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DEPARTMENT OF THE ARMY — CORPS OF ENGINEERS

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BEACH EROSION BOARD
OFFICE OF THE CHIEF OF ENGINEERS

GRAPHICAL APPROACH TO THE FORECASTING OF WAVES IN MOVING FETCHES

TECHNICAL MEMORANDUM NO. 73

Catalogued

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APRIL 1955

FOREWORD

A method of rapidly determining hindcast wave conditions over a period of time is greatly to be desired in obtaining statistical wave data for determination of design criteria in shore regions. Most methods used today, however, ignore the complications introduced by moving and changing fetches, or take them into account only subjectively. This report describes the development and application of a graphical technique for the determination of wave characteristics attained in moving wind systems, as well as stationary ones.

The report was prepared at the Agricultural and Mechanical College of Texas by Basil W. Wilson, an Associate Oceanographer and Research Engineer at that institution. This report is a revision and extension of a paper presented by the author at the May 1954 meeting of the American Geophysical Union in Washington, D. C. Although some of the material had been initiated under other projects at Texas A.& M., the completion of the work was performed in pursuance of Contract DA-49-055-eng-45 between the Beach Erosion Board and the Texas A.& M. Research Foundation which provides for the determination of a statistical wave climate along the Gulf coast, and for the development of the methods necessary for this determination.

Views and conclusions stated in this report are not necessarily those of the Beach Erosion Board.

This report is published under authority of Public Law 166, 79th Congress, approved July 31, 1945.

TABLE OF CONTENTS

LIST OF SYMBOLS

c	phase velocity of waves in water
c_g	group velocity of waves in water
F	length of fetch or distance over which wind is operative
$F_U(t_d)$	F as a function of t_d for a particular value of U
g	acceleration due to gravity
H	significant wave height
${}_{max}H$	maximum value of significant wave height
$H_U(F)$	H as a function of F for a particular value of U
k	numerical coefficient
t	variable time
t_d	time of duration of wind
T	significant wave period
${}_{max}T$	maximum value of significant wave period
$T_U(t_d)$	T as a function of t_d for a particular value of U
u	function defined by equation (7)-(ii)
U	wind velocity at ocean surface
x	variable distance (or fetch)
λ	wave length of a wave
ϕ	function of variables
ψ	function of variables

GRAPHICAL APPROACH TO THE FORECASTING OF WAVES IN MOVING FETCHES

by
Basil W. Wilson
Agricultural and Mechanical College of Texas

Abstract

This paper describes the development and application of a graphical technique to the determination of maximum significant wave heights and periods attained by waves in moving wind systems. Existing deep water forecasting data, representing the work of Sverdrup and Munk [1947] and modifications since introduced by Arthur [1951] Bretschneider [1951, 1952] are assembled in a single chart over which a space-time wind-field representing any given moving wind system (in relation to a particular point on a coast) can be placed by superposition for the evaluation of the characteristics of the waves generated at any specific point in space and time within the wind field. The space-time tracks of the waves can then be followed in their advance to the coastal station and the time of arrival, heights and periods there determined to give in effect a synthetically constructed wave spectrum for forecasting or hindcasting purposes. The method is applicable to both approaching and receding storms and permits of decay aspects being taken into account in the usual way. An example is given of the application of the method to the forecasting of wave conditions in the path of a hurricane.

Introduction

The present stage of development of the science of wave forecasting in deep water may perhaps be said to rely as yet upon a number of empirical relationships involving the variables of significant wave height, H, significant wave period, T, wind velocity, U, wind duration, t_d, and length of fetch, F, in the generating area. These relationships, suggested by the basic theoretical concepts of Sverdrup and Munk [1947] , and inferred also from principles of dimensional analysis, link the variables in combinations of dimensionless parameters. A fair measure of agreement coming from a number of different observational and experimental sources now testifies to the over-all character of the functional relationships between these parameters [Sverdrup and Munk, 1947; Thijsse and Schijf, 1949; Arthur, 1951; Bretschneider, 1951, 1952; Thijsse, 1952; Johnson and Rice, 1952; Neumann, 1952; Hamada, et al., 1952].

While, it seems, there is nothing inherently deficient in these statistical studies of wind generated waves on a basis of significant wave heights and periods, there has been a recent trend towards a more fundamental understanding of the origin [Eckart, 1953] and spectrum distribution [Pierson, 1952; Neumann, 1952 (ii)] of wave frequencies and heights, resulting from wind activation, and to the adaptation of this approach to forecasting work [Neumann, 1952, 1953; Pierson, et al., 1952, 1953; James, 1954]. In most applications of either kind, however, there has existed some difficulty in making adequate allowance for the continuously changing nature of the wind-field which results from an approaching, receding, intensifying or weakening isobaric system. The problem has been examined by Kaplan [1953] by a somewhat discrete process of classification and tabulation, but the space-time representation of the wind-field used already with considerable success in the study of ocean waves, [Munk, 1947; Barber and Ursell, 1948; Darbyshire, 1952] seems to hold out the greatest promise for successful treatment of these complicating factors.

In the outline of the graphical technique here presented use is made of this space-time concept of changing wind, and the effects of the wind in generating waves are examined through the particular relationships governing the variables H, T, U, t_d, and F, adapted to the purpose in hand from the revised data of Bretschneider [1952]. It will be shown that despite its dependence on significant measures of wave height and period, the method offers some explanation for the statistical distribution of wave heights and periods in any given situation. While, as yet, the writer has not had the opportunity of considering whether the somewhat different treatment of fundamental wave data employed by [Neumann 1952, 1953] could be better adapted to what follows, no loss of generality in the method to be employed need be conceded if the data, in the form it is presented, should be modified at any time to conform with the best and most up-to-date available.

Basic Empirical Relationships of Wind-Wave Parameters

Deep water empirical relationships involving the wind-wave variables, already referred to, are most usually presented in the non-dimensional forms:

$$\left.\begin{aligned} &\text{(i)} \quad \frac{gH}{U^2} = \phi\left(\frac{gF}{U^2}\right) \\ &\text{(ii)} \quad \frac{c}{U} = \psi\left(\frac{gF}{U^2}\right) \end{aligned}\right\} \qquad (1)$$

where c has the usual meaning of phase velocity of the waves, g that of acceleration due to gravity and ϕ and ψ are functions of the bracketed parameters.

The absence of wind duration, t_d, in these statements implies, of course, that, in respect of the data sorted and plotted to these dimensionless parameters, the duration is effectively unlimited and therefore unimportant. Perhaps one of the most complete compendiums of observational and experimental results from varied sources, towards establishment of the nature of the functions ϕ and ψ, is that of Bretschneider [1952]. While his results really need to be amplified from the further resources now available in the work of Thijsse, [1949, 1952] and of Neumann, [1952] it seems unlikely that fresh data will cause any very radical deviation from his best-fit curves defining these functions.

Reid and Bretschneider [1953] have developed simple empirical expressions for the two functions, covering limited ranges of values of the parameters, within which the best-fit curves on log-log scale can reasonably be regarded as straight lines. The present author with the valued assistance of R. O. Reid has now found it possible to secure remarkably good fits to the data over the entire range of values of the parameter (gF/U^2), using functions ϕ and ψ of the forms:

$$\left.\begin{aligned} &\text{(i)} \quad \frac{g\,H}{U^2} = 0.26 \tanh\left(\frac{1}{100}\left(\frac{g\,x}{U^2}\right)^{\frac{1}{2}}\right) \\ &\text{(ii)} \quad \frac{c}{U} = 1.40 \tanh\left(\frac{4.36}{100}\left(\frac{g\,x}{U^2}\right)^{\frac{1}{3}}\right) \end{aligned}\right\} \qquad (2)$$

where F is replaced by the more conventional variable, x.

Figure 1 shows the extent of fit of these relationships to the curves of Sverdrup and Munk and the data of Bretschneider with the superposed experimental results of Thijsse inserted for comparison.

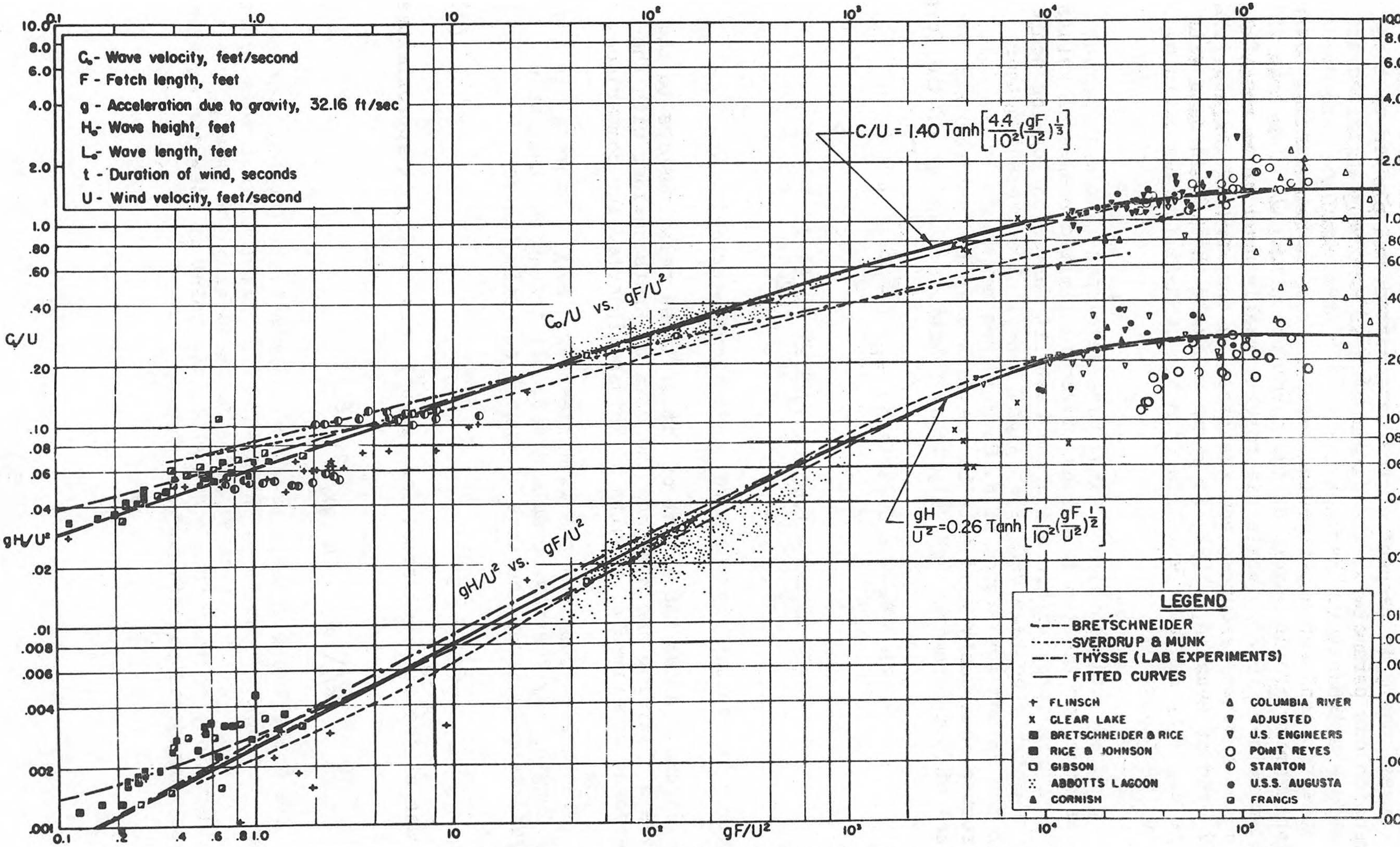
From these equations the wave steepness, H/λ, where λ is the wave length, may readily be determined. It transpires that when (gx/U^2) is very large the wave steepness approximates to

