NAVY SCIENTIFIC PAPERS, No. 2.

TIDES AND TIDAL PHENOMENA:

FOR THE USE MORE PARTICULARLY OF U. S. NAVAL OFFICERS.

BY

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WASHINGTON:
GOVERNMENT PRINTING OFFICE.
1868.

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Tidal phenomena present themselves to the observer under two aspects: as alternate elevations and depressions of the sea, and as recurrent inflows and outflows of streams.

The word *tide*, in common usage, is applied without distinction to both the vertical and the horizontal motion of the sea, and much confusion has arisen among navigators from this double application of the term. Careful writers of modern times, however, use the word *tide* in strict reference to the *changes of elevation*, while they distinguish the recurrent streams as *tidal currents* or *tidal drifts.* With regard to the words *ebb* and *flood*, no distinction of application has been observed. We advise, however, that in the field-book these terms should be used in reference to the *current*, and that the words *rise* and *fall* should replace them when the *tide* is referred to.

The words *stand* and *slack* are often confounded; the former, correctly used, designates that period of time during which the height of the tide remains essentially the same; while the latter indicates the interval of time between the cessation of flood or ebb current and the commencement of the opposite stream.

It is often the case that the elements of the *tide*, obtained from a series of observations at a single port, may represent, in a general way, the conditions for a considerable extent of the adjacent coast, and even be applicable to other ports in the neighborhood; whereas the elements of the *tidal current* are so strictly local that the same port may require several distinct series of observations in its different approaches and avenues. From these simple considerations the importance of a strict use of terms and phrases will be obvious to the voyager who may design to collect data for the use or information of others.

Although it is often desirable that observations of the tides and their dependent currents should be made simultaneously, we must, for the sake of perspicuity, refer to them separately in this article.

TIDES.

Tidal observations consist simply of a record of the heights of the water above a fixed zero at stated times. These heights are measured by gauges of different forms according as the station is more or less exposed to waves, ice, &c. In the Appendix to this article we have enumerated the different kinds of gauges which have been used, and described them briefly. The field-book should contain descriptions of the instruments used, locality of the station, means of obtaining the true time, together with notes on the weather, &c.

§ 1. To form a clear notion of the tide, it must be conceived to be a long wave or undulation, propagated to our shores from mid-ocean without necessarily causing visible agitation of the water particles.* Its *range* is the vertical distance between the low and high water levels; its *length* the distance measured on the surface of the sea from one low water to the next. The tide wave, considered as an undulation, is always moving in a single direction, but is subject to changes of figure from point to point in its journey, by which its range and its length are altered. The rate with which the tide wave moves depends upon the depth of water; it is measured by comparing the times of high water observed at different determined points along its path.

§ 2. When we speak specifically of the form or *figure* of the tide at any given place, we refer to the curve which the observations describe when plotted upon paper, using the heights and the hours of the day as co-ordinates. The tidal curves for ports in the same neighborhood differ but slightly, but those of different seas in some cases present striking contrasts of figure.

§ 3. The observed tide is not a simple wave; it is a compound of several elementary undulations, rising and falling from the same common plane, two of which can be distinguished and separated by a simple grouping of the data, to which we shall hereafter refer. These two waves are known as the *semi-diurnal* and the *diurnal* tides, because the first, if alone, would give two high and two low waters in a day, while the second would give but one high and one low water in the same or an equivalent period of time. In nearly all ports these two tides coexist, but the proportion between them varies remarkably for different seas.

Along our Atlantic coast the semi-diurnal wave predominates, and

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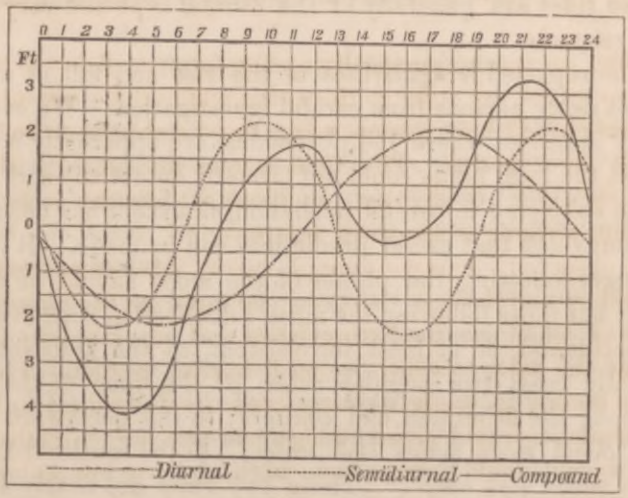
* For descriptive articles on tidal phenomena we may refer the reader to Laplace's "*Exposition du Système du Monde*" and to the American Encyclopædia, Article "Tides."

the diurnal is so small that its presence is made scarcely sensible in the small differences which it causes between the morning and the afternoon tides—*diurnal inequalities.* In some parts of the Gulf of Mexico it is the diurnal wave which usually prevails, and so much does it exceed the semi-diurnal in height that, upon the average, but one high and one low water occur in twenty-four hours. Upon our Pacific coast, the two elementary waves have nearly the same range, so that although there are usually two tides per day, they are very unequal.

In undertaking to investigate the tides of a port, it is important to ascertain as early as possible the form of the tide; that is, whether it resembles the semi-diurnal, the diurnal, or the mixed type; because not only may this information be itself of scientific value, but the knowledge thus gained at the outset will enable the observer to fix upon the best method of keeping his record.

§ 4. The type forms to which we have referred are illustrated in the annexed diagram, where the figures of the waves are plotted in curves, using the times as abscisses and the heights as ordinates:



In this diagram the curve traced in dotted line is a tide wave of the semi-diurnal type; that traced by the broken line one of the diurnal, while the full line is one of the mixed type—in this case the compound of the two others. It will easily be seen that upon the magnitudes and relative positions of the two elementary waves depend not only the *relative heights*, but also the *relative times* of the observed high and low waters.

The semi-diurnal tide increases in magnitude as the moon approaches her conjunction or opposition with the sun, and diminishes as she nears the quadratures.

To sketch the history of the diurnal wave in the least critical way, it may be said to increase with the angular distance of the moon from the equator—that is to say, with her declination (north or south)—to reach a maximum when this declination is greatest, to decline as it declines, and to vanish when it vanishes. Unlike the semi-diurnal wave, it is evanescent.*

In order to determine the type to which the tide of any port belongs, it is usually only necessary to make hourly observations for a day or two at the date of the moon's maximum declination, and to repeat the series about a week later when the moon crosses the equator.

Information relative to the type forms of the tides among the Pacific islands has long been desired. From the few observations made at the Sandwich Islands and at some other points, it would appear that these tides are generally of the diurnal type and very peculiar in many respects.

§ 5. The reported irregularities of the rise and fall at any place should not deter persons from careful investigation. We could mention many instances where the phenomena are apparently so complicated that the local pilots could not formerly detect any sort of order; yet, when subjected to careful tabulation, the skein has been so completely unraveled that useful predictions can be made. It is natural that changes following the phases of the moon should be easily recognized; but those following the moon's declination must everywhere appear accidental, or at least inconsistent, to the ignorant. Upon our Atlantic coast two popular rules for the time of the tide are found among the fishermen and coasters: to the northward of Nantucket "*South moon makes high water;*" to the southward, "*South-east moon makes high water.*" These two rules are nearly as correct as they are convenient; for, between Nantucket and the Bay of Fundy, high water occurs in the various ports shortly before the moon reaches the meridian; while along the southern coast, between Nantucket and

* Both of these elementary waves are, in reality, compounds of lunar and solar tides—the latter usually small—and here, as in other natural phenomena, there are considerable intervals of time between the causes and their observed effects.

Florida, high water visits the ports four or five hours before the moon's transit, or while she is seen in the southeast. Another general rule which applies to our entire Atlantic coast is, that "*the greatest tides (springs) follow soon after the full and new moon, the least (neaps) soon after the quarters.*"

In the Gulf of Mexico no such rules as those we have mentioned would apply, because the tides belong to the diurnal and mixed types. If, for instance, the new or full moon occurs at her zero declination, the tides, instead of increasing as the time of syzygy draws near, undergo a decline and perhaps vanish. The phenomena of spring and neap tides are not recognized in some parts of this sea, and yet the tides are generally obedient to the influences of the sun and moon.

To collect data for the construction of prediction tables has been the leading object of tidal observations, and a multitude of such tables have been constructed for different ports. Those for the North Atlantic, and those for the Pacific coast of America, are practically complete, but for other parts of the world often inaccurate.

We shall sketch out the most recent and approved plans for tabulating the field-notes, taking up each type separately.

Tides of the semi-diurnal type.

§ 6. Let us consider the case of a station where the tides are semi-diurnal in type, considerable in magnitude, and generally well defined.

The data required for practical use are the times and heights of high and low water, together with such meteorological notes as may bear upon the matter.

To obtain the true times and heights, the observations for each tide should be made every two minutes, commencing at least twenty minutes before and continuing till twenty minutes after the *stand*. The middle of the stand is the true time of the high or low water. With tides of small range the culminations are often very slow, so that the observer is doubtful of the exact time when the vertical changes cease; a change of wind or a squall may interrupt the normal conditions and disturb his confidence in his record. Under such circumstances, it is a good plan to plot upon profile paper the observations obtained, using the times and heights as co-ordinates, (very much as we have done in § 4,) so that irregularities may appear to the eye and may be struck out by drawing a smooth curve through them. This method of "*graphical correction*" is a guide to the judgment in estimating the probable instant of culmination. It was introduced by Dr. Whewell in his tidal essays, and has been long familiar in many other studies of variable numerical data.

§ 7. Having carefully reviewed the field-book and marked the true times of the high and low waters, the computer is prepared to take the first step in the compilation of a tide table. This first step is the drawing up of a tabular statement in the form given below. This form is called the "First Reduction," and, in the specimen we have given, we have placed a few observations to illustrate its use.

1	2		3				4				5				6				7		8						
Date.	Moon's Transit.		TIME OF—				LUNITIDAL INTERVAL.				HEIGHT.				DURATION.				STAND.		METEOROLOGICAL DATA.						
			High water		Low water.		High water		Low water.		High water		Low water.		Rise.		Fall.		High water.	Low water.	Wind.		Barometer.			Temperature.	
	Hrs.	Mins.	Hrs.	Mins.	Hrs.	Mins.	Hrs.	Mins.	Hrs.	Mins.	Feet.	Dec.	Feet.	Dec.	Hrs.	Mins.	Hrs.	Mins.	Mins.	Mins.	Direc'n.	Force	In.	Dec.	Temp. °	Air.	Water.
1860.	23	49	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	......	......	......	....	....	....	......	....	......
Aug. 31	12	09	9	07	2	37	9	18	....	....	4	81	2	33	6	30	....	....	01	05	NW.	2	30	15	68	74	65
	8	....	21	25	14	46	9	16	14	57	5	14	2	35	6	39	5	39	03	15	S.SE.	1	30	04	67	65	65
Sept. 1	0	29	9	39	3	00	9	10	14	51	5	24	2	30	6	39	5	35	01	04	W.	4	29	92	69	78	65
	12	48	21	50	15	36	9	02	15	07	5	16	2	61	6	14	5	57	07	06	SW.	3	30	07	63	81	66

The first entries in this table are made directly from the field-book, and occupy, in order, spaces numbered 1, 3, 5, and 7.

Next, the space numbered 2 is filled from the tables of the moon given in the Almanac, after due correction. In the "American Ephemeris and Nautical Almanac" the *upper* and *lower* transits for each astronomical day are given in mean time as calculated for the meridian of Washington. For our use these transits must be reckoned back to the *civil* day, by reversing the rule laid down in the Almanac, ("Use of the Tables,") and corrected for the longitude of the tidal station by *adding* about two minutes for each hour of *west*, and *subtracting* the same for each hour of *east* longitude from Washington.

