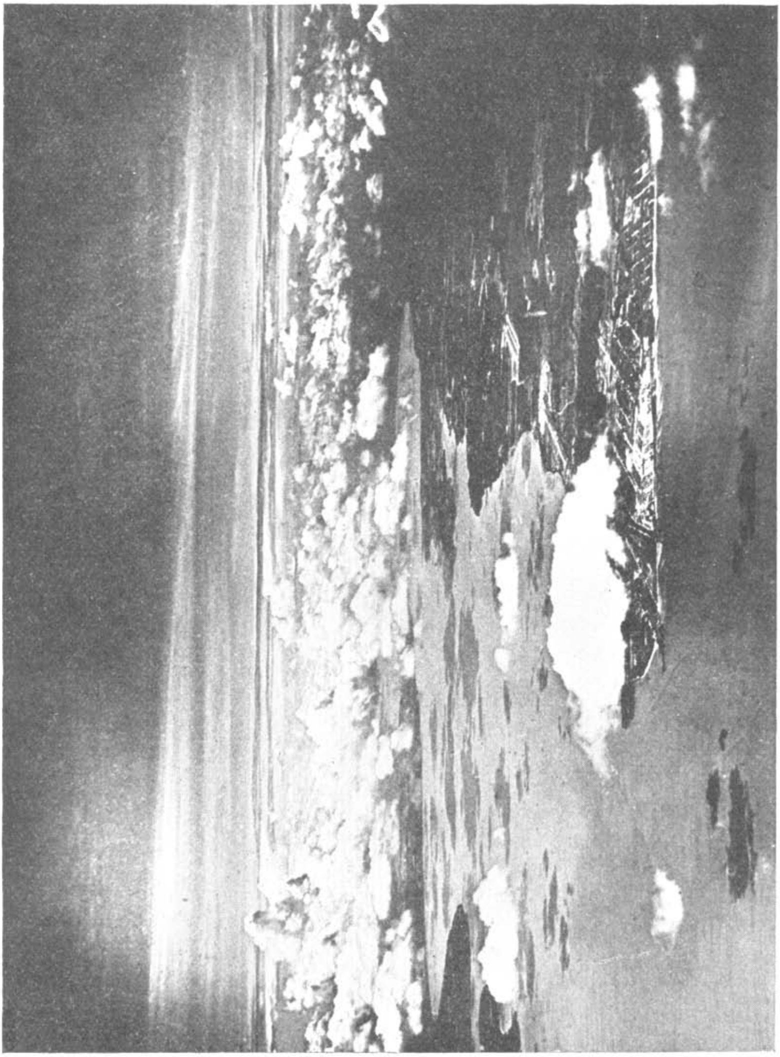
Haze usually tends to lower visibility because it absorbs light reflected from the objects which are viewed and chiefly because

FIG. 9.



Above a dense cloud layer several thousand feet in depth.

FIG. 10.



Illustrating cloud and haze levels also cloud shadows upon water.

it is a luminous veil. In the regions in which these studies were made, the "dust" or low-lying haze extends ordinarily to an altitude of about one mile. This haze is quite absorbing, as is readily seen in viewing the earth obliquely, and also is fairly luminous. On some days the sky, even at altitudes of 10,000 feet, appears quite bright and very unsaturated in color. This upper haze seems to be of the nature of a very thin uniform cloud. Inasmuch as low visibility of airplanes, as viewed from below, for practical reasons is dependent largely upon a dark sky, this upper haze, when it is at such altitudes as to contribute to the brightness of the sky background against which an airplane is viewed, increases the visibility of the craft. The lower or dust haze operates to lower the visibility of craft at moderate and high altitudes.

No very accurate measurements of the luminosity of the low-lying dust haze were obtained, but attempts were made to obtain the order of magnitude. For example, on a cloudless day brightness measurements of water normal to its surface were made at various altitudes from 1000 to 18,000 feet. Although the values for various areas of the water varied slightly, it appeared that the values were about 25 per cent. higher at extremely high altitudes than at the lowest altitudes. This would indicate that, on this particular day, the net result of the haze was to increase the relative brightness of the earth about 25 per cent. On very hazy days this value may be greater.

A better organized attempt was made to determine the change in brightness of the earth with the altitude of observation on a clear day. In order to determine this it is necessary to have a large earth surface of uniform brightness. The brightness of this surface may be determined as viewed from various altitudes. For this purpose a deep channel in the Chesapeake Bay was selected and its brightness was determined for altitudes up to 10,000 feet. No appreciable change was noted, but unfortunately the day was not very hazy. It is doubtful if the change is very much on very hazy days, because the increase in brightness due to the luminous haze as viewed from above is compensated more or less by the decrease in brightness of the earth due to the absorption by the haze of some of the light reflected from it.

No appreciable variation of the total illumination was noted for different altitudes even on very hazy days. On some remarkably clear days, measurements indicated that the sky contributed about 10 per cent. of the total light received at the earth's surface at noon with the sun at about 50 degrees altitude. These results were the lowest ever obtained by the author at the earth's surface.

