BAY OF FUNDY TIDES

by

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(Reproduced from *United States Naval Institute Proceedings,* Annapolis, May 1938, page 693).

Much has been written but little is known of the cause of the exceptionally large range of tide in the Bay of Fundy, and the explanation of the phenomenon about to be given here may add to the confusion which exists. The explanation must be spectacular, reached through bold thinking, for were it not so, the more timorous minds would have discovered a prosaic one.

For the reader who is unfamiliar with tides, a brief description of the several terms and related material is introduced in sufficient detail to enable him to comprehend the underlying principles involved without digressing too far from the subject.

Since the tides exist, and their occurrence is so well understood, no discussion of the severa theories regarding them will be introduced. In general, all tides are composed of a number of component tides which result from the variable attractive forces of the sun and moon. The tides group themselves into three classes : (1) those having a period of approximately half a day

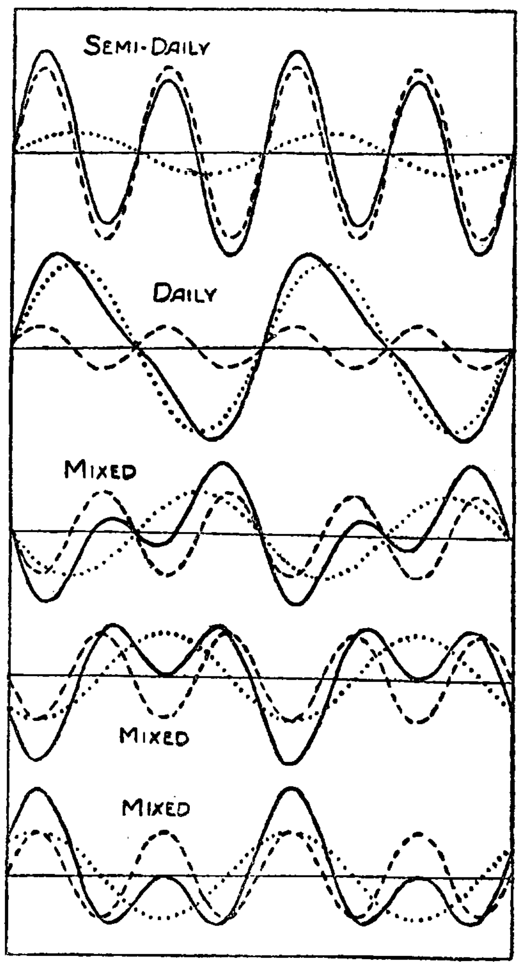

FIG. 1.

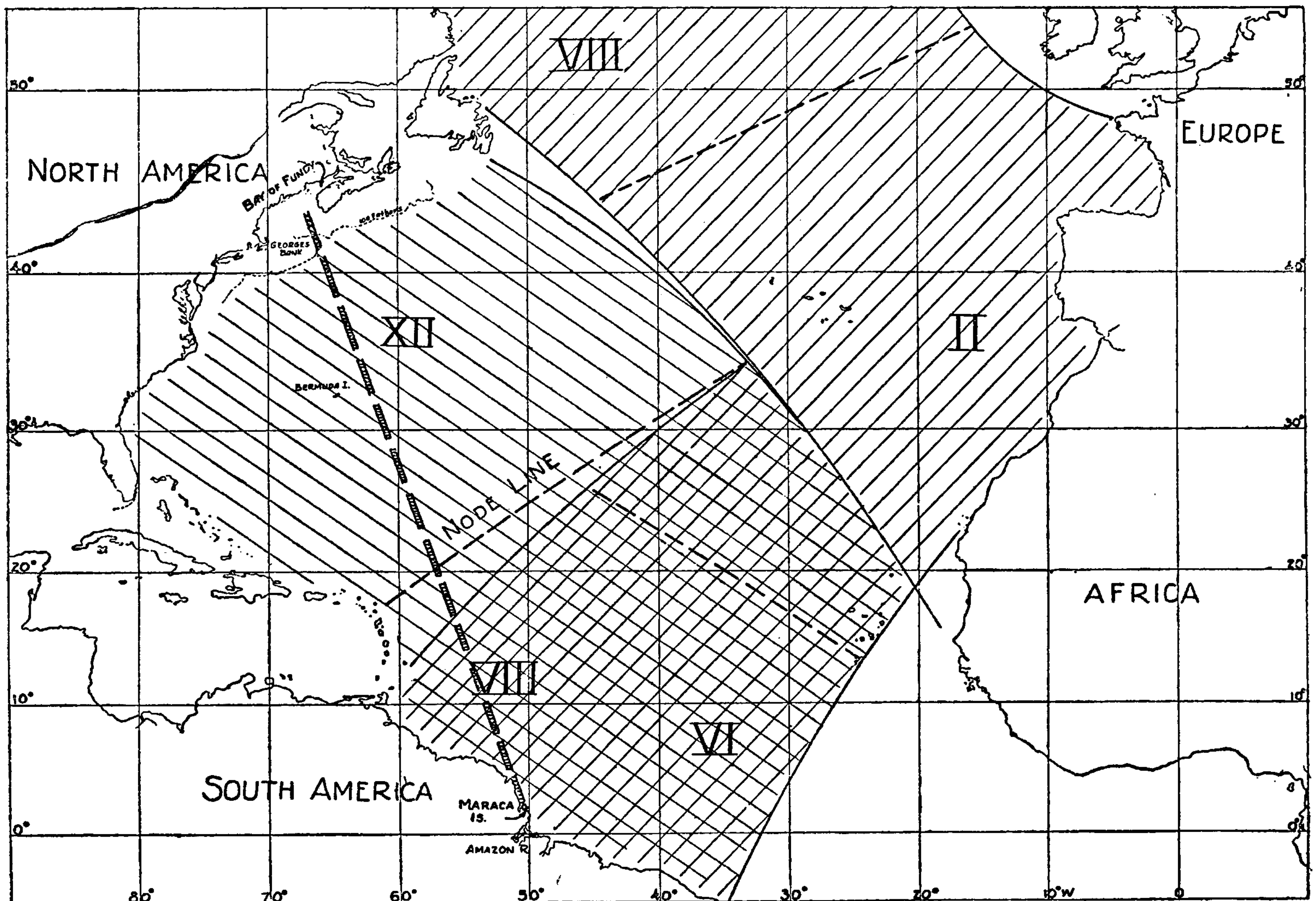
NORTH AMERICA
SOUTH AMERICA
EUROPE
AFRICA
VIII
XII
II
VI
VIII
NODE LINE
BAY OF FUNDY
GEORGES BANK
BERMUDA I.
MARACA IS.
AMAZON R.
50°
40°
30°
20°
10°
0°
80°
70°
60°
50°
40°
30°
20°
10°W
0

