Royal Meteorological Society

ESTIMATION and MEASUREMENT of the VISUAL RANGE

by

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CANADIAN BRANCH

25¢

VOL. 3 NO. 7

Published by

ROYAL METEOROLOGICAL SOCIETY, CANADIAN BRANCH

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The Secretary,
Royal Meteorological Society, Canadian Branch
315 Bloor Street West,
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THE ESTIMATION AND MEASUREMENT

OF THE VISUAL RANGE

by

W. E. K. Middleton

National Research Council, Ottawa, Ontario.

Presented at the regular monthly meeting of the Royal Meteorological Society, Canadian Branch, Toronto, Thursday, October 30, 1952.

THE ESTIMATION AND MEASUREMENT

OF THE VISUAL RANGE*

I propose to talk this evening about observations of visibility, and to try to suggest some ways in which they could be improved. We all know that these observations are really very rough estimates that frequently leave a great deal to be desired. I propose to document that statement; and I shall also say something about the special problems that arise when an attempt is made to use these observations at large airports in thick weather.

We had probably better begin by discussing some of the elementary theory which describes the obscuring of distant objects by the atmosphere. It is a very common observation that if you stand on a hill and look out over a distant landscape, the objects farther away look lighter in colour and often bluer than objects nearby until, when an object is far enough away, it is so nearly as bright as the sky behind it that the two cannot be distinguished apart and the object cannot be seen. Similarly, if we look at a series of lights at night, those farther away appear fainter because the light on its way to the eye is partly absorbed and partly scattered by the intervening atmosphere.

This second case is the simpler of the two, and the law controlling it was discovered about 200 years ago by Bouguer, a very famous French physicist. Bouguer's Law is expressed by the following equation

$$F = F_0 e^{-\sigma r}$$

where σ is a quantity known as the extinction coefficient which describes the absorbing and scattering properties of the atmosphere, r the distance of the lamp at which we are looking, F the light flux in the pencil of light that we are considering, and F_0 the flux in the same pencil just as it left the lamp. There are other ways of writing Bouguer's Law of which a useful one is as follows

$$F = F_0 \tau^{r}$$

where, in this case, τ is known as the transmissivity, and is equal to $e^{-\sigma}$ where e is the base of natural logarithms.

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* Contribution from the Division of Physics, National Research Council of Canada

The same quantity σ (or τ) appears in the expression for the apparent luminance* of a dark object seen through the atmosphere in daylight. This Law, which was discovered by Koschmieder (5) in 1924, can be stated in the following formula

$$B = B_h(1 - e^{-\sigma r})$$

In this formula, B is the apparent luminance of a black object seen at a distance r through an atmosphere of extinction coefficient σ, and B_h is that of the horizon sky in the same azimuth. There are certain assumptions behind this equation which are generally fairly well fulfilled provided we are looking in a horizontal direction.

What we are interested in is not primarily the apparent luminance of the distant object, but the contrast between it and its background. This contrast is defined as follows

$$C = \frac{B - B'}{B'}$$

where B is the luminance of the object, and B' that of its background. If we are considering an object against the horizon sky, which is the simplest case, B will represent the luminance of the object and B' that of the horizon sky. It was shown by Duntley (3) that in this case the apparent contrast at a distance can be expressed by the very simple formula

$$C = C_o e^{-\sigma r}$$

where C_o is the contrast which would be observed if one were very close to the object. In other words, the apparent contrast between the sky and the object is a decreasing exponential function of the distance. Sooner or later, as we go farther away from the object, this contrast will sink to such a small value that the object cannot be seen against the sky. The argument can be extended quite easily to objects against a terrestrial background farther away, or even to objects seen against the sky looking upwards, or looking downwards against the ground, though in this last case the determination of the necessary parameters sometimes becomes almost impossible. Since we are talking about visibility estimates we shall, for the moment, confine ourselves to objects seen against the horizon sky, because such objects are supposed to be used for visibility marks. The distance which we can go away from the object in a given sample of atmosphere before it becomes invisible obviously depends on how small a contrast the eye can appreciate. Koschmieder thought that it would be adequate to use the value $C = 0.02$ for this limiting contrast, but many investigators have found that this will not do at all because the limiting contrast depends on the luminance of the background and the size of the object, quite apart

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* Luminance is now the term internationally adopted for the quantity which used to be called (photometric) brightness.

from individual differences between observers. The great extent of this variation is shown in Fig. 1, taken from a paper by Blackwell (1). We shall not discuss this in detail except to point out that, even for a given background brightness, the contrast varies by more than 100:1, depending upon the size of the object. It is obviously fortunate that objects as small as half a minute of arc in diameter are not used as visibility marks.

The thresholds of contrast shown in Fig. 1 were obtained under laboratory conditions. Field investigations have been made which show that if the laboratory experiment is transferred to the field much the same results are obtained. We shall have more to say later on in this talk about the thresholds of contrast actually obtained by meteorological observers, but for the moment let us denote the threshold of contrast, whatever it is, by ϵ and write down an equation showing the relation between the extinction coefficient and the distance V at which a black object against the horizon sky should be visible. This relation is quite simple. It is

$$V = \frac{1}{\sigma} \log_e \left| \frac{1}{\epsilon} \right|$$

which shows that for a given threshold of contrast the visual range varies inversely as σ.

