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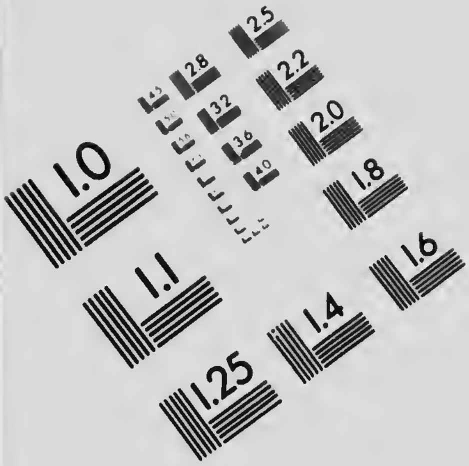

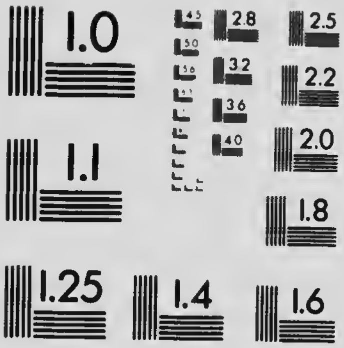

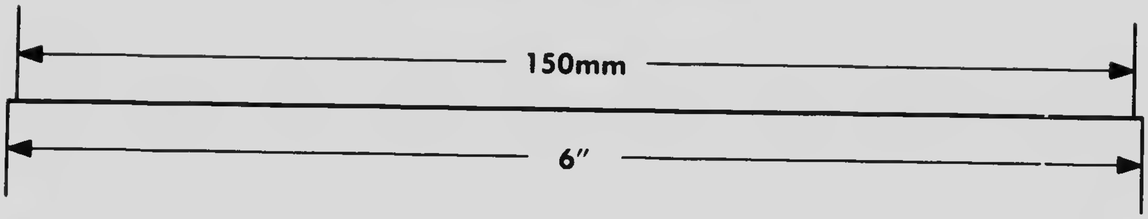

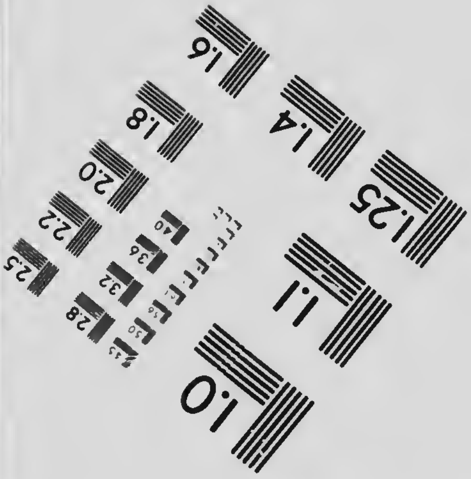

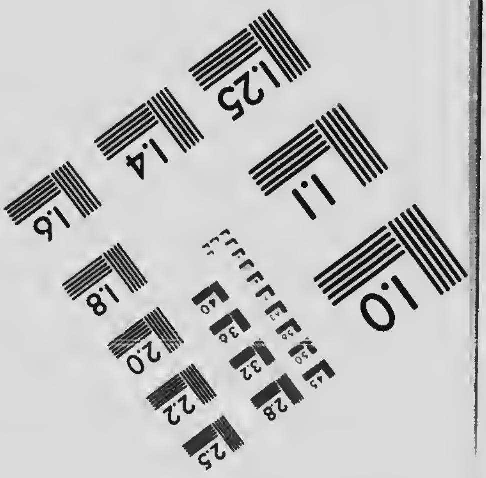

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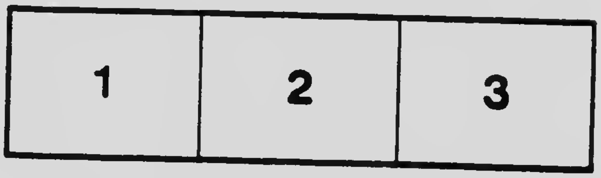

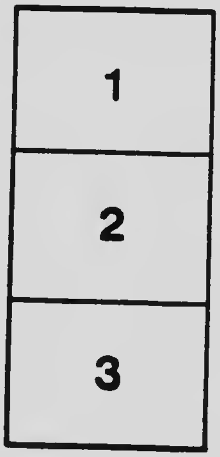

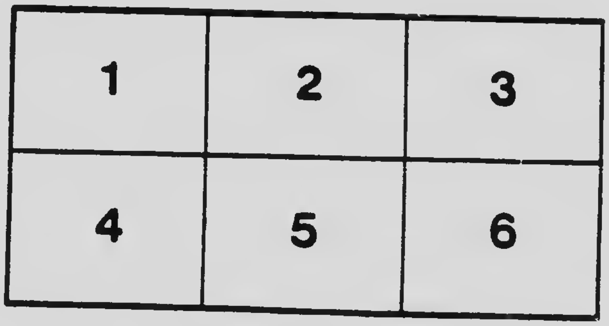

THE TIDES

AND

TIDAL STREAMS

with Illustrative Examples from

CANADIAN WATERS

W. Bell Dawson, M.A., D.Sc., M.Inst.C.E., F.R.S.C.,
Superintendent of Tidal Surveys.

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INTRODUCTORY.

In dealing with the tides, we must approach the subject with considerable caution, because there are several standpoints from which they may be regarded. There is first of all the main distinction which must be made in any such subject, between the descriptive side which explains what the tides are and how they behave; and the theoretical side which undertakes to explain the causes and forces that produce them. In much that has been written about the tides, both these sides of the subject are inadequately dealt with; for in describing their behaviour, some features of the tide which occur in some one region of the world, are carefully explained as though this were the whole story. Such a description gives a very unsatisfactory account of the matter. It is equally possible on the theoretical side, to emphasize one point of view; as for example, to give the impression that the tide is entirely an astronomical phenomenon, and quite to ignore on the terrestrial side the hydraulic questions regarding the momentum of water in motion, frictional resistence, and such physical influences.

These partial and one-sided descriptions and explanations are the more unfortunate, because they throw discredit on the subject, and stand in the way of progress. For the navigator in voyaging from one ocean to another, may find that the description he was given does not apply, and the explanation no longer explains; and he may be tempted to discard it all as erroneous. There is at the other extreme, the theorizer, who for want of sufficient knowledge of the facts, begins by imagining how the tides ought to behave, and proceeds to invent an entirely new theory to explain them.

It is very evident therefore, that a satisfactory account of the tide can only be given by describing all types or classes of tides, however briefly, so that the account may at least be complete. We do not propose to take up tidal theory beyond the least amount necessary to make the subject clear, and to assist the memory in following the facts. We will also endeavour to make the plainest distinction between the behaviour of the tide as it is actually observed, and the reasons or causes for this behaviour. When once the facts are clearly stated, the reader is always at liberty to ask: Why is this so, and not otherwise? The candid answer may be that there are points which we are only able to explain partially, or in a very general way; and it is indeed by this admission only, that progress in knowledge can be made.

The examples and illustrations of the tide here given, will be taken from the shores of Canada, with which the writer is familiar from long experience with them. It is not too much to say that we have on the Canadian coasts, examples of every kind of tide that is found anywhere in the world. On the Atlantic and Pacific coasts, in various regions in the land-locked waters of the Gulf of St. Lawrence, in the Bay of Fundy and the immense estuary of the St. Lawrence, in Hudson Strait, and Hudson Bay which is an area larger than the North Sea, the three leading astronomical types of tide are strongly in evidence and almost all modifications of these leading types which one can think of as possible, are actually found. In range, they vary from almost nothing to amongst the highest in the world. The currents and tidal streams which stand related in their movements to the rise and fall of the tide, present the same wide variety in their behaviour: for all conditions under which tidal flow can occur that can be imagined in making a complete classification, are actually exemplified. It would thus appear that for purposes of classification and discussion, little of importance is likely to be overlooked if Canadian tides and currents are taken as examples.

THE TIDE IN GENERAL.

On the shore of the ocean, the water does not remain at one level as in a lake: but the level rises and falls. It will gradually rise till it reaches its highest point which is termed High Water, and it then falls and recedes on the shore till it reaches the lowest point which is termed Low Water, when it turns and rises again. The difference of level is called the Range of the tide. This fluctuation occurs twice in the course of a complete day; so that there are two high waters and two low waters in the period of a day and night. Also, where there is a long bay or a river mouth on the coast, the water when high will flow inland into it; and when low, it will flow out again. The inflow during the rise of the tide, is known as the Flood, and the outflow during the fall of the tide is the Ebb. In ordinary language, all these movements of the water are included under the general word, tide. But it is well to note that in reality there are two distinct movements; a vertical rise and fall in the level of the water which is the Tide proper, and a horizontal flow in the two directions alternately, which is distinguished by the term Tidal streams.

On looking into these movements more closely, and comparing the behaviour of the tide in different regions and different oceans, there are certain general features which come to light. The amount of the rise and fall is not the same everywhere, as it varies from almost nothing to a range of over fifty feet in some localities. On the other hand, the time of high water is not always at the same hour of the day; but on the average it is about an hour later from one day to the next. This is found to be the case in every part of the world; as in a period of fourteen or fifteen days it comes around to the same hour again. At every locality in every ocean, there is also found to be a well-marked variation in the range of the tide. which usually recurs twice in the course of each month; or in some regions, once a month. This variation may be very different in its character; in one region it may be a change in the range of the tide, from a large difference in level to a small difference: in another region, the two tides of the day are sometimes exactly equal in their range, and at another time, one of the two is much greater than the other, alternately. But whatever the character of the variation may be, the change always recurs in a period of about a fortnight or about a month in every ocean.

It is thus evident that there must be some general cause for these changes; and we soon find that they are related to the movements of the moon. Indeed, the further we go into the details of these variations, the more closely we find that all the leading changes in the tide correspond with the position or the distance or some other movement of the moon. The sun has also an influence which is very similar, but its effect is less marked. It is interesting to find that the connection between the moon and the tide was noticed as far back as the Roman times. When Julius Caesar first came upon tidal waters, in the English Channel, he noted that the tide rose higher when the moon was full or new than at other times. This is the leading variation in that region during the course of the month. Those who depend on the tide for a living, are also naturally observant of its movements. On parts of the coast of France, the people depend on gathering crabs and shell fish for food at low tide; but they find that when the moon is at its quarters the tide moves so little that they call it Dead-water; and it is only about the time when the moon is full or new that there is Live-water or Springing water, and the tide falls low enough to expose a wide beach, and make it worth while to take out carts to gather sea food. Fishermen also watch the tide to learn its behaviour; as the catch of fish usually depends upon the right time of tide.

To explain why the tide is about an hour later each day, we must notice first that our reckoning of time is by the sun, which we naturally find the most convenient. We thus divide the period from noon to noon into 24 hours. But the moon takes an hour longer than the sun to come back to the meridian again, or nearly 25 hours; as it circles around the sky in a month, and thus moves further in a day than the sun does. As the time of the tide accords with the moon's position, and the moon is an hour later each day, the time of high water is also an hour later from one day to the next. For tidal purposes, it is really the lunar day that we should count by, rather than the ordinary solar day; and as there are two tides in the course of the day, the true time unit is the half lunar day; which is 12h. 25m. in ordinary time (or exactly, 12h. 25m. 14s.). For purposes of tidal calculation, all the movements of the moon are expressed in terms of this unit, which is termed the "Tide-interval." This is the *average* interval between successive high waters; but it must not be supposed that they have always this exact interval of time between them; as this is far from being the case, as we shall see later on.

With regard to the variations in the tide which occur during the course of the month, these will be more readily understood in connection with the causes that produce them, which we will reach after the moon's motions are explained. We must first try to make clear how it is that there are two tides in the day, which is not easy without entering upon highly mathematical proofs. The explanation that we here give is in accord with these, and is the one which is generally accepted.

The diagram represents the earth, looking down upon the North Pole; the surface of the paper thus representing the plane of the equator. The moon is on one side at M; and we suppose the earth to be entirely surrounded with water. As the attraction of the moon decreases rapidly with the distance (decreasing indeed inversely as the square of the distance) its attraction for the water at S is greater than for the earth itself; for the attraction on the earth as a whole corresponds with the distance M P to the earth's centre. Again, the attraction on the earth itself is greater than on the water at the farther side of the earth at T. We have thus three attractions, each greater than the other; and the result is that the water is drawn forward under the moon, and left behind on the opposite side of the earth; and consequently, two protuberances of water are formed on the opposite sides of the world. An observer on an island at A will therefore find as the earth revolves that the water rises and falls twice in the course of the day.

If this explanation is difficult to grasp, it is because we are so apt to think of the earth as fixed, with the moon revolving around it. The earth and moon are equally free in space, and in reality they revolve around each other; or more properly, around their common centre of gravity. If this is thought out, it will be seen that it is just as reasonable for the earth as a whole to move away from the water at T and leave it to stand higher, as for the water at S to be raised under the moon.

Although this explanation is correct in a general way, there are some misconceptions to guard against. It might be supposed, for instance, that the chief effect of the moon's attraction would be to draw the water along horizontally at the points H, H. An objection is also made to the explanation, because it is found on investigation that the direct lifting power of the moon is slight. When the attractive forces are worked out mathematically, it is found, however, that the greatest effect occurs midway between H and S on the one side, and midway between H and T on the other. The water is thus drawn together from the two sides under the moon, rather than lifted.

It is also clear that if the water surface is raised above its mean level at S and T, it must be below the mean level at H and H. Hence, the true or mean level of the sea is midway between the level of high and low water; or in other words, the tide falls as much below the mean or undisturbed level as it rises above it, on the average. This is found to be true, wherever measurements can be obtained to corroborate it.

If we consider the attraction of the sun, it can be shown that the effect is precisely similar, in raising two opposite protuberances of water. We thus have a solar tide as well as a lunar tide; but the solar tide is much less in amount. Although the sun is so much larger a body than the moon, its distance is immensely greater; and when the relative tide-raising powers of the sun and moon are worked out mathematically, on the basis of their relative masses and distances, it is found that the amount of the solar tide is only 46 per cent of the lunar tide. This is the theoretical proportion; but as a matter of fact, the proportion of the solar tide to the lunar is not the same in different oceans. This is one of the things that cannot be fully explained.

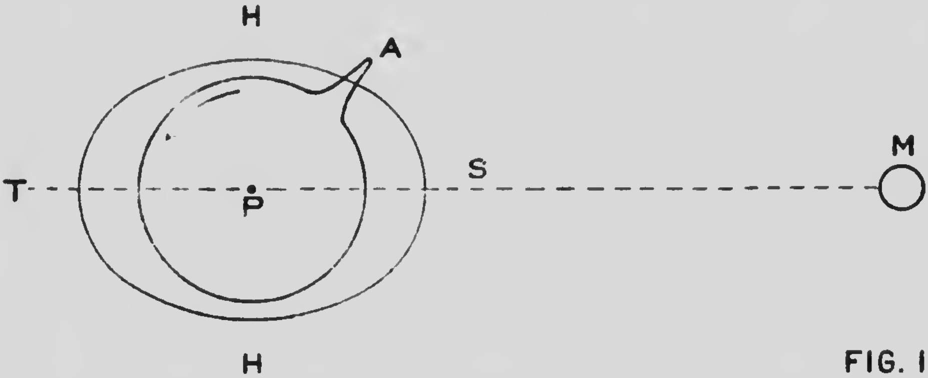


FIG. I.

We have been supposing the earth to be entirely surrounded by water, whereas the water is divided into oceans by the continents. Yet the characteristics of the tide correspond closely with the explanations we have given. First, the tide in the various oceans progresses through them as an undulation. This can be proved by observations along their shores, or on islands in them. For example, the tide runs up the Atlantic ocean as an undulation from its south end between South America and Africa, to its north end between Canada and Europe. The range of these oceanic tides is not usually more than 4 or 5 feet. Again, in all the oceans, there are two tides in the course of the day; which accords with the accepted explanation. It is true that there are some localities where at certain times in the month the tide becomes diurnal; that is, there is only one high water and one low water during the day. But a reason for this exception can readily be given, which does not conflict with these general principles. Thirdly, the tide is found to rise and fall equally above and below the mean level of the sea.

There is one important respect in which the actual tides differ from the explanation given. The summit of the undulation is not found to be directly under the moon; or in other words, it is not high water at each locality when the moon is on the local meridian. The summit lags, often by many hours, behind the position of the moon. The reason of this was explained very early in the history of tidal investigation; and it was pointed out that for high water to remain always directly under the moon, the ocean would not only require to cover the whole earth, but would also have to be exceedingly deep; probably many miles in depth. The lag is therefore due to the circuitous path which the tidal undulation is often obliged to take in traversing the various oceans; and also to the comparative shallowness of the oceans and the inequalities in their depth, which in so wide an undulation causes drag from bottom friction.

There are two characteristics of all undulations, which should be pointed out to make this subject clear. An undulation is not a raised ridge of water entirely above the standing level; but it consists of a positive part or rise, and a negative part or trough, which are equally above and below the still surface. This should be kept in view in dealing with the progress of the tide, especially in straits or estuaries. Also, the relation between the vertical and horizontal movements in an undulation should be understood; more especially when we have to face the unfortunate accident of language, by which both movements are included in the one word, tide. This may best be illustrated by the wash or surge of water from one end of a narrow bath or trough to the other. The water rises first at one end and then at the other, and there is a point in the middle where there is no change of level. On the other hand, it is at the middle of the length that the greatest current or horizontal movement occurs, but at the ends there can be no horizontal motion. There is thus the greatest amount of current, to and fro, where there is no vertical motion; and the greatest amount of rise and fall where there is no current. This will help to make clear many undulatory phenomena, in which the rise and fall and the horizontal current are often the converse or reciprocal of one another; and it will show the need of avoiding confusion between vertical and horizontal motion. We will recur to this again in dealing with the relation of tidal streams to the time of high and low water, which is an important practical problem for the navigator.

TERMS DESCRIPTIVE OF THE TIDE.

We may give at the outset descriptive definitions, which may be convenient for reference and helpful as a basis for explanations. They will no doubt be more fully understood when the behaviour of the tide is more completely described.

Vertical Movement of Tidal Waters.

Range.—The difference of level between high and low water, or between low and high water, on any individual tide.

Technically speaking, this is the amplitude of the tidal undulation; or the elevation of the summit of the undulation above the trough. Its amount is independent of any datum or fixed plane of reference from which heights are measured. In comparing the relative amount of tide at different localities, the comparison can best be based therefore, upon the range or amplitude.

Rise.—The movement of the surface of the water vertically upward, from the low level of the tide to the high level. The amount of the rise is the actual difference of level, measured vertically from the low-water datum to high water, at any tide.

(The amount of the rise under various conditions may be distinguished; as the "Spring rise" meaning the greatest rise at the spring tides, or the "Neap rise" meaning the least rise during the neap tides. Similar expressions, such as "Solsticial rise" or "Equinoxial rise" are equally allowable.)

Fall.—The movement of the surface of the water vertically downward, from the high level of the tide to the low level.

High Water.—The highest point reached by the tide, when the rise ends and the fall begins.

Low Water.—The lowest point reached by the tide, when the fall ends and the rise begins.

The time at which the change occurs, and the height of the tide when it turns, are the elements of most importance for marine purposes. It is therefore the time and the height of high water and low water at each tide, that are given in tide tables; as these define most adequately the vertical movement of the water.

Low-water datum.—A plane of reference established near the level to which the lowest low waters usually fall, and from which the height of the tide can be measured vertically upward, and the depth of the water vertically downward.

This is the datum almost universally used for tide tables, from which to measure the height of the tide. The height at high water, as well as at low water, can both be given above the datum. The same datum is used for marine charts, to show the least depth of water which mariners can count upon when the tide is low.

A suitable level for the low-water datum, which is consistent with its level at other localities, requires careful consideration with regard to the behaviour of the tide. It should be so low that few tides will fall below it under any ordinary conditions; but if it is too low, the chart will show less depth of water than the mariner will usually find. Any extreme tides that fall below datum are always indicated in tide tables by a negative sign or some other special mark. On such tides, the depth will be somewhat less than the chart shows, and the sign or mark serves as a warning to that effect.

Horizontal Movement of Tidal Waters.

Set.—The set of a current is the direction towards which the movement carries a vessel. The direction is thus indicated in the opposite way to wind direction. For example, if the air is moving from west to east, it is termed a West wind; but if the water is moving from west to east, it is termed an Eastward set.

Flood stream.—The horizontal movement of the water, or flow, caused by the rise of the tide. The term is probably derived from the fact that on flat shores the tide as it rises appears to flood the land. But the expression Flood tide should be avoided, as it confuses vertical and horizontal movement.

Ebb stream.—The horizontal movement of the water caused by the fall of the tide; usually in the opposite direction to the Flood stream, or nearly so.

The flood and ebb streams are defined by their direction and velocity. They are most noticeable and definite in estuaries and straits. In more open waters, the direction of the set may veer completely around the compass during the rise and fall of the tide.

Slack water.—When the flood stream ends and the ebb stream begins (or vice versa) there is a moment or a short interval of time when the water is motionless. This is termed Slack water; and as it occurs twice in the course of a complete tidal period, the two turns are distinguished as High-water slack at the end of the flood, and Low-water slack at the end of the ebb.

Slack water is thus the time at which the horizontal motion is reversed, just as High water and Low water are the times at which the vertical motion is reversed. It must not be supposed that these coincide in time, however; as practically speaking, they never do. There are some conditions, indeed, which make Slack water occur at half tide, or midway in time between high water and low water.

There are straits and passages in which the tidal streams are so rapid that navigation through them is only possible near the time of slack water. This may become therefore the item of paramount importance amongst all tidal data, in aid of water transportation, especially when carried on by towing.

OBSERVATIONS OF THE TIDE AND TIDAL CURVES.

In observing the tide at any locality, the chief points to note are the time at which high and low water occur, and the height to which they rise and fall. These results may be obtained by means of a vertical tide scale marked with feet or other divisions, together with some means of knowing the time of day. A much better result will be obtained, however, with a registering tide gauge. This is an instrument which consists essentially of a vertical cylinder which revolves once in the 24 hours, and a pencil which rises and falls in accordance with the tide, but on a reduced scale to correspond with a convenient height for the cylinder. The cylinder is made to revolve by clock-work; and a sheet of paper placed around it, is ruled with vertical lines for the hours of the day. The pencil is actuated by a float which rises and falls with the tide; and by means of suitable gearing or wheel-work, its motion is reduced to any desired scale. In this way, as the cylinder revolves, an undulating line or tide curve is traced on the paper, which represents the tide continuously, day and night. From this curve, the time and height of the tide, and any other tidal measurements can be made. Tide curves thus obtained are given in Plates I and II.

Many precautions and devices are required in erecting tide guages, which we cannot here enter upon. The float must be placed in a tide pipe for protection; and this again may have to be surrounded by an air space with heating in winter to prevent its freezing. Devices must be used to check or reduce wave motion; as there are exposed localities where the height of the waves may at times be almost as great as the range of the tide. It may not be practicable to use an open tide scale in winter because of ice, and measurements for height have to be obtained otherwise. There may be no means of obtaining time correctly, except directly from the sun. But on meeting these difficulties successfully, a continuous tide curve is obtained, with a base line or datum maintained at a constant level, from which the height can be measured. Those interested in the construction of the gauges, are referred to a paper by the writer on "Tide Gauges in Northern Climates and Isolated Situations," in Proceedings, Institution of Civil Engineers, London, Vol cxlix, Part iii, 1902.

TIDAL STATIONS AND TIDE TABLES.

In countries which publish tidal information, the general system adopted is to have principal tidal stations which are equipped to obtain continuous observations of the tide throughout the year, as a basis for the calculation of primary tide tables; and to bring other localities into relation with these principal stations, so that the time and height of the tide may be known at all harbours of any importance. In the primary tide tables, the time and height of high water and low water are given day by day; and for other localities there are "Tidal Differences," to apply to these tables by addition or subtraction and thus to find the time of the tide. The rise of the tide at these localities is also indicated; or it can be found more correctly by applying a difference or a percentage to the rise at the principal station as given in the tide tables.