$$H/\lambda = 0.021 \qquad (3)$$

whereas at the other extreme, for (gx/U^2) very small, it approximates to

$$H/\lambda = 0.114\,(gx/U^2)^{-\frac{1}{6}} \qquad (4)$$

The Michell criterion places an ultimate limit (0.143) upon the value that (H/λ) can have. Equations (2) only trangress this limit, via (4), when (gx/U^2) is so small as to be outside the pale of practical consideration, so that from a compatibility point of view the equations may be considered satisfactory.



RELATIONSHIP OF WIND-WAVE PARAMETERS (After Bretschneider)

FIGURE 1

The usefulness of the general equations (2) lies in their mathematical tractability for purposes of plotting relationships between H, F, T, and t_d at particular values of wind velocity U.

The duration, t_d, for which waves are under the influence of the wind, enters the relationship through the statement that

$$\frac{dx}{dt_d} = c_g \simeq c/2 \tag{5}$$

where c_g represents the group velocity at which waves effectively progress in deep water in the direction of distance x. Thus, use of equation (2) (ii) in (5) yields

$$t_d = \int_0^F \frac{dx}{0.70\, U \tanh\left(\frac{4.36}{100} \left(\frac{gx}{U^2}\right)^{\frac{1}{3}}\right)} \tag{6}$$

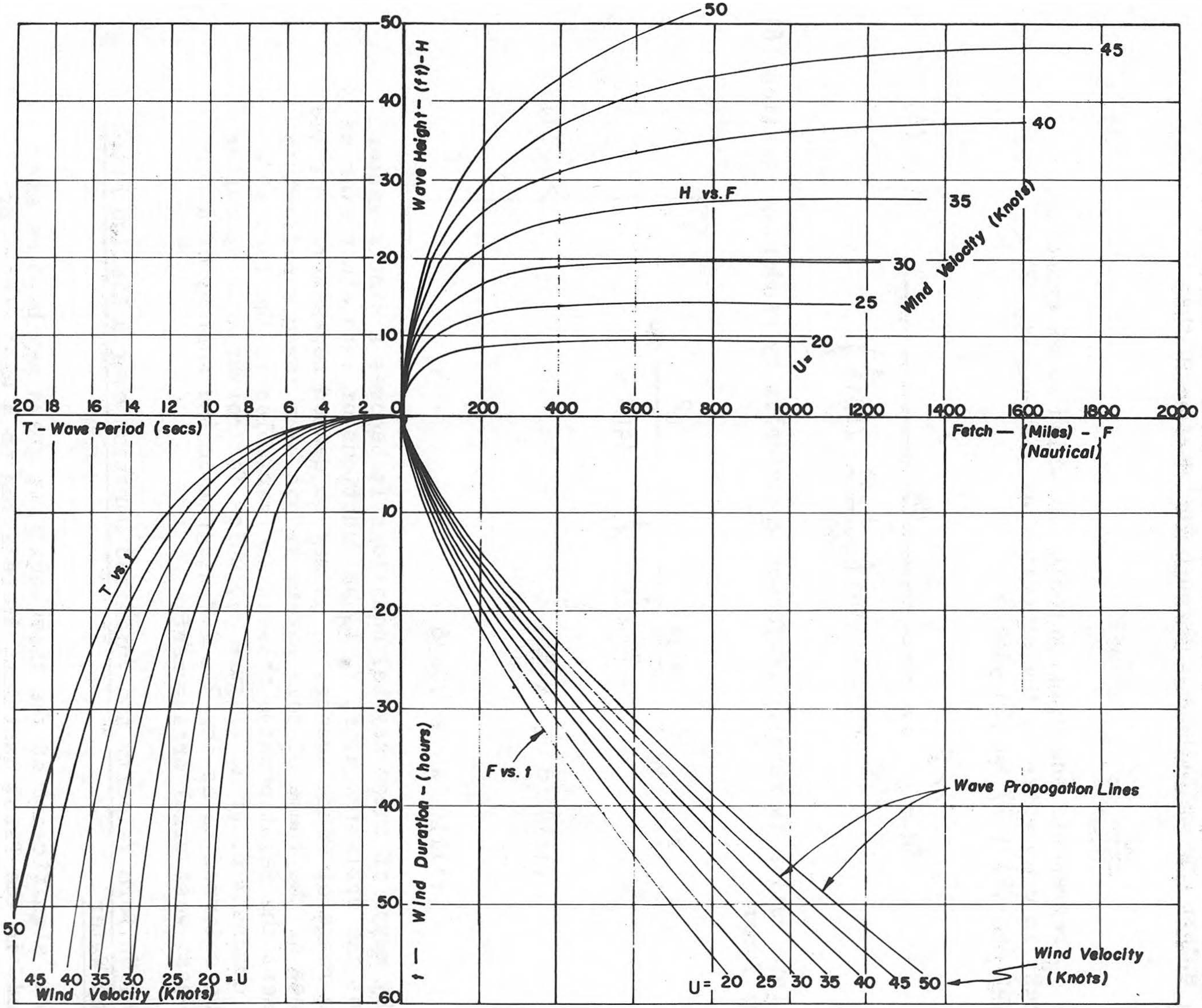
Integration is readily performed graphically by rendering equation (6) in the form:

$$\left.\begin{aligned} &\text{(i)} \quad t_d = \frac{3U}{0.70\, k^3 g} \int_0^u \frac{u^2}{\tanh u}\, du \\ &\text{(ii)} \quad u = k\left(\frac{gx}{U^2}\right)^{\frac{1}{3}} \\ &\text{(iii)} \quad k = 0.0436 \end{aligned}\right\} \tag{7}$$

By means of these several equations it becomes a simple matter to plot the variables H, F, T, t_d as functions of each other over as wide a range of winds speeds, U, as may be deemed necessary. For the purposes of the theme of this paper, it has been found expedient to represent the relationships between the variables in the form of a three quadrant diagram, (Figure 2), which for convenience hereafter will be referred to as the H-t-F-T diagram on the analogy of a north-south-east-west axial arrangement.

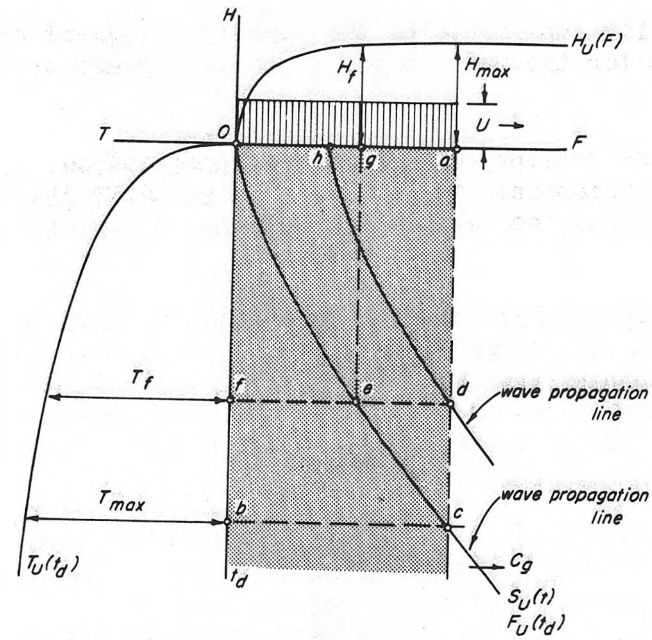
<u>Wind of Uniform Velocity and Unlimited Duration over a Limited Fetch in Deep Water</u>

The significance of the three-quadrant graph may best be explained, in the first instance, in relation to a wind system of uniform velocity, U, extending over a stationary fetch of finite length Oa (Figure 3). The width (or the two-dimensional nature) of the fetch



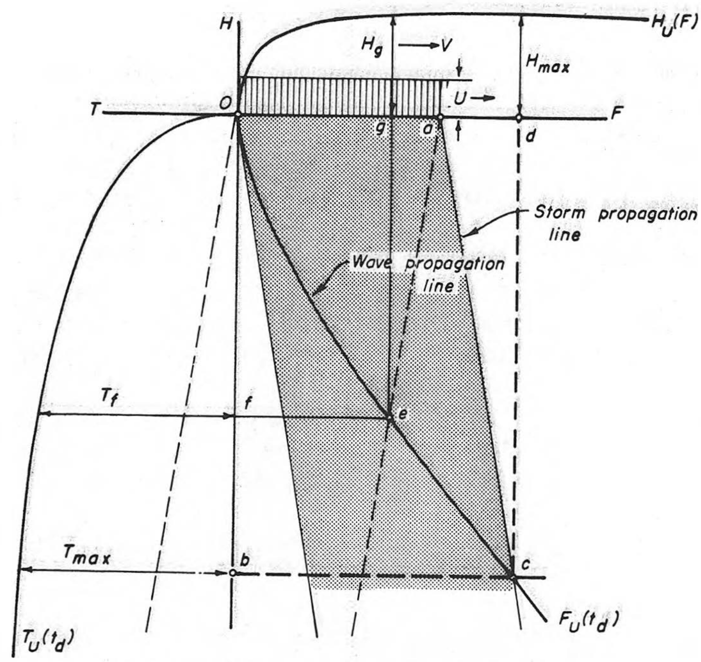
HT - FT DIAGRAM FOR FORECASTING WIND-GENERATED WAVES

FIG. 2



WIND OF UNIFORM VELOCITY IN A STATIONARY SYSTEM OVER A LIMITED FETCH

FIG. 3



WIND OF UNIFORM VELOCITY IN A STEADILY MOVING WIND SYSTEM OF LIMITED FETCH

FIG. 4

area is not really important to the immediate argument except in so far as the wind for the time being is to be regarded as invariable across it.