FIG. 2

(semidiurnal tides); (2) those having a period of approximately one day (diurnal tides); and (3) those having a period of a fortnight, month, year, or longer intervals, called long period tides.

The coalescence of the various component tides takes place in such manner as to produce three general classes of tides, known as daily, semidaily, and mixed. Combining the several daily and semidaily component tides into resultants, omitting any longer period tides, and giving varying relative values to these resultants, both in amplitude of the wave and their phase relations, the derivation of the different types is shown in Fig. 1. The semidaily component tide is shown in dashed lines, the daily component tide in dotted lines, and the resulting tide in full lines.

When the semidaily component tide is much greater than the daily component, the resultant tide falls into the semidaily type, which has two low waters and two high waters each lunar day with but little difference in their heights. Practically all Atlantic Ocean tides are of this type.

When the daily component tide is much greater than the semidaily component, the resultant falls into the daily type, in which only one low water and one high water occurs each lunar day. This type is rather rare in its pure form, although the tides in the Gulf of Mexico, Manila Bay, Bering Sea, and many Pacific Ocean stations frequently assume this form.

When the daily and semidaily component tides are of nearly equal heights, their combination gives the mixed type of tide, which in turn may be subdivided into three classes, depending upon the inequalities which occur in the high and low waters. When the inequality is nearly the same in the highs and lows, the tide resembles that of Los Angeles, California. When the inequality is chiefly in the low waters, the tide is similar to that of Seattle, Washington, and when the inequality is chiefly in the high waters, the tide resembles that of Honolulu, T. H.

A progressive wave is one in which the crests and troughs move or progress, such as those formed when a stone is tossed into a still pond. When a progressive wave impinges on a surface capable of reflecting it back upon itself the coalescence of the primary wave with its reflected counterpart forms another type of wave in which the water level is alternately high and low at both ends of the oscillating area, with a point midway between where the level does not change. This type of wave, easily generated by lifting one end of a partly filled dish, then quickly lowering it, is called a stationary wave. The axis about which the water oscillates is called a node and the high and low extremes are termed "loops" or "antinodes". It should be noted that end walls for reflection are necessary but no limitation has been placed upon the width of the wave; it may be very narrow or extremely broad in relation to its length.

The profound and scholarly work of the late Dr. Rollin A. Harris, of the U. S. Coast and Geodetic Survey, on the subject of tides, has never been accorded the honor and recognition it merits. His stationary wave theory of oceanic tides is the finest approach to an understanding of this complicated subject yet published. Later additions to the knowledge regarding tides have not altered the underlying basic truths contained therein and the results of his work have been drawn upon in large measure in this monograph.