When tidal investigations were begun in Canada in 1894, there was a clear field on both the Atlantic and Pacific coasts, in regard to the choice of principal stations; as the only tide tables were a crude attempt for Quebec. The steps taken in devising a system which would cover an extent of eight degrees of latitude on the two coasts, as well as Hudson bay, would afford a most interesting example of general procedure. The main object in view was to have as few principal stations as possible, by placing them at strategic positions, where each would dominate an extensive region. It was also found that an important harbour might be quite unsuitable as a reference station for its region, whereas some isolated lighthouse or solitary island might prove by its situation, a reference station of the first importance. For example, the only localities that can be referred to Vancouver harbour are on the arms of Burrard inlet in which it is situated; whereas a lighthouse at Sands Heads, on a group of piles off the mouth of the Fraser river, has proved an excellent reference station for all the harbours throughout the Strait of Georgia. As another example, the tide gauge built in the cliffs of St. Paul island, in the main entrance to the Gulf of St. Lawrence, where there are no marine works except a boat landing, serves by its situation as the reference station for the greater part of the coastline throughout the gulf.

The principal stations are maintained in continuous operation, in winter as well as in summer; and sufficient data for the secondary stations which are referred to them, can be obtained by a short series of observations during a few months in the summer season. As the observations are thus simultaneous, the time-differences and proportionate ranges can be correctly determined, as well as a corresponding low-water datum from which to measure the rise of the tide. Also, the limits of the region that can best be referred to each of the principal stations, are eventually ascertained.

These stations serve also for reference in regard to the movements of the tidal streams and the time at which they turn; as all such movements must be correlated with the time of the tide to afford the data necessary to the mariner.

The continuous record of the tide, obtained at the principal stations, is made the basis for the calculation of the primary tide tables by methods of reduction and analysis which would be too technical to enter into. The general procedure is to bring all the features and variations of the tide into relation with the various movements of the moon and the sun; and when these relations are established, the tides of a future year can be predicted by reversing the process, and deducing them from the positions of the moon and sun throughout that year as calculated in advance by astronomers.

It may give a sufficient grasp of the subject to describe the leading movements of the moon and the sun with their influence on the tide; and to group the tides broadly into classes or types, in accordance with the movement of the moon which may chiefly influence their behaviour in any region.

REFERENCE LINES FOR POSITIONS OF THE SUN AND MOON.

In describing the movements of the sun and moon, we have to take a somewhat different view-point from the astronomer; as we are dealing with terrestrial phenomena in relation to the heavenly bodies. It is necessary therefore to refer everything to the poles and the equator. The poles are points on the heavens which are directly over the north and south poles of the earth, in a line with its axis; and the equator is a line around the heavens midway between the two poles. We may consider these as fixed, on the face of the sky; as their actual motion is so slow that it is scarcely appreciable from one century to another. We must endeavour to think of the equator as a real line, as though it were ruled on the face of the heavens; and so also with other reference lines on the sky, such as the meridian. These lines are often called imaginary, especially in school books; but this is absolutely incorrect. They are no doubt invisible; but so is the air and the wind, yet this does not make these imaginary. Our own eyes are invisible as we look through them. To understand what imaginary lines and points really are, would require an advanced knowledge of algebra and analytical geometry, and we cannot enter into an explanation regarding them. We must do our utmost, however, to realize or visualize these actual lines on the sky from which all our measurements for position, as well as for time, have to be made.

There are other lines and points that we use for reference and measurement, which are related to our standpoint on the world. Wherever we may be, the surface of the ocean always appears to be level or horizontal. But we must be careful to define the horizon correctly. It is a line around the sky which is exactly on a level with the eye. This simple definition of the true horizon is strictly correct. In using accurate instruments, to measure angles upward from the horizon, we measure from a plane set by a spirit level. It is no doubt possible to define the horizon geometrically, as a plane tangent to the surface of the earth; but such a definition requires considerable explanation to be comprehensive. But it is true at any height, even on top of a mountain, that the true horizon is at the level of the eye.

The visible horizon is quite another matter. A land horizon can never be quite correct; but even at sea, or on the shore, the visible horizon where the sea meets the sky line is always a little below the true horizon, by an amount which increases with the height of the eye above sea level. The difference, measured as a small angle between the true horizon and the visible horizon, is known as the dip of the horizon. It is convenient at sea to measure angles from the visible horizon; but the dip must then be allowed for. This affords a good example of a visible line being only an apparent one, and not the true line that measurements must be reduced to.

Again, from any standpoint on the world, the point directly overhead is the zenith. It is given truly by the direction of a plumb line. The meridian can next be defined as a line from the pole through the zenith to the horizon at each side. It is necessary to think of the meridian as a complete circle around the sky in a vertical position, which passes under the earth as well as overhead. It is called the meridian, because it is indicated by the position of the sun at midday; and it thus stands midway between the points of sunrise and sunset. This is roughly correct; but the meridian is fixed precisely in position with reference to any standpoint on the earth, by the pole and the zenith through which it passes.

Let us now take the circle in this diagram to represent the verticle circle of the meridian from any standpoint A, on the earth, and the line H H′ to be the direction of the horizon. This meridian passes through P the pole, and Z the zenith; and it intersects the circle of the equator at E. P A E is thus a right angle. We may now give the following definitions of terms required in explaining our subject:—

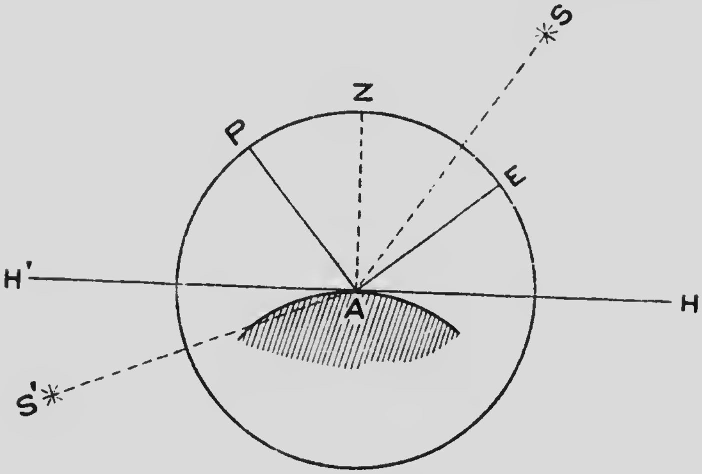


FIG. 2.

Altitude.—This is the angle measured vertically upward from the horizon to any point or heavenly body. Thus the angle P A H′ is the altitude of the pole; which it is easy to show, is the same as the latitude of the point A on the earth. The zenith may be defined as the point which has an altitude of 90° from the true horizon.

Meridian altitude.—As the circle represents the meridian, the angle S A H is the altitude of any heavenly body S, when on the meridian; or its meridian altitude.

Upper and lower transits.—These are the two crossings of the meridian which every heavenly body must make in the course of the day. In a general way it may be said that the upper transit is the crossing of the upper or visible part of the meridian, when the body is at S; and that when it revolves around the pole to S′ the lower transit occurs when it crosses the meridian where it is below the horizon.

It is evident, however, that in the case of stars near the pole, their upper transit is across the part of the meridian south of the pole and their lower transit, across the part north of the pole; and in northern latitudes, both transits may be visible.

As it is often essential in explaining the tides to distinguish the two transits of the sun or the moon, we must make the matter quite clear in their case. The upper transit of the sun across the meridian is visible everywhere in the world at all seasons between the limits of the Arctic and Antarctic circles; and its lower transit is across the part of the meridian below the horizon, and is therefore invisible everywhere and always between the same limits. The same statement is approximately true for the moon also; although for it, the limiting latitudes are by no means so definite. In regard to the visibility of the transits, therefore, it will be the same for the moon as for the sun in all the central parts of the world, except the polar regions.

Declination.—The declination is the angular distance of a body north or south of the celestial equator. Taking this circle as a section of the earth through the poles P P, it is the angle S C E. It is thus evident that declination has the same meaning as latitude on the earth, and it can be remembered by this. The term latitude cannot be used for it however, as astronomers use this word to designate an entirely different thing. To connect declination with latitude on the earth, we may note that when the sun or moon is at any given declination, it passes through the zenith of every place around the world which has the same latitude as its own declination at the time, whether north or south of the equator.

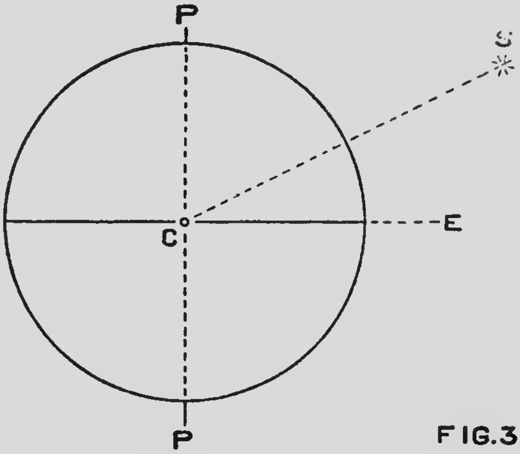


FIG. 3.

As viewed from a point A on the earth's surface (see Fig. 2) the angle S A E from the equator to a heavenly body at S, is very nearly the same as its declination. It only differs from the true declination, S C E in Figure 3, as measured at the centre of the earth, by a small amount known as parallax. In the case of the moon however, because of its being so near the earth, it is possible for the parallax to amount to a whole degree.

MOVEMENTS OF THE SUN AND MOON.

It may be well to state, to begin with, that every movement of the sun and moon has its influence upon the tide. This becomes more and more evident the further we go into the subject, and the more closely and carefully we investigate matters. The trouble with the usual text book on the tide is that it places the whole emphasis on one aspect of the question, as though this explained everything; which has stood in the way of a correct understanding of the subject. The best way therefore to make the matter clear, is to begin by describing in the simplest way possible, all the leading movements of the sun and moon; as the tides themselves can best be grouped into classes, in accordance with the characteristics they present in relation to these movements. We will also endeavour to go no further into astronomy than is necessary for an understanding of the tides.

The path of the sun on the face of the heavens is a line, inclined to the equator, which is called the Ecliptic. The sun, as it travels along this line during the course of the year, crosses the equator in March, and goes gradually further north, until it reaches 23° north declination in June, then begins to go south, crossing the equator again in September; and on reaching 23° south declination in December, it turns northward once more. The points at which it crosses the equator are the Equinoxes, and the turning points where it reaches its maximum declination, north and south, are termed the Summer and Winter Solstices, respectively. It may be well to recall these well-known movements of the sun, because the moon moves almost exactly in the same way. In a period somewhat less than the ordinary month, the moon crosses the equator going north, and again going south, just as the sun does in the course of the year. These changes in declination have a marked influence on the tide.

It is clear that this change in the position of the sun gives it a higher meridian altitude in summer and a lower altitude in winter, which is very noticeable. The meridian altitude of the moon varies also in the same way during the course of the month; but this is less noticed than it should be, because the moon is not always full; and the period of this change does not correspond with its phases. To know whether a heavenly body is north or south of the equator, we may refer to Figure 2. It is evident that as the angle P A E is a right angle, the angle E A H must be the difference between a right angle and the latitude P A H′; that is, E A H is the complement of the latitude, or the co-latitude. We can therefore make the following statement: If the sun is on the equator (at E) its meridian altitude is equal to the co-latitude of the place; if its meridian altitude is greater than the co-latitude, it is north of the equator, and if less, it is south of the equator. This statement may be taken as correct for the moon also, as viewed from a point on the surface of the earth, if we overlook the displacement due to parallax.

The variation in the sun's distance has also a calculable effect on the tide. The earth's orbit around the sun being an ellipse and not perfectly circular, the distance is less at one season of the year and greater at the opposite season. The variation is not large; but the attraction of the sun on the earth varies as the square of the distance; and not only so, but when everything is taken into account, it is found that the "Tide-generating force" as it is called, varies as the cube of the distance. Hence a comparatively small variation in actual distance may occasion a change in the tide which is quite appreciable. For the moon, this force is 18 per cent greater when nearest and 15 per cent less when farthest, than at its mean distance.

As the moon revolves around the earth, it is new when it passes the sun, and full when it is opposite the sun; and its quarters occur when it is at right angles to the direction of the sun. These phases of the moon are due to its position relatively to the sun, and its illumination by sunlight; and they have nothing to do with its actual position in its orbit. Yet this revolution of the moon has an important relation to the tide; as it brings the attraction of the moon on the waters of the ocean into line with the attraction of the sun at new and full moon; and the attraction becomes transverse at its quarters.

The period from new moon to new moon is the Synodic month. It is longer than the true period in which the moon traverses its own orbit, because in the course of the month the sun has moved 1-12th of the distance around the heavens, or about 30°, and the moon has this extra distance to go before it is again in conjunction with the sun. The length of the Synodic month is thus 29½ days; which is almost exactly two days longer than the true period of the moon's revolution in its orbit.

The moon's orbit is properly speaking an ellipse; but the ancient Greeks described it as a circle with the earth a little out of the middle. If the orbit were drawn to scale, this would describe its appearance remarkably well; but to discuss the matter, we may exaggerate the ellipticity, as in Figures 4 and 5. The earth is at E; and the line P A is the axis of the ellipse which represents the moon's orbit. The point P where the moon is nearest the earth, is Perigee; and the point A, where it is farthest, is Apogee. The period of rotation from perigee to perigee is called the Anomalistic month. Its length is slightly over 27½ days.

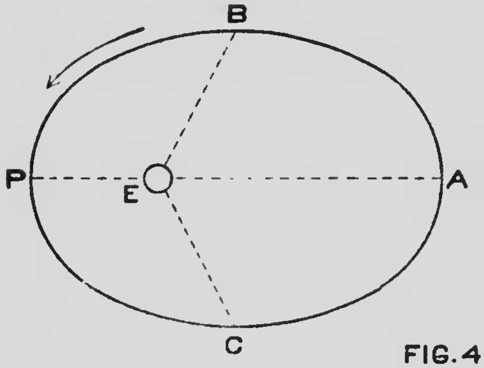


FIG. 4.

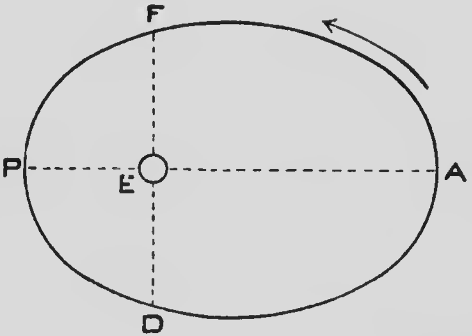


FIG. 5.

The motion of the moon in its orbit is not uniform, however; but it travels faster through perigee and more slowly when near apogee. For, the law of elliptical motion requires that the areas passed over by the line from the moon to the earth, shall be equal in equal times. Hence, in Figure 4, if the area E B P C E is equal to the area E C A B E, the time of travel from B through P to C, is equal to the time from C through A to B. The points B and C in the orbit are thus midway in time between perigee and apogee.

We must now consider the moon's orbit as it revolves around the sun in company with the earth, during the course of the year. For the relation of the moon's phases to the orbit itself, concerns the tides closely. In Figure 5, P A is again the axis of the orbit, and D E F a line at right angles to the axis through the earth at E. We must not suppose that the long end of the lunar orbit points always towards the sun, because of its attraction, as it might be natural to think. On the contrary, as the earth goes round the sun, the axis of the lunar orbit maintains the same direction in space, with little variation. The axis of the orbit does rotate, it is true, in a period of years; but in any one year we may consider the axis as maintaining a fixed direction, or as remaining parallel to itself. It therefore follows that with relation to the line from the earth to the sun, which we view as the sun's direction, the orbit assumes all possible positions during the course of the year. This will become clear as we follow the details.

When the axis points to the sun, with the sun in the direction E P, the moon will be new when at the point P and it will be full when at A, if we overlook the slight change in position relatively to the sun in the half month. Six months later, the axis will again point to the sun; and the moon will be new when at A and full when at P. We can therefore make these statements: (1) The new moon and the full moon may occur at either perigee or apogee. (2) If the moon is new at perigee, the following full moon will be nearly at apogee; and vice versa. (3) In either case, the lengths of time from new to full moon and from full to new moon, will be equal. Or we may say, the two "halves" of the synodic month will be equal. The exact half of the average synodic month is 14 days 18 hours 22 minutes.

About three months after the line E P pointed towards the sun, the axis of the moon's orbit will be transverse to the direction of the sun; and the line E D will point towards it. The moon will then be new when at D and full when at F. These points are nearly at the mean distance of the moon, although not exactly so. Because of these conditions, we can make the following statements: (1) The quarters of the moon may occur at either perigee or apogee. (2) If one of the quarters is at perigee, the following quarter will be nearly at apogee. (3) When this is the case, the two "halves" of the Synodic month, from new to full moon and from full to new, will be quite unequal. For when the moon is new and full at the points D and F, it is evident that the distance D A F is not only longer than F P D, but also the rate of motion is slower near A and faster near P. The actual intervals of time between new and full moon or full and new moon may thus be 13 days 22 hours 32 minutes, and 15 days 14 hours 12 minutes; which shows how very unequal it is possible for them to become.

THE THREE LEADING TYPES OF TIDE.

Although every movement of the sun and moon has its effect on the tide, yet one of the most singular facts is that in different regions of the world some one movement of the moon has a dominating effect, and the others become of secondary importance. This is seldom pointed out as it should be in works on the subject; and we may also state quite frankly that we do not know the reason for it, although some partial explanations may be given. The same may be said as to the relative influence of the moon and sun being different in different parts of the world. These variations have the advantage however, of enabling all tides to be grouped in three leading classes or types, according to the dominant feature which they present.

The three types which we thus find are: (1) The synodic, in which the leading variation in the range of the tide takes place twice a month; the range being greater at new and full moon, and less at the moon's quarters. (2) The anomalistic, in which the greatest variation in the range accords with the moon's distance, and takes place once a month. (3) The declinational, in which the changes due to the moon's declination (which makes the two tides of the day unequal in range) are so large and obvious that all other features of the tide are obscured. This declinational type of tide, we will take up later, after we describe more fully the moon's own behaviour in regard to declination.

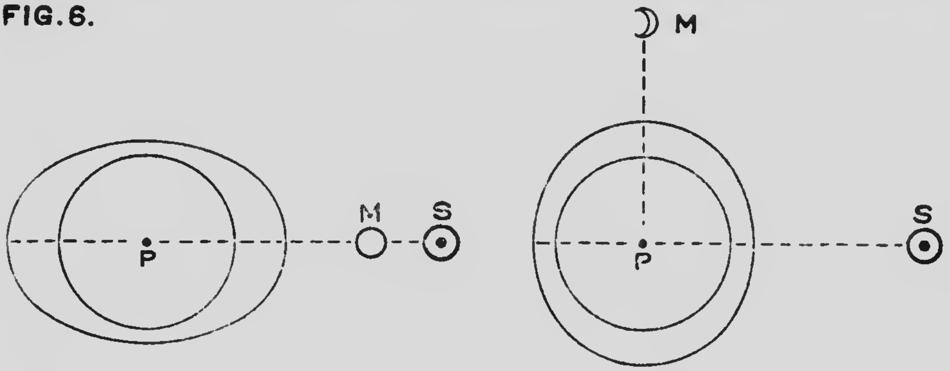
It is to be understood, however, that though one of these variations is dominant, the others are never entirely absent. Also, although these variations may be stated broadly to take place in the course of the month, their actual periods are not the same, but they have the following values expressed as tide-intervals, or half lunar days, which is quite the best way to measure them for our purpose: (1) The synodic, in the month of the moon's phases, from new moon to new moon; period 57·06 tide-intervals. (2) The anomalistic, in the month of the moon's distance, from perigee to perigee; period 53·24 tide-intervals. (3) The declinational, or the interval between the times at which the moon crosses the equator in the same direction, say, going northward; period 52·79 tide-intervals. The declination month is the same in its period as the average length of the Tropical month of the astronomers. The convenience of these measures is that they represent the number of high waters (or of low waters) in the course of each of these periods. Thus the number of high waters from new moon to new moon is 57; from perigee, the number of tides will be 53 to the next perigee, with the addition of one number every fourth month; or if the numbering begins from the moon on the equator, there will be 52 tides to count, with an extra number in three months out of four. By such numbering, the position of each tide with relation to the moon's position can readily be fixed, in the month dealt with.

These three periods are all called "months" because each is measured by one of the movements of the moon. But as their periods are all different, it is evident that the corresponding variations in the tide will over-run each other; so that they may or may not coincide in time. This may seem to make the matter complex; but we are again helped by the classification, which enables us to consider one type at a time. It may also help in distinguishing them to mention regions where these types are found. The synodic type is predominant in the North Atlantic, on most of the coasts of Europe and North America. Noteworthy examples of the anomalistic type occur in the Bay of Fundy and Hudson strait, where with a range of tide exceeding 30 feet, the greatest variation is with the moon's distance. The declinational type is predominant in most parts of the Pacific ocean; and there are also regions in the Gulf of St. Lawrence where it is very highly developed. It is interesting to note that the solar influence, relatively to the lunar, seems to be greater in these declinational regions. With these general explanations, we may proceed to consider these types separately.

THE SYNODIC TYPE.

When the moon is either new or full, the line of its attraction coincides with the sun's attraction; and the lunar and solar tides are added to each other by being superposed. It is immaterial whether the moon is new or full, because the tides on the opposite sides of the earth are practically equal. Again, at the moon's quarters, the solar tide stands in the hollow of the lunar tide, at each side of the earth; and the resulting range of the tide is only the difference between the two. These relations will be seen in Figure 6. In theory, the solar tide is 46 per cent of the lunar.

FIG. 6.



The higher tides, at new and full moon, are called Spring tides; a name connected with springing up, or greater activity; and in no way related to the spring of the year. The tides of less range, at the moon's quarters, are called Neap tides; which is again a Saxon word meaning decreased or inactive. This is the only variation of the tide for which names are available, and for other variations we have to use astronomical terms. The reason of this undoubtedly is that this change happens to be the leading variation on the coasts of Europe, where the tides were first studied. This circumstance has stood seriously in the way of a correct understanding of the tides in general; since in most text books, it is assumed to be the only noteworthy variation that there is.

The average interval between the Spring tides, is the half synodic month. We have already seen how very unequal the two "halves" of the synodic month may be; but as the Spring tides depend upon the moon being in line with the sun, on one side of the earth or the other, they will have the same time-relation to the full moon as to the new moon, however far out of the middle of the synodic month the full moon may happen to be. We will see the importance of this in a moment, with regard to other tidal factors.

The interval from the moment of the new or full moon to the highest Spring tide, is about 36 hours (or three tide-intervals) on either side of the North Atlantic; and this interval is the same from full moon as from new moon. As the tide travels up the Atlantic from its southern end, this long interval has given rise to the view that the ocean most immediately influenced by the moon, is the Antarctic, where there is a belt of water completely around the world; and from this the tide proceeds northward, reaching the coasts of Europe and eastern Canada 36 hours later. This may indicate the way in which the amount of lag may become so large; if the data are sufficient to make the explanation acceptable in this instance.

The synodic tide is found to be a wide-spread type. As examples in Canada, we may cite the Atlantic coast of Nova Scotia, on the south-eastern side of that province; and also the whole of the St. Lawrence estuary, having an extent of 335 miles from Point des Monts opposite the Gaspé coast, to the head of tide water in the river at Lake St. Peter. The tides of Hudson Bay, an area larger than the North Sea, appear also to be of this type so far as they have been investigated. There are regions on the Pacific coast, some hundreds of miles in extent, where the tides are such that Springs and Neaps can be distinguished, although this may not be their really dominating characteristic. (See Plate III.)