Let us now see what happens when we vary the threshold of contrast. If we plot the product σV against the logarithm of the contrast we should get a straight line. This straight line is shown in Fig. 2, and you will note that if we adopt Koschmieder's value 0.02, we arrive at a formula

$$V = \frac{3.91}{\sigma}$$

If ϵ is 0.01, we find that V is approximately $4.6/\sigma$ and if it is 0.05, V is about $3/\sigma$. These are probably the approximate limits within which we can expect ϵ to lie in broad daylight, and this restricts our problem a little. However, at night or in twilight it can lie almost anywhere along this line to the right of 0.02. The data of Fig. 1 and the equation relating contrast and distance, have been combined by Duntley (3) in a remarkable series of nomograms, one of which is reproduced as Fig. 3. There are a number of others for different values of background luminance. These nomograms can be used for an object of any area and any inherent contrast C_0 provided we know the extinction coefficient σ or some quantity correlated with it. In these nomograms this quantity is called the meteorological range, which is the value of V deduced by assuming a black object ($C_0 = -1$) and a value of ϵ equal to 0.02. This quantity the "meteorological range" is thus simply a convenient substitute for the extinction coefficient and is a distance not very greatly different to that which would be obtained by the meteorological observer in his observation of visibility. All we have to do to use one of these nomograms is to lay a straight edge across it, joining the meteorological range with the inherent contrast of the object, and read off the distance at which the object can just be seen. The nomogram shown in this figure has been revised to correspond to a fair certainty of detection.*

The discussion up to this point can be summarized by saying that for a given observer under given conditions of light, the visual range of a given object is a single-valued function of the extinction coefficient of the atmosphere. This is very simple and seems very fortunate, but there is one catch in it. Up to this point we have not defined what we mean when we say that an object is visible. All the difficult psychophysical experiments which have been done to determine these values of contrast threshold, were done on the assumption that when we can see that an object is there we will say that it is visible. This is not the official meteorological definition, as you are no doubt aware. The official definition is contained in two "Notes" to Resolution 147 of the Conference of Directors, Washington, 1947, (4) and is not particularly clear.

"Note 1: There has been a difference in the instructions in different countries in regard to daylight visibility. In some countries daylight visibility has been determined by the distance at which the outline of objects seen against the sky disappears. In other countries the instruction has been that visibility is the distance at which an object such, for example, as a tree, can be recognized as a tree. Note 2: Thus the instructions to meteorological services should be the distinguishing of objects as such". The official French text is no clearer, but I am in a position to assure you that the meaning intended is that a tree, etc., should be recognizable for what it is. This definition makes it very difficult to use the excellent psychophysical observations which are available to relate instrumental measurements on the atmosphere to the distance of visibility demanded by the meteorologist. Between 1930 and the present time there have been several attempts to do this, and the result has usually been that the contrast threshold which has apparently been obtained by the meteorological observer is several times as high as that which would be expected from the psychophysical observations. As a matter of fact, the psychologists know very little about the phenomenon of recognition, although they know a great deal about that of detection. This is one reason why I think that progress in the improvement of visibility observations is held up by this official criterion of recognition. There are two more. The first of these is that the criterion is non-uniform. An object a hundred yards away could be any number of things, but a mark fifty miles away can only be one thing, a mountain, or it would not be big enough to be useful as a mark. In the second place it seems to me that the criterion is not realistic because as soon as an observer has been at a weather station for more than about a week, he becomes so familiar with the entire field of view that he knows what an object is merely because he can tell where it is by reference to nearer and more clearly visible marks.

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* A number of such nomograms will be found in reference (7).

In defence of the criterion of recognition, it may, on the other hand, be urged that those who must use the data, such as the pilots of aircraft, do not necessarily know what an object is just because they see it in a particular place in the visual field. This is quite true and we must not forget to discuss the implications of it later on. It must also be remembered that the techniques of estimating visibility were developed (or rather they grew up) long before there was any coherent theory of the subject, and indeed before very many scientific experiments on seeing through the atmosphere had been made at all.

The several researches referred to a minute or two ago, depended usually on simultaneous measurements of the extinction coefficient and estimates of the visibility. The results they gave were very discordant and in particular they did not agree with the laboratory psychophysical experiments at all, even allowing for a good deal of experimental scatter in the field experiments. Finally, a programme of observations was initiated at Ottawa with a view to finding out by direct photometry the actual contrast between marks and their background, at the time when they were adjudged to be at the distance of visibility by service observers actually making routine observations (8).

This was done by rapid photoelectric photometry of marks and background. A very precise photoelectric telescope was constructed which had a narrow angle prism immediately in front of the objective so that by turning a knob the operator could select fields of view just above and just below the horizon alternately. In this way it was possible to measure the actual contrast between an object on the horizon and the horizon sky a good many times in the course of halfa minute,the actual values of luminance being recorded on a chart and worked out later. This was done at the time when the observer made his ordinary observation of visibility, and he was simply asked to tell the operator of the photometer which mark he had picked out as being at the distance of visibility. These experiments were carried out at Rockcliffe Airport over a period of nearly a year, and were continued until one thousand observations had been accumulated, made by eleven observers. The frequency distribution of the values of contrast thus obtained is shown in Fig. 4. The median of this distribution is 0.030, but it will be seen that there are a great many observations greater than 0.05 and even greater than 0.1. The extreme range of values of ϵ is greater than 20:1. If we compare this with Fig. 2 we shall see that this corresponds to more than a 3:1 spread in the visual range calculated by the equation

$$V = \frac{1}{\sigma} \log_e \left| \frac{1}{\epsilon} \right|$$

Or alternatively to a more than 3:1 spread in the values of σ that might be deduced from the estimates of visibility by the adoption of observed values of contrast.

Another way of illustrating what these results mean is by a diagram such as that in Fig. 5, which was made from these data by Mr. J. M. Waldram of Wembley, England. The left-hand curve in this figure shows the cumulative frequency distribution derived from Fig. 4. The right-hand curve shows the transmission of various thicknesses of an atmosphere for which the extinction coefficient is assumed to be 1.3×10^{-3} ft. $^{-1}$. The points corresponding to 5, 10, 90, and 95% of the observations have been marked on the frequency curve, and by transferring horizontally to the other curve it is at once seen that 20% of the observations would lead to calculated values of visual range less than 600 yards or greater than 1000 yards. 10% would lead to values less than 560 yards and greater than 1100 yards.

This then is the degree of uncertainty in observations of this sort, due, no doubt, mainly to the valiant efforts of the observers to interpret the official instructions and their natural desire not to give any values of visibility that are dangerously low. Each of the observers taken individually showed almost this much variation and it was ascertained that these figures were not due to the use of some unusual or difficult marks.