Figure 2 shows the oceanic oscillating systems for the semidaily tide-producing forces in the North Atlantic Ocean as conceived by Harris. The Roman numerals refer to the time (in lunar hours) of high water after the Greenwich meridian passage of the moon and the dashed line crossing the area near the middle, which separates it into two parts with time of tides 6 hours apart, is the node line of the oscillating system. Three systems are shown. The first extends from the vicinity of Hudson Strait eastward to Iceland, to the northwest coast of Africa, and to the English Channel, with times of tides as II and VIII. This is the northernmost system. Almost parallel and contiguous thereto is another system which embraces the entire Atlantic coast of the United States, and thence to a line from Cape San Roque, the easternmost point of Brazil, to Cape Verde, on the northwest coast of Africa, with times of tides as VI and XII. Overlapping the southern half of the latter system and extending to the southern limit of the northern Atlantic system, is a third system with times of tides as II and VIII.

Each of these systems may be considered as a vast, more or less rectangular dish in which the waters oscillate with a stationary wave movement. The node line, on which there should be the least range of tide for VI-XII system, extends from the northern end of the Lesser Antilles northeastward into mid-Atlantic. The adherence of the tides as noted on the shore stations from the northern United States along the West Indies and thence along the northeast coast of South America, both in range and time of tides, clearly indicates the validity of Harris' conclusions. In comparing ranges and times, only coastal salients should be used, because when the stationary wave impinges upon the continental shelf it again becomes progressive; the distance to and into the various embayments of the coast causes variations in the times and heights of the tides, making the former later and the latter higher. In general, the average range on coastal points from Nova Scotia to Cape Canaveral, Florida, is 4 feet, at the node point less than 1 foot, and rising again to 6 feet at Cape San Roque. The increase on the South American coast results from the coalescence of the two systems on this part of the coast.

The Bay of Fundy, as is well known, lies between Nova Scotia and Maine. The tide there is of the semidaily type, so the oscillating system of HARRIS would accommodate the greater portion of the component tides.

Compare now the range of tide on the eastern shore of Nova Scotia (4.4 feet) at the northeast entrance point of the Gulf of Maine, and at Wauwinet on the outer shore of Nantucket Island (3.3 feet) at the southwestern point, with the range of 39.4 feet in Minas Basin, at the head of the Bay of Fundy, an arm of the Gulf of Maine.

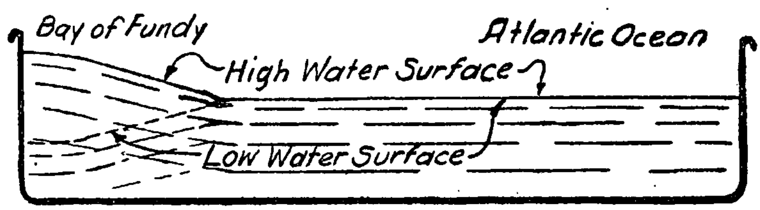

FIG. 3.

It has been shown in several writings on tides in the Bay of Fundy (H. A. MARMER in *The Tide*), that the tide therein is a stationary wave. When such a wave occurs in a natural water body, it is called a "seiche" (sash). (See pp. 775-788, June, 1937, U. S. Naval Institute Proceedings).

From Fig. 1, semidaily type of tide, note that there is an inequality in both the high and low waters, but it is of much lesser extent than in the mixed type of tide. An examination of the predicted tides for the several reference stations given for the Gulf of Maine and Bay of Fundy (Boston, Mass., Portland, Me., Eastport, Me., and St John, N.B.) shows that the same differences exist for all stations on the same days, regardless of the ranges of tide, indicating that the same coalescence of the daily and semidaily tidal components occurs. This condition demands that an independent factor must be introduced into the tides which is not a part of the ordinary components. This factor is the seiche, greatest at the loop, and zero at the node. The location of the nodes will be given later.

The Bay of Fundy will support a seiche of about 12-hour period; *i. e.*, each succeeding tide will give an additional impulse to the oscillating water until the amplitude is of such magnitude that the work done against gravity and the friction of the sides and bottom of channels prohibits further increases. An example of such action is a child in a swing. The length of the supporting ropes (length of pendulum) determines the period; each additional push, after motion has been started, if given at the end of the upswing will tend to send the swing higher and higher, again within proper limits.

Thus far, nothing new has been adduced, but here also is the end of published knowledge on the Bay of Fundy Tides, The fact that a seiche has a node, and must have a counterpart, has been carefully kept dark. The present explanations place the oscillating area in the state shown in Fig. 3, which is obviously an absurdity.

The problem is then to determine the node line; to find an oscillating area capable of supporting a 12-hour tide; and to find a counterpart for the seiche in the Bay of Fundy, which will manifest itself by a large range of tide.