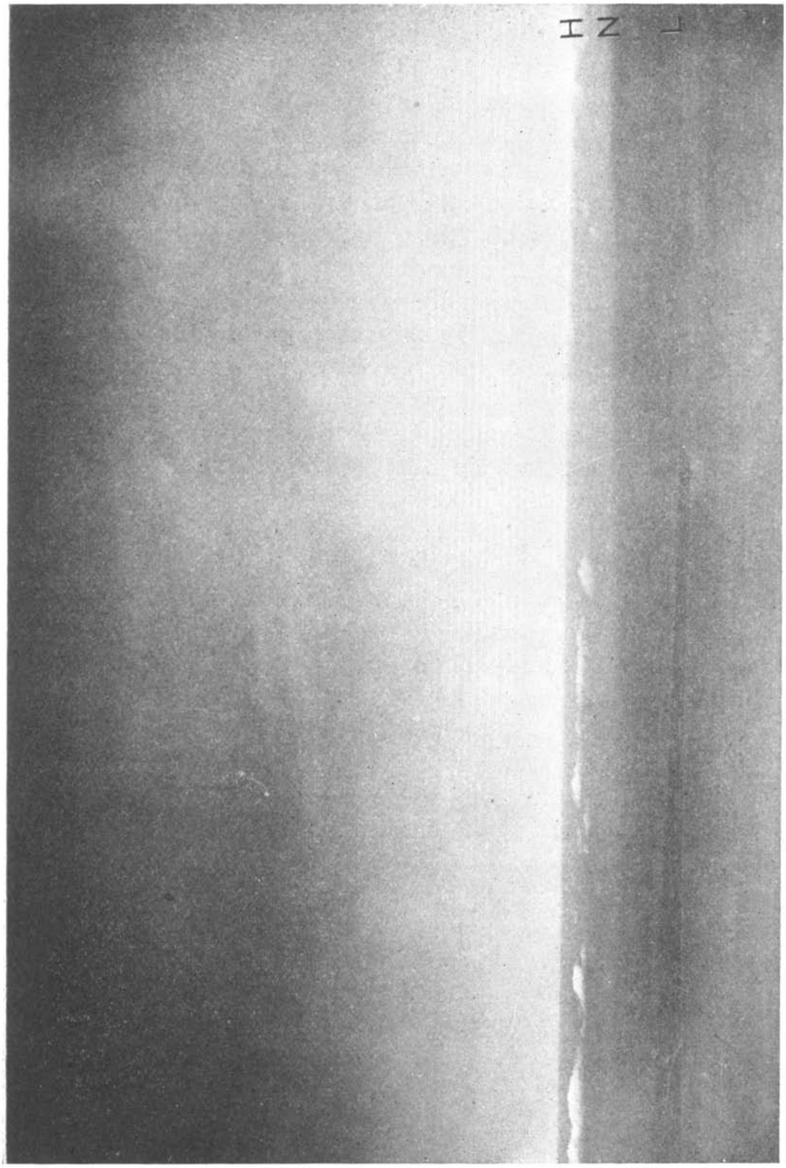
Some measurements of the ratio of upward light to downward light at altitudes of 11,000 feet indicated that about one-tenth as much light was reflected upward as was received downward. Owing to the conditions under which the measurements were made there may be large errors in the results, but they indicate the order of magnitude which checks well with what would be concluded from Table I. Measurements were made of upward light in terms of the sky brightness; that is, of the brightness of a perfectly white horizontal surface illuminated by light reflected upward from the earth, in terms of the brightness of zenith sky. These values were about 1.07 for the particular conditions. Obviously the result depends largely upon the brightness of the sky on a clear day and this varies considerably. The foregoing result was obtained on clear but moderately hazy days. This shows the futility of obtaining low visibility for airplanes, as viewed from below, by merely painting their lower sides white.

The presence and the effect of the earth haze, which ordinarily possesses a fairly definite upper surface at approximately a mile above the earth, are shown in Fig. 11. The "false" horizon due to this dust haze is clearly visible with a few cumulus clouds projecting above it like icebergs. The upper level of this haze is indicated by H on the margin of the photograph. The natural horizon N is faintly visible below H. The remaining portion below N is water with the exception of a peninsula of land (Cape Charles), indicated to the left of L. Of course, photography cannot accurately reproduce the actual effect of haze on visibility.

9. WATER.

Water forms a part of the background when airplanes are viewed against the ordinary landscape, but it is of little importance individually except as a background for seaplanes. As seen in Table I the mean relative brightness or apparent reflection-factor of inland water, as obtained by measurements perpendicular to its surface, was 0.068. Practically all the values obtained on different days were within the range from 0.05 to 0.1

FIG. 11.



Illustrating haze horizon and cumulus cloud level.

and most of them were close to the mean value. If the surface of water is perfectly smooth it will reflect at its surface about 0.02 of perpendicularly incident light. This reflection-factor varies only slightly with increasing angle of incidence until about 50 degrees is reached. It begins to increase more rapidly from this angle until obviously at an angle of incidence of 90 degrees it reflects all the light. All values in this paper were obtained by viewing the surface perpendicularly unless otherwise stated.

Owing to the fact that the brightness of an area of water, viewed from above, is due partially to specular reflection, its brightness will depend partially upon the brightness of the objects whose images are reflected. These objects are blue sky, haze, clouds, and the sun; however, the latter will be neglected in this discussion because it is a very special case. It will be seen in Table I that the mean value of the relative brightness of inland water is fairly constant on different days. In fact, this value varies surprisingly little for deep water which would be considered fairly clear. An increased brightness is noted for shallow water and for water which holds fine particles of earth in suspension. For example, measurements on the James River, about 30 miles from its mouth, gave values of 0.10 for shallow water near the shore and 0.075 in mid-stream. The latter value was very constant for its deep channel. Near Richmond where the river was very yellow, due to suspended particles of earth, the relative brightness rose to 0.20, which is very unusual. Many measurements of the brightness of water viewed normal to its surface in terms of the brightness of the zenith sky yielded a mean value of about 0.87. From the position of the observer directly overhead on clear days, the surface reflected only images of portions of blue sky regardless of the character of the waves. It is thus seen that an overwhelming portion of the brightness of the water is due to the light diffused within it. This is obvious in Fig. 10 from the definite shadows on the water cast by the clouds.

(To be concluded.)