Title
Water clarity nomographs

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Publication Date
1953

University of California

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WATER CLARITY NOMOGRAPHS

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The nomographs presented in this report were prepared by the Visibility Laboratory to expedite the preparation of the handbook for submariners described in RDB Project NS 714-100. The work was supported primarily by the Office of Naval Research by means of contract N5ori-07831 with the Massachusetts Institute of Technology and secondarily by the Bureau of Ships under contract NObsr-43356 with the Scripps Institution of Oceanography of the University of California.

SIO Reference 53-46

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1. INTRODUCTION

In an earlier report by this laboratory[1] it was shown that the time-averaged apparent contrast of any submerged object as viewed by an aerial observer is given by the equation:

$$\bar{C} = C_0 \left(1-e^{-1000\,\mathrm{Tan}^2 \phi_T / S}\right) \left(1 + \frac{s_\alpha r_\alpha b_\alpha}{b_{w_2}}\right)^{-1} \left(e^{-3.912\, d v_{\alpha'}^{-1} \sec\alpha'}\right) \left(1 - J\left[1-e^{3.912\,\bar{R}/v_0}\right]\right)^{-1} \tag{1.1}$$

The nomographs presented in this report relate to the third bracketed factor in equation (1.1). This factor specifies the contrast reduction imposed by optical processes within the water along the observer's path of sight. Let this factor be denoted by F_3.
Thus

$$F_3 = \exp\left[-3.912\; d\, v_{\alpha'}^{-1} \sec\alpha'\right] \tag{1.2}$$

d is the depth of the target, α' is the angle between the path of sight in the water and the vertical, (see Fig. 2.1), and $V_{\alpha'}$ is the hydrological range* measured along the path of sight α'. $V_{\alpha'}$ may be evaluated from experimentally determined optical properties of water by means of the first of the two nomographs described in this report; F_3 can then be found with the aid of the second nomograph.

2. NOMOGRAPH FOR HYDROLOGICAL RANGE

The equation

$$V_{\alpha'} = \frac{V_H}{1 + \frac{V_H}{V_K}\cos\alpha'} \tag{2.1}$$

states the relation between the hydrological range ($V_{\alpha'}$) at angle α', the horizontal hydrological range (V_H), and a parameter (V_K) which is a measure of attenuation of scalar irradiance with depth.[1] α' is the angle between the path of sight in water and the vertical. Equation (2.1) can be rewritten as

$$\frac{1}{V_{\alpha'}} = \frac{1}{V_H} + \frac{1}{V_K}\cos\alpha' \tag{2.2}$$

* Hydrological range is the distance, measured along the path of sight, for which the contrast transmittance is two percent.[1]

In the absence of water waves, the relation between angle α' in water and angle α in air (see Fig. 2.1) is, from Snell's Law:

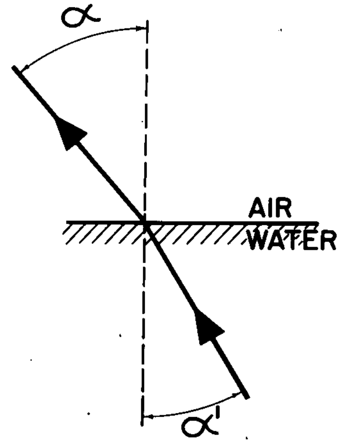


Figure 2.1

$$\cos \alpha' = \sqrt{1 - \frac{\sin^2 \alpha}{n^2}} \tag{2.3}$$

Substituting (2.3) in (2.2)

$$\frac{1}{V_{\alpha'}} = \frac{1}{V_H} + \frac{1}{V_K} \sqrt{1 - \frac{\sin^2 \alpha}{n^2}} \tag{2.4}$$

Let

$$\frac{1}{V_K} \sqrt{1 - \frac{\sin^2 \alpha}{n^2}} = \frac{1}{V_{K'}} \tag{2.5}$$

Then

$$\frac{1}{V_{\alpha'}} = \frac{1}{V_H} + \frac{1}{V_{K'}} \tag{2.6}$$

Equation (2.6) is of the type $\frac{1}{A} + \frac{1}{B} = \frac{1}{C}$. Such equations canbe solved by hexagonal alignment charts of the type shown in figure 2.2.[2] Lines $\overline{OA}$, $\overline{OB}$, and $\overline{OC}$ converge at the point O in such a manner that they form 60° angles with one another. $\overline{PQR}$ is a line drawn at random so as to cut $\overline{OA}$, $\overline{OB}$, and $\overline{OC}$. $\overline{OA}$ is extended to S , so that $\overline{OS}$ forms one side of an equilateral triangle with $\overline{OR}$ and $\overline{RS}$.