In Fig. 2 note that HARRIS did not include the Gulf of Maine in his system, but stopped at the southern edge of Georges Bank. In Fig. 4, which is a portion of U. S. Navy Hydrographic Office Chart N° 941, note the current diagrams on Georges Bank. The explanation states that,

> the arrows indicate direction and velocities of currents. The length of an arrow measured from the circumference of the position circle represents the corresponding velocity on the given scale. The arrows are numbered with regard to the time of high water at the Navy Yard, Boston; 0 representing the time of high water and 1, 2, 3, etc., the hours after high water. Therefore, at each position circle the current for any given time is indicated by the arrow with number corresponding to elapsed time since high water at the Navy Yard, Boston.

It will be noted that the direction of the current changes with the hands of a watch, swinging through 360 degrees in something over twelve hours.

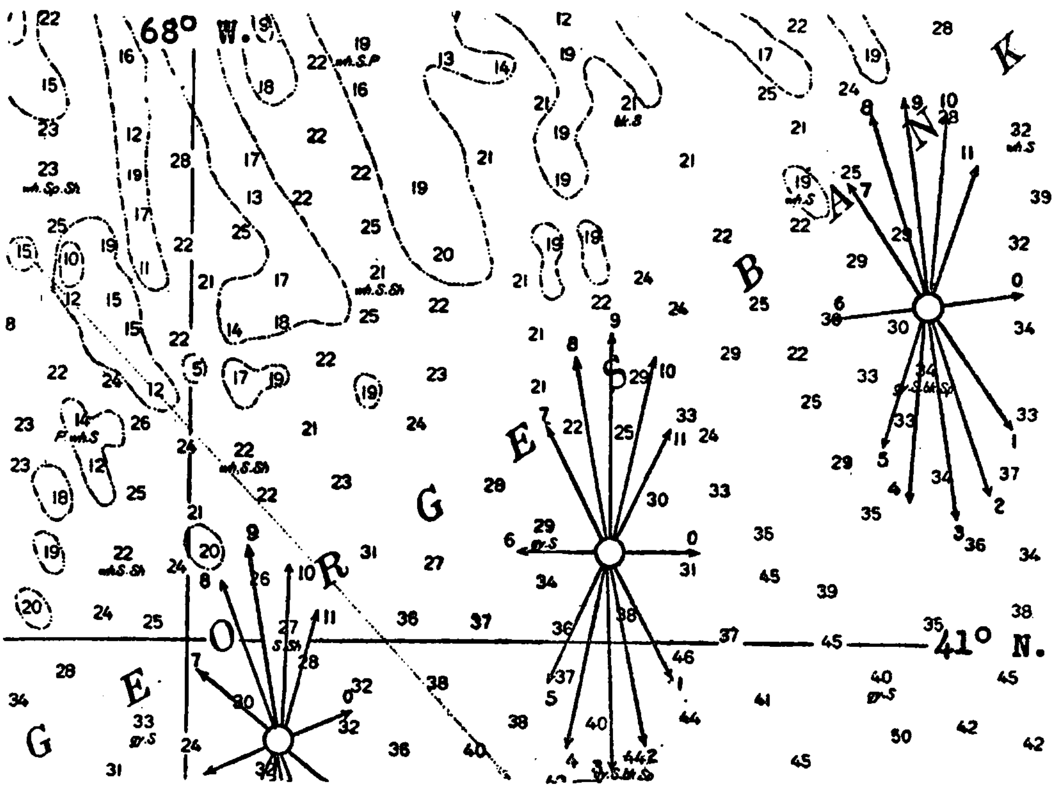

FIG. 4.

In general, oceanic currents are rotary in character, and, were they not influenced by winds, proximity to shore indentations, etc., would diagram into a circle with equi-angular and equidistant direction arrows. Now take, for example, the current diagram near the center of Georges Bınk (N. 41°, W. 67°-30') and separate it into component parts by ordinary graphical vector analysis methods. Some assumptions must be made to start with, among which are that the diagram is composed of the rotary currents of an oceanic tide and the rectilinear currents of a seiche into the Bıy of Fundy, and that the 0-6 lines give the velocity of a uniform rotary tide.

Figure 5 shows the results of the analysis. After the removal of the rotary portion of the current, a true seiche current remains. Such a current must have a minimum value at the time of high and low waters, and a maximum value halfway between them, since, at high and low waters, no interchange of water takes place, therefore no current, while at half tide, or when the water in the dish in the example is level, the greatest exchange is taking place, therefore the greatest current — to the right at one time, and to the left another, in the dish example, or into and out of the Bıy.

The ranges of the tide to either side of the Gulf of Maine demand that the oscillating band of water which produces the seiche be quite narrow. Assuming then that the diagram which was analyzed represents the center of the band, it is obvious that a "vortex" system of currents must result, the outermost stations giving the strongest currents pointing towards the center on the flood tide. This condition is shown to exist, so the assumptions were probably correct.