The "Lunitidal Interval" is the time elapsed between the transit of the moon and the occurrence of high or low water. It is customary to refer both the high and the succeeding low water to the same transit, viz: that which immediately precedes the high water; for this reason the lunitidal intervals of low water appear in our table about six hours longer than those of high water. On the 31st of August it will be seen by our table that the first high water occurred at 9*h.* 07*m.*, and the succeeding low water at 14*h.* 46*m.*; both of these are referred to the transit which occurred at 23*h.* 49*m.* on the preceding day, and the intervals are, respectively, 9*h.* 18*m.* and 14*h.* 57*m.* By these simple calculations the space 4 is filled. The sign ☍ (opposition) is introduced to fill the blank, and, as we use it, simply indicates that the upper transit occurs after midnight so as to fall in the next civil day. If it were the other transit that passed over, we should use the sign ☌ (conjunction) with the same specific meaning. The proper motion of the moon to the eastward causes her transits over the same meridian to be later each day about forty-eight minutes in the average, so that in the course of every fifteen days one of her transits (either the *upper* or *lower)* fails to fall within the same civil day as the other. There are not, then, two transits in every calendar day; on the contrary, in twenty-nine and one-half days (the average time elapsed between one new moon and the next) there are but fifty-seven. In the same way the tides, which follow the moon, do not always give us two *high* and two *low* waters within the same day; but in the course of a month two days occur in each of which only one high water obtains, and two also in each of which but one low water takes place.

The space 6 is filled by reckoning the time between each high water and the succeeding low water for duration of fall; and between each low water and the succeeding high water for the duration of rise.

To this table are usually attached columns of meteorological data transferred from the field-book. They serve occasionally to explain disorderly results, and in nicer computations appear as elements of correction.

§ 8. If the observations of several weeks are placed in this table, and reduced as we have described, a general inspection will discover traces of certain laws which govern the phenomena:

1st. With regard to the heights, the *greatest* elevations and depressions (spring tides) will be found to occur shortly after those dates when the moon crosses the meridian at noon or midnight, (when she is near her conjunction or opposition with respect to the sun;) and the *least* (neap tides) shortly after those dates when the moon's transits occur at 6*h*. or 18*h*. (when she is near her quadratures.)

2d. The lunitidal intervals will be found similarly, and even more closely, dependent upon the hours of transit; the least intervals occur at or near the 3*h*. or 15*h*. transits, and the greatest intervals at or near the 9*h*. or 21*h*. transits.

§ 9. In order to exhibit more clearly the dependence of the tidal variations in height and interval upon the moon's hours of transit, another table, called the "Second Reduction," is necessary, in which the results are grouped according to those hours. An example of such a table, arranged for high water, is given below, the data for which is borrowed from actual observations of the Coast Survey in Hampton Roads.

	Moon's transit.		Lunitidal interval. High water.		Height of high water.		No. of observations.
	Hrs.	Mins.	Hrs.	Mins.	F.	Dec.	
	0	30	8	58	5	43	48
	1	30	8	46	5	42	48
	2	30	8	38	5	35	48
	3	30	8	30	5	20	48
	4	30	8	26	5	10	48
	5	30	8	32	5	04	48
	6	30	8	44	4	97	48
	7	30	9	08	5	12	48
	8	30	9	18	5	14	48
	9	30	9	21	5	06	48
	10	30	9	19	5	26	48
	11	30	9	09	5	32	48
Means.	......	......	8	54	5	20	

§ 10. In this second reduction each interval and height is the mean of all those observed, referable to the same hour of transit; the transits between 0*h*. and 1*h*., 12*h*. and 13*h*., being classed as 0*h*. 30*m*.; those between 1*h*. and 2*h*., 13*h*. and 14*h*., being classed as 1*h*. 30*m*., and so on. At the foot of each column is given the arithmetical mean of the quantities above. The mean interval is called upon our charts the "corrected establishment," and is the leading expression of the ordinary tide table, such as we give below, which requires now but little further explanation.

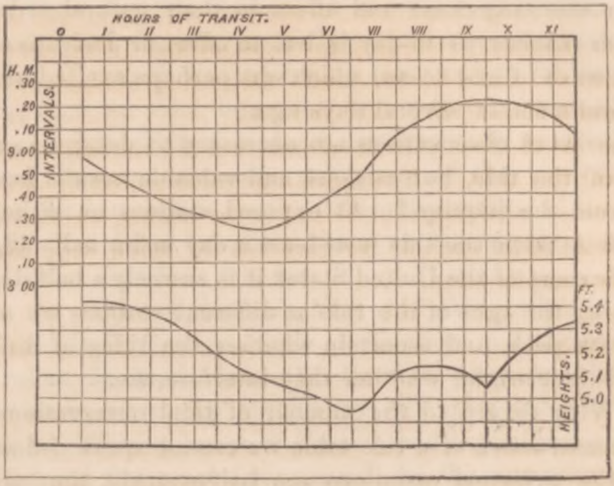
Corrected establishment	VIIIh. XVIIm
Rise of highest tide observed above the plane of reference	4.8 feet.
Fall of lowest tide observed below the plane of reference	1.7 feet.
Fall of mean low water of spring tides below the plane of reference	0.2 feet.
Height of mean low water of neap tides above the plane of reference	0.2 feet.
Mean rise and fall of tides	2.5 feet.
Mean rise and fall of spring tides	3.0 feet.
Mean rise and fall of neap tides	2.0 feet.
Mean duration of rise, } Reckoning from the middle of one stand to the middle of the next.	6h. 01m.
Mean duration of fall, } Reckoning from the middle of one stand to the middle of the next.	6h. 25m.
Mean duration of stand	0h. 14m.

The greatest high water in the table of second reductions is assumed to be that of spring tide; the least, that of neap tide. The reverse holds for low water. The durations of rise, fall, and stand, as well as heights of highest and lowest observed tides, are taken from the first reductions.

The plane of reference mentioned in this table is that from which the soundings of the chart are measured; the depths, as now represented upon the charts of our coast survey, are referred to mean low water. We shall have further remarks to make in this connection when we come to speak of the *mean level of the sea.*

With regard to the "stand" there may be some uncertainty. Its very existence, as a measurable tidal phenomenon in the strictest sense, is very doubtful; but as there must always be a period when the vertical changes are slow, it is well to express it in the table, in order that the pilot may estimate about what length of time he may expect to carry a certain maximum or minimum draught across a bar or flat.

§ 11. It will be seen by an inspection of our second reduction that the variations of intervals and heights, to which we referred in § 8, are distinctly indicated; and if we plot these quantities, using the hours of moon's transits as abscissæ, as in the following sketch:



we discover that curves possessing some degree of regularity appear. These are called the curves of "*half-monthly inequality*," because the moon's hours of transit advance from 0*h.* to 12*h.* in a half lunar month.*

In our sketch we have given only the curves for high water, because our limited space does not admit of extending the diagram. In actual practice it will be found convenient to present, on a larger scale, the intervals and heights both for high and low water upon the same diagram, so as to furnish at a glance a compend of the tidal laws of the port. In drawing up a report of tidal observations, or in furnishing the statistics of a seaport, a diagram like that we have described will add scientific value to the tide table, and may also engage the attention of the reader where an array of numerical data would fail.

§ 12. One of the most striking features of the curves of half-monthly inequalities is the retard of the tide which they make apparent. The highest tides and the mean interval do not occur at full and change as might be expected, but a day or so after these events—a considerable period of time has elapsed between the creation of the tide and its propagation to our shores. This at once suggests to us that, in referring the tide of to-day to its next preceding transit, we

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* The synodical lunar month, the time from one conjunction or new moon to the next, is in the average 29 days, 12 hours, 44 minutes, and 3 seconds.

are not connecting cause and effect in their natural order; for the tide which reaches us to-day is but an offset or derivative from the true tide wave of mid-ocean, which was perhaps excited or raised by the sun and moon of several days ago.

Long series of observations are necessary to determine accurately the *age* of the tide, but curious and valuable results have already sprung from the inquiry.* At exposed stations on either shore of the North Atlantic the tide is at least a day and a half old, while on the Pacific coast of the United States it is scarcely a half day old. By determining the ages of the tide at different stations we may obtain a clue to its path, and ascertain whether the tides of different seas are of distinct origin, whether they interfere, &c.

§ 13. With regard to the number of tidal observations requisite for the construction of a tide table we cannot speak definitely. Although the principal variations are half-monthly, they are not coincident, so that it can very rarely happen that the deviations in the heights and intervals from the *true mean* will cancel in a single half month. By reason of the changes in the distance of the moon from the earth and the alterations of her angular distance from the equator, the heights and intervals of consecutive springs differ materially at times upon some coasts; the same may be said of consecutive neaps. As a general rule, *at least fifty-seven consecutive high waters and the corresponding low waters should be observed before a suitable tide table can be made for a chart.*

§ 14. When several tidal stations are occupied in a river, a bay, or an arm of the sea, the march of the phenomena is best represented by referring all the tides to the same transit, viz: that which precedes the high water at the entrance. The stations, in this case, should be furnished with time-pieces set to one standard, viz: the *mean time* of the entrance. This matter will require our attention again when we reach the subject of the disturbances of the tide wave.

§ 15. The tide table offers the means of making a rude prediction of the principal tidal phenomena, and the diagram of half-monthly inequalities gives the variations for different hours of transit. If the series of observations extends through a sufficient period, we may add three other important corrections, viz: those for the changes in the moon's declination, those for changes in the moon's distance from the

* The true age of the tide is that derived from the heights. Airy, Phil. Trans., 1845.

earth, and those for the changes in the sun's declination.* These three astronomical elements are independent of each other and of the moon's hours of transit, so that, taking observations for long periods, we may tabulate our tidal data according to the increase or decrease of any one of them while the others remain nearly constant at mean values; and thus, by successive groupings of the observations, we may evolve the corrections for the different positions of the heavenly bodies without recourse to special theory or the use of formulæ. The manner of procedure is as follows:

1st. To the table of *first reductions* add three columns, in which state the moon's declination, sun's declination, and the moon's horizontal parallax for each, from the Nautical Almanac. The second reductions made out for the whole series will give, as we have shown, the values for different hours of transit; and the differences between these values and the general means will be the corrections for those half-monthly inequalities which depend upon the moon's phases.

2d. From the first reductions take out the intervals and heights and arrange them in groups for every three degrees of declination, (irrespective of sign,) 0° to 2° inclusive, 3° to 5° inclusive, and so on to maximum. We shall then have, on taking the means in each group, eight values for intervals and heights, the differences between which and the grand means from the whole series will be the corrections for another class of inequalities of a half-monthly character, dependent upon declination.

3d. By another arrangement of the tabulations just mentioned, class the elements following *superior transits of north declinations* with those following *inferior transits of south declinations;* then class the elements following *inferior transits of north declinations* with those following *superior transits of south declinations;* making two classes of eight groups each, the differences between the means of the corresponding groups of which give the corrections for *diurnal inequalities*—the differences in intervals and heights of consecutive tides.†

4th. From the first reductions take out the elements for each minute of horizontal parallax and group separately; then take the means

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* The corrections for variations in the sun's distance from the earth are too small to require consideration in ordinary computations.

† In making the first reductions, with these subsidiary tables in view, it is well to distinguish superior transits and their corresponding heights and intervals from inferior transits and their elements by using differently colored inks.

Although in tides of the semi-diurnal type these inequalities are always presumed to be small, the cases are very rare in which they are wholly absent.

of each group and compare with the grand means. By this computation the corrections for the different distances of the moon from the earth, represented by her parallax, will be exhibited. These corrections are *half-monthly* in long averages.

5th. From the first reductions take out the average intervals and heights for the six pairs of opposite months, grouping January with July, February with August, and so on; then compare these with the grand means to obtain the corrections for half-yearly inequalities dependent upon the sun's declinations.

The five corrections which we have described are different for different ports, and especially so for different seas, so that no tables for general application have yet been arranged. A great deal has been done by Professor Airy and others towards the construction of formulæ which should make it possible to predict the tides of a port from a limited series of observations; but a great deal remains to be learned of the general laws of tides. For the full application of the numerical method we have described, we must refer the reader to the articles of Sir John Lubbock and Dr. Whewell, in the Philosophical Transactions of the Royal Society of 1834 and 1835. For the application of this method, as far as consistent, to a very short series, (four months,) and comparisons with theory by application of Professor Airy's formulæ, see an article by Charles A. Schott, Esq., entitled "Tidal Observations within the Arctic Circle," in the Smithsonian Contributions to Knowledge, 1865. This article is the most exhaustive of the data which it employs, and is perhaps the best example in the treatment of short series of observations.*

Tides of the Mixed Type.

Thus far we have spoken only of the tables for the tides of the semi-diurnal type, in which the differences in magnitudes and intervals for the two tides of the same day are insignificant; we now propose to consider tides of the mixed types, whose diurnal inequalities are so large that the tide table described in § 10 would be quite inadequate for practical use. For these tides we are obliged to resort to a different arrangement of the data, and more extended tables; but as the reader has become familiar with our phraseology in what has gone before, he will be prepared to comprehend each step without special explanation.