The Establishment, and Luni-tidal interval.—In regions where the tides are of this type, there is a very convenient way to find the time of high water by a difference of time known as the Establishment, which we may first explain broadly. When the moon is new or full, it is with the sun or opposite to the sun; and it then crosses the meridian at the same time, that is, at either noon or midnight. Now, it is found at any locality, that the interval of time between the moon's transit and the high water following, is always the same at new or full moon. Hence the Spring tides are always at the same hour in any given harbour, if the hours are counted from noon as well as midnight as we usually do. The hour of the day or night at which high water occurs at the Spring tides, is known as the "Establishment" for that harbour.

This is a general explanation, but by being more precise, we can give a better definition of the Establishment, and extend its use. The interval of time between the moon's transit and the first high water that occurs after it, is called the "Luni-tidal interval." The influence of the sun, which causes the range at the Springs to be greater than at the Neaps, also causes the Spring tides to be closer to each other in time, and the Neap tides to be more widely separated. Consequently, the Luni-tidal interval is not quite the same during the course of the month. The Establishment is therefore defined as the Luni-tidal interval from the moon's transit at noon or midnight.

As it is seldom that the moon does cross the meridian at the exact moment of noon or midnight, it is best to find the actual time of the moon's transit on the date, from the Nautical Almanac. It is then merely necessary to add the Establishment in hours and minutes, to obtain the time of high water when the moon is new or full. This is a great convenience where no tide tables are available. At other dates in the lunar month, the Establishment may also give a fair approximation to the time of high water, which may be a useful indication for want of anything better.

(Those familiar with astronomy will note that the moon is not necessarily new or full at the moment when its transit is at mean noon or mean midnight; for the moon is new when in conjunction with the sun, and on the day that conjunction occurs, the sun itself may be as much as 16 minutes from the meridian at noon, by the equation of time. This represents almost a third of a lunar day, in the moon's motion in right ascension. It is thus best to define the Establishment as an hour angle from the moon's own transit on the local meridian, to make its value as constant as possible in different months.)

It is to be noted that the Establishment affords a means of finding the time of high water which will only work out correctly where the tide is purely of the synodic type, and not affected to any great extent by other motions of the moon. To attempt to determine the Establishment for all the harbours of the world is therefore illusory.

THE ANOMALISTIC TYPE.

The leading variation in this type of tide accords with the moon's distance; and if this feature were so dominant that all others could be overlooked, the tide would always have its greatest range at perigee and its least range at apogee; and the period of this variation would be the anomalistic month of 53½ tide-intervals, which is shorter than the synodic month by nearly two lunar days. Also, as the motion of the moon is so much faster near perigee than elsewhere in its orbit, the range increases quite rapidly near perigee and falls off again equally rapidly; whereas when the moon is on the apogee side of its orbit, the change is much slower.

Although there do not appear to be any tides which are as purely of the anomalistic type as those of the synodic type, yet there are regions where this variation with the moon's distance is distinctly greater than the variation from Springs to Neaps. This is the case in the Bay of Fundy, as will be seen in the following table, showing the variations at St. John at the middle of the length of the bay; as well as at Burntcoat head in the Cobequid arm, where the range attains its maximum amount. When the range is so large, all the variations are amplified also.

Description of Tide.	St. John, N.B.		Burntcoat Head.	
	Range in feet.	Difference.	Range in feet.	Difference.
At Perigee. Range at Spring Tides	26·60	6·[illegible]	50·50	10·32
At Apogee. Range at Spring Tides	19·92		40·18	
Spring range. Mean of the above	23·26	5·22	45·34	6·56
Neap range, at Moon's mean distance ...	18·04		38·78	
Average range during the month	20·65		42·06	

As the anomalistic month is so much shorter, its point of beginning falls gradually back through the synodic month; and perigee may thus fall successively at any phase of the moon. If we follow these changes carefully, keeping in mind that the corresponding tidal variations in the Bay of Fundy are not far from being equal in amount, the curious outcome will become apparent. When perigee falls at new moon, the full moon in the same month will be near apogee, and the two Spring tides of the month will be extremely unequal. In such a month, the moon's quarters will occur at about mean distance, and the Neaps will have their true average value. But the apogee Springs, because of the relative amounts of the variations as explained, are practically equal to the Neaps. Hence, the height of the tide remains almost the same for three-quarters of the month, and reaches an extreme height at one point in the month only. This helps to explain the great rise of the tide in the Bay of Fundy, which thus reaches its extreme only occasionally under these conditions. (See Plate III.)

In the other kind of month, when perigee falls at one of the moon's quarters, it is the Neap tides that will be so very unequal; and the two Spring tides will occur near the moon's mean distance, which will make them practically equal and give them their true average value.

Another feature of interest in these variations, depends on a curious astronomical movement, which merits explanation. It is that perigee does not fall back evenly around the synodic month, but it appears to "hang" or remain quite near the new moon for three or four months; it then moves rapidly past one of the quarters, and again "hangs" at the full moon before going on past the next quarter. Perigee thus remains sufficiently near the new or full moon to occasion the extremely high Spring tides referred to, for about three months in succession before they fall off in height.

The tide of the Bay of Fundy affords a striking example of the equality of the rise and fall above and below Mean Sea level. This is proved by careful levels across the isthmus of Chignecto, from Cumberland basin at the head of the bay, to Northumberland strait in the Gulf of St. Lawrence. These levels were taken in 1870 and 1871 for a proposed canal across the isthmus; and the simultaneous tidal observations on the two sides were compared with reference to a truly level datum. The range at the head of the Bay of Fundy at one end of the canal line, may be as much as 47 feet, and at the other end on the Gulf of St. Lawrence it is only 1 to 7 feet; yet the half-tide level is practically the same in both cases. The Bay of Fundy may thus show at its head, a depression of 23 feet below Mean Sea level, and an elevation of 23 feet above it, alternately; which is in accord with the general principles of undulatory movements, as we have already pointed out.

For a full description of these interesting tides, with levels and comparative data based upon all information available, see "Tides at the Head of the Bay of Fundy," published by the Tidal and Current Survey of Canada. For the features of the tides of Hudson strait, see "Tides of Hudson Bay" in the Journal of the Royal Astronomical Society of Canada; Vol. VIII, page 98; 1914.

Combined tides.—The two types of tide that we have described, are often more or less combined with each other. Even when the tide is dominated by the moon's distance, the variation from Springs to Neaps may be quite evident. On the other hand, when the type is synodic, there is not unusually an anomalistic influence which affects the range appreciably. If the Neaps vary from this cause it is not of much consequence, but any change in the range of Spring tides is important in affecting the highest and lowest levels that can occur. When perigee falls at either new or full moon, the difference in range between the two Spring tides of the month is known as "Semi-monthly inequality." In regions where this is at all large, relatively to the average range of the tide, it must be taken into consideration; especially in determining the level of average Low water at Spring tides, which is much used as the reference level to which chart soundings are reduced. It is also possible for either of these types to show some amount of diurnal inequality, as will be seen in the examples given in Plate III.

THE DECLINATIONAL TYPE.

In regions where the tides are dominated by the moon's declination, the variations which result are greater than from any other movement of the moon, considered separately. As we have pointed out, there are no ordinary words in European languages to designate these changes; and we are therefore obliged to indicate them astronomically or to use technical terms for them.

In Figures 7 and 8, the circle represents a section of the earth through the poles. When the moon is on the equator, the raised tide-water is symmetrical between the poles; and an observer at A as he moves around his parallel of latitude to A′ with the rotation of the earth, will find the two tides of the day to be equal in height. This will be the case at every locality in the world, as Figure 7 shows.

To be quite correct, in a matter of so much importance, we must take the influence of the sun into account also; and say that the two tides of the day will be exactly equal in height when the sun as well as the moon is on the equator. Otherwise, to have them exactly equal, the moon requires to be somewhat south of the equator in summer, when the sun is north; and somewhat north of the equator in winter, when the sun is south; to balance the solar influence. The moon when crossing the equator, is moving so rapidly north or south, that it may gain enough declination in a day or two to give this balance.

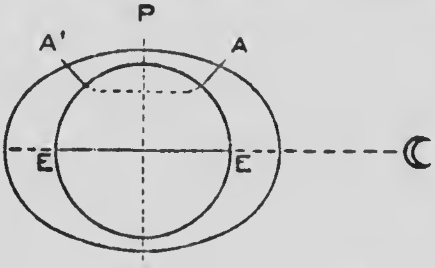


FIG. 7.

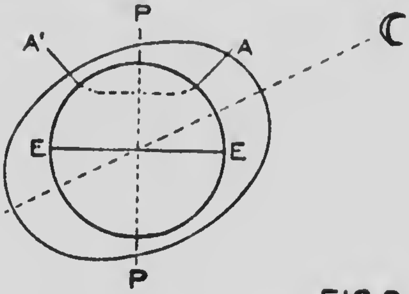


FIG. 8.

(To obtain this balance, the resultant attraction of the sun and moon must coincide with the plane of the equator. The solar tide-generating force is 0·458 of the lunar; being in direct proportion to their masses and inversely as the cube of their distances. Hence when the sun is at its extreme declination of 23° the moon requires to have nearly 11° of declination on the opposite side of the equator to balance; and with the sun at a mean declination of 11½° the moon requires to have 5½° of opposite declination. Reduced to time, the moon after crossing the equator, takes 2½ days or one day respectively, to attain these declinations. The astronomical conditions are then such as exactly balance out the diurnal inequality).

Whatever the range of the tide may be at any date, because of its other variations, the two tides of the day will be equal under the conditions here described. This equality of equatorial tides, in their range and their time-intervals, is a universal feature for all types of tide and in all parts of the world. It is one of the few definite statements that can be made regarding the tide, without any exception or qualification.

If the tide is of the type which we are now considering, when the moon is at a high angle of declination, as in Figure 8, the height of the two tides of the day at A and A′ will be quite unequal. This change in the height of the tide is termed "Diurnal inequality"; and when it occurs, there is also a pronounced inequality in the interval of time between successive high waters. The form of the tide curve will become as here shown, when the moon is at maximum declination. In the 25 hours of the lunar

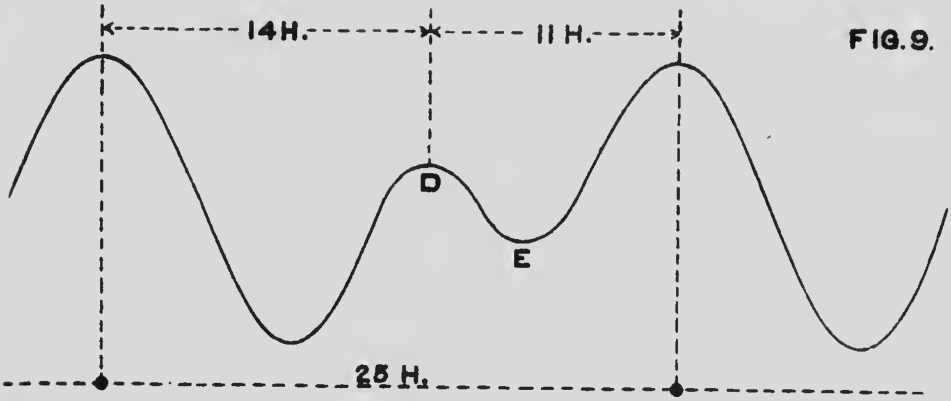


FIG. 9.

day, there will be a "Large tide" and a "Half tide" alternately; and the time intervals between successive high waters will also become very unequal. The tidal streams are affected in the same way, and there will be a "Long run" or a "Short run" in correspondence with the amount of rise or fall. When the moon returns to the equator, the tides become perfectly equal again, in their height and their time intervals. These changes are so evident in this type of tide, that in a series of tide curves for a month, the dates at which the moon crosses the equator can be picked out at a glance without reference to an almanac. (See Equatorial tides at Sand Heads, Plate IV.)

There are localities where the inequality in the tide becomes so extreme when the moon is in high declination, that there is no fall from D to E. This part of the curve becomes level, representing a "stand" in the tide; or it may even slope upward, leaving only a secondary shoulder on the curve at D. There is then, practically speaking, only one high water and one low water in the day, as the other two are effaced. The tide is then said to become diurnal. Such a tide occurs at Victoria at the south end of Vancouver island; and at Hong Kong and other localities in the Pacific ocean. It is also found on the north shore of Prince Edward island, and some other localities in the Gulf of St. Lawrence. The tide curve only assumes this form, however, (causing the Half tides to be wanting in the Tide Tables) for a few days at a time, near the moon's maximum declination. At other times there are two tides in the day; and with the moon on the equator, these become equal as they do everywhere.

Where the tide is of the declinational type, the change in the declination of the sun during the course of the year, has also a marked effect. The solar inequality is precisely similar to the lunar; as it is greatest at the solstices and falls to nothing at the equinoxes when the sun is on the equator. In consequence, the extreme tides of the year occur when these effects are combined; that is, at the date of the moon's maximum declination, which falls nearest to the solstice. The extremes thus occur about June and December.

There are regions in which the amount of diurnal inequality at high water and at low water are equal to each other, as shown in the typical example in Figure 9. This is the case in the Bay of Fundy, although it is not a dominant feature of the tide there. But it is a curious feature of these declination tides, that the inequality may affect high water almost entirely, or else low water almost entirely. In the Strait of Georgia, lying inside of Vancouver island, the high waters remain nearly at the same level, and practically the whole inequality is in low water. At Charlottetown, in the middle of Northumberland strait, which lies south of Prince Edward island, the inequality is also chiefly in the low water level. There are other places in the Gulf of St. Lawrence where the reverse is the case. For example, at Richibucto, and at Caraquet in Chaleurs bay, the low waters remain nearly at the same level, and by far the greater part of the inequality is in high water. (See Plate IV.)

It is quite possible from a physical view-point, that the diurnal inequality and its special effect upon high or low water, may be due to some extent to the interference of two tidal undulations from different directions. When conditions are carefully studied in parts of the Gulf of St. Lawrence, it is more than likely that such interference occurs. This may afford a secondary explanation; but it is important to point out that all such secondary influences can be overlooked, as the movements of the tide can always be directly correlated with the positions of the sun and moon. The primary explanation, as shown in Figures 7 and 8, therefore holds good.

This direct reference to the moon's movements remains applicable under the most complex conditions. No better example of this could be given than the Gut of Canso, between Cape Breton island and Nova Scotia; a narrow strait only 15 miles in length. At the north end of the strait, the tide is of the declinational type which we are describing, while at the south end it is the synodic tide of the Atlantic. There is thus a large diurnal inequality in range at one end, and the change from Springs to Neaps at the other end, these variations being entirely out of accord, as they recur in months of different lengths. The run of the current through the strait undoubtedly depends on differences of level due to the quite discordant fluctuations of these different types at its two ends; and the resultant water-slopes might no doubt be worked out in detail. Yet notwithstanding these proximate causes, it has been found possible to reduce the behaviour of the current to laws which are correlated directly with the moon's change in declination. (See explanation of this, in "Tide Tables for the Eastern coasts of Canada," under Gut of Canso.)

Combined tides.—Although the tide may be predominantly of the declination type, it must not be supposed that the effect of Springs and Neaps is entirely absent, or that no variation with the moon's distance can be detected. For the tide to be properly classed under this type, there must be a greater difference in range between the two tides of the day than there is from any cause during the course of the month: and when the type is highly developed, these other variations are obscured. They only become noticeable if they occur when the moon is on the equator, as the diurnal inequality then disappears. The most evident of the other variations occurs when new and full moon are both close to the equator as they may be in the same month. The equatorial tides will then show at the opposite sides of the month, all the difference in range between Springs and Neaps that there is in the region.

Inequalities in time.—In tides of the declination type, there is not only the inequality in range between the two tides of the day, but the following inequalities in time occur when the moon is in high declination: (1) The intervals of time between successive high waters become unequal, as well as between successive low waters. The inequality may become as great as 8½ and 16⅓ hours alternately, as in the Strait of Georgia; the two together making up the total 24⅚ hours of the lunar day. This appears to be the limit of inequality in any harbour throughout the Pacific ocean; for if it tends to be any greater, the tide becomes diurnal. (2) The intervals of time between successive slack waters when the tidal streams turn, become similarly unequal; in correspondence with the long and short runs of the current which occur alternately. (3) The luni-tidal intervals, from the moon's transit to the time of high water, show a large alternation for successive tides. The difference between the consecutive values may be as much as 3 or 4 hours. It is thus evident that if the moon happens to be at its maximum declination when new or full, the use of an Establishment, even though it may be a good theoretical average, will give quite erroneous results. When the moon is crossing the equator, all these inequalities disappear for the moment, at the same time that the ranges become equal.

The following table gives an example of the alternation in the time values that may occur when a tide of the declination type, as at Pictou, is compared with a synodic type, at Halifax. It illustrates the variation that can arise from declinational inequality:—

Date.	Time of High Water.				Difference		Remarks.
	Pictou.		Halifax				
	H.	M.	H.	M.	H.	M	
1896, July 8	7	10	6	15	0	55	Moon's declination maximum north
" " 8	21	11	18	02	3	09	
" " 9	8	02	6	50	1	12	
" " 9	22	07	18	55	3	12	
" " 10	9	00	7	50	1	10	
" " 10	23	15	19	30	3	45	New moon
" " 11	9	45	8	35	1	10	
" " 11	23	57	20	22	3	35	
" " 12	10	35	9	15	1	20	

It is clear that mariners should concern themselves with declination much more than they do. It is also quite unfortunate that there are no names to designate the points at which the moon crosses the equator, as they cannot properly be called nodes;

nor is there any name for the maximum declination of the moon, to correspond with Solstice in the case of the sun. This want of names makes the explanation sound much more cumbrous than it should.

Declination in relation to the Moon's transits.—This relation requires to be more fully explained, because much additional help could be given to mariners, in Tide Tables and other Nautical works, if it were understood. For it enables the similar conditions of inequality in the tide and of alternation in tidal streams, to be made clear.

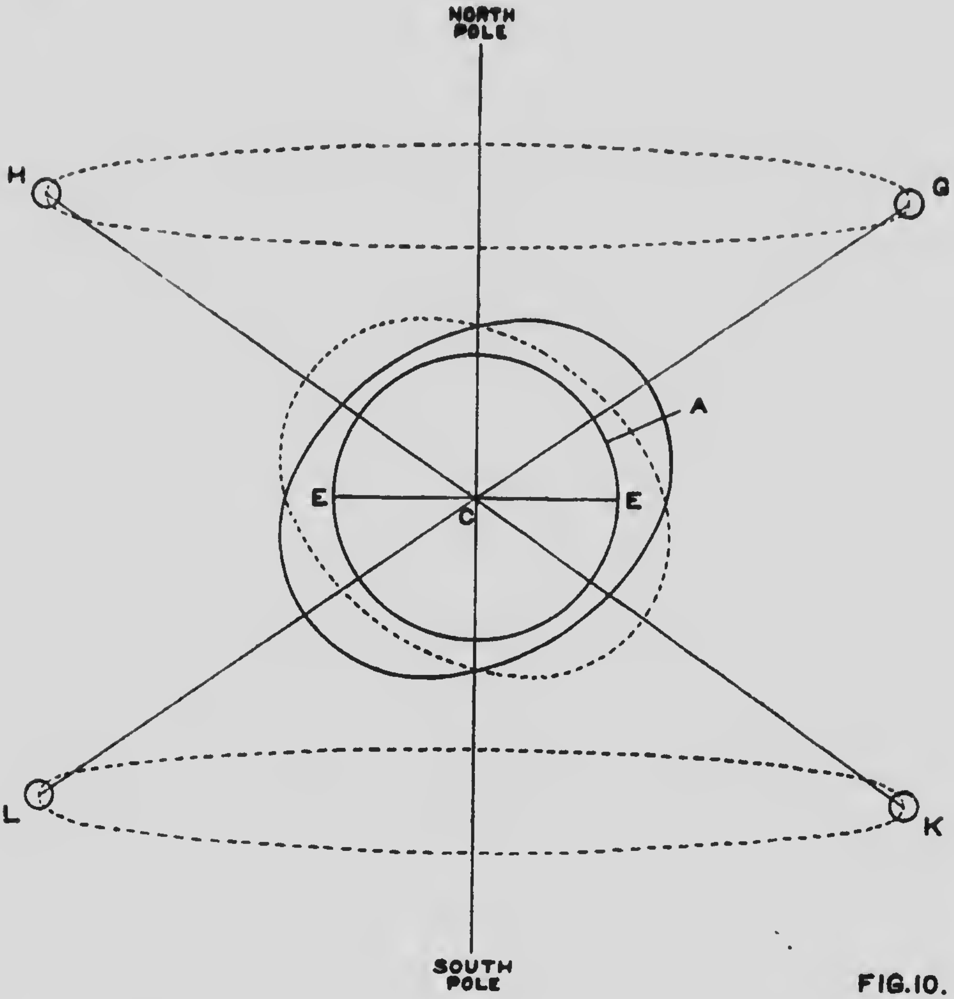


FIG. 10.

The circle in the middle of Figure 10 is a section of the earth through the point A, and the little circles represent positions of the moon. When the moon is in North declination at G, it will appear to circle around the parallel of declination G H. As seen from A, its upper transit across the meridian will occur at G and its lower transit at H, which will be below the horizon at A. The North declination of the moon will then decrease, till it crosses the Equator and goes into South declination; and after half a month it will appear to circle around the parallel of declination K L. Its upper transit across the meridian will then occur at K and its lower transit at L.

When the moon is in North declination, the tide will circle around under it from the full oval to the dotted oval; and when it is in South declination, it will circle around from the dotted oval to the full oval. As observed at A, we can therefore class the tides in pairs; as it is evident that the conditions are the same when the moon is at either G or L, and they are also the same when it is at either H or K. These may be given names for distinction; and the tides may be described as following the moon, as there is always some amount of lag. The names are these:—

"Similar" tides are those which follow the Upper transit of the moon in North declination, or the Lower transit in South declination.

"Opposite" tides are those which follow the Upper transit of the moon in South declination, or the Lower transit of the moon in North declination.

In many tidal calculations these distinctions must be carefully observed; but this may be left to tidal experts, although it may interest the mariner to know how he arrives at his results. There are two general ways in which this concerns the mariner more directly: (1) In knowing which of the tides of the day will be the higher of the two, in crossing bars. When the time of the tide only is available, as when it is found by means of a tidal difference applied to a Tide Table or otherwise computed, the higher tide of the day may thus be designated. (2) In finding the time at which a tidal stream turns, with relation to the time of the tide. For in regions where this type is developed, when the moon is in high declination, the turn of the current is alternately earlier and later than the average, in relation to the time of high and low water; and the strength of one flood and one ebb in the day is much greater than the strength of the other two.

Explanations of this character are given in the Canadian Tide Tables, regarding the height of the tide in Miramichi bay, and the turn of the current in Northumberland strait. (See "Currents in the Gulf of St. Lawrence," page 33; published by the Tidal and Current Survey.) On the Pacific coast of Canada, where there are many passes and narrows in which navigation is only possible at slack water, the turn of the tidal streams is calculated on these principles and published in the form of Slack Water tables. (See explanation as given for Seymour Narrows, in "Tide Tables for the Pacific coast of Canada.")

MOTIONS OF THE MOON'S ORBIT.

While the moon rotates around the earth in its orbit, the orbit itself is affected by two movements. One of these movements we can pass over in a few words, but the other requires explanation as it has an important bearing on the tides.

Revolution of the Axis of the orbit.—We have explained that in any one year, as the moon's orbit revolves round the sun in company with the earth, the axis of the orbit remains nearly parallel to itself. But the axis has in reality a slow movement of rotation, and it makes a complete revolution in about eight years. We may leave this to the astronomers, however, as it merely alters the position of perigee, which they allow for in their calculations. Those acquainted with astronomy will recognize that this is the reason that the anomalistic month which we have to deal with, differs in length from the sidereal month.

