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The Transmission of Light by Fog.

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ABSTRACT

The report describes new experiments in which the transmission of infrared light by 0.244 km of foggy atmosphere was measured in the infrared spectrum from 1 to 12μ. Transmission curves obtained with a residual ray apparatus employing quartz plates, and with an infrared spectrometer, are non-selective with wave-length and show that no regions of high transparency exist in fog out to wave-lengths at which the clear atmosphere becomes highly absorbing. The results of the experiments are in complete agreement with previous investigations of the transmission of light by natural fog and with the theory of scattering by large particles. It is now known that fog is not transparent to any usable wave-lengths of infrared light.

Existing data on the penetration of fog and haze by visible and infrared light are summarized. These data lead to the conclusion that there is no advantage in using colored rather than white visual signals in any state of weather and that infrared light is no more easily detected than white light through thick haze or fog. The extreme long wave-length region of the infrared spectrum between 13.5 and 300μ is not useful in penetrating fog because of strong absorption by carbon dioxide and water vapor in the atmosphere. Theory indicates that short radio waves 5 cm long and longer are not seriously scattered even by large particles of water such as exist in a cloudburst.

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APPENDICES

I. INTRODUCTION

1. Many investigations have been made on the transmission of visible and infrared light by fog, and they all have led to the result that, in penetrating natural fog, yellow or red or infrared light sources have no advantage over white light. This report has the two-fold purpose of describing new experiments in which the transmission of infrared light by fog was measured to longer wave-lengths than in earlier investigations, and of summarizing the known facts of transmission of light of all wave-lengths by fog.

II. TRANSMISSION OF LONG WAVE-LENGTH INFRARED BY FOG

2. Earlier data on the transmission of long wave-length infrared light by natural fog, obtained by Granath and Hulburt (1) and Hulburt (2), showed that fog becomes only slightly more transparent with increasing wave-length, and that infrared light offers no practical advantage in penetrating it. The wave-lengths employed in their experiments were 0.4 to 7μ. The measurements did not extend through the 9 to 11μ region of high transmission by water vapor and, although the distinction between absorption by water vapor and scattering by particles of water is clear-cut, it seemed desirable that experimental measurements be extended to cover this region.

3. The experiments were begun with a simple residual ray apparatus and the transmission by fog of rather broad wave-length bands was measured. Subsequently, more comprehensive measurements were made with an infrared spectrometer which permitted the determination of transmission coefficients, through the spectrum from 1 to 12μ, of several fogs of fairly uniform density. Measurements with both instruments led to the same result: that the attentuation of light by fog is uniform across the spectrum and, particularly, that no advantage is to be derived by using light of wave-length 9 to 11μ in penetrating fog.

4. The experiments were made on the bank of the Potomac River; the fogs were apparently free from smoke and probably were typical of fogs encountered at sea. The source of light consisted of two 600 watt Globar heaters at the focus of a 65cm metal mirror, 0.244 km from the point of observation. The temperature of the source was about 1200° K.

Residual Ray Apparatus

5. The residual ray apparatus is shown in Plate 1. Light from the source was focussed by the 10 cm diameter, 20 cm focal length aluminized glass mirror M_1 onto the thermocouple T after two reflections by the plane mirrors M_2 and M_3. M_2 and M_3 were two quartz plates which reflected strongly a narrow band of wave-lengths centering at about 9μ or, alternatively, two aluminized glass plates which reflected all wave-lengths radiated by the source.

6. Further purification of the 9μ reflection band of quartz was effected by the use of a differential mica filter, F, 0.1 mm thick, which became opaque at 7.5μ, where quartz begins to show metallic reflection,

while transmitting some 60 per cent of the light at shorter wave-lengths. The procedure was to take as 9μ galvanometer deflections the quantities obtained by subtracting from the total galvanometer deflection with quartz plates, the deflection obtained with the mica filter in place. Using a galvanometer of good sensitivity (0.1 μv/mm) and a scale distance of 2.5 meters, the clear weather deflection was about 400 mm, of which 300 mm represented 9μ light.

7. With the aluminum reflectors in place, the thermocouple was connected to a Rubicon galvanometer (1.25 μv/mm) the sensitivity of which was further reduced by a 2 ohm shunt to 8 μv/mm. Under this condition, the deflection obtained for the entire energy of the source was about 100 mm in clear weather. Needless to say, the shunt was removed from the galvanometer during the most dense fogs.

8. By interposing the mica filter, galvanometer deflections arising entirely from light of wave-length less than 7.5μ could be determined. Three different spectral distributions of energy were thus available for comparison: the complete energy of the source, the part of this energy below 7.5μ, and the relatively sharp reflection band of quartz at 9μ.

9. The transmission data were obtained by observing the galvanometer deflections with quartz and aluminum reflectors, with and without the mica filter interposed, and taking the ratio of these or the proper differences to corresponding deflections observed when the fog had lifted sufficiently (as it generally did) so that no further increase in energy could be measured.

10. It was soon apparent that a satisfactory measure of visibility was the total energy received from the source, and all the transmission factors were plotted with total energy (galvanometer reading with aluminum reflectors) as abscissae. The results of measurements on three separate days of fog are given in Plate 2, in which the transmission for 9μ light and light from the source of wave-length less than 7.5μ are shown. Each curve obviously is the locus of points representing transmission of the total energy of the source, so that the deviation of points representing other wave-length bands from these curves is a measure of the behavior of fog toward those wave-lengths.

11. The wave-length range of the total energy is specified rather arbitrarily on the plates as 1 to 14μ. The source emitted visible light of shorter wave-length than 1μ, but subsequent spectral distribution measurements of the energy showed that it was so weak as to contribute nothing to the energy measured by the thermocouple. At 13.5 or 14μ, the atmosphere itself becomes opaque in moderately thick layers because of strong carbon dioxide and water vapor absorption, and no light of longer wave-length reached the thermocouple. The variation of maximum total energy values for clear weather conditions meant only that the thermocouple sensitivity was not exactly reproduced for the three separate sets of measurements. This, in turn, resulted from the practice of pumping the thermocouple at intervals of two or three weeks.

12. Since galvanometer deflections with aluminum reflectors in place were used as abscissae, these were determined immediately before and after observations with quartz plates, so that a great many more measurements resulted for the broad bands 1 - 7.5μ and 1 - 14μ than for the narrower 9μ band. There was difficulty in making 9μ measurements under known conditions of fog density because of the time required for temperature equilibrium to be established between the thermocouple and the quartz plates when they were put in position, with the obvious result that often the scene changed somewhat between determination of an abscissa, with aluminum reflectors, and a 9μ measurement. This necessitated that some 9μ measurements be discarded, because it was not possible to record them except by interpolating by guess between two abscissae. Of course, all the data could have been plotted with visibilities as abscissae, but the difficulty of determining this quantity visually is great, and better consistency of results was found to exist when total energy values were used.

13. The three curves of Plate 2 show that while transmission values for the individual wave-length bands may deviate from the curve to which they belong by as much as 10 per cent, the deviation is irregular and not at all indicative that any spectral region is better transmitted than another. The single event of apparent high transmission for 9μ light occurred for the most dense fog (V = 0.2 km, curve 1) and the abscissa could not be checked at this point because of a sudden clearing; undoubtedly, this point is out of place.

14. With the same apparatus, two sets of measurements were made through thickly falling snow, and they have been incorporated in one curve shown in Plate 3. The points for 1 and 4 per cent transmission contain measurements for all the wave-lengths employed. It is worthy of remark that through snow so dense as completely to obscure the scene, no galvanometer deflections were obtained. The 9μ points lie consistently below the transmission curve for other wave-lengths, but under the difficult conditions of observing through snow in the presence of blustery winds, the effect is probably only experimental error.

Measurements with Infrared Spectrometer

15. The measurements with a crude residual ray apparatus were made under spectral resolution comparable with that of all earlier experiments on the infrared transmission by fog. The data are considered to be consistent in view of the difficulty of observing through a continually changing medium.