Now the direction or trend of the nodal line has been determined to be the 0-6 hour direction of no seiche current. Note that it is nearly parallel for all current stations shown. Any small variations could be explained away by the statement that the varying depths and irregular surface of Georges Bınk introduce local changes in current directions. Having determined the node line, the obvious place to seek the counterpart of the seiche wave, of period 12 hours in an unobstructed ocean, would be somewhere normal to the node line, and 12 hours away.

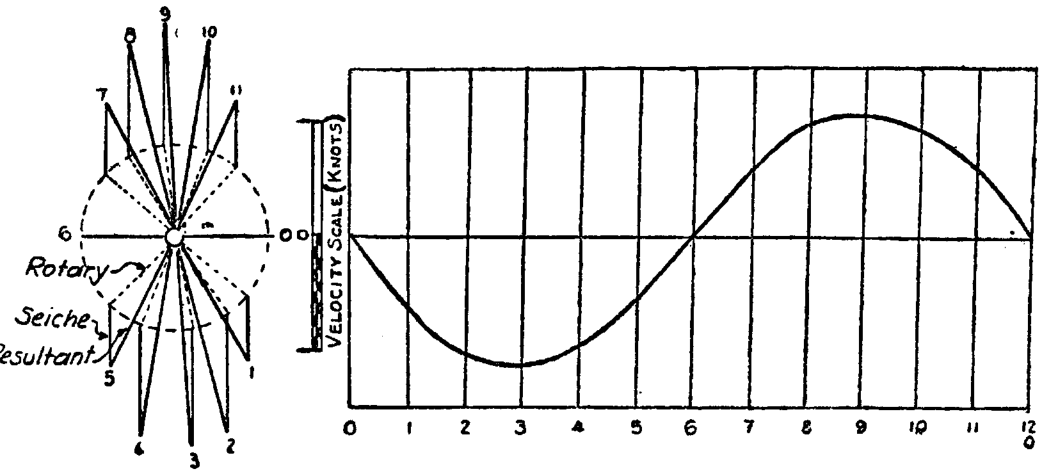

FIG. 5.

Figure 2 gives the 12 hours distant, in the VI-XII system of HARRIS for the North Atlantic and the right direction would place the counterpart in the vicinity of the Amazon River mouth on the northeast coast of Brazil. This counterpart must be a narrow band of very high tides sandwiched between the areas having the normal tide range of about 6 feet. With the U. S. Coast and Geodetic Survey Tide Tables for the Atlantic Ocean as a guide, a region such as the conditions of the problem require for its solution is readily determined to be in the immediate vicinity of Maraca Island, about 150 miles northward of the northern entrance to the Amazon River. Here the mean range of tide is given as 22.9 feet, while within a few hundred miles either way the range is about 6 feet.

A detail of this area is shown in Fig. 6, based on the U. S. Navy Hydrographic Office Chart N° 886. Note the rather small bay which could not, in itself, produce any contraction sufficient to increase the tide range. The currents are given as 6 to 7 knots at the syzygies (spring ranges), and are accompanied by a bore, called locally a "prororoca" ("pororoca" in Coast Pilot). The bore is also an attribute of the Bay of Fundy tides. The coast line for hundreds of miles on either side of Maraca Island is low, so no increase in tide range can be attributed to a change of character of the coast. Since the underwater depth curves usually follow the above-water contours of the adjacent shore, no abrupt changes in depth are shown in the vicinity.

It is then difficult to assign a reason for this vast increase in tide range unless the Carapaporis Channel tide is the counterpart of the Bay of Fundy tide as advanced in this discussion.

The water surface condition necessary to support the theory herein advanced is shown in Fig. 7. The Gulf of Maine and Bay of Fundy support a 12+ hour tide, and, placing the nodal line where HARRIS gives the end of his 12– hour oscillating area, viz., at the south side of Georges Shoal, a companion seiche will then exist at the southern end of the narrow band of oscillating water which traverses HARRIS' system. The seiche will coalesce with the tides formed by the semidaily system to produce the tides as found in nature. Resulting differences in the ranges are possibly due to contraction of the Bay of Fundy towards its head.

Fig. 8 shows, as an insert in a chart of the Bay of Fundy and vicinity, the water slope at high water in detail, rather than the schematic sketch of Fig. 7. It should be borne in mind that the trinodal seiche on the Bay of Fundy-Maraca Island "string" is superimposed on the fundamental oscillation of HARRIS, or any embayment rise resulting from a progressive wave movement induced by the fundamental.

Therefore, the node line northward of Boston (actually abreast the entrance to the rather indefinite southern limitations of the Bay of Fundy) has its node at high water on top of the high water heights, as shown. This line, at about elevation 5, is the resultant of the lower portion of the cosine curve as indicated within the Bay of Fundy and the fundamental tide, so that, were there no additional seiche operating in the Bay of Fundy, the ranges of the tide in the Gulf of Maine would be approximately 4 feet greater than the existing ranges, making allowance for the relative areas of the two regions and attempting an equivalent water distribution.