Now, in my opinion, the use of the official criterion of recognition has something to do with this great variability. It is still an open question whether the adoption of a criterion of detection would reduce the variability to something similar to that obtained in the laboratory psychophysical experiments. At least I would suggest that a programme of observations should be set up at a special station using a specially trained staff who had not become accustomed to the official way of taking visibility observations, but were simply asked to record the distance at which an object could just be distinguished from its background without regard to the identity of the object, other than whatever was necessary to find out its distance. Some very preliminary experiments in this direction have strongly suggested that the contrast threshold would not only be lower and more nearly like that of the laboratory experiments, but would also show a much smaller variability. You will, by this time, have certainly formulated in your minds the objection that this is not the sort of observation that a pilot has to make when he is coming in to land. This is quite true, but if it should turn out that observations using the criterion of detection were much more precise and reproducible, then it would be reasonable to prepare tables on the basis of one or other of the equations given above, which would relate the results of such an estimate directly to the distance that objects of various sorts could be seen under various conditions. As a basis for such computational aids, nomograms similar to that illustrated in Fig. 3 could, of course, be used. This sort of approach is not practicable at present because of the enormous scatter in the values of the threshold of contrast obtained by the meteorological observer, which render it quite unjustifiable to deduce values of the extinction coefficient from the estimates of visibility.

The point of view which I have just expressed is the one adopted by those of us who have been engaged during the last few years in investigations on the atmosphere and on visual processes. As a result of a great deal of experimentation, and I may say of a good many very arduous and extensive field tests, both on land and at sea, many of these people are prepared to argue that if you can measure the extinction coefficient they can tell you whether or not you will be able to see an object. This is probably quite true provided you can tell them sufficient about the object, and provided the object is not too greatly different from the sort of objects for which the experiments have been made. There are certain great lacunae in our knowledge of the contrast threshold. One of them concerns the sort of long, low, horizontal strip which is the universal appearance of a low coast line seen from the ocean. This may extend quite beyond the field of vision to right and left and may be only a few minutes of arc in angular extent in a vertical direction. I have been trying to interest some of my psychologist friends in making experiments to remedy this deficiency in our knowledge. Such experiments should not present any particular difficulty. Much more difficult because less general is the problem presented by an object which is in the immediate vicinity of another object of much greater contrast with the background. It is almost certainly true that a small contrast is made more difficult to see by being in the immediate vicinity of a very large contrast, but as far as I know nothing is known about the magnitude of this effect. Another subject about which we need much more information is the contrast threshold of a small object rising out of an extensive and almost level horizon. Such objects frequently have to be used as visibility marks.

Supposing that this further information is obtained, we must now ask how much justification there is in the claim that if we can measure physical quantities we can tell what we can see. The answer to this question is twofold. In the first place, there is very little doubt, at least in my mind, that these techniques of prediction can be applied with great success to many military situations and to almost all marine situations that are likely to arise. The marine case is a particularly happy one because the variability of the optical properties of the atmosphere in time and space are much less marked at sea than over land, at least on an average, and at sea the occasions when they will be important can usually be determined with the naked eye without further trouble. Where we are concerned with aviation, the matter is much more complex. There are two quite distinct uses of atmospheric optical data in aviation. The first is to provide a general idea of the course of atmospheric obscurity for the purpose of regulating the opening and closing of airports and the general conduct of air traffic. It seems evident that if the proper physical quantities are measured this function can be performed with much more precision than at present. The other function, and probably the more important one, however, is to assist in the actual landing of aircraft at major airports in bad weather. Here the pilot needs to know whether or not he can see the approach lights, the threshold lights, the runway lights, and the taxi strip lights, and here it will not do to make any mistakes.

The most serious difficulty about this problem is not any difficulty in constructing suitable instruments, but is the variability of the atmosphere itself. The atmosphere, or at least its optical properties, can vary so rapidly both in time and in space that any observation more than a few seconds old is likely to do more harm than good. Furthermore, it is precisely when the observations are most needed that the state of the atmosphere is likely to vary most rapidly. A further difficulty is caused by the fact that in bad weather it is lights rather than solid objects which the pilot has to see in order to orient himself with respect to the runway. While the threshold of contrast is relatively constant over a large range of background luminances in daylight, the threshold of illumination from a source of light varies rapidly with the background luminance. It is therefore necessary to have knowledge, not only of the extinction coefficient of the atmosphere at the actual moment when the information is needed, but also of the luminance of the background against which the pilot will see the lights.

It is very difficult to obtain these quantities with the required speed and precision. Probably the most urgent instrumental problem in this field at the present time is the provision of a necessarily rather complicated instrument which will measure the extinction coefficient of the atmosphere integrated over a slant path from a point about 100 metres up, down to the ground, and at the same time measure the brightness of the background which will be seen by the pilot approaching the end of the runway. In order to be useful this will have to be combined with an extremely rapid computing device which will take the data furnished by the rest of the instrument and convert it into a prediction of the distance that the pilot will be able to see the lights. This is not an easy problem. I do not know the solution of it but I am convinced that if the right people tried hard for enough time, the problem would be solved. It would be an expensive problem to solve, but not as expensive as the cost of one large aircraft, and I believe that it is worth solving and should be solved; but because of the variability of the atmosphere from one point to another, I do not believe that it could completely replace the technique now being used very successfully in a number of places of stationing an observer at the end of the runway, preferably in radio communication with the pilot, to tell him how many lights or markers down the runway he can see from moment to moment. The receipt of such information must be extremely comforting to the pilot, because it can at least assure him that when he gets down on the runway he can see where he is going, or alternatively it can make him quite certain that he must not try to come down. There is little doubt in my mind that the combination of these two methods of observation would greatly increase the safety of approaches and landings in bad weather. Beyond this I do not at the moment care to go in this direction.