Since we are dealing with a single steady value, U, of the wind velocity it is appropriate to consider in the HtFT diagram just those curves applicable to the particular velocity U, namely $H_U(F)$, $F_U(t_d)$, and $T_U(t_d)$.

With the wind blowing in the direction OF, waves generated as ripples from the beginning of the fetch O, will gain in height and period in accordance with the curves $H_U(F)$ and $T_U(t_d)$ respectively. The waves will progress in space and time along the propagation line $F_U(t_d)$ or Oec, and at any time, Of, their height will be H_f and period T_f.

The ultimate limit of their development will, however, be reached at c the point on the propagation line marking the end of the fetch Oa. Here the waves obviously pass out of the influence of the wind with the maximum attainable significant height and period $_{max}H$, $_{max}T$. It matters not how much longer the wind continues to blow over the fetch Oa, but the waves are incapable of reaching greater heights and periods, and in this sense fetch is the criterion determining the magnitudes of these wave characteristics. If on the other hand the wind ceased to blow suddenly after the lapse of time Of, the determining factor in the situation would be the duration and the maximum significant height and period of the waves would be H_f and T_f respectively.

At zero time waves may be assumed to originate from ripples at any other point, h, in the fetch length Oa, and to follow a propagation line hd exactly similar to Oea. Such waves would pass out of the wind at d with significant period T_f and height H_f, of which the latter is determined by the intersection point e on the curve $F_U(t_d)$.

It is clear that the same result in respect of the point h could be secured simply by displacing the HtFT diagram relative to the fetch so that the origin coincided with point h. In this way the situation deriving from any other point in the fetch length could be studied.

The waves passing out of the fetch across the boundary, cda at different times will thus tend to comprise a whole gamut of periodicities from (theoretically) zero to $_{max}T$ with heights from zero to $_{max}H$.

<u>Wind of Uniform Velocity in a Steadily Moving Wind System of Limited Fetch.</u>

In Figure 4, the hitherto stationary fetch Oa over which wind velocity was assumed to be constant, is considered to move forward at a steady speed V. In consequence, both front and rear of the fetch describe space-time propagation paths whose slopes equal the velocity V.

Waves that are generated from the beginning of the fetch at O describe, as before, the space-time path Oc along the $F_U(t_d)$ curve, until at c they run out ahead of the wind. The maximum significant period and height are respectively ${}_{max}T$ and ${}_{max}H$ as defined by the intercepts at b and d. The forward movement of the fetch has thus resulted in an effective increase in the length of fetch from Oa to Od.

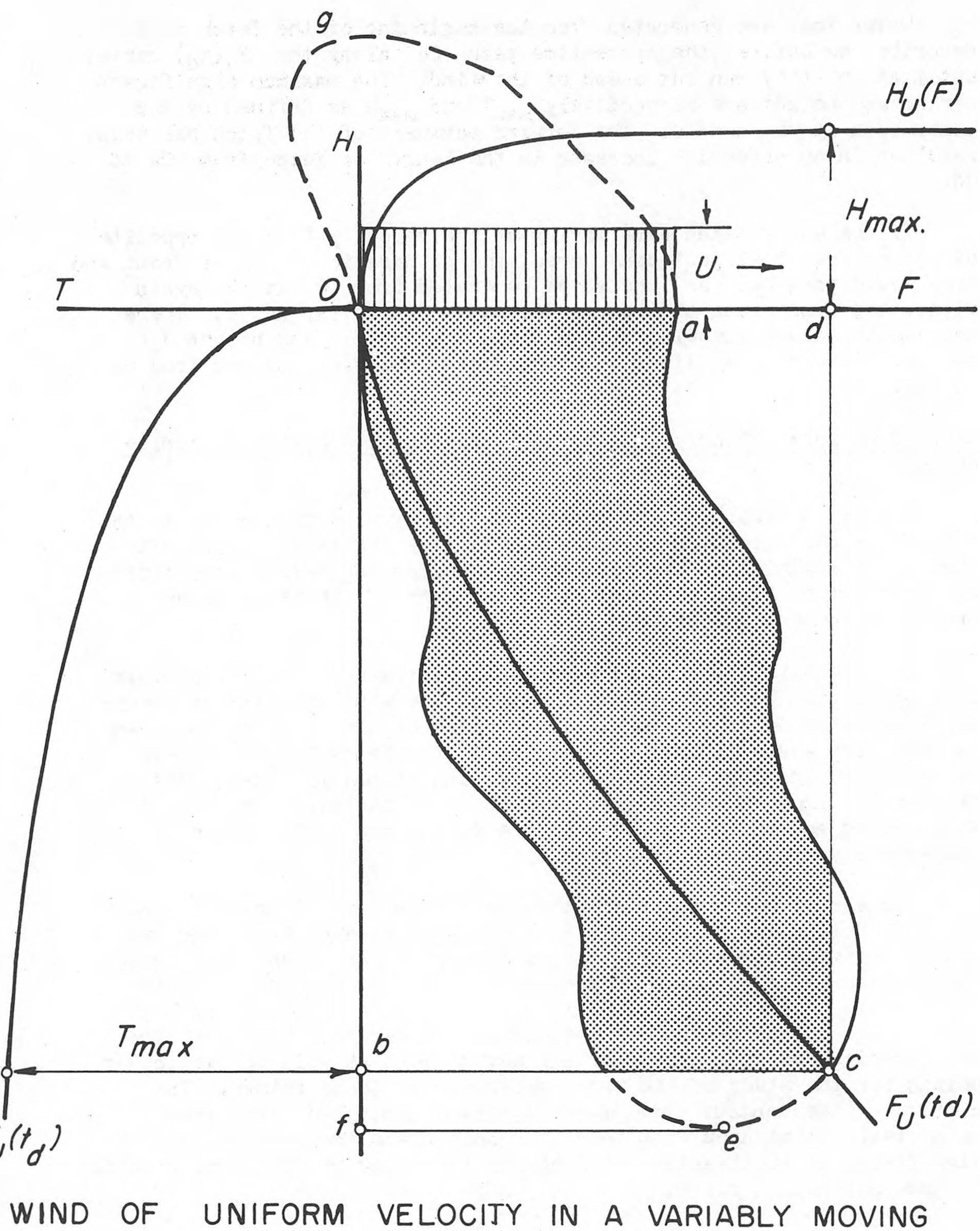
If the whole fetch were moving at the velocity V in the opposite direction from that just considered, the propagation lines of front and rear would parallel ae and waves generated from O would remain within the wind along the space-time path Oe as far as e. There they would escape the wind with maximum period T_f and height H_g and in this case the effective fetch would have been reduced from Oa to Og.

Wind of Uniform Velocity in a Variably Moving Wind System of Finite Fetch.

If, as in Figure 5, the constant velocity wind system Oa moves forward in the direction of the wind, varying its fetch length with time as it might do in practice under changing barometric conditions, the propagation lines defining front and rear of the fetch become irregular space-time curves.

It is possible to conceive of these curves as boundary contours of a space-time "wind-field" within which the wind velocity is everywhere constant and equal to U. The closing of the contour, as shown in dash line would imply the shrinking of the fetch length to zero at e after the lapse of time Of. For the situation shown, waves originating from O would then pass clear of the wind-field at c with period and height as given by the $T_U(t_d)$ and $H_U(F)$ curves respectively at b and d (Figure 5).

The earlier discussion of wave generation from other points than O in the fetch length Oa will be equally applicable here, and the characteristics of waves originating from such points and passing out of the wind-field would be determinable by moving the HtFT diagram relative to the wind-field. This leads to the concept of the HtFT diagram and the space-time wind-field as two separate entities, the one superimposed upon the other and moved about at will to particular points for the study of the waves generated at those points. The closing of the contour Oga above Oa shows, too, that there need be no restriction upon what point, in both space and time within the wind-field, is arbitrarily selected for the study of the waves peculiar to that generating point.



WIND OF UNIFORM VELOCITY IN A VARIABLY MOVING WIND SYSTEM OF LIMITED FETCH

FIG. 5

Wind of Variable Velocity in a Variably Moving Wind System of Finite Fetch

Dispensing now with the restriction of a uniform wind velocity, U, but retaining the concept of uniformity along closed contours of a space-time wind field, it becomes possible to represent a wind system that has both variable wind velocity and variable speed of forward (or rearward) progression by a wind-field of closed contour lines whose intervals apart represent equal increments of wind velocity U.

Figure 6 shows such a wind-field with contours of wind velocity at 5-knot intervals from 20 to 40 knots. Superimposed thereon at an arbitrarily selected point O in space and time is the HtFT diagram with H(F), $F(t_d)$ and $T(t_d)$ curves drawn in for the same 5-knot intervals of wind velocity U from 20 to 40 knots.

