DECLASSIFIED

FR-1036

Report No. H-1036
On the problem of visibility.

[redacted]

REPORT No. H-1036

DATE 7 March 1934

SUBJECT

REPORT ON THE PROBLEM OF VISIBILITY

DEPARTMENT OF THE NAVY · BUREAU OF ENGINEERING

DECLASSIFIED by NRL Contract
Declassification Team
Date: 15 APR 2014
Reviewer's name(s): H. Do, P. Hanna

Declassification authority: NAVY
DECLASS GUIDE, 11 DEC 2012, 03 SERIES, 05 SERIES

BY

NAVAL RESEARCH LABORATORY

BELLEVUE, D. C.

DISTRIBUTION STATEMENT A APPLIES
Further distribution authorized by UNLIMITED only.

CLASSIFICATION CHANGED TO UNCLASSIFIED
BY AUTHORITY OF 2628-506; HWS:dl
7 May 57 Reference Authority Ser 3367
(DATE)
(Signature of Custodian)

DECLASSIFIED

7 March 1934

Report No. H-1036

NAVY DEPARTMENT

BUREAU OF ENGINEERING

REPORT ON

The Problem of Visibility.

NAVAL RESEARCH LABORATORY
ANACOSTIA STATION
Washington, D.C.

Number of pages: Text - 15 Plates - 4.

Authorization: Director, Naval Research Laboratory and Hydro. 2nd end. H4-9(170052) of 6 Sept.1932.

Date of Tests: Tests conducted 1927 - 1933.

Reported by:

E.O. Hulbert, Physicist.

Approved by:

H.R. Greenlee, Captain, USN,
Director.

Distribution:
C.N.O. (1)
BuEng. (1)
BuOrd. (1)
BuC&R. (1)
BuAero. (1)
Hyd.Off.(5)
War College (1)
P.G. School (1)

[redacted]

vmh

TABLE OF CONTENTS

APPENDICES

[redacted]

A B S T R A C T

Some remarks, mostly trivial, are made about visibility at night, visibility from airplanes, contrast meters, gray color of ships, and comouflage of ships to achieve invisibility.

Experiments showed that some improvement in seeing in daylight was occasioned by the use of polarized light and infra-red photography and little or no improvement by the use of color filters and of dark adapted eyes. Experiments indicated a faint chance that paint of concealed spectral character, and red lights with red filters, might possess naval utility.

It is suggested that the Navy decide whether it wishes to make use of camouflage of ships to deceive, and if so, to envisage finding out how to do it.

A detailed description of the NRL visibility meter is given.

[redacted]

INTRODUCTION

The subject of visibility has been of concern chiefly in military circles and not to scientists in general, for published scientific work on visibility is practically non-existent. In this Laboratory various experiments dealing with visibility have been carried out from time to time. Some of these have been reported completely; others have been mentioned in brief notes and others have not been the subject of record. In the following pages are gathered together various experiments and ideas bearing on the problem of visibility and its ramifications. Not all of the items are of equal importance. Some of the experiments gave negative or unpromising results, some are unfinished, and some of the questions have as yet received no answer at all. Various suggestions are offered for further experiments.

"Visibility" may be defined as the maximum distance at which an object can be seen. It depends on: (a) the haze in the atmosphere, and (b) the color and illumination of the object and the background. These are discussed in Chapters I and II, respectively.

Visibility also depends on the inhomogeneity of the atmosphere, caused by hot and cold streaks which give mirage effects, on the size of the object, on obstructions between the observer and the object, such as the curve of the earth, on the goodness of eye-sight of the observer, etc. These we propose to neglect by making the following assumptions, that the atmosphere is of uniform refractivity, that the object is fairly large, that there are no massive obstructions, that the observer has good eyes, good binoculars, etc.

[redacted]

CHAPTER I

VISIBILITY AS DETERMINED BY HAZE IN THE ATMOSPHERE.

1. Measurement of visibility on the surface of the sea. This problem may have two aspects, one for war and one for peace conditions. In other words, one may be ready or willing to use apparatus for peace conditions which, because it is too elaborate or takes too much time, etc., is not desirable for war conditions. And in war conditions one may be ready to put up with some sort of approximate method which would not satisfy him in times of peace.

To measure visibility as determined by atmospheric haze requires some standard which we take to be a ship of moderate or large size painted gray under full daylight illumination on the open sea. Obviously, the visibility of the ship will depend to some extent on whether the weather is cloudy or clear and on the position of the sun with respect to the ship and the observer. But we dodge this complication by remarking that there will be some distance at which the ship can just not be seen because of the obscuration due to the haze. It is this distance which the method should measure, with full recognition that the measurement is of a quantity which is not very definite or accurate, and can only be pinned down within fairly wide limits, say, within 20%.