Revolution of the Plane of the orbit.—This occasions a change in the range of the moon's declination; or the limits which it can reach, north and south of the equator, in any given year. If we begin with its most restricted movement in declination, which in even degrees is from 18° north to 18° south, this limit keeps increasing for nine or ten years until it reaches a maximum range of 28° north and 28° south, when it again decreases gradually, and eventually completes the cycle in 19 years. These variations are quite noticeable to any one who observes the moon; for there is not very much change in one year, and consequently there are years in which all the full moons are within a limit of 36° in their meridian altitude, and other years when they extend to the wide range of 56° on the meridian. The north and south limits will be best seen in different months, however; because for three months in succession the moon is within two or three days of being full when at its maximum north; and again at the opposite season of the year, for three other months in succession, when at its maximum south. These things can thus be clearly seen by any one who combines observation with memory. We will now consider the cause of this, and its effect on the tide.

These changes could not be fully explained without a larger amount of astronomical phraseology than we wish to enter upon; but we will endeavour to make clear the reason for the two extremes in the range of the moon's declination, as it is found to occur in different years. The plane of the earth's orbit is the most fixed plane of reference that there is; but the moon's orbit does not lie in this plane; it is inclined to it at an angle of about 5°. While this inclination remains the same, the position does not remain fixed, as the orbit is continually gyrating. This motion, as an eminent astronomer has described it, may be compared in its relation to the earth's orbit, to the gyrating motion of a dinner plate on a table just before it comes to rest, after being originally spun on its edge to start it. A rolling hoop, falling over sideways on a pavement, will illustrate the same thing. The last of the wobbling motion, when nearly flat, represents this movement of the moon's orbit. The period, however, is long; as it takes 19 years for the orbit to make one gyration of this character.

As seen on the face of the heavens, the earth's orbit gives the line of the ecliptic; which is inclined to the equator at an anglo of 23°. In consequence of this gyration of the moon's orbit relatively to the ecliptic, a year will arrive in which its orbit will lie between the ecliptic and the equator, and its inclination to the equator will be 5° less than 23°, or 18°. This is the limit of north or south declination which the moon can reach in such a year, in travelling around its orbit during the month. At its opposite position in the cycle, there will be a year when the inclination of the moon's orbit to the equator will be 5° greater than the inclination of the ecliptic. In such a year, the limits of declination which the moon can reach are extended to 28° north and south of the equator. As these changes depend on so low an angle of inclination as 5°, the limiting values of the maximum and minimum show very little variation in the course of a single year. These periods of greatest and least range in declination, are separated by an interval of 9½ years from each other.

(In astronomical language, the change is due to the revolution of the moon's nodes; and the direction of the revolution is retrograde. The extremes occur when the ascending node coincides with one or other of the equinoxes; and thus when the longitude of the node is 0° the range in the moon's declination is from 28° N. to 28° S., and when the longitude is 180° the range is from 18° N. to 18° S. The mean range in the declination occurs when the phase of the cycle is in quadrature with these points, or when the longitude of the node is 90° or 270°. The table in the Nautical Almanac which gives the longitude of the moon's ascending node, will thus show at a glance where any year stands in the progress of the 19-year cycle.)

There is probably nothing in connection with the various motions of the moon that gives so much trouble as this does, in tidal calculations. For it is evident that there are years in which the moon reaches the zenith over parallels of north and south latitude that are half as far again from the equator as the parallels it is able to reach at the other extreme of the cycle. The effect of such a change on the diurnal inequality in the tide is pronounced, especially if this inequality is already large. In the world as a whole, the tidal variation due to declination is the greatest that occurs from any one cause. It is not therefore surprising, that this large change in the amount of the moon's declinational motion is found to cause variation in a number of values or factors, used in the calculation of the tides, which would otherwise remain constant.

PRACTICAL USES OF TYPES OF TIDE.

Although we cannot explain at all adequately why it is that one type or another is found in any particular region, yet their development can be traced in some degree. It appears that a wide ocean like the Pacific is required to develop the declinational type, unless it is due to tidal interference. Also, an exhaustive analysis, by which the various lunar and solar elements in the tide can be distinguished, may show that one influence of the moon remains constant while another develops as the tide progresses. For example, in British Columbia while the tide progresses about two hundred miles, the effect of the moon's distance remains as small as in the open ocean, while the great increase in range which takes place locally is due almost entirely to development of diurnal inequality. In the Bay of Fundy, where this inequality is not conspicuous, there is no great increase in its actual amount from the mouth of the bay to the head, while the general range of the tide is more than doubled because of the increase of other elements. Such examples point to lines of investigation which might throw light on the matter, though they are far from explaining why these changes take place as they do.

The practical side is more encouraging, however; for it is evident as a general principle, that the method to follow in dealing with the tides of the world is to calculate primary Tide Tables from the position of the sun and moon for each of the three types of tide, and for some of their more usual combinations. The time and height of the tide in all the harbours of the world could then be found from these primary tide tables, by means of differences of time and proportionate heights; as the character of their variations would always be similar, because of the type being the same.

The first systematic and thorough investigation of the tides, astronomically and mathematically, was carried out by Laplace; and the French seem to have assumed that the influences of the sun and moon, being general, would be the same everywhere; and that accordingly any one harbour would answer as a "port of reference" for all tides. In their early tide tables, the whole world was therefore referred to Brest. But it was soon found that a constant difference of time from Brest, gave entirely erroneous results in many regions. On the other hand, the general procedure in tidal development has been to calculate primary tide tables (that is, direct from the sun and moon) for harbours that were sufficiently important to justify the labour of doing so, without any consideration of what type of tide was being dealt with.

In our Canadian work, we have been able to show that it is often possible to produce satisfactory tide tables by means of a constant difference of time from a port in a distant ocean, provided the type of the tide is the same. For example, the time of high water at Nelson (which will be the railway terminal on Hudson Bay) can be computed from a port in the North Sea. The tide in Miramichi bay is of the same type as in the Strait of Georgia on the Pacific, except that the tide curve is inverted; and accordingly low water in Miramichi bay shows a constant difference with high water in the Strait of Georgia, although these places are on the opposite sides of North America. As the tide in Hudson strait is of the anomalistic type just as in the Bay of Fundy, both high and low water there can be computed from the tide tables for St. John, New Brunswick, which is 1,200 miles to the south.

These correlations result from investigations carried out to save the expense of erecting permanently equipped tidal stations at remote localities; since by the methods referred to, adequate data can be obtained from a restricted series of observations in the summer season. But they corroborate the view that a proper classification of the tides should enable a limited number of typical ones to be found which would represent the tides of the whole world adequately. This question is discussed in a paper by the writer entitled "Variation in the leading Features of the Tide in different Regions," in the Journal, Royal Astronomical Society of Canada, Vol. I, page 213, 1907.

EXTREME TIDES AND STORMS.

The occurrence of extreme tides is a question of importance from several points of view. Exceptionally high water may cause serious damage to goods stored near the water-front in harbours; and also by the overflowing of dykes and flooding of reclaimed lands, or dyked marshes, along the sea coast. Exceptionally low water may be dangerous to navigation by giving less depth than is counted upon ordinarily. There is an extreme range which is of a normal character due to astronomical conditions, and also an exceptional raising or lowering of the tide during storms.

In general, the normal extremes are caused by combined conditions. In any type of tide, the other astronomical influences besides the dominant one [illegible] not altogether absent; and when these coincide, extremes will be produced. Where the Springs and Neaps are the dominant feature of the tide, the influence next in importance will be either the moon's distance or its declination; and accordingly extreme tides will occur either at perigee Springs or when the moon is at its maximum declination at the Springs. Similarly combined conditions will carry the other types of tide to their extreme ranges.

The highest tides, which cause damage by flooding, are usually due to the further coincidence of a storm with the maximum astronomical tide. Such extremes are therefore rare, because it is not often that a storm happens to coincide with the highest astronomical tide, and at other times a raised tide will not likely be high enough to give trouble. These storm tides are also difficult to predict; because the direction of the wind is reversed, according as the storm centre passes to the right or to the left of the locality in question. For example, as regards the Bay of Fundy, if the centre of a storm which is known to be coming up the Atlantic coast should swerve northward and pass over southern New Brunswick, there will be a heavy wind up the bay; but if it passes on the other side of the bay the wind will be outward, and will not raise the tide. The best that those interested can do, is to note the dates of the highest tides in the Tide Tables for their region, and to take precautions in case a storm should occur at such dates.

The greatest recorded disturbance of the tide in the Bay of Fundy, is known as the Saxby tide, which broke over the dyked lands and flooded the country on October 5, 1869, during a severe gale. This gale occurred on a day when the moon was new and also in perigee, so that its effect was added to a very high tide. The level of the water in Cumberland basin was raised 6·20 feet above the normal height at perigee Springs; and in Cobequid bay, in the other arm of the Bay of Fundy, it was raised nearly 5 feet. These values were obtained by instrumental levelling and comparison with the normal tides as observed in other months.

At Quebec, the following examples show the amount by which the tide may be raised by storms; from a comparison of the actual level with the calculated height in the Tide Tables: On March 26, 1909, 4·2 feet; on November 25, 1912, 4·6 feet; and on November 20, 1914, 5·4 feet.

The extreme low level at low water is more difficult to obtain; as it leaves no mark and cannot afterwards be determined by instrumental levelling. It can seldom be obtained, therefore, without a recording tide gauge. It is of importance to navigation, however, and with relation to the low-water datum.

THE TIDE IN ESTUARIES, STRAITS AND INLETS.

In dealing with the tides, there are two leading aspects of the matter in general, which may be distinguished as, firstly, the causes which produce the original tidal undulation in the oceans; and next, the character of the transmission or mode of travel in passages bordering the ocean. These two aspects must not be separated too arbitrarily, because even in the large oceans, there are not only the astronomical causes of the tide to consider, but also its transmission as an undulation which impinges upon the shores. Yet when the tide leaves the open and enters straits, inlets and estuaries, it undergoes further change which is much more closely related to the laws of hydraulics and wave motion, than to its astronomical aspects which we have been chiefly considering so far.

The most usual arm or inlet which opens off the ocean, is the estuary at the mouth of a river. The consideration of estuaries is also very important, because so many large harbours are situated in them. The tide has also a useful relation to these, because it enables ocean traffic to be carried further inland than it otherwise could be.

When the tide of the ocean reaches the mouth of an estuary, two noticeable effects are produced; the tidal undulation enters the estuary and makes its way in, causing high water and low water at successive points along it; and also the rise and fall of the ocean at the mouth of the estuary causes an inflow and outflow of the water, which we will consider later on, when dealing with tidal streams.

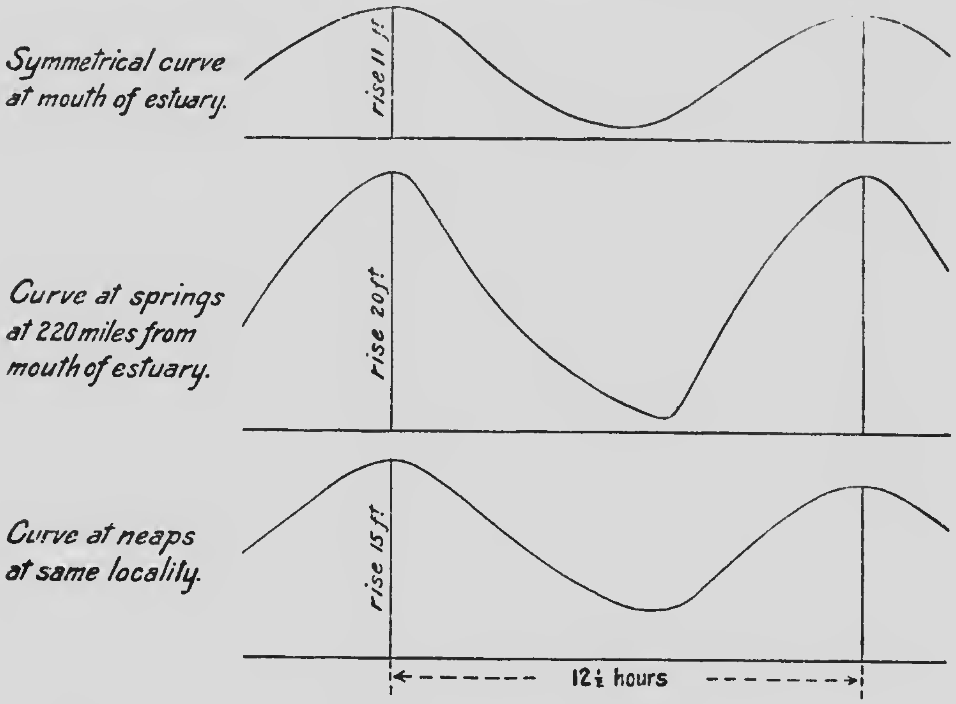
The Tidal Undulation.—Throughout the ocean, the tide is almost always a symmetrical undulation, having the same form as the long swell of the ocean; the summit of the undulation occasioning high water and the trough low water. But when it enters an estuary its form undergoes the same kind of modification as waves do in the shallowing water near the shore; and it is even possible in extreme cases, for the tidal undulation to break, like a wave on the beach.

The modifications of the undulation in passing up an estuary, are chiefly these: (1) It becomes steeper on the advancing side, and accordingly as it passes any given point, the rise of the tide is more rapid and the fall longer. The interval of time from low water to high water becomes less, and from high to low greater; although the two together still make up the total tide-interval of 12½ hours. (2) The range of the tide increases; and it generally attains its maximum range about the point where the wide mouth of the estuary narrows to the width of the river emptying into it. This may be considered the true head of the estuary and the beginning of the river. It is in this vicinity that harbours in estuaries are usually situated. (3) From this point, the tide decreases in range as it proceeds up the river proper. The river slope, up which the undulation has to travel, together with bottom and side friction, combine to reduce the amount of the undulation until it is eventually effaced.

These conditions characterize the usual estuary, where a river widens towards its mouth and is not extremely deep. We will see how very different the conditions are in the case of inlets of great depth. The same conditions obtain in long bays, and possibly in some straits, especially those which narrow rapidly towards one end.

The steepening of the tidal undulation on its advancing front, is chiefly due to the higher rate of progress of the crest of high water when the estuary is flooded and deepened, and the slower progress of the trough of low water. For at low water, it is not only shallower, but the channel is more restricted, and shoals or bars may appear. The greater speed of high water under these conditions, and the retardation of low water, is in accord with the hydraulic laws governing undulations; and low water is thus overtaken by the following high water. This would be the case to some extent even in a long narrow bay; and it must not therefore be attributed entirely to the flow of the river against the incoming tide, although it no doubt becomes accentuated in the tidal part of the river above the true head of the estuary. It is even possible for the tidal undulation to break and form a "Bore," as it does in the Petitcodiac river in one arm of the Bay of Fundy; where a foaming wall of water which may attain a height of over five feet, advances against the opposing current of the river. (See description with diagrams, in Report of Progress, Tidal Survey, December, 1898.)

There may also be a marked difference in the form of the tide curve from Springs to Neaps. This is very evident in the St. Lawrence estuary. At the Spring tides, the estuary conditions due to change of depth, are much accentuated, and at any point of observation the rise of the tide is rapid and the fall more gradual, and at low water the turn is sharp. But at the Neap tides, the tide curve is more nearly symmetrical, as the proportionate depths at high and low water are not so extreme; and the bottom friction, retarding low water, is much less than at Spring tides.



Rate of Progress of the Undulation.—It is important to ascertain what this is, to enable tidal differences to be given for the various points along the estuary with relation to a reference station in it. The progress of the tide in the middle part of the estuary of the St. Lawrence, from Father Point to Quebec is given as an example. The values are based on simultaneous observations, taken day and night to eliminate diurnal inequality; and all the differences are in absolute time. The larger time-intervals in the case of low water are noticeable.

St. Lawrence Estuary.	For H.W.	For L.W.
Father Point to Orignaux Point. Distance 103 miles. Average Spring range for the two places, 16 feet.................	1 h. 35 m	1 h. 48 m.
Orignaux Point to Quebec. Distance 77 miles. Spring range 18 feet..	2 h 45 m	3 h. 45 m.

Tidal Differences in Estuaries and Straits.—According to the theory of wave motion, the rate of progress of the tidal undulation in an estuary or strait, will vary with the amplitude and also with the depth of the water. The amplitude or range varies from Springs to Neaps, or in relation to other movements of the moon; and the depth remaining below the trough of the undulation, is less at Springs than at Neaps. There are two methods therefore, by which the variation in the difference in the time of the tide between two localities can be reduced to law: (1) With relation to the period of the moon's phases, or some other lunar period in which the greatest variation in amplitude occurs. (2) With relation to the absolute height of any tide as observed on a scale at one of the localities, or the height as given in tide tables for a reference station in the region. These methods are discussed, with examples, in a paper entitled "Progress of the Tide in deep Inlets and ordinary Estuaries," by the writer. (Trans. Royal Society of Canada, Third Series, Vol. v, 1911.)

From the practical standpoint, if the variation from the average difference of time is too large to be overlooked, the estuary or strait may be divided into two sections, and two reference stations established in it. If this is not practicable in the circumstances, there are three other plans that may be taken: (1) The difference of time at Spring and Neap tides may be distinguished; and separate tidal differences at each, may be given for high water and for low water. (2) The difference in time may be given with reference to the actual height of the tide at the reference station. It is for low water that this relation is most required; for it arrives later as the height at low tide becomes less, as it is then more retarded. (3) A series of variable differences between a locality and the reference station must be determined, and used to compute special tide tables for the locality.

The choice between these plans may be influenced by the effect of the freshet in the river, at one season of the year. If the leading variation in the difference of time between localities along the estuary is due to freshet conditions, it may be necessary to give two sets of values, one for the freshet season, and the other for ordinary months. Such values have been worked out for the tidal portion of the St. Lawrence river above Quebec, and for a series of localities along the Fraser river in British Columbia.

The division of an estuary into two sections was adopted for the St. Lawrence, after every effort was made to deal with the estuary as a whole by means of some system of variable differences. The outer section of 175 miles in the wider part of the estuary is referred to Father Point; and a section of 160 miles further up, extending to the head of tide water, is referred to Quebec. In each case, the reference station is about the middle of its section; and the tidal differences thus become constant in each half section, for all practical purposes; with the exception of the freshet season in the upper half-section above Quebec, which can be specially allowed for, as already explained.

As examples of the three plans referred to, the first is adopted for the Skeena river, and the second for New Westminster on the Fraser river; as will be seen in the Tide Tables for the Pacific coast. The third plan is adopted in Northumberland strait, where the tide tables for Pictou are calculated from Charlottetown by means of two series of variable differences in the period of the synodic month. The series for high water varies from 26 m. to 49 m. and for low water from 38 m. to 60 m. In this way, Pictou is made a secondary reference station for the greater part of Northumberland strait; and as it is centrally situated in the section which is referred to it, the tidal differences on Pictou are quite constant; since the main variations are already allowed for in the calculation of Pictou from Charlottetown.

All these plans can thus be exemplified from the methods used for Canadian tides. It should also be noted that when once these methods are devised, they make the application of the resulting tidal differences extremely simple for the mariner; for the object in view is to reduce variation and to obtain differences on the reference station that are practically constant. It is also evident that as a general rule, it is best for the reference station to be centrally situated in the estuary or bay, rather than at the mouth or head. As a further example of this, St. John, N.B., halfway up the Bay of Fundy, proves an excellent reference station for all localities both in the outer and inner parts of the bay.

Deep Estuaries and Inlets.—These afford a complete contrast to ordinary estuaries; for when the depth is great, there is no progress of the tidal undulation in the ordinary sense. Even on the Lower St. Lawrence towards the mouth of the estuary, this is exemplified. From Cape Chat to Father Point, where the depth is 124 to 189 fathoms in the offing, the time-interval on a distance of 90 miles is only 8 m. at high water and 10 m. at low water. Also in the Strait of Georgia, the tide is very nearly simultaneous from the tidal station at Sand Heads to Comox, a distance of 88 miles. From Sand Heads to Lund at the northern end of the strait, a distance of 108 miles, the time-interval is only 14 m. at high water and 16 m. at low water. The depth varies from 90 to 180 fathoms throughout, and in places exceeds 200 fathoms. The Saguenay has a depth of 90 to 140 fathoms from Tadoussac at the mouth to Bagotville in Ha-Ha bay at the head of the salt water inlet; and in that distance of 60 miles, the difference in the time of the tide is only 12 minutes. For a similar length on the St. Lawrence, where the width is about the same, it would be over two hours.

The long inlets on the coast of British Columbia which are similar to the Fjords of Norway, afford a still more noticeable example. These are often 50 or 60 miles long and very deep; although, unfortunately, their actual depth is not known. In making the coast charts, although the height of the mountains was measured, these inlets were not sounded to the bottom. Judging by the best indications, the depth is probably not less than 100 fathoms.

In these inlets the time of high and low water at the head is very little later than at the mouth. This has been ascertained by simultaneous records from registering tide gauges, operated day and night continuously for a period of several months; the time being kept accurately at the mouth and head by the use of chronometers. The results for three inlets are here given:—

Long Inlets. (Average range of tide, 13 feet.)	H.W.	L.W.
From Whaletown on Cortes island to the head of Bute inlet Distance, 52 miles. From comparison of observations in two different seasons with the same reference station..	3 m. later.	9 m. later.
From Namu to Bella kula, by Burke channel and Bentinck arm Distance, 69 miles. From 144 simultaneous observations .	2 m. later.	7 m. later.
From Hartley bay in Wright sound to Kitimat, by Douglas channel. Distance, 49 miles. From 222 simultaneous observations..	4 m. later.	4 m. later.

The range of the tide at the head of these inlets is only from 2 to 12 per cent greater than at their mouth. It thus appears that the whole surface of the inlet rises and falls simultaneously, in correspondence with the impulse at its mouth given by the rise and fall of the tide in the open. It is also observed that there is little current except in the mouth of the inlet, where the pulsation takes place.

This action of the tide may best be exemplified by supposing a long and deep trough in which the water is retained by a movable end. If the end, consisting of a sliding partition or dam, is pushed in and drawn back slowly, the whole surface of the water will rise and fall simultaneously; and there will be no appreciable current, relatively to the sides, except near the movable end itself. The action of the tide of the outside ocean at the mouth of these deep inlets must be very similar to this. The rising tide creates an impulse at the mouth which pushes the water in at the end only. The volume required to raise the level 15 feet in height over the area of an inlet 60 miles long, half a mile wide, and 100 fathoms deep, corresponds with an inthrust of only 2½ miles in length at the mouth. This inthrust and recession on so few miles of length every six hours, gives rise to a comparatively slight current which is found near the mouth only; as is verified by observation.

As regards the ratio of the amplitude to the depth, it may be said in the cases cited that the average range is from 1/40th to 1/60th of the total depth, as nearly as this can be estimated.

TIDAL STREAMS.

The horizontal movement of the water as a current or tidal stream, may be quite as important to the mariner as the vertical movement of rise and fall. In foggy weather especially, he may be more concerned as to the direction in which his vessel is set by the current, than as to the exact level of the water surface in relation to the stage of the tide.

When the investigations of the Tidal Survey were first commenced, the currents were the question of primary importance, as many wrecks were attributed to unknown currents. The tidal stations established, were therefore quite as much required to determine the time of high and low water with which to correlate the turn of the tidal streams, as to determine the amount of rise and fall. For it is only by means of these time relations, that the direction of the flow at any given hour, can be known in advance, with reference to a tide table.

We thus find two distinct sub-divisions of the whole tidal problem from the practical standpoint: (1) The height of the tide in relation to time, which is completely shown at any locality by a tide curve. (2) The movement or flow, as to its velocity and the reversal of its direction, in relation to time. It is also interesting to note that it is possible to treat these two aspects of the tide quite independently; which shows the clear distinction that can be made between the vertical and horizontal tidal movements.

Tidal Streams on Open coasts.—We have little or no definite knowledge regarding forward and backward flow in mid-ocean, in relation to the passage of the general oceanic undulation of the tide. We can feel sure however, that such a movement must take place; and equally sure that it must be very slight, when the rise and fall of the tide itself cannot be very great in mid-ocean. We do not here refer to the well-known ocean currents, which move constantly in some one direction, and may have considerable strength; as we are here dealing with tidal effects only.