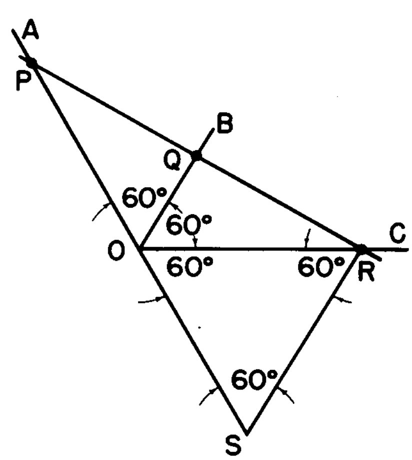


Figure 2.2

Comparing the similar triangles OPQ and SPR :

$$\frac{\overline{OS} + \overline{OP}}{\overline{OP}} = \frac{\overline{SR}}{\overline{OQ}} \tag{2.7}$$

But

$$\overline{SR} = \overline{OR} = \overline{OS} \tag{2.8}$$

Hence

$$\frac{\overline{OR}}{\overline{OP}} + 1 = \frac{\overline{OR}}{\overline{OQ}} \tag{2.9}$$

$$\frac{1}{\overline{OP}} + \frac{1}{\overline{OR}} = \frac{1}{\overline{OQ}} \tag{2.10}$$

If linear scales in A , B , and C are plotted along $\overline{OA}$, $\overline{OB}$ and $\overline{OC}$, with the zero of each scale at O , then

$$\overline{OA} = aA, \quad \overline{OB} = bB, \quad \overline{OC} = cC \tag{2.11}$$

where a , b , and c are scale factors. Then (2.10) can be written as:

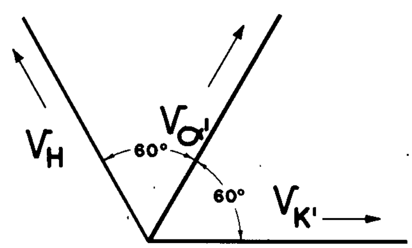
$$\frac{1}{aA} + \frac{1}{bB} = \frac{1}{cC} \tag{2.12}$$

If the scale factors are made equal, then

$$\frac{1}{A} + \frac{1}{B} = \frac{1}{C} \tag{2.13}$$

A hexagonal alignment chart of this type representing equation (2.6) is shown in figure 2.3.

Figure 2.3



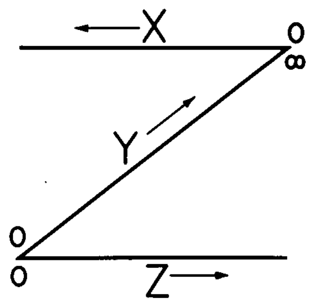
Equation (2.5) can be rewritten as follows:

$$V_K = V_{K'} \sqrt{1 - \frac{\sin^2 \alpha}{n^2}} \tag{2.14}$$

Equation (2.14), which is a simple multiplication, can be charted by means of an N diagram. An N diagram will plot the equation $X \cdot Y = Z$, if it is so constructed that two parallel lines (X and Z) with linear scales are cut by a third slanting line (Y).

The Y scale has the equation $S_Y = \frac{aY}{b+Y}$, where a and b are constants. Y = 0 at the "Z" end of the scale and $Y = \infty$ at the "X" end of the scale.

Figure 2.4



If

$$X = \left(1 - \frac{\sin^2\alpha}{n^2}\right)^{-\frac{1}{2}} \qquad (2.15\text{ a})$$

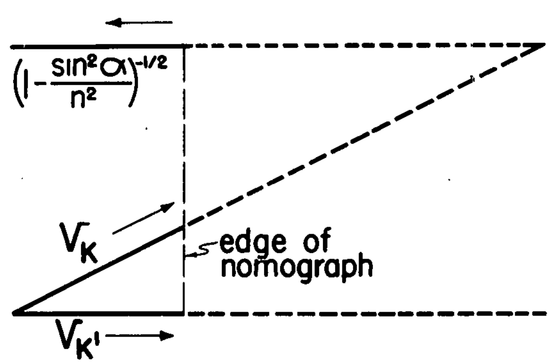
$$Y = V_K \qquad (2.15\text{b})$$

and

$$Z = V_{K'} \qquad (2.15\text{ c})$$

where $V_{K'}$ is the same scale as in figure 2.3 so that the N diagram is superimposed upon the hexagonal diagram, then the complete expression (2.4) will be charted.