The direct method is to have two ships and to let one steam away from the other until it just disappears through the haze. A method similar in principle is to have a known target at a known distance, at least a mile, and to make certain optical measurements of its brightness. Direct methods of this sort are, of course, the best and may or may not be regarded as worth the trouble. They would probably be considered practicable only in times of peace.

Another type of method which has often been proposed requires apparatus only in the space of a ship. It involves the measurement of the light absorption of a sample of the atmosphere by apparatus on the ship from which is inferred the visibility at considerable distances from the ship. The method, however, demands an accuracy difficult, indeed practically impossible, of attainment on shipboard, and involves the assumption that the air over a wide area have the same optical characteristics as those of the shipboard sample. It is not known whether anyone has used the method successfully; we have attempted to and failed.

A method which has been suggested is based on the known fact that the atmospheric potential gradient varies with the visibility. From various researches (1) the conclusion is clear that one could distinguish between

---

(1) Chree, Proc.Roy.Soc., 95, 210 (1919); Wait, Terr.Mag., 36, 125 (1931); Schweidler, Jahrb.f.Rad.u.Elekt. 18, 1 (1921); etc.

[redacted]

thick fog and clear atmosphere by an atmospheric potential measurement, but that thin hazes could not be so distinguished. The same conclusion holds for dust counts or droplet counts of samples of the atmosphere.

Humidity has no direct relation to visibility; the visibility may be good with the humidity high or low and the visibility may be poor with the humidity high or low.

The NRL visibility meter made use of the fact that the ratio of the brightness of the sea near the horizon to that of the sky near the horizon is a function of the visibility. The instrument is described in detail in Chapter III. It has been tested at sea and further tests are underway.

2. <u>The measurement of visibility at night</u>. It is somewhat uncertain whether the measurement of visibility at night is really a problem or merely an inchoate idea; or, in other words, it is not certain whether anyone wishes to measure the visibility at night. Two definitions of night visibility may be mentioned which are concerned with two different situations: "night visibility" may be defined (1) as the maximum distance at which a ship's navigational lights may be seen, and (2) as the maximum distance at which a moderate or large sized gray ship, with no lights, may be seen.

To measure the night visibility the direct method is the best, that is, by observing a ship moving away to known distances, or by measuring the brightness of a known light at a known distance. This sort of method is ordinarily impracticable.

Obviously, the night visibility varies with haze, clouds, moon, the state of the sea, etc. Two experiments directed toward a measurement of night visibility as it depends on haze are as follows: (1) Turn a searchlight in a horizontal direction and, from a station at 50 or 100 yards away from the searchlight, make some sort of measurement of the beam of light such as the apparent length of the beam, or the degradation of brightness along the beam, etc. Some measurable quantity of the beam may be discovered which depends on the haze in the atmosphere, and this in turn may be related with the visibility by a series of calibration experiments. (2) In case that a visible searchlight is undesirable one might contemplate similar observations of the beam of an ultra-violet searchlight. It is known (2) that one can see

---

(2) NRL Report H-1017 "Signalling and Detection with Ultra-Violet and Infra-Red Radiation".

---

the ultra-violet beam from such a searchlight by means of an ultra-violet telescope or by photography.

[redacted]

3. Visibility from airplanes. At present only very hazy notions are available about the visibility from airplanes. It seems a waste of time for a person on the ground to attempt to define the term or to consider what to measure and how to measure it. The ideas can best be made definite by someone with much flying experience.

4. Improving seeing by the use of color filters. For seven years we have experimented with many kinds of color filters, either colored gelatin or colored glasses, at sea to find out if they would improve seeing. In general there was no improvement of sufficient magnitude to be of value. Almost never were conditions at sea experienced under which one could see something with a color filter which could not be seen as well or better without the color filter. This is a sweeping statement and like all such statements not entirely true. It is not the purpose here to attempt to state the opposing ideas and to show wherein they are wrong. We merely reiterate the foregoing experimental conclusion and add a further fact in its support, namely, that color filters are available everywhere, yet there are practically none in use on the bridges of ships, except, perhaps, for amber or dark glasses which are worn to reduce the glare, but everytime the wearer wishes to look at something intently he takes off the glasses.