I should now like to turn to a subject which is in essence quite of a different nature. I refer to the problem, somewhat interesting to the climatologists, of relating observations of visibility taken in the daytime to observations taken at night. I am not sure that it is of direct interest to anybody but the climatologists, and I should be very grateful if one of them would tell me just why they want to do this, but apparently they do want to do this, and there is a table in Resolution 114 of the Conference of Directors, Washington, 1947, (4) which is supposed to make this possible. This table was prepared on the assumption that the threshold of contrast is 0.02, and uses three values of the threshold illumination E_t required to see a point source of light, namely, 1, 0.1, and 0.01 lumens per km^2 (10^{-6}, 10^{-7}, 10^{-8} lux.). Now in the first place we have seen a little while ago that as far as meteorological estimates of visibility are concerned, the threshold of contrast is not generally 0.02, but let us neglect this for the present and inquire into these threshold values of illumination. We may begin with the remark that the lowest of them is certainly much too low since it is below the threshold at any level of illumination when you are actually looking at a light, and indeed in that region useful only in nearly complete darkness when you have to look somewhat to one side of a light to see it properly. This is known as the region of rod vision, and while it may have some pertinence to a mariner who has been on the bridge of his ship for half an hour, it certainly has nothing to do with the meteorological observer.

Two or three years ago, some of us realized that we had not much information about the state of adaptation of the eyes of meteorological observers when they were actually making night visibility observations. You are all aware how this is done. The observer, who has been plotting charts in a brightly lighted forecast office, suddenly realizes that it is time for the hourly observation. He grabs a pad and a flashlight, probably puts on a sweater, and stumbles out into the night. If we were with him we should probably trip over something because at this stage our eyes (and his) are scarcely at all adapted to the comparative darkness. The darkness, however, is only comparative and by the time he gets to the thermometer screen he is probably beginning to become adapted to it. If he is in a hurry, as he usually is, he will not be completely adapted even to the prevailing illumination when he has finished the other observations and finally makes the observation of visibility. But even if we may suppose that he becomes adapted to the prevailing background luminance, what is this luminance? About two years ago, I recommended to the U.S. Armed Forces-N.R.C. Vision Committee that an investigation should be made of this, and at the request of the committee Colonel Victor A. Byrnes of the U.S.A.F. School of Aviation Medicine set up a programme of measurements designed to provide some information.

At three small military airports, six large military airports, and five very large civil airports, Dr. H.W. Rose, who was assigned to this research, made numerous measurements of three quantities: (1) The level of illumination in the meteorological office which determines the adaptation level of the observer when he goes out to take the observation; (2) The brightness of the background against which lights are observed; (3) The illumination on the horizontal plane out of doors at the place where the observer stands (9).

Fig. 6 presents a conspectus of the results. The upper rectangles marked A, show the usual high range of values found in modern illumination practice, say 100 to 600 lux. The brightness of the background against which the lights are observed is shown by the rectangles B. This is the quantity in which we are particularly interested. Even excluding the narrower portion of these figures, which refers to periods of twilight or incomplete darkness, it will immediately be seen that this brightness varies over a range of about 100:1, or rather more at the small military airports. At the righthand side of the diagram is a scale showing the logarithm of the threshold of illuminance for a point source at the adaptation brightnesses denoted by the figures on the remainder of the diagram. The values of E_t are in lumens/km^2 while those of background brightness are in apostilbs*. I believe that this diagram makes it obvious why it would be very dangerous to use a table such as that annexed to Resolution 114, or any table purporting to convert an estimate of the visual range at night to values of daytime visibility. This conclusion is valid quite independently of our earlier remarks about the threshold of contrast, and is merely strengthened by them. The real reason why it is no use attempting to perform this conversion is because estimates of night visibility are always rendered abortive because of the uncertainty in the adaptation level of the observer. If it were necessary to adduce other reasons for the unsatisfactory nature of night observations, it would be easy to do so. For instance, there are never enough lights to observe, especially at the longer distances. Furthermore, most of the lights around an airport are highly directional in their distribution of intensity and will vary greatly in intensity in the direction of the observer. It would obviously be very expensive and usually impossible to provide a complete series of suitable lights for the use of the observer, and as a matter of fact, the other solution to the problem, namely the provision of suitable instruments, would be very much simpler.

I should now like to say a few words about instrumentation. Apart from the elaborate instrument suggested for measuring the slant visual range at the end of a runway, there is a requirement for an instrument for measuring and possibly for recording the visual range in a horizontal direction, especially at night. Using modern electronic techniques and modulated light, it ought to be possible to build an instrument which would operate satisfactorily both by night and by day, although such an apparatus would not be cheap. There are two possible types of apparatus for this purpose, one being a telephotometer, that is to say, an instrument that measures the attenuation of a nearly collimated light beam. The theory and sources of error of telephotometers have been discussed by a number of writers. The other type of instrument which seems useful is an integrating scattering meter such as the one proposed by Beuttell and Brewer (2). This would be particularly useful at sea, but might have rather large errors near cities because it measures only the component of the atmospheric extinction due to scattering and completely neglects that due to absorption. There are many other types of instruments, but most of them can only operate in daytime. In general, I believe that photoelectric instruments are preferable to visual instruments for this purpose. If any visual instruments are used, they should be constructed on sound physical principles. I do not believe that any of the empirical "visibility meters" which have been suggested from time to time are nearly as good as a properly constructed telephotometer, and none of them are satisfactory at night in view of the uncertain state of the observer's eye as mentioned above. Of such meters for use in the daytime, the disappearance range gauge invented independently by Waldram (11) and by Shallenberger and Little (10) seems to hold the most promise. There is at present some doubt about the proper constants to be employed in the calibration of this instrument, but if this difficulty can be overcome it would seem to

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* 1 apostilb is the brightness of a perfectly diffusing white surface receiving an illumination of 1 lumen/m^2. It is equal to $\frac{1}{\pi}$ candles m^{-2}.

be a useful auxiliary for small stations which have not a very extended series of marks available.

In conclusion, I should like to make a plea to meteorologists to give some study to the new "science of outdoor seeing", and to use those of its results which can be helpful. While it may have no ready-made solution to some of the problems of aviation, it can, I think, provide a good deal of real assistance.