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* We are indebted to the Smithsonian Institution for an advance copy of this article.

As the tables for low water are constructed upon precisely the same plan as those for high water, we shall confine ourselves particularly to the description of the latter.

§ 16. Having made the first reduction, as in § 7, separate the heights and intervals following the *upper* from those following the *lower* transit. Next separate each of these classes into two others, distinguishing those belonging to *north* from those belonging to *south* declinations. It will be seen after this that the tidal elements following *upper transits* with *south declinations* are similar to those following *lower transits* of *north declinations*, and those following *lower transits* of *south declinations* similar to those following *upper transits* of *north declinations*. The same statement applies to the smaller tide and to the greater and smaller intervals.

From the data, classified as we have directed, two final tables are made out. These two tables differ only in the general heading. We give the form of one of them below.

Intervals and heights of high water for upper transit of south declination or lower transit of north declination.

Hours of transit.	Days before														Moon's maximum declination,		and after.													
	7		6		5		4		3		2		1		0		1		2		3		4		5		6		7	
	Int.	Ht.	Int.	Ht.	Int.	Ht.	Int.	Ht.	Int.	Ht.	Int.	Ht.	Int.	Ht.	Int.	Ht.	Int.	Ht.	Int.	Ht.	Int.	Ht.	Int.	Ht.	Int.	Ht.	Int.	Ht.	Int.	Ht.

Into the above table are put the heights and intervals which follow the *upper transit of south declination* and the *lower transit of north declination*, arranged according to hours of transit and days before or after the maximum declination of the moon. In a second table the heights and intervals following *lower transit of south declination* and *upper transit of north declination* are placed with similar arrangement.

One of these tables will be found to contain the greater tide and the lesser interval, while the other will contain the lesser tide and the greater interval.

If to these, two other tables of similar headings are added for *low water*, all the elements are complete. The navigator has then only to look in the almanac for the hour of transit, its kind, (whether *upper* or *lower*,) with the number of days from maximum declination, and then entering the table, he can at once reckon the time when the tide will occur, and its height.*

The heights in these tables are measured from a fixed plane, which should be stated. Mean low water, as computed from the data in the first reduction, is the best plane of reference for practical use, since it is the datum for the soundings upon modern charts.

§ 17. The highest high water and the lowest low water occur, usually, when the moon's maximum declination happens at full or change. If the zero declination happens with the moon in quadratures, the nearly equal tides are at their least average.

§ 18. The diurnal inequalities do not, at any station yet visited, vanish exactly at zero declination, but at some places they become insensible several days before and at others several days after the moon crosses the equator; in other words, the epochs of these inequalities do not coincide with those of declination. Again, the epochs of the intervals do not correspond with those of the *heights* for either high or low water separately; but the *intervals of high water* seem to vary with the *heights of low water*, and the heights of the former with the intervals of the latter. These peculiar relations of epoch and magnitude can only be studied critically by decomposing the observed tide into its diurnal and semi-diurnal components—a matter to which we shall presently refer.

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* In the "Tide Table for the use of Navigators, prepared by Prof. A. D. Bache, Superintendent U. S. Coast Survey," a different order of tables is given to avoid the reference to the *lower transit*. As we have all along used both transits, we are able to indicate a less complex system without fear of misconception and without the long explanation which a description of the method of computing the Coast Survey tables would require. Seamen use the word "*southing*" for the *upper transit* and "*northing*" for the *lower transit* in northern latitudes, but reverse those terms in southern latitudes.

§ 19. When the inequalities are at or near their maximum, we find at the stations on the northwest coast of the United States that *the greater fall is that which succeeds the greater rise, and the lesser rise is followed by the lesser fall.* A rule of this kind, when stated distinctly and concisely, has great practical value for the navigator; it assists him in the use of his tide table, and enables him to foretell at what time he may expect the greatest or the least depth of water over bars, and whether for any length of time he is likely to have a favoring or adverse current. This rule for our northwest coast seems to hold, less constantly, for the few tidal observations which we have seen from the Pacific coast of Asia.

In connection with the study of tides, we know of no field of inquiry about which so little is known as this of diurnal inequalities. In the Pacific Ocean, even where the tides are of medium height and well defined, the variations in the relative positions and magnitudes of the diurnal and semi-diurnal waves from point to point are not comprehended. From a few stations we have ample data, so that accurate local tide tables have been drawn up; but until we have observations from many other points we cannot hope to possess a connected view of the phenomena.

§ 20. In the present state of our knowledge information is wanted from the tropical islands of the Pacific and from the extreme northern portions of the same ocean; also from the coasts of Mexico, Central America, and the southern borders of the Caribbean Sea.

In the attempt to trace the march of the phenomena connected with the diurnal inequalities, it has been found a great advantage to separate the two elementary waves which compose the observed tide, and study their changes independently.

§ 21. Let us suppose that we have a connected series of very frequent observations for equal intervals of time extending through three lunar days, and that we designate these days as A, B, and C. We first take the mean of all the heights of each lunar day to find the *mean level;* then take out the ordinates of the tidal curves for each interval as referred to this axis for each day. If now we move the ordinates of A a half lunar day *forwards*, and those of C the same amount of time *backwards*, and add the corresponding ordinates to those of B, we shall have a column of sums which, divided by two, will give the ordinates of the semi-diurnal waves for the day B. By inspecting the diagram given in § 4, it will be readily seen that by this process the diurnal wave is eliminated.

We use *lunar days* and *lunar hours* because they represent equal intervals of *tidal time* very nearly. A lunar day is the time elapsed between two successive transits over the same meridian, and a lunar hour is one twenty-fourth of this period.

In order to avoid the half-monthly inequality in this method of decomposition, we move each set of half-day ordinates both forwards and backwards, obtaining in this way two sets of semi-diurnal waves, of which we take the mean.

As the mean level alters a little from day to day, it is well to regard our determination of it as the position for the middle of each day, and interpolate for the hours intermediate between one midday and the next, so that our axis of ordinates becomes an inclined or curved line.

Having obtained the ordinates of the semi-diurnal waves for any day, we have simply to subtract these from those observed on that day to obtain the ordinates of the diurnal wave.

By plotting the observed tides just as they are taken from the field book, and shifting the curves backwards and forwards with tracing paper, this method may be made a graphical one. In this case we need not compute the mean level, and we may regard half the time between one low water and its correspondent of the next day as a *tidal half day.**

Tides of the Diurnal Type.

§ 22. Tides of the diurnal type are usually small, and it is not, therefore, necessary to draw up elaborate tables for the use of navigators. The *first reductions* should be made in the usual manner both for high and low water, with columns of moon's declinations appended. In these reductions the transit used is shifted on passing the date on which the tide vanishes. If the superior transit has been used with north declinations, the inferior transit is to be used for south declinations, and vice versa.

The diurnal tide follows the moon at a decreasing interval. If we were to reckon by lunar days and lunar hours, we might say that the diurnal tide comes on earlier each day than on the day previous. The lunitidal interval is nearly constant for a few days at or near the time when the tide has its maximum range, (usually when the moon

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* This direct and simple method of decomposing tides is essentially the same as that devised by L. F. Pourtales, Assistant U. S. Coast Survey. In his own work this gentleman prefers the graphical mode to the numerical. See description in Mr. Schott's article on "Tidal Observations in the Arctic Seas," Smithsonian Contributions, 1860.

is at or near her greatest declination.) The greatest change of interval occurs on the day when the tide vanishes or passes its minimum range. At this time the variation is so great that the reappearing or newly growing wave seems to follow a preceding transit. By shifting back one transit for each reappearance, we are able to obtain similar intervals for the maximum tide of each half month.

§ 23. It is not a settled question whether the diurnal tide is continuous or actually evanescent. In the curves plotted from observations upon the northwest coast of America, the diurnal wave does not become insensible. Its range gets very small near the time of zero declination, and the point of culmination is ill defined, but the diurnal vertical change is always to be traced.*

§ 24. The information which the navigator requires relative to tides of the diurnal type is the following:

1st. The number of days before or after maximum declination at which the greatest tide of the half month occurs.

2d. The average range of this "greatest" tide.

3d. The lunitidal interval of this "greatest tide," and the daily variation of the interval for two days before and two days after.

4th. The number of days before or after zero declination at which the tide becomes insensible or passes its minimum.

The value of the first three data is obvious. The fourth is also important, since it furnishes to the navigator the dates of the tideless sea when the water remains nearly at *mean level*, and neither favoring nor adverse currents are to be expected.

§ 25. By a coincidence, the high water of the greatest diurnal tide falls nearly in the same sidereal hour, whenever it occurs, at the same place; so that a rule for the time of the tide may often be given which shall refer it to the southing of a familiar star or constellation—a rule like the following:

"At this port the greatest tide of each half month occurs (three) days after date of moon's maximum declination with its high water, at the time when (the belt of Orion) crosses the meridian."†

§ 26. For the proper study of tides of the mixed and diurnal types, frequent and continuous observations are necessary. It will not suffice to observe only the high and low waters, even if these are distinct

* Since there is a solar as well as a lunar diurnal tide, an absolute evanescence can very rarely occur.

† Pourtales' Rule.

phases, but the whole tidal curve for each day should be developed by recording the heights at least every fifteen minutes. Series of observations of less than a month are of little value for practical use in drawing up tables and rules for navigators, although they may serve, as we have before said, to indicate to what type the tides of a place belong. In classifying tides according to type, no very exact rule can be followed. We should call those tides *semi-diurnal* in which the maximum difference between successive high waters does not exceed the difference between springs and neaps; and those *diurnal* in which the existence of two tides in the same day cannot ordinarily be traced. From the data thus far collected, it would appear that the tides of our globe may, for the most part, be classed with the mixed type; notwithstanding that those of the Caribbean Sea, Gulf of Mexico, and China Sea are *diurnal*, and those of the Atlantic *semi-diurnal*. In the central islands of the South Pacific one station at least (Tahiti) is visited by semi-diurnal tides with the anomaly of an excess of the solar wave, so that, for the larger part of the year, high or low water occurs about the same hour of day; springs and neaps, however, are well marked.*

Mean Level.

§ 27. We have already used the term *mean level* in § 21, and explained the manner of computing it for one lunar or tidal day when continuous observations at short intervals of time have been made. It is the plane from which the tide waves rise and fall, and corresponds nearly with *half tide*, as this phrase is ordinarily used, if the diurnal inequality is insignificant. If the observations comprise only the heights of high and low water, and considerable inequality appears, the following method, employed in the discussion of the Arctic observations, (already referred to in § 15,) may be used: Having plotted the observations upon profile paper, take the mean of two successive high waters and plot with the proper ordinate directly over the intermediate low water. Repeat this till a point appears over each low water of the series; then through these points draw a line—this will be the line of average high water. Obtain the line of average low water in a similar manner—the points representing the

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* We refer here to the observations of Captain John Rodgers, U. S. N.—a remarkable series covering six months. If the opposite six months could be added to this series, the history of the solar tide would be complete.

mean of successive low waters being plotted directly under the intermediate high water. A line drawn midway between the two already described will be *mean level.* With the proper care in the grouping of the figures representing the averages, this method of obtaining mean level may be used numerically, and the diagram dispensed with.

§ 28. The plane of mean level is subject to changes of elevation, which appear to be independent of the tidal range, except in shallow places where the low water is considerably more obstructed as a travelling phase than high water. Not only does this plane remain at the same elevation for springs and neaps, other things equal, but it is known to be nearly the same for different derivations of the tide wave in several remarkable instances. The British Association ascertained from levelings between stations on the Bristol and English channels that the mean levels for these arms of the sea differ in height but 9 inches, although the mean tidal ranges are 35½ feet in one case, and 10 feet in the other. The writer of this article, in a recent physical survey of the approaches to the site of the proposed Cape Cod canal, determined that mean level during the dry season is essentially a common plane for Cape Cod Bay and Barnstable Bay, notwithstanding that the tidal range of the former is double that of the latter, and the establishments of high and low water, respectively, three and four hours later for the former than for the latter. These two tide waves were also observed upon at several points on the inside and outside shores of the islands of Nantucket and Martha's Vinyard, and the stations connected by lines of levellings which gave the same plane for mean level.*

Results quite at variance with those we have given were obtained by Mr. Airy from a discussion of the tides observed upon the coast of Ireland by the Ordnance Survey. If the levellings used by Mr. Airy are reliable, a variation in the height of mean level exceeding two feet may occur in the propagation of the same derivation of the tide wave in a distance of fifty miles.†

We have mentioned these results from different inquiries to show the want of further knowledge in this matter. In the location of railroads and canals, opportunities are offered for connecting different harbors and bays by lines of levels; and if, in these cases, the benches of tidal stations are referred to, and more than usual care exercised

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* Appendix No. 37, Coast Survey Report, 1856.

