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UNITED STATES
EXPERIMENTAL MODEL BASIN

NAVY YARD, WASHINGTON, D.C.

BENDING LOADS ON CUYAMA AT SEA

BY LIEUT. W. P. ROOP, (CC), U.S.N.

EXPERIMENTAL MODEL BASIN
ERECTED 1898
BUREAU OF
CONSTRUCTION AND REPAIR
NAVY DEPARTMENT

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MAY 1931

REPORT NO. 297

BENDING LOADS ON U.S.S. CUYAMA AT SEA

by

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U.S. Experimental Model Basin
Navy Yard, Washington, D.C.

May 1931 Report No. 297

Note: This report forms Section III (3) of E.M.B. Report No. 260, "Elastic Characteristics of Fleet Oilers".
The essential data of E.M.B. Report No. 260 have been published as "Elastic Characteristics of a Naval Tank Vessel", Lieut. W. P. Roop, (CC), U.S.N., in the Transactions of the Society of Naval Architects and Marine Engineers, 1932, Vol. 40, p. 314.

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PLATES.

BENDING LOADS ON U.S.S. CUYAMA AT SEA

(a) Summary.

Gear for recording bending strains was in operation during about 50 days of steaming. During most of this time the weather was fine and the bending loads small. Five periods, including all cases except one in which significant bending loads occured, were selected for detailed study. The data obtained, reduced to terms of bending load in foot tons, are shown in Plates I to V.

(b) Nature of the Data Obtained.

Before proceeding to conclusions drawn from these plates it is necessary to consider the peculiar features of the method used in obtaining them.

The quantities measured were two: First, the elastic changes in length of a strength member; Second, the bending deflection of the whole structure. Of these, the second gave satisfactory data only for part of the time, and was in general agreement with elastic strain data, as shown by crosses in Plates I and IV. Attention will therefore be given chiefly to the elastic strain data. These were obtained at 3 stations, a port and a starboard stringer plate, and a plate over the centerline bulkhead.

No attempt was made to obtain a truly continuous record of the fluctuations in length of these three plates, for two reasons: First, this would have called for recording gear capable of following fluctuations with a frequency of the order of 10 per minute, if wave action alone were considered, or 100 per minute if vibrations induced by engines were desired on the record. This would have required an instrument of oscillograph type, using photographic methods, as no mechanical recorder, working at a distance, is available for such frequencies; Second, the values desired are only the maxima.

The gear actually used gave the maximum in compression and that in tension separately. At definite intervals of time resetting was accomplished, so that the record consists of a series of maxima in each direction.

If a record of oscillograph type were available, we would have a series of maxima and minima on a single chart, which would define a band of varying and extremely irregular width. In work of other observers the width of this band was taken as defining the range of elastic strain due to wave action, and in default of information to the contrary, the range was assumed to be equally divided into compression and tension. The null value, or reference datum, is thus considered to follow the middle of the band. Such an assumption, however, if applied to an interval including only a few cycles, would require us to suppose the null value itself to be subject to violent fluctuations. This is obviously not the case. The null value, taken as the length of the extensometer base with the ship in still water, varies only with gradual shifts in weight and in temperature. Such shifts within a period of a minute or 10 minutes are negligible.

But within an hour or a day such shifts are by no means negligible. It is impossible to establish a reference datum in still water which will remain fixed during the time required to obtain data among waves unless the ship is moved with that special purpose in view. For voyages lasting several days such as were made by the U.S.S. CUYAMA, the reference datum must be established by some process of averaging.

Dealing still in terms of the fictitious continuous record of oscillograph type, imagine the effect of integrating the curve over a variable interval of time. If very short intervals are chosen, say one or two cycles, the mean value established by integration will be subject to fluctuations due to the irregularities of wave action. If the integration is extended to very long intervals slow changes due to shift of weights and temperature will enter into the result. One would expect to be able to find an intermediate length of time interval long enough to eliminate irregularities due to wave action yet short enough not to conceal the slower variations. If the oscillograph record were actually available a suitable length of interval could be found experimentally. That is not the case, however, and it is necessary not only to make an arbitrary decision as to length of interval, but to base all inferences on the specific assumption that a length of interval exists, over which <u>the mean length of the extensometer base equals that which it would have under equal temperature and weight conditions in still water.</u>

The actual data obtained depart from a record of oscillograph type in following the fluctuating extensometer gage only for a small fraction of the time, namely, while the gage plungers were held in contact with the pin by the action of the solenoids. During the remainder of the observing cycle the plungers remained in the position to which pushed by the pin at its maximum departure from null until, with the beginning of a new cycle, the solenoid circuits were again closed.

These two parts of the observing cycle may be distinguished as the "null phase" and the "maximum phase".

(c) Null Phase.

During the null phase the gage plungers followed the motion of the extensometer continuously, but the recorders did not follow accurately the gage plungers. In one type of recorder this is a matter of time lag, such as will cut the peaks off the maxima and minima. In the other type the record itself is momentarily correct but discontinuous; the spots selected by the instrument for record are located on the oscillograph curve, but since they occur at fixed intervals of time, the phase relations on this curve are entirely at random. In either type of record, however, it seems fair to take the half sum of the absolute maximum and minimum in the null phase of each observing cycle; the average of such values taken over a number of such cycles should approximate the desired null by eliminating effects of the instrumental action and those due to neglect of intermediate maxima and minima.

Three tests, all rather indirect, were applied to estimating the accuracy of these assumptions. In the first the mean of the plus and minus extreme values for each gage for the null phase of each observing cycle was taken from the record. The sum of these for compression and tension gages* should be constant except for instrumental errors, and the departure of this sum from constancy should become less as averages are taken over longer intervals. The results of this check are shown in Table VII. The mean error in the sum is divided equally between compression and tension.

TABLE VII

Null Errors due to Recorders.
Average Departure from Average, in Foot Tons Moment.

Recorder Type	Average of		
	4 Cycles	4 Averages of 4 Cycles Each	Averages of 4 Averages
Voltmeter	± 1030	± 810	
Voltmeter	± 3300	± 2510	± 2390
Potentiometer	± 1170	± 830	± 540
Potentiometer	± 1300	± 900	± 1150

Although, in all cases but one, the scattering is less as averages are extended to longer intervals, the convergence is rather slow.

In the second test null values were averaged, separately for tension and compression, and departure from this average of the value for each observing cycle taken. Then the sum of null values for tension and compression was taken with the departure of this sum for each cycle from its average. In other words, first averaging was done before adding, then the same data were averaged after adding compression and tension values together. In the first case effects of temperature changes enter as well as instrumental errors; in the latter case the temperature effects are eliminated. The difference in the average departure from the average in the two cases thus represents the residual effect due to temperature. This process was carried through for intervals of 4 cycles and of 24 cycles. The results are shown in Table VIII.

The temperature variations in the longer interval are greater, as would be expected. Since the errors due to the recorders are not much greater in the short intervals than in the longer ones, analysis was actually carried thru on a short-

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*Since all extensometers were on the top member of the ship girder, compression corresponds to sag throughout, and tension to hog.

interval basis.

The data were examined again from a third point of view, to determine whether instrumental error in recorded values of bending moment might not be eliminated at least in part by substitution of average values for the erroneous momentary null values. The application of this correction to data from the port extensometer shown in Plate III gave an average departure from the 6-cycle average of 3725 foot tons in corrected data as compared with 3795 foot tons in the uncorrected data. The scattering of the recorded values of bending moment is therefore practically all due to irregular wave action in this typical case, and not to null errors. This led to the conclusion that the correction was not worth making.

TABLE VIII

Variations of Null due to Temperature
and to Errors in Recorders.
Average Departure from Average, in foot tons Moment.

Interval	Variations due to		
	Temperature and Recorders	Recorders only	Temperature only
4-Cycles	± 1750	± 1300	± 450
6 Groups of 4-Cycles Each	± 1690	± 1040	± 650

The whole study of data obtained on the null phase may be summarized by saying that uncertainties of the order of ± 1500 foot tons were found in the null point, due to instrumental error, for which no practicable method of correction exists. It is believed that the true null point in still water agrees with the averages obtained within a tolerance of this order.

In the actual procedure the null point for each 10-minute observing cycle was used without correction. In general to the extent of about ± 1500 foot tons the scattering in Plates I to V may be attributed to instrumental error in null points.

(d) Maximum Phase.

The recording of the maximum is not attended with instrumental errors of the type occurring in the null phase, as the gage setting is maintained long enough to far outlast the lag in the recorders.

The primary influence in the random distribution of the load maximum is the irregularity of the sea itself, and an appreciation of the degree to which uniformity is present or absent in wave action is fundamental to clear thinking about loads on ships at sea. One of the most obvious features of Plates I to V is the large scattering of the spots; it should be noted that each of these spots represents the extreme value among a number of pitching cycles and therefore of bending load cycles of the order of 100.

The time during each maximum phase at which the highest load for that measuring cycle occurs is given by the record. It is found that uniformity in distribution of these times of highest load through the cycle is quickly attained. Even in a series of 24 measuring cycles this time occurs about as often in one part of the measuring cycle as in another; thus in a group of 100 pitching cycles as the first ten. It is a little more surprising to find, however, that the same applies to a series of 600 pitching cycles, when the sea is uniform in the sense that it receives a uniform rating on the log scale. If the sea is rising, the top maximum will come toward the end of the series; if subsiding, toward the beginning; in a series of 600 cycles in which the state of the sea is not changing progressively, it might seem fair to suppose that a load value as great as any that would come later would occur early in the series. This, however, is not the case, as numerical test shows, and the actual distribution approximates that which would be expected on the assumption of purely random fluctuations.

Further information as to the random character of the action of the sea was sought by tabulating the deviations of 10-minute maxima from their hourly averages. Simple inspection of Plate IA and comparison with Plate I show the smoothing effect of averaging. In Plate VI the departures of about 1700 10-minute maxima from their hourly averages are plotted, with the normal distribution curve drawn in for comparison. Although the agreement is not perfect, no reason appears for supposing that these fluctuations are distributed otherwise than in accordance with the curve associated with the operation of pure chance.

It is significant that even one-hour averages do not iron out all the irregularities. It is clear, however, from Plate I that progressive change in the state of the sea can easily occur within an hour. We therefore conclude that there is no interval at once long enough to eliminate chance fluctuations and short enough to eliminate progressive changes.

It is therefore necessary to analyze the conditions exhibited in Plates I to V into a mean curve which corresponds to the numerical estimate, logged hourly, of state of the sea, plus fluctuations following the normal distribution law.

The adoption of this point of view implies acceptance of the idea that it is impossible to specify the absolute maximum bending moment which a given ship will ever encounter. The whole subject must be considered with respect to probability rather than certainty.

(e) Procedure in Analysis.

On 16 February 1930, at noon, the vessel was on a northwesterly course, in the Gulf of Mexico, and during the following 24 hours encountered a "norther".

A complete record was obtained from the port extensometer and the flexuremeter.

A partial record was obtained from the centerline extensometer. Data from all three showing recorded bending moment maxima in 10-minute intervals during the period of increase are given in Plate I.

This is perhaps the simplest case which occurs, the ship heading close into sea and wind. Light airs from the south, with very calm sea, had lasted for about 24 hours. Suddenly at 1604 (16th day, 4:00 A.M.) the wind reversed and blew from the north with an intensity which by 1608 had risen to No. 6 on the Beaufort scale, where it remained until 1620, after which it gradually moderated to No. 2 at 1716. The sea built up under the influence of this wind, and from 1613 to 1704 was logged as No. 4, moderate swell.