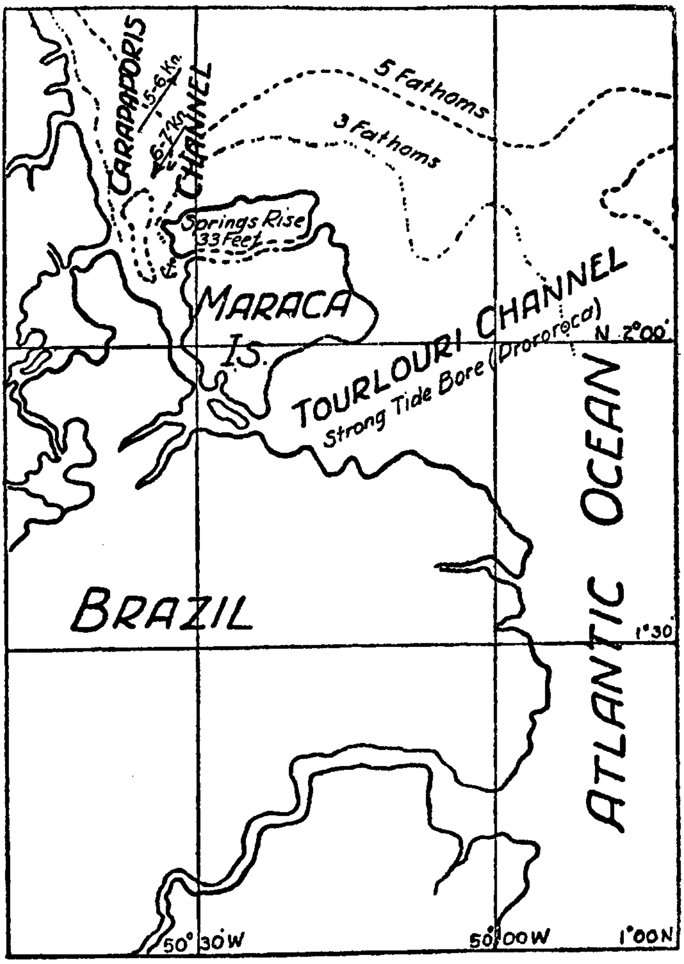

FIG. 6.

From the foregoing demonstration (that large tides are the result of seiches which exist on *both* sides of a node line at such distances over the oceans as, by their depths, will satisfy the time requirements) it is apparent that the exceptionally large tides throughout the world must

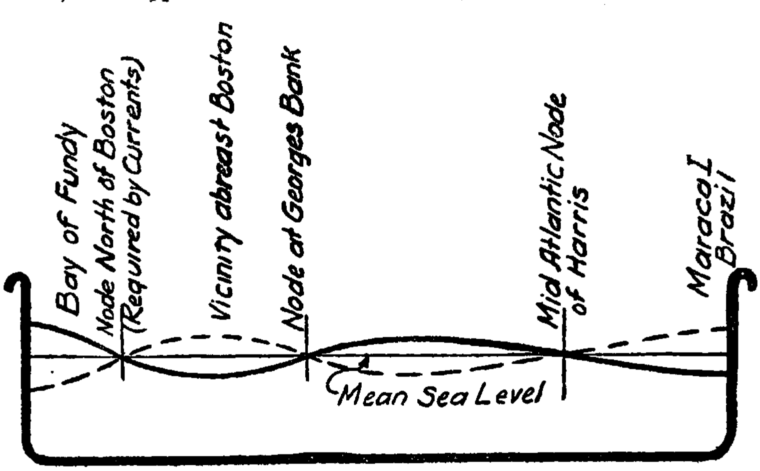

FIG. 7.

occur in pairs. Further study may disclose the possibility of a bifurcation of the stream at either end but, for the time being, a grouping of the large tides of the world into pairs will be made. The necessary data of currents and depths, and HARRIS' systems as guides, were available only for the Bay of Fundy-Maraca Island pair; the pairing herewith given should then be accepted only as suggestive and subject to research and proof.

The progressive wave which accompanies the actual tides affects the times so that difficulty arises when the 12-hour period is sought.

