UNITED STATES EXPERIMENTAL MODEL BASIN

NAVY YARD, WASHINGTON, D.C.

THE EFFECT OF WIND ON SHIP TRIALS

BY E. F. EGGERT, CAPTAIN, (CC), U.S.N.

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

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The present method of running standardization trials, as practiced by the Navy, has been in use for many years, and has been supposed to give very precise results. Certainly, if one considers the occasional practice of the Trial Board, of giving measured speeds on individual runs to three places of decimals, one must conclude that the results are considered to be very exact, yet many of these measured speeds vary, by large amounts, sometimes half a knot, a whole knot, or more, from the values they should have had, if the conditions had been favorable.

Experience has shown that in many cases trials of sister ships do not give good agreement. Trials of the same ship, at different times, often fail to show agreement. There must then be a factor hitherto neglected which must be taken into account, - this factor is the wind effect. Of course it is assumed that the trial measurements are accurately made; nevertheless it happens, as in all other experimental work, that errors creep in and are not detected. This however is outside the scope of this paper.

It has been assumed, tacitly at least, that modern ships are immune to wind, at least moderate winds. At the most, a correction was to have been made by averaging runs with and against the wind, if any, in the same way as a tide or other current is accounted for. It must be here emphasized that this paper does not deal with the air resistance of a ship, in still air. That is in most cases a small amount, of between two to four percent, of the water resistance. What is referred to is the additional resistance a ship experiences when steaming against a moderate wind, for instance, a battleship, steaming at 20 knots, supposedly, against a wind whose absolute velocity is also 20 knots. Going with such a wind, the relative wind velocity is nothing, and the ship saves no more than the two to four percent of power that is represented by the still air resistance. Going against it, the relative wind is forty knots, and the resistance, varying as the square of the speed, becomes a very respectable total.

It will perhaps astonish many to learn that this battleship, steaming against such a wind, which is of force 4, Beaufort scale, will at the same revolutions, and at about the same power, lose nearly a knot in speed. If however we consider the enormous upper works of such a ship, all acting as so many sails in an old-timer, it will not seem so surprising. Another result which will interest the navigator, if no one else, is that this wind sets up a current in the water, against which the ship must steam, of three tenths of a knot. According to the Coast and Geodetic Survey, a wind sets up a current of one and a half percent of its velocity. Upon reflection, it will be realized that a wind of force 4 has considerable energy, and it might be readily allowed that its effect is considerable. But the matter goes further than that. A MARYLAND, steaming against a wind of force 1, described as a "light air", velocity seven knots, will, at the same revolutions, at nearly all speeds, lose over a third of a knot. Yet these large vessels are supposed to be superior to wind and sea.

Ship trials, like all other measurements, are in essence comparisons with a standard. A standard is set perhaps by the contract, or it is set by another ship. In any case, the question is always – how does the ship compare with the standard? This is the object of all contract requirements as to speed, or power, or consumption measurements. It should not need to be pointed out that the comparison with the standard must be made under the same conditions. These must be standard conditions. The only standard conditions possible to be specified are those free from disturbance, such as current, heavy sea, foul bottom, damage – and adverse wind.

Since a ship cannot always be tried under conditions when there is no adverse wind, there must be a method for correcting the results. Correcting to the standard conditions is an important reduction in all measurements. It will be shown that this correction is not automatically made by alternate runs with and against the wind. A method of reduction will be indicated by which at least approximate reduction to the standard is obtained.