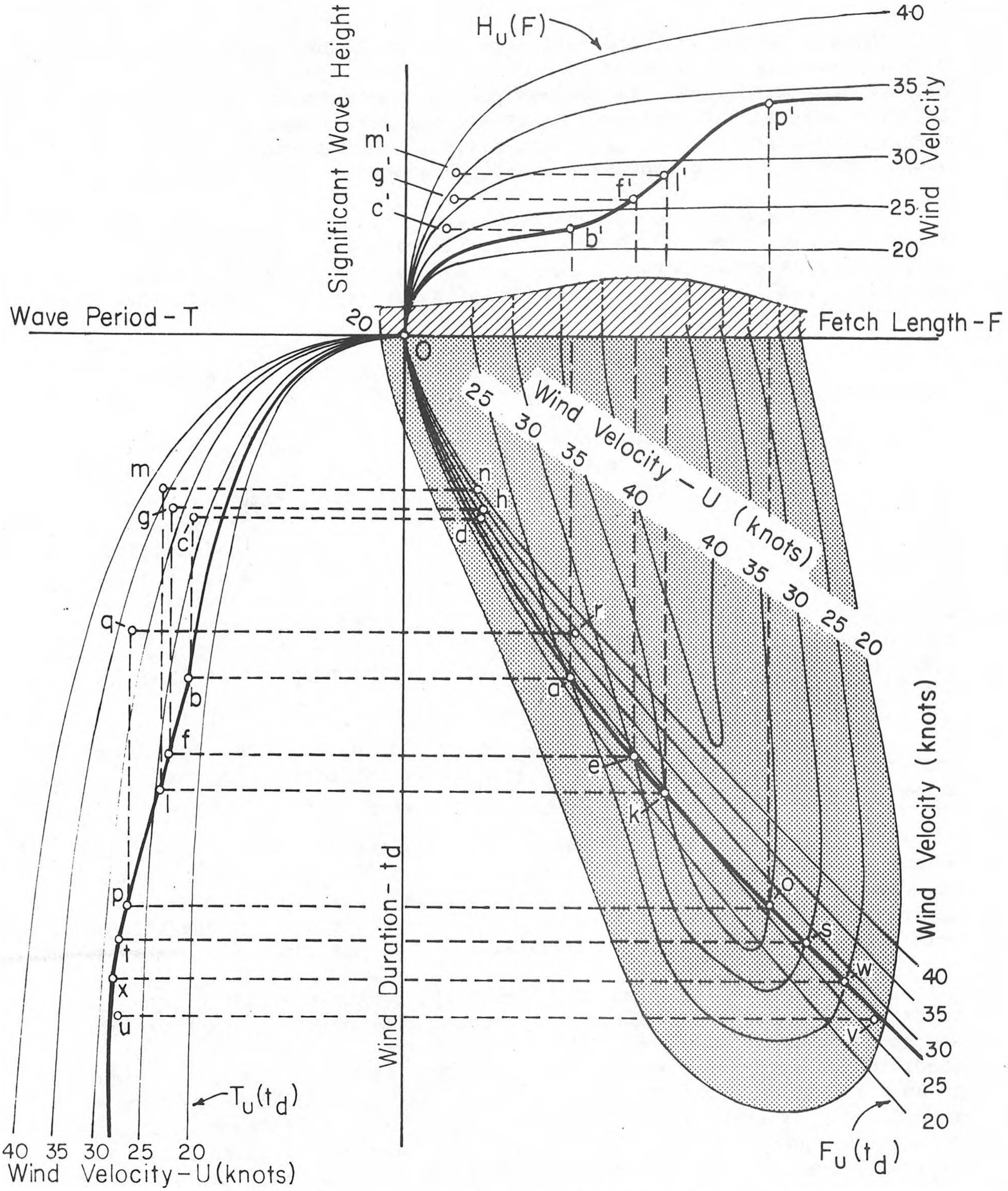
The problem now is one of determining the history of the height and period growth of the waves originating at the point O.

In relation to the wind-field the origin O is seen to be at a point where the wind velocity would be of the order of 21 knots. Waves originating at O would be obliged to follow a space-time path somewhere along the belt of propagation lines forming the relationships $F_U(t_d)$. It is clear that the actual path of the waves must initially be along a line intermediate between the propagation lines for U = 20 and U = 25 knots as far as a, the intersection point with the 25-knot wind-field contour. Along the path Oa the waves would be under the influence of winds ranging from 21 to 25 knots so that, to all intents and purposes, Oa can be regarded as the propagation line for U = 23 knots.

Over the same interval of time the growth in significant period of the waves will follow the line Ob (Figure 6), equivalent to the curve $T_U(t_d)$ for U = 23 knots.

Having arrived at a, the waves pass into the next incremental wind zone over which wind velocity rises from 25 to 30 knots. Their further space-time path from a to e must be at a rate (or group velocity) appropriate to the average wind of U = $27\frac{1}{2}$ knots, but the propagation rate must start off from a at the same slope as the line Oa has at a.

To ensure that the group velocity shall remain the same at the transition, it becomes necessary to trace a line bc at constant period and locate a point c intermediate between $T_{25}(t_d)$ and $T_{30}(t_d)$. The condition of constant period ensures constant wave group velocity since group velocity is directly proportional to wave period under deep water conditions. By drawing the abscissa cd, the point d is found intermediate between the curves $F_{25}(t_d)$ and $F_{30}(t_d)$. An imaginary propagation line $F_{27\frac{1}{2}}(t_d)$, drawn through d would now have the same slope as the curve Oa



SIGNIFICANT HEIGHTS & PERIODS OF WAVES GENERATED IN A VARIABLY MOVING WIND SYSTEM OF VARIABLE WIND VELOCITY

FIG. 6

at a. To find ae, therefore, it is only necessary to transcribe, as it were, a piece of the $F_{27\frac{1}{2}}(t_d)$ curve from d, parallel to itself, and add it to the curve Oa at a. By this means the point e is established.

In the same sense, by transcribing a portion of the curve $T_{27\frac{1}{2}}(t_d)$ from c, parallel to itself, and adding it to the curve Ob at b, the point f can then be located (via ef), marking the further growth in period of the waves, bf, under the influence of the 25 to 30-knot wind.

This procedure may be followed consistently to trace the actual space-time path of the waves, Oaekosw, through the wind-field and to give the history of the period growth of the waves, Obflptx. It will be noted that the same method applies in the zone of declining wind velocities as in the zone of increasing velocities. Thus the portion os of the wave propagation curve is drawn parallel to $F_{32\frac{1}{2}}(t_d)$ at r, the wave group velocity at O and r being different in the declining 35 to 30-knot wind zone from that at h and k in the increasing 30 to 35-knot wind zone.

The graphical charting of the corresponding growth in significant height of the waves follows essentially the same procedure as described above. The curve Ob' follows the $H_{23}(F)$ isoline as far as b', which is the intersection point with the ordinate drawn through a. Further increase in height of the waves in the next incremental wind zone (U = 25 to 30 knots) must continue at a rate appropriate to $H_{27\frac{1}{2}}(F)$, starting, however, at the same height as at b'. Accordingly b'f' is drawn, parallel to $H_{27\frac{1}{2}}(F)$ at c', to give the intersection point, f', with the ordinate drawn from e on the propagation line.

The final curve of significant wave height follows the line Ob'f'l'p' and tapers off to a maximum value which is maintained to the end of the wind field. In the same way the curve of significant wave period, Obflptx, is found to taper off to a maximum value of wave period.

Mathematical Confirmation

The complete mathematical justification for the above graphical procedure would be long and involved and quite beyond the scope of the present paper. Suffice it to say that the method has been checked both in regard to the propagation and the height growth of waves as generated within the variable winds of a hurricane, comparable to that which invaded Galveston in 1915, but regarded as stationary for purposes of simplicity. The particular wind velocity distribution considered is shown in Figure 7 and conforms to a wind cross-section of the storm at a distance of about 45 nautical miles from the center of the eye, the velocities given being the components of wind velocity directed along a straight fetch-line, parallel to the normal direction of advance of the hurricane.

The computation of wave heights within the variable wind has been performed by numerical integration with respect to x, regarding U as variable, of the derivative $\partial H/\partial x$, obtainable from equation (2)(i). A necessary initial requirement of this integration is that $\partial H/\partial x$ be expressed as a function of (gH/U^2) by suitable elimination of the parameter (gx/U^2).

Somewhat similarly the propagation of the waves within the variable wind has been derived from numerical integration with respect to x, regarding U as variable, of the derivative $\partial c/\partial x$, represented as a function of (c/U). The derivative $\partial c/\partial x$ is obtainable directly from equation (2)(ii). The elapsed time of travel of the waves follows from further numerical integration with respect to ∂x of the evaluated quantity $(2/c)$.