† Mr Airy on the Laws of the Tides on the Coast of Ireland. Phil. Trans., 1845.

in the levellings, very useful and important information may be gained.

§ 29. Theoretical investigations upon the laws of the tides show that periodical variations of mean level may be expected, dependent upon the declinations of the sun and moon; and those dependent upon the moon certainly appear at some of the stations at which careful series of observations have been made. At Plymouth, England, and at Boston, U. S., averages of many observations give about three inches rise in the height of mean level as the moon's declination increases from 0 to 25°, (north or south.)* Prof. Bache, in a discussion of the tides of Key West, (Coast Survey Report, 1853,) discovered half-yearly and half-monthly variations following, respectively, the declinations of the sun and moon, but in the reverse order, the greatest altitudes being reached at zero declinations. There are many stations at which no variations of this class can be distinctly traced; and unless the computer is furnished with at least six months' observations, he can scarcely trust the results he may obtain except as the most general indications of the existence and character of such variations. The uncertainty which attends the investigation of these small periodical oscillations arises chiefly from the difficulty of eliminating such irregular causes of disturbance as winds and barometric changes.

§ 30. In deep and open seas it is supposed that the winds produce only short undulations, but upon the boldest coasts long-continued gales from seaward raise the general level of the water sensibly. In shallow districts, in sounds and bays where the depths are inadequate for the restoration of equilibrium by the retrograde motion of particles lying below the influence of the winds, the water is actually driven forward and accumulated to leeward; and although at most tidal stations the irregularities of mean level caused by winds are often so large as to be detected in a general manner by the most cursory inspection of the data, they offer to the computer great perplexities. These effects are not usually eliminated by such a grouping of the observations as will cause the recorded velocities and directions of the wind to cancel, because winds from certain directions act at much greater advantage than those from others. A bay, for instance, may be sheltered by hills from off-shore winds, but particularly ex-

* The results from Plymouth observations are to be found in the Phil. Trans., 1839; those from Boston in unpublished computations of the Coast Survey Office.

posed to winds from seaward, so that the observer's record cannot be relied upon to represent accurately the forces which act upon the bay as a whole.

Observations of long duration are requisite for the proper measurement of the effects of winds; because the computer should be able to group, first, the data from a selection of quiet days, and, after this, the observations from dates on which strong winds prevail from each quarter separately; and yet, in all these groupings, there should be data enough to cause the other inequalities to cancel. In working up short series of observations for tide tables, &c., the tidal records made during storms should be rejected.

§ 31. The mean level is observed to undergo changes which resemble in character, and inversely correspond with, those of the mercury in the barometer. These changes are generally attributed to the unequal and varying pressures of the atmosphere upon the ocean. With this theory of the case, it may well be doubted whether the *local barometer* and the simultaneous reading of it are proper criteria for the pressures under which the changes in the elevations of the sea occur at a tidal station; but the comparisons have thus far been made in this way, and with pretty good agreements for different series at the same place, but with great discrepancies when results from different points have been compared. At Brest 1 inch fall in the mercurial barometer is attended by 16 inches rise of mean level, and the rise of the barometer by a fall of mean level in the same ratio. At Liverpool the ratio is 1 to 10; at London 1 to 17, &c.* Here we observe that stations not far apart give different results, notwithstanding that tidal series of many years' duration have been used in each case. With the theory of unequal pressures of the atmosphere we have to conceive of waves of unequal length, propagated, therefore, with unequal velocities, and differently modified by resistances, so that the ratios might be expected to vary from time to time and from place to place.

§ 32. Aside from the fact that these barometric variations of mean

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* Results given by Captain J. C. Ross in a paper "On Effects of Barometric Pressures on the Mean Level of the Sea." Phil. Trans. R. S. At Port Foulke, Greenland, the ratio is 1 to 4 nearly.

The Peninsula of Aliaska, and the Aleutian Islands, which separate the Sea of Behring from the Pacific, offer positions where (*with the barometers on either shore in agreement*—because not far apart) the effects of atmospheric pressures upon different oceans can be compared, and the propriety of referring these effects to the local barometer ascertained.

level are often too large to be neglected in tidal computations, the peculiar interest which attaches to them, in connection with meteorology, would seem to recommend them to special investigation. There are some familiar meteorological facts and theories that have peculiar significance in this connection. The oscillations of the barometer are much greater near the sea than elsewhere, and at many points on the coast a great rise or fall of the barometer is a forerunner of a long blow from a certain direction. Meteorologists conceive that the equilibrium of the atmosphere is restored by compensating currents which lie *side by side* in the temperate zones, but one above another in the torrid zone. All of the long series from which these variations of mean level have been thus far computed lie in the North Atlantic.

Barometric changes of mean level should not only be studied from observations at single stations, but from comparisons between stations simultaneously occupied, in order that the local features may be evolved and the general features connected. Comparisons between stations but a few miles apart on the coast would be useful for tracing individual cases, and the mean results from stations widely separated in latitude are much wanted for general comparison. Again, the variations for *rising* and *falling* stages of the barometer should be separately compiled and then compared.

The mean level rises from station to station as the point of observation moves up a tidal river, giving, when determined, the true slope of the stream precisely as it would have been if no tides traversed it.

§ 33. In all projects for the improvement of tidal harbors the mean level is an important datum plane, so that a careful determination of it is indispensable to the engineer. It is for him the proper plane of reference for the soundings and the tides, especially in places where no fresh-water feeders exist, since it is not only more general and permanent, but more easily obtained and recovered than any other stage. In preparing charts for navigation, however, the plane of *low water* has been found most acceptable to the pilot who chiefly desires to know the minimum depth under ordinary circumstances.

For the charts issued by our government, the plane of reference is the mean of all the low waters observed if the tides belong to the semi-diurnal type, and the mean of all the *lower* low waters if the tides belong to the mixed type. It would be a good custom to give upon all charts the height of mean level. In the case where the tides belong to the mixed type, the few tidal observations that can be made during the progress of the survey are usually insufficient for the accurate determination of the low-water reference, but might suffice for obtaining the mean level very closely. In places where the tides are diurnal, there are several days in each fortnight when the surface of the sea remains at or near the mean level. In this case a statement of the position of this plane would enable the navigator to correct his chart accurately on certain dates by applying the constant to each sounding.

Bench Marks.

§ 34. At each tidal station a *bench mark* should be made, to which the zero of the tide gauge should be referred. If, in the neighborhood, there is a solitary sharp-topped rock, known by name, or easily described, which is only covered at a certain stage of the tide, it may serve as a bench if the observer records its position, name, and the height of the water upon his gauge at the instant when its highest point disappears. If the waves make this record a little uncertain, the observation should be repeated on several quiet days. A bench of this kind should not be too distant from the shore, because such marks are often used in the location of railroad tracks, canals, and other structures where levellings are required.

Where a bench is made on shore it should be marked by a circle of two or three inches diameter with a cross in the centre, indicating the reference point. The levellings between this point and the gauge should be run over twice, and the details recorded. A bench made upon a wharf or other perishable structure is of little value, but in the absence of permanent objects it is better than nothing. Portions of piles, never exposed above water, remain sound for many years. In all cases the marks should be *cut in* as deep as convenient, if on stone, and if on wood copper nails should be used.

§ 35. A bench mark should always be made in connection with a hydrographic survey. It affords the means of recovering at any future time the exact plane of reference of the soundings, and makes the chart valuable for comparisons when the discovery of new rocks or the formation of new shoals makes a partial resurvey necessary. Many of the old charts, bearing evidences of careful work, are now useless for comparison because the reference planes for the soundings cannot be recovered.

A bench mark has value from a geological point of view. In many parts of the world the relative elevations of the land and sea are changing by the gradual rising or subsidence of the former; and notwithstanding that these changes are usually very slow, they have already been accurately measured in some parts of Europe.

Propagation of the Tide Wave and the Changes of its Figure.

§ 36. Wherever upon the same coast the observations have been carefully made at several stations equally exposed to the sea, there has been discovered a connection or mutual relation between the tides of different points, so that they could be recognized as progressions or propagations from a single-wave system. At such stations the visits of the tide preserve nearly the same relative order of times, indicating that the approach of the wave is always from the same direction. We may conceive of high water as the crest and low water as the hollow of this great undulation. If upon any straight shore the high waters occur at the same time from point to point, we conclude that the direction of the tide is at right angles, or, what amounts to the same, that the wave advances with its crest parallel to the beach. If, on the other hand, the times of high water are later and later from point to point on this shore, we conclude that the approach is oblique to the coast line. It is by comparisons of this sort that the positions of the crest lines of the tide wave for stated hours have been plotted upon charts, under the name of *cotidal lines*, by Young, Lubbock, Whewell, and Bache.*

These charts of cotidal lines may be regarded as essentially complete for the shores of Europe and of the United States, but for other parts of the world comparatively little has been done. Indeed, the cotidal lines already determined furnish little or no clue to the course and rate of travel of the ocean tide. Even for the North Atlantic no connection has yet been discovered between the tides of the opposite coasts, and the absence of islands to furnish the intermediate links makes the problem a very difficult one. The Pacific Ocean offers a better field for efforts of this kind, because, in its broadest portion, the numerous islands may furnish stepping stones for the inquiry. It is probable that the tides in the middle of this ocean are very small and much disturbed by prevailing or periodic winds, but these things should not discourage the efforts of the inquirers.

As the tide approaches a continent it is retarded; and its length, although still essentially the same as measured in *time*, is much reduced in space upon the earth's surface.

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* They were first suggested by Lord Bacon in an essay called "The History of the Wind."

The velocity of the tide wave is dependent, almost exclusively, upon the depth of water in which it is propagated; but the changes of range appear to depend less upon variations of depth than upon those of width.

§ 37. The true velocity of the tide wave is that of its crest. Comparisons of the times of high water along the tidal path show fewer inconsistencies with each other, and with theory, than those of low water. The cotidal lines drawn from the mean lunitidal intervals of high water (using the same transit over the same meridian) seem to confirm Mr. Airy's rule that "*the velocity is the same as that which a free body would acquire by falling from rest, under the action of gravity, through a space equal to half the depth of the water.*"*

As the tide wave approaches a shallow coast its range is, as a rule, slightly augmented, and this augmentation is perceived to bear some relation to the diminution of distance between the cotidal lines; but where the wave enters a bay or arm of the sea whose shores converge, the increase of range is often very great, and in rivers an increase of range is often found at points where the area of the cross section lessens. The contrasts of range which the tides of different ports present, however, are not fully accounted for. A very interesting and instructive method of pursuing this inquiry is to prepare charts with lines of equal range. This has been done for our Atlantic seaboard, and the dependence of the heights upon peculiarities in the configuration of the coast well illustrated.†

§ 38. If, by simultaneous observations at many different stations, an entire tide wave could be followed through an arm of the sea of which a thorough survey has been made, it might lead to a better understanding of the circumstances under which the changes of range occur. We should be able to compare the volumes from point to point with the widths, depths, sections, &c., at each stage of the tide. We have not yet obtained the history of an entire tide wave, except in certain rivers and bays where the conditions are complicated.

§ 39. It has been ascertained from the little data we possess, that, in localities where the diurnal inequalities are large, on passing through straits or into arms of the sea, the two elementary waves, the

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* "Tides and Waves." Enc. Metropolitana, page 292.

† See paper "On the heights of the tides of the Atlantic Coast of the U. S., from observations in the Coast Survey, by A. D. Bache, Supd't." Proceedings of the Am. Association of Science, 1857.

diurnal and semi-diurnal, alter their relative positions and ranges in a manner that thus far seems to baffle inquiry. Several suppositions may be made respecting the causes of these changes, and we shall mention the most probable of them in order to explain some of the suggestions we shall have to offer for the manner of pursuing the investigation.

1st. Since the waves have different masses, they may be supposed to be differently affected by resistances—the diurnal may outlive the semi-diurnal and appear without its companion; or the same causes may augment one more than the other.

2d. The two elementary waves may have different rates of travel as the wind waves are observed to have, which would alter their relative position from point to point, and also give contrast to the effects of resistance. It would appear from the observations made in Puget Sound, that in this place the diurnal waves travel with double the velocity of the semi-diurnal. Within certain limits the length of a wave enters into the function of velocity. The diurnal wave is the longer, and in a shallow sea might be expected to preserve a greater velocity than the semi-diurnal.