Figure 2.5



Since a knowledge of the value of $V_{K'}$ is not necessary in solving the equation by the nomographic method, the scale is left blank, and the line is used only as a base for a turning point.

2.1 USE OF THE NOMOGRAPH

To find a desired value of V_{α}' given V_K , V_H , and α , lay a straightedge across the α and V_K scales and the unmarked 'turning line,' so that it intersects the scales at the given values of α and V_K . Using the point where the straightedge intersects the unmarked line as a turning point, lay the straightedge so that it falls across the V_H scale at the given value. The correct solution will be read where the straightedge intersects the V_{α}' scale.

2.1.1 Numerical Example

It is desired to find the hydrological range for a path of sight in water corresponding to a path of sight in air so oriented that it makes an angle of 60° with the vertical. The properties of the water have been measured, and it is known that $V_K = 55$ feet and $V_H = 35$ feet. Find V_{α}'.

Lay a straightedge across the nomograph so that it falls across the points $\alpha = 60°$ and $V_K = 55$ feet. Turn the straightedge about the point of intersection with the unmarked scale so that it falls on $V_H = 35$ feet. The correct answer, $V_{\alpha}' = 23.6$ feet, will be read where the straightedge intersects the V_{α}' scale. The answer can be checked by substitution in equation (2.4).

2.2 SCALING THE NOMOGRAPH

The scale equations for the N diagram may be found as follows. From (2.14) and (2.15) $X \cdot Y = Z$. The scale equation for X is:

$$S_X = xX = x\left(1 - \frac{\sin^2 \alpha}{n^2}\right)^{-\frac{1}{2}} \qquad (2.16)$$

where S_X is the distance measured along the X scale from the origin, and x is the scale factor. Let L be the length of the Z scale. Then, by construction:

$$x = 2L \qquad (2.17)$$

The scale equation for Z is of the same form as for X. The scale factor z is related to L by the following:

$$z = \frac{L}{100} \qquad (2.18)$$

Therefore

$$S_Z = zZ = \frac{L}{100} V_K' \qquad (2.19)$$

The scale equation for Y is:

$$S_Y = \frac{3hY}{\frac{x}{z} + Y} = \frac{3h V_K}{200 + V_K} \qquad (2.20)$$

S_Y is the distance measured along the diagonal from the origin in whatever units L is measured, and h is the length of the diagonal as measured in the same units.

$$\frac{1}{V_{\alpha'}} = \frac{1}{V_H} + \frac{1}{V_K}\sqrt{1 - \frac{\sin^2\alpha}{n^2}}$$