LIST OF FIGURES

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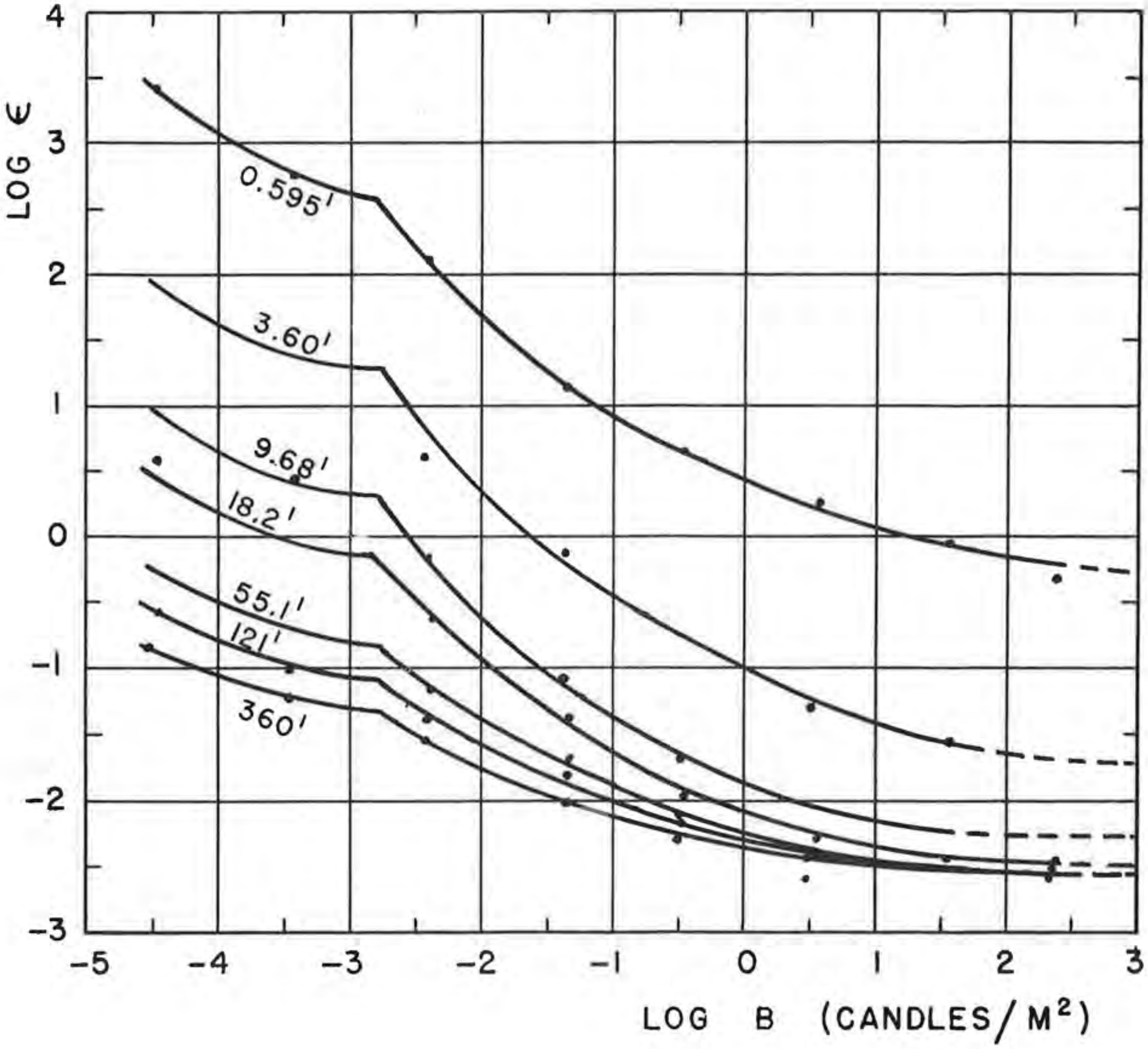

LOG ∈
4
3
2
1
0
-1
-2
-3
-5
-4
-3
-2
-1
0
1
2
3
LOG B (CANDLES/M²)
0.595'
3.60'
9.68'
18.2'
55.1'
121'
360'