The recorded data on loads show increase until about 1618, and moderation beginning about 1622. In Plate IA are shown the hourly averages which define a mean curve exhibiting this somewhat more clearly than Plate I. The fact that moderation of the sea was not logged until 1704 may be attributed to deficiencies in the manner of estimating state of the sea. The estimate of wind is perhaps somewhat better; the fact that the load ceased increasing about 1618 although the No. 6 wind continued until 1621, shows that the sea had reached its maximum development under this wind in this locality. We may therefore associate an average load of 38,000 foot tons in sag and 50,000 foot tons in hog with a No. 6 wind from nearly ahead, at 68 r.p.m., ship displacing 12,000 tons.

The maximum observed loads at this time were 56,000 foot tons in sag and 73,000 foot tons in hog. The observed mean absolute departure from the average in the 4-hour watch 1616 to 1620 is 4,000 foot tons in sag, 6,300 in hog. The maximum observed departure from the average is therefore in sag 4.5 times the mean value, and in hog 3.7 times. These are high departures; according to the normal distribution law they are associated with very small probabilities. The determination of this ratio, however, is essential in establishing limiting load values.

(f) Reduction to Standard Conditions.

In order, from such data as these, to draw inferences as to maximum loads to which the ship might be subjected, a bold extrapolation is necessary. In addition to the uncertainties attaching to all extrapolations, conclusions about maximum bending loads depend also on assumptions which must be, in fact, rather precarious. Those made here are as follows:

1. Bending loads are proportional to height of waves, at wave lengths up to that of the ship, but do not increase at greater wave lengths, regardless of wave height.

2. Height of waves in open sea is proportional to wind velocity. (Vaughan Cornish's formula).

3. Height of waves generated in limited spaces is proportional to the square root of the fetch, or distance over which wind acts on the water. (Thomas Stevenson's law).

4. Only a moderate length of time, a few hours at most, is required for waves to adjust themselves to wind conditions.

5. Length of waves in feet is equal to 0.5574 times square of speed of wave in knots, which is about equal to the speed of the wind. Length = 18,420 divided by square of frequency per minute.

By Assumption 1, the greatest bending moment would occur on a wave 455 feet long. This has a speed of 28.6 knots, and would be generated by a wind of the same speed.

By Assumption 2, a wind of 28.6 knots would give wave heights 1.2 times those occurring in a wind of force 6*.

As northers are a local phenomenon, the effective fetch is not great, possibly of the order of 200 miles. Greatest effective fetch in the North Atlantic is given by Cornish as 600 miles. In the Pacific somewhat greater fetch probably occurs, that corresponding by Stevenson's law to the greatest waves cited being 1,000 miles or more.

By Assumption 3, wave heights about 2.3 times as great as those encountered 16 February might thus occur in open sea, under a fetch of 1,000 miles.

Under the given circumstances of load, speed, and course, the U.S.S. CUYAMA might thus expect to encounter bending loads 1.2 times 2.3, or $2\frac{3}{4}$ times as great as those recorded in Plate I, amounting to 150,000 foot tons in sag and 200,000 foot tons in hog.

[illegible] 72,[illegible]

As a summary of this analysis the information desirable in interpreting bending load data obtained at sea is suggested in Appendix F, which might also possibly be used as a guide in planning future work.

Comment on this form might be made to the effect that as an estimate of wave heights is called for, the procedure might be simplified by reducing directly to a standard wave. There is nothing to prevent doing this, provided data on actual wave dimensions are accurate enough. In general, however, wind and weather data are much easier to obtain and it is thought that the analysis will gain considerably by the correlations thus offered.

The relation between length and height of waves given under Item 23; namely, $\frac{\text{Length}}{\text{Height}} = \text{Height} = \sqrt{\text{Length}}$; differs radically from the time-honored assumption of waves of height one-twentieth their length, but agrees with it at the single length of 400 feet. This was not an uncommon length for a large ship at the time, say 30 years ago, at which the fixed ratio of 1 to 20 was permanently adopted. Practice has for a long time given smaller vessels relatively heavier scantlings, and recently very large vessels have had relatively lighter scantlings; the relation here proposed might be considered to offer a more rational justification than has hitherto been given for this practice.

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*Wind speeds on the Beaufort scale are taken from Bowditch.

(g) Data on Bending Loads.

I. Plate I has been discussed in Section (e).

II. Data shown on Plate II were obtained in the open Pacific, between San Pedro and Honolulu. Beginning at January 0412, wind rose rapidly to No. 6 where it stayed for 24 hours. The sea also rose rapidly and was logged moderate to heavy swell for the same period.

Great swells estimated at 300 x 12 to 15 feet came rolling down from the northward, suggesting stronger winds at a distance in that direction. Instead of coming as in Plate I from nearly ahead, however, they were about two points abaft the starboard beam.

The scattering of the spots in Plate II is more pronounced than in Plate I. Even the 60-minute maxima shown in Plate IIA are more scattered than those in Plate IB. This could hardly have been due to the rolling, and is probably inherent in the state of the sea. The ratio of extreme to mean departure is even greater than in Plate I.

The 1,000-mile fetch is considered fully effective in this case. The actual waves are perhaps a little larger than could be accounted for by the actual wind, but not much. Ratio of actual to standardized maximum bending load is 1.2, giving for load, reduced to standard conditions, only 64,000 foot tons in sag and 86,000 foot tons in hog.

These values are less than half those obtained from Plate I. The reduction represents the relief obtainable by taking sea on the quarter instead of nearly ahead.

III. Plate III shows conditions on the return trip from Honolulu to San Pedro. Conditions of wind and sea were similar in the interval 1408 to 1508 to those for Plate II and the average and maximum loads recorded are also similar, but the scattering is less. The values obtained from the extensometer on the centerline are rather consistently less than those from the port extensometer, for no known reason. The heel of the ship under beam wind was in the right direction to account for this but was not great enough, being only about 3 degrees. The high values between 1300 and 1400 on Plate IIIA are due in part to higher speed during this time, but mostly to the fact that, though the sea was lower, it came from more nearly ahead.

IV. Wind of intensity 5 was encountered on courses varying from east to nearly north in the Gulf of Panama, though the sea did not log higher than No. 2. Bending loads shown in Plate IV are very moderate though the scattering is high. Fetch is estimated at 50 miles, giving ratio to reduce to 1,000-mile fetch of 4.5. Ratio of wind speeds would give a factor of 1.5, making a combined factor of 6.7. In sag no outstanding maximum occurred; adopting a ratio of maximum to average departure of 4, a maximum of about 18,000 foot tons might presently have been expected. That in hog is 33,000 foot tons. These calculations lead to values of load under standard conditions of 120,000 foot tons in sag and 220,000 foot tons in hog.

V. The last case selected for discussion presents some novel points. The time covers the approach from northward to Colon, which has a bad reputation for heavy swell. Bending loads of two or three thousand foot tons were observed even after the ship was at anchor inside the breakwater. Wind No. 3 and sea No. 2 were logged from 2618 except that from 2707 both were logged No. 4. The increase in sea is apparent in Plate V, beginning 12 hours earlier. It is believed to be due to the conformation of the shore in its relation to the prevailing winds.

Prior to this increase, maximum load, based on averages and mean departures, is 23,000 foot tons in sag and the same in hog. Fetch is estimated at 1,000 miles as the wind had been steady from the east for several days. The factor due to wind speeds is 3.4, giving loads under standard conditions somewhat under 80,000 foot tons, in good agreement with those for a beam sea from Plates II and III.

(h) General Comment and Conclusions.

The bending loads here reported are those due to action of the sea. They are superposed on those occurring in still water due to the unequal distribution of weights and buoyancy. The still water bending moment with all cargo tanks full and all end tanks empty is 120,000 foot tons in sag.

In Plates I to V data from different instruments have all been plotted together . In general no well- defined separation appears of data from different instruments. Although mean values might show considerable differences in places, they are not such as would be caused by calibration errors. These differences are believed to reflect irregularities actually existing in the action of the sea on different parts of the ship. Other actions beside those of simple bending in the vertical plane, such as horizontal bending, contribute to these differences.

A striking feature is the consistently higher loads in hog than in sag. This might be accounted for by heaving action. Maximum displacement of the ship would sometimes coincide with the occurrence of a wave crest amidships, and sometimes with a hollow amidships. If the displacement were the same in the two cases the bending load due to a crest amidships would exceed that due to a hollow amidships, due to the non-symmetrical form of the trochoid and the non-uniformity of transverse section of the ship.

The standard condition is that with wave equal to ship in length, of average height produced by wind of velocity equal to that of wave, acting through a fetch of 1,000 miles, with the maximum wave departing from the average as shown in the observations, producing bending loads of the order of double the average. This may not be absolute top possible load, but it is near it, and offers a good basis for comparison.

The standard load in sag, head to sea, averaged from Plates I and IV, is 140,000 foot tons due to sea. Adding 120,000 foot tons static load gives a total of 260,000 foot tons.

In hog standard loads due to sea are 210,000 foot tons. Hogging loads of 120,000 foot tons were obtained in static tests, but in service such conditions, with midship tanks empty and end tanks full, would hardly occur. In ballast, bending moments in still water are small, and in sag rather than hog. The total hogging load is therefore not greater than in sag.

Designed nominal load is 234,740 foot tons. The ship has therefore probably withstood loads in excess of that for which designed.

Bending load due to action of sea can be cut to half by change of course to bring sea on the quarter.

(i) Recommendations as to Bending Loads.

1. It is recommended that in strength calculations as hitherto standardized on a wave of height one-twentieth length, additional data be obtained as to nominal loads on a wave whose height equals the square root of the length.

2. It is recommended that recording extensometers be placed on at least one ship of each major type, arranged for operation by ships' personnel; and that each ship so equipped be calibrated by shifting of weights in still water.

3. It is recommended that the Bureau of Construction and Repair cooperate with the Hydrographic office in obtaining resumption of reports of observations of waves at sea on ships without extensometers as well as on those having them, especially in order to obtain more extensive correlations of wave data with weather data.

4. In view of the very limited scope of the observations at sea on the U.S.S. CUYAMA, no specific recommendation for a revision of standard nominal loading for use in future design is made.

APPENDIX D

REFERENCES ON WAVES OF THE SEA

Thomas Stevenson's Law is discussed at some length in the article on "Harbours" in the Encyclopedia Brittanica, 9th edition. The same data are presented in his work "The Construction of Harbours".

Professional Paper No. 31, U.S. Engineers, dated 1904, is a book of 230 pages on "Wave Action in Relation to Engineering Structures" by D. D. Gaillard. It contains a complete account of observations on waves, but the interest is chiefly in their effect on harbor works.

Recent treatises on harbor works, as for example that of Joly, "La Mer et les Cotes", 1923, and Engels, "Handbuch des Wasserbaues", contain summaries of the same data with little or nothing additional.

The shipman's point of view is better represented by Vaughan Cornish whose "Waves of the Sea", Open Court Publishing Company, 1911, makes interesting reading. More recent publications by the same authors are in Scientific American Supplement, 1914, pp. 285-289, and Encyclopedia Brittanica, 14th edition, article on "Waves of the Sea".

A collection of photographs is presented in "Sturmsee und Brandung", 1925, by Lasching-Moennich. The author quotes data on wave dimensions, but has not attempted quantitative studies comparable with those of Cornish.

A summary of observations on which report to the Hydrographic office was made is given in Bureau of Construction and Repair file No. 001239. Plotted data are reproduced herewith as Appendix G.

An exhaustive summary of the subject of waves of the sea is contained in Krümmel's Handbuch der Ozeanographie, Vol. II, 2nd edition, 1911.

The most elaborate analysis, though applied only to limited data, is that of C. Börgen, Annalen der Hydrographie, 1890, pp. 1-11.