3d. Two branches of the tide may interfere in such a manner as to reduce one of the elementary waves more than the other. Let us instance an extreme case: suppose two equal tides, whose intervals differ six hours, should meet; the resulting tide would be diurnal in character, because the semi-diurnal waves would cancel each other, the crest of one falling directly upon the hollow of the other, and a compound of the two diurnal waves would remain.

If the change of diurnal inequalities occurs high up in a bay or in a lagoon, make several stations, one of which should be at the mouth, another at the head, and others intermediate. These should be simultaneously occupied, and the results arranged for decomposition. When these decompositions are made, observe whether one of the elementary waves steadily decreases, or is retarded, or is distorted. Ascertain the depths along the channel-way, and with these depths and the distances between the stations endeavor, by repeated trials, to discern relations between them and the tidal changes observed. If the bay or lagoon is very broad, but with only a narrow inlet, both of the elementary waves will undergo *degradation;* that is to say, they will be flattened out laterally so as to have less range. Observe whether the shorter wave suffers more degradation than the longer. By watching the ordinary wind waves as they enter lagoons, one may notice that the long swells of the ocean penetrate much farther before becoming insensible than the short ones. Even on the supposition that the diurnal and semi-diurnal waves are not distinct undulations, it is obvious that in a lagoon the elevations and depressions will represent most conspicuously those features of the tidal figure which are of the longest duration, other things being equal. An elevation of the sea above its mean level for six hours may not raise the surface of a lagoon perceptibly, because the inlet may be too small to admit a sufficient supply of water in this short period of time, but a rise of double this duration might, perhaps, sensibly elevate the water in the basin. We may conceive an extreme case where the surface of an extensive lagoon is unaffected by the tides of a single day, but which, nevertheless, rises or falls gradually with the *mean level* of the ocean as the moon's declination increases or decreases.

If the peculiar change of diurnal inequality is observed in a strait having two entrances from the sea, make simultaneous observations at three stations—one at each entrance and the third midway. Then ascertain by trials whether the intermediate tide is a compound of the extremes. The first step in this undertaking will be the reduction of the three tides to the same zero of times and heights. The mean level of the sea may be assumed to be a plane common to all, and the ordinates referred to this axis taken out for the same equal periods of time for the several stations. The simple addition of the corresponding ordinates of the extreme stations, with due regard to signs, will give a compound curve, which should be compared with the middle tide observed. It will probably differ considerably in form, because it is hardly likely that the two waves approaching from different directions can, in their journeys from the entrances to their meeting point, have suffered equal delays and changes of range. This comparison will suggest what constant of time and coefficient of height may be required by one or both of the components to make a combination more nearly resembling the middle tide observed. This amounts simply to shifting the relative positions of the extreme tidal curves upon their axis of abscissæ and multiplying the ordinates of one or both by a whole or fractional quantity, and computing successively different compound curves for each change. By repeatedly subtracting the newly computed compounds of the extreme tides from the observed intermediate tide we may obtain at last a combination giving the least possible residual; and if this residual, upon plotting, indicates no recurrent forms, and is very small, we conclude that we have decomposed the interference tide and fully accounted for its peculiarities. In this manner of resolving interferences, we are not obliged to decompose the extreme tides into diurnal and semi-diurnal waves, so that we avoid many perplexities.

In the cases of interferences which have been examined on our eastern coast, where the tides are semi-diurnal in character, the observed interference wave has been found to bear evident traces on its profile of its twofold character. The meeting waves are usually of dissimilar heights, and their difference of outline, hardly perceptible when single, is made evident and exaggerated by combination. There are four high waters each day at the meeting point of the tides near the junction of the Nantucket and Vineyard Sounds, and these are distinctly exhibited in the profile of the observed tide. A combination has been made of the observations at the extreme limits of these sounds which compares well with the observed tide at their meeting place. In this instance a fractional coefficient of heights had to be applied to each of the simple waves to make their compounds agree with observations; that is to say, by the local action of gravity, the contrasts of heights, offered by the two tides, were found to be, in part, reconciled.

§ 40. The tidal curve undergoes changes of figure after leaving the open sea and passing into harbors or rivers, and these changes have been studied at places where improvements to navigation or the reclaiming of lands have given practical value to the information. In some instances the distortions of the tide are very marked, and afford a curious insight to the physical relations existing between it and the avenue traversed; so that information of this kind has often more than local value.*

Before we proceed to speak of the manner of exhibiting these changes, it is necessary to define the terms which we shall have occasion to use. Let us suppose that we have plotted upon profile paper a day's tides of the semi-diurnal type. If we draw the line of mean level across our curves, we cut them into two portions—*positive* and *negative* waves. The positive wave lies above the mean level and culminates in high water; while the negative wave lies below the mean level, and its apex is low water. That portion of the line of mean level which lies between the rising and the falling curve is

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* For method of combining the curves of different dates, so as to ascertain the average form, and represent this by a mathematical expresion, see Airy, Tides and Waves, § 479; and in this connection see also "Development of Bessel's Functions for the Effect of Periodic Forces." Appendix No. 22 of Coast Survey Report of 1862.

called the *diameter*. The distance between two successive low waters as we have already stated, is called the *length;* it is measured in *time* along the base of the tidal figure as we plot it. Lines parallel to the diameter are called *chords*, and a line drawn down from high water so as to bisect the chords, the diameter, and the base, is called the *vertical axis*.

§ 41. The figure of the normal tide, that observed near the open coast, is nearly a curve of sines from a circle of the same *diameter* whose radius is half the entire range of the tide. This statement applies to the tide at the time when no diurnal inequality exists, or to the decomposed waves at other times.

Let us suppose the diameter of a certain tide to be divided into six equal parts which we may call *tidal hours*, (they will be a trifle over one clock hour each,) then the ordinates of the theoretical curve will be simply four repetitions of the multiples of the sines of 0°, 30°, 60°, and 90°, the first and last set having the minus sign. If the half range of the tide is unity, then the theoretical tide will be — 1.00, (L. W.,) — 0.87, — 0.50, 0.0, + 0.50, + 0.87, + 1.00, (H. W.,) + 0.87, + 0.50, 0.0, — 0.50, — 0.87, — 1.00, (L. W.)

A mere inspection of the plotted curve of observations will usually show whether it approximates to the normal form. If the profile of the tides corresponds with the curve of sines exactly we shall have the following results: The rise and the fall will be reciprocals, the durations and the rates of rise and fall for corresponding stages will be equal, and the chords in each case will be bisected by the high-water ordinates. The tide upon the open coast answers to these tests under favorable circumstances; but an advance of only a few miles into a bay or harbor usualiy changes them all in a remarkable manner. The fall is no longer the reciprocal of the rise; the maximum rates of both rise and fall are obtained later—that is to say, at greater interval after high or low water—and the chords are no longer bisected by the high-water ordinate. Moreover, if we obtain data from several stations at different distances from the open sea, we may follow the progress of these changes somewhat as follows: the length of the wave, measured in time, remains pretty much the same, but the lengths of the chords grow less; in other words, the wave sharpens and the axis becomes inclined to the horizontal. This last change may be stated in other words, thus: the positive portion of the wave preserves more of the original impulse and hastens forward at a greater speed than the negative. By plotting the tide and drawing the chord, say for every vertical foot of the entire height, then drawing the axis, this tendency of the tide wave may be exibibited to the eye. It is essentially the same change as that which we observe in ordinary waves upon the sea shore. Their crests appear to hasten forward as they come upon shallow ground, the front of the wave gets steeper, and ultimately the crest falls over, forming a *breaker*. The phenomenon called the *bore* is supposed to be a similar action of the tide, but we have no careful observations to show this.

The sharpening of the tide wave is often observed at points nearer the sea than those which give a reduction of range; showing that the *order* of the influx or reflux is altered, but not the total effect. Some quality of the channel is accountable for this change.

§ 42. The changes in the figure of the tide to which we have referred are those which seem to be caused by the resistances of shallow and confined paths, but the precise manner in which these causes act is not known. In some bays which have few or no fresh-water feeders the rise of the tide occupies a longer period than the fall. Whether this is a general rule for bays of this character we are unable to say—it would seem opposed to the idea we have formed of a shoreward impulse of the tide wave. It may be, however, that the inclined bed of a bay resists the influx but favors the reflux of the tide. In rivers the opposite relations for durations of rise and fall obtain.

§ 43. It will sometimes be found, on analyzing the tide, that the vertical axis is curved out of place near the middle of the figure. When this is the case, inquire if any obstacle lies in the path of the tide, and whether this obstacle affects the rise more than the fall. Tides above bridges have their vertical axes curved as we have described, and the amount of disturbance caused by a bridge has been measured in this way.*

We speak of any tidal phase as an *approaching* phenomenon, and we speak correctly, for the times of both high and low water are later as we go up a bay or harbor; but we are not to conceive that the water particles are always pursuing a single direction; on the contrary, they approach the land on the flood and recede from it on the ebb. It is no doubt true that the tide wave, in mid-ocean, is propagated without requiring any essential alteration in the geographical position of water particles, it being simply necessary that each particle should move in an ellipse whose axes measure but a few feet.

The best idea that we can present of the tide of a harbor is that

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* Tenth Report of U. S. Commissioners on Boston Harbor.

of a bodily movement of water under pressure. When, on a rising tide, the sea without is higher than that of a harbor, a grand movement of the water takes place, a pushing in to restore equilibrium. In this operation a single water particle may have to make a considerable advance, but the motion is communicated to the particles beyond by *impact*, so that it is not necessarily a pouring in of an entirely new supply, although, in small creeks, it degenerates into this. So long as there remains the smallest horizontal film of water in a channel the tidal propagation does not wholly degenerate into a current—*the phases will still travel faster than the water particles.* High water and low water are phases that are always *moving up* a river, but the current may never actually cease to run down. This current must, however, receive at least a check before any rise can take place, and this check causes the "*backing up*," which is the usual phrase applied to river tides.

§ 44. In the tides of harbors or confined channels, the greatest activity among the water particles is excited at or soon after half tide, because then the ocean rising or falling most rapidly creates the greatest disparity of heights between itself and the basin, and induces the most powerful efforts of gravity to restore equilibrium. If the axis of the tide is thrown out of place near the plane of mean level, the observer will at once perceive that something obstructs the free passage of the water and breaks up the continuity of its transmitted motion.

§ 45. The tides of rivers are but imperfectly understood. Their peculiar characteristics may be summed up as follows:

The duration of the fall is much greater than that of the rise; or, in other words, the phases of the rise travel up the stream much more rapidly than those of the fall, if the inland or fresh-water supply is considerable.

The ranges of the tide vary with the width, depth, and irregular course of the channel, but in a manner not yet reduced to rules.

The *mean level* rises as we go up a tidal river, but to what limit is not known. Instances are known of rivers up which the tides advance till the low water of the upper reaches attains the same absolute height as the high-water level at the mouth.

In some rivers double tides occur, giving two high waters within a few hours of each other, with an intermediate fall of small extent.

In some rivers the tides at certain intermediate stations are observed to have greater ranges than at points above or below, where no causes connected with form or dimensions of the channel are reported.

River tides should be studied from simultaneous observations at different points, and careful gaugings of inflows and outflows. Many of the phenomena connected with the varying ranges may be traced to alterations in the length of the base, and the chords of the tidal figure measured in *space* as well as in *time*. If the stations are sufficiently numerous and well disposed, profiles of sections along the channel-way can be plotted for every hour, so as to reveal the experiences of every phase of the rise and the fall. If changes in the rate of travel for different phases between the same stations are observed, they may be traced to the alterations of depth and width of channel due to the tide itself, or they may result from the setting back or return of the current higher up the river. A relation may, perhaps, be found between the slope of the river bed and the rate of travel—a comparison of the rising with the falling phases may be suggested in this connection.

The tides of high stages of the river should be compared with those of low stages. If the sea water underruns the river in dry seasons, as it does in the Hudson for many miles, some curious facts may be evolved from this comparison, especially as regards the *surface slope* and that of *mean level*.

Observations of river tides should be, when convenient, accompanied by current observations at different depths, and by hourly trials of specific gravity at the surface and near the bottom. A complete history of a tidal river has not yet been compiled, and till this is done by patient labor, there is little hope that the various phenomena will be connected and interpreted.