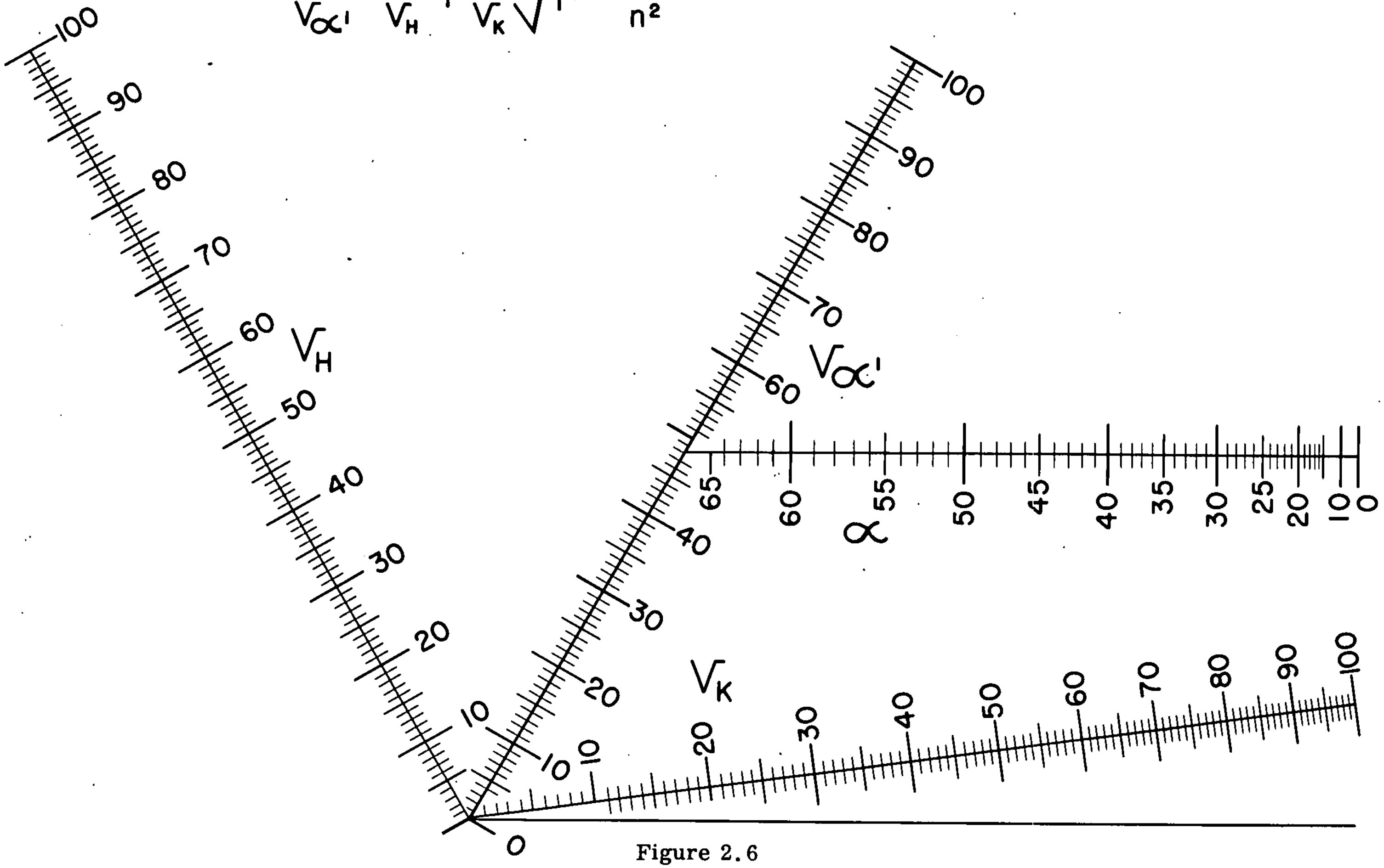


Figure 2.6

To find a desired value of $V_{\alpha'}$ given V_K , V_H , and α , lay a straightedge across the α and V_K scales and the unmarked 'turning line,' so that it intersects the scales at the given values of α and V_K . Using the point where the straightedge intersects the unmarked line as a turning point, lay the straightedge so that it falls across the V_H scale at the given value. The correct solution will be read where the straightedge intersects the $V_{\alpha'}$ scale.

As was previously shown, the scale equations for the variables v_H and $v_{\alpha'}$ are linear equations, and the scale factors must all be equal.
Hence:

$$S_{v_H} = \frac{L}{100} v_H$$

and

$$S_{v_{\alpha'}} = \frac{L}{100} v_{\alpha'} \qquad (2.22)$$

The scale equations as inscribed on the nomograph are shown in Figure 2.7.

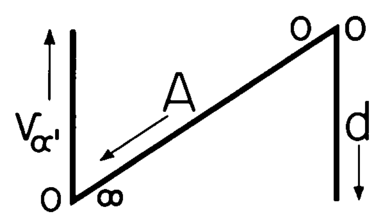
3. NOMOGRAPH FOR FACTOR F_3

For convenience, let equation (1.2) be combined with equation (2.3).
Then:

$$F_3 = \exp\left[-3.912\, d v_{\alpha'}^{-1} \left(1 - \frac{\sin^2\alpha}{n^2}\right)^{-\frac{1}{2}}\right] \qquad (3.1)$$

The nomograph, for equation (3.1) consists of two N diagrams arranged so that the two slant bars coincide. Let $d v_{\alpha'}^{-1} = A$. Then $A v_{\alpha'} = d$, and this equation is illustrated in figure 3.1.