Complete specifications of the Beaufort scale and the log scale of state of the sea will be found in recent editions of Bowditch: Practical Navigator.

A recent brief summary is in the Handbuch der Physikalischen und Technischen Mechanik, Auerbach-Hort, Band V, pp. 353-360.

The most recent comprehensive review of the data is that of Zimmermann, Schiffbau, 1920, Vol. 21, pp. 633-640 and 663-670. Extensive original data and 72 references.

APPENDIX E

MISCELLANEOUS ADDITIONAL NOTES AND COMMENTS

1. Length of Cycle.

Before the decision was reached to establish 10 minutes as the length of the observing cycle, two sets of data were obtained, one with each type of recorder, in which observing cycles of only one minute were used. Under these conditions the voltmeter type of recorder gives only a broad band fairly uniformly covered with spots (Figure 13a). The null phase and the maximum phase are indistinguishable; the width of the band gives only the range between the minimum during the null phase and the maximum during the maximum phase. But means of interpreting such results are lacking.

The potentiometer type of recorder on a 1-minute cycle gives a record quite similar to that on the longer cycle except for the compression along the time scale. Of the examples of such records, (Figure 13b), one is on paper running at 6 in. per hour, the other at 3 in. per hour, which accounts for the apparent difference in the time scales. The two phases are sufficiently separated in either to make reduction of the data feasible, and partial application of the tests described in section (c) indicates that such records would be entirely acceptable, in spite of the fact that the null phase contains only one or two pitching cycles.

On the other hand there is no marked advantage in these short cycles, and the labor of reducing the data is materially increased. In fact even the 10-minute cycle seems shorter than necessary and a 20-minute cycle is proposed in new tests which may be taken up. This, howerer, seems about the limit beyond which temperature variations would enter unduly.

2. Combination of Loads.

When engine speeds passed through the critical range, stresses were always momentarily increased. A rather extreme example of this is shown in Figure 13b.

Comparison of records from different instruments shows such a maximum due to engine vibration on all the charts, but especially high maxima due to the action of the sea frequently show on one instrument only. For example, Figures 7a and 7b cover the same time on different stations, and the two records show important differences. This indicates that other actions beside bending in the vertical plane are occurring. Effects of transverse bending should be eliminated by taking mean from two extensometers, one port and one starboard. The longitudinal stresses induced by torsional action, however, are more obscure, and it is doubtful whether two extensometers on stringer plates would average them out. During static tests torsional moments of 60,000 foot tons were put on the ship, to port forward and starboard aft, and 20,000 foot tons in the reverse direction. Shear stress on the section was not high, even under this moment, being of the order of 2 or 3 tons per inch square, though it was probably higher than occurred in service. This appeared to affect extensometer readings on stringer plates about equally, producing an increase in compressive stress on each side of about 10 percent, and a decrease in compressive stress along the center line roughly corresponding. Such differences, however, are of the same order of magnitude as the departures of single observations from averages due to experimental error. The only conclusion possible is that torsional loads at sea probably did not seriously affect extensometer readings.

3. Static Tests and Tests at Sea.

Some discussion has occurred as to the relative merits of static tests and tests at sea. The truth is that both are necessary. Static tests give information as to characteristics of the ship structure and tests at sea are necessary to find actual loads.

Static tests cannot entirely reproduce actual loading conditions. On the other hand it is impossible to ascertain actual loads at sea except by calibration of the ship in static tests. Measurement of strains and deflections is useless unless accompanied by load measurements.

Differences in loading conditions in static tests and at sea cannot be eliminated altogether, but they can be minimized. Dynamic effects are fully accounted for by the methods used in the U.S.S. CUYAMA. The static tests were limited in range of load obtainable, but higher ranges necessitate artificial loads, application of which causes concentrations not occurring in practice, and leads to distribution of shear and bending stresses which are somewhat different from those in service.

The distributions and concentrations occurring at sea, however, are actually unknown. The only complete solution of the problem lies in static tests to determine the elastic behavior of the structure under each of the different possible types of load, combined with further tests at sea to find the extent to which each type enters into the total load, made up of superposed vertical bending, shear, torsion, transverse bending, etc.

Longitudinal bending in the vertical plane is the primary mode of loading, and the only one considered in these tests. The bending loads recorded are those which, acting alone, would produce effects at the extensometers equivalent to the combined loads actually acting.

4. Function of Elastic Measurements.

Measurement has traditionally played only a small part in elastic design of ships. The actual process has been one of evolution, experiments being made on full scale, guided by calculation and detailed study of casualties.

There is no doubt that this gives ships that are strong enough, but the objective now is to obtain ships that are also light enough. It is necessary not only to eliminate weak points but also areas that are too heavy. This cannot be done until definite standards of strength and stiffness are available, and these are impossible without extended measurement of strains and deflections.

APPENDIX F

FORM FOR RECORDING BENDING LOADS AT SEA

Observed	Time Interval
1. Date	1 hour
2. Position	4 hours
3. Wind: Force	1 hour
4. Direction	1 hour
5. Sea: State	1 hour
6. Direction of Swell	1 hour
7. Ship: Displacement and Trim	Single entry
8. Course	1 hour
9. Speed	1 hour
10. Maximum Amplitude of Pitch	20 minutes
11. Extensometer Reading	20 minutes
Estimated	
12. Waves: Height Mean	1 hour
13. Maximum	1 hour

14.	Waves: Length Mean	1 hour
15.	Maximum	1 hour
16.	Frequency	1 hour
17.	Effective fetch, or distance to windward over which wind has same direction.	As weather reports permit.
	Calculated	
18.	Bending Load: Average	4 hours
19.	Average Departure from Average	4 hours
20.	Maximum	4 hours
21.	Ratio of Last Two	4 hours
22.	Ratio of wave height on 1,000-mile fetch of equal wind to observed actual wave height.	
23.	Ratio of actual wave height to that corresponding to ship's length.	
	Extrapolated	
24.	Bending load corrected to 1,000-mile fetch of equal wind.	
25.	Bending load corrected also to wave corresponding to ship's length.	

EXPLANATION OF FORM
FOR RECORDING BENDING LOADS AT SEA

1. Enter time hourly as in ships's log.
2. Latitude and longitude in degrees and tenths, to permit determination of fetch
3. Anemometer data if possible, otherwise Beaufort.
4. In points.
5. Officially designated number-scale.
6. In points.
7. Approximate,
8. In degrees.
9. In knots and tenths.
10. By pitch recorder if available, otherwise by estimate on jack staff.
11. Turn in chart records with proper calibration, identification, and time markings. Although a 10-minute observing cycle was used on the U.S.S. CUYAMA a 20-minute cycle is considered short enough.
12. Estimate height of waves.
13. (a) By finding a height of eye amidships from which wave crests just touch horizon.
    (b) By comparison with known vertical dimensions on own ship or another in company.
    (c) If otherwise, explain method.

14.
15. Estimate length of wave by comparison with length of ship, with due allowance for obliquity of course.

16. Count number of wave crests actually passing fixed point on ship per minute. Make allowance for speed and course of ship only after uncorrected number has been recorded.

12 – 16. See form of Hydrographic office, copy attached, Appendix G.

17. If in open sea, consider weather reports from other vessels or shore, changes of wind, or any other data available. If in restricted waters, consider also coast line contour.

18. Extensometer record charts give short time maximum (20 minutes). Factor for reducing extensometer readings to bending loads must be found by calibration of the ship.

19 – 21. By simple reduction from 18.

22. Heights proportional to square root of fetch. Thomas Stevenson gives 1.5 as ratio of <u>maximum</u> height in feet, wind maximum, to square root of fetch in sea miles. To obtain a check, the schedule of observations calls for independent estimate of actual height and actual fetch.

23. A wave equal to the ship in length has a speed in knots equal to the square root of 1.794 times length in feet. This relation is well established. The value 1.8 for the coefficient is close enough for present purposes.

    Cornish shows that a fully developed storm wave has about the same speed as the wind. Accepting this relation as nominally exact we come to a definite wind speed which will generate waves equal to the ship in length, viz. square root of 1.8 times length in feet.

    But by Cornish's formula this wind, if acting steadily in open water, will generate waves of an average height in feet (trough to crest) equal to 0.8 times speed in knots.

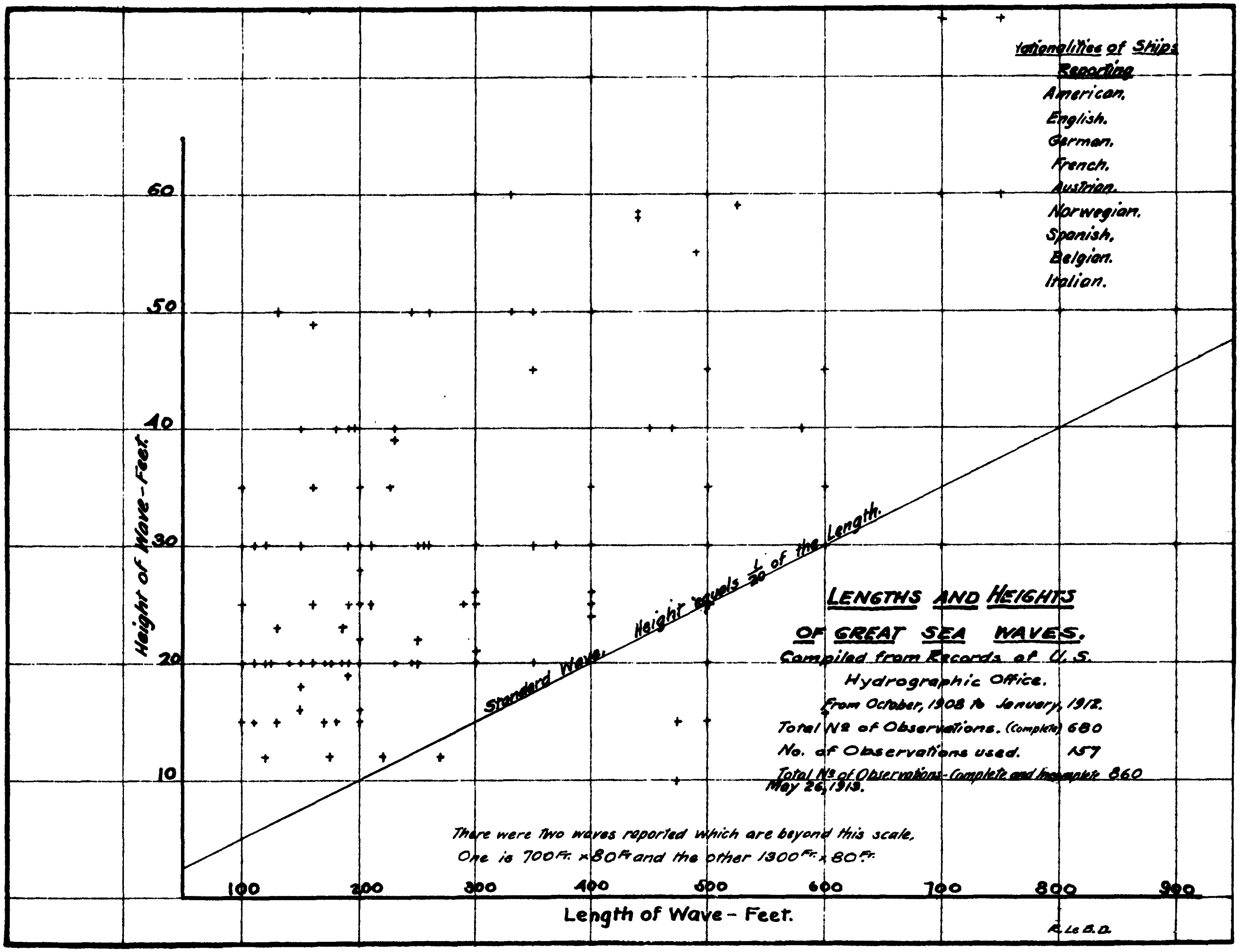
    Combining these relations, we see that a fully developed storm wave will have an average height equal to 0.8 times square root of 1.8 times length. Nominal values of numerical coefficient 0.8 times square root of 1.8 may be taken as unity. In slightly different terms,

$$\frac{\text{Length}}{\text{Height}} = \sqrt{\text{Length in feet}}.$$

    Item 23 calls for the ratio of the actual wave height associated with maximum bending moment, found by this relation from the length of the ship.