16. More complete data were subsequently obtained by using an infrared spectrometer with 4 cm potassium chloride prism in place of the residual ray apparatus. An image of the source was formed on the first slit by a concave mirror of 40 cm focal length, and the slit was opened to 1.25 mm, so that it received the entire image. The second slit was also 1.25 mm wide. Energies were measured with a vacuum thermocouple and galvanometer.

17. The effective slit widths, defined as the width in wave-length units of the spectral band transmitted by the second slit, were

large, being about 2μ in the 3 to 5μ region and about 0.75μ at 9 or 10μ. Regardless of the wide slits, the spectrometer enabled transmission measurements to be made under higher resolving power than has been applied to the problem heretofore and, in addition, the mechanical advantage of the spectrometer was great, since measurements for wave-lengths 1 to 12μ could be made with such rapidity and freedom from extraneous disturbances that complete transmission curves for several fogs, each of nearly constant density, were obtained.

18. The experimental measurements comprised galvanometer deflections for wave-length settings of the spectrometer at intervals of 0.5μ through the spectrum 1 to 12μ. The measurements were not made progressively through the spectrum, but at random, so that a progressive change in fog density with time might not give rise to an apparent variation in transmission with wave-length. In addition, frequent recursions to some arbitrary wave-length, usually 2.5μ, were made, and constancy of energy at that wave-length was taken to mean constant fog density. As a result of this procedure, several transmission curves were obtained for fogs known to have remained nearly constant throughout the course of the measurements.

19. Spectral distribution curves of the energy received from the source in clear and foggy weather are shown in Plate 4. The strong 6μ absorption band of water is the outstanding feature of these curves, although other atmospheric absorption bands of water at 1.5μ and of carbon dioxide at 2.7 and 4.4μ were not resolved because of the wide slits. Because the water vapor absorption is strong, it is clear that transmission curves for fog obtained by taking ratios of ordinates would be sharply modified, especially in the 6μ region, if the energy curves for clear and foggy weather were obtained through atmospheres containing different amounts of water vapor. It was thus required that clear weather measurements and those through fog be made under conditions of approximately constant humidity. This was accomplished by making the clear weather measurements as soon after the fog had lifted as possible.

20. Thus, the curves given in Plate 5 represent the transmission by fog without undue influence of water vapor. The curves 1 to 6 are essentially flat and show that the attenuation of light by fog is nonselective. Curve 1, for least dense fog, shows the greatest relative transparency in the 9μ region; but it will also be observed that three separate measurements in the 9 to 10μ region are nearly as low as those at shorter wave-lengths so that it is clear that the state of fog was not steady. The variations in transmission that occur are no greater than are allowable for thin fog under conditions of clearing. The points of curve 2 for visibility 0.8 km are also erratic. The behavior of points in the 9 to 11μ region, not determined consecutively, indicates that the scene was changing in an irregular manner. Curves 1 and 2 show clearly the nature of the difficulties inherent to measurements of phenomena not under the control of the observer.

21. The remaining transmission curves 3 to 6 were obtained under conditions of more constant fog density. No selective region of high transmission appears in any of them. All the curves show increased absorption in the 6μ region, indicating that the humidity actually was less

during the clear weather measurements than during fog, but not much less, because such a curve obtained by dividing galvanometer deflections for a foggy day by clear weather deflections of a subsequent less humid day always showed intense absorption at 6.5μ. The stronger absorption at 12 and 13μ in some of the curves may have resulted in part from drift of the galvanometer superimposed on the small galvanometer deflections at those wave-lengths.

22. The conclusion that must be drawn from consideration of all of the curves of Plate 5 is that the attenuation of light by fog particles is fairly uniform across the spectrum, and that no spectral region of optimum transmission exists.

23. Plate 6 represents measurements through falling snow which also lead to the conclusion that no significant variation in the loss of light by scattering occurs with change in wave-length. The curves were not drawn through the 6μ region of water vapor absorption because no reliable galvanometer defections could be obtained there, even though it had been possible to measure the light transmitted by fog at this wave-length. However, the sharp downward trend of each curve near the water band indicates that the humidity was lowered considerably with the cessation of snow fall.

24. It will be seen upon comparing Plate 2 with Plate 3 and Plate 5 with Plate 6 that, for a given visibility range, higher transmission of infrared light by fog than by falling snow was observed. This phenomena probably finds its cause in the increased brightness of the scene during snowfall and with snow covered ground, which may have been great enough to lower the threshold brightness difference necessary for visual discrimination between object and background. This does not mean that visible light penetrates snow more easily than fog, but only that there was more of it during snow, and that the scene was enough brighter to make the eye more sensitive to small brightness differences.

Conclusions from Theory

25. The results of this investigation do not permit the discussion of any scattering theory in detail, because they, and all others determined for natural fog, may contain experimental errors arising from inconstancy of fog density greater than the differences in calculated attenuation coefficients that might arise from different scattering theories.

26. The most complete theory of scattering by fog particles is that of Stratton and Houghton (3), in which the attenuation coefficient for any wave-length λ is given by

$$\sigma = 2\pi r^2 nK, \qquad (1)$$

where r is the radius of the water droplet, n the number of drops per cm^3 and K is a function of λ/r given in Plate 7, after Breckenridge (4). The intensity of light transmitted by fog is given by the equation

$$I = I_o e^{-\sigma Z} \qquad (2)$$

where I and I_o are transmitted and incident light intensities, respectively, e is the base of the natural logarithms, and Z is the distance in cm through which the light passes in the scattering medium.

27. It is seen that K (Plate 7) passes through a minimum value at $\lambda/r = 0.56$, which means that a fog consisting of particles all of nearly the same radius r, should show maximum transmission at the wave-length $\lambda = 0.56$ r. This phenomenon has been observed by Houghton (5) who made measurements on artificial fogs of small particle size. It is not to be expected, however, that a natural fog consisting of a wide array of particle sizes would show such a region of maximum transmission, because a summation of terms $2\pi r^2 nK$ over all the particles in the fog would flatten out such peaks of transmission.

28. Houghton (6) (7) and Houghton and Radford (8) have measured the size distribution in many natural fogs and have found that a fog contains 1 to 10 drops per cm^3 of diameters about 5 to 100 microns and with an average diameter of about 50 microns, while a cloud may contain 50 to 500 drops per cm^3 with an average diameter of 20 microns. Typical size distribution curves for fog and cloud are given in Plate 8 a-b, after Houghton (7). The ordinates of these curves are relative volumes of particles of any diameter, and are proportional to nd^3. By dividing ordinates by d^3, distribution curves showing the relative number of particles of given diameter were obtained. They are shown in curves a'-b'. These distribution curves can be used, together with Plate 7, to compute the attenuation coefficients as a function of wave-length of the cloud and fog, the computation consisting of evaluating the quantity

$$\sigma = \sum 2\pi r^2 nK / \sum n \qquad (3)$$

for each wave-length and for several particle sizes. If $\sum n = 1$, the values that are obtained apply to a cloud or a fog consisting of 1 particle per cm^3. Values of σ for the fog and cloud of Plate 8 are given in Plate 9; their magnitude is about 10^{-5} cm^2 and is comparable with the absorption coefficient of moist air in a region of moderate absorption, say 3 to 4μ (9).

29. The calculated attentuation coefficients are of the same order of magnitude as those observed for fog through which the visibility was 0.6 km curve 6 (Plate 5) and which are represented by the dotted line on Plate 9. It is seen that the computed attenuation coefficients increase slightly with wave-length, i.e., the transmission <u>decreases</u> with wave-length. This result is not important to the present discussion, because a slightly different particle size distribution in the fog or cloud could well result in attenuation coefficients constant in value with wave-length or becoming smaller with increasing wave-length. The

variations in the calculated σ values over the spectrum amount to no more than the errors of measurement in the experimental determination of the transmission of light by fog.

30. The facts of importance are, that the magnitudes of the computed and observed attenuation coefficients are about equal, and that in neither theory nor experiment are there any results suggesting that long wave-length infrared light should penetrate fog more readily than visible light.