The question may be asked, "True, you have experimented with a large number of color filters, but certainly there are thousands of dyes and dye combinations which yield many color filters, dichroic, polychroic, with complex patterns of absorption bands which have not been tried. May not some of these offer possibilities not brought out by those already tested?" The answer is almost certainly in the negative, for the spectral distribution of the light of objects at sea and of the background of sea and sky contains usually no sharply marked absorption bands, and the inclusion of various new tints or absorption bands or transmission bands would not be expected to lead to any important novel effects of seeing.

In a war-time report is described experiments in which an observer on the ground looked at airplanes through various colored filters. The conclusion was stated that a blue filter made an improvement in seeing the planes. We have repeated the experiments with all the filters which we had, over 75, but were unable to find any which improved matters very much.

All of our experiments with color filters were done from surface ships at sea, nothing was done from the air. It may be suggested that here is a problem worth investigation, namely, to test out all kinds of color filters from planes at sea looking down at ships, etc., to find out if the seeing can be improved. As far as available information goes, the problem is untouched at the present time at sea.

5. Improving seeing by the use of dark adapted eyes. An experiment may be mentioned which gave a negative result. The idea was that perhaps the observer might do better with color filters if his eyes were dark adapted. He was shut up in a dark room in which there was a small hole giving a view over a clear, misty or hazy scene (down the Potomac River). Over the hole various color filters were placed. It was found that using dark adapted eyes under these conditions was no improvement over light adapted eyes.

Actually, of course, when lightish filters were used, such as yellow, amber or green, the eyes did not remain entirely dark adapted. When deep red, purple or blue filters were used the eyes remained fairly dark adapted.

6. Improving seeing by the use of infra-red photography. It is possible by the use of infra-red plates and good cameras to photograph distant objects which are obscured by haze. The gain of the infra-red plate visibility over the eye visibility was practically zero in thick or moderate fog and increased as the haze became thinner. For example, experiments (3), (4) showed that objects could be photographed at 1.2,

---

(3) NRL Report H-1022 "Photography with Infra-Red Plates".

(4) Rawling, "Infra-Red Photography", 1933.

4, 8 and 300 miles when the haze and fog were such that the objects could just be seen with the eye at 1, 3, 6 and 150 miles, respectively. It was suggested (3) that further experiments with infra-red photography at sea might be of value.

7. Improving seeing by the use of polarized light. Experiments at sea with binoculars equipped with polarizing prisms improved the seeing under bright weather conditions. The investigation is described in a recent report (5) and it seems unnecessary to repeat it here. The report may be

---

(5) NRL Report H-1017. "The Polarization of Light at Sea"; Hulburt, J.O.S.A. 24, 35 (1934).

---

consulted for details of use and effectiveness of polarizing binoculars and the polarizing sextant.

CHAPTER II

VISIBILITY AS IT DEPENDS ON THE COLOR AND ILLUMINATION OF THE OBJECT AND THE BACKGROUND.

1. Camouflage of ships to achieve invisibility, and contrast meters. Camouflage of ships to achieve invisibility was attempted vigorously during the war with, as far as is known, complete failure, for nothing successful of this sort was put into practice.

In connection with the experiments there were developed three meters called "visibility" meters. It would be better to term them "contrast" meters. The meters were all based on the same principle and were developed independently by Jones (6) of the Eastman Kodak Company in America, by Wigand (7) in Germany, and by Bennett (8) in England (the Bennett-Cassella visibility meter). The meter consisted of a telescope through which the object and the background were viewed. Then a series of absorbing screens were placed over the field of view until the scene became so dim that the object was just discernible. The thickness or number of the absorbing screens gave a measure in arbitrary units of the "visibility" of the object, or more exactly, the "contrast of the object with its background". One of the meters used absorbing screens, two used ground glass screens, and the suggestion was made that instead of the screens a dazzle light could be thrown into the field and the intensity varied until the object was just blotted out. The essential principle and purpose of the three instruments were, as far as is known, identical.

---

(6) Jones, Phil.Mag. 39, 96 (1920).

(7) Wigand, Phys.Zeit. 20, 151 (1919); 22, 484 (1921); 25, 212 (1924).

(8) Bennett, Nature, November 12, 1932, page CLV.