There have been quite a number of measurements of the wind resistance of a ship, by various experimenters, and by many methods. It may be said that the wind resistance of any ship, given the absolute velocity of the wind, and its direction, can be very easily computed, with sufficient accuracy for practical purposes. When the <u>relative</u> wind, that is, the wind velocity compounded with the ship velocity, is within four points of the bow, the resistance can be defined as that of a transverse plane of outline a silhouette of the ship's upper works. Practically speaking, this is a plane of rectangular form, its width the same as the beam of the ship, its height that from the waterline up to about the bridge, or about half the beam. The resistance, calling the area of this plane A, the ship velocity V, in knots, and the absolute wind velocity W, is

$$R = .004\ A\ (V + W)^2.$$

This resistance at times can become a large fraction of the water resistance. Thus, the battleship at eight knots, going against a wind of force four, has a wind resistance more than forty percent of the water resistance. The loss in speed, curiously, will, with a given wind, be almost the same absolute amount, at any speed of ship; but the resistance, and the difference in power at the same speed, will be widely different at different ship speeds.

It is not necessary to know this wind resistance very accurately. An approximation such as given by the above formula, is good enough. Trial data are not so precise as has been supposed, and this approximate value is as good as the data will warrant. Besides, the computation of the resulting speed through the water, from the trial data, taking account of the wind, will itself show whether or not the wind resistance has been assumed too high or too low. The above reference to the inaccuracy of trial data may be illustrated by the fact that at 30 knots, an error of one second in the elapsed time over the mile, an error not at all great, gives a corresponding error in the speed over the ground of one quarter knot. A measured mile is too short for a speed of thirty knots. At 20 knots such an error in the time gives an error in speed of .11 knots.

The above wind resistance can be readily used to determine the loss in speed, if the EHP curve of the ship is available. The resistance is converted into effective horsepower, and its amount stepped down the curve from the speed corresponding to the given power, assuming no wind. That is, we subtract the EHP due to wind from the EHP of the ship at the supposed speed, and the difference is the EHP of the actual speed. This assumes that the wake, thrust deduction percentage, and efficiency are the same, as well as the RPM. For relatively small variations in speed this is the case. There is an increase in the slip, corresponding to the reduced speed through the water.

On the standardization trial, if there is no wind, and if the current is constant, a run in each direction, at the same revolutions, will give, when averaged, the speed through the water. For, if V_o and V_o' are the speeds measured, over the ground, with and against the current, and if V is the true speed through the water, and c the current, then

$$\begin{array}{r} V_o = V + c \\ V_o' = V - c \\ \hline V_o + V_o' = 2V \end{array}$$

If the current changes uniformly, so that its amount for each run varies by a constant difference, three runs alternately will, when averaged as is now the custom, give the correct value of V, provided there is no wind. For, let c, c + m, c + 2m, be the values of the currents on the three runs, then

$$\begin{aligned} V_o &= V + c \\ V_o' &= V - (c + m) \\ V_o'' &= V + (c + 2m) \\ \text{And,}\quad V_o + 2V_o' + V_o'' &= 4V. \end{aligned}$$

Now suppose, the current still varying uniformly, the revolutions constant, that the first and third runs are made against a wind of constant force, and that there is therefore a reduction of the speed through the water during those runs, of amount dV. The run with the wind will not show any marked change. Then

$$\begin{aligned} V_o &= V - dV + c \\ V_o' &= V - (c + m) \\ V_o'' &= V - dV + (c + 2m) \end{aligned}$$

If now these results are averaged in the usual way, we find $V_o + 2V'_o + V''_o = 4\,(V - \frac{dV}{2})$. In other words, the average is not the correct mean speed for standard conditions, but varies with the wind. The speed so obtained is too small by the amount $\frac{1}{2}$dV. If the wind is constant, the corrected value can be found by adding $\frac{1}{2}$dV. Thus, if on any series of three runs the loss of speed against the wind is one half knot, the average found in the usual way must be increased by one quarter knot. It is readily seen that the results are the same when the wind is in the opposite direction, that is, when the loss in speed comes on the second run. There is a small correction in the opposite sense to the runs made with the wind, and in exceptional cases this must be taken into account, but as the wind resistance is then a function of the difference of the velocities, it is usually too small to be significant. From the point of view of the Model Basin, the trial results are wanted with all air resistance eliminated, for that is the condition under which models are run.