31. Practically, since the average particle size in fog is large compared with useful wave-lengths of light, the attenuation coefficient is approximated closely enough by

$$\sigma = \sum \pi r^2 n , \qquad (4)$$

which is simply the cross sectional area, or total blocking power, of the particles and which does not depend on the wave-length in any significant way for natural fogs. This quantity is only one-half as great as the result to which (3) leads when $\lambda/r << 1$, so that K = 1 (Plate 7). The rather intricate calculations involved in evaluating K of the Stratton-Houghton theory are not given by them in detail, so that it is not easy to determine whether (3) is in error. The point is not important since in either case the result remains unchanged, that the scattering of light by large particles is non-selective.

Transmission of Light by a Moist Foggy Atmosphere

32. The proposal is sometimes advanced that the 9 to 11µ region of high water vapor transparency should also be a region of transparency in fog. This results from a misunderstanding of the nature of scattering by large drops of water, which depends only on the size of the drops and not on the transparency of the vapor from which the drops have been condensed. The experimental results of the present experiments have made it clear that the loss by scattering is as great at 9µ as at any other wave-length, but it is instructive to calculate the transmission of light through, say, a mile of moist air also containing fog. Under this condition the transmission will be greater in regions of water vapor transparency because to the non-selective loss of light by scattering will be added selective losses by water vapor absorption.

33. The attenuation coefficient of fog derived from curve 6, Plate 5, representing transmission through 0.244 km of fog with visibility about 0.6 km is, calling the transmission 0.62,

$$\sigma = 2 \times 10^{-5},$$

or for visibility 1 km, t = 0.75 (curve 3),

$$\sigma = 1.18 \times 10^{-5}.$$

When these values were used to calculate the transmission of a mile of fog of these respective densities and containing also 1 cm of precipitable water in a column of base 1 cm^2, the transmission coefficients of Table 1 were obtained. The calculations were based on the naive assumption that a mixture of scattering and absorbing media behaves in the same way as contiguous unmixed layers of these media, so that

$$I = I_0 e^{-(\alpha + \sigma) Z} \tag{5}$$

where α is the absorption coefficient of the clear atmosphere and σ is the scattering coefficient of fog.

34. Examination of Table 1 shows that the transmission of a foggy atmosphere is higher in regions of high water vapor transmission, but not significantly greater for 9 to 10μ than for green light of wave-length 0.55μ.

Observations on the Sun Through Clouds

35. Another experiment was carried out to determine whether the infrared radiation from the sun is attenuated less than the visible light. The reflecting telescope and thermocouple that were used need not be described in detail except to say that the sensitivity was such that one-millionth of the total solar radiation would have produced a measurable galvanometer deflection. When this instrument was directed toward the sun on cloudy days, no galvanometer deflection was observed when the sun was hidden from view by clouds. Additional observations were made through a selenium powder filter (11), opaque up to 2.5μ but 70 per cent transparent to wave-lengths greater than 8μ, which served to eliminate much of the intense scattered field light of short wave-length. No galvanometer deflections were obtained when the sun was not visible to the eye.

36. There seems to be no basis in fact for claims that the sun can be detected through clouds by its infrared radiation when it is not visible to the eye.

Summary

37. The experiments that have been described in this chapter have established the result that natural fog scatters all wave-lengths of light from 1 to 12μ equally. This result is in agreement with earlier measurements which extended to 7μ. The new information has been added that wave-lengths greater than 7μ do not penetrate fog more readily than shorter wave-lengths. It follows that no practical advantage is to be gained in employing infrared light in "seeing" through fog.

38. It may be well to point out that smoky fogs consisting of small particles through which the sun's disc appears red instead of pearly white would be expected to show greater transmission in the infrared than in the visible spectrum. In looking at the sun through fog it should be kept in mind that the sun appears red even in clear weather when its altitude is low because of molecular scattering by the air; and in this case it would appear red through intervening fog, even though the fog consisted of large particles.

III. REVIEW OF INVESTIGATIONS ON THE TRANSMISSION OF LIGHT BY FOG.

Photographic Infrared and Visible Light

39. The popular conception that yellow or red or infrared light penetrates fog better than white light arises in part from the known fact that aerial mapping and photography of distant objects through aerial haze are best done with infrared plates. However, the distinction between the scattering action of clean air or air containing a few dust particles on one hand, and that of thick haze or true fog on the other is well defined; for, light passing through long columns of clear air is scattered selectively, and the intensity of the transmitted light is relatively greater at longer wave-lengths. But as the haze thickens and the particles grow larger, the advantage of the longer wave-lengths quickly disappears.

40. The selective molecular scattering by dust free air is described by the Rayleigh (12) law

$$I = I_0 e^{-\sigma Z}$$

$$\sigma = 32 \pi^3 (\mu - 1)^2 / 3 n \lambda^4 . \qquad (6)$$

μ is the index of refraction of air, n the number of scattering molecules per cm^3, λ the wave-length of light, and Z the light path in cm. The loss of light by scattering can be calculated from (6) for clean air containing no dust. Table 2, taken from Hulburt (13), gives values of σ for the visible spectrum. There have been added to the table the calculated transmission factors of 5, 20 and 100 miles of air, and the advantage of the longer wave-lengths in penetrating the atmosphere is obvious; for it is seen that the transmission falls off rapidly with decreasing wave-length. The light lost from the beam is scattered in all directions and the part of it that reaches the observer constitutes a veiling glare which reduces the brightness difference between objects and the background, and, therefore, the visibility. Consequently, elimination of the strongly scattered light of short wave-length by a filter opaque to it results in greater contrast on the plate and extended photographic range.

41. Aside from the fact of greater penetrability of red light through haze, the contract of the photographic material itself contributes to "plate visibility". A plate of high contrast will record an image of a brightly illuminated area of the scene much more sharply delineated from neighboring darker areas than will a plate of lower contrast.

42. Although a yellow or a red filter increases plate visibility, it would not increase the eye visibility through haze, because any filter successfully removing the blue scattered light would at the same time reduce the apparent brightness of the scene. This effect is overcome photographically by increasing the exposure time when a filter is used.

43. As the atmosphere becomes increasingly impure by the presence of dust particles upon which water condenses to form thick haze, the advantage of the longer wave-lengths becomes smaller. Hulburt (13) (14) and Mohler (15) have made comparative photographs through haze and fog using panchromatic and infrared plates. The panchromatic plates gave a "plate visibility" identical with the eye visibility. The several types of infrared plates were sensitive to the wavelength range 0.76 to 1.02μ. The results of both investigators showed that when the eye visibility was already great, say 5 to 20 miles, the infrared plate visibility was about 1.8 times greater, but when the eye visibility was only 1 or 2 miles, the infrared plate visibility was only 1.1 times greater - that is, when the visibility was poor, the use of infrared light did not extend it by a significant amount.

44. Clark (16), on a round crossing of the Atlantic, made many photographs using infrared plates with results in agreement with those of Hulburt and Mohler and from which he concluded that "..... in no case where the fog was a serious menace to navigation was there any advantage gained by the use of infrared photography".

Visible Light

45. Experiments with visible light have been made by Breckenridge and Nolan (17), who observed flashes from neon light, white light, and white light covered with a red filter giving approximately the same spectral distribution as that of the neon light. The observations were made at Moody Point, Maine, in clear and foggy weather, in daylight and at night, over distances of 1.19 to 4.35 miles. They concluded that there was no difference in the visibility of the neon light and red filtered light of the same horizontal candle power, and, more significantly, that the addition of a red filter to the white light did not increase its range under any conditions of weather.