§ 46. There are some facts easily collected with regard to rivers which are always of practical value, viz: The farthest point reached by the tide at springs and at neaps, in dry and in wet seasons; whether at any former period—before the building of a bridge or the formation of a sand-bar or other encroachments—the tide was felt higher up the stream. The distance to which the flood tidal current and slack waters extend during the dry and during the wet seasons. The point where the ranges begin to lessen, and the average rate of this decline above. The difference of mean level between the lowest and the highest fresh-water stages at several points, and the approximate rates of outflow. The limits of salt or brackish water in wet and in dry seasons. The limits of ice, duration of its stay, usual time of breaking up, danger to vessels at anchor, &c.

§ 47. At some stations a singular indenture occasionally appears in the tidal figure about the time of high water—instead of a stand, there is a falling away of the water for a brief interval, and then a return to about the same height. Interferences sometimes produce such effects, but these are repeated from day to day. Where the phenomenon is only occasional, it may be the effect of long swells from sea which become conspicuous near the stand, but would not be noticed during the rise or fall. On our Atlantic coast this indenture of the profile is only observed at stations very much exposed. Under ordinary circumstances the ocean is not traversed by any waves intermediate in magnitude between the tide and the "rollers" which break along our shores, and the comparative lengths of these two wave systems may be judged from their times; the tide passes any given point once in twelve hours, while the time of the ordinary swells at the same point will not exceed as many seconds.

At rare periods the sea is troubled by earthquakes, which create undulations which, once in motion, continue for several days, and extend perhaps from continent to continent. These waves are too long to produce any sensible roughening of the sea at a distance from their origin; but they discover themselves by the unusual elevations and depressions of the water in quiet ports—not perhaps unusual in the matter of *height*, but more especially in that of duration.*

Now that permanent tidal stations are kept up on both the Atlantic and Pacific shores of our country, the visits of these strange waves cannot escape critical observation; and if they are accounted for by distant earthquakes of which the time and place are reported by voyagers, they may lead to much knowledge of the character of such undulations, their rate of travel, longevity, depth of the ocean, &c.

Tidal Currents.

Tidal currents are rarely sensible far from land, since they are called into activity by the delays and the distortions of the tide wave consequent upon the resistances of shoals, or confined and shallow

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*The earthquake waves of December, 1854, which were observed on the gauges of the Coast Survey on our Pacific coast, were perhaps the longest swells ever measured, yet the longest of these did not exceed 35 minutes of time, or less than one-twentieth the length of the tide. These waves crossed the Pacific from the neighborhood of Japan, at a rate of travel exceeding 350 miles per hour. (See notice of earthquake waves on western coast of the U. S., 23d and 25th Dec. 1854, by A. D. Bache, Supt. U. S. C. S., Am. Ass. Science.)

channels. As a general thing the observer's station will be a vessel or boat at anchor within sight of the shore.

§ 48. The elements for a table of tidal currents are obtained by very simple means, and the following set of rules will be found a sufficient guide to the observer:

I. The observer designing to measure the currents of any particular channel should select straight portions of the water-way, and anchor or moor his vessel in the axis or thread of the stream.

II. For position he may take angles from his vessel on three or more determined objects on shore, suitably situated; or if these do not exist, he may measure a base line on shore, and by triangulation fix the position of his vessel and develop the neighboring shore line on either side of the channel-way. The article on surveying in Bowditch's Navigator may be referred to in this connection.

III. The immediate objects of the current observations are three-fold.

1st. The determination of the velocity, which is obtained by the use of the log-line and a time-piece. 2d. The epochs of slack water. 3d. The direction of the flow, which is determined by the use of a sextant or a compass.

IV. The log-line must be examined each day, and the error in its divisions due to its stretching or shrinking must be ascertained and noted.

V. The log-line is divided into a certain number of parts, and these are so arranged that, passing off the reel during a period of thirty seconds, they measure the motions of the log in nautical miles and decimals per hour. The larger divisions are marked by leather straps, in which holes are perforated indicating the number of miles. The straps are secured to the line at intervals of fifty feet, eight and one-half inches (more nearly 50.72 feet.) Each mile is divided into tenths by nine knotted cords placed at equal distances between the leather straps. The number of tenths is indicated by the number of knots upon each cord. Each of these smaller divisions is five feet and seven-eighths of an inch in length, (more nearly 5.072 feet.)

VI. There should be at least sixty feet of *stray line* between the float and the zero division, in order that the float may drift out beyond the eddies of the vessel before the measurements commence.

VII. In making an observation on the current, one man holds the reel while another notes the time. When the log is cast and the stray line is run out, the person holding the reel cries, *Now;* the person with the watch repeats the signal, notes the position of the second hand, and when thirty seconds have elapsed, cries out, *Stop.*

The person at the reel now notices to what division the line has run out, and without restraining the log, the experiment is repeated in precisely the same manner as that described, except that in this latter case some even division of the line is chosen as the initial point, instead of the zero, as in the former observation.*

VIII. A pair of observations for velocity having been taken, the log is still suffered to drift until the angle which its line of direction makes with some known point on land is carefully measured.

IX. In selecting the fixed object to which to refer the directions of the current, the observer should give the preference to the most distant, in order that any error in the determination of his position may not so materially affect the accuracy of his observation.

X. Angles of direction should always be measured with the sextant, where its use is possible; but if by reason of darkness or thick weather no fixed objects upon the shore can be seen, the observer must note the direction by compass in degrees, as N. 43° E., &c. Richie's "liquid compass" is the best now in use.

XI. After using the compass for such purposes, the first opportunity should be improved for checking the error of the needle.

XII. The observations would better commence at *slack water*, and after continuing a half day or a day, terminate with the *commencement* of a *flood* or an *ebb*.

XIII. The velocities and directions should be noted at least every thirty minutes while the drift is strong, and more frequently as its motion fails, in order that the exact times of cessation and commencement of current may be obtained.

XIV. If the current turns without absolutely slacking, the nature and progress of this turning should be ascertained by repeated observations made at least once in five minutes. In this case, the times of most rapid change of direction and the least velocity must be obtained.

XV. Soundings should be made and the depth of water noted at every slack water.

XVI. The direction and force of the wind, together with the appearance of rips, eddies, and any other interesting phenomena, should be observed.

XVII. The observer's watch should be set to mean time each day.

XVIII. The most convenient form of record is the following:

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* The half minute sand-glass is used in ordinary observations, but the watch is preferable, because the former alters its rate with the humidity of the atmosphere.

Current Observations.

At [No. of station and locality.] (Date.)

Angles for position. {

Time.		Angle of Direction.			Veloc'y per Hour.		Wind.		Remarks.
Hours.	Minutes.	Float Right or Left.	of	°	Miles.	Deci-mals.	Direc'n.	Force.	

§ 49. The current table, if intended to accompany a chart or sketch of a harbor, should be of the annexed form.

Station.		Cur't Turns after Moon's Transit.		Maximum Velocity.				Duration.		Slack.		Remarks.
No.	Local-ity.	Flood to Ebb.	Ebb to Flood.	Flood.	Direc-tion.	Ebb.	Direc-tion.	Flood.	Ebb.	Flood to Ebb.	Ebb to Flood.	

The time of turning is the middle of slack water, and the intervals as well as the durations are reckoned from this time. In the column of remarks it should be stated whether the directions are magnetic or true bearings; and if the former, the variation of the compass should be given.

As currents are much affected by the winds, it is better to occupy a station for a single calm day, and correct the results for mean value by tidal comparisons, than to carry the series through a semi-lunation of variable weather. The tides in deep channels are but little affected by the winds, so that if guage observations are made on the day when the current station is occupied, and kept up through not less than a semi-lunation, the means are afforded for correcting the current observations for half-monthly inequalities. By comparing the tidal intervals of this particular day with the mean establishment, we shall find what to add or subtract from the current intervals and durations.

§ 50. The corrections for velocity may be made by the following rule: *the velocities of the currents for corresponding hours of different tides are to each other as the rates of rise or fall at these hours.* With the use of this rule the hourly velocities may be computed for tides of the mean range, for springs and for neaps, from not less than twelve hours' current observations made under the most favorable circumstances. The rule is applicable to places where the figure of the tide remains essentially the same from point to point. It is not applicable to inlets or lagoons, nor to very shallow channels.

§ 51. Strictly speaking the flood and ebb currents which we observe in channels have no direct dependence upon the range of the tide, nor upon its rates of rise or fall, but upon the *slope* of the water's surface. They are bodies of water flowing under *variable heads,* and the *observed* difference of level is that portion of the head which is balanced by the resistances of the channel and the inertia of the mass of water.*

A closer and more generally applicable rule, therefore, for correcting velocities, is the following: at the same station, *the velocities for corresponding stages of different tides are to each other as the square roots of the observed heads.* We use the word stages here to signify depths of water; corresponding stages, therefore, give equal sections and wetted perimeters.

§ 52. The heads of the tidal current may be obtained by placing two gauges on the border of the channel—one above, the other below the current station—and subtracting the observed heights one from the other, after referring their zeros to the same datum plane by levellings.

If the channel is deep and straight, *mean level* may be assumed to be a common plane, and the heights referred to this, avoiding thus the use of a levelling instrument. If a comparison of the velocities is made with heads observed in this way, it will usually be found that maximum velocity occurs at a brief interval after the time of maximum head, and that motion ceases soon after the head becomes zero. If the two gauges are observed upon for at least a semi-lunation, the means may be obtained for correcting the epochs and velocities of a day's current observations in the most exact manner.

At many ports, even where the rise and fall of the tide is very small, the tidal currents are strong, and correct tables of them have

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* A tidal head is not the measure of angular and frictional resistances in the same exact sense as the head of a river or canal in permanent motion. The conditions of a tidal stream resemble those of a river when a rise is coming down in the form of a swell.

great value. At such places the time of high or low water may be shown very indefinitely by the nicest observations, but the time of restoration of sea level may be easily and closely ascertained. The inlets on our Atlantic coast present cases of this kind.

§ 53. The relationships between the forms of channels and the velocities of the tidal currents which traverse them are so intimate, that a knowledge of the tidal range at any place furnishes no adequate guide for estimating the velocities or even the times of the currents. In ports that are open to the sea the tidal currents are usually feeble, while in ports communicating with the sea by narrow avenues they are usually strong. At the entrance to the Bay of Fundy, where the tides have a range of fifteen feet, they are not so strong as at the entrance to Mobile Bay, where the tidal range is less than two feet. In the former case the tide wave moves rapidly and without sudden changes of figure, while in the latter it is retarded, and, having to pass through a narrow inlet to a broad basin, undergoes a sudden *degradation* which produces a contrast of elevations between the ocean without and the bay within.

§ 54. A *degradation* of the tide wave is always accompanied by a change of epoch in the tidal currents, because the time of restoration of sea level is changed. At inlets communicating with extensive inland basins the phenomenon of "*tide and half tide*" often occurs. The inlet being narrow, the tide wave which enters is scarcely able to raise the general surface of the basin, which remains, therefore, nearly at the mean level of the sea; so that restoration of level between the basin and the ocean occurs at or near time of half tide both on the ebb and on the flood. Instead of having slack water at or near the times of high and low water stand, we have at these times the strongest flood and ebb. The phrase "tide and half tide" has been applied to such inlets by those who conformed the rise and fall with the horizontal motion of the water. One may frequently hear the remark "that the tides rise earlier on the shore than in the channel-way;" the more accurate statement is, that the epochs of the tide precede those of the dependent currents.

§ 55. It is usually of more practical importance to the navigator to be accurately informed of the currents at inlets than of the tides, because the former are usually very strong in the very localities where the latter vanish.

§ 56. If a sound or harbor is visited by two branches of the tide wave entering by two different and widely distant avenues, a certain intermediate district will be the scene of alternate drifts which cannot be characterized by the words *ebb* and *flood*, since they are interchanges of water between two wave systems which have disturbed the sea level near their place of meeting by their contrasts of time. These interchange currents have peculiar epochs which have no dependence upon those of either tide separately considered, but follow the times of restoration of level between the two tides. In a case of this kind the observer will be presented with three sets of currents; each tide will be accompanied for a certain distance by its normal drifts, and the intermediate space will be occupied by the interchange drifts. Three stations, properly located, will give him the order of luni-current intervals, and perhaps the characteristic velocities; but this will not be all the information required to meet the practical wants of navigation. The limits of each of the three current districts should be ascertained, and if these limits are the scenes of conflicts or stagnant water, full descriptions should be given. At or near each of the entrances to the sound or harbor, the best position of current station will be found for giving the normal epochs; and the point at which the tides meet will be that of which the *interchange current* is most steady and strong.