FIGURE 1

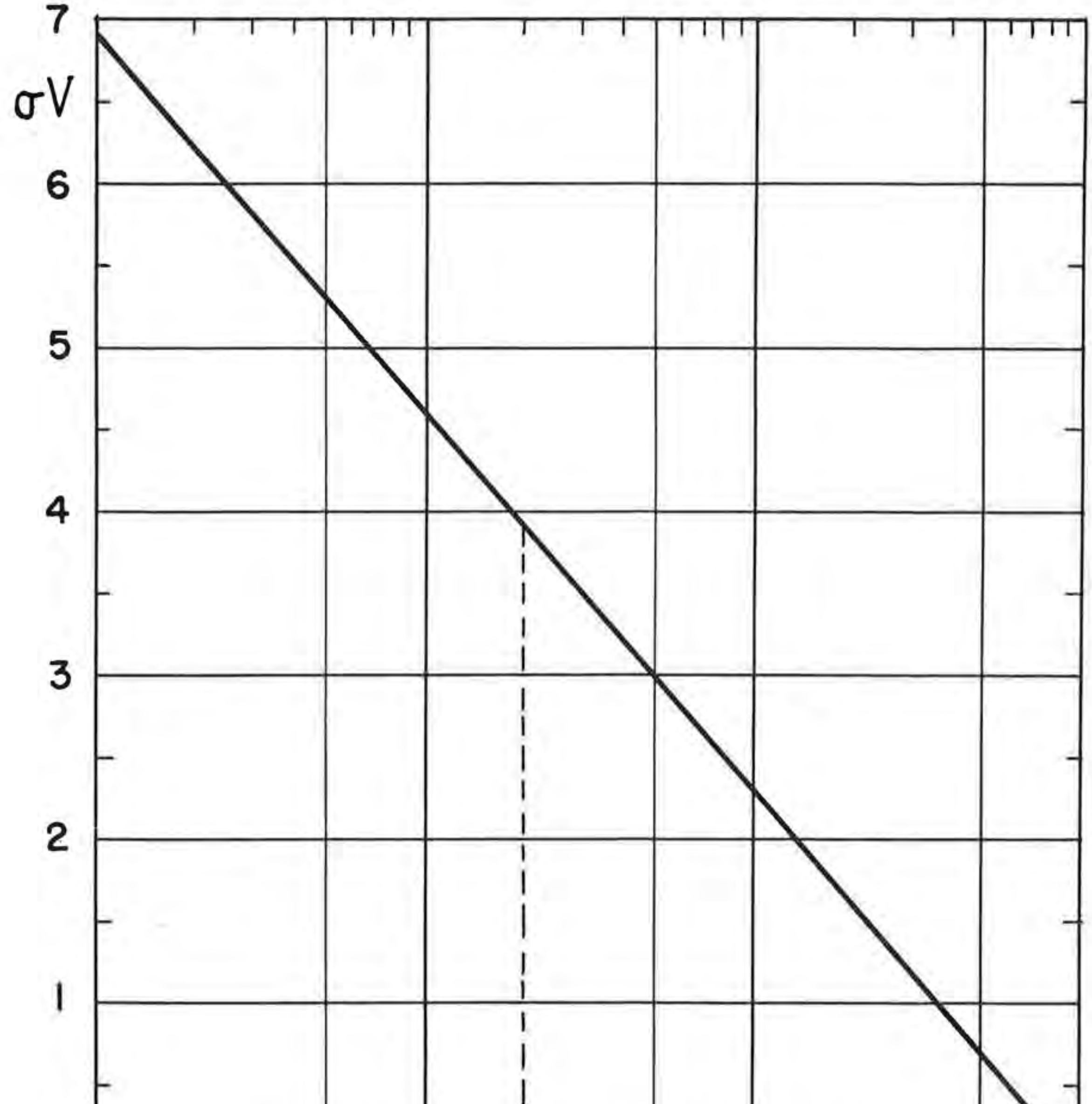


FIGURE 2