24. Item 20 times Item 22.

25. Item 24 times Item 23.



LENGTHS AND HEIGHTS OF GREAT SEA WAVES.

Compiled from Records of U.S. Hydrographic Office.

From October, 1908 to January, 1912.

Total No of Observations. (Complete) 680

No. of Observations used. 157

Total No of Observations - Complete and Incomplete 860

May 26, 1913.

There were two waves reported which are beyond this scale, One is 700 Ft. × 80 Ft. and the other 1300 Ft. × 80 Ft.

Nationalities of Ships Reporting

American.
English.
German.
French.
Austrian.
Norwegian.
Spanish.
Belgian.
Italian.

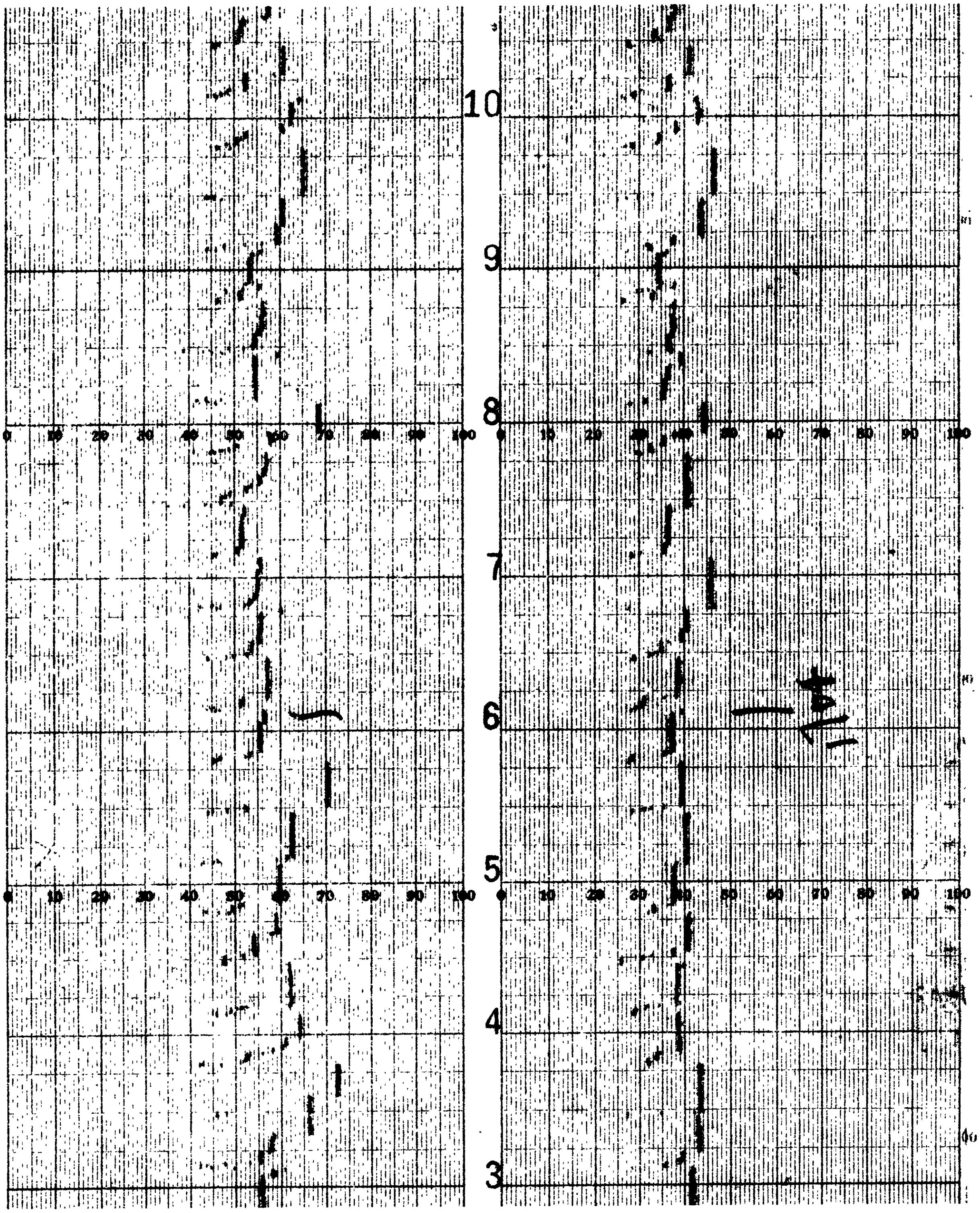


Fig. 7a. Typical chart from Voltmeter type Recorder. Paper speed 2 inches per hour. Voyage Colon–Port Arthur, February 17, 1930.
Flexuremeter on Centerline. Sag above, Hog below. Observing cycle 10 minutes.

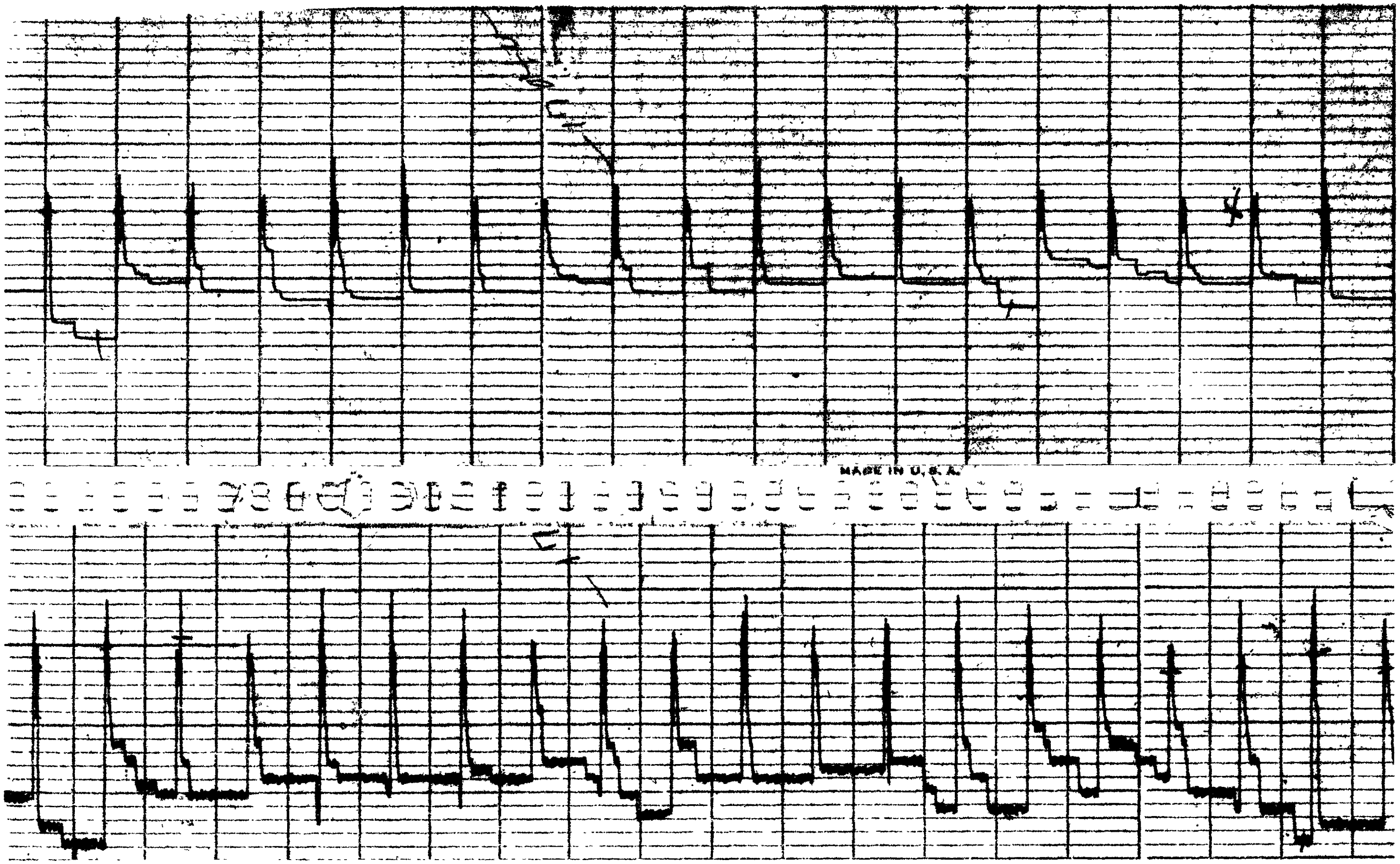


Fig. 7b. Typical chart from Potentiometer type Recorder. Paper Speed 3 inches per hour. Voyage Colon–Port Arthur, February 17, 1930.
Port Extensometer, Sag above, Hog below, matched on time scale. Observing cycle 10 minutes.