LOCALITY.	*Lat.*	*Long.*	*Range. Ampl.*	*LOCALITY.*	*Lat.*	*Long.*	*Range. Ampl.*
(1) NW. Arm of Frobisher Bay, Baffin Island	N. 63°45'	W. 68°40'	Ft. 34.6	Cancale, France......................	N. 48°40'	W. 1°50'	Ft. 28.8
(2) Koksak, River Ungava Bay Labrador	N. 58°33'	W. 68°05'	29.6	Bristol, England....................	N. 51°27'	W. 2°35'	31.1
(3) Turnagain Arm, Cook Inlet, Alaska........................	N. 60°53'	W. 149°26'	30.3	Hingwha Channel, China	N. 25°20'	E. 119°35'	18.0
(4) Port Santa Cruz, Argentina	S. 50°07'	W. 68°25'	24.2	Gulf of Cambay, India	N. 21°48'	E. 72°09'	22.4

In numbers 1 and 2, the reverse combinations may pair with Bristol, England, or the two streams may be only one in fact. Their possibility is indicated on Fig. 2, since the stations lie on the northernmost of the North Atlantic semidaily oscillating systems.

For number 3, the two stations lie on the binodal system for the North Pacific Ocean, as given by HARRIS.

For number 4, the route would lead on a great circle course south of Africa, through Mozambique Channel, and thence across the Indian Ocean. HARRIS does not attempt a system for the western portion of the South Atlantic Ocean, but the tide tables suggest a binodal seiche for number 4, with the additional loop near Beira, Mozambique Channel, Lat. S. 19°-49', Long. E. 34°-50', and a range of 11.3 feet. This may be one branch of a bifurcated system with one loop near the eastern end of Magellan Strait, the other branch having its loop on the northwest coast of Australia, where, at Hall Point, Lat. S. 15°-40', Long. E. 124°-21', the range is 19.2 feet. The high tides cover an appreciable coast line of southern South America, and also on the Australian coast, so that, if the binodal to India is eliminated by research, the Australian branch offers the most promising lead. In view of the fact that HARRIS shows a binodal system in the Indian Ocean extending from the northwestern Australian coast to the southeastern shore of Arabia, the pairing of the Australian and Indian tides seems the obvious solution. It should also be pointed out that the binodal system as first suggested, through Mozambique Channel, likewise conforms to a system as shown by HARRIS. He places the loop at the northern end of Madagascar, rather than near Beira, on the African coast abreast the southern end of Madagascar. Southward from this loop, HARRIS does not indicate sufficient to uphold or negate the theory. This, however, leaves the southern Argentine tide unexplained unless future data concerning the antarctic regions show a companion seiche there.

In the wave action of vibrating strings, pipes, or membranes, familiar to all with even a cursory knowledge of music, the nomenclature is essentially that of sound. The simplest vibration gives the "fundamental" tone or pitch, while the partial tones, caused by multi-nodal vibrations, are called "overtones" From this view-point, we may call the oscillatory system and the northeastern coast of Brazil the "fundamental" of this portion of the Atlantic basin, and the narrow bands, such as the Bay of Fundy-Maraca Island, one, a vibrating string of water capable of sustaining "overtones" In this case the overtone is a trinodal seiche. While this seiche is of such magnitude that it was easily separated from the fundamental, its presence does not preclude the possibility of other multi-nodal seiches existing on this "string". A clue to their existence would be their effect on the tidal phenomena of the shore stations and they may