On approaching the coast, the tidal streams begin to manifest themselves. At an offing of 20 or 30 miles, which is as far out as they have been investigated by the Tidal Survey, in the offing of Newfoundland and off the outer coast of Nova Scotia, these streams have a constantly veering direction. They set towards every point of the compass successively, and thus veer completely around in the tidal period. This is well illustrated in the Plates appended to "Currents off the coasts of Newfoundland," published by the Tidal Survey.

Nearer the shore on open coasts, say at an offing of five to eight miles, the tidal streams are obliged to reduce their veering, and to set more nearly up and down the shore, parallel with its direction. Also, any constant currents which follow the direction of the shore, such as the Labrador current off the east coast of Newfoundland, or the Gaspé current in the Gulf of St. Lawrence, always show a distinct fluctuation in velocity in correspondence with the tide.

The behaviour of such streams and currents will be found described and illustrated for the coasts of Canada, in existing publications. This brief reference may therefore suffice, as it may be said in general that the strength of the tidal streams off coasts which are open to the ocean, away from the vicinity of bays and straits, seldom exceeds one knot per hour, and is usually less than this.

It is in estuaries, straits and passages, opening off the ocean, that tidal streams become accentuated; and the strength of the currents that result, depends chiefly upon the greater or less rise of the tide that produces them. In most estuaries and straits, the tidal streams are sufficiently moderate to permit of navigation at all stages of the tide; but under other conditions, the rise and fall of the tide may create rapids or even torrents, which render navigation impossible except when there is slack water, about the time when the direction turns. To follow the subject clearly, we must first classify the various kinds of arms of the sea and other passages, that are found to exist.

Tidal Streams in Estuaries, Straits and Inlets.—We offer the following classification of these as comprehensive, in their relation to the tide:—

Class A.—Arms of the sea connected with the ocean at one end. In this case, the tide entering the arm can only be of one type, and all the movements are related to the time of rise and fall at the mouth of the arm. From a tidal standpoint, there are three possible kinds of such arms.

(1) The ordinary estuary, more or less funnel-shaped as a rule, and of moderate depth. This type is so common, and it forms the entrance or passage way to so many important harbours, that its tidal streams will require a more extended consideration later on.

(2) The deep inlet. This is the type that we have already described, in which the rise is practically simultaneous over its whole area, and there is little current except in the mouth. It is interesting to note that in nature there is seldom any gradation between these two types. They are sharply distinguished as either shallow or deep, with few to be found that are intermediate between the two. This appears to depend upon their mode of formation, in geological time.

(3) Large basins or expanded inlets, connected with the ocean by narrow entrances; their area being so large that there is not time for them to fill up during the tidal period. This type of inlet is more common than might be supposed, and we may give two examples of it.

The Bras d'Or lakes, in the middle of Cape Breton island, are connected with the ocean by two passages which communicate with the first expanse; and this again communicates through Grand Narrows with a second and larger expanse. The rise of the tide in the open is 4 to 6 feet, but the lakes have not time to fill up in the tidal period, and their variation in level is only about six inches. As their level is so nearly constant, the time at which the current turns in the passages connecting them with the ocean. is not far from the moment of half tide, rising or falling; because the level of the lakes naturally corresponds with the level of half tide in the open. This has been ascertained by gaugings in the lake, and instrumental levels across the narrow neck, where the St. Peters canal enters the inner expanse. The tidal streams in the passages are moderate, however, as the range of the tide is not great

Seymour inlet on the Pacific coast, runs into the mainland opposite the northern end of Vancouver island. There is one narrow entrance into the inlet at the end of Slingsby channel; and it is 35 miles long, together with five other inlets and sounds, which open off it. The total area of these is so large that the rise of the tide within them is inconsiderable, while in the open the rise is from 12 to 15 feet. Such a difference of level causes the tide to pour through the one narrow entrance in a torrent, as it rises and falls. The district around this group of inlets is an important lumbering region; and the need for some method of determining the time of slack water is very evident; as any attempt to tow lumber out at any other stage of the tide necessarily results in wreckage.

Class B.—Straits or passages connected at both ends with the sea. From our present viewpoint, these may be divided into two categories: (1) Passages where the tide is of the same type at the two ends. (2) Passages where the tide at the two ends is of different types.

In the first instance, it is possible that there may be no current through the passage. For we may suppose an island with a strait behind it, on a coast which the tide meets squarely; making the time of high water simultaneous at the two ends of the strait, and causing no through current in the strait. But in general, this is not the case; and tidal streams through a passage occur because of a difference in the time of the tide at the two ends, or difference in the range. The strength of the streams will depend upon the amount of these differences.

The passes between a chain of islands on the west side of the Strait of Georgia might be cited as examples of tidal streams caused in this way; but the most noteworthy example that can be given is Seymour Narrows, between Vancouver island and the mainland, near its northern end. A very large traffic passes through these narrows; not only the Canadian coasting steamers, but also the United States trade to Alaska. The swiftness of the current makes navigation impracticable when the tidal streams reach their strength; although a few powerful steamers attempt it, when conditions are favourable. This rapid current in Seymour Narrows must be due to the difference in the time of the tide to the north and to the south. The difference is five hours, or practically the tidal interval; and consequently, high water at the northern end of the straits leading to these narrows is simultaneous with low water to the south in the Strait of Georgia, and vice versa. There is thus a difference of level in the two directions equal to the whole range of the tide, which in these regions is 13½ feet on the average. This may well account for the swiftness of the current.

The Gut of Canso, between Cape Breton island and Nova Scotia, affords an example of a passage of the second category. It connects two regions in which the tide is of two distinct types, although the range is nearly the same; being 4 and 4½ feet at its two ends respectively. At the northern end diurnal inequality is highly developed, and one tide in the day may be reduced to a level stand for 10 or 12 hours. At the southern end, the tide is of the synodic type usual in the Atlantic, and the inequality is scarcely apparent. Also, as the time of high water is not simultaneous at the two ends of the Gut, the tidal streams are the more complex. After careful investigation, however, it was found that their behaviour could be explained with relation to the declination of the moon.

The classification here given would appear to include all the varieties of arms or passages connected with the sea that are possible, in relation to tidal behaviour; and it is interesting to note that they can all be illustrated by Canadian examples. There are no doubt modifications, with relation to tides of different ranges and types, which might be detailed further; but the present outline will serve to indicate all the leading conditions that there are.

Tidal Streams in Estuaries.—These deserve full consideration, because so many estuaries form the avenue of approach to important harbours; and the characteristics of the tide in them bring out principles which apply to the behaviour of the tide in general.

Where the estuary of a river opens into the ocean, the rise and fall of the tide causes tidal streams to develop, which run in during the flood, and run out for a longer time during the ebb; especially so, if the river running into the estuary is of large volume. These tidal streams become more and more unequal in the two directions, up to a point where they can no longer reverse the river current. Above this point, although the flow is always one way, it is stronger during the period of the ebb. The tidal undulation, which is manifested by a rise and fall in level, may still be appreciable as far up the river as this inequality in flow is noticeable.

These conditions characterize the usual estuary, where a river widens near its mouth and is not extremely deep. The conditions are very different in the case of inlets of great depth, as we have seen. But in estuaries, they are due to some extent to the quantities of sand and gravel, brought out by the river in the course of centuries, and forming banks or bars with channels between them.

If we first examine the laws which govern the flow of water, we will be better able to follow the behaviour of the tidal streams in an estuary or strait. It is by no means a simple matter; because works on hydraulics give attention chiefly to continuous flow in one direction, through channels or pipes; and we have here to deal with flow which not only changes its direction, but which runs in a channel of constantly varying depth and width. Yet in most localities, it has proved possible to bring the practical results to a simple form, for the purposes of navigation. We will here endeavour to give the laws of friction and momentum as they apply to flowing water, in as brief outline as possible to enable tidal streams to be understood.

Friction.—It is well known that the friction of water on itself is lower than the friction between water and any solid substance. This is evident from the flow of water in pipes; for the co-efficient of friction is the same whatever the material of the pipe may be; whether iron, earthenware, wood, or a tarred surface; so long as there is no mechanical roughness. This is explained by supposing that a film of water adheres to the surface of the pipe, and that the water really flows against this water film. There is thus less friction on a wet surface than on a dry one. The conclusion is that water prefers to slip on itself, one layer on another, rather than to move bodily over a solid surface.

When water is flowing uniformly in a channel, the greatest speed is therefore found on the surface and at the middle. It decreases gradually towards the bottom, and also from the middle towards the sides. This is true in the squarely-cut channel of a canal or aquaduct, and is much accentuated in an ordinary river which becomes shallower towards the sides.

Momentum.—If the water of an estuary is running out towards the ocean during the fall of the tide, when the tide begins to rise again it will not immediately stop. Its momentum carries it forward against the rising water. Perhaps we are more accustomed to think of momentum in connection with solid matter. Let us suppose then that instead of moving water we have square blocks of ice with just enough water to float them; moving forward like a train of barges down the estuary. As the outside water begins to rise, these blocks will not stop at once; they will go forward against it and may even slide up the rising surface for some distance before they come to rest, and begin to move inward again with the rising tide. Now, these solid blocks are no heavier than the same bulk of water; indeed not quite so heavy. A block of water a yard square and four feet deep weighs a full ton; so that we can readily realize the enormous momentum of the ebb stream in an estuary, even when moving comparatively slowly; and the great force from the rising of the tide that is required to stop its movement and push it back landwards. It is this momentum of the water that explains the continued flow of a tidal stream for some considerable time after the turn of the tide at high or low water.

When the ebb stream is flowing out of an estuary, which usually widens towards the sea, let us consider what will happen when the tide begins to rise, in view of these laws of motion. The rising water of the ocean may act in one of two ways to commence with: (1) It may begin to flow up the middle of the estuary as a tongue of water, while the ebb stream still continues to run at the sides. It does this because the water in the middle is deepest, and the first inward flow has thus the advantage of keeping as far as possible from bottom and side friction. It cannot oppose the ebb stream squarely, and stop it, unless the channel is quite restricted in width and the rise of the tide rapid. But in most estuaries, it is best able to make its way, in the first place, up the middle. This central tongue of inflowing water gradually widens, till it occupies the whole width from shore to shore.

Navigators are well aware of these estuary conditions, and coasting vessels take advantage of them by keeping to the middle of the estuary, or making out along the sides, according as they are inward or outward bound, as the tide may favour them.

(2) In some estuaries, especially where the river discharge is large, the river water may be warmer, as well as fresher even in the estuary, than the incoming sea water. The rising tide has then a more difficult task, as it can only make its way in along the bottom, because it is heavier owing both to its coldness and its greater saltness. The sea water is thus obliged to make in with bottom friction below it and the friction of the outflowing fresh water above it. It is thus greatly retarded; and the surface water continues to flow outward for a long time after the tide begins to rise. For, this upper flow has the double advantage of its momentum and of the very low frictional resistence over a water surface below it. At length, however, the rising tide will gain the mastery and reverse the flow to the inward direction.

This action of sea water in under-running the river outflow during the rise of the tide, can be made quite evident by investigation with adequate appliances. It appea indeed to be usual in some stretches of any ordinary estuary, provided that the of tide is considerable. In the wider part of the estuary, it is more likely that the firs of the flood will make in at the middle of the width; but further up, where the estuary narrows to a width not much greater than the width of the river itself, this under-running will probably be found. It also occurs commonly in channel-ways which extend seaward through the shallow waters beyond a river mouth; as for example off the Fraser river in British Columbia, where these channels extend between sand banks for more than five miles before reaching deep water. The main channel there, has a depth of 18 feet below low water, and the rise of the higher tides is 12 feet.

The resistance which sea water has to overcome in flowing inward under fresh water, need not be exaggerated. Before low water, the outflow is swift and it extends to the bottom; as there is not only the river volume to be discharged but much additional water which has accumulated while the tide was high. But after low water, as the surface level rises and the depth increases, there comes a time when a thickness of a few feet at the surface affords sufficient area for the whole discharge of the river. Below this, therefore, there is little to prevent the inflow of the colder and heavier sea water except bottom friction, which it must overcome if it is to flow in at all; for the friction between the two layers of water which move in opposite directions is extremely slight, as we have already pointed out.

These conditions of flow may not be so disadvantageous to an incoming vessel as they might appear, and a vessel of any considerable draught may have the body of the flow in its favour in spite of surface appearances. The reverse directions of the upper and under water may thus be made curiously evident. For example, at the mouth of the Fraser river, a deep-draught vessel which was being towed in, at a certain stage of the tide, was carried forward by the under-current faster than the tug with half the draught could make against the swift-running surface water. The tug had thus difficulty to avoid being over-run by the vessel it was towing.

The turn of Tidal Streams in relation to the Time of the Tide.—This relation is evidently of importance to navigation. In new regions or in the early days before there were tide tables, the turn of the tidal streams could be ascertained with reference to the time of high or low water on the shore. This information is usually obtained during chart surveys; and although it may be only a local relation at the time, it becomes more valuable when it serves later to bring the turn of the current into relation with tide tables when they are published.

Because of the momentum of water and other conditions as already described, it would evidently be incorrect to suppose that the turn will occur at the moment of high or low water. It is even too much to assume that there is always a constant difference in time between high or low water and slack water when the stream turns. There are considerable regions, however, in which this difference proves to be constant; and the time of slack water, or the reversal of the direction, can then be found from high or low water as given in the tide tables for the reference station, by adding or subtracting a constant difference of time. The entrance to the Bay of Fundy may be given as a noteworthy example of this. In the region extending outward from the middle of the bay to Cape Sable, 150 miles in extent, the turn of the strong tidal streams has a constant time-relation to high and low water at St. John, N.B.

In estuaries, the character of slack water when the tide is high and when it is low, may be quite dissimilar, and thus require consideration. At the slack which occurs about the time of high water, when the estuary is flooded, the standing water usually extends over a large area simultaneously; but near low water, when the flood stream begins in the middle and the ebb may still be running along the shores, there is no still water anywhere when the current is turning. The moment which is taken as low-water slack must either be the time when the extent of the opposite currents is judged to be equal across the width of the estuary or passage; or, if there is a restricted ship channel, it should be the time when the turn occurs in the channel-way.

These conditions are found in the St. Lawrence estuary; and the time of slack water which is computed for the Traverse is the time of turn in the channel, based on observations on lightships that were anchored on the edge of the channel-way. It is also evident that shore observations may not give a true result for low-water slack, unless the estuary or passage is narrow enough to see entirely across it; to know what is taking place in the middle as well as at the sides. (See Plate V.)

Methods for obtaining Constant Differences.—A constant difference of time between high or low water and slack water is usual in ordinary estuaries and deep bays which resemble them; as they are in the class of arms of the sea connected with the ocean at one end; so that the tide in them is necessarily of one type, and due to one system of rise and fall. But in the case of large expanses connected with the ocean by narrow entrances, and for the whole class of straits and passages connected with the ocean at both ends, it is quite usual for the time-differences between high or low water and the corresponding slack waters, to be variable. Also, with respect to the type of the tide, the variation is most likely to be strongly accentuated when the tide is of the declination type, with a large diurnal inequality.

When the difference in time between slack water and high or low water in the locality is thus found to be variable or irregular, there are three possible ways in which an endeavour can be made to obtain a constant relation with the tide, and which have proved successful in Canadian waters: (1) In a strait behind an island, where slack water is out of accord with the local tide, (which may really be the result of the two tides entering at the opposite ends of the strait) the time of slack water may correspond with the tide of the open ocean, on the outside of the island. The first step taken to reduce the complexities in Seymour Narrows, was in accord with this. (2) Instead of correlating the time of slack water with the tide, it may be possible to obtain a constant difference of time between the moment of maximum strength on the flood and ebb, and high and low water. This may succeed where the variation is due to diurnal inequality in the tide; and it is almost equally serviceable to the mariner to know the time of maximum strength in each direction, as to know the times of slack water; provided the strait or passage is navigable at all stages of the tide. This method is the basis of satisfactory data for Northumberland strait. It is necessary, however, to have continuous observations with a current meter, from which the moment of maximum can be correctly determined, in order to apply it. The current velocity, laid out as a curve, is shown in Plate V. (3) When the time of slack water is out of accord with the tide, the mid-time between one slack water and the next, may give a constant difference of time with high and low water. This method has the advantage of making observations with a current meter unnecessary, to determine the time of maximum velocity. The result, from the mariner's view-point, is practically the same as in the previous case; as it serves to show whether flood or ebb is running at any given time, and when they will be strongest. This method is used for the entrance to the Bras d'Or lakes and Grand Narrows. The converse relation, between the time of half tide rising or falling, and the time of slack water, did not prove successful in reducing variation.

In applying the above methods, it may be found that a constant difference of time results for one of the two slack waters, but not for the other. For example, the difference of time between high water and the slack nearest to it may be constant, whereas the corresponding difference at low water may be variable. In that case, it is best to take another reference station in the opposite direction, and to try a correlation of the low-water slack with it. This procedure has often proved successful, in affording time-differences for both high-water and low-water slack which are constant with relation to two different reference stations; as for example, in the case of the tidal streams of Miramichi bay. It has also given constant relations for the maximum strength, or the mid-time on the flood and ebb, when combined with the methods above explained.

It is specially to be noted that all the results obtained by these methods, are extremely simple in their application. It may require much investigation and research to arrive at the best method to adopt, especially in beginning without any clue for guidance. But when a solution has been achieved, it is only necessary for the mariner to apply a time-difference, by addition or subtraction, to the tide table that is indicated, to obtain the result he requires. Many examples of this, including those already referred to, will be found in the Tide Tables for the Eastern coasts of Canada, and for the Pacific coast.

Variable Differences.—It may be that no method can be discovered, such as those indicated, which will afford differences of time between tide and current that are reasonably constant in relation to any reference stations. The resource afforded by these methods is also much restricted when dealing with passages or narrows in which the tidal streams are so rapid or violent that navigation is only possible near slack water; because for them, it is the time of slack water alone that is of any service. It may thus become necessary to adopt variable differences. The variations are always in accord with one of the moon's periods; but they may form two distinct series with relation to high water and low water respectively, which are dissimilar in character.

These differences when determined, are used to calculate special tables of slack water, in which the times are given for each day, as in a tide table. For calculation purposes, a series of variable differences may give quite as accurate results as a constant difference does in other cases; as any variation will always recur in some astronomical period, and the variable series represents its reduction to law.

It would involve highly technical explanations to follow out this subject of variable differences, either in their determination or their application. The resulting Slack Water tables will be found in the tide tables published for Canadian waters. There is one principle, however, that has greatly reduced the calculation of such tables, by limiting the number required; which deserves to be mentioned.

It has been ascertained by comparative observations, that the variations between slack water and the time of the tide, are concordant in passes which are similarly situated in any region. The difference in the time of slack water between two corresponding passes may thus prove to be closely constant, as the variations with the time of the tide are the same for both, and therefore disappear in the comparison of the passes with each other. Because of this, Slack Water tables can be calculated for one of the leading passes in a region, and the time of slack water in several other passes can be found by applying a difference of time to these tables. This is quite similar to the usual plan of finding the time of high water at a locality, by means of a tidal difference applied to a tide table.

In the network of channels between the northern end of Vancouver island and the mainland, there are a number of passes and narrows which well illustrate this method. The primary or reference pass for which Slack Water tables are calculated, is Seymour Narrows; and by differences of time applied to these tables, the time of slack water can be found correctly in eight other passes; namely, Chatham channel, Whirlpool rapids, Green Point rapids, Mayne passage, Hole-in-the-Wall, Okisollo, Surge Narrows and the Yuculta.

In all of these, the time of slack water is of the first importance to the lumber industry; as they are extensively used in towing booms of logs, and by local steamers which supply the lumber camps. Similar examples might be given from the passes between the Gulf Islands on the routes from Vancouver to Victoria and Nanaimo; which are not only used for general navigation but for water transport by towing, in the coal trade.

THE EFFECT OF THE WIND ON TIDAL STREAMS.

In discussing the question of the influence of the wind on tides and currents, it is first necessary to make a clear distinction between the effect of the wind on the rise and fall of the tide, and its effect in increasing or retarding the horizontal motion of the water and disturbing the normal movement which would otherwise prevail

The influence of the wind and barometer in modifying the height of the tide has been carefully studied, especially in Holland where it is of the first importance, as well as in England. With regard to the influence of the wind on the horizontal movement of the water, there appears to be little information available. The general oceanic circulation is very often ascribed to wind influence; but whether this is the dominating cause relatively to other influences, is probably still open to discussion. It is also difficult to obtain satisfactory information from vessels, as during storms they cannot usually distinguish between their leeway and the drift which is due to the movement of the water itself.

Our fullest knowledge thus relates to the disturbance in the height of the tide. It is erroneous to suppose that an abnormally high tide is followed by an unusually low tide. The investigations on the coast of Holland indicate that the effect of gales on the tide is to raise both the low and high water level. This is abundantly corroborated by our Canadian tide curves from recording gauges. Not only so, but the time of high and low water often remain unaffected, although the whole tide curve may be two or three feet above or below its normal position. But in very severe storms, both the time and the height may become irregular and indefinite.

There is thus little if any support for the assumption that if the tide is raised or lowered by the wind, there will be a corresponding increase in the strength of the tidal streams. For the range of the tide remains practically unaffected, as in reality it is the mean level of the sea which is temporarily disturbed. The rise and fall of the tide appears to be caused by a deep pulsation which extends throughout the whole depth of the water in straits and channels, however great that depth may be. There is strong corroborative evidence for this view from several sources. It is also fairly certain that difference of barometric pressure causes a flow which extends throughout the whole depth of the water. In contrast with this, wind disturbance necessarily begins on the surface as a wind drift, and only when long continued will its influence extend to any great depth.

Amount of the Disturbance.—When the investigations of the Tidal Survey were first begun, the general impression derived from books was that the current would always be found to set in the same direction as the wind. But the longer the investigations were carried on, and the greater the care to assign each movement of the water to its true cause, the less residuum there remained to ascribe to the wind, as otherwise unaccounted for.

There appear to be several reasons which may largely account for this impression that the current goes with the wind: (1) A faulty method of observation, by which the drift of small floating objects was taken to represent the set of the current. It is well known that the wind will set a film or skin of smooth water in motion in a few minutes; but to accept this as the direction of the current is misleading in navigation, because the surface current should mean its movement at a depth of at least half the draught of an ordinary vessel; as the speed at this depth represents its average effect on a vessel. (2) The difficulty of distinguishing leeway from current drift, especially in the old sailing-ship days. Possibly even yet there are few masters of vessels who have ascertained accurately the exact leeway made by their vessels for each given force of the wind. (3) Where the tidal streams present great complexity, owing to tidal conditions which can now be explained, it was assumed without due consideration that their behaviour was due to the influence of the wind. (4) It is noteworthy that in obtaining information from fishermen, only the least observant men speak in a vague way of the current running with the wind. The more intelligent men attribute less to the direct action of the wind, and distinguish the various effects more carefully.

The Under-current.—The investigation of the under-current is of primary importance in relation to wind disturbance; as the wind necessarily influences the surface of the water first, whereas the under-current will continue to run in accordance with the tidal streams or the general set, or whatever may be the normal conditions of the locality. It will also come up to the surface as soon as the disturbing influences, which have been acting on the surface of the water, cease to operate. It does not appear that wind disturbance can extend to a greater depth than 8 or 10 fathoms at the most, under the influence of any gales that occur in the summer season. A comparison of the surface current with the under-current thus holds the first place as a method of detecting wind disturbance. Otherwise, a comparison must be made with the normal conditions, or tidal periods, deduced from observations in fine weather.

Where the current is as strong down to a depth of 30 fathoms as it is on the surface, and when it turns in direction on the surface and below at practically the same time, this has an important bearing upon wind disturbance, as it shows that the current will soon regain its normal direction and strength after a storm moderates.