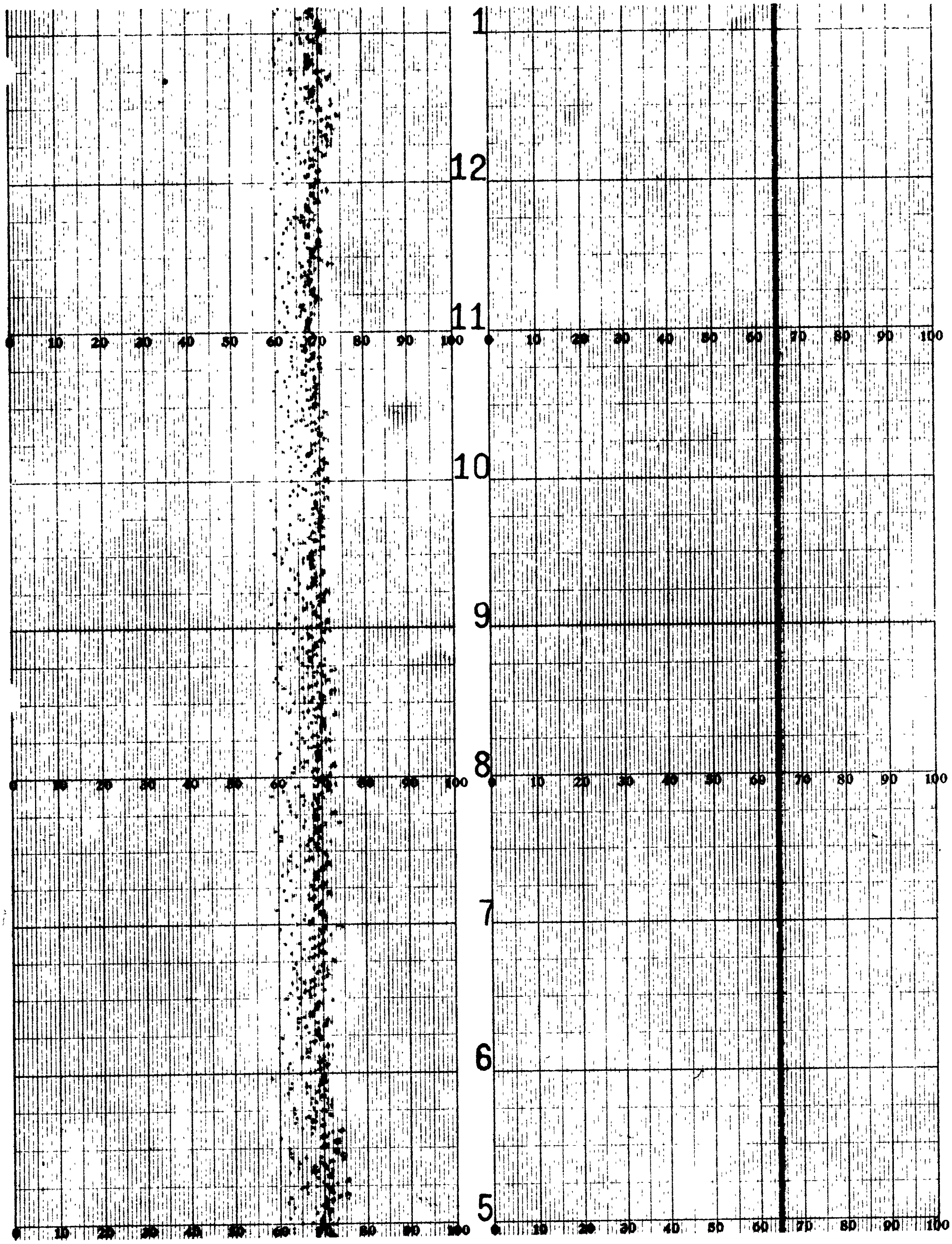


Fig. 13a. Voltmeter type Recorder. Observing cycle 1 minute.

In lower record gage is inoperative.

Straight line shows balance of voltmeter unaffected by motion of ship.

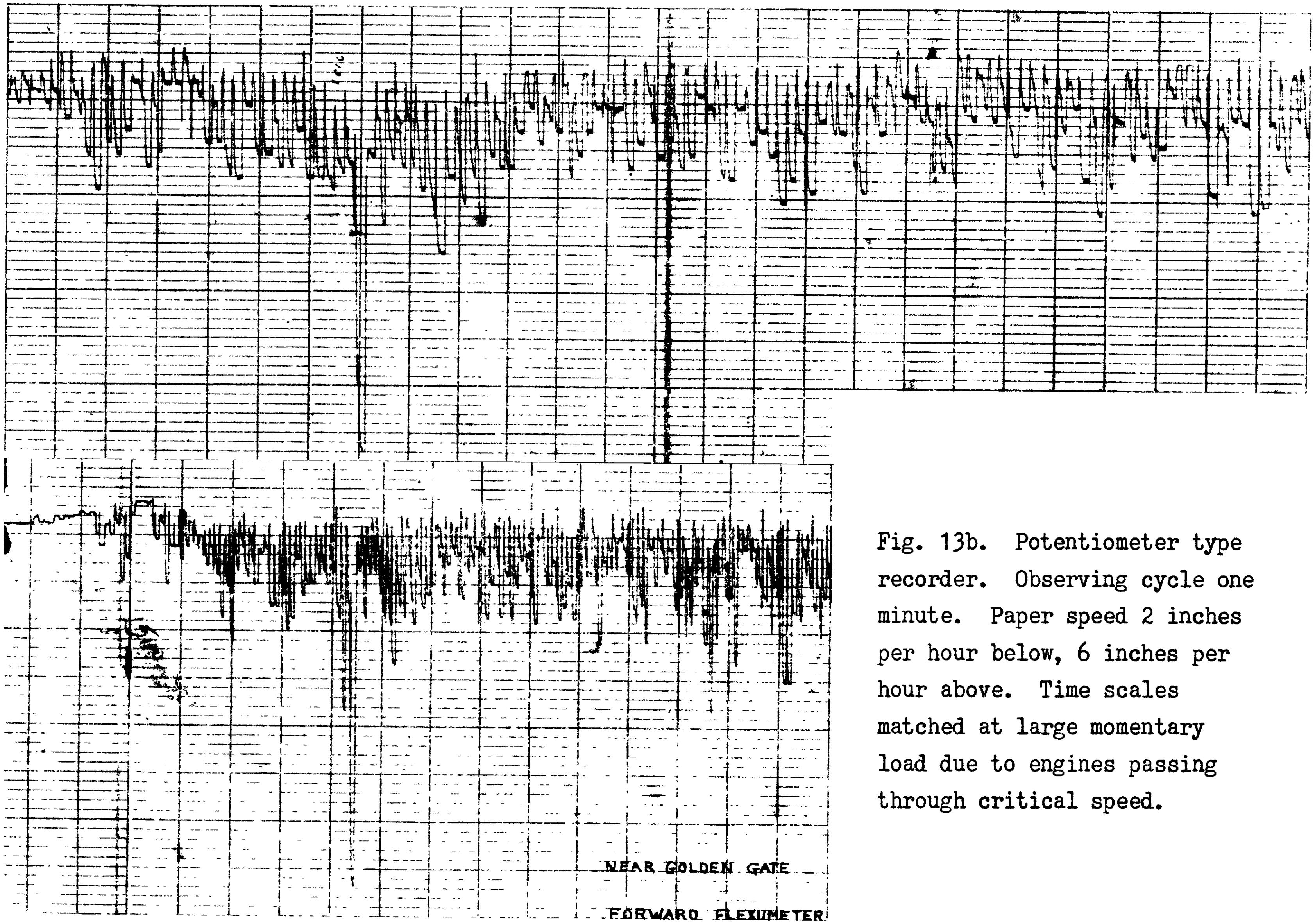


Fig. 13b. Potentiometer type recorder. Observing cycle one minute. Paper speed 2 inches per hour below, 6 inches per hour above. Time scales matched at large momentary load due to engines passing through critical speed.

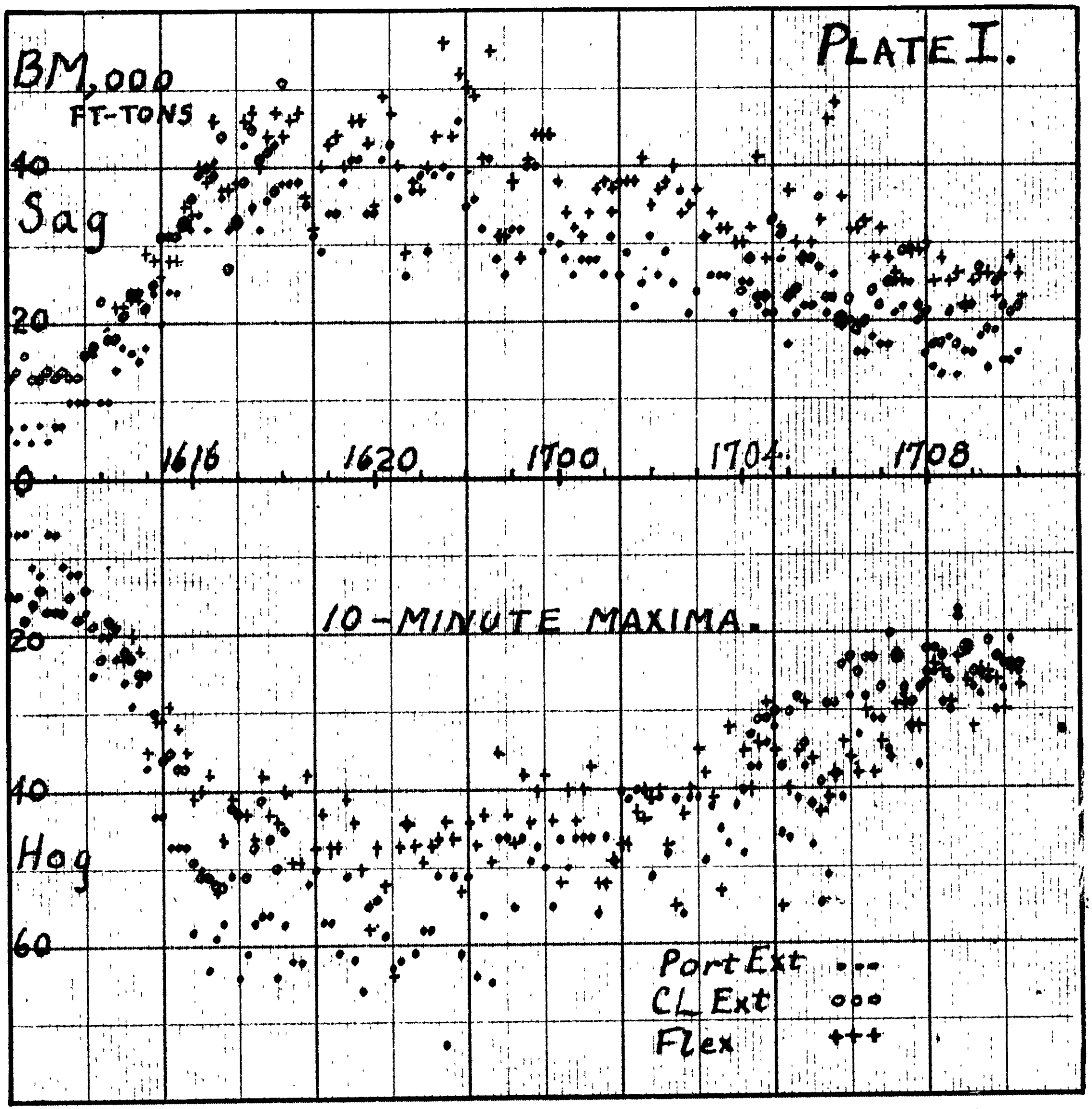


Plate I. Colon - Port Arthur, February 1930, 10-minute maxima.