If now the wind is not constant, but varies from run to run, as is often the case, a different procedure is indicated. If the variation is small, and uniform, an average of the values of dV can be applied, and the runs when thus averaged and corrected will give satisfactory results. But if the wind changes abruptly from run to run, the speeds over the ground must first be corrected by the amounts of the change in ship speed due to wind. Then when the corrected speeds are averaged, the true mean speed is obtained, that is, the speed that would have been obtained if there had been no wind. The value V is of course not the true speed through the water when a wind is blowing. It is the speed that would have been obtained when all air resistance or wind was absent. This is the only basis on which trial results can be compared with a standard, or with results of other trials, or with results from model runs.

We have

$$\begin{aligned} V_o + dV &= V + c \\ V'_o &= V - (c + m) \\ V''_o + dV' &= V + (c + 2m) \end{aligned}$$

Now adding twice the second equation to the sum of the other two, and dividing by four, we get

$$\frac{1}{4}\,(V_o + dV + 2V'_o + V''_o + dV') = V.$$

It will be noted that the value dV is different on the two runs against the wind, but this variation, handled in this way, does not affect the accuracy of the value of V. The result is of course the same if the wind is in the opposite direction.

The rule can then be laid down: Add the loss in speed on each run, due to the wind, to the speed over the ground measured. Average these corrected speeds as usual.

It is difficult to find among the many records of Naval trials, cases where the wind prevailing during the trial is sufficiently described to allow satisfactory correction to be made. It has not of course been realized that special correction for wind was necessary, and that determination of the amount and direction of the wind, averaged for each run, was needed. A general and sometimes vague statement is made, such for instance as "Wind NE, N, SE, calm, force 1". These statements would be helpful if the times when the wind had these directions had been given, and the times when the wind changed in velocity from 1 to 3. From the CALIFORNIA trial may be also quoted the description of the wind, "Wind NW, shifting WNW, then SSW and W, force 1 to 3". A trial with no better determination of the wind is hopeless.

There are a few exceptions, where the wind is perhaps reported steady all day, or where the Board noted the changes and the times when they took place. Such was the trial of the MARYLAND, at Rockland, November 14 and 15, 1921. Here the wind was described as, for November 14, NE, force 2, and for November 15, NW, force 4. The sea on the latter day was moderate. High water was at about 9-40 am. on the 14th, and at Rockland high water and slack water are about coincident. The tidal curve follows the law of sines closely, and the maximum flow is moderate. The sheet attached shows the calculations of the results of these trials, corrected for wind, The first four columns give the measured trial results, the others are self-explanatory, except those following N/V. This last gives the revolutions per knot obtained by dividing the mean revolutions per minute by the mean speed, after correcting for wind, Here it might be noted that it has been customary to average RPM, as well as SHP, in the same way as speed is averaged, that is, the value for the middle run is doubled, and the sum divided by four. This is incorrect, for these quantities have nothing to do with the tide, they are obtained by averaging on time. A straight arithmetical mean is the only correct way, though the difference is too small to be significant.

It has been assumed, in all the above, and in any consideration of standardization trials, that the revolutions per minute are kept constant during all three or more runs of one speed spot. This is usually not obtained, though for the purpose of obtaining the mean speed of the spot a small variation in the RPM will have no effect. It will be seen that the values of V'_o in the table are averaged without regard to the variation in revolutions. But if we attempt from the results to derive the current existing, during the trials, a further correction is necessary, for the average value of V does not obtain on each of the runs. This speed is indeed proportional to the RPM. The column V' is obtained by dividing the RPM for each run by the average value of N/V for the spot. This is the actual speed through the water on each run, on the assumption of no wind. The current then is obtained by subtracting V' from V'_o.