Wind Effects in Belle Isle strait.—This strait affords an exceptionally good opportunity to investigate wind effects, because of its situation and the usual regularity of the strong tidal flow in the two directions. In the line of the strait to the westward there is a clear stretch of 470 miles of water across the Gulf of St. Lawrence to the New Brunswick shore; and to the eastward it opens into the Atlantic with no other shelter than what the small island of Belle Isle affords. During the two seasons in which the currents in this strait were investigated, a careful watch was kept while at anchor in it, to detect any influence of the wind upon the movement of the water. Continuous meteorological observations, taken on board, afforded complete weather data for comparison; and the relation of the surface current to the under-current was investigated. It may be stated in general that the effect of the local winds in producing a drift in their own direction is remarkably slight, considering the situation of this strait. On the other hand, the effect of the wind in raising a sea quickly in this strait, is very noteworthy.

The current in Belle Isle strait is primarily tidal in its character. While under the control of the tide alone, it will turn regularly and run with equal strength in each direction; the flood setting westward and the ebb eastward. But in addition to this tidal fluctuation, the water has almost always a tendency to make through the strait in one direction more than in the other. While the tidal fluctuation goes on uninterruptedly, the water is thus gradually making a gain to the westward, or to the eastward, as the case may be.

The best indication of the effect of the wind upon the movement of the water is afforded by a difference between the surface current and the under-current, in direction or in the time at which they turn; as it can be stated definitely that the water at a depth of 20 or 25 fathoms, at which the under-current was here observed, is unaffected by any storm, at least in the summer season. A departure from the general relations between the surface and under-current as established by these observations, will thus reveal any disturbance occasioned by wind.

It was frequently observed, especially in unsettled weather, that if there is a change, it will occur at slack water. For example, when the barometer is low, and a change is to be expected, east wind will come up with the flood. Also, a westerly wind will seem to be held back by the flood and will be light and variable till slack water, when it will come out strongly with the ebb. These changes with the tide, in unsettled weather, are exactly similar to those which are so familiar on the Lower St. Lawrence. It would thus appear to be quite as necessary to point out that the turn of the tide may influence the wind, as that the wind may cause the tidal stream to run longer in its own direction.

The large mileage of wind required to produce a true wind drift is further shown by the behaviour of the tidal streams with relation to the wind. While anchored in mid-strait, it was often found during a strong steady wind, either east or west, that the current in its ordinary change from flood to ebb would set directly into the wind for the usual tidal period. A strong wind has thus little appreciable effect, during a tidal period of five to seven hours, in checking the current on the surface. It appears to require a large mileage of wind to produce any noticeable effect by its direct action on the water.

The actual influence of the wind upon the movement of the water, may be summarized as follows, from the observations obtained in this strait:—

(1) It is anything but true that the current always sets with the wind which is blowing locally in the strait; since the ordinary tidal streams as they turn, will set directly against the wind, even when it is fairly heavy. On the other hand, in unsettled weather, the wind often comes up with the turn of the tide; and it thus appears to be held back until slack water by the tidal stream setting against it.

(2) There was no evidence, after any of the gales, that the wind was able to reverse the direction of the tidal streams, or that it was able to check to any noticeable extent, the dominant flow which prevailed at the time.

(3) From direct comparisons of the velocities of the surface and under-current, it appears that when a period of several days is considered as a whole, the current which sets against the wind prevailing at the time, is somewhat retarded on the surface. This is inferred from the velocity it otherwise would have had, as indicated by the under-current.

(4) The only other effects of the wind upon the movement of the water which can be detected, are these:—There may be a slight change in the time of veering at the turn of the current when it is weak; and the period of flood or ebb which is in the direction of the wind may become slightly longer on the surface than in the under-current.

Some of these results are based upon observations taken as soon as the weather moderated after a gale. If the effects are greater while the gale lasts, the current must recover its usual behaviour almost at once, when the wind falls.

Modification of the Current before the Wind begins.—So much evidence for this has been obtained, and in such different regions, that the matter deserves special mention. The current is found to run more strongly before a heavy wind comes on, and this change is so noticeable, that fishermen when anchored in their boats, take it as an indication of the approach of heavy weather. This is found to occur on the coasts of Newfoundland, and also in the Gulf of St. Lawrence on the north shore and in the bays and straits on its south-west side. There is also some evidence of its occurrence in the Bay of Fundy.

According to this wide-spread testimony, a change in the behaviour of the current is noticeable for about twelve hours before a storm comes on. In most localities, the current sets more strongly towards the direction from which the wind is about to come; although there are other localities where the reverse of this behaviour may occur. Where the currents are weak and variable, the set may become continuous for 12 or 18 hours before the wind begins. Where the currents are tidal with definite ebb and flood directions, the flow towards the coming wind will be much stronger than usual, and also longer than the ordinary tidal period; and in the opposite direction it will be checked or retarded. These effects are much more marked before north-east or south-east gales than before heavy winds from a westerly direction, as this is the usual direction of the prevailing winds.

These statements of the fishermen are confirmed by observations obtained by the Tidal Survey, and their main feature is the fact of the current setting "into the weather" as they express it; and for this it is difficult to give a satisfactory explanation without more extended investigation. But the set of the current towards the point from which a wind is about to come, is in accord with the universal testimony of the fishermen throughout these regions. Of all signs of bad weather, it is the one which they appear to find the most trustworthy.

These effects seem to be due to the action of the wind in first holding back the water and then releasing it; and the influence of the low pressure area of the storm as it passes along, also increases the result.

In a paper by the writer entitled "Effect of the Wind on Currents and Tidal Streams," the subject is discussed with examples from observations during many seasons. These show the effect of the wind on currents, which are grouped in three classes; namely, tidal streams which are weak and veering, constant currents, and strong tidal streams. The influence of the wind was investigated with relation to the under-current, as well as immediately after storms. (See Trans. Royal Society of Canada, Third series, Vol. III., 1910.)

A noticeable effect of the direct action of the wind upon the water, in changing the surface temperature, is also explained in this publication. This may occur after a long period of quiet weather when the water has become warm for a few fathoms at the surface, resulting in a rapid fall of temperature with the depth. A heavy wind, especially when off shore, may then drive the surface water out to the offing, and allow the cold under-water to come up to the surface. A fair estimate can even be made, by careful comparison, of the depth to which the wind disturbance extends.

ICE IN RELATION TO THE CURRENT.

To infer the behaviour of a current from the drift of ice with any certainty, the indications given by flat ice and by icebergs must be carefully distinguished. The flat or pan ice runs with the surface current, and is much influenced by the wind; whereas the icebergs indicate the average movement of the body of the water as a whole, and the wind has no appreciable effect upon them. This distinction is well known to sealers, and they habitually take advantage of it. When working against a gale of wind, they will moor their vessel to an iceberg, and lie in its lee while the small ice goes past with the drive of the wind; because, as they express it, the wind takes no hold on an iceberg at all. They thus save a long drift to leeward.

The berg ice, from its great depth in the water, will evidently move with the under-current; and it will not be appreciably affected by the wind. These bergs do not necessarily indicate the direction of the current as affecting shipping, except when the surface current has also the same direction. They show in reality the average direction the current has, between the surface and the depth of their draught. They are thus of much value as an indication of the general movement or circulation of the water.

The relation of the flat ice to the wind and current requires some little consideration. It is, of course, just as true of this ice as of the berg ice, that the greater part is under water; but, as it is almost always in broken pieces, more or less piled and with upturned edges, the wind has a much greater hold upon it in proportion to its total weight, than on the berg ice. Even when this is allowed for, its depth in the water still gives the current a greater hold upon it than the wind has. For example, if such ice is drifting with a current in a given direction, and the wind is blowing across that direction at right angles, the ice will seldom be set more than two points, or three at the most, off the true direction of the current. When the ice becomes soggy or water-soaked and loses its edges, as it does later in the spring, it will set still more correctly with the current.

When the surface current itself is moving in the direction of long-continued or prevailing winds, the flat ice naturally follows the same direction too. Also, in regions where the current is tidal, and the ice in calm weather would drift as far in the one direction with the flood stream as in the other direction with the ebb, the direction in which it makes on the whole will depend upon the wind. It is probably for these reasons that it is so often said that the ice drifts with the wind; although this merely expresses the result, without distinguishing between the relative influence of the wind and the current upon it.

There is also a direct effect which the ice has upon the strength of the current in regions where the direction of the surface drift is under the influence of the wind. The broken and upturned edges of the ice give the wind a much greater hold upon the water than it otherwise would have. Hence during long-continued winds, the speed of the current is appreciably greater than if the ice were not present. This is undoubtedly the explanation of the common belief which is expressed by saying that "the ice makes its own current." It may be well to recall that the weight of the ice itself is the same as the water which it displaces; and therefore, the wind has no greater mass to set in motion in producing a surface current than if the ice were to melt and refill the hollow which it makes in the water; while the presence of the ice gives the wind a better hold than it would have upon the surface of open water. free from ice.

There is one condition of the ice which may prevent it from showing correctly the drift of the water. When it is set against an island or headland and packed together for a long distance out, with open water beyond, it may circle around as on a pivot. The outer edge of the pack may thus make a long sweep very different in its path from the true set of the current; and its movements also become irregular.

EXPLANATION

of the Signs and Letters in the Plates.

MOON'S PHASES.—Denoted by the usual signs for New and Full moon, and the moon's quarters.

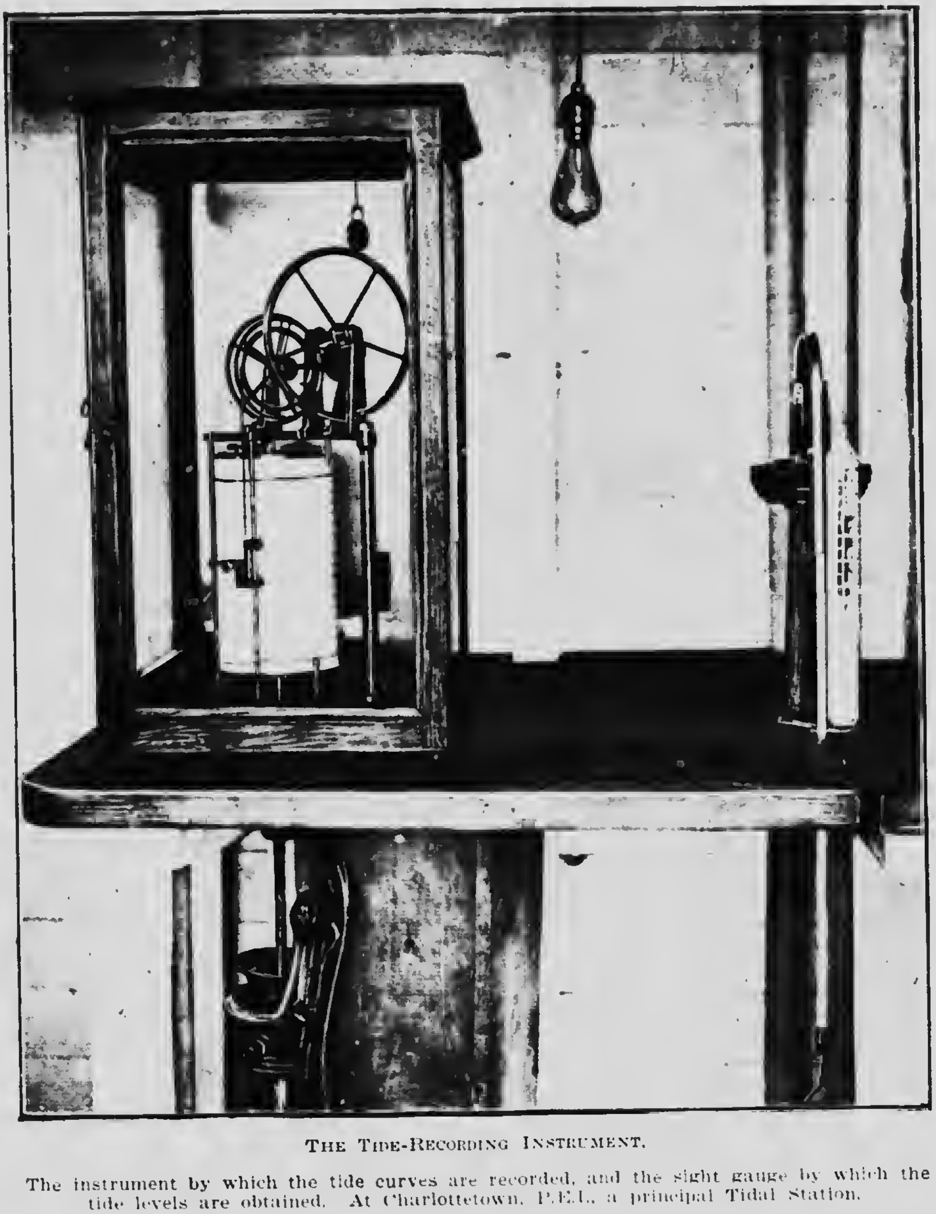
P.—Moon at Perigee, nearest the earth.

A.—Moon at Apogee, farthest from the earth.

E.—Moon on the Equator.

N.—Moon at maximum declination North of the equator.

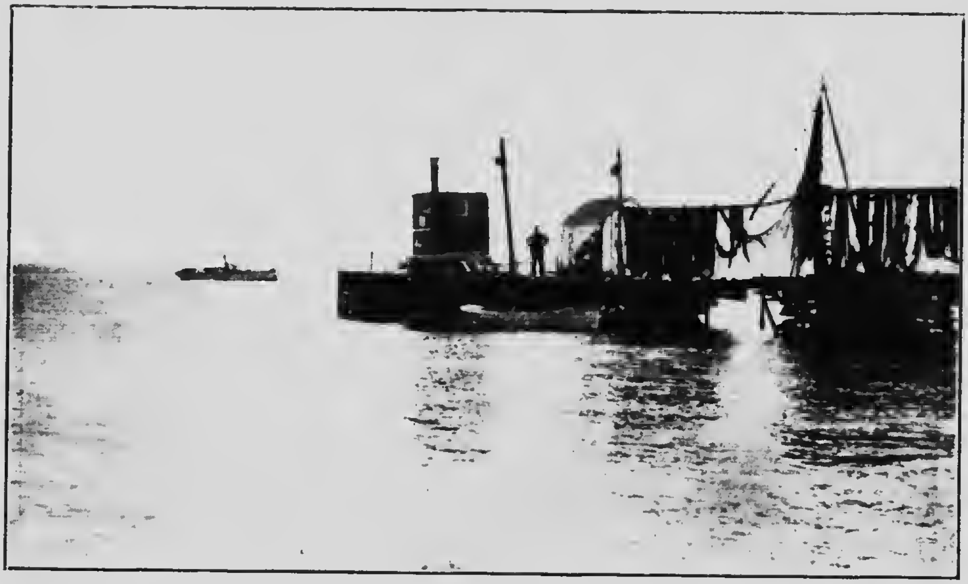
S.—Moon at maximum declination South of the equator.



THE TIDE-RECORDING INSTRUMENT.

The instrument by which the tide curves are recorded, and the sight gauge by which the tide levels are obtained. At Charlottetown, P.E.I., a principal Tidal Station.

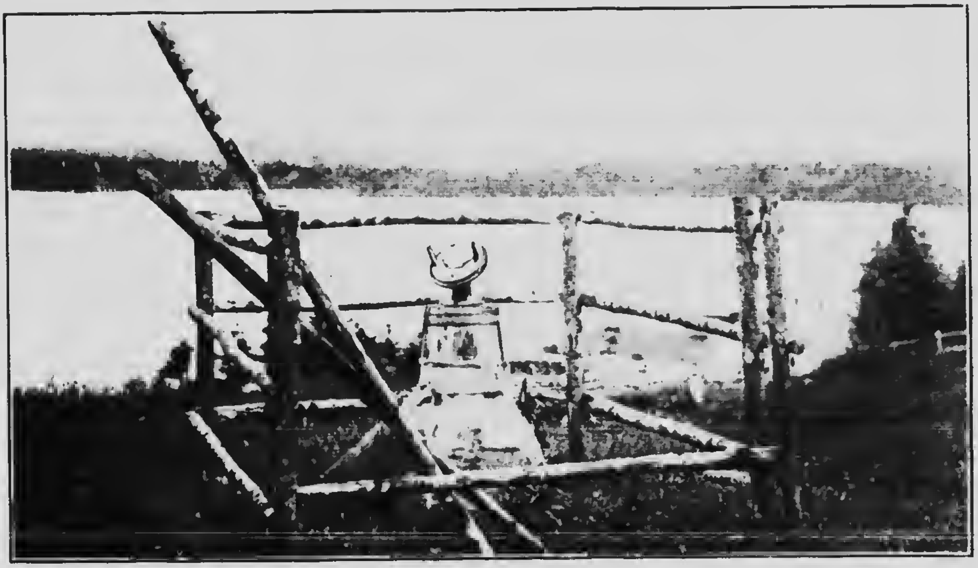
A principal Tidal Station. The Tide gauge on St. Paul Island, Cabot Strait; a small island at the main entrance to the Gulf of St. Lawrence.



A principal Tidal Station. The Tide-house at Forteau Bay, in Belle Isle Strait. Built on cribwork, ballasted with stone, placed at the end of a fishing stage.

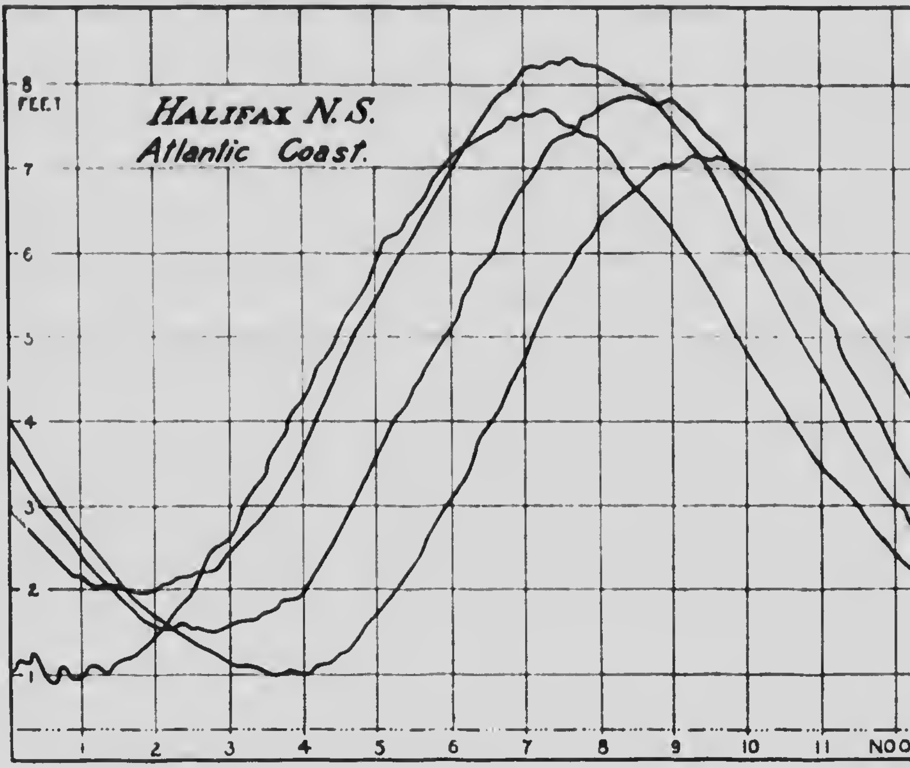
PLATE VIII.

TEMPORARY TIDAL STATION showing a scale and tide column with shelter box on top which contains the Recording Instrument.



MERIDIAN INSTRUMENT by which accurate time is obtained direct from the sun for tidal observations in isolated localities.

TIDAL SURVEY OF CANADA.