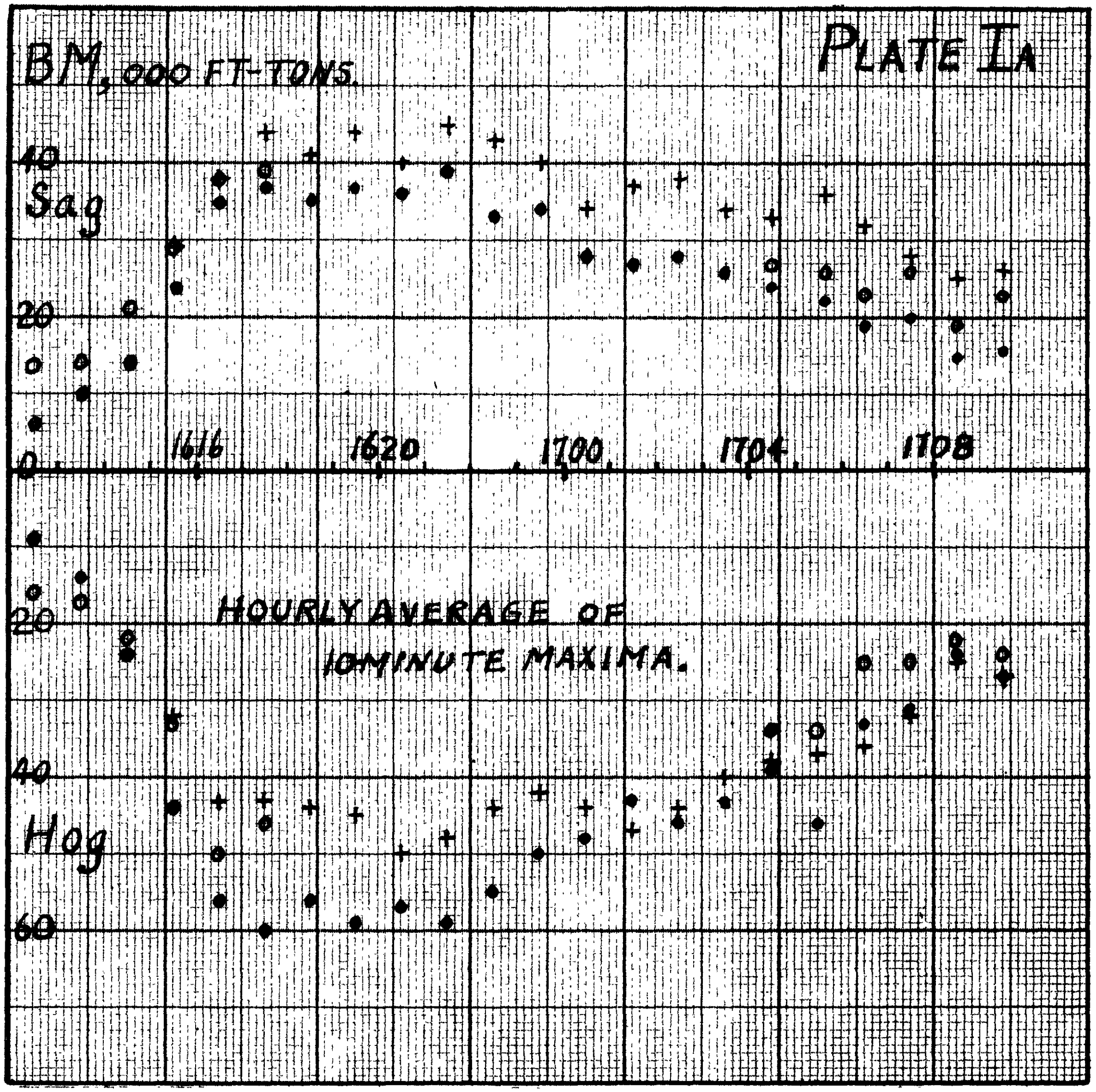


Plate IA. Colon – Port Arthur, February 1930, hourly average of 10–minute maxima.

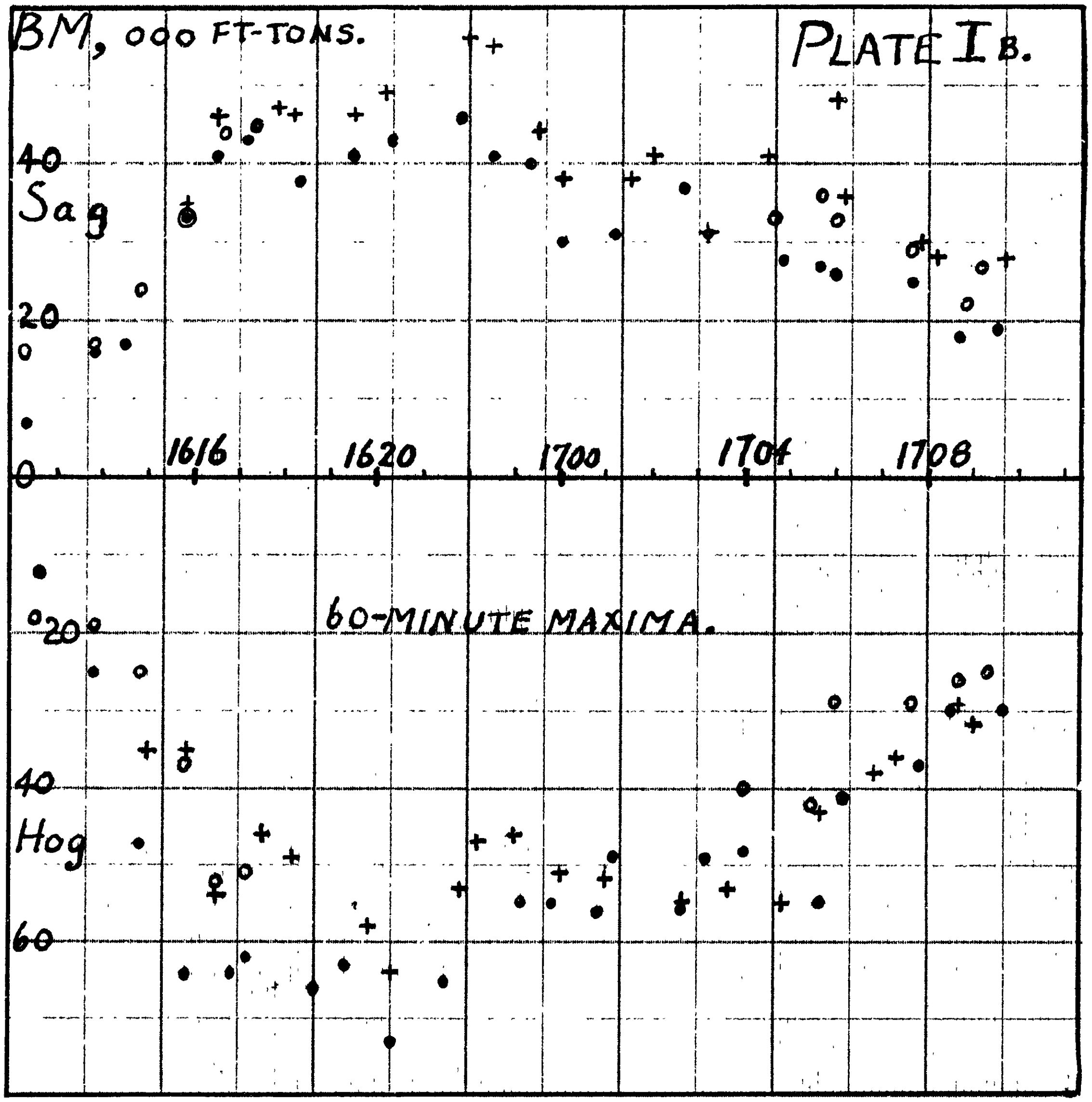


Plate IB. Colon - Port Arthur, February 1930, 60-minute maxima.

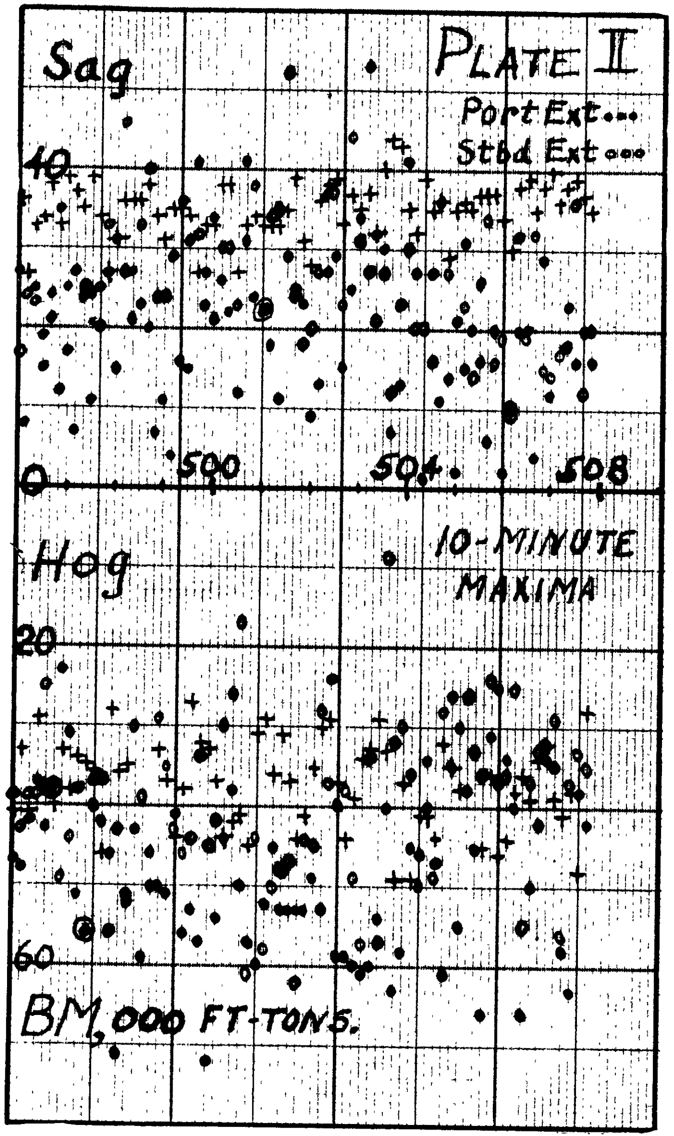


Plate II. San Pedro – Honolulu, January 1930, 10–minute maxima.

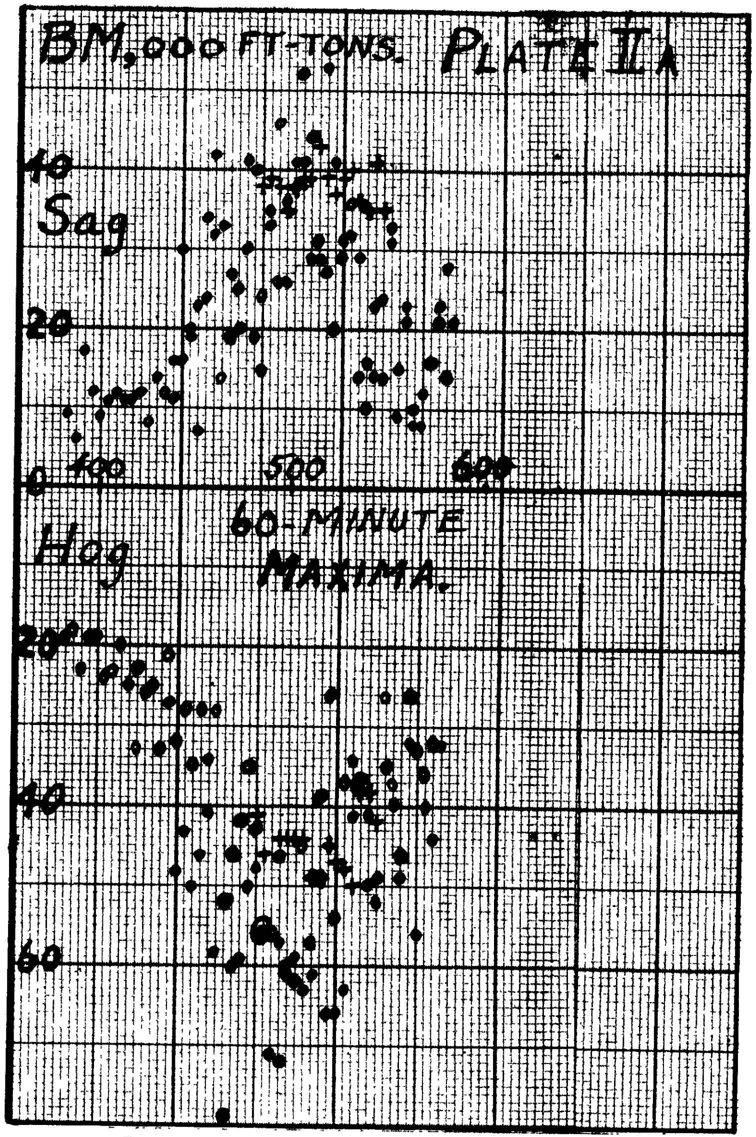


Plate IIA. San Pedro – Honolulu, January 1930, 60–minute maxima.