46. The measurements of Hulburt and Granath (1) showed that the transmission of visible light by fog increased slightly with wave-length, and Benford (18) obtained a similar result; but in neither case was the effect sufficiently great to suggest the use of long wave-lengths in penetrating fog. The results of Hulburt and Granath, for example, gave transmission factors for 400 meters of fog through which the visibility was 600 meters. The observed values of transmission increased from about 11 per cent for green light to 14 per cent for red light and 15 per cent for infrared light of wave-lengths 1.4 to 3μ. Hulburt has satisfactorily explained the effect by applying the Stratton-Houghton formula (1) to an assumed fog consisting of a great many small particles of diameter 0.15μ, which would be more transparent to longer wave-lengths, and a few large particles of diameter 30μ, which would scatter light non-selectively with wave-length. The large particles in such a fog account for most of the loss of light while the small particles determine the

form of the transmission curve. The small observed increase in transmission at longer wave-lengths is good evidence that the fog did contain small particles; even so, the increased transparency at long wavelengths was not great enough to be of interest. On the other hand, Clark (19) has reported a private communication from Houghton, who stated that he has observed the transmission coefficient of natural fog to be constant from 3500 to 10000 A.

47. All the measurements on the transmission of visible light by fog clearly show that there is no gain in replacing white lights by colored lights either in navigational aids or in searchlights. A beacon containing a colored light may be more easily distinguished among white shore lights than a white light beacon because of the color contrast, but the colored beacon would not be visible at a greater distance through fog than white light of the same brightness.

Signalling by Means of the Scattered Light

48. The preceding discussion applies to the transmission of the direct, unscattered beam of light through fog. The unscattered light can be formed into an optical image and, therefore, definitely identifies the position of the source. The part of the light that is lost from the beam by scattering illuminates the cloud but does not permit location of the source.

49. Langmuir and Westendorp (20) have considered the possibility of signalling by means of the diffuse scattered light within the cloud to an aviator flying above the cloud but unable to find the airport beacons because of general illumination from city lights. In this case, flashing lights directed vertically upward would periodically increase the diffuse illumination in the fog and enable to aviator to distinguish between airport lights and city lights. In order to determine what colors of light would be most useful for such beacons, experiments were made in which flashes of white and colored lights were superimposed on a background illuminated with white light, varying the intensity of the flashes of light until they could just be seen by the observer, and measuring the threshold intensity at which they were definitely recognized. It was found that flashes of white light on a white background were more easily perceptible than flashes of colored light which means that even when fog obscures beacons from view, there is no advantage in using colored lights.

Direction Finding with Scattered Light

50. An observer in a cloud so dense that beacons can not be located sees only the scattered light which illuminates the cloud all around him, and the intensity of the scattered light is greatest toward the source. Langmuir and Westendorf (20) have given a theoretical discussion of the case, and they have showed that by employing a modulated source of light and a tuned receiver consisting essentially of two photoelectric cells placed back to back so that they see the diffusely scattered light from opposite directions, it would be possible to direct flight of the plane by finding the position of the photoelectric cells at which each sees the same light intensity. Then the indicating device of the receiver would show no reading and the plane of the two

photoelectric surfaces would pass through the source. Such a device does not appear to have been put to actual use for direction finding purposes, and if it were practicable it probably would not compete with the radio direction finders for blind flying.

Far Infrared

51. The infrared measurements described in Chapter II extended to 12 or 13µ, and at those wave-lengths the scattering by fog particles was found still to be independent of wave-length. At longer wave-lengths the atmosphere becomes increasingly opaque because of the strong carbon dioxide absorption band at 15µ and the rotation spectrum of water vapor extending from 18µ to well beyond 100µ (21). Although long wave-length light, say 50 to 100µ, would be expected to penetrate fog more readily than visible or near infrared light, it can not be used because of the opacity of the atmosphere, even if sources of light rich in those wave-lengths were available.

52. Experimental data at still longer wave-lengths are available only for 314µ light, which is emitted by quartz enclosed mercury arcs. Rubens and Wartenberg (22) observed the absorption at this wave-length by a 40 cm tube of water vapor, at 100°C and 76 cm pressure, to be 50 per cent. This is less than the absorption of 100µ light, which was 80 per cent under the same conditions, but is still so great that the light would be completely extinguished by a relatively short layer of normally moist air. In addition, the intensity of the 300µ light from mercury arcs is so weak that the most sensitive laboratory devices are required for its measurement.

Radio

53. The transition region of the spectrum between wave-lengths 0.3 mm and 1 cm has not been completely explored, nor are there any data on the transmission of radio waves of length 1 to 20 cm by fog, but it would appear that the loss by scattering is not great. Stratton (23) has made a theoretical investigation leading to the results given in Table 3, which show that the loss by scattering is negligible for waves of length 5 to 100 cm, transmitted through any state of fog or rain. In Table 3, σ is the theoretical scattering coefficient and Z is the distance in km through which the wave must travel to be reduced to one-tenth its original intensity. Stratton has also estimated that for 1 cm waves, Z is 1.3×10^2 km in moderate rain, neglecting true absorption by water vapor.

IV SUMMARY AND CONCLUSIONS

54. All investigations of the transmission of light by natural fog have shown that for wave-lengths 4000 A (blue) through the visible spectrum and to 12µ in the infrared, the attenuation by scattering is non-selective and that white light is as useful as any other group of wave-lengths in penetrating fog. The addition of yellow or red filters to a white light source can have only the effect of reducing the distance at which the light can be seen. Colored light of whatever wave-length and white light, if they produce the same visual sensation in clear weather, will be equally visible through fog.

55. Photography of distant objects through light haze with infrared plates succeeds because haze consists of relatively few small particles which scatter short waves more strongly than longer ones. When the haze becomes thick enough so that the eye visibility is reduced to 1 or 2 miles, the advantage of infrared light in penetrating it disappears.

56. Infrared light of wave-length greater than 13μ is of no use because the clear atmosphere is opaque to it.

57. Radio waves of length greater than 5 cm are not seriously attenuated by scattering, even by raindrops.

58. It must be concluded that optical signalling devices employing special filters and reflectors for which unusual properties are claimed have no merit so far as fog penetration is concerned.

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TABLE 1

TRANSMISSION OF LIGHT BY MOIST FOGGY ATMOSPHERE

Wave-length μ	Transmission by 1 cm precipitable water vapor	T for water and 1 mile of fog	
		V = 1 km	0.6 km
.55*	98.3 per cent	14.0 per cent	4 per cent
.75 – 1	93	13.8	4
1 – 1.25	89	13.2	3.8
1.25 – 1.5	51	9.5	2
1.5 – 2	70	10.5	3
6 – 7	0	0	0
7 – 8	2	0.3	0.1
9 – 11	100	14.8	4.3
11 – 12	93	13.8	4

* From data of Table 2.

TABLE 2

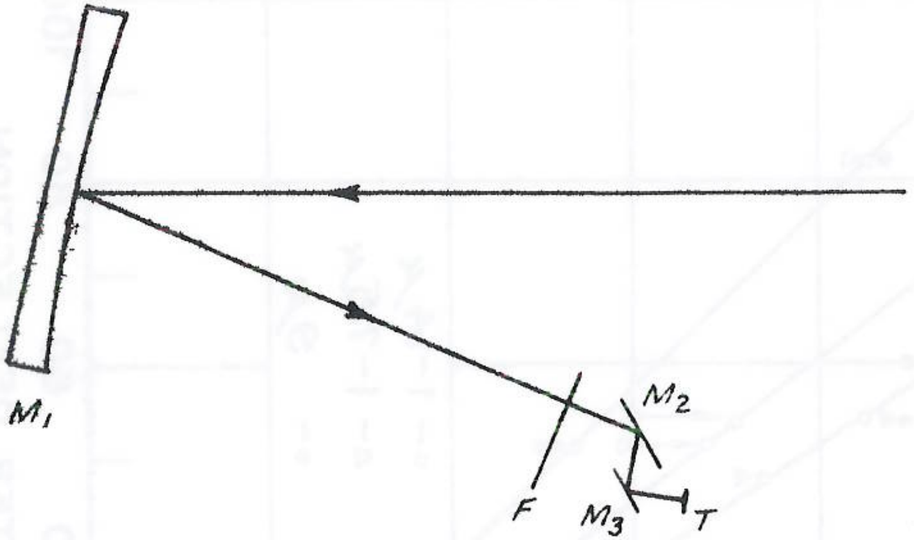
TRANSMISSION OF CLEAN AIR

Wave-length	σ	Transmission 5 miles	 20 miles	 100 miles
7000 A	0.040×10^{-6}	0.97	0.88	0.53
6500	0.054	0.96	0.84	0.42
6000	0.075	0.94	0.78	0.30
5500	0.107	0.92	0.71	0.18
5000	0.160	0.88	0.60	0.07
4500	0.240	0.83	0.47	0.02
4000	0.400	0.73	0.28	-
3500	0.680	0.58	0.11	-
3000	1.350	0.34	0.01	-

TABLE 3

SCATTERING COEFFICIENTS σ , AND DISTANCES Z (km) IN WHICH WAVE-LENGTHS λ ARE REDUCED TO ONE-TENTH THEIR ORIGINAL INTENSITY, (after Stratton).