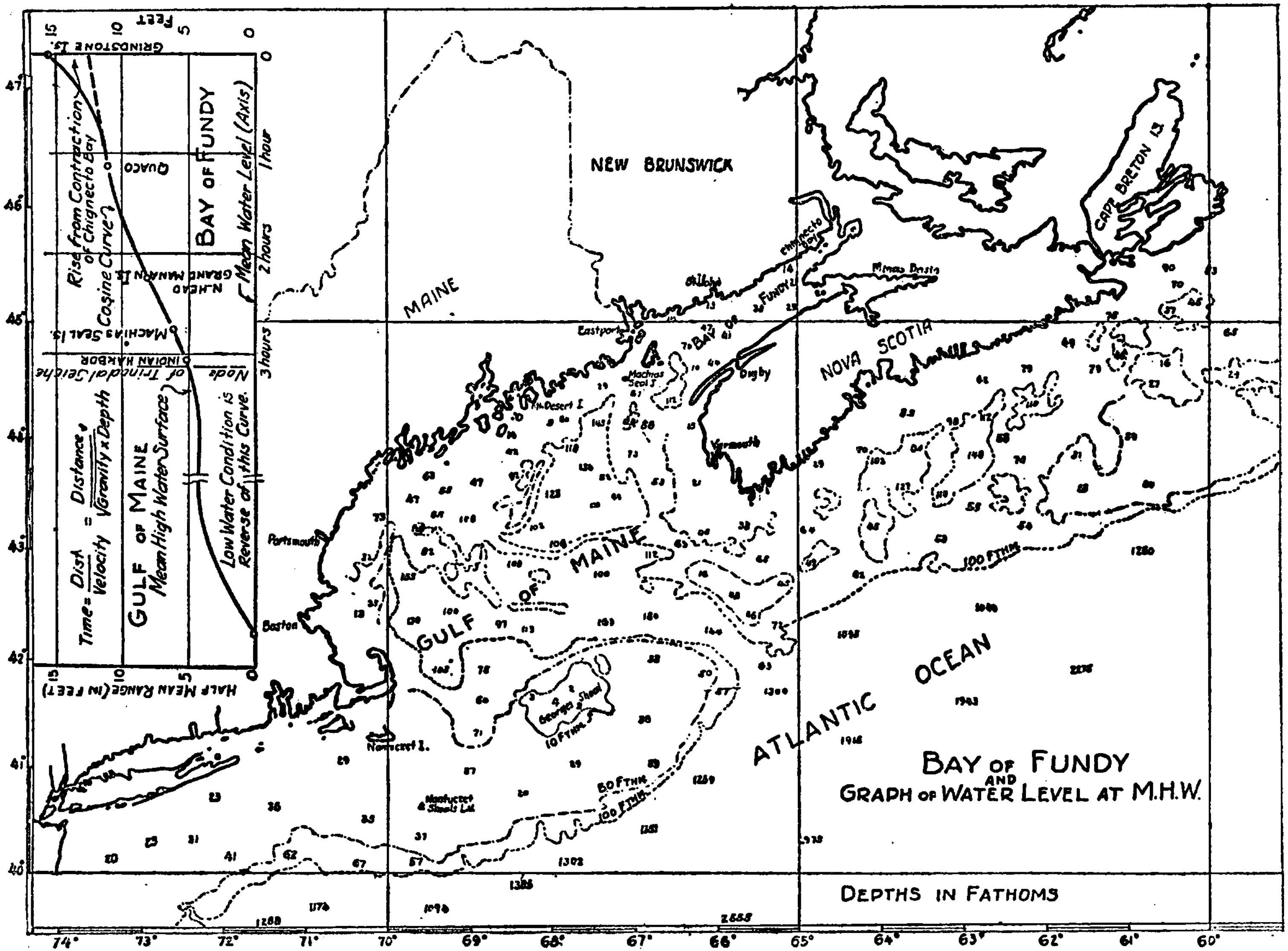
Time = Dist / Velocity = Distance / √Gravity x Depth
GULF OF MAINE
Mean High Water Surface
Low Water Condition is Reverse of this Curve.
Node of Trinodal Seiche
Rise from Contraction of Chignecto Bay
Cosine Curve
BAY OF FUNDY
Mean Water Level (Axis)
HALF MEAN RANGE (IN FEET)
FEET
GRINDSTONE IS.
QUACO
N-HEAD GRAND MANAN IS.
MACHIAS SEAL IS.
INDIAN HARBOR
Boston
Portsmouth
3 hours
2 hours
1 hour
MAINE
NEW BRUNSWICK
NOVA SCOTIA
CAPE BRETON IS.
Eastport
Digby
Yarmouth
Minas Basin
Chignecto Bay
Nantucket I.
Georges Shoal
GULF OF MAINE
ATLANTIC OCEAN
100 FTHS.
BAY OF FUNDY AND GRAPH OF WATER LEVEL AT M.H.W.
DEPTHS IN FATHOMS

Fig. 8

possibly be ascertained and evaluated from comparisons of their harmonic constants with those of near-by stations not on the "string". This "string" may be compared to the "rip tides" on the Southern California coast. Since waves do not approach the shore in vast fronts, but in staggered ranks of a few hundred feet width, at times only one front will be reflected to form beach seiches, locally called rip tides.

Other United States Atlantic coast bodies of water which entertain "seiches" that have not been separated from the fundamental tide of HARRIS are Long Island Sound and Delaware Bay. Their counterparts on the South American coast should exist and their location and determination, as well as additional points on the coast of the United States, possibly in the vicinity of the Carolina and Georgia coasts, are left for other students of the tides. In this entire discussion, whenever the time necessary for a wave to traverse a basin was used, the fundamental oscillation time was assigned, otherwise we would be searching in a dark cellar for a black cat which did not exist, since HARRIS shows that the conformation and depths of the Atlantic Basin are such that it cannot support a daily oscillation; so that, when "12 hours" is used, it means the time from: Time = distance/velocity, where velocity $= \sqrt{\text{gravity} \times \text{depth}}$.

In conclusion, while only the very large tidal ranges were herein paired, the same forces and wave motions are undoubtedly at work elsewhere to form tidal ranges in places which are somewhat greater than those adjacent, but not in such marked contrast as to be so conspicuous, and their location and pairing are also left for further study.

From the foregoing exposition of tidal behavior, the validity of the HARRIS stationary wave theory is given added weight in comparison to the several progressive wave theories. The only possible variation to the basic idea is that instead of the tidal oscillation in any basin being a broad, expansive sheet, smaller bands are operating, the most vigorous bands being those whose period more nearly coincides with that of the tide-producing forces. The addition of "overtones" to the fundamental of any narrow area is also new.