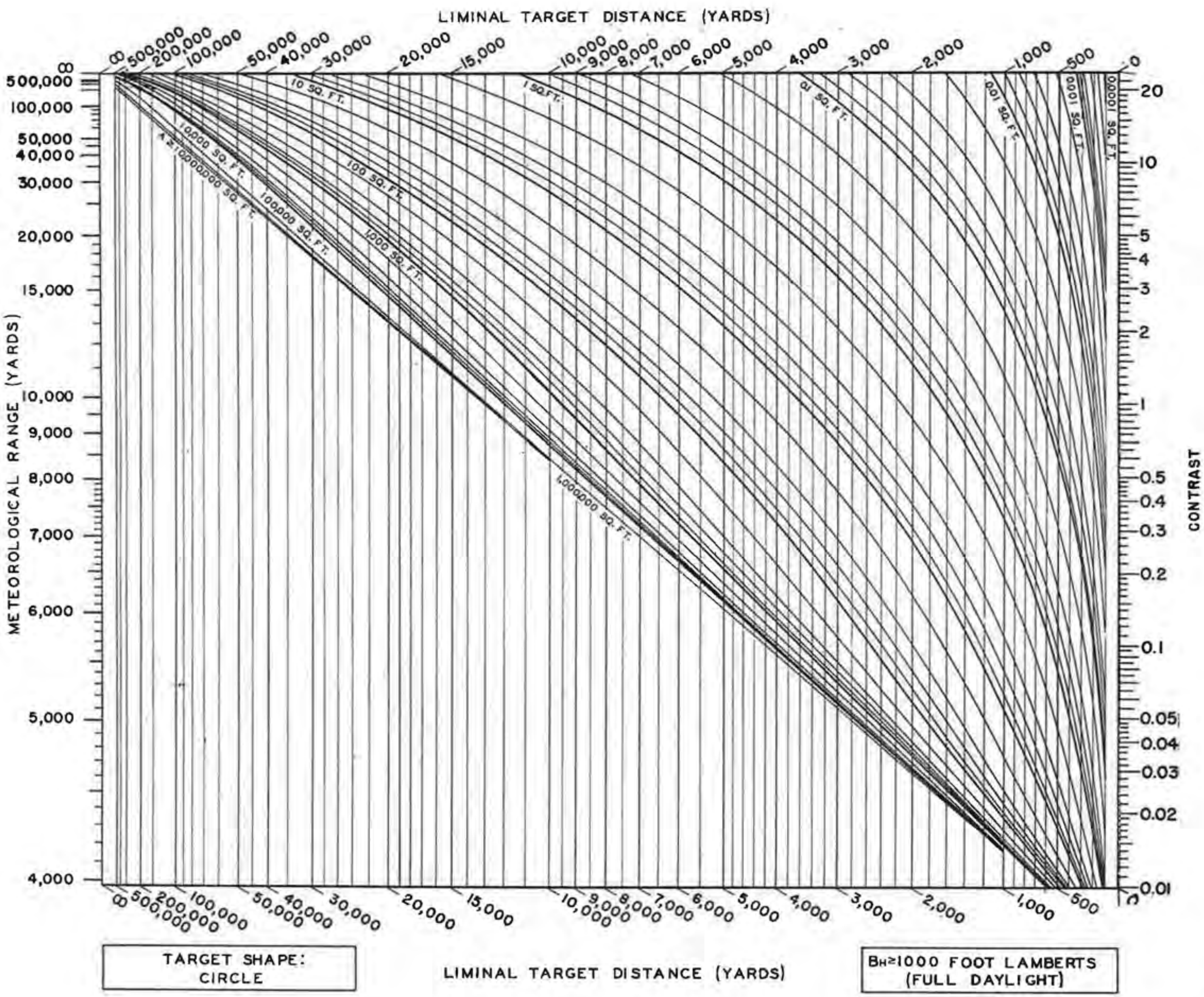
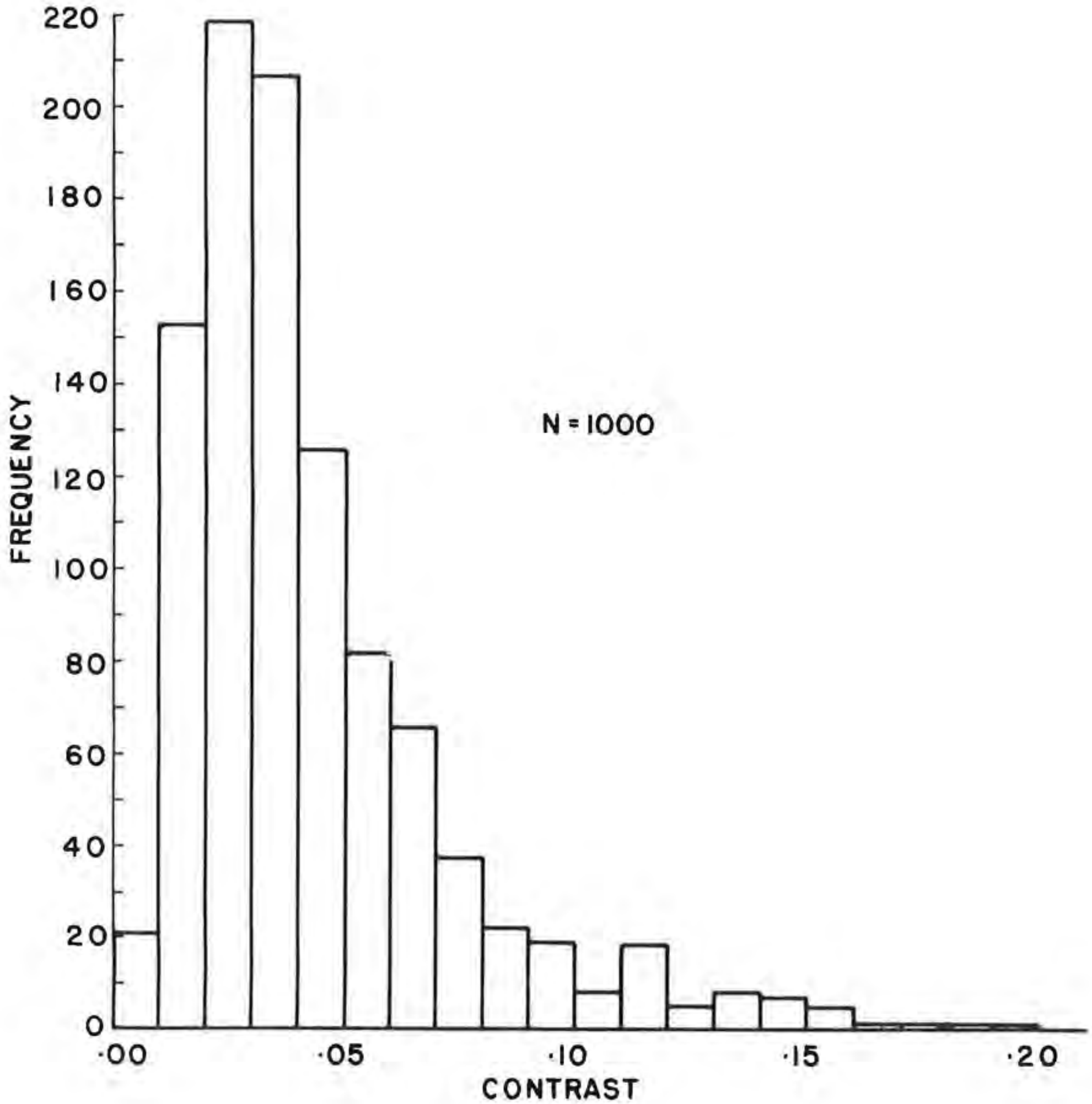