	Particle Diam. (mm)	λ = 100 cm		λ = 50 cm		λ = 10 cm		λ = 5 cm	
		σ	Z	σ	Z	σ	Z	σ	Z
Cloudburst	3 - 5	8.86×10^{-13}	2.6×10^{9}	1.4×10^{-11}	1.6×10^{6}	8.86×10^{-9}	2.6×10^{5}	1.4×10^{-7}	1.6×10^{2}
Moderate rain	1.00	16.9×10^{-16}		2.7×10^{-14}		16.9×10^{-12}	1.3×10^{6}	2.7×10^{-10}	8.5×10^{4}
Fog	0.01							5.7×10^{-18}	4×10^{12}



RESIDUAL RAY APPARATUS

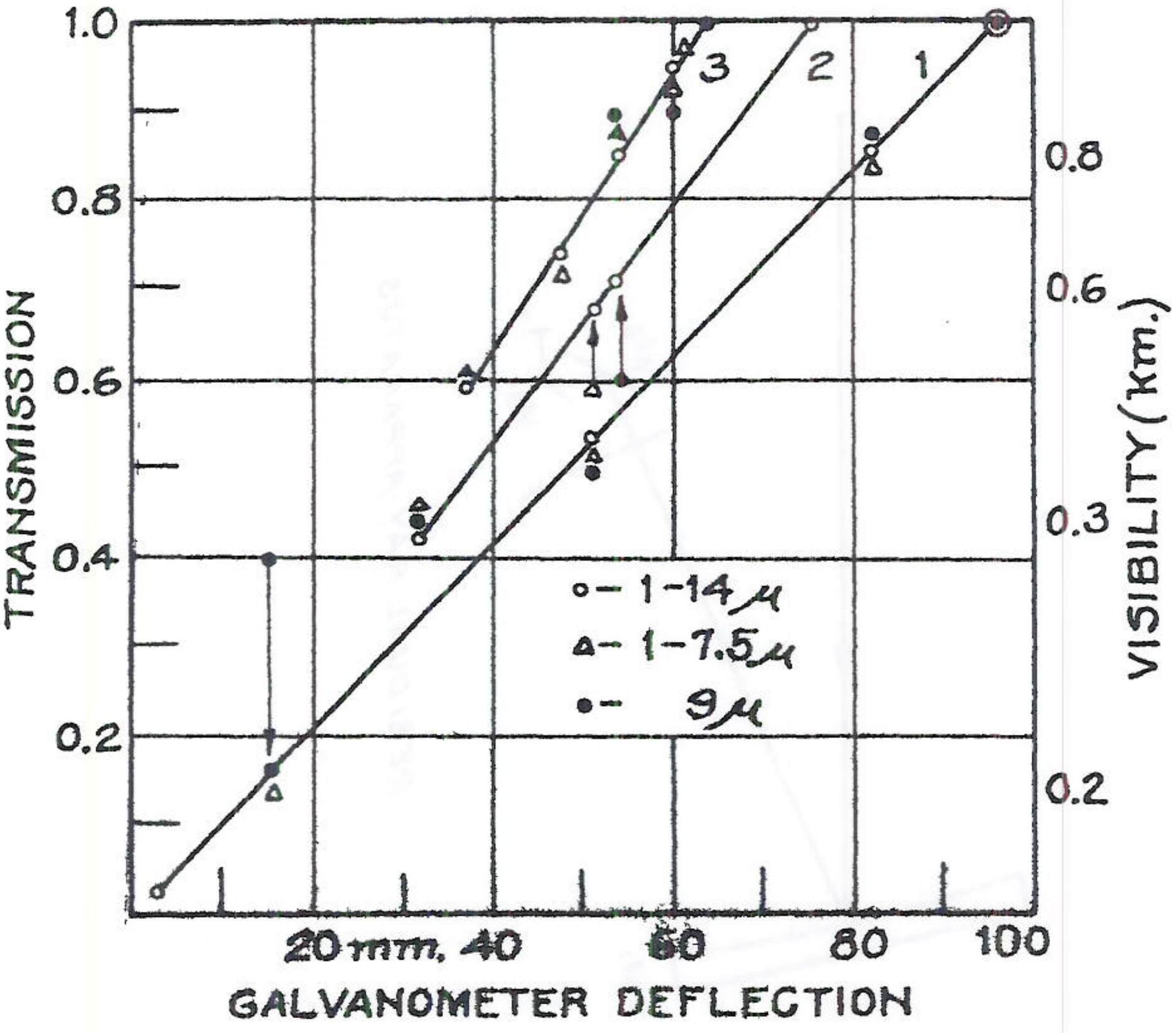

1.0
0.8
0.6
0.4
0.2
TRANSMISSION
0.8
0.6
0.3
0.2
VISIBILITY (km.)
3
2
1
○ – 1-14 μ
△ – 1-7.5 μ
● – 9 μ
20 mm. 40
60
80
100
GALVANOMETER DEFLECTION