---

2. The Navy gray color of ships. Painting a ship gray is, after a fashion, an attempt to make it invisible, or to reduce its visibility. The question has often been raised whether the present Standard Navy Gray is the best color and the suggestion offered that a particular shade of gray might be the best for certain areas, and another shade for other areas, etc. We had this question in mind when, during a voyage in the Caribbean Sea in 1931 we made measurements of the color and brightness of the sea and sky by means of a Munsell Color Chart. It was concluded, although with considerable uncertainty, that perhaps a slightly lighter shade than the Standard Navy Gray might be better. It was suggested that records of the number of times a Navy ship at a distance appeared lighter than the background, sea or sky, and the number of times it appeared darker, might be of value. In such observations the "contrast" meters of the previous section

might be a help. This is the only suggestion which has been made of a way to employ the "contrast" meter profitably.

However, it seems reasonable to think that the exact shade chosen for a Standard Navy Gray is perhaps of no great importance. For in general the darkness or lightness of the color of a distant ship would appear to depend much more on the illumination, as against or away from the sun, than on the exact shade of its paint.

3. The Navy gray color of submarines. The question has often been asked, Why are submarines painted a Standard Navy Gray? One would think that a darker shade would be better. The submarines are almost always seen against a water background and are usually lighter than the background, for Navy gray is more suited to a sky background.

On several separate and independent occasions the Navy has conducted tests in which aviators flew over submerged submarines, and has concluded each time that painting the horizontal structures of the submarines black rendered them less visible to the airplane observer.

4. Camouflage of ships to deceive. Camouflage of ships to deceive was accomplished with some success during the war by painting large designs and spots on the ships in such a way that an observer misjudged, or was supposed to misjudge, the course of the ship. Just what success was achieved is unknown at this Laboratory. The principles of the design were worked out in this country, and perhaps reports on the work were made. We have been unable to find any such reports.

It is believed that it is of importance for the Navy to consider the question of deceptive comouflage; in the advent of war the question might be among the first to arise. If it is decided that deceptive camouflage is desirable, an attempt should be made to obtain the reports of the wartime work, or to rewrite them and put them away on file. To do this it may be advisable to get the aid of the group of men who did the work during the war.

Enough is known at this Laboratory, and it is about all that we do know at present, to make us appreciate the fact that one can not achieve successful deceptive camouflage in a haphazard manner or by an untrained guess. It is thought that the general principles are simple and that from these a program of effective camouflage patterns could be drawn up suitable to various types of ships.

5. Invisible paint for recognition insignia. It is possible to prepare two paints of apparently the same color and brightness, which, however, contain a concealed spectral difference, so that when viewed through a proper color filter they appear different, for example, one appearing dark and the other light. On this idea two gray paints were made which matched Standard Navy Gray in appearance. On looking at these paints and Standard Navy Gray paint through a red color filter, one of the paints, No. 1, appeared lighter than the Navy gray and No. 2 darker, almost black. Insignia about 10 feet in size were painted on the sides

of certain Navy ships using No. 2 for the central portion of the design and edging this with a wide margin of No. 1. The design was imperceptible to the unaided eye but seen through the red filter stood out against the Navy gray background as a dark marking with a light margin. Tests during a cruise on the Pacific Ocean showed that the designs could be seen through the red filter up to several miles when well illuminated by sunlight, but not as far as the distance at which the ship could usually be recognized by other features, such as silhouette, etc. The range at which the design could be seen depended upon the conditions of illumination, whether the design was in the sunlight or shadow, etc. It was therefore concluded that the secret paint insignia offered no important advantages for surface ship recognition purposes from surface ships. Further tests with marking the ship for recognition from airplanes were contemplated.

If, however, deceptive camouflage were adopted it may be that paint with concealed spectral characteristics put in the camouflage pattern may have some possibilities. The suggestion is rather hazy and can not be made definite until more is known about the types and conditions of use of the camouflage patterns.

6. Visibility of red lights seen through red filters. It is an old suggestion that the visibility of a red light may be increased by viewing the light through a red color filter. Thus, in daylight a red light on a ship at sea, two miles away, or a red light on land with a background of trees will not be visible, if the intensity is not too great, merely because the contrast of the light with the background is so low that the light is invisible or is not conspicuous. Whereas if the observer views the scene with a red color filter the red light is plainly visible because the background and the glare of daylight is much darkened and the red light is not obscured by the filter.

Preliminary experiments at distances up to 1,000 yards showed that the visibility of a moderately bright red light in the daytime was increased by roughly a factor of 1.5 or 2 when the observer used a properly chosen red filter. In the experiments the sky and the Potomac River were used as backgrounds. That is, without the filter the light could not be readily seen at distances beyond 500 yards, and with the filter the range was increased to about 1,000 yards. It was concluded that the effects were not very striking, but that further experiments with brighter lights and greater distances at sea would be necessary before one could say with certainty what possibilities, if any, the system offered. For one could not infer from these preliminary observations what sea conditions would bring out. Perhaps the most promising case would be to have the red light on the deck of a surface ship and view it from an airplane.