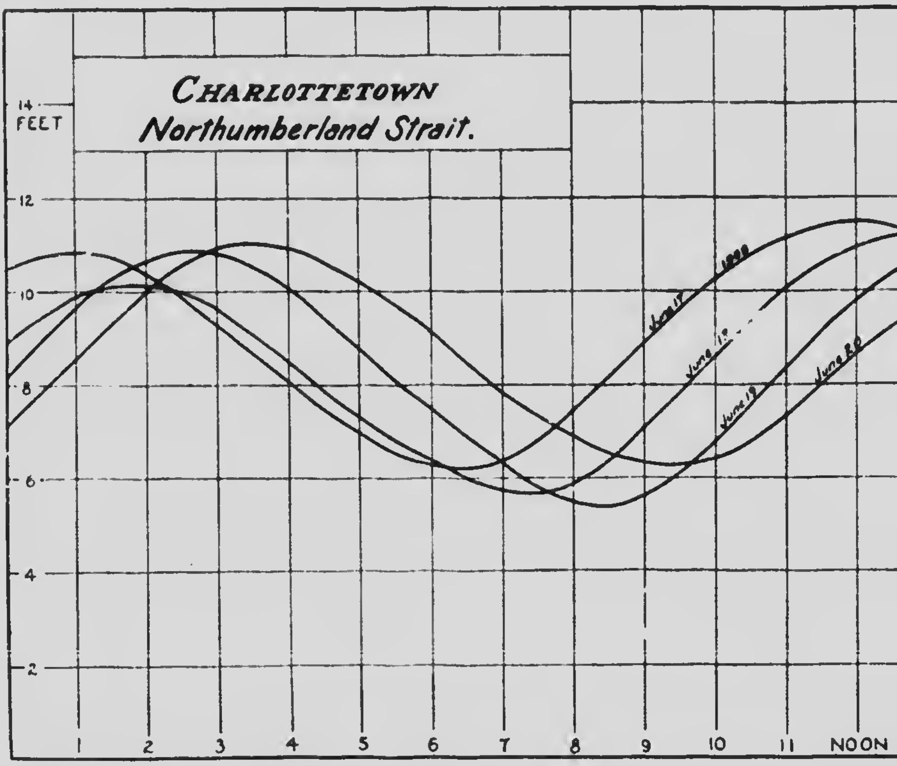


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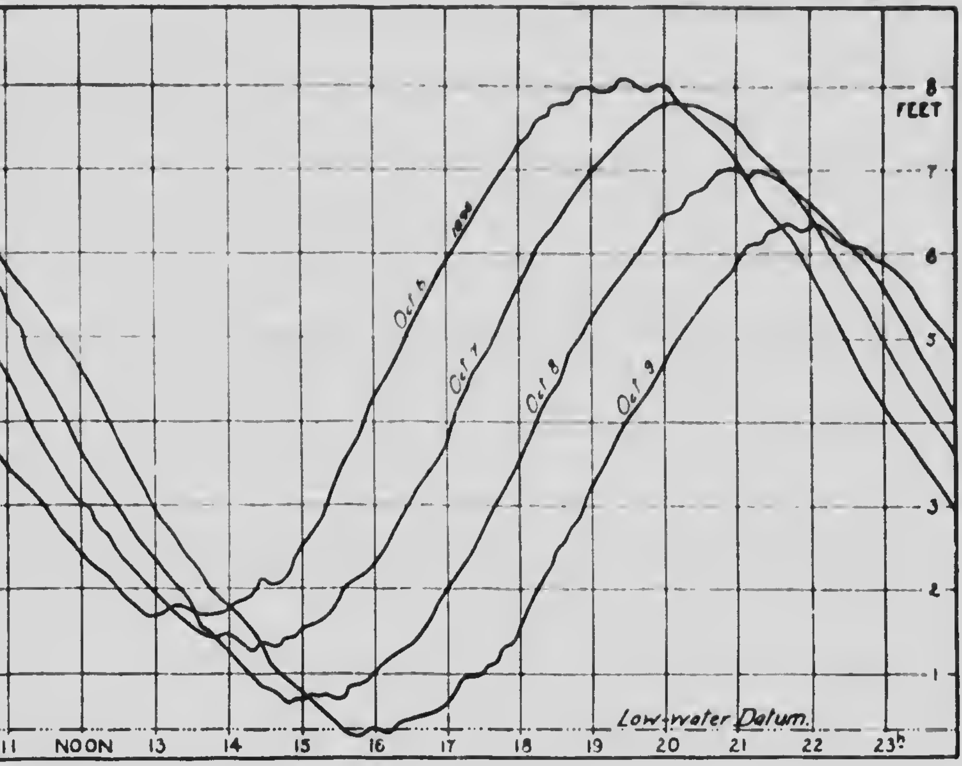
PLATE I.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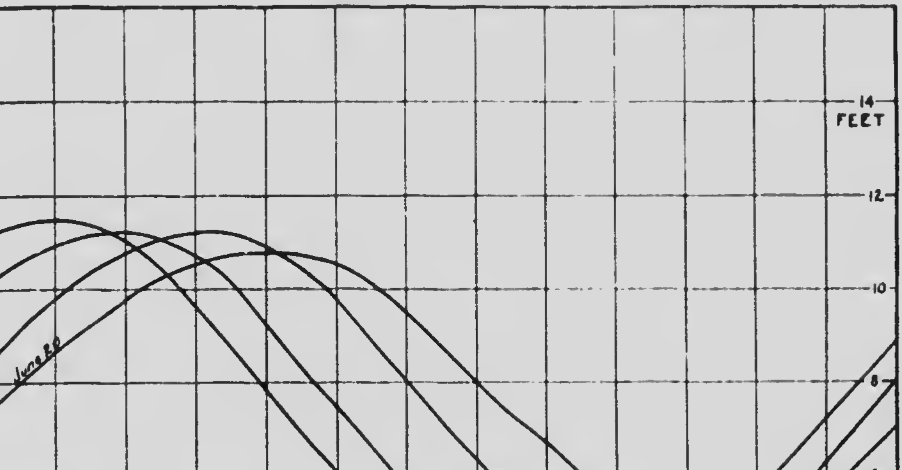
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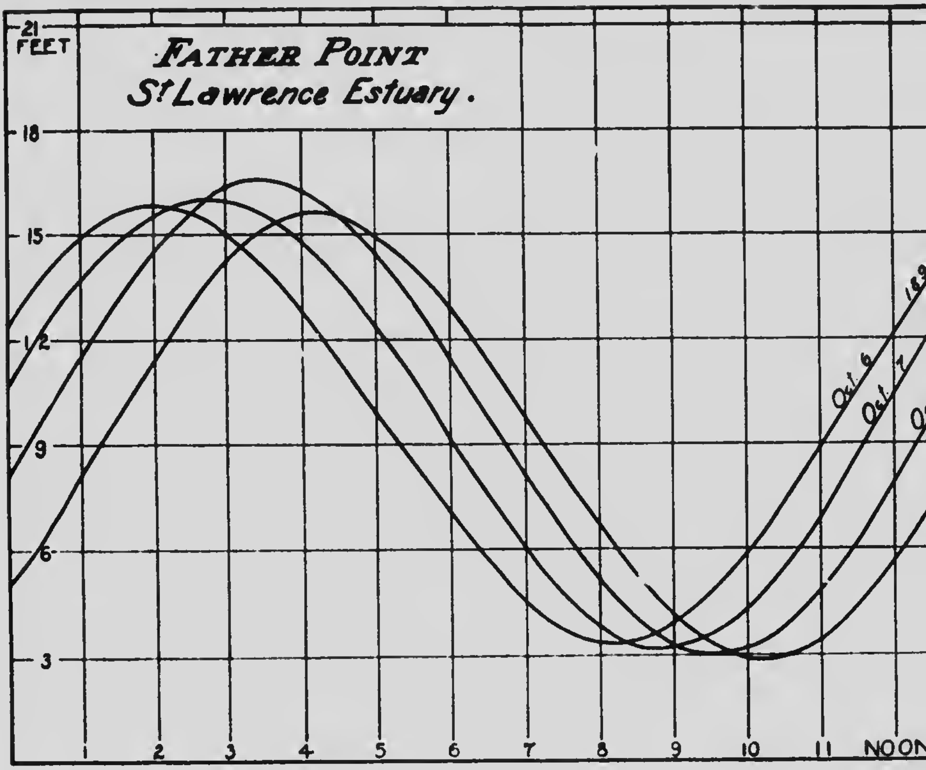
TIDAL SURVEY OF CANADA.



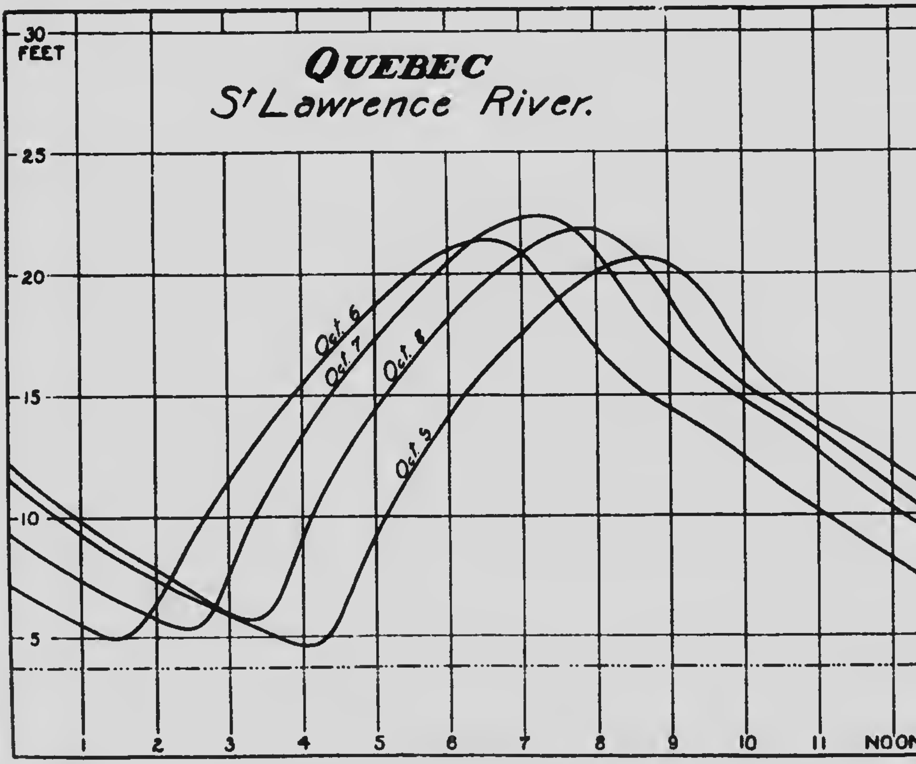


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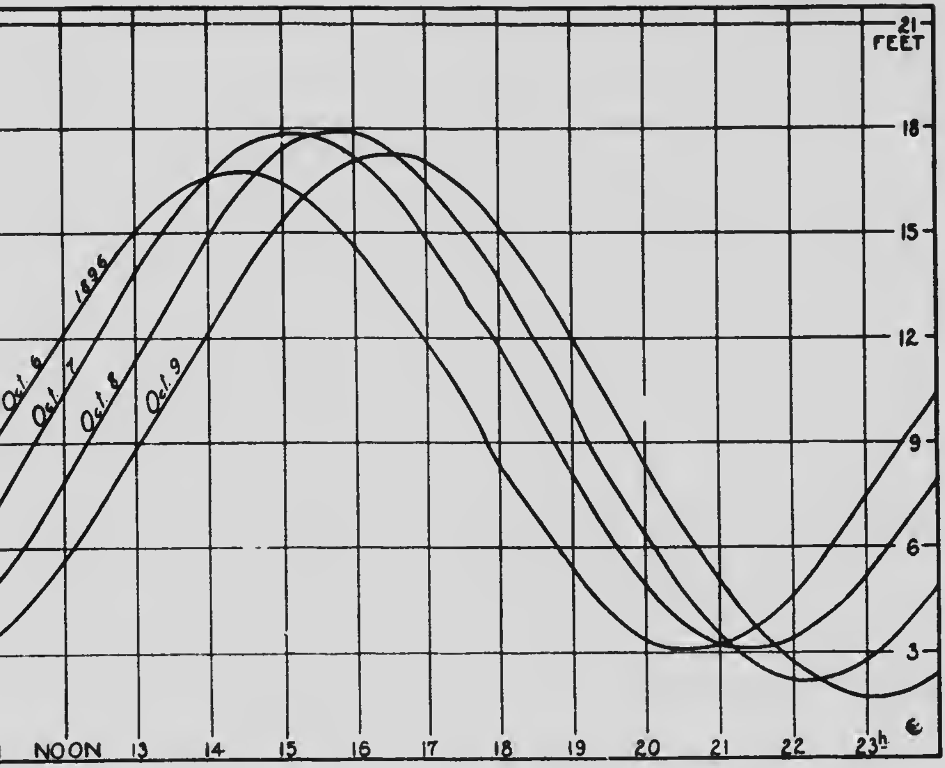
PLATE II.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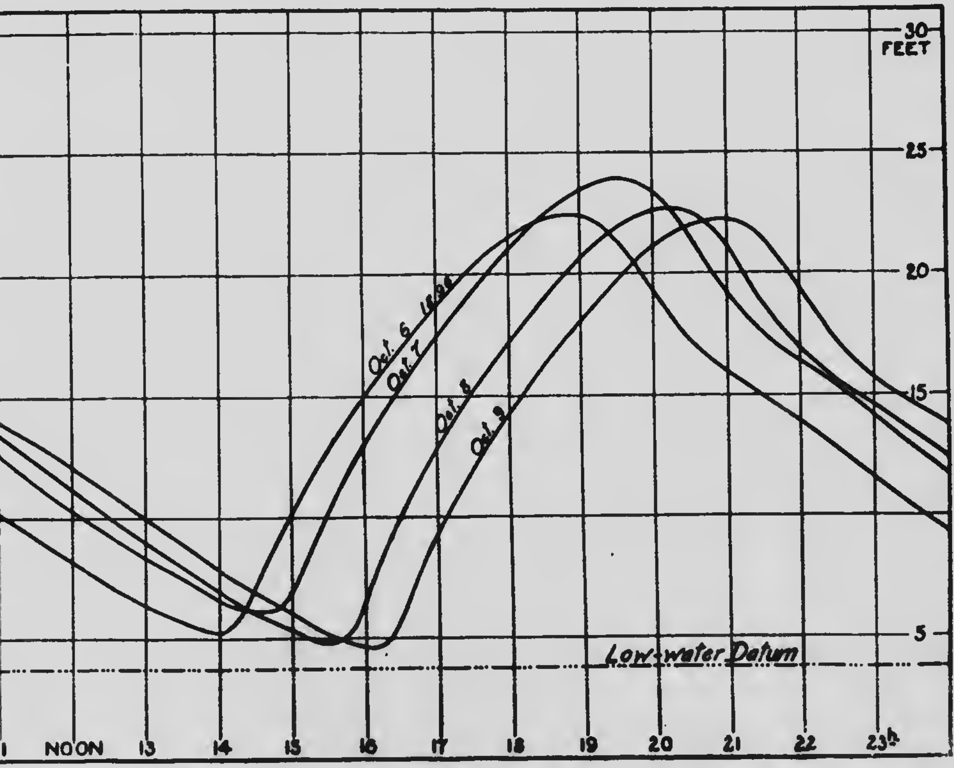
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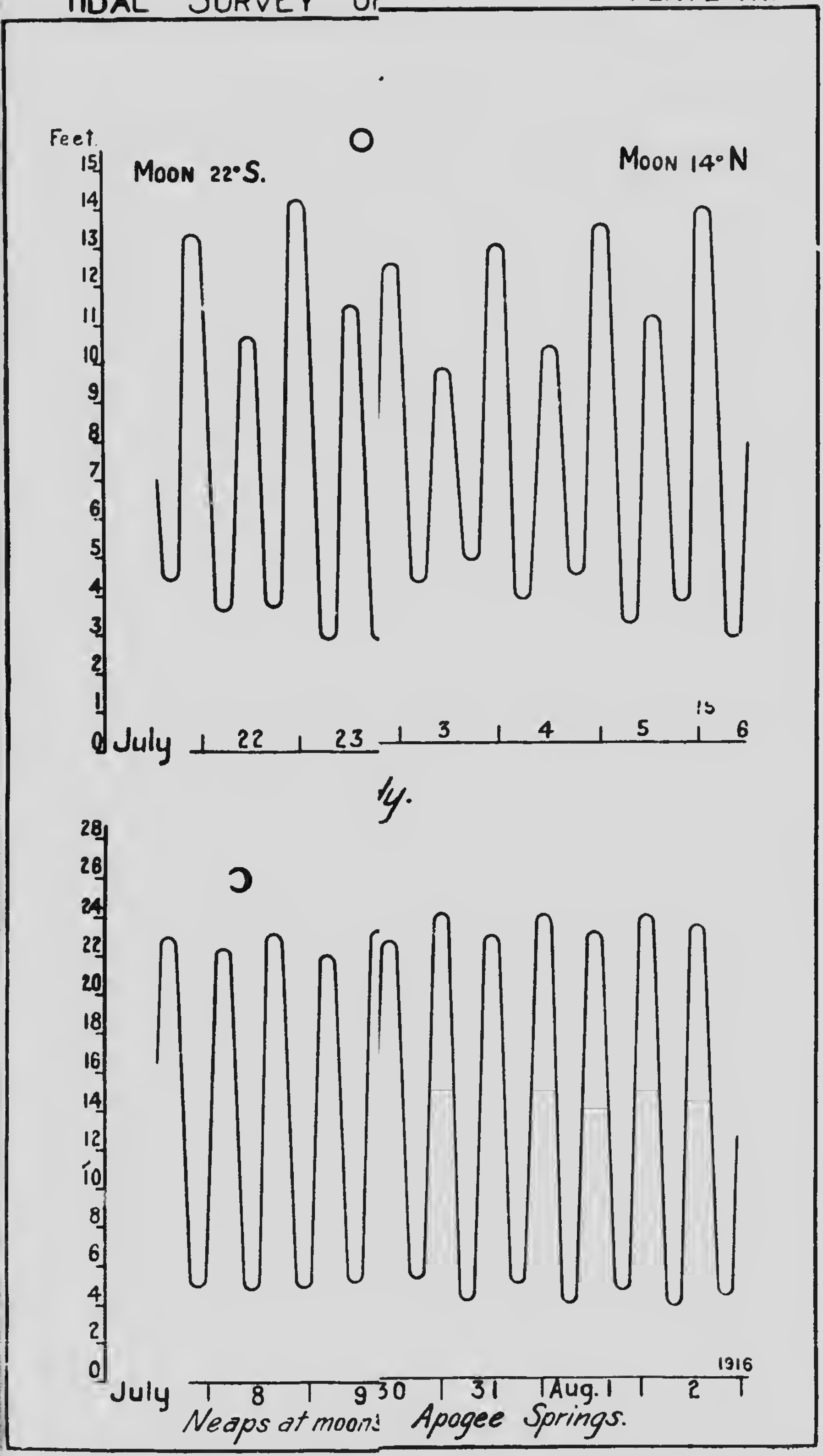
TIDAL SURVEY OF

PLATE III.



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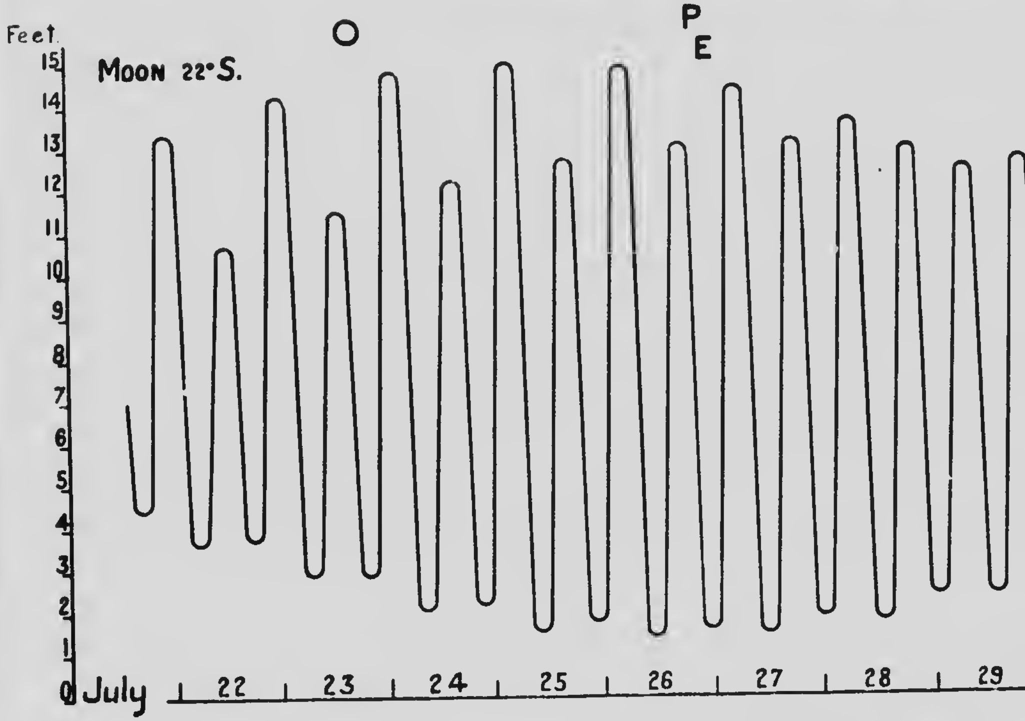
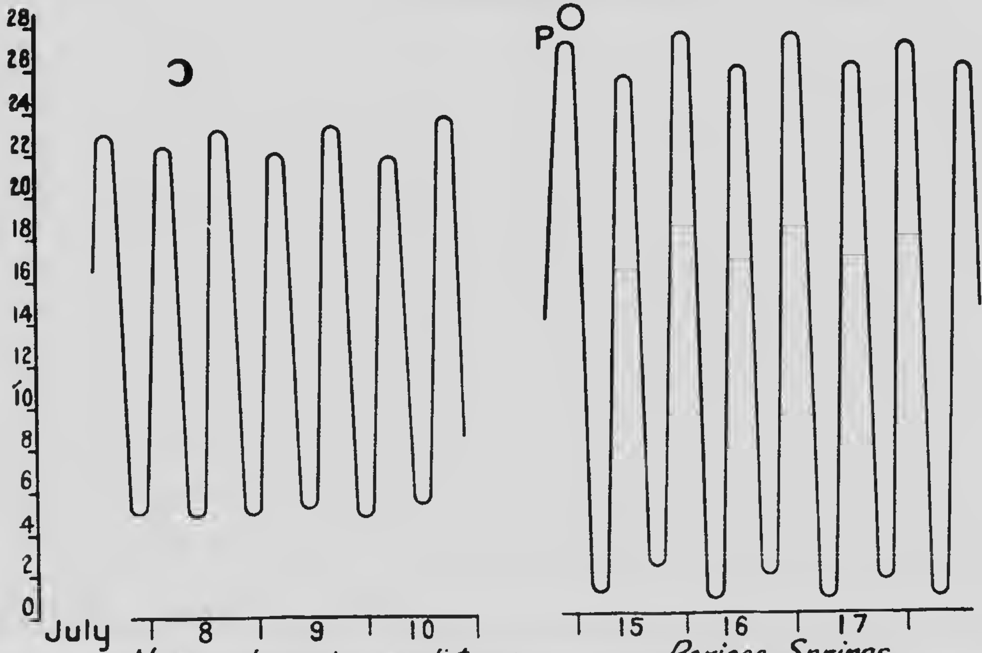
TIDAL SURVEY OF CANADA.

SYNODIC TIDE — Father Point



ANOMALISTIC TIDE —

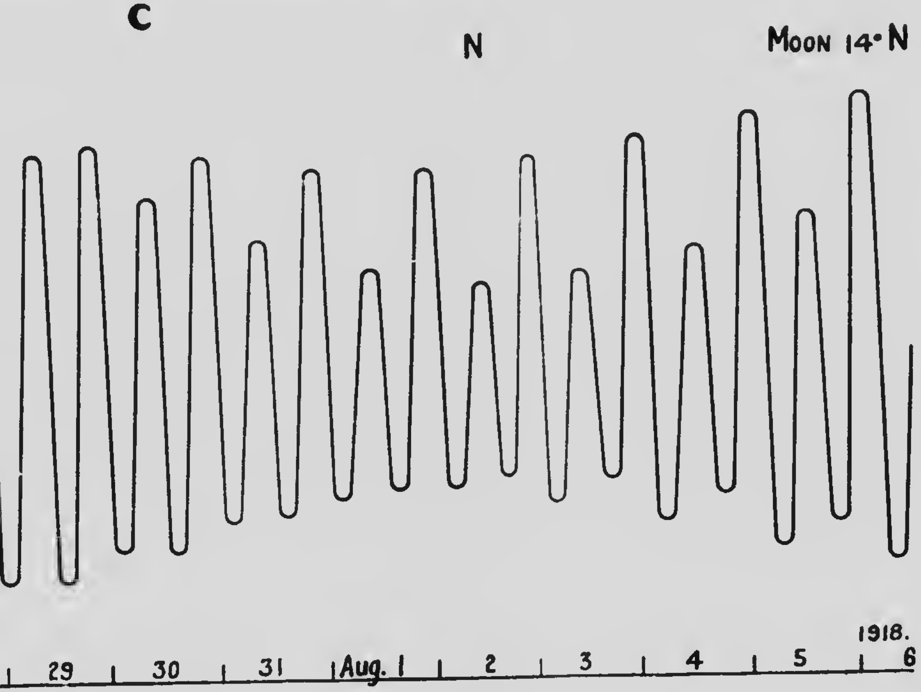


Neaps at moon's mean distance.

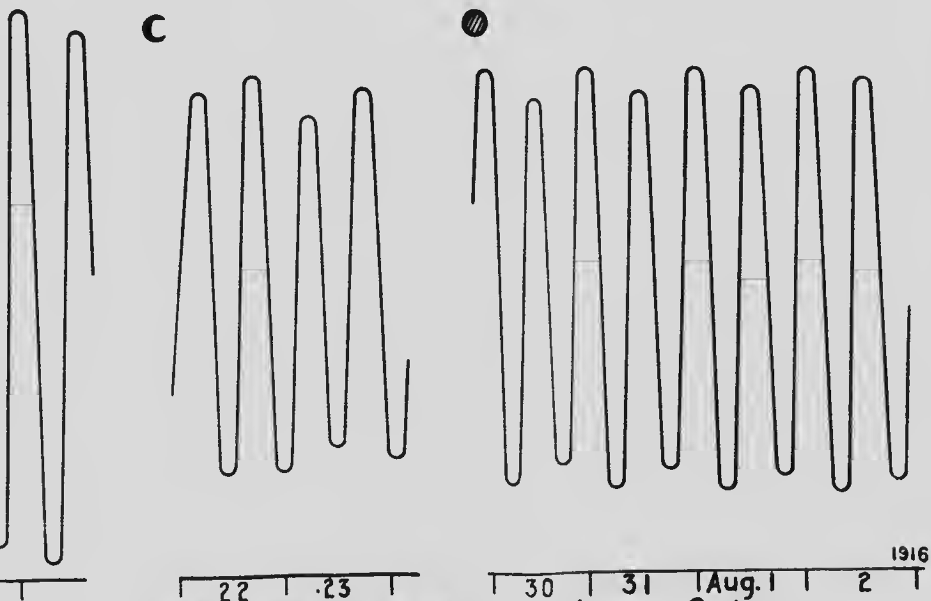
Perigee Springs.

PLATE III.

Point in St Lawrence estuary.



E — St John, in Bay of Fundy.



Neaps, mean distance.