PLATE 2

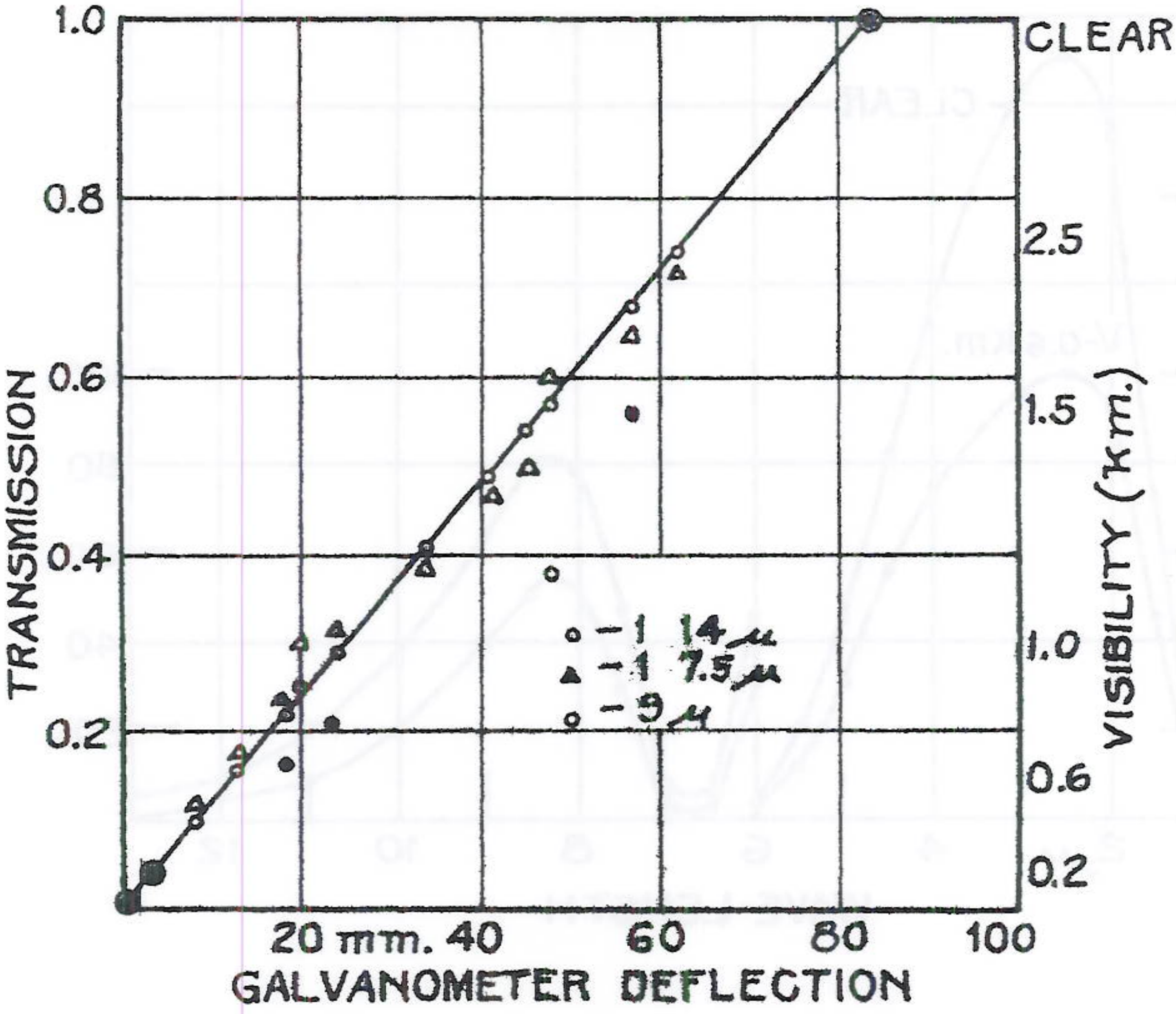

1.0
0.8
0.6
0.4
0.2
TRANSMISSION
CLEAR
2.5
1.5
1.0
0.6
0.2
VISIBILITY (Km.)
○ – 1 14 μ
▲ – 1 7.5 μ
○ – 9 μ
20 mm. 40
60
80
100
GALVANOMETER DEFLECTION

PLATE 3

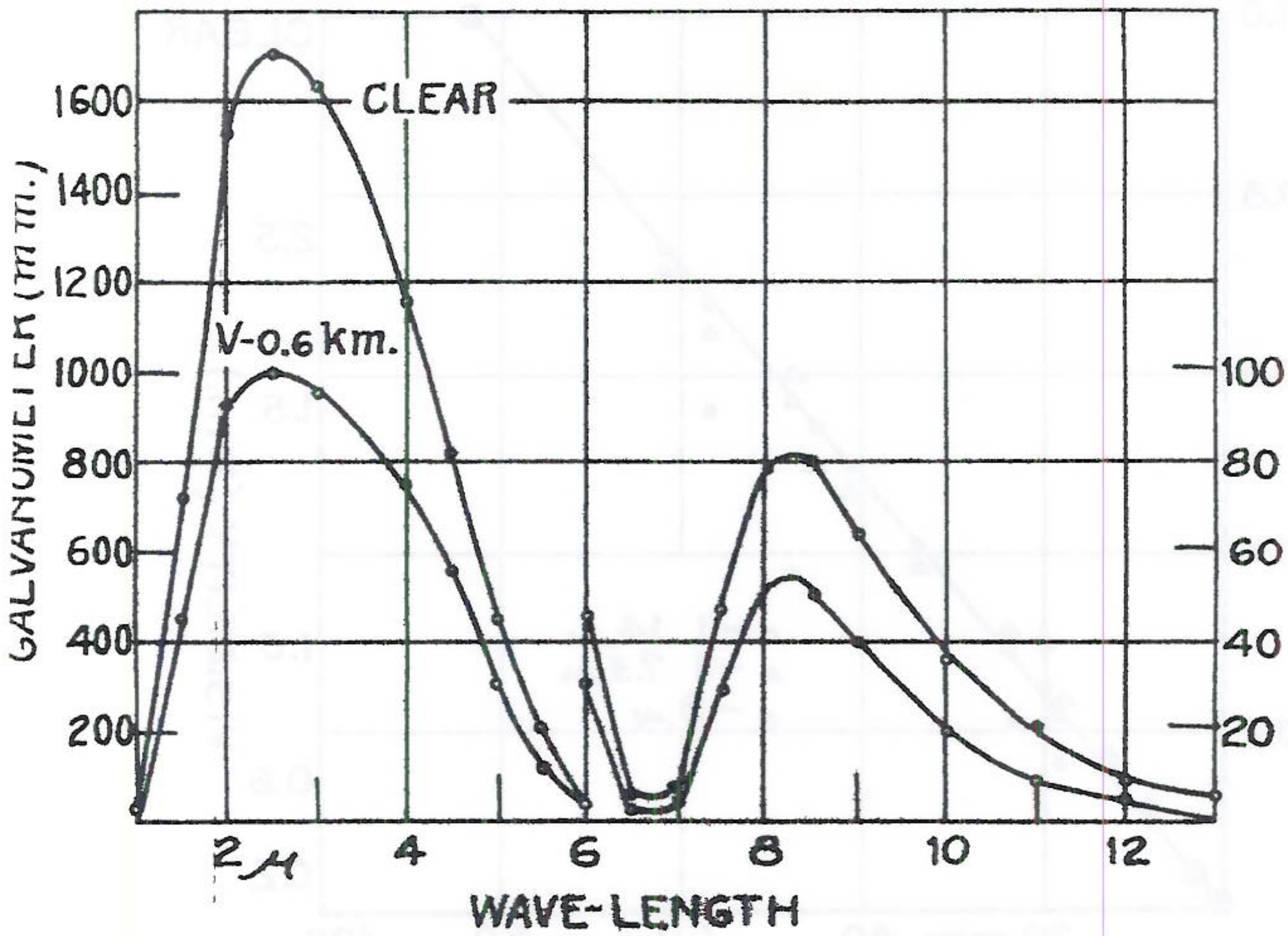
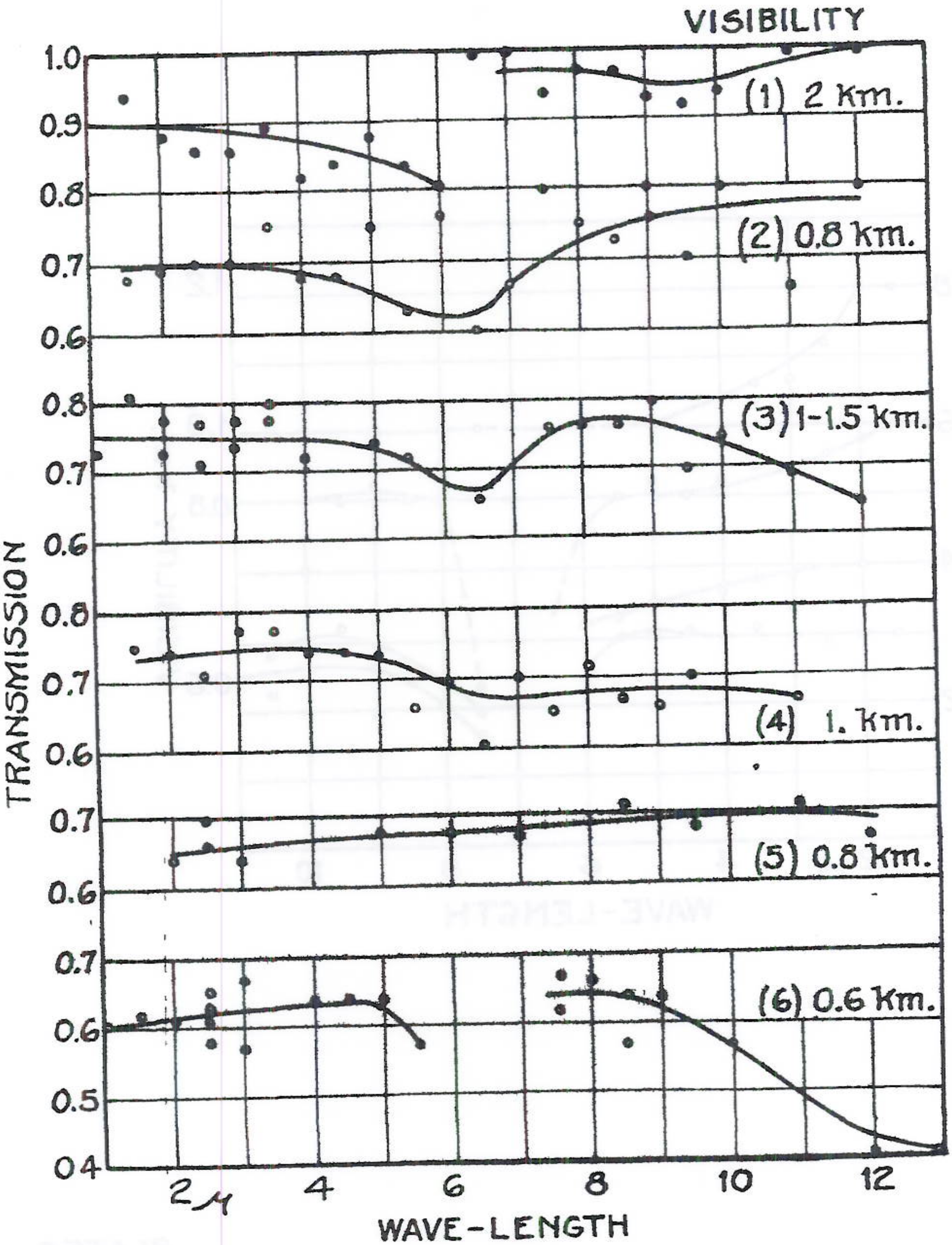
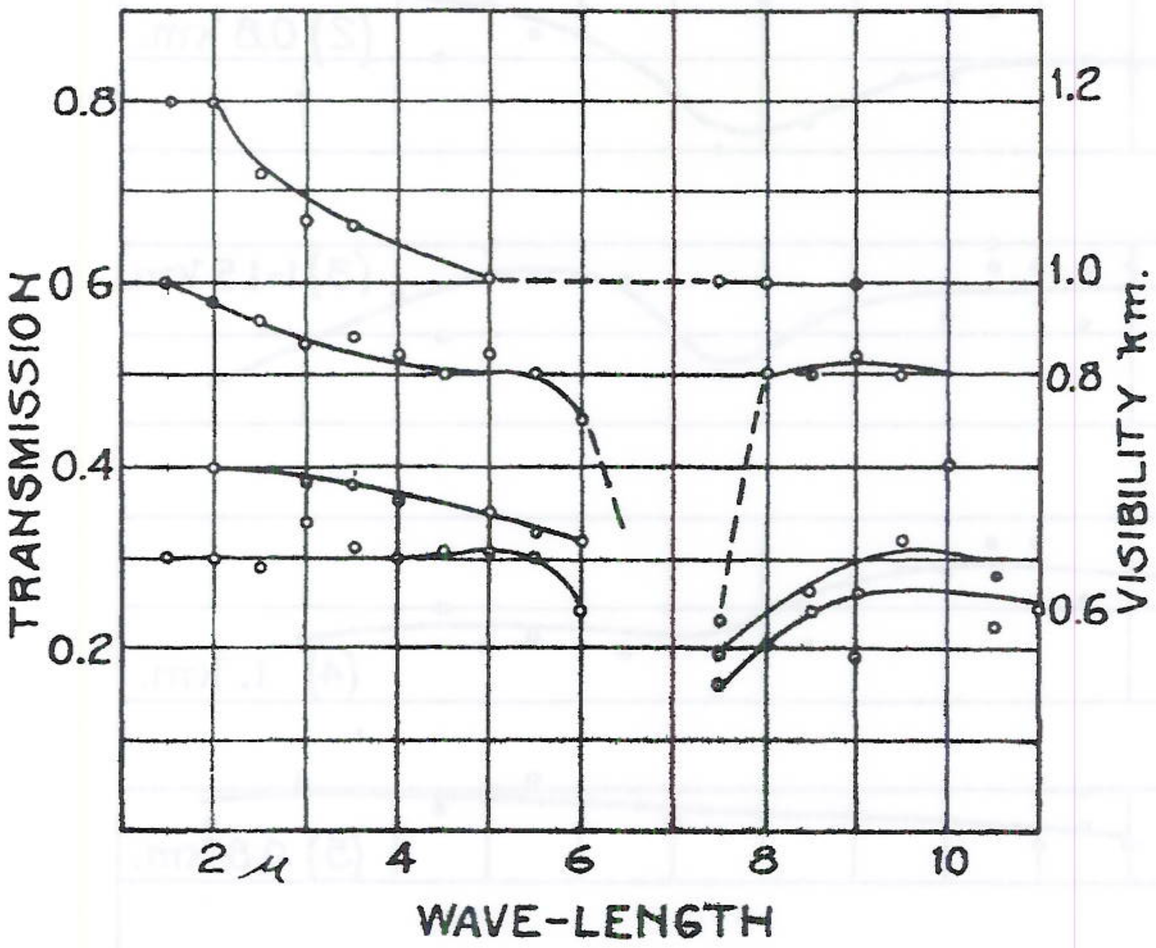