The most violent tidal currents which occur in navigable channels upon our coast are those of Hell Gate, New York, and those near the junction of Vineyard and Nantucket Sounds. In each of these cases the drifts are called into activity by the meeting of two branches of the tide wave, which, approaching by different paths, after undergoing different experiences, present to each other a contrast of elevations.

§ 57. In confined and tortuous channels of small depth, the maximum velocity of the current does not occur at half ebb or half flood, but perhaps a half hour or an hour later, because the water-way is so inadequate for the conveyance of the tide that the contrast of elevation of the water above and below goes on increasing with the rise or the fall till some time after half tide. If this state of things appears at a station the current table should contain a remark upon it, or, in an additional column, the time of maximum drift should be given in hours and minutes after that of turning.

§ 58. The epochs of the currents upon shoals are usually earlier than those of the neighboring channels, partly because large bodies of water, by reason of their inertia, continue longer in motion or less readily submit to a change, and partly because upon shoals the water moves under the more immediate influence of local tides. It is of considerable importance to the navigator to be made aware of these differences of epoch which cause rips and whirls along the margins of shoals at certain times of tide.

§ 59. Very little is known of tidal currents on outside coasts except in the immediate neighborhoods of certain dangerous shoals. A knowledge of them would, however, be often a great advantage in the saving of time in the passages of coasters. To the want of tables of the coastwise currents the loss of vessels has in several instances been attributed. Coasters frequently lose their reckoning in quiet and thick weather by being swept out of their courses by these drifts. The coast currents in some places have a velocity of a third of a mile per hour in thirty fathoms water. They are, in some localities, nearly parallel, in others nearly normal, to the general trend of the shore line; and, as far as the few observations we have seen may indicate, the directions of ebb and flood are not usually opposed, although lying at an oblique angle with each other. The epochs of coast currents may be expected to differ widely from those of the local tide, especially on a shore where differences of tidal range appear from point to point. As as an aid to navigation, we especially recommend the observation and tabulation of the currents "*on soundings.*"

Thus far we have referred to tidal currents from the navigator's point of view, and have described the character of those observations and results which prove most useful to him. To the engineer projecting the improvement of a harbor, and to the physical enquirer, the subject is no less important and interesting.

§ 60. It is only in rare instances that a knowledge of the currents below the surface of the sea can be of practical value to the navigator, but the engineer, who looks upon tidal drifts as working agents which he may restrain or direct, is especially called upon to measure the power and the office of sub-currents.

To obtain the general motion of a stream of no great depth, a tin cylinder a few inches in diameter, and long enough to reach from the surface nearly to the bottom, may be used as a log. Tubes of forty-eight feet length have been used for this purpose. These were three inches in diameter, made in separate sections, air-tight, but with stop-cocks for letting in water, that they might be partially filled so as to sink to the proper depth. As the tube drifts nearly upright in the water, with its top protruding a few inches above the surface, its velocity must indicate the *mean motion* of the stream. If it leans forward or backward, we at once perceive that its foot rests in a stratum which has less or greater motion than the surface drift; and if its angle of direction differs from that of the surface log, we recognize the action of a sub-current whose course is at variance with that of the surface drift.

§ 61. To obtain the velocities and directions of the currents of a specific water stratum, we may observe upon the motion of two bodies connected by a slender cord, the one sunk to the required depth, the other floating, and compare the results obtained with those given by the surface log. Very good results have been obtained by using two hollow copper globes of two feet diameter each, connected by one-eighth inch wire rope. The sinking globe is filled with water, but the other is loaded only enough to sink nearly to its pole. The upper globe has a log-line secured to it, and its motion is recorded at the same time that an observation is made with the surface log.

Let us suppose that the two globes present equal effective areas (great circles) to the drifts in which they swim; then their velocity will be a true mean of the rates of the surface and sub-currents; *i. e.*, $\frac{1}{2}(x + y)$ where x and y represent, respectively, these rates. *The velocity of the sub-current may therefore be found by subtracting the surface rate from twice that of the connected globes.*

The above rule applies to the case where the paths of the drift coincide in line of direction, which they usually do. It is sometimes the case, however, that the sub-current apparatus takes an opposite direction to the surface log; in this case its rate is regarded as having an opposite sign to that of the surface in the application of the rule.

If the surface and sub-currents pursue paths at an angle with each other, we have a simple question in the resolution of forces in which the motion of the connected globes represents one-half the resultant (the diagonal of the parallelogram, of which the surface rate is one side) and corresponds with it in direction.

The wire rope connecting the upper and lower globes should pass up through the former and be secured to the portion of the float which is above water, so that the observer may alter the draught of his apparatus and examine different depths by simply letting out the connecting line or drawing it up, without taking the globes from the water.

Although, for several reasons, spheres are the best forms for use in these experiments, the difficulty of managing and connecting the floating globe is often so great that the substitution of cylinders is resorted to, the floating cylinder being provided with a conical top or air chamber which is kept above water. For rough determinations barrels or boat breakers may be used.

The surface log would better be a globe or cylinder corresponding in dimensions with the float of the sub-current apparatus and equally immersed, so that the effects of winds and waves may be equal.

§ 62. The *yawing* of a vessel at anchor in the "tide-way" is often a serious obstacle to the collection of good results, especially from the sub-current apparatus; and, again, the graduated log-line used with the apparatus, being necessarily of considerable size, is borne away by the surface drift so as to deceive the observer. To obviate these difficulties, in some cases the use of an anchored vessel is dispensed with and the floats set free, but followed by the observer in a boat, who frequently determines the position of the surface log, and notes the separation of the sub-current apparatus from it. Instead of the large log-line referred to above, a very slender graduated cord is carried from the upper globe to a reel within the surface log. The reeling off of this line measures the difference between the surface rate and that of the mean of upper and lower drifts.

If the surface log is a sphere, the line is suffered to run freely out through a hole in the pole. In this manner the currents of great depths may be examined. The connecting wire between the upper and lower globes may be very slender, so as to offer very little resistance to the water, and yet be sufficiently strong to bear the steady strain to which it is subjected when the apparatus is disconnected from the vessel. Very good results have been obtained from a depth of thirty fathoms in the open sea.*

§ 63. The variation in velocity from surface to bed in the channels of tideless rivers and in canals has been the subject of much study, and the curve which this variation usually describes has been found to be parabolic, the maximum velocity being a short distance below the surface.† The depth at which the maximum velocity may be found varies in a remarkable manner, and no satisfactory explanation has yet been offered. It has been urged that the friction of the air would suffice to render the surface flow preceptibly more tardy. Perhaps the same effect would follow from the greater irregularities of the shore line near the surface. At contractions the point of maximum velocity usually descends, as if the more superficial drifts were converged less favorably for reinforcing each other than those at greater depths. If the contraction is very great, but of short extent, the current descending a precipitate slope is sometimes inclined to underrun the quiet body of water beyond, the particles preserving, as it would seem, their inclined direction for a while.

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* See Annual Report of Coast Survey, 1859, for description and sketches of sub-current apparatus, together with formulæ for reducing particular cases.

† See Humphrey and Abbot's report on the Mississippi river for the best determination of such curves.

In the neighborhood of extensive flats the tidal currents below the general level of these flats follow a different law of variation from those above, and sometimes differ ten, fifteen, and twenty degrees in direction.

Currents flowing into channels from shallow flats or creeks frequently continue on as superficial streams for some distance, but ultimately their motions become merged with the general drift.

§ 64. In rivers whose beds lie below the level of the sea very singular variations may be expected. Sea water frequently flows into such a river along its bed during the dry season, even while the lighter fresh water upon the surface is flowing towards the ocean. In the wet season the same river, acquiring head, is able to expel sea water again, and so the bed is alternately traversed by salt and fresh waters. The use of a hydrometer in testing specimens of water is indispensable in observing such phenomena, because we must in this case measure the *weight* of the head before we can account for the degree and kind of activity which it induces.

The effect of very strong winds blowing up a river is to check the surface current, but if the water is deep the outflow below the influence of the wind and waves will be greatly increased.

Rivers flowing into broad basins become superficial and diverge rapidly, suffering often a very sudden slacking-up, which permits the sediments to fall to the bottom and form bars or mud-banks.

The waves of the sea break up the currents flowing from rivers and harbors, but after long periods of quiet weather, when the waves are so small that their influence is not felt at the bottom, the outflow in the lower water stratum is often found steady and strong.

§ 65. From a few observations made along the coast in the midst of tidal drifts, it appears that in midsummer cold belts or spots are found in certain positions on the surface of the sea, differing ten to fifteen degrees from the general surface temperature, but corresponding with the temperature of the water near the bottom. Even in localities where the water is uniformly deep, and there seem to be no shoals or other obstacles calculated to sheer the current upward, this phenomenon appears.* The use of a thermometer in connection with current observations made in summer is to be recommended. If the flows for different depths do not occur upon parallel planes, the thermometer will not only detect the general facts, but may follow them back to their causes.

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* Coast Survey Report, 1861.

§ 66. In the formation of mud-banks or shoals the currents take usually a prominent part. In confined portions of their journeys they scour away the bed and banks of the channel and carry off the material only to cast it down again in broader sections where their reduced velocities disable them from continuing to bear such burdens. The following statements, compiled from direct experiments, show the power of currents:*

Clay, fit for pottery, is removed by water having a velocity per second of 0.26 feet.

Fine sand is removed by water having a velocity per second of 0.53 feet.

Gravel, about the size of peas, is removed by water having a velocity per second of 0.63 feet.

Shingle about one inch diameter is removed by water having a velocity per second of 2.12 feet.†

We may divide the material borne along by currents into two classes, viz: the *suspensible* and the *rolling*. To the suspensible class belong muddy sediments composed of vegetable earths, clays, &c., which are lifted by the stream and partake fully of its motion; while to the rolling class belong sands and gravels, which are not lifted from the bottom by currents of ordinary strength, but are urged forward at a rate bearing but a small ratio to that of the water.

In tidal waters muds are observed to accumulate in sheltered coves and in the broader portions of the channel. Wherever they are found they indicate inactivity, or at least the recurrence of long periods of slack water. It is not so of banks and shoals of sand, which are often observed to accumulate in places traversed by strong drifts. *Sand-banks may accumulate wherever the resultant of the current forces is zero.* A particle of sand rolls along so short a distance in a single day that the hourly velocities of the currents for the period of two floods and two ebbs may be regarded as forces acting simultaneously.

§ 67. It is often desirable to ascertain whether a shoal is the result of natural operations now in progress, or is the remains of a wasted island, or the effect of some past conditions; and it often happens that there is in such a shoal little or no geological indication of its age or history. If we make a current station upon it, and observe the drifts for a tidal day, then compound the velocities according to

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*Dubant's Experiments.

† More modern experiments reduce these velocities somewhat.

the rules for the composition of forces, we shall be able to determine whether, in the event of its being dredged away, it would gradually form again or not.

The formula for the composition of forces lying upon the same plane is so simple in its application to this experiment that we may introduce it here: If the hourly velocities are represented by p_1 p_2 p_3 &c., their angles by a_1 a_2 a_3 &c., (measured, we may assume, from the south round by west,) the resultant by P and its angle of direction by φ, we shall have—

$$P^2 = (p_1 \sin. a_1 + p_2 \sin. a_2 + p_3 \sin. a_3 + \&c.)^2 + (p_1 \cos. a_1 + p_2 \cos. a_2 + p_3 \cos a_3 + \&c.)^2$$

$$\text{Tan. } \varphi = \frac{p_1 \sin. a_1 + p_2 \sin. a_2 + p_3 \sin. a_3 + \&c.}{p_1 \cos. a_1 + p_2 \cos. a_2 + p_3 \cos. a_3 + \&c.}$$

These forces are to be added with due regard to signs. The angle φ is measured from the same point as those of the component forces (from the south we have assumed.) It is acute if the numerator and denominator of the above fraction are both positive; it lies between one and two right angles when the latter is negative and the former is positive; between two and three when both are negative; and between three and four when the numerator only is negative.

§ 68. It will be found most convenient to arrange the hourly velocities as in the following table, and to use natural sines and cosines:

Tidal Hour.	Angle (a)	Cosine a	Sine a	Velocity. p	p cos. a	p sin. a
O				00	00	00
I	311	656	—755	0.65	426	—491
II	313	682	—731	1.16	791	—848

The table should commence with slack water and end with slack water occurring about twenty-four hours later, if possible, to avoid confusion and error in the first and last terms of the series. Velocities less than three-tenths of a mile per hour must be reckoned as nothing, because, by the table given in § 66, it appears that these are too small to move a grain of sand.