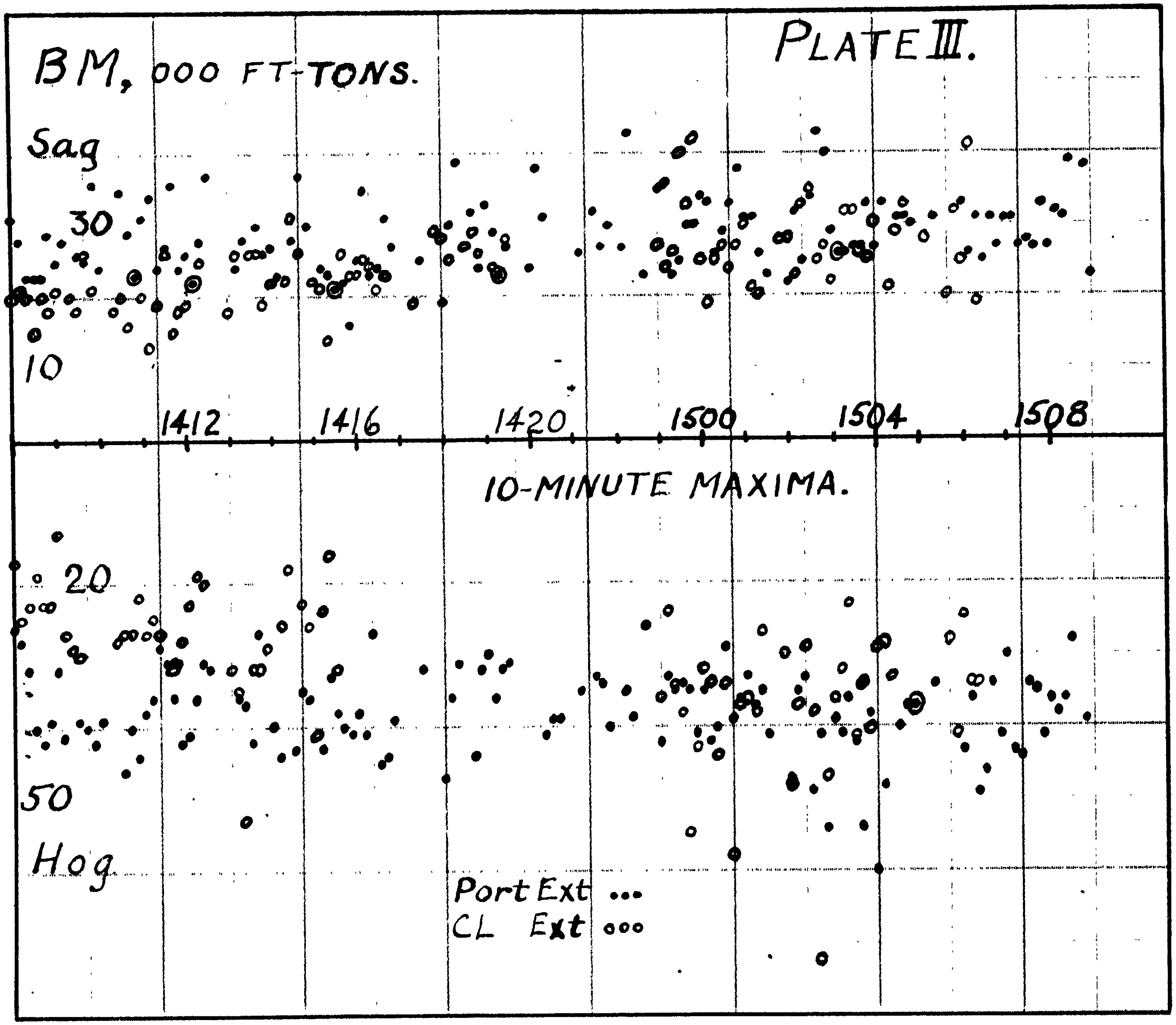


Plate III. Honolulu – San Pedro, January 1930, 10–minute maxima.

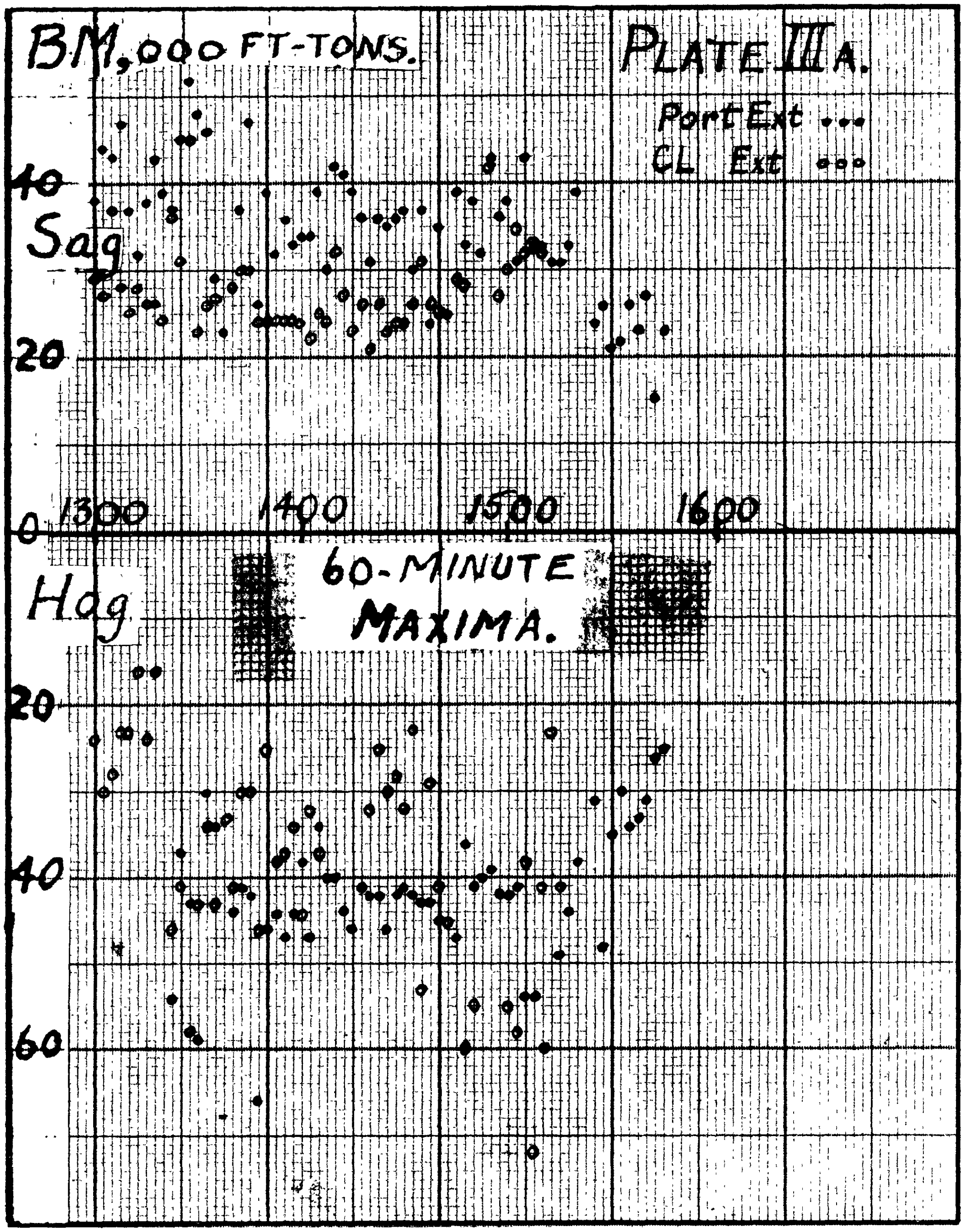


Plate IIIA. Honolulu - San Pedro, January 1930, 60-minute maxima.

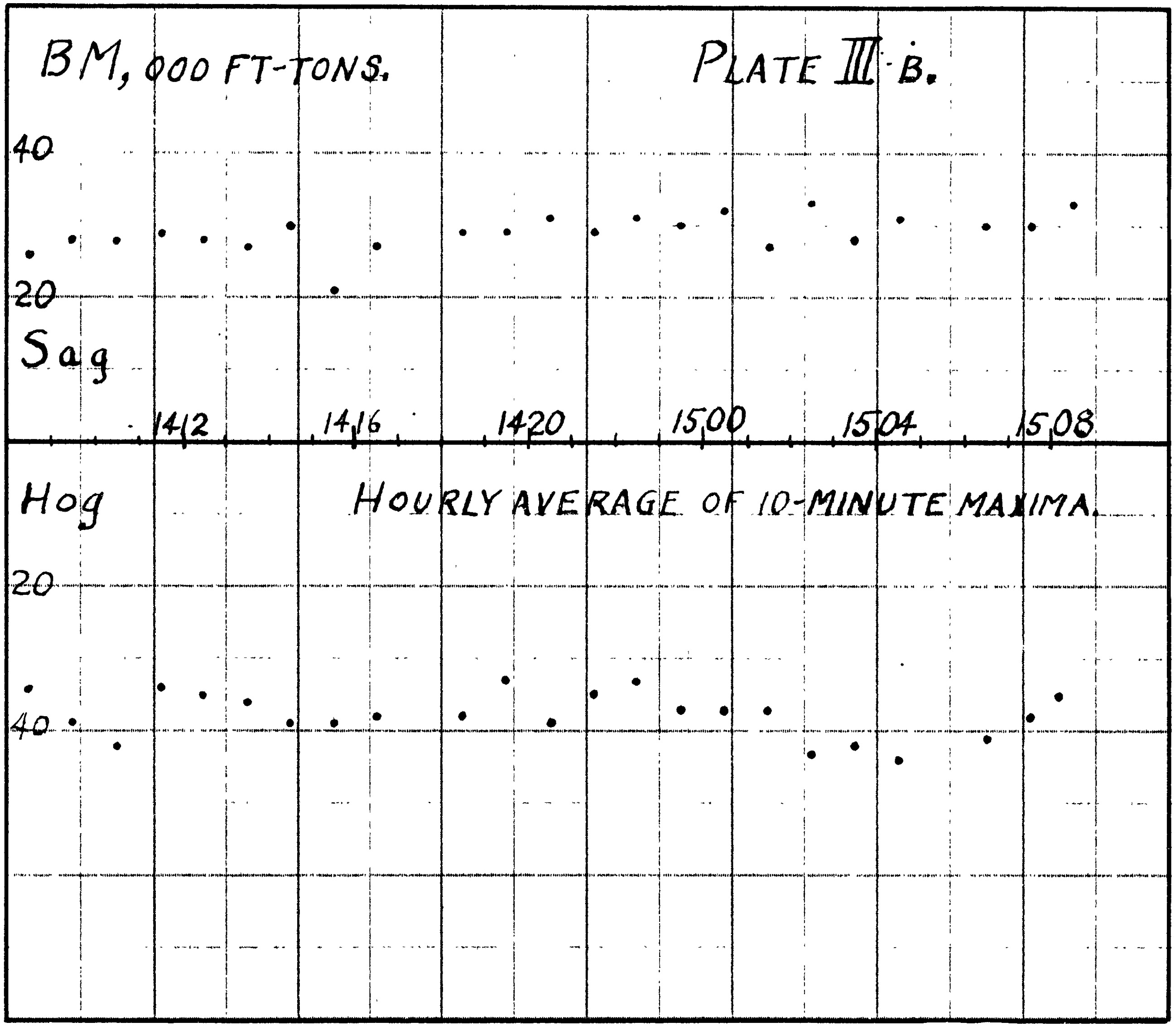


Plate IIIB. Honolulu - San Pedro, January 1930, hourly average of 10-minute maxima.