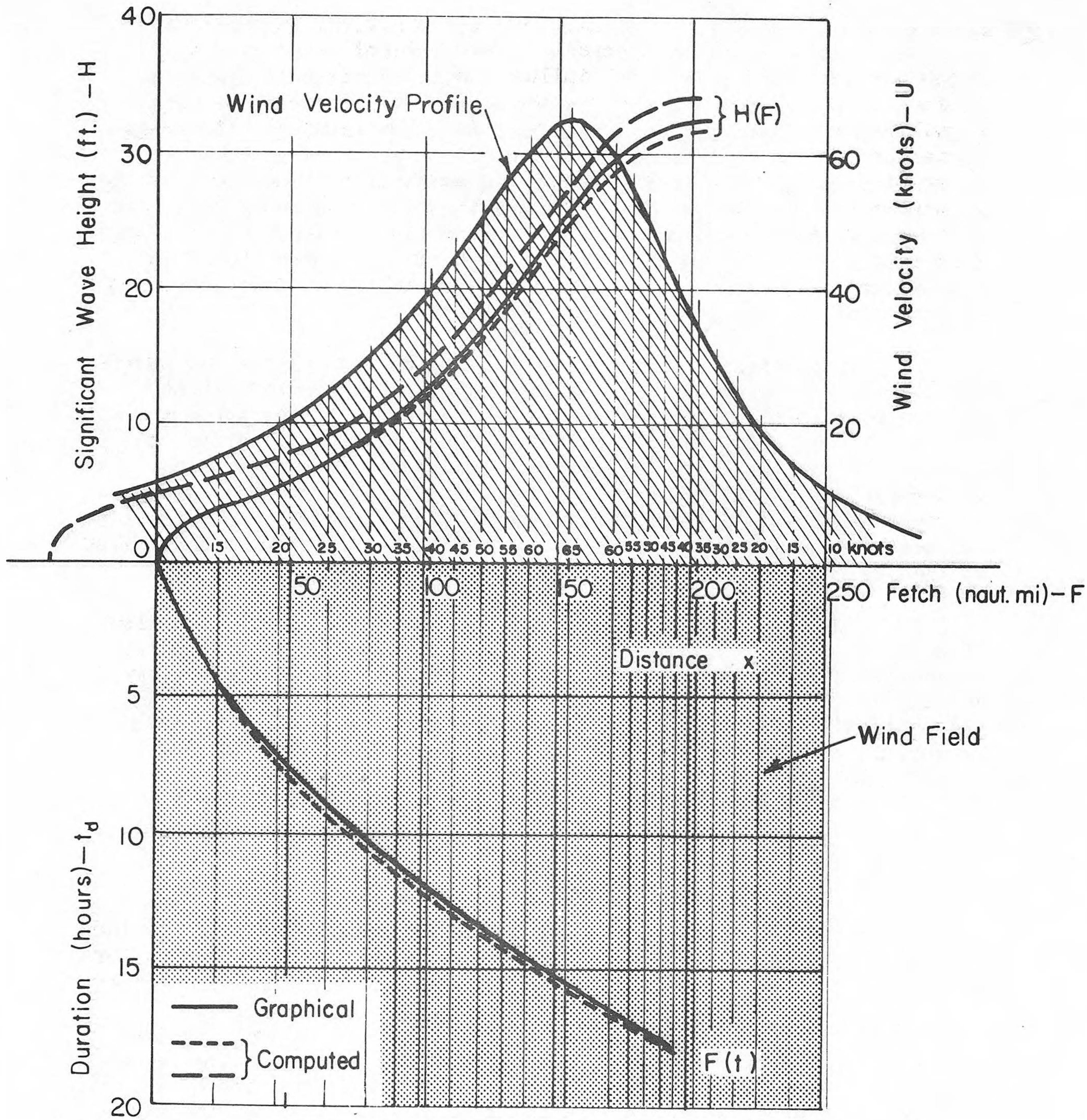
The results of the calculations, which are necessarily protracted, are shown in Figure 7 alongside the corresponding relationships as determined by the rapid graphical procedure already outlined. Having regard to possible small sources of error in both methods the agreement may be regarded as satisfactory confirmation of the reliability of the graphical technique.

An advantage of the graphical method is the facility with which, in effect, elaborate integrations are performed. By superimposing a wind-field transparency over one of the HtFT diagram, on a drafting table illuminated from below, it is possible without relative movement of the two sheets, to plot on the wind-field the three curves $H(U,F)$, $F(U,t_d)$ and $T(U, t_d)$ originating from the point in the wind-field with which the origin 0 of the HtFT diagram is coincident. A shift in relative positions of the diagrams is only necessary when a new point in the wind-field requires investigations.

Space-Time Wind-Field in Relation to a Coastal Station

Up to this point the moving line-fetch has been regarded as one dimensional, but since all wind systems in their effect upon the ocean surface are two dimensional, some attempt must be made to overcome the limitation of the uni-dimensional restriction, particularly in-as-much as the loci of storms in the general case will not pass directly through the coastal area that may happen to be the subject of study.

To this end, Figure 8 envisages a frontal storm (defined by its isobars), considered for the moment to be stationary off the west coast of a land mass in the northern hemisphere. The normal circulation of winds within a storm of this nature tends to be anticlockwise across the isobars, at a slight angle, directed inwards towards the center.



COMPARISON OF COMPUTED & GRAPHICALLY DETERMINED HEIGHTS & TRAVEL DISTANCES OF WAVES GENERATED WITHIN A STATIONARY HURRICANE

FIGURE 7

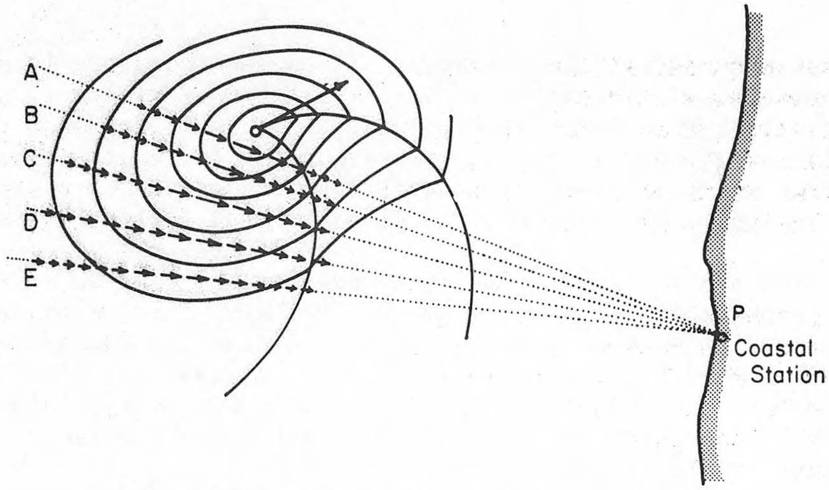
Waves generated within the ambit of the storm will on this account almost certainly be short-crested as a result of the interference effect of multi-directional influences. With increase of distance from the storm center however, the prevalence of short-crestedness will inevitably decrease and waves will tend to assume the characteristics of long-crested waves or swells. It seems a reasonable assumption then that whatever long-crested waves finally emerge from the wind area in a particular direction are the wave components that have been consistently operated upon by the wind components directed along that line of action. This implies that the time-honored process of resolution in a particular direction can be applied to the dissection of both winds and waves within the storm area.

If then particular radial lines PA, PB, PC ... (Figure 8), passing through the southern part of the storm area, be considered, it may be assumed that the resolved horizontal components of the surface wind velocities along any single radius, such as AP, will alone be responsible for the characteristics of the waves propagated along AP towards the coast. In Figure 8, the lengths of arrowheads along the various radial lines represent these wind velocity components, and each radius may be regarded as a line-fetch in the sense considered at the beginning of this paper.

It seems categorical that the highest waves of all will emanate from just one optimum radial direction along which the wind velocity components have maximum wave-generating capacity. As this capacity depends upon the square of the wind speed [Sverdrup and Munk, 1947] the particular radial-line distribution of wind velocity components, U, will be that for which $\int U^2 \, dx$ is a maximum. The distribution, of U^2 values with x for different trial radial lines such as AP, BP, ... would be expected to follow the trends shown in Figure 9. The particular curve containing maximum area beneath it would then determine the optimum fetch-line, (CP, for example), for generating highest waves.

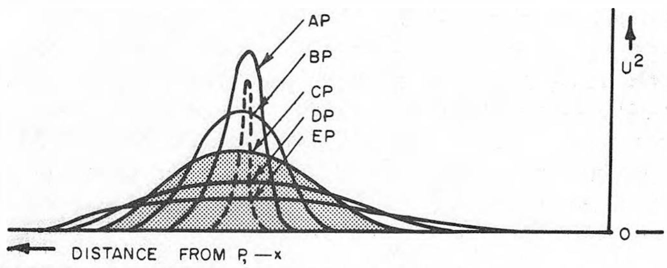
For the stationary wind system the forecast of heights and periods of waves emerging from the wind area would follow much the same pattern as Figure 7, as determined by the graphical procedure already outlined.

If the storm be considered now to move forward in the direction indicated in Figure 8 and to be subject to time-changes in the isobaric formation, the general rate of progression and the direction of motion,-- leading, of course, to changes in the wind circulation, and the magnitude and distribution of wind velocity components directed towards P, -- then, for any particular radial line, AP, say, (Figure 10) there will be a continuously changing distribution of horizontal radial wind velocity components with passage of time as the storm moves forward on its course, MN.



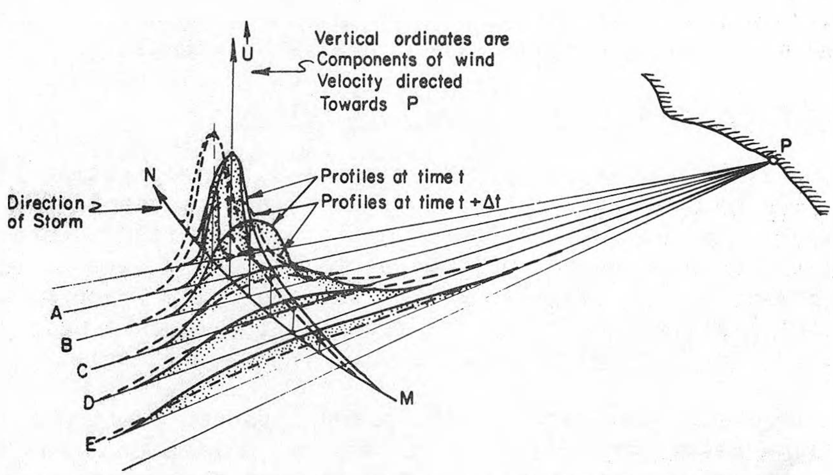
STATIONARY STORM IN RELATION TO A WEST COAST STATION

FIGURE 8



DETERMINATION OF OPTIMUM FETCH LINE FOR GENERATING HIGHEST WAVES

FIGURE 9



DISTRIBUTIONS OF HORIZONTAL WIND VELOCITY COMPONENTS ALONG FIXED RADIAL LINES FOR MOVING STORM

FIGURE 10

For any such radial line therefore it becomes possible to determine a space-time wind-field after the fashion of Figure 11 by suitably plotting wind velocity components. Typical data such as might be found for the times t_1, t_2, t_3, corresponding to successive storm positions for which information is available, thus enables contours of wind velocity to be drawn in, defining the wind field (Figure 11).

This wind system is entirely analogous to that considered in Figure 6, so that by superimposing the HtFT diagram and applying the processes already described it becomes possible to investigate the maximum significant height, period and space-time direction of waves emanating from any point within the wind-field up to the stage of their passing out of effective wind domination on their route towards the station P, along the chosen radial line.