[redacted]

CHAPTER III

THE NRL VISIBILITY METER

1. Introduction. The NRL visibility meter, developed in the past two years, was worked out to enable an observer to measure the visibility at sea as dependent on haze, simply and quickly by means of apparatus on the ship without the necessity of artificial targets at a distance from the ship. Actually, natural targets are used, the sea and the sky. Preliminary tests of the meter at sea have been encouraging; further tests are underway. At present it is not known how satisfactory the instrument will turn out to be. It can not be said to be very accurate and it has the limitation that it can only be used in the daytime and when the sea is ruffled by a breeze.

2. General principle of the instrument. If the sea is ruffled by a breeze the sky near the horizon is much brighter than the sea near the horizon when the atmosphere is clear, i.e. good visibility. In thick haze or fog, i.e. poor visibility, the sky and the sea near the apparent horizon are more nearly the same brightness. a and b, Plate 1, are photographs toward the horizon when the visibility was 15 and 3 miles, respectively. Since the relative brightness of the sea and sky near the horizon varies with the visibility, a measurement of their relative brightness properly calibrated yields a measurement of the visibility. This is the fundamental principle of the instrument.

3. Calibration. Denote the visibility by v, where the visibility is the maximum distance that a moderate or large sized object can be seen through the haze in the daytime. Define t for a breezy day by

$$t = \frac{\text{brightness of sea near horizon}}{\text{brightness of sky near horizon}}, \qquad (1)$$

where "near the horizon" means the region from the apparent horizon to about 2° from the apparent horizon.

With a small photometer t was observed during daylight at sea along the Atlantic Coast for a series of values of v mainly on days free from clouds, v being taken from the distance of known islands, headlands, lighthouses, etc. The observed values of t were averaged and a smooth curve was drawn through them. The curve is shown in curve 1, Plate 2, and the values of t are given in Table 1; this is the calibration curve.

[redacted]

TABLE 1

Visibility v nautical miles	t
0	1.00
1	.65
2	.62
3	.58
4	.53
5	.48
6	.42
7	.38
8	.35
9	.32
10	.29
11	.27
12	.25
13	.24
14	.23
15	.22

Curve 1 was found to be approximately independent of the altitude and bearing of the sun for the sun more than 20° above the horizon and avoiding the zero bearing of the sun, i.e. directly down the sun path. Curve 1 was found to remain approximately unchanged as the breeze increased from 3 to 25 knots and for altitudes of the observer from 5 to 50 feet above sea level. If these relations had not been true, that is, if t, besides varying with haze, had been found to be dependent upon such things as the position of the sun, the height of eye of the observer, the state of the sea, etc., the entire method would have been discarded at once as impracticable. As a matter of fact, the relations are in general only approximately true.

If the sea is mirror calm the method fails, for in this case there is, of course, no difference in the brightness of the sea and sky at the horizon, i.e., $t = 1$, for all values of the visibility.

4. <u>Description of the visibility meter</u>. A photograph of the NRL visibility meter is shown in Plate 3. It consisted of a small telescope, actually, one barrel of a 6 power 30 mm objective pair of binoculars was used. Across the field of view could be slid an optical wedge of gelatin cemented with balsam between glass plates. The wedge slid across the upper half of the field of view, the lower half being unobstructed by the wedge. The telescope was pointed at the horizon so that the lower edge of the wedge was in approximate coincidence with the horizon, the sky appearing in the upper half, and the sea in the lower half of the field of view. The wedge was then slipped along until the sky was darkened to be of the same brightness as the sea. At

the point of setting the transmission of the wedge gave v from the calibration curve 1, Plate 2. In the instrument the visibility v was marked on the wedge by means of laboratory measurements of the transmission of the wedge and curve 1, Plate 2, so that the observer read v directly.

Since the sky and the sea vary in brightness and also slightly in color it was found most suitable to use a yellow green color filter in the telescope and a yellow green optical wedge. In this way the observer matched two fields of the same color which differed only in brightness. If, for example, a blue wedge was used, a good color match of the sea and the sky was obtained on clear days but not on gray days.

5. Tests on the Pacific Ocean. The NRL visibility meter was tested (9) at sea near the California coast, mainly in the San Pedro

---

(9) Lieut. W.E. Gist, USN, "Report of Test of NRL Visibility Meter No. 1", September 9, 1932.