The curve sheet shows these values of current plotted on the time of middle of run. This time is given in the table, column 2, in hours and tenths, from the midnight before, in other words, civil time. Through the spot on the base line corresponding to the time of slack water is plotted a curve of luni-solar tide current. From this again is stepped off and plotted a correction corresponding to the current generated by the wind, in amount one and one half percent of the wind velocity. This curve then represents the resultant current that should have obtained on that trial. It is seen that the separate spots of each trial run fall near to the corrected current curve, with some significant departures. Thus, for the runs of November 14, beginning with run 5, there is a very decided departure from the curve, which persists for some time, but disappears with run 9. It is clear that during this time there was a change in the wind, that it was actually, for runs 5 and 6, of force 3 or thereabouts, but that it gradually slacked off again to force 2 at about 9.5 hours. Later in the day there appears again a slight increase in the wind, up to about noon. On November 15, it would seem that the wind did not quite reach the strength estimated, force 4, on most of the runs. There are variations from run to run which would indicate variable wind, if we could be sure of the accuracy of the speed measurements.

If we assume a wind resistance different from that estimated, the three spots for the current, for each average speed, will not fall into one line, parallel to the current curve. The middle spot will be higher or lower than needed to match up with the other two. Here is a very nice criterion of the accuracy of the assumed resistance due to wind.

It will be noted from the table that all mean speed spots as obtained by the Trial Board, during this trial, namely, the means in column V_o, are, by the wind correction, increased by about a quarter of a knot on the first day, and by about four tenths of a knot or more on the second day. The method of reducing trial results, hitherto in vogue, therefore needs radical revision. Satisfactory results can be obtained as indicated above. It is very necessary to have precise information as to the wind during each and every run. With the wind aft no correction is usually needed, but a reliable determination of the resultant wind velocity, when steaming against the wind, is essential. It has been said above that one formula will give satisfactory results for the resistance, when the resultant wind is within four points of the bow. It has been found by experiment on a number of classes of ships, that the maximum resistance is obtained when the resultant wind is about two points off the bow. The excess might reach twenty percent. This difference is not very important until trial results become much more accurate than at present. When the wind is more than four points off the bow, the resistance due to it rapidly drops off, and can then often be neglected.

The analysis sometimes gives evidence of error in the records of the wind. Thus, in the case of the COLORADO, in 1924, a consistent current curve can not be obtained unless with the assumption that the wind direction given in the report is 180° in error. Data since obtained from the Weather Bureau tend to confirm this error. In the case of the WEST VIRGINIA, on September 3, 1924, it is evident that the wind must have been of force 3, and not 1 to 2 as reported.

It is very necessary that means be taken to obtain better records of the wind conditions during trials. An accurate anemometer, so placed as to give reliable results, should be included in the trial equipment, and careful readings made to determine the mean wind during each run. In this connection it is recollected that, on the trial of the Holland, there was encountered during one run a strong squall, which very perceptibly reduced the speed. No correction was however made. This squall lasted for only part of the run, and an anemometer would have given the average wind.

It is not necessary to be very accurate as to the direction of the wind, at least in the present state of the art. An estimate of the direction of the resultant wind can readily be made, close enough for all practical purposes.

There is recollected a statement by Mr. Adams, formerly of the Shipping Board, relative to an analysis of a large number of transatlantic runs, that the average increase of resistance, at a given speed, as compared to model results, was thirty percent going eastward, and one hundred percent going westward, the difference being due to the greater wind encountered, and perhaps heavier sea, on the westward run. The ship encountering an adverse wind must not only overcome the wind resistance, but stem a current which the wind sets up. A slow ship with relatively much tophamper will show a large wind effect, even with a wind of force 1. It should also be noted that endurance trials are vitiated by the wind, that, especially at low speeds, the wind effect may be very large, and the results largely in error, as compared to a standard, unless correction is made for the wind, and the latter accurately measured. Endurance runs should be made with the wind aft. The differences often found, between the SHP for a given value of the RPM, on the standardization runs and on the endurance runs are easily explained by the effect of the wind.

Until this question of wind correction is more carefully handled, little can be discovered as to such questions as the effect of fouling. The wind on a trial might make as much difference as the fouling, and an adverse wind with clean bottom might reduce the speed enough to show but little effect of fouling, if the trial foul is run with no wind.