To investigate adequately the nature of the waves converging on the coastal station P from different directions it will obviously be necessary in the general case to select a number of representative directions of approach, A_1P, A_2P, A_3P, ... (Figure 12), and to submit the wind-fields appropriate to each to the graphical procedures described.

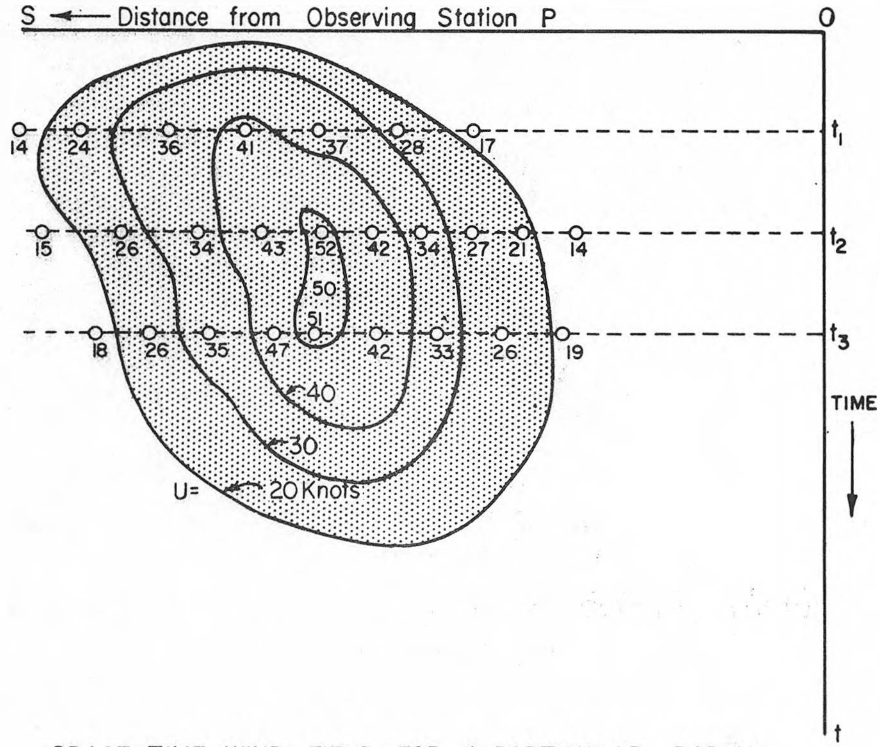
All of the above considerations would be applicable equally well to a receding storm as to one approaching a coastline. Figure 13 might represent the case of a storm moving out to sea across the east coast of a land-mass in the northern hemisphere. In keeping with the arguments already presented it would be possible to find radial lines of wind velocity components, directed towards a coastal observing station P for any instantaneous position of the storm, for plotting the space-time wind-fields for each chosen direction.

As distinct from an approaching storm, the wind-field of a receding storm would show an inclination, with time, away from the time axis, as illustrated in Figure 14. It will immediately be seen from this that, with the HtFT diagram superimposed as before, the overall extent or width of the wind-field in the direction of wave propagation will tend to be relatively shorter than that pertaining to an onshore storm: in consequence, the chances of high wave generation will usually be much less.

Influences of Depth, Ocean Currents and Local Winds

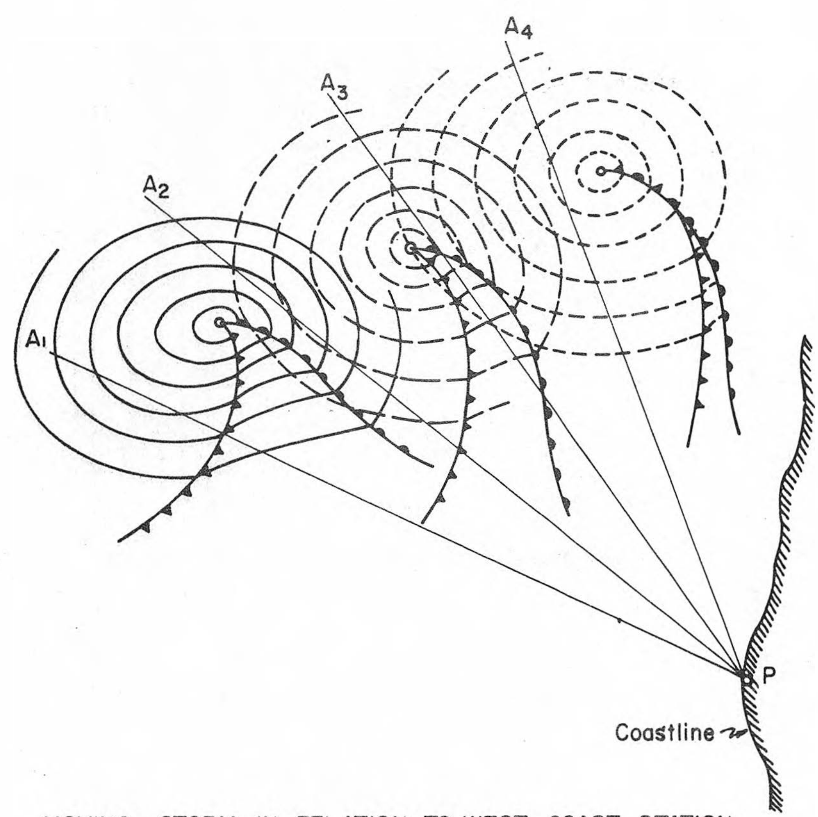
There remains to note that an HtFt diagram with propagation lines applicable strictly to deep water conditions might not be usable for near-shore conditions. In such circumstances depth factors tend to become important and the wave propagation lines would correctly have to be based upon the 'intermediate' or 'shallow water' wave velocity formula, while the H(F) and $T(t_d)$ curves would require modification to make suitable allowance for shoaling, refraction and bottom friction effects.

While it is beyond the scope of the present paper to attempt to deal with shallow water complications, it may be pointed out that the influences of depth are best kept in mind and allowed for by the insertion



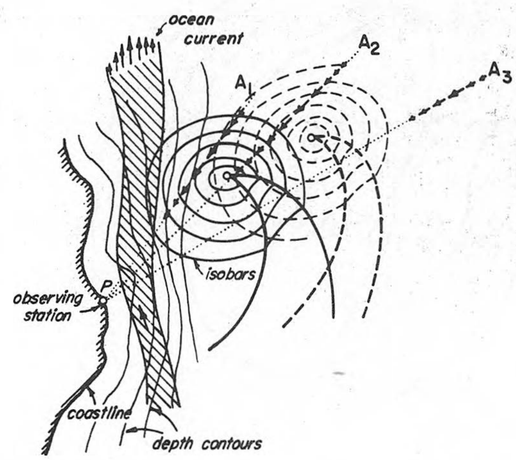
SPACE-TIME WIND-FIELD FOR A PARTICULAR RADIAL DIRECTION

FIGURE 11.



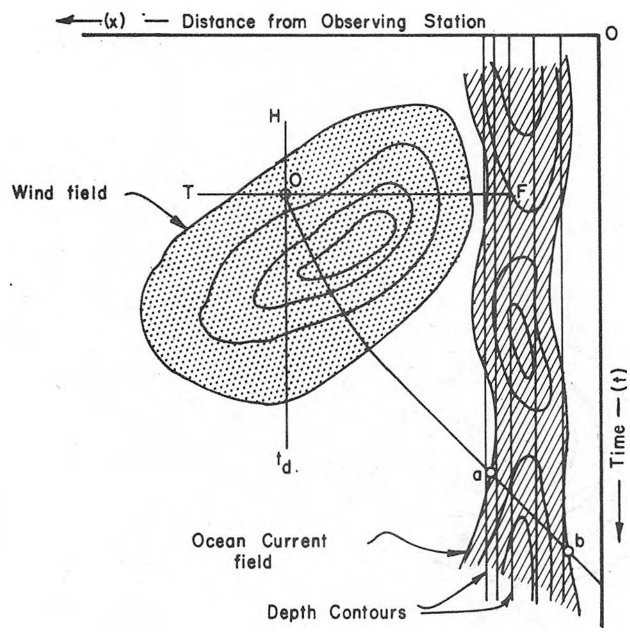
MOVING STORM IN RELATION TO WEST COAST STATION NORTHERN HEMISPHERE

FIGURE 12.



COASTAL STATION IN RELATION TO A RECEDING STORM

FIGURE 13



SPACE-TIME WIND FIELD: RECEDING STORM

FIGURE 14.

of depth contours on the space-time chart of the wind-field, as shown in Figure 14.

The effects of local winds and ocean currents on the waves leaving a generating area are other complications which really require treatment if forecasting is to be accurate. Again it would be outside the province of this paper to deal with all these ramifications at this stage but the graphical technique could be made adaptable to these circumstances also. An ocean current, for instance, such as that shown in Figure 13 would refract and delay the waves converging on the observing station P. Plots of the components of the current velocities directed along a particular radial line, tending to oppose free transmission of the waves, would thus provide an ocean-current field such as indicated in Figure 14. The variable trend with time suggested in Figure 14 might derive from tidal flux or from other perturbations. The influence of the current on the propagation of the waves emanating from any particular point O in the wind-field would obviously be felt over the extent ab of the propagation line crossing the current field.

In much the same way local wind-fields, providing either assisting or retarding winds, could be plotted and their effects suitably taken into account in tracing the progression of the waves towards the station.

Example of Forecasting Waves in the Path of a Hurricane

As an example of the methods described in this paper Figures 15 and 16 represent respectively the HtFT diagram and wind-field developed for the special case of a (design) hurricane assumed to be travelling at a steady speed of 10 knots towards a coastal station on the Gulf of Mexico. Figure 15 is an enlargement of part of Figure 2 with additional curves inserted, on the basis of equations (2) , to cater for hurricane wind velocities up to 100 knots.