Figure 3.1



Hence

$$F_3 = \exp\left[-3.912\, A \left(1 - \frac{\sin^2\alpha}{n^2}\right)^{-\frac{1}{2}}\right] \qquad (3.2)$$

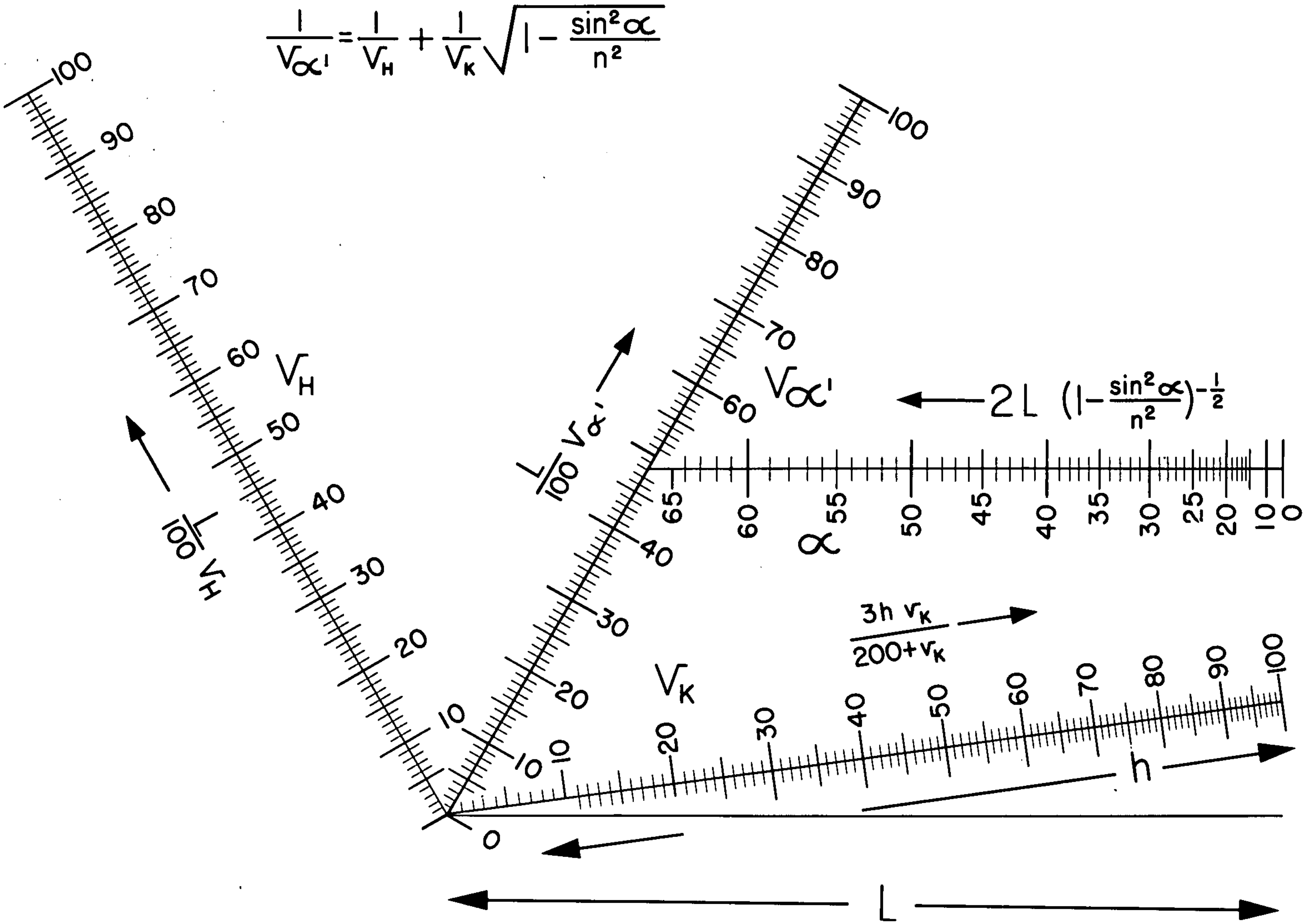
Let the term $3.912 \left(1 - \frac{\sin^2\alpha}{n^2}\right)^{-\frac{1}{2}} = f(\alpha)$ since it is a function only of α.

The bottom scale of the nomograph is a plot of this function.
Then

$$F_3 = \exp\left[-A f(\alpha)\right] \qquad (3.3)$$

or

$$-\ln F_3 = A f(\alpha) \qquad (3.4)$$



$\frac{1}{V_{\alpha'}} = \frac{1}{V_H} + \frac{1}{V_K}\sqrt{1 - \frac{\sin^2\alpha}{n^2}}$
V_H
$\frac{L}{100} V_H$
$\frac{L}{100} V_{\alpha'}$
$V_{\alpha'}$
$2L\,(1-\frac{\sin^2\alpha}{n^2})^{-\frac{1}{2}}$
α
$\frac{3h\,v_K}{200+v_K}$
V_K
h
L

Figure 2.7

If $-\ln F_3$ is plotted along the top scale, the multiplication indicated by (3.4) is completed and F_3 is nomographed.