In the first column the number or hour of each observation is given. It is well to divide the whole time into twenty-four equal parts, and call these I, II, III, IV, &c. In the second column are the observed angles, (a_1 a_2 a_3 &c., of our formulæ;) and in the fifth the observed velocities, (p_1 p_2 p_3 &c., of our formulæ)

In this computation we use the two ebbs and the two floods of the same tidal day in order to eliminate the diurnal inequality. If the tides of the same day are also observed, the velocities may be corrected for *inequalities* by method explained in § 50 and 51.

As repeated trials would have to be made of stations upon a shoal to discover the equilibrium point, (supposing one to exist,) and since this point would be likely to shift from day to day as the tides vary, it will be found more convenient and satisfactory to surround the shoal with a cordon of stations, and at each repeat the experiments and computations; then, after plotting the values of p^2 upon the chart, observe whether they converge towards some point upon the shoal or radiate from it; in either case the sand swept along by the tidal drift will lodge. We compare the squares of the resultants because *work* is to be represented, *i. e.*, *scour.*

At the different stations in the cordon about the shoal the observations should be made at the same depth. Perhaps the *mean velocity* of a stratum twice the depth on the shoal will answer best; for this purpose the tube log should be used.

This method of examining into the causes of shoals has been successfully used in several of our most important harbors and sounds.

Bars and shoals exposed to heavy breakers are found to be the joint work of the waves and the currents, while banks in quiet basins and channel-ways are usually the work of currents only. The inside bars or "swashes" of lagoon inlets represent the action of tidal currents in a very distinct manner. As the lagoon is less affected than the ocean by the tides, there is at a certain stage of the ebb and of the flood an inclined surface across the swash, and the water pours in or out with great power, the inflow gathering its greatest strength on one side, and the outflow on the other, of a certain intermediate point. At this intermediate point the inflow and outflow are both strong, but in equilibrio, so that here a shoal forms, which is usually known by the name "*bulkhead.*" These bulkheads are curious objects for observation. The sand of which they are composed may be seen in great agitation on either ebb or flood; it is incessantly on the move, continually advancing upon the flood, and retreating upon the ebb, but gaining nothing on the whole. A great deal may probably be added to our knowledge of inlets and their bars which may have a practical as well as philosophical interest, if data can be collected from observations upon similar formations under different conditions of tides, &c.

§ 69. In the complete gauging of a tidal avenue to obtain the measure of its service as a conduit, and its qualifications for this service, the following data should be collected: From a close survey profiles of characteristic cross sections and a profile of depths along the track of greatest depression of channel bed should be plotted. From these the mean depth, mean width, mean area of cross section, and mean wetted perimeter for each foot of tidal range, may be calculated, also the distances measured along the centre of the stream. From simultaneous tidal observations at several points, the form of the tide and its changes of figure in its journey, as well as the slope of the water's surface for each hour, should be made known. From current observations the curves of velocities from side to side and from top to bottom in each characteristic section, and for each tidal hour, should be given; also, the directions of motion at many different points and the durations of slack water.

If the avenue communicates with an interior basin, the measurement of the tidal prism in this basin is advisable, as a check upon the results given by the gauging of the channel.

§ 70. It is conceded that in the currents of rivers the velocities depend upon the surface slope, and not upon that of the channel bed, when other things are equal. The same result seems to be reached in a single comparison, which we have made, of ebb and flood tidal currents at equal stages; no effect for reverse slope of channel bed could be detected.*

Frequent articles on tidal currents may be met with in the transactions of the Royal Society and in the U. S. Coast Survey Reports; also in the reports of the commissioners on Boston, Portland, and New York Harbors, and Cape Cod Canal. Works upon the currents of rivers are numerous. The most recent, and the most complete, is the "Report upón the Physics and Hydraulics of the Mississippi River; No. 4 of the professional papers of the Corps of U. S. Top. Engineers." The reader is especially referred to this work for the laws of running water in large rivers; and for minute inquiries in small streams and canals he may consult "*Recherches Hydrauliques, Tome XIX des mémoires présentés par divers savants a l'Institut Impérial de France.*"

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* Tenth Report of U. S. Commission on Boston Harbor.

APPENDIX

TO ARTICLE ON TIDES AND TIDAL PHENOMENA.

Tide Gauges.

Simple Staff.—For sheltered and quiet harbors, the most reliable gauge that can be used is a simple staff graduated *upwards* in feet and tenths. This staff should be secured in a vertical position with its zero below the greatest fall of the tide; and this zero, by levellings, should be referred to a permanent bench-mark. If very nice observations are required, a glass tube of about a half inch diameter with a colored float (a red glass bubble, or a few drops of tinted oil) may be attached to the staff to enable the observer to read the heights more accurately. If this tube extends at all times several feet below the surface of the sea, and if its lower end is partly stopped by a cork with a tube through it, the float will not be agitated by the surface ripples.

Box Gauge.—There is an inconvenience in the use of the simple staff in places where the tidal range is great, since the observer is obliged to alter his position frequently to follow the surface of the water up or down. To obviate this, an apparatus called the box gauge is used. In this gauge the staff has a tin or copper float at the foot of it, and moves up and down within a *tube* or *box* which is secured in a vertical position, with its lower end as far below the greatest fall of the tide as practicable. The water is let in at the foot of the box at several small holes; and the observer reads the relative heights as the figures of the rising or falling staff pass a certain mark seen through a convenient opening in the box. This mark, which remains fixed throughout the period covered by the entire series of observations, is technically called the *reading point*, and should be referred to the bench by levellings. In order, however, to furnish the computer with the means of reducing the observed heights so as to read from the bench, it is further necessary to record the distance from the water line on the float to a stated figure upon the staff; and since the float line is subject to change as the staff becomes saturated, or otherwise alters its weight, frequent measurements of this distance should be made and recorded.

The chief source of error in the results from this gauge is found in the want of sufficient freedom for the ingress and egress of the water at the foot of the box. In order to keep out the swells and chopples and at the same time to avoid the trouble or inconvenience of sinking the foot of the gauge box below their influences, the holes are often made of the minimum size at the outset, and soon become more or less choked by weeds and barnacles, so that the observer unwittingly records a distorted tide. The effect of inadequate water holes is to increase the *intervals*, reduce the *ranges*, alter the magnitudes of all the *inequalities*, and especially to displace the middle portion of the wave figure.

Self-Registering Gauge.—The bog gauge is sometimes provided with a self-registering apparatus, so arranged that the rising or falling float carries a pencil with which it describes a curve upon paper wrapped about a cylinder revolving by clock-work. In the self-registering gauge the graduated rod is replaced by a wire kept taut by a counterpoise. In the form of apparatus used in Great Britain the paper is secured to a vertical cylinder which makes one revolution in twenty-four hours, and the same sheet is suffered to remain for about a fortnight, or until some twenty-eight tides are drawn upon it. In the Phil. Trans. of 1838 may be found a full description of this form of the self-registering tide gauge by Mr. Bunt.

The self-registering instrument used by our government, devised for the U. S. Coast Survey by Joseph Saxton, Esq., differs from the British instrument in some essential particulars. The vertical motion of the float is converted into horizontal motion for the pencil, and the paper unrolls from one cylinder and rolls up upon another so that the curves do not repeat. By this improvement a continuous line is traced for upwards of thirty days before the paper is exhausted. The receiving cylinder makes two revolutions in the course of a day, and each half hour is pricked through the paper as it rolls up by needle points projecting from either end of the cylinder.

The Saxton self-registering gauge is portable, and may be set upon an ordinary timber wharf or on a platform supported by a half dozen piles well tied and braced together. The instrument will work well in any situation where the jar is not too great for the proper motion of the pendulum attached to the clock. A full description and sketch of this instrument is to be found in the Report of the Coast Survey for 1853.

In connection with the self-registering gauge, occasional observations upon a staff gauge fixed in the immediate neighborhood are requisite, in order to give the absolute heights represented by the curve upon the sheet. These staff observations should be made on very quiet days, at even hours, and about the time of tidal stand. If at these even hours the pencil of the self-registering gauge is drawn back for an instant so as to make a vertical mark upon the sheet, and the record of the true time and height by staff made on this line, a check upon the working of the clock and gauge will be given. Such checks cannot be made too frequently or too carefully. The curves on the sheet of this gauge are read off and converted into figures by the use of scales. In order to make the sheet convenient for future reference, it is well to write out the dates and hours; also to draw vertical lines connecting the corresponding pricks of the upper and lower margins, and equidistant horizontal lines parallel to the lines of pricks, which shall divide the verticals into feet and tenths.

The freezing up of tho box in winter may be prevented by pouring in a small quantity of kerosene or other oil which remains fluid at low temperatures. To insure success under ordinary circumstances, it has not been found necessary to displace the water to a great depth in the box, but simply to sink its surface about the depth of frost in still sea water—a foot, perhaps.

For stations exposed to the open sea, peculiar modes of securing tide gauges have been resorted to, and in some cases the gauges themselves have been made in peculiar forms. In most cases where short series of observations are required, a slender iron staff with tube attached may be held in place by securing it within a skeleton pyramid of iron rods anchored to the bottom. In the form used in the recent survey of the Cape Cod canal sites, the base of the pyramid was a triangle of one-and-a-half-inch iron rods, to each angle of which a small anchor was lashed by its shank. The staff was let down from the apex of the pyramid and driven into the bottom, within the base, then firmly fixed by screw at top. The observer occupied a boat which he could always fasten to the apparatus without disturbing it.

In the Coast Survey Report of 1854, Appendix 53, a form of tide gauge is described which was successfully used at many stations on the open coast of Massachusetts. An iron tube with an augur at foot is passed through the ring of a heavy anchor and screwed into the bottom. It is held in a vertical position by three chain guys secured by screw band to the middle of the tube, and extending to three other anchors well buried at short distances from the foot. Within the tube a rod and float are placed as in the ordinary box gauge.

Again, in the Coast Survey Report of 1857, a device for observing tides at a short distance from the coast is described. It was very successfully used in ten-fathom water, but would not probably answer so well in less depths, where the waves would offer too great disturbance. A long pine spar, bolted at the foot, with a universal joint, to a block of stone, is lowered down to the bottom of the sea. The portion above the surface of the water is slender, so as to be less affected by the wind, while the part near the bottom is large, in order to be as buoyant as possible. To the top of this spar, which projects some ten or fifteen feet above the water, is attached the rod of a heavy pendulum, which slides over an arc five to eight feet below, and determines the inclination of the spar. To this buoy, thus arranged, is fastened the gauge, which is a glass tube set into a graduated staff, and having a red glass bubble rising and falling within. By a small hole in this tube, some eight to ten feet below the surface of the sea, the water enters, upon which the bubble floats. The observer records at once the height of the bubble and the angle of inclination of the gauge. The computer, with the aid of a table of natural cosines, readily reduces these observations to perpendicular heights.

"*Off-shore Tide and Sounding Meter*" is the name given to an apparatus in which the heights of the water are determined *barometrically*. The pressure of the sea upon an elastic air bag lying upon the bottom is communicated, through a flexible tube, to a manometer above. It was invented by Major E. B. Hunt, U. S. A., as a sounding instrument, in 1857, and as such is described in the Coast Survey Report of that year. Subsequently this instrument, in an improved form, was proposed by John M. Batchelder, Esq., as a tide gauge, and has been successfully used during the recent war, by the Coast Survey, off Charleston bar. In connection with hydrographic work on the open coast and in the neighborhood of exposed shoals, this gauge has a decided advantage over many others proposed, because a continuous record can be made from the deck of a vessel, the observer being required simply to note the position of a hand upon a dial plate.

Another ingenious method of measuring tides by weight has recently been proposed by Mr. Batchelder in a paper read before the National Academy of Science, 1865. It has not yet been put to the test, but it promises to provide against trouble from ice.

In the Arctic expeditions of Dr. Kane and Dr. Hayes the "pulley tide gauge" was used. The observations were made by the party of Dr. Hayes on a graduated vertical line which was stretched, from an anchor on the bottom, over a pulley at the apex of a tripod built over a hole in the ice. A counterpoise kept the line taut as the tripod rose and fell with the tide, and the observer read off the heights as he would have done from a staff gauge. For further descriptions we must refer the reader to Dr. Kane's "Arctic Expeditions," vol. 1, chap. xi, and to the Arctic tidal articles in the Smithsonian contributions of 1860 and 1865.