The effect of rough water also is indeterminate, until the wind correction is carefully made. As far as data are available, it would appear that moderate roughness on the water has no effect on speed or power.

It has been said, by noted authorities, that the propeller is a very accurate and reliable dynamometer, and also a reliable speed log. This latter is indeed common opinion. How far the propeller may be in error in its indications of either speed or power, as determined from its revolutions per minute, can easily be imagined after a careful consideration of the wind effect. Results of trials are on record, on which, at constant **revolutions**, the wind caused loss in speed of over 1.3 knots, and a difference in power of from twenty to forty percent compared to standard conditions. The wind was of about force 5, and the ship a fast, relatively high powered vessel.

The question of the possibility of reducing the wind resistance of a given ship has not been touched upon. That is another question, but it can readily be imagined that such a reduction might be a great advantage in a given case.

July 1931.

NOTES ON THE DETERMINATION OF POWER ABSORBED BY WIND RESISTANCE DURING THE SPEED TRIAL OF SHIPS

References:

(a) "Test of Drawing Room Model of 10,000 ton Light Cruisers (CL24, 25) in water to determine the Forces due to wind", E.M.B. Report No. 276 of December 1930.

(b) "On the Analysis of Ship Trial Data", E.M.B. Report No. 293 of April 1931.

(c) "The Effect of Wind on Ship Trials", E.M.B. Report No. 264 of August 1930.

In any determination of the wind resistance offered by the exposed portion of a vessel, consideration must be given only to the relative or apparent wind, both as to velocity and relative direction.

Although the component of retarding (or assisting) force offered by wind resistance along the fore and aft center line of the vessel is the only one which is of ordinary consequence, it is not correct to resolve the true wind into components, one of which lies parallel to the fore and aft axis of the ship, and then to calculate the "head-on" resistance due to a relative wind having a velocity equal to that component.

When the relative wind is from dead ahead, the wind strikes directly on the bow, on the fore side of the bridge or deck erection, on the foremost funnel, on the ventilators and on the masts. The boats, for example, lying somewhat in the eddy of the bridge, the second (or third or fourth) funnel, deckhouses behind the bridge, cargo masts and derricks and the like are not exposed to the full force of the wind, due to the presence of eddies, hence the resistance offered by them is of a secondary amount.

When, however, the relative wind is off the bow, at an angle of say 20° to 30° to the ship's axis, the wind has an opportunity to blow full force on the entire length of hull, on all the deckhouses and erections, on all the funnels and on the remaining deck erections (such as turrets, hangars, fire control towers, etc. on war vessels). The result is that the total force exerted on the ship is appreciably greater than if the apparent wind were blowing with the same velocity from dead ahead. In the case of some light cruisers, this increase is of the order of 50 percent. When the total force thus produced on the ship is resolved into its two components, the one parallel to the axis of the ship may be greater than the whole force due to wind resistance with a relative wind of the same velocity from dead ahead.

On ships of special design, such as described in reference (a), the maximum retarding force in line with the axis is obtained when the angle between the ship axis and the relative wind is of the order of 33°. Assuming a true wind equal in velocity to the ship speed, this would bring the direction of true wind, as compared to the true course of the ship, at an angle of 66° to the bow, or well aft toward the beam. On those same ships, when the relative wind is blowing at an angle of 60° abaft the bow, the component of total force due to wind resolved along the axis of the ship, is still greater than the total force which would be exerted by the same velocity of true wind, blowing from dead ahead. That the relative wind may blow at this angle of 60°, the direction of true wind must be 30° abaft the beam.

Were such a true wind resolved into two components one giving velocity parallel to the axis, the result would give a force to assist the ship on her way, (or at least to reduce the still air resistance) instead of the correct result, which gives a force to retard the ship equal in amount to that derived from the usual wind resistance formula (see E.M.B. Report No. 264, ref. (c)).