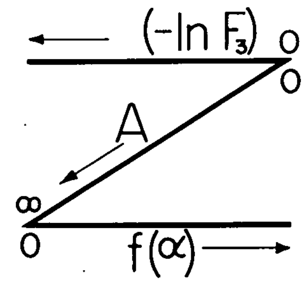


Figure 3.2

When the legends are inscribed, they can be done so in terms of α and F_3 . Since a knowledge of A is not necessary for the final solution, the diagonal scale is left blank and used only for a turning line.

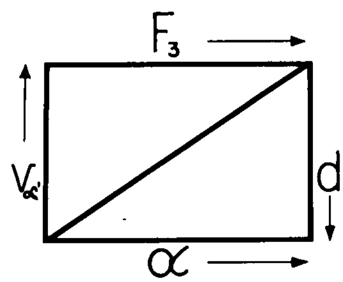


Figure 3.3

3.1 USE OF THE NOMOGRAPH

To use the nomograph lay a straightedge across the $V_{\alpha'}$ and d scales so that it intersects the desired values. Pivot the straightedge about the intersection point on the diagonal so that it falls on the required value of α. The answer may then be read from the point where the straightedge intersects the F_3 scale.

3.1.1 Numerical Example

Suppose that a target is submerged at a depth of 10 feet in water whose $V_{\alpha'}$ for the path of sight was found in Section 2.1.1 to be 23.6 feet. The observer is in such a position relative to the target that his path of sight makes an angle of 60° with the vertical. Find F_3.

Lay a straightedge across the nomograph so that the value 23.6 on the left hand scale is connected with the value 10 on the right hand scale. Mark the point where the straightedge intersects the diagonal. Then pivot the straightedge about the diagonal point so that it falls on the value 60 on the lower scale. The straightedge will intersect the upper scale at the value $F_3 = 0.112$. If desired this answer can be checked directly by using (3.1).