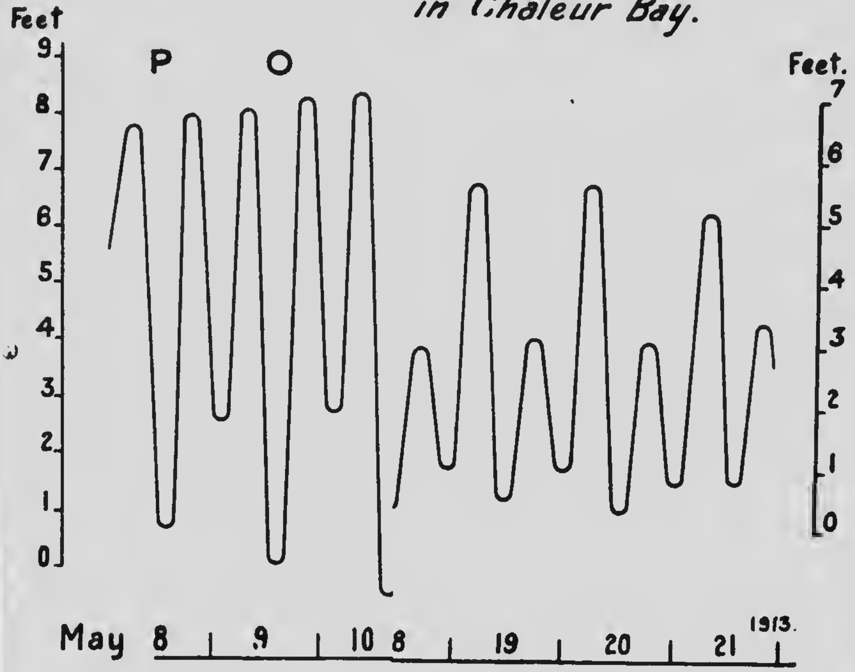
Apogee Springs.

Fe

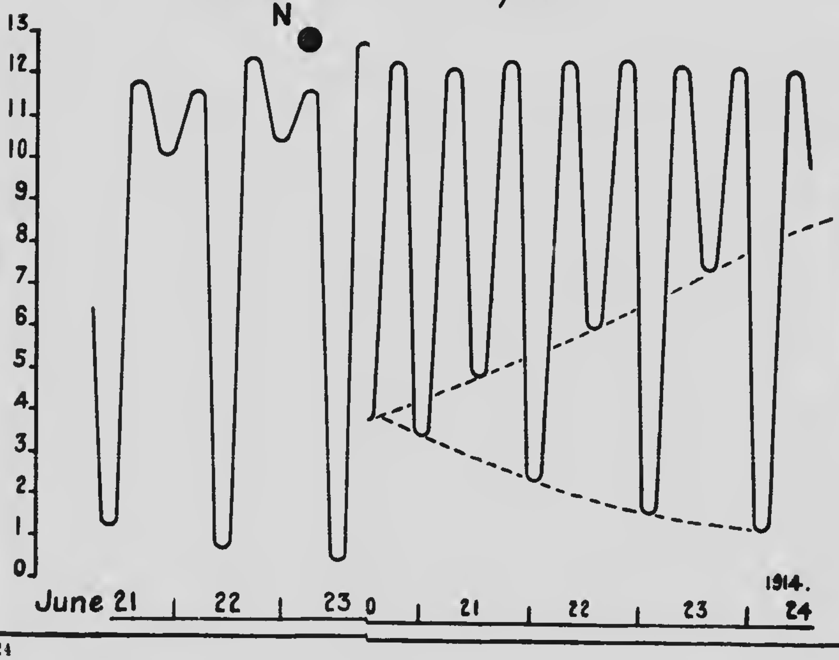
PLATE IV.

INEQUAL WATER.

quet
in Chaleur Bay.



Moon and Sun in on Equator.



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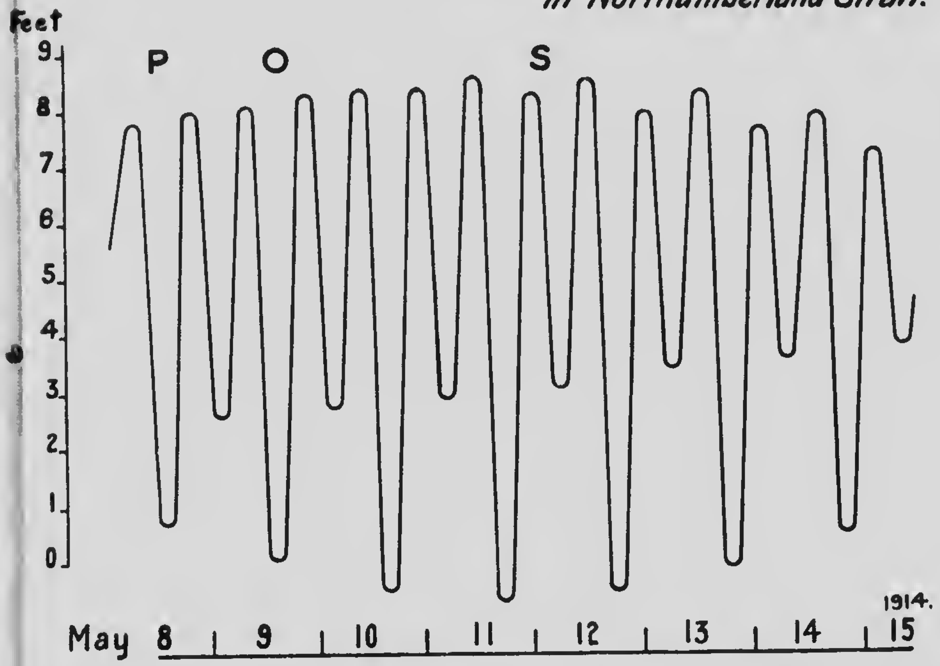
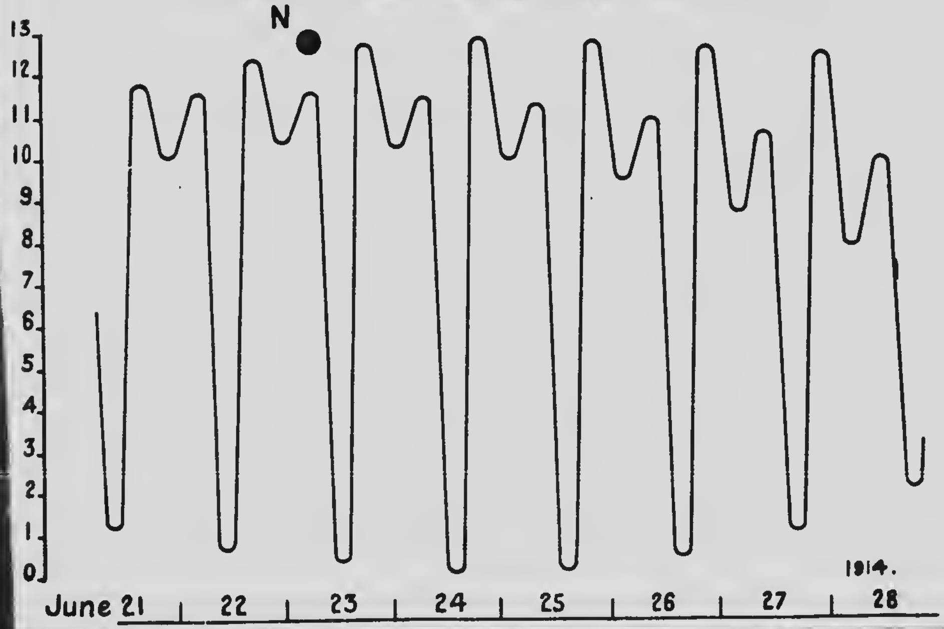
DECLINATION TIDE

INEQUALITY IN LOW WATER.

At Charlottetown in Northumberland Strait.



Moon and Sun at maximum declination North.



INEQ

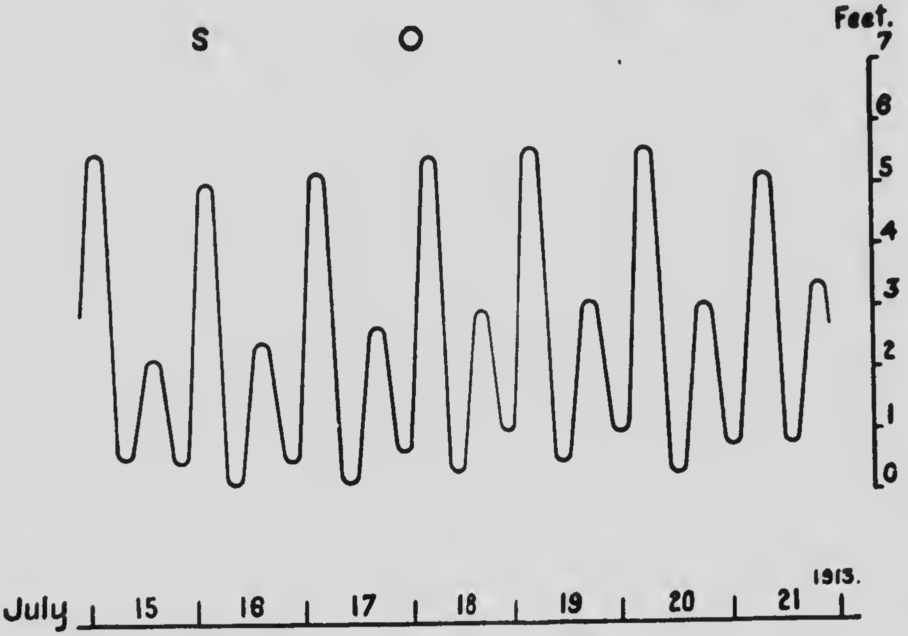
July

At Sand Heads, Str

TIDES. **PLATE IV.**

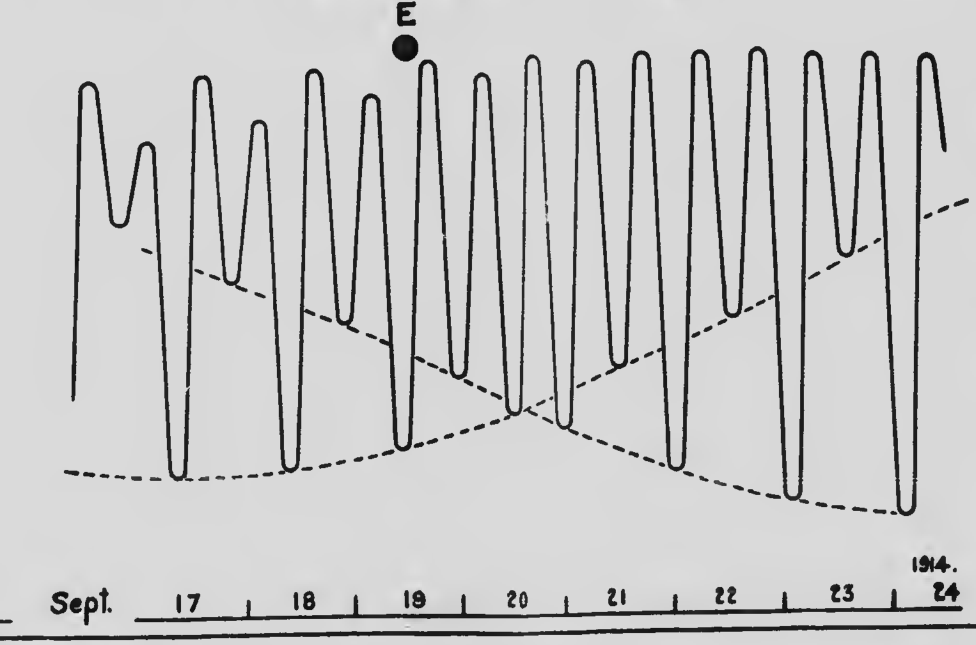
INEQUALITY IN HIGH WATER.

At Caraquet in Chaleur Bay.

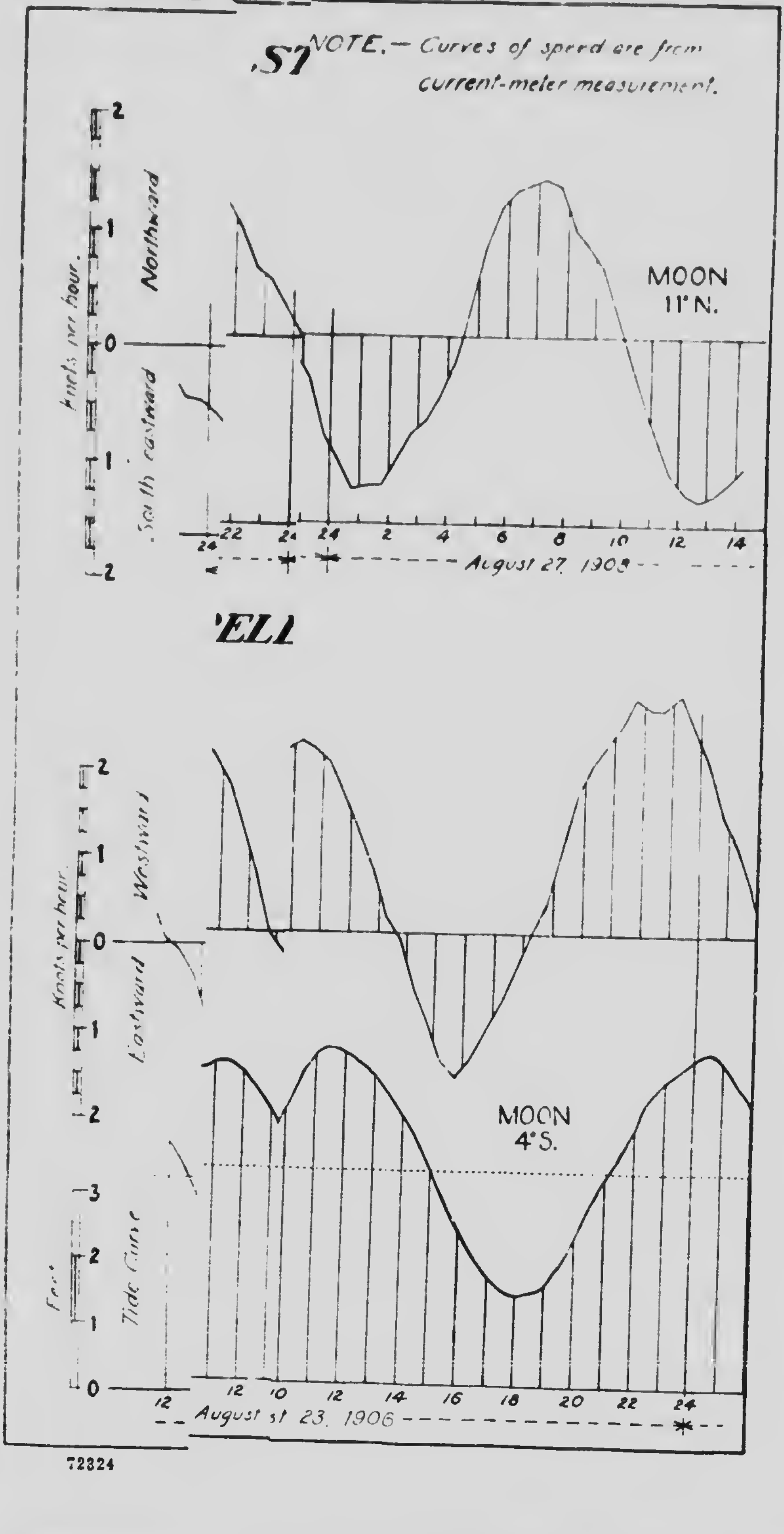


ls, Strait of Georgia.

Moon and Sun on Equator.



TIDAL PLATE V.



NOTE.— Curves of speed are from current-meter measurement.

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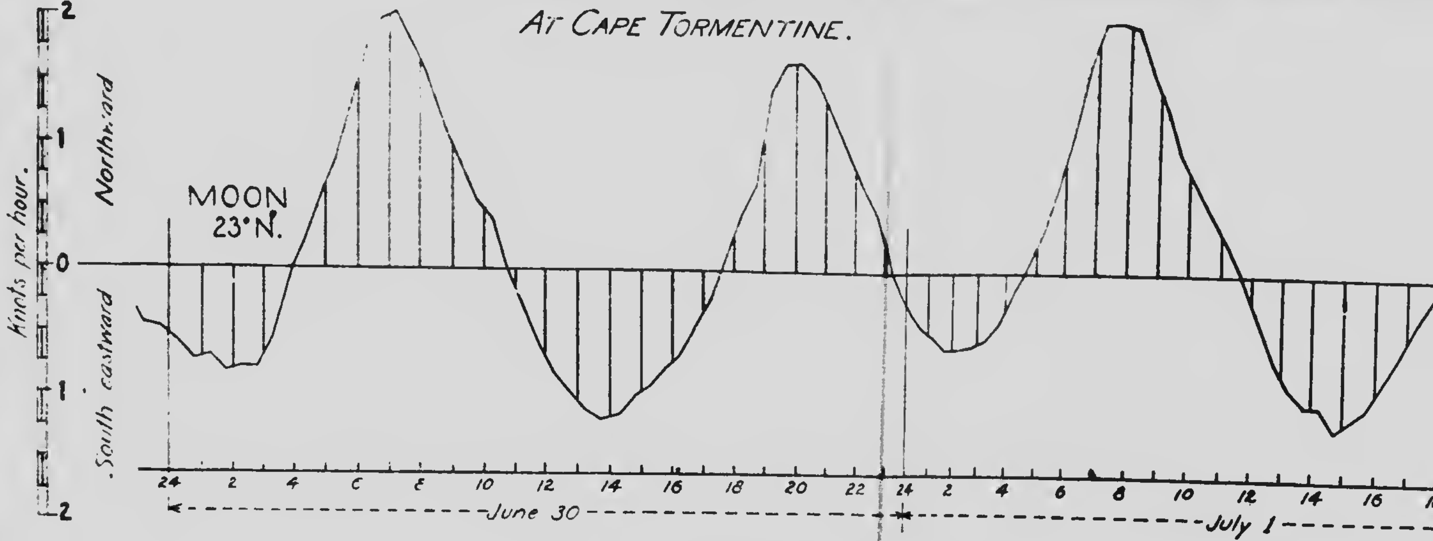
TIDAL SURVEY OF CANADA.

TIDAL STREAMS. — NORTHUMBERLA



TIDAL STREAMS AND TIDE.

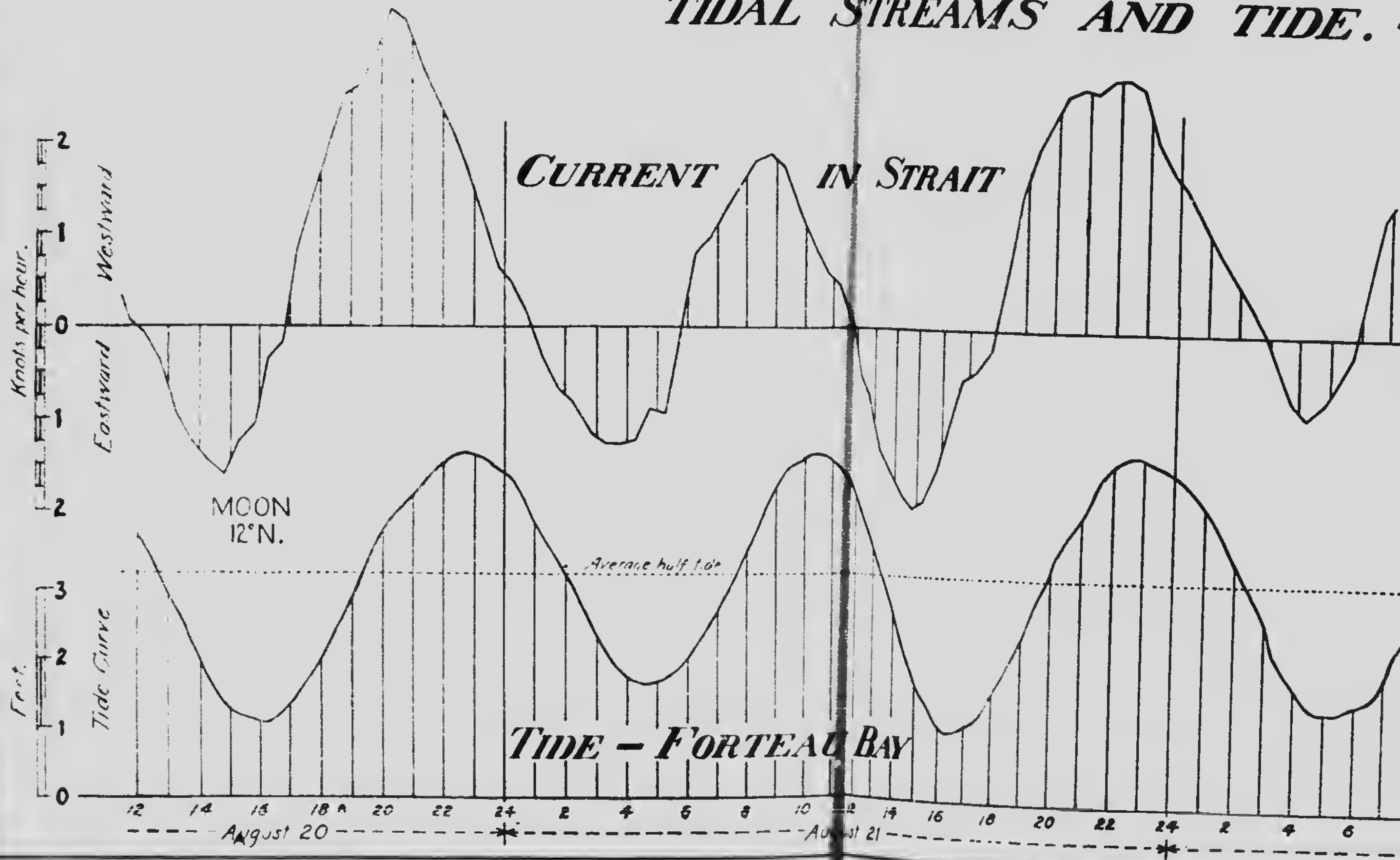


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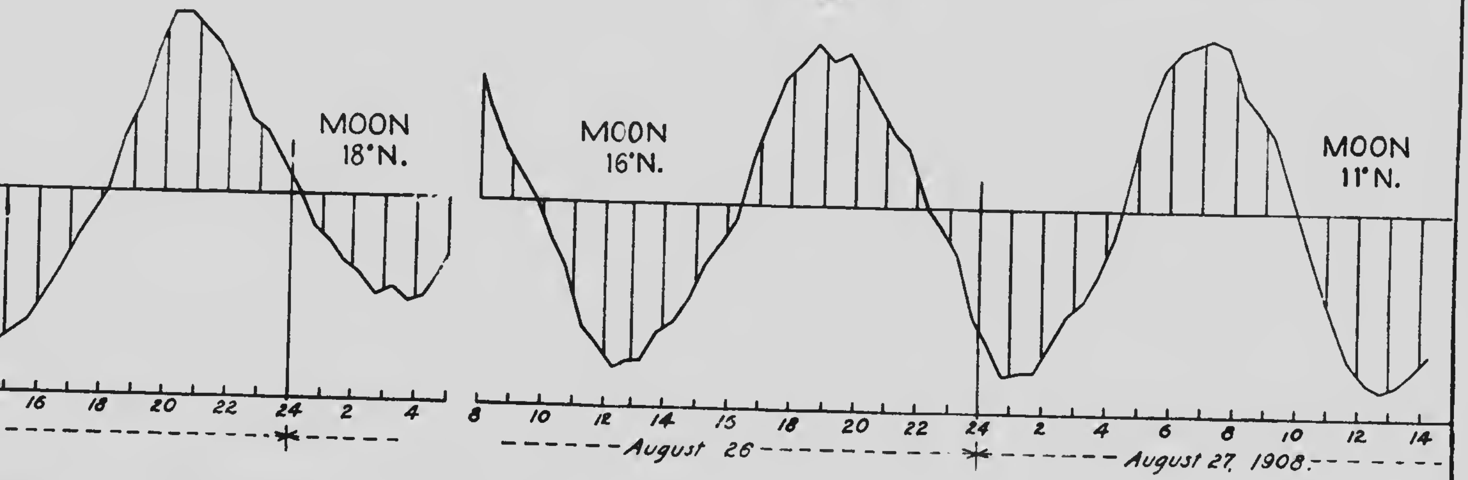
PLATE V.

ERLAND STRAIT.

NOTE.— Curves of speed are from current-meter measurement.



DE. — BELLE ISLE STRAIT.