It is unnecessary to enter here upon details of the design hurricane, suffice it to say that, generally, in extent and intensity, it might be considered comparable to the Galveston hurricane of 1915. The radius of the eye of the hurricane measured to the zone of peak winds is 36.8 nautical miles, and the maximum sustained wind speed at this radius 71.3 knots (82 mph). The particular distribution of horizontal wind velocity components for optimum wave generation, determined on the basis of Figure 9, is found to lie along a line passing at a distance of 54.7 nautical miles to the right of the hurricane center, in the direction of motion. In the wind-field of Figure 16 this distribution is assumed to remain unchanged as the hurricane moves to wards the coast, with the result that the contours of wind velocity are all parallel diagonal straight lines whose gradients represent the forward velocity of progression (10 knots) of the hurricane. Inserted on the wind field are contours of depth defining the continental shelf to the 600 foot depth limit, across which the hurricane must pass.

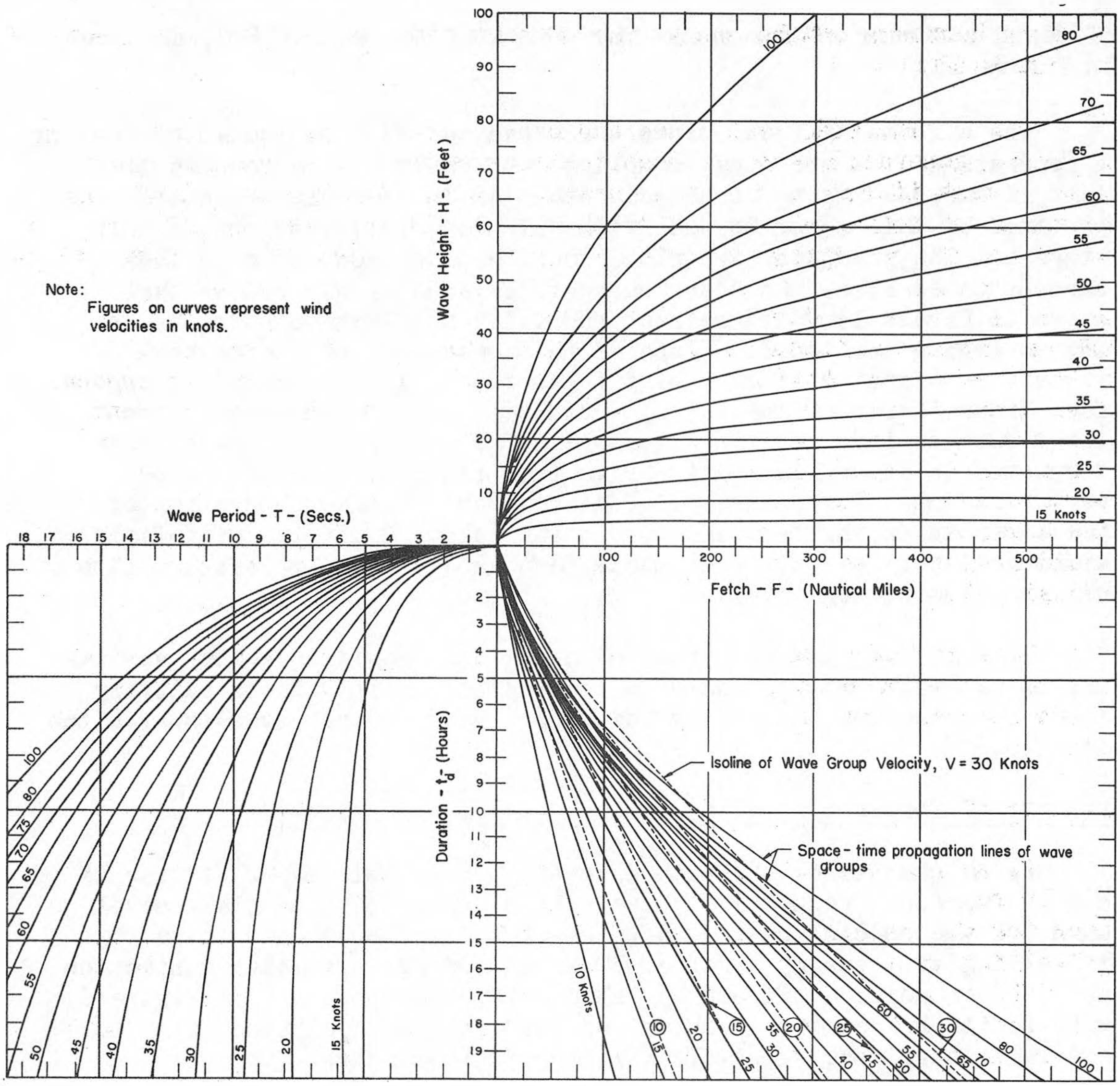
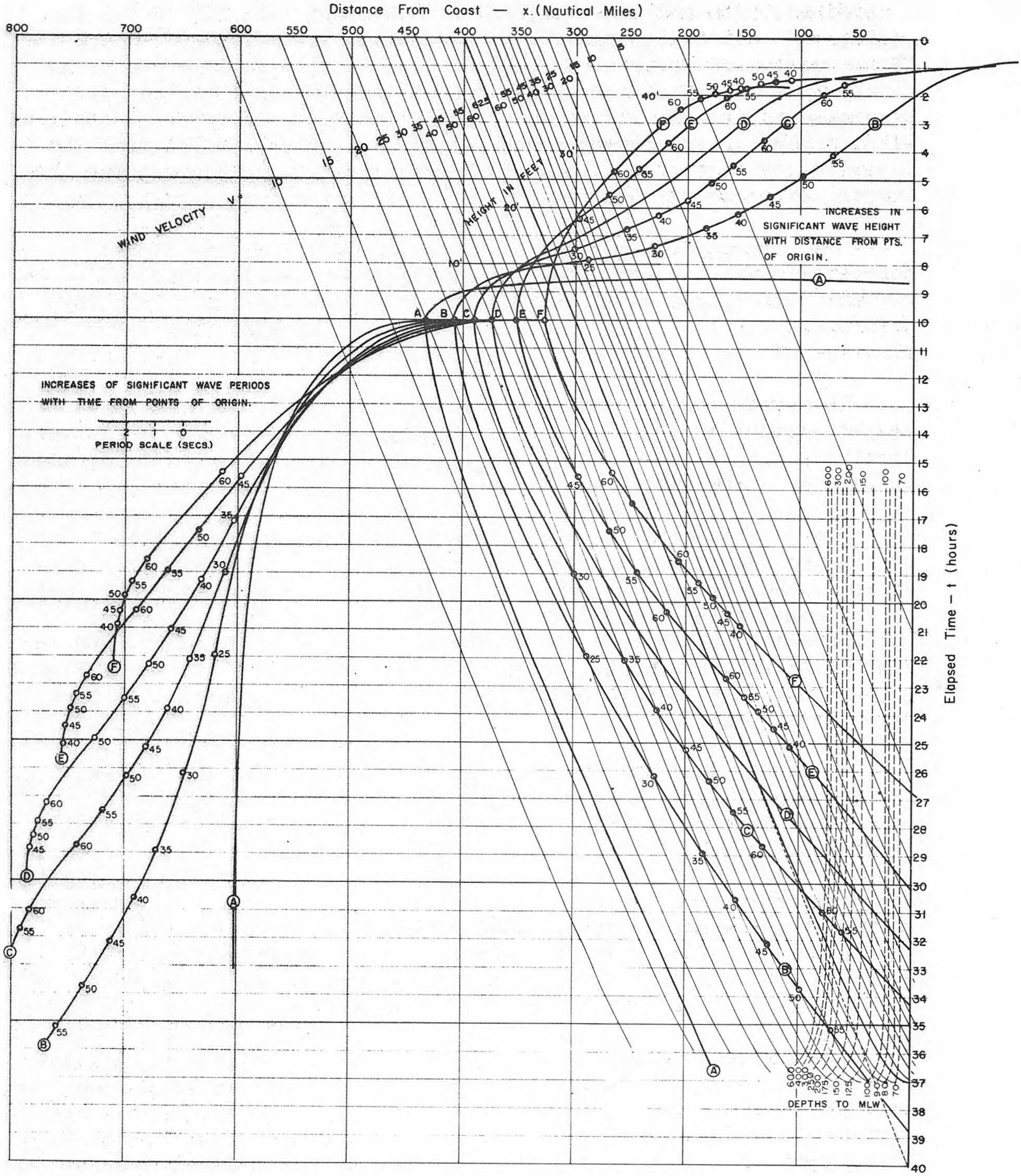


FIGURE 15 · RELATIONSHIPS FOR FORCASTING SIGNIFICANT HEIGHTS AND PERIODS OF WAVES IN DEEP WATER UNDER WIND OF PARTICULAR VELOCITY, DURATION AND FETCH



DERIVATION OF CHARACTERISTICS OF WAVES FROM SEVERAL DIFFERENT POINTS OF ORIGIN WITHIN THE DESIGN HURRICANE

FIGURE 16

Several case histories of wave generation have been worked out, according to the methods outlined in this paper (cf. Figure 6), for different incipient points in the space-time wind-field of Figure 16, These points are designated A, B, C, D, E and F. To take one as an example, say F, this records the growth in height and period, and progress in distance and time, of the waves supposed to originate from wind ripples in an already rough sea at 300 nautical miles from the coast at the hurricane time of 10 hours; that is, 10 hours after the hurricane center was 400 nautical miles from the coast.