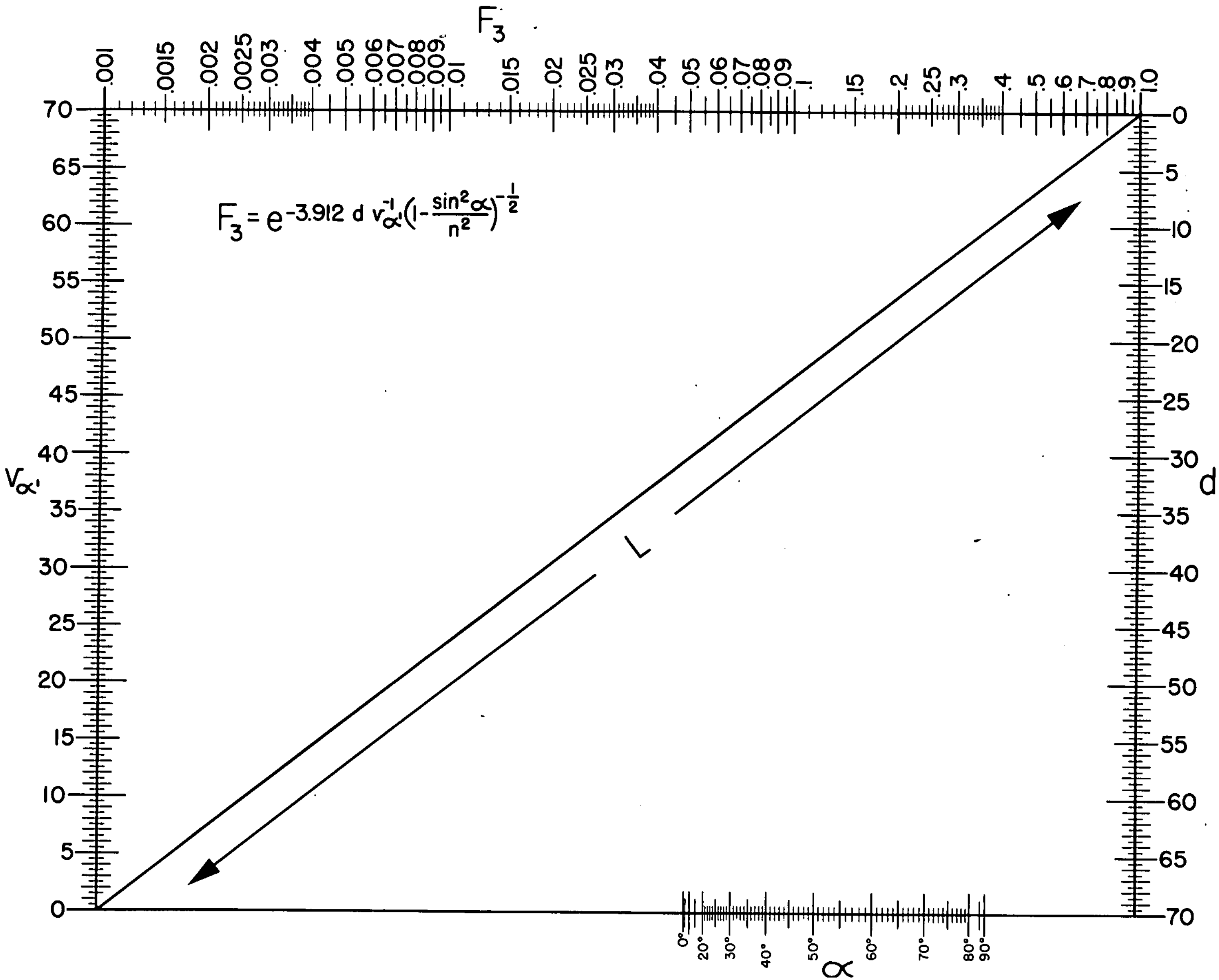


Figure 3.4

To use the nomograph lay a straightedge across the $V_{\alpha'}$ and d scales so that it intersects the desired values. Pivot the straightedge about the intersection point on the diagonal so that it falls on the required value of α. The answer may then be read from the point where the straightedge intersects the F_3 scale.

3.2 SCALING THE NOMOGRAPH

The scale equations for the first N diagram are:

$$S_{V_{\alpha'}} = \gamma V_{\alpha'} \tag{3.5a}$$

$$S_d = \delta d \tag{3.5b}$$

and

$$S_A = \frac{LA}{\frac{\gamma}{\delta} + A} \tag{3.5c}$$

$S_{V_{\alpha'}}$ and S_d are the distances measured from the origin along the $V_{\alpha'}$ and d scales respectively. S_A is the distance as measured along the diagonal from the origin and L is the length of the diagonal. The scale factors γ and δ are equal and are related to the dimensions of the nomograph by the following:

$$\gamma = \delta = \frac{h}{70} \tag{3.6}$$

where h is the length of the $V_{\alpha'}$ and d scales. Hence

$$S_{V_{\alpha'}} = \frac{h}{70} V_{\alpha'} \tag{3.7a}$$

$$S_d = \frac{h}{70} d \tag{3.7b}$$

$$S_A = \frac{LA}{1 + A} \tag{3.7c}$$

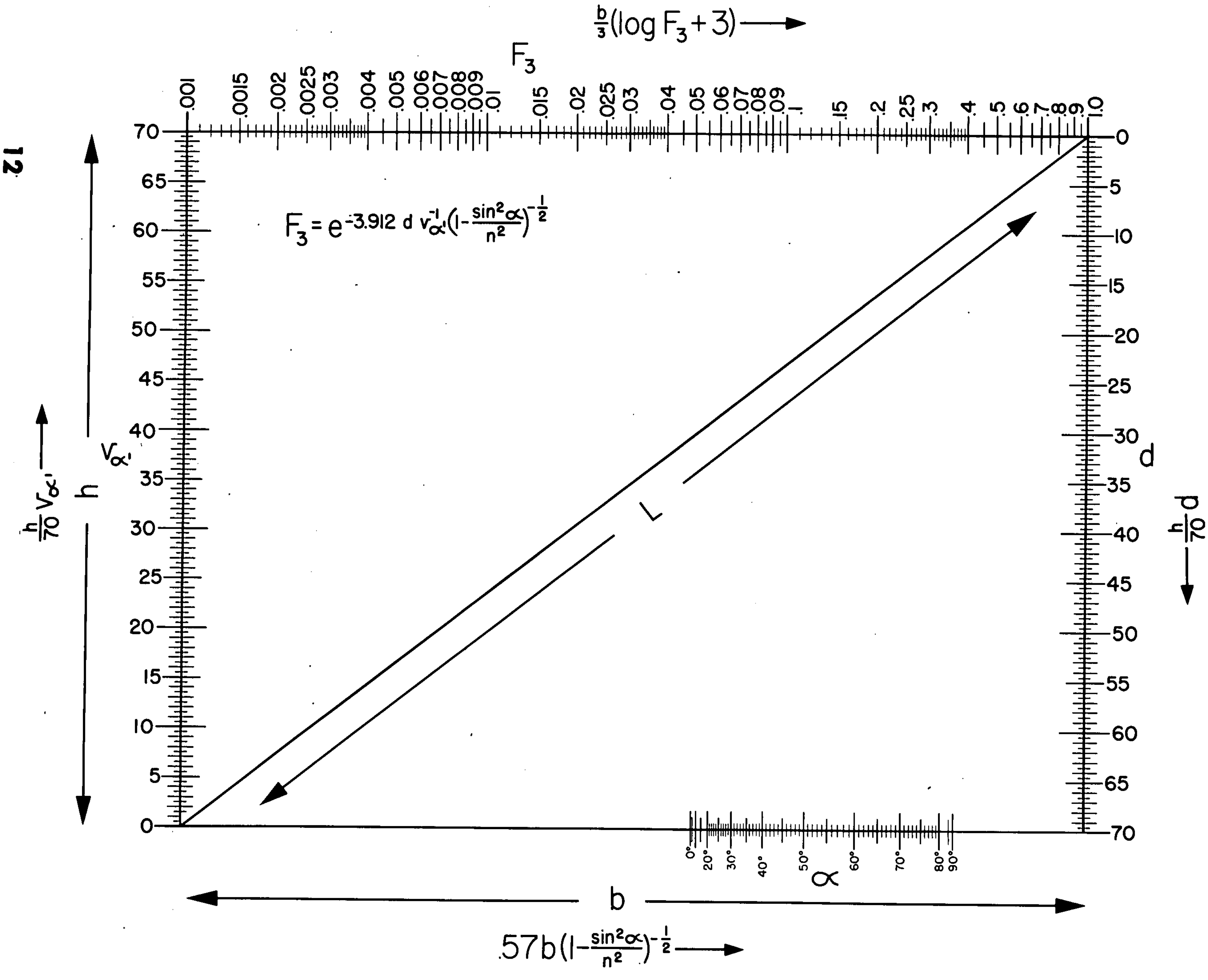
The scale equation for the α scale is:

$$S_\alpha = .57b \left(1 - \frac{\sin^2\alpha}{n^2}\right)^{-\frac{1}{2}} \tag{3.8}$$

where $b^2 = L^2 - h^2$ and S_α is measured from the intersection with the $V_{\alpha'}$ scale. The scale equation for F_3 is:

$$S_{F_3} = \frac{b}{3} (\log F_3 + 3) \tag{3.9}$$

where S_{F_3} is also measured from the intersection with the $V_{\alpha'}$ scale.



b/3(log F3+3)
F3
.001 .0015 .002 .0025 .003 .004 .005 .006 .007 .008 .009 .01 .015 .02 .025 .03 .04 .05 .06 .07 .08 .09 .1 .15 .2 .25 .3 .4 .5 .6 .7 .8 .9 1.0
F3 = e^-3.912 d v^-1 α' (1 - sin²α/n²)^-1/2
70 65 60 55 50 45 40 35 30 25 20 15 10 5 0
Vα'
h
h/70 Vα'
0 5 10 15 20 25 30 35 40 45 50 55 60 65 70
d
h/70 d
L
0° 20° 30° 40° 50° 60° 70° 80° 90°
α
b
.57b(1 - sin²α/n²)^-1/2

Figure 3.5

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Visibility Laboratory, University of California, Scripps Institution of Oceanography, SIO Reference 53-46, WATER CLARITY NOMOGRAPHS, by Frances R. Culver, 15 July 1953.

A description is given of two nomographs which expedite calculations of the expression specifying the contrast reduction of a submerged object due to attenuation processes in the water along the observer's path of sight. By means of the first nomograph the hydrological range for any path of sight can be found from experimentally determined optical properties of the water. The contrast reduction of the submerged object due to this attenuation can then be calculated using the second nomograph.

Illustrations of the nomographs, accompanied by explanations of the construction, the scale equations, and details of procedure for use are discussed. Illustrative examples are included.

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Underwater

Visibility

Calculations

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