San Diego area. Two of the curves given by Gist are plotted in curves 2 and 3, Plate 2, curve 2 being for a clear sky and curve 3 for a uniformly cloudy sky. It is seen that there is fair agreement between curves 1 and 2. The curves were obtained, as far as can be judged, under similar conditions of clear sky, curve 1 being obtained near the Atlantic Coast and curve 2 near the Pacific Coast.

6. Accuracy and sources of error. It is known that even in the laboratory it is difficult by visual photometry to adjust two fields to be equal in brightness with an accuracy of less than about 3%, unless special and rather elaborate optical devices are employed. And in using the visibility meter under shipboard conditions at sea, an accuracy of less than 10% in a single reading of t was hard to achieve. From Table 1 it is seen that an error in t of 10% amounts to an error in v of about 50, 20 and 20% for visibilities 2, 6 and 12 miles, respectively. So that under normal working conditions an accuracy of v greater than 20% is hardly to be expected. The accuracy of the mean of a number of observations might be reduced below 20%.

The error just mentioned is inherent in the instrument. There is another error arising from external causes, sometimes very large, due to the fact that the sky is a non-uniform and erratic source of light due to clouds. The visibility meter can give a correct value of v only if the sea-sky scene obey the t,v relation of Table 1. And certain cloud distributions in the sky disturb this relation. Thus, we had the experience of "wild points", that is, occasionally a reading of the instrument made with apparent care gave an obviously wrong visibility. At first it was not understood why this was so, although it was realized that light and shade effects of scattered clouds often had something to do with it.

The matter has recently become clear as the result of a new fact brought to light in the investigation of the polarization of light at or $$\left[i_w = \tau\int_{x_1}^{\infty} \alpha i_{30}\, \varepsilon^{-\beta x}\, dx\right]\varepsilon^{-\beta x} + \int_0^{x_1}\alpha i\, \varepsilon^{-\beta x}\, dx$$

$$= i\frac{\alpha}{\beta}\left(\tau\gamma\varepsilon^{-2\beta x_1} + 1 - \varepsilon^{-\beta x_1}\right) \quad , \qquad (3)$$

where $\gamma = \frac{i_{30}}{i}$ (4)

From (1) $t = \frac{i_w}{i_s}$ and from (2) and (3)

$$t = \tau\gamma\varepsilon^{-2\beta x_1} + 1 - \varepsilon^{-\beta x_1} \qquad (5)$$

If the brightness of a ship or object be b_o, its brightness at a distance x_b from the observer is b where

> b = the light of the ship b_o degraded by absorption in reaching the observer plus the light of the haze between the ship and the observer,

or $$b = b_o\,\varepsilon^{-\beta x_b} + \int_0^{x_b}\alpha i\, \varepsilon^{-\beta x}\, dx$$

$$= b_o\,\varepsilon^{-\beta x_b} + i\frac{\alpha}{\beta}\left(1 - \varepsilon^{-\beta x_b}\right) \qquad (6)$$

Define the visibility to be the distance away of the ship or object when its contrast with the background is small, or, in other words, let x_b be the visibility v when

$$\frac{b}{i_s} = 1 \pm e \qquad (7)$$

where e is small compared to 1.

Substituting (2) and (6) into (7) yields

$$V = \frac{1}{\beta}\,\log_{\varepsilon}\frac{1}{e}\left(\frac{b_o}{i}\,\frac{\beta}{\alpha} - 1\right) \qquad (8)$$

[redacted]

The ratios $\frac{b}{i}$ and $\frac{\beta}{\alpha}$ are approximately independent of changes in haze and (8) becomes approximately

$$v = \frac{a}{\beta} \qquad (9)$$

where a is constant with changes in haze.

From (5) and (9) we obtain

$$t = r\gamma\varepsilon^{-2\frac{a x_1}{v}} + 1 - \varepsilon^{-\frac{a x_1}{v}} \qquad (10)$$

This is the relation between t and v which is the calibration curve of the visibility meter.

The ratio γ of the brightness of the sky at 30° to the sky at the horizon depends on the haze, cloudiness and direction of the sun. γ was measured on a number of days of varying visibility; some of the values for conditions of few clouds are given in Plate 4, the smooth curve being a rough average. For a cloudy sky and v = 10 miles γ was 1.6 to 2. For the visibility below 2 to 3 miles due to thick haze or thin fog it made little difference in γ whether the sky was cloudy or not.