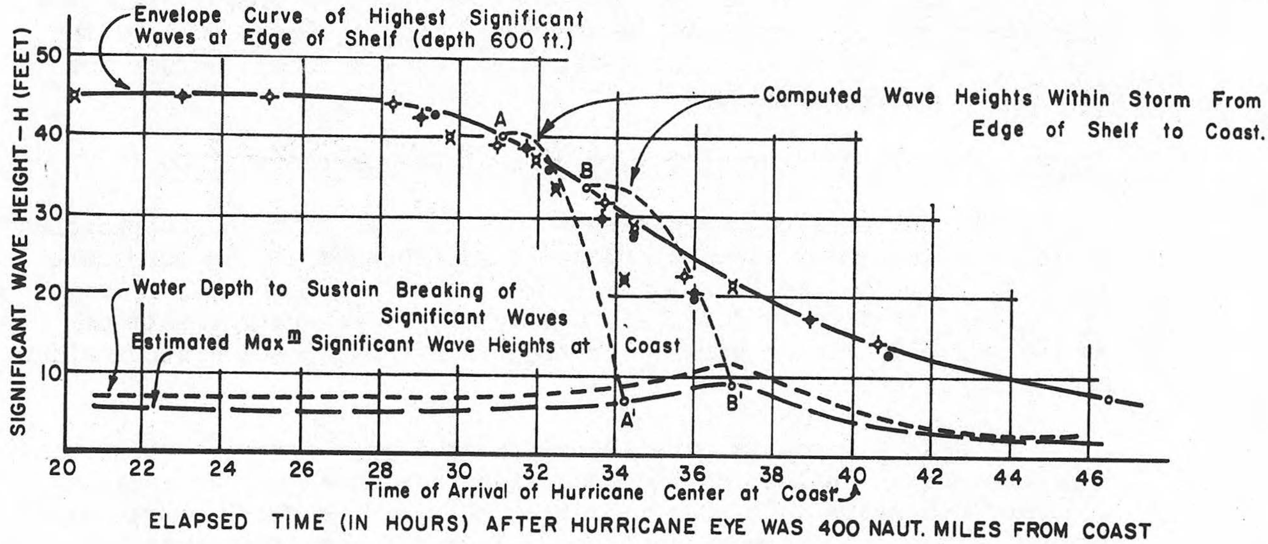
The propagation path of the waves in space and time from F curves across the wind-field. Initially under the influence of 55 to 60-knot winds, the waves enter a zone of somewhat higher velocity before escaping to a region of declining wind speeds. The waves are finally seen to reach the coast at 26.75 hours.

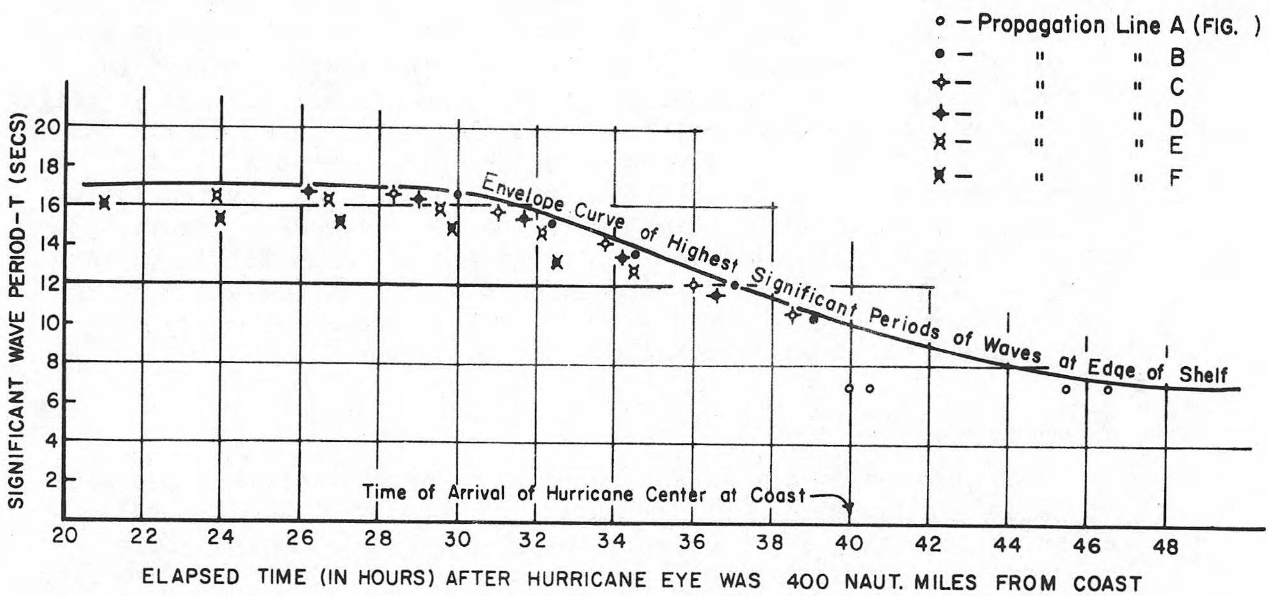
The curve rising above the point of origin, F, records the height growth; that to the left of F, the period growth of the waves. Circled points on these curves correspond with similar points on the propagation line and indicate the wind velocities encountered.

The case histories traced in this fashion for points A to F within the wind field are, of course, valid only for deep water conditions, that is, up to the point of the waves entering the shallows of the continental shelf (depths of 600 feet and less). In this latter region they become subject to the effects of friction, and the laws of height and period growth no longer follow the curves of Figure 15, although the wave propagation lines, extended through this zone, will, as it turns out, be very little in error.

It is possible in this particular example to use the AA, BB, ... FF curves of Figure 16 to determine the significant heights and periods of waves arriving at the edge of the shelf (depth 600 feet) from other points of origin in the space-time wind-field. Thus the simple expedient of moving the curves parallel to themselves along the diagonal contours of the wind field permits the plotting of envelope-curves of maximum significant wave heights and periods as depicted in Figure 17. These envolope-curves give the maximum significant heights and periods of waves at the shelf edge at any time, both before and after arrival of the hurricane at the coast.

It will be remarked that at the shelf-limit maximum significant wave heights vary from 45 feet to about 10 feet, depending on the time, and wave periods from 17 seconds down to about 7 seconds. The highest and longest waves tend to arrive first, ahead of the hurricane. From Figure 16, it will be noted that the hurricane center reaches the shelf at about 32.5 hours, by which time wave heights and periods, as shown in Figure 17, will already be less than they were when the hurricane was more distant.





FORECAST OF HEIGHTS & PERIODS OF WAVES ARRIVING AT GULF PORT FROM DESIGN HURRICANE

FIGURE 17

The trends predicted by Figure 17 accord satisfactory with the general facts of observations on swells and waves arriving at a coastline from meteorological disturbances over the ocean. Thus the consistent diminution of wave period with time conforms well to the established facts of spectrum analyses of wave records [Barber and Ursell, 1948; Deacon, 1949].

Propagation of the Hurricane Waves Across the Continental Shelf

While the present paper cannot hope to deal with the intricacies of the shallow water wave generation that proceeds as the hurricane moves in over the shelf in the example quoted in Figure 16, it may be remarked that these details are amenable to separate treatment on the basis of recent work by Bretschneider [1954] and Bretschneider and Reid [1954].

The general problem here is complicated by the fact that as the hurricane moves in towards the land it raises ahead and under it a considerable storm tide which entirely changes the depth characteristics of the nearshore environment. Then too, besides refraction effects which diffuse or concentrate the wave energy, there occurs a shoaling effect tending to augment wave heights over and above any building up of the waves by continuous generation under the wind. Opposed to all this are the frictional effects of the shelving bed, which, in the circumstances of the particular example treated in Figures 16 and 17, prevail to bring about an overall decline in height of the waves with advance of time according to computed curves such as AA' and BB' (Figure 17) from which the final curve A'B' of significant wave heights at the coast is obtainable. In concluding it may be noted that the waves following the curve BB' (Figure 17) enter upon the shelf with smaller heights than those following AA'. This is attributable to the wind generation in shallow water being so much more effective for BB' than for AA' because of virtually continuous 60-knot winds pertinent to the former.

Summary and Conclusion

The graphical representation that has been given here seeks to assemble available wind-wave data in the form of a readily usable chart or HtFT diagram, such as shown in Figures 2 and 15. This diagram inter-relates significant wave height, period, wind velocity, duration and fetch and expresses the cumulative distance travelled by deep water waves, assumed to start from the origin and increase their phase velocity in keeping with their growth in period under wind influence, but progress, withal, at the group velocity of deep water waves. The diagram functions as a working tool in the graphical process of analysis of any specific marine meteorological situation resulting in excitation of waves by wind.

Ancillary to the HtFT diagram is a space-time representation of the anemometrical conditions. This gives the wind-field applicable to any particular fetch-line through the storm area whose direction of action passes through a given coastal station. The essential process by which this wind-field is plotted consists in determining, for each synoptic chart available, the components of horizontal surface wind speeds directed along the chosen fetch-line towards the station. Fetch and wind speed are hereby positively determined and are no longer open to arbitrary selection methods such as have been commonly employed.

The conception of a line-fetch, of course, raises the issue of diffraction effects in the generated short-crested waves; effects which could derive from possible non-uniform characteristics in the wind velocity distribution across the (unit) band width of the fetch-line. Ordinarily, however, this complication should be unimportant since gradations of wind velocity, transverse to the fetch-lines, will tend to be slight.

The operation of the tool on the material is the final step in the graphical procedure, though this phase is actually more conveniently performed by superposing the material on the tool. If the wind-field is plotted upon transparent paper or cloth it may readily be aligned over the HtFT diagram. Wave propagation lines for any points in the wind-field can then be drawn upon the latter and projected to their destination to record arrival times upon the time axis.

An interesting feature of the overall process is that it accounts for the capacity that the wind apparently has for continuously generating new waves from ripples at all points along any given fetch-line and at all times, and for progressively building the wavelets into ever bigger waves. An infinite number of wave propagation lines, theoretically, can be drawn from the area of a space-time wind field, applicable to a given fetch-line, to give a continuous time spectrum of wave heights and periods for the waves arriving at the destination point. These may be expected to be in substantial agreement with successive periodograms, such as have been obtained from spectrum analyses of wave records [Barber and Ursell, 1948; Deacon, 1949] demonstrating that it is always the longer period waves that arrive first and are followed by the higher frequencies. The composition of the time spectra of wave heights and periods, indeed, could be further expected to reveal the dominant influences of the extent of the fetch and the strength of the wind as they have usually been observed and empirically stated [Stevenson, 1863; Cornish, 1934; Neumann, 1952 (i)].

Acknowledgement

This apaper is the by-product of an effort to understand by simple graphical analogy the somewhat complicated processes of wind generation of water waves. Before the ideas presented took on a

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