GALVANOMETER (mm.)
1600
1400
1200
1000
800
600
400
200
CLEAR
V-0.6 km.
100
80
60
40
20
2μ
4
6
8
10
12
WAVE-LENGTH

PLATE 4



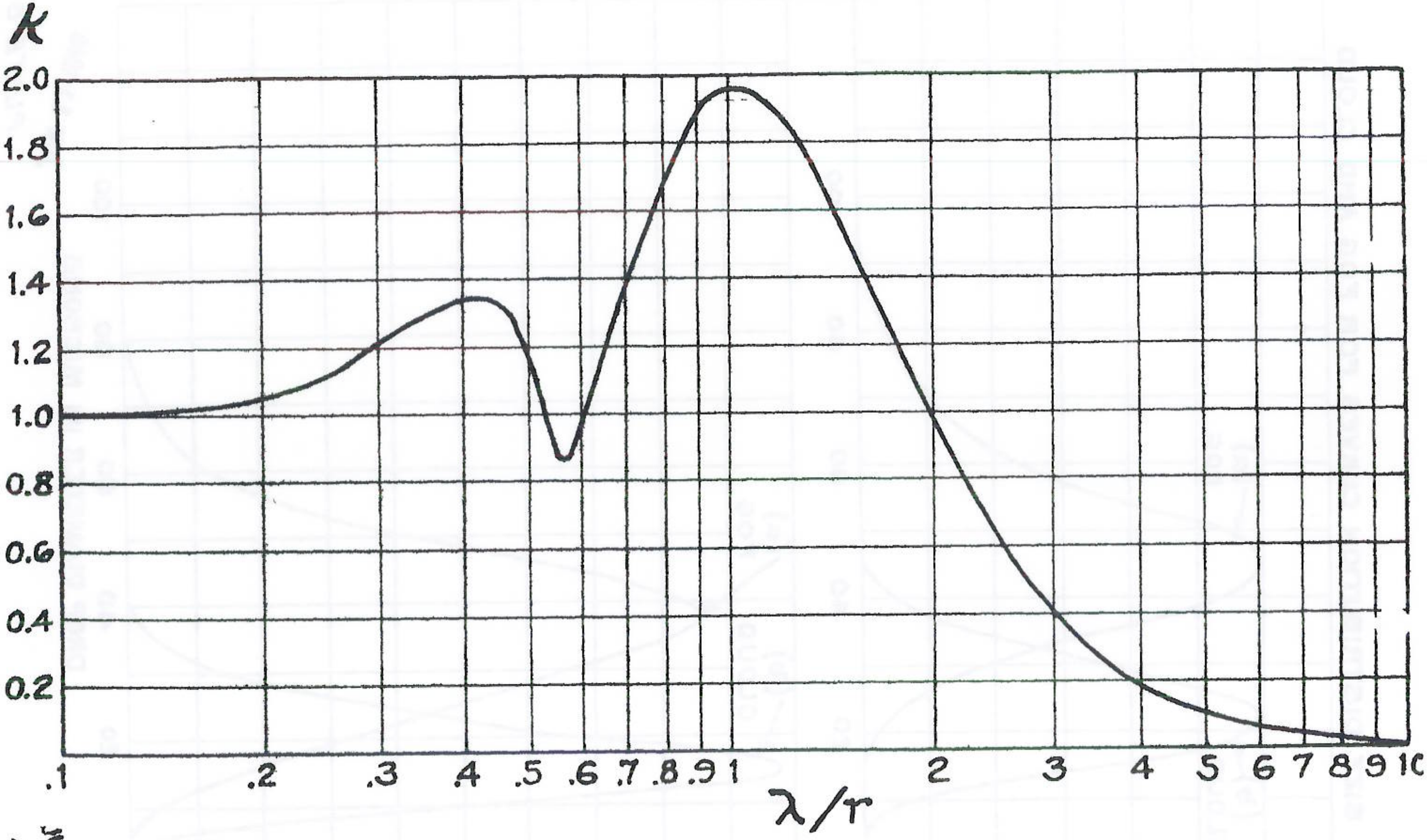
VISIBILITY
(1) 2 km.
(2) 0.8 km.
(3) 1-1.5 km.
(4) 1. km.
(5) 0.8 km.
(6) 0.6 km.
TRANSMISSION
1.0
0.9
0.8
0.7
0.6
0.8
0.7
0.6
0.8
0.7
0.6
0.7
0.6
0.7
0.6
0.5
0.4
2 μ
4
6
8
10
12
WAVE-LENGTH