From (10) the t,v curve was calculated with r = 0.20 and using γ from Plate 4, the curve being passed through the observed point t = 0.53 v = 4 miles to determine the unknown constant $a x_1$. The t,v curve is given in curve 4, Plate 2, and is seen to agree fairly well with the observed curves 1 or 2. The deviation at the high values of v is within the error of observation, and the departure at the low values is perhaps due to many factors left out of the theory, such as the decrease of visibility with total illumination, etc.

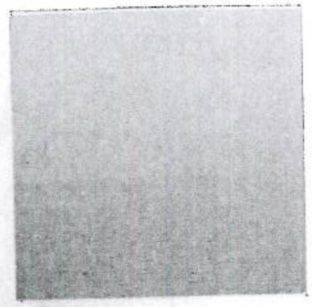
The theory is in accord with the observed fact that for v constant t is greater for a cloudy than for a clear sky. For example, for v = 10 miles and a clear sky γ was 0.75 and from (10) t = 0.32. For v = 10 miles and a cloudy sky γ was roughly 2 and from (10) t = 0.46.

8. Conclusions and discussion. The conclusion at present seems to be that the principle of the visibility meter is theoretically sound and that the instrument may be expected to give satisfactory results only under the following circumstances:

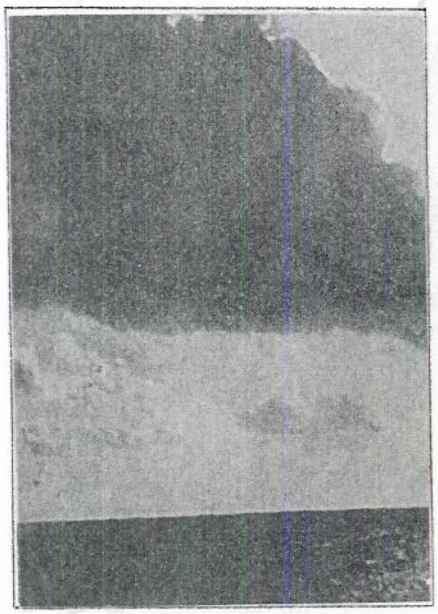
(a) that the sea be ruffled by a breeze,
(b) that the sky be uniformly clear, or uniformly hazy, or uniformly cloudy, from the horizon to about 30° above the horizon on the bearing where the visibility is to be determined. Just how many clouds are necessary to disturb the uniformity of a clear sky is unknown.