Consider the diagrams, Figures 1 and 2, in which the vessel is running alternately on N and S courses, with a true wind from the N.E., of velocity equal to the nominal speed of the vessel. It is quite evident from the diagrams that the vessel is retarded by the wind on both runs. Resolving the true wind into components, as is frequently done, would give an entirely erroneous result. Likewise the effect of "canceling out the wind", by averaging the results of runs, would be equally erroneous. These features are treated at length in E.M.B. Report No. 264.

In brief, one must remember always that it is force due to relative wind, and not true wind, which must be resolved into components to find correct wind resistance.

The accurate determination of the total force due to apparent wind, when the latter is not dead ahead, can of course not be made by using a simple formula of the type R_w = constant x air density x cross section of ship and upper works x (wind velocity)^2. A fair approximation can however be so made, with allowance for direction obtained from experiments.

The best means of arriving at an answer to the general problem of wind resistance, but at the same time the most elaborate and expensive, is to prepare a model of the ship in question and to measure its resistance in air (or in water) with varying angles and velocities of relative wind.

This has been done for a number of ships and the results published (see the references) for general information. It is on the program of the Model Basin to undertake similar work on a model of the U.S.S. HAMILTON.

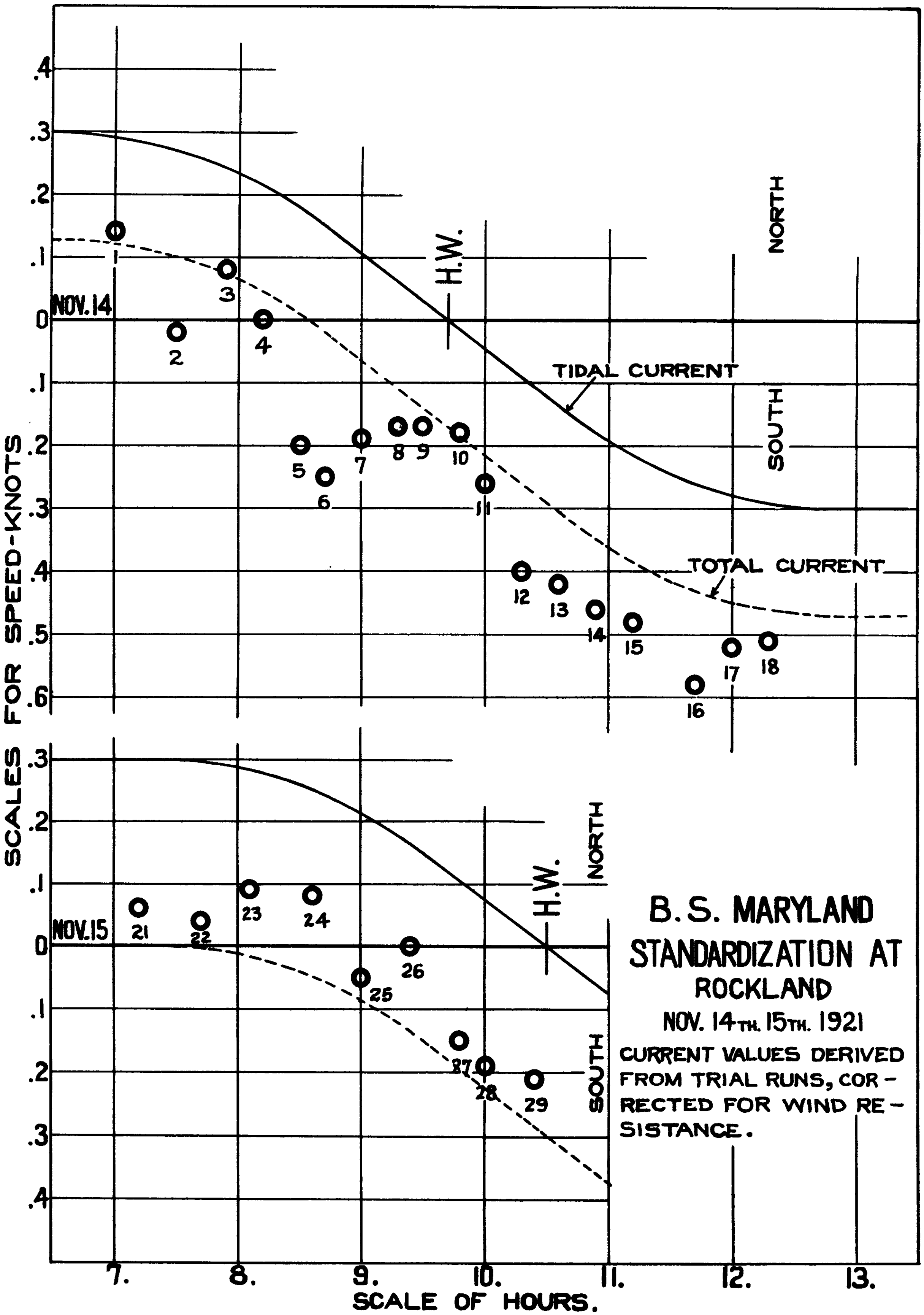
MARYLAND AT ROCKLAND NOV. 14TH. 15TH. 1921