PLATE 5



TRANSMISSION
0.8
0.6
0.4
0.2
VISIBILITY km.
1.2
1.0
0.8
0.6
2 μ
4
6
8
10
WAVE-LENGTH

PLATE 6



June 11 1940

PLATE 7

SIZE DISTRIBUTION CURVES FOR FOG AND CLOUD

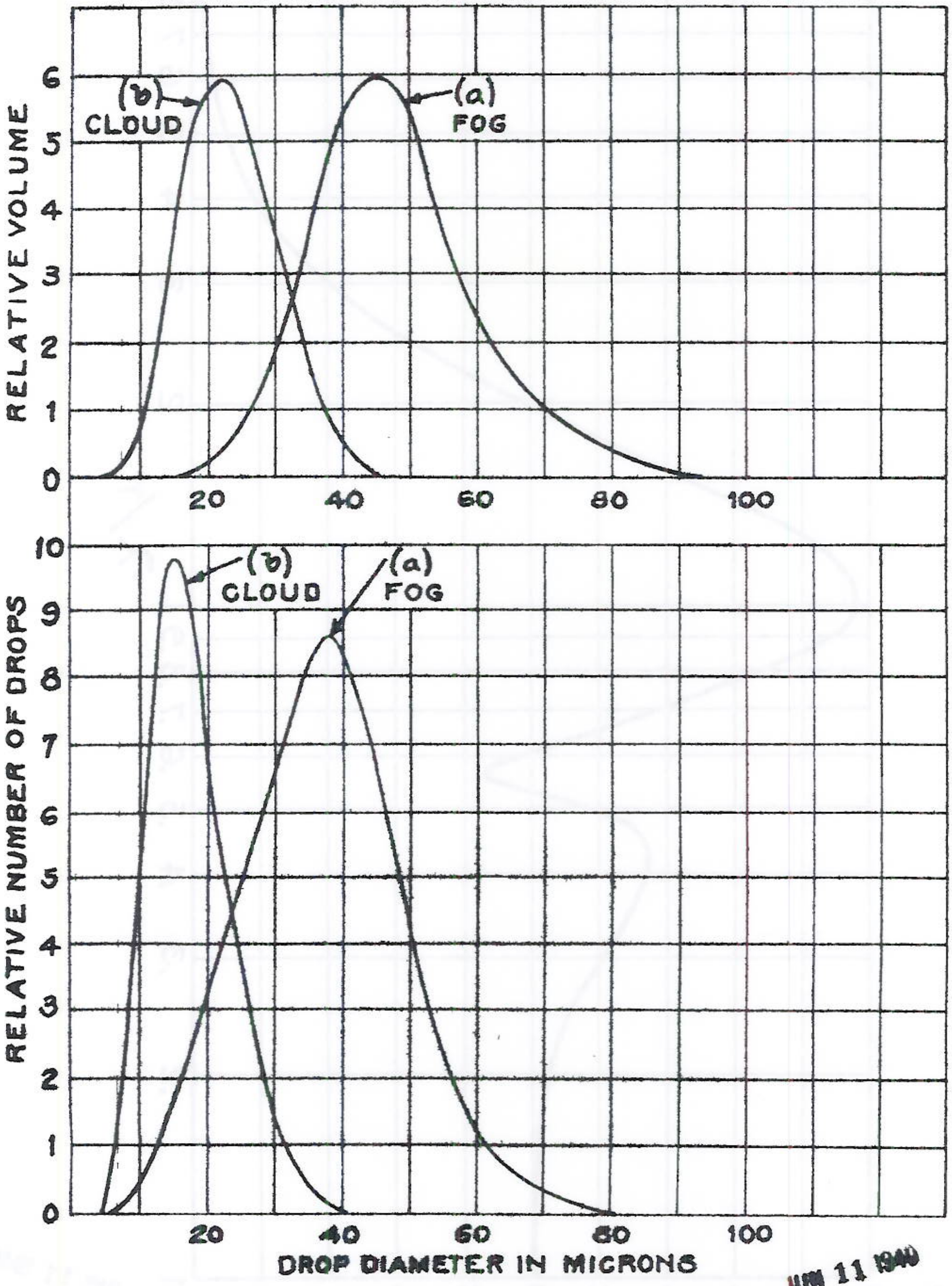


PLATE 8

ATTENUATION COEFFICIENTS FOR FOG AND CLOUD

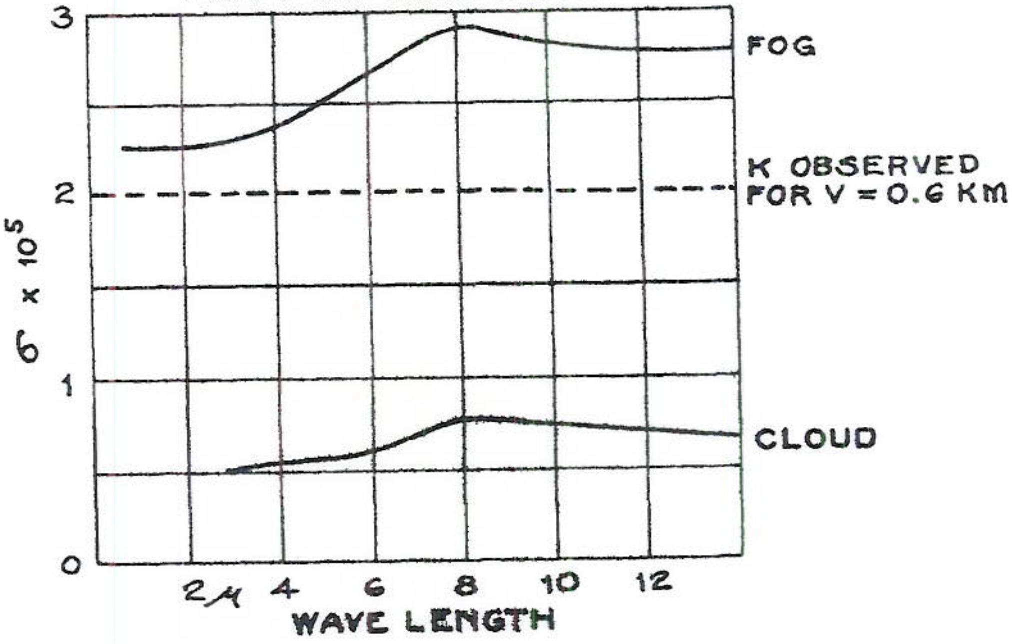


PLATE 9