a

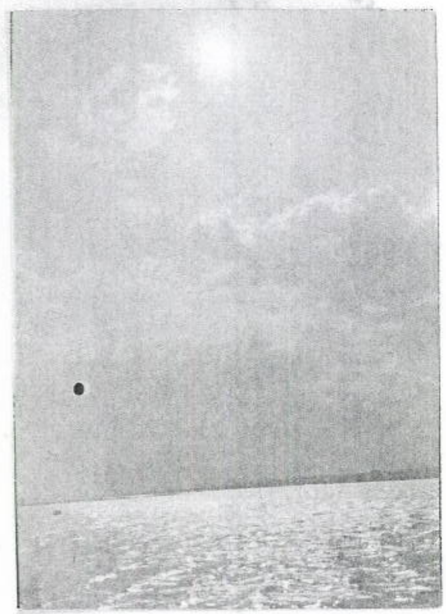
b



c

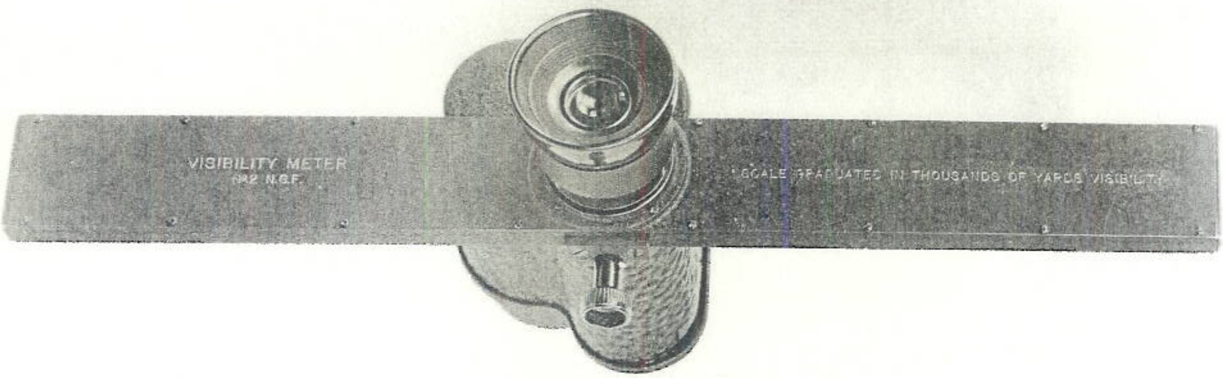


d



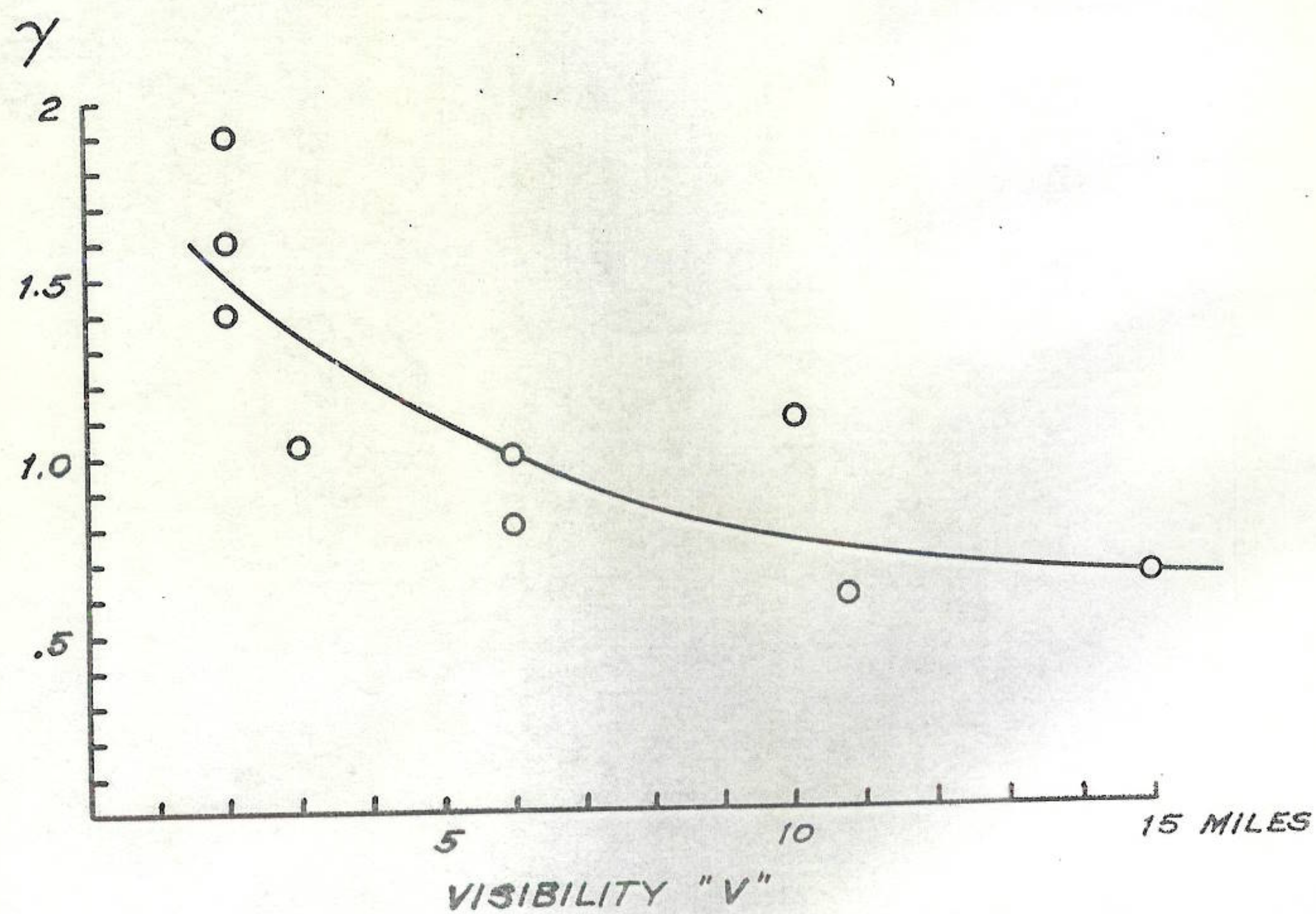
Photographs of sea and sky.

PLATE 1



NRL Visibility Meter

[redacted]



SKY BRIGHTNESS CURVE

PLATE 4