LIMINAL TARGET DISTANCE (YARDS)
METEOROLOGICAL RANGE (YARDS)
CONTRAST
10 SQ. FT.
1 SQ. FT.
0.1 SQ. FT.
0.01 SQ. FT.
0.001 SQ. FT.
0.0001 SQ. FT.
10,000 SQ. FT.
100 SQ. FT.
100,000 SQ. FT.
1,000 SQ. FT.
1,000,000 SQ. FT.
TARGET SHAPE: CIRCLE
LIMINAL TARGET DISTANCE (YARDS)
BH≥1000 FOOT LAMBERTS (FULL DAYLIGHT)

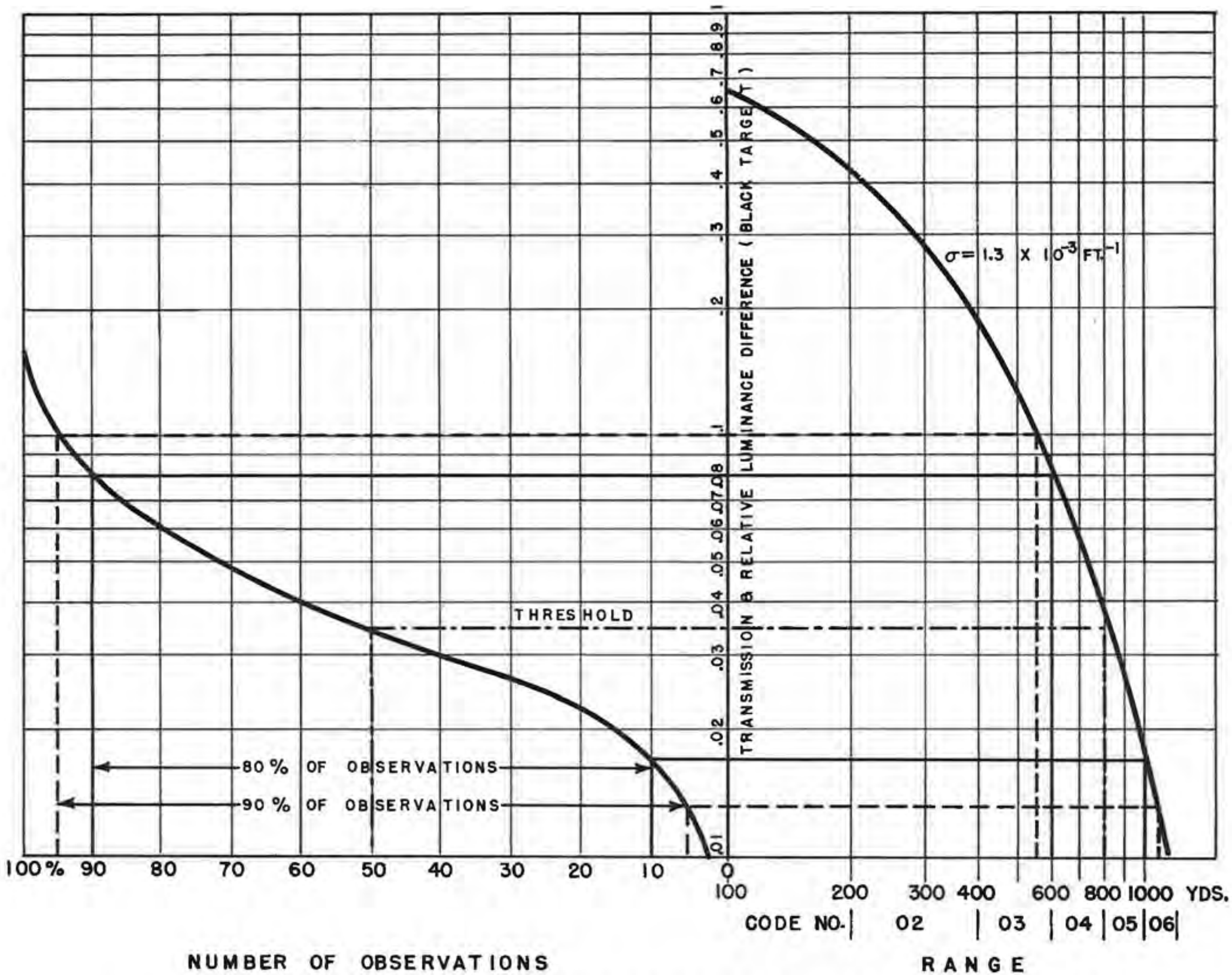
FIGURE 3



220
200
180
160
140
120
100
80
60
40
20
0
FREQUENCY
N = 1000
·00
·05
·10
·15
·20
CONTRAST

FIGURE 4

FIGURE 5



CURVES SHOWING PRECISION OF DETERMINATION OF VISUAL RANGE
BY OBSERVATION OF CONVENTIONAL MARKS

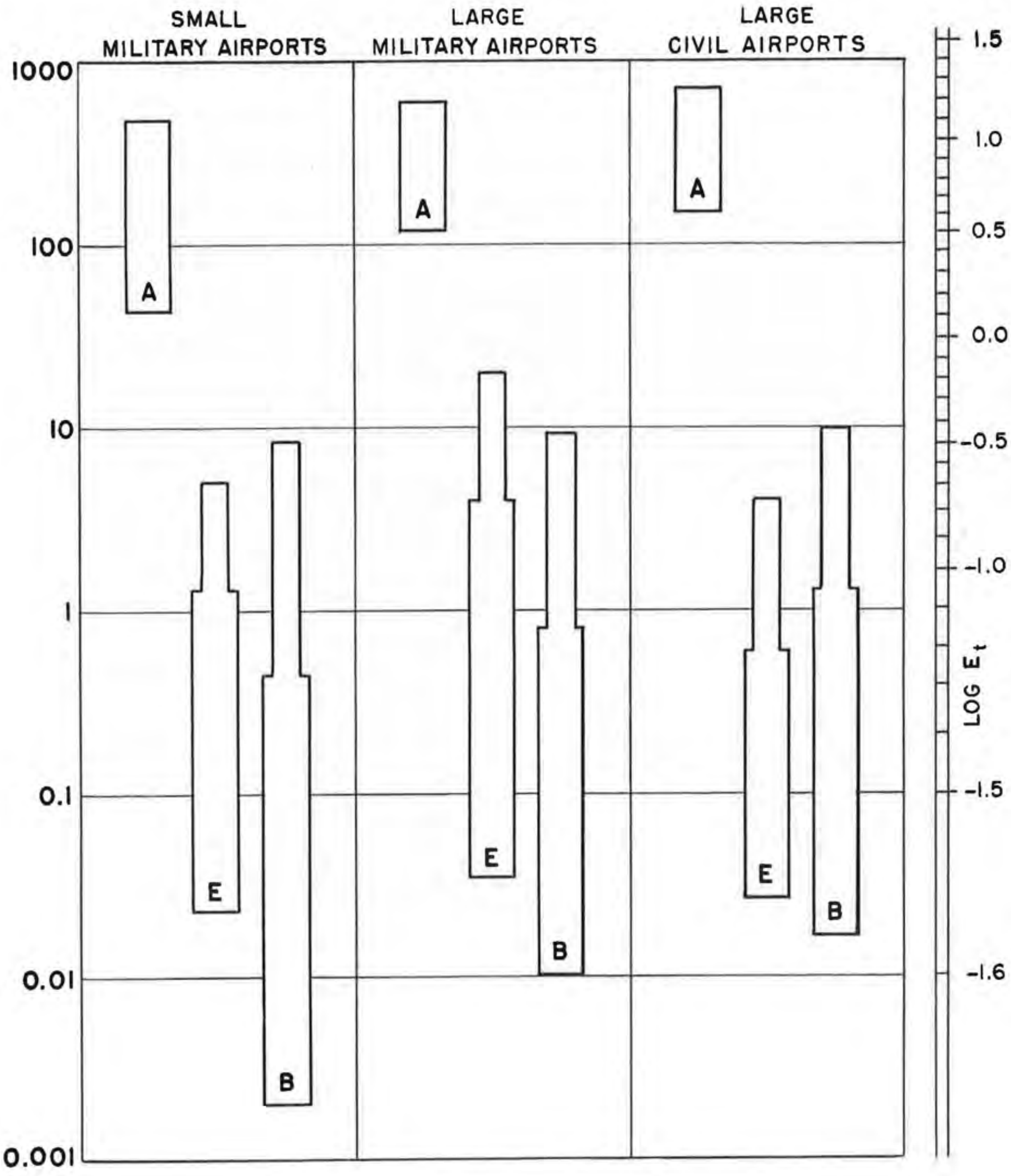

SMALL MILITARY AIRPORTS
LARGE MILITARY AIRPORTS
LARGE CIVIL AIRPORTS
1000
100
10
1
0.1
0.01
0.001
A
E
B
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
-1.6
LOG E_t

FIGURE 6