DISPLACEMENT 32,500 TONS

NOV. 14TH. WIND N.E. FORCE 2 — NOV. 15TH. WIND N.W. FORCE 4

WIND AREA 5,000 SQ.FT. — WIND RESISTANCE = $20\,(W+V)^2$ LBS.

NOV.14 RUN	TIME HOURS	V_0	N_0	S.H.P.	ΔE.H.P.	dV	V_0'	$\frac{N}{V}$	V'	CURRENT
1 S.	7.0	17.17	134.68	13385			17.17		17.31	.14 N.
2 N.	7.5	17.19	137.46	14496	770	.45	17.64		17.66	.02 S.
3 S.	7.9	17.10	133.64	12990			17.10		17.18	.08 N.
			135.26			V=	17.39	7.78		
4 N.	8.2	18.50	149.29	18767	1040	.49	18.99		18.99	0
5 S.	8.5	19.09	148.41	18173			19.09		18.87	.20 S.
6 N.	8.7	18.46	150.94	19387	1040	.49	18.95		19.20	.25 S.
			149.55			V=	19.03	7.86		
7 S.	9.0	21.28	169.41	28358			21.28		21.09	.19 S.
8 N.	9.3	20.65	171.11	29562	1380	.48	21.13		21.30	.17 S.
9 S.	9.5	21.52	171.51	29607			21.52		21.35	.17 S.
			170.68			V=	21.27	8.03		
10 N.	9.8	20.88	176.34	———	1390	.44	21.32		21.50	.18 S.
11 S.	10.0	22.18	179.86	35051			22.18		21.92	.26 S.
12 N.	10.3	21.20	180.83	36087	1400	.44	21.64		22.04	.40 S.
			179.01			V=	21.83	8.20		
13 S.	10.6	22.42	181.06	36544			22.42		22.00	.42 S.
14 N.	10.9	21.10	181.05	36312	1540	.44	21.54		22.00	.46 S.
15 S.	11.2	22.49	181.14	36399			22.49		22.01	.48 S.
			181.08			V=	22.00	8.24		
16 N	11.7	16.04	166.39	INBOARD SCREWS ONLY		.45	16.49		17.07	.58 S.
17 S.	12.0	17.81	168.45				17.81		17.29	.52 S.
18 N.	12.3	16.30	168.14			.45	16.75		17.26	.51 S.
			167.66			V=	17.22	9.74		
NOV.15										
21 S.	7.2	8.15	60.79	1095			8.18		8.24	.06 N.
22 N.	7.7	7.51	61.88	1366	400	.91	8.42		8.38	.04 N.
23 S.	8.1	8.19	61.15	1100			8.19		8.28	.09 N.
			61.27			V=	8.30	7.38		
24 N.	8.6	9.71	77.92	2659	570	.83	10.54		10.46	.08 N.
25 S.	9.0	10.53	78.08	2522			10.53		10.48	.05 S.
26 N.	9.4	9.46	78.13	2594	570	.83	10.49		10.49	0
			78.04			V=	10.48	7.45		
27 S.	9.8	15.27	115.91	8590			15.27		15.12	.15 S.
28 N.	10.0	14.14	116.35	8904	1130	.86	15.00		15.19	.19 S.
29 S.	10.4	15.44	116.60	8800			15.44		15.23	.21 S.
			116.29			V=	15.18	7.66		