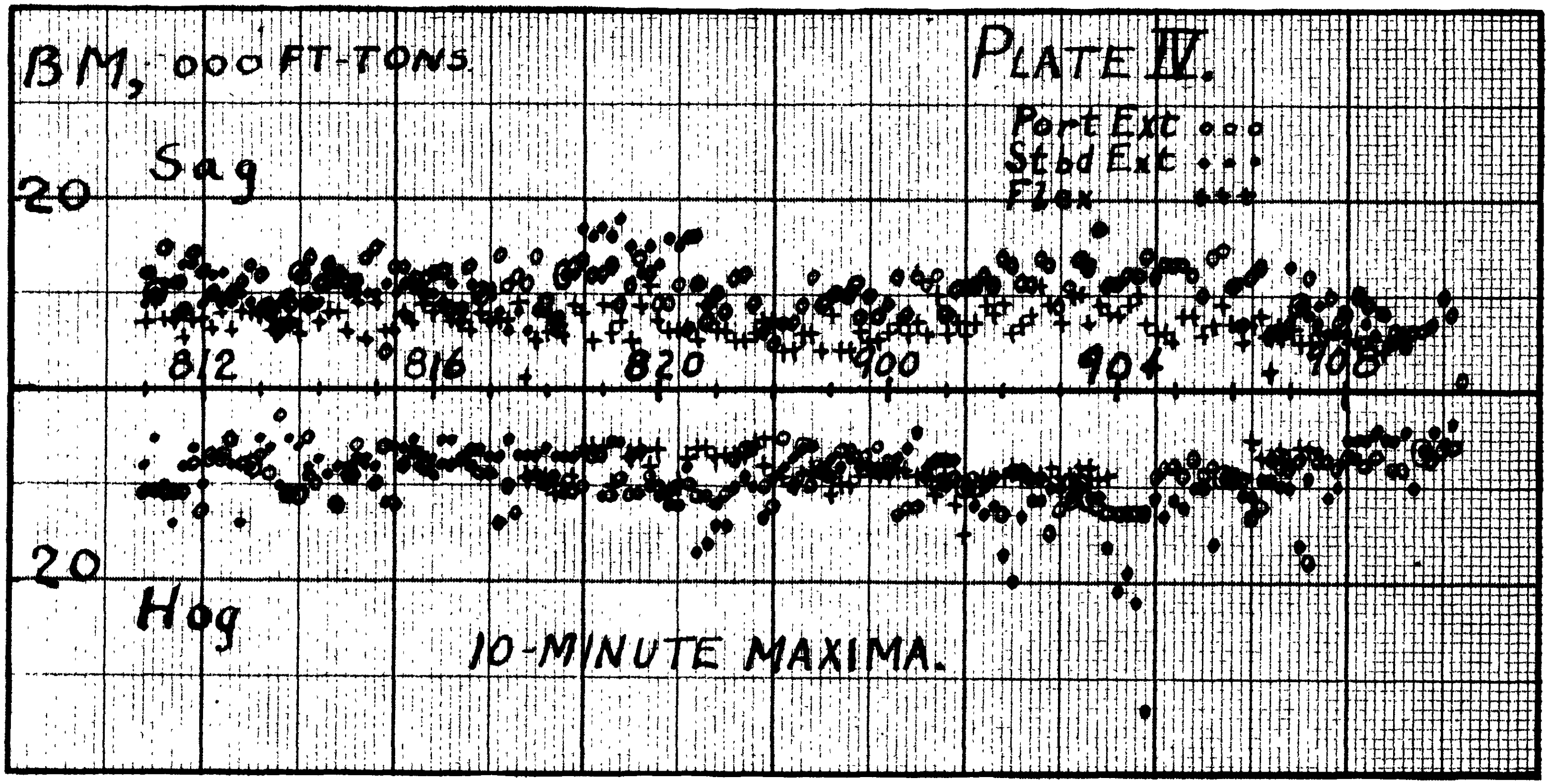


Plate IV. Gulf of Panama, January 1930, 10–minute maxima.

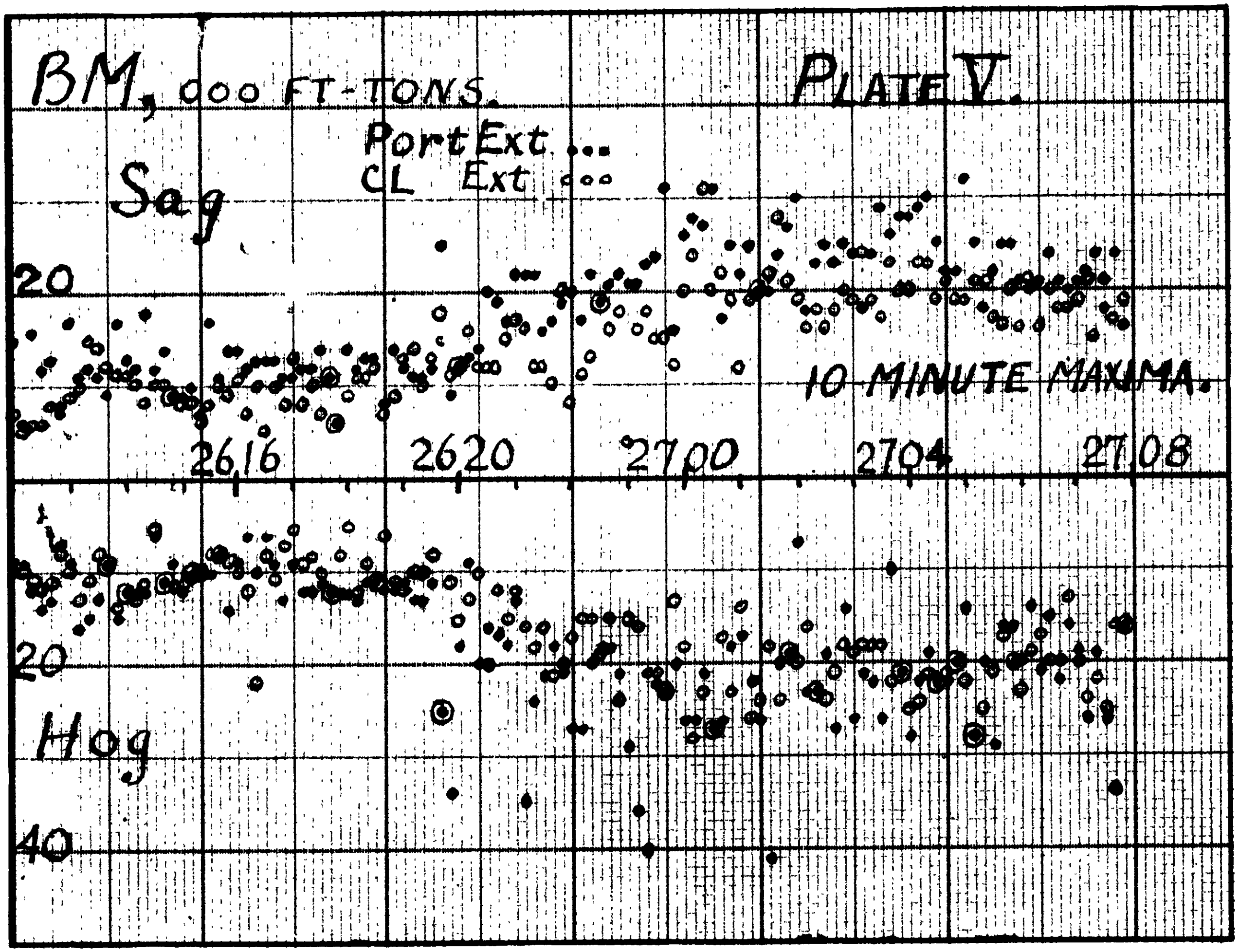


Plate V. Approach to Colon, February 1930, 10-minute maxima.

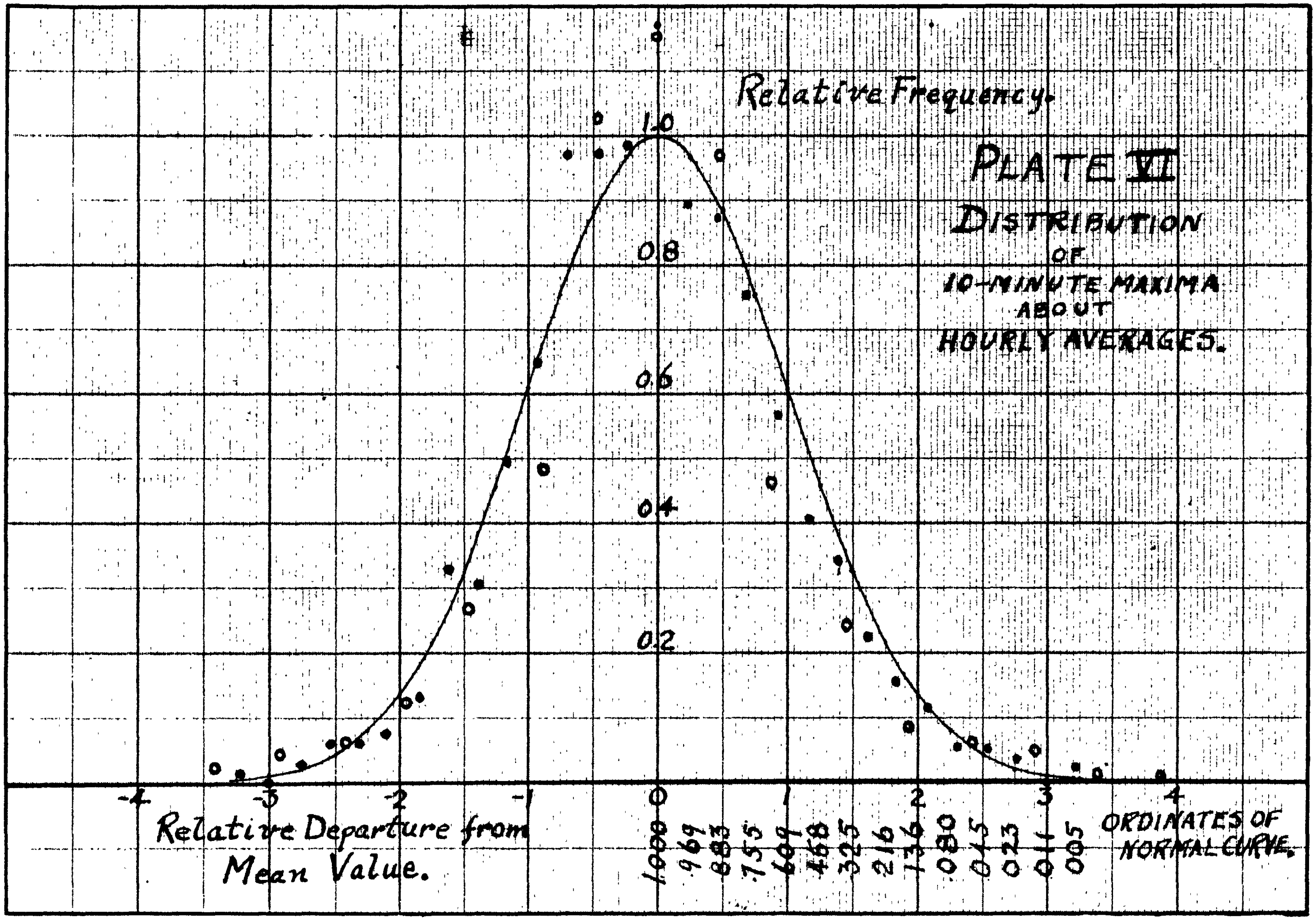


Plate VI. Distribution of 10-minute maxima about hourly averages.