NOV. 14
NOV. 15
SCALES FOR SPEED-KNOTS
SCALE OF HOURS.
H.W.
NORTH
SOUTH
TIDAL CURRENT
TOTAL CURRENT
B. S. MARYLAND
STANDARDIZATION AT
ROCKLAND
NOV. 14TH. 15TH. 1921
CURRENT VALUES DERIVED FROM TRIAL RUNS, CORRECTED FOR WIND RESISTANCE.

ROCKLAND TRIAL COURSE

TRUE WIND ~ 45° VELOCITY ~ V

NOMINAL SHIP SPEED ~ V

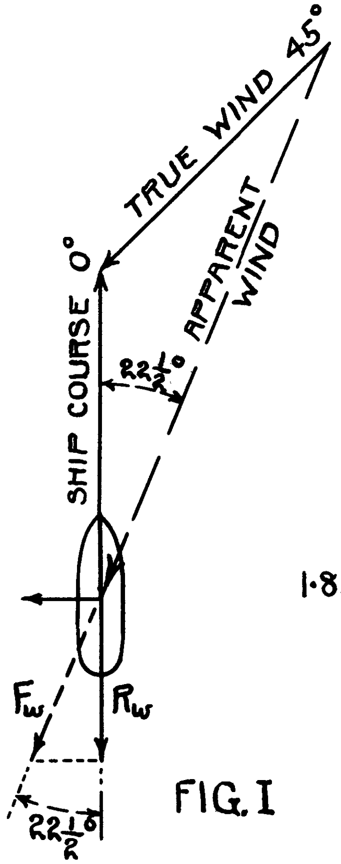


FIG. I

GOING NORTH

APPARENT WIND ~

DIRECTION, FORWARD, $22\frac{1}{2}°$ STARBOARD

VELOCITY, $2 \times V \times \cos. 22\frac{1}{2}° = 1{\cdot}85\ V$

F_w = FORCE DUE TO APPARENT WIND OF VELOCITY $1{\cdot}85\ V$ AT ANGLE WITH AXIS OF $22\frac{1}{2}°$

R_w = RESISTANCE TO FORWARD MOTION OF SHIP ALONG AXIS = $F_w \cos. 22\frac{1}{2}°$

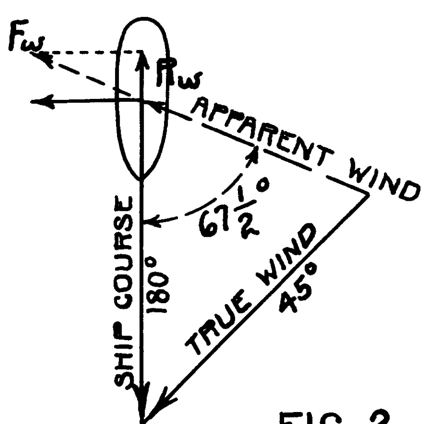


FIG. 2

GOING SOUTH

APPARENT WIND ~

DIRECTION, FORWARD, $67\frac{1}{2}°$ PORT

VELOCITY, $2 \times V \times \sin. 22\frac{1}{2}° = {\cdot}77\ V$

F_w = FORCE DUE TO APPARENT WIND OF VELOCITY $\cdot 77\ V$ AT ANGLE WITH AXIS OF $67\frac{1}{2}°$

R_w = RESISTANCE TO FORWARD MOTION OF SHIP ALONG AXIS = $F_w \cos. 67\frac{1}{2}°$