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CALIBRATION OF THE R/V ATHENA SPEED SENSOR,(U)
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DAVID W. TAYLOR NAVAL SHIP RESEARCH AND DEVELOPMENT CENTER

Bethesda, Maryland 20084

CALIBRATION OF THE R/V ATHENA SPEED SENSOR

Shelton M. Gay, Jr.
James A. Heffner

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SHIP PERFORMANCE DEPARTMENT
DEPARTMENTAL REPORT

April 1981

DTNSRDC/SPD 0996-01

CALIBRATION OF THE R/V ATHENA SPEED SENSOR

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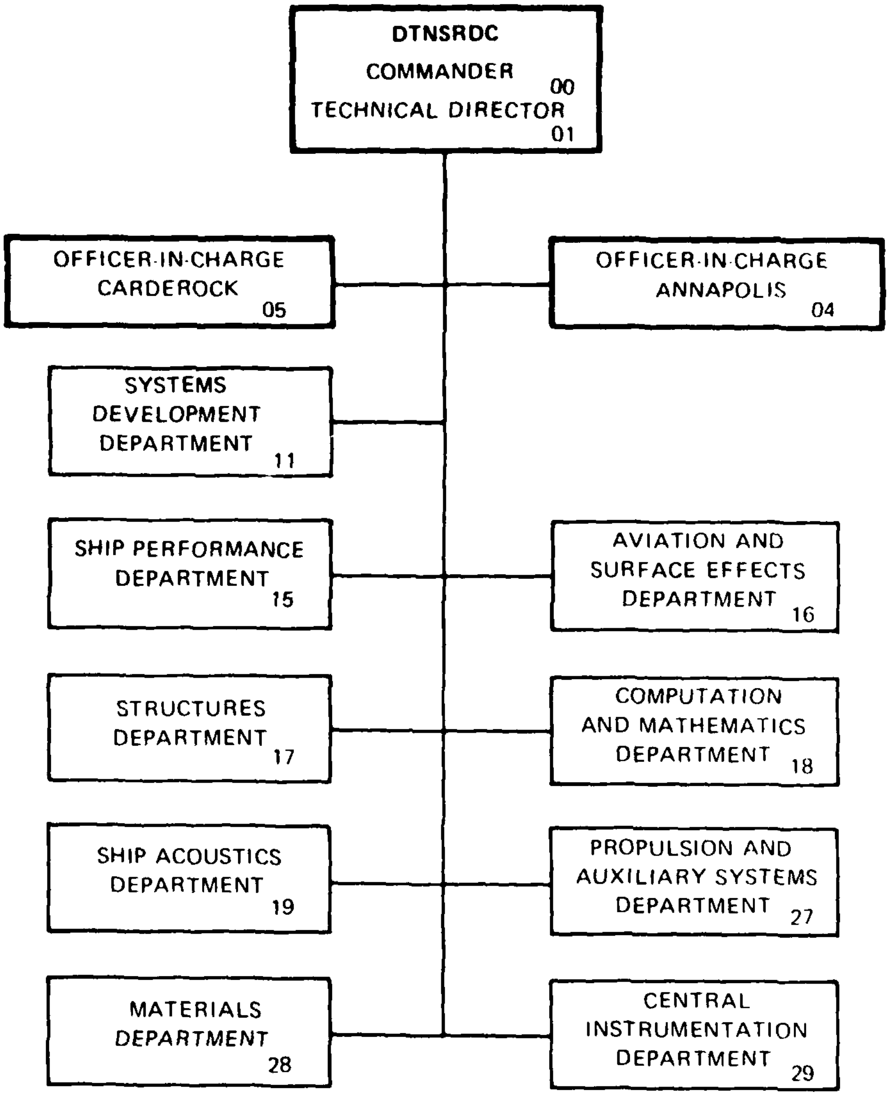

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The Kenyon knotmeter on the R/V ATHENA was calibrated at sea. The calibration method is based on use of the ship's LORAN-C and CC-2 computer to provide a measure of ship speed relative-to-ground. However, the calibration procedure also accounts for ocean current speed and direction. Thus the technique results in an accurate measure of ship speed relative-to-water upon which the knotmeter calibration can be based. Calibration data indicate that the sensor is subject to friction and other factors which results in prior

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

NOTATION

C	Current speed
C'	C/U
N	Kenyon meter 10 second count (voltage pulses/10 seconds)
SE	Standard Error of the Mean
TB	True bearing
U	Ship speed relative to water
V	Ship speed relative to ground
$\overline{x}$	Mean of the quantity x
α	$\phi_1 - \theta$
$\Delta_{x\ y}$	Sum or difference of square of speeds relative to ground for legs indicated by subscripts x, y
θ	Direction of current relative to true North
σ	Standard deviation
ϕ_1	Heading of ship on reference leg relative to true North

ABSTRACT

The Kenyon knotmeter on the R/V ATHENA was calibrated at sea. The calibration method is based on use of the ship's LORAN-C and CC-2 computer to provide a measure of ship speed relative-to-ground. However, the calibration procedure also accounts for ocean current speed and direction. Thus the technique results in an accurate measure of ship speed relative-to-water upon which the knotmeter calibration can be based. Calibration data indicate that the sensor is subject to friction and other factors which resulted in prior underestimation of speed through the water from about 1.5 knots at low speed (below 15 knots) to 2.25 knots at high speed (15 to 30 knots). This report presents both the method of calibration and the new Kenyon knotmeter calibration curve. The variation in the sensor output data is examined and recommendations are made regarding smoothing of the output data.

INTRODUCTION

R/V ATHENA is a patrol gunboat converted by the David W. Taylor Naval Ship Research and Development Center (DTNSRDC) to serve as a high-speed research platform. Since ship speed relative to water has a significant effect on performance of many research systems (acoustic systems in particular), it is important that its value be known accurately.

ATHENA is equipped with two hull mounted sensor systems for measuring ship speed relative to water:

1. A Kenyon knotmeter, Model KS245, manufactured by Kenyon Marine, Guilford, Connecticut, and

2. An underwater electromagnetic (EM) log, 0 to 40 knots, manufactured by Chesapeake Instrument Division, Gould, Inc.

In January 1979, ATHENA was fitted with an external girth band, which protrudes from the hull 2.25 in. (5.7 cm). The locations of the band and speed sensors are shown in Figure 1. This band installation near the sensors raised questions concerning the accuracy of the water-speed sensors. Therefore, trials were conducted on 12 December 1979 in the Fort Lauderdale area to determine the accuracy of the speed-relative-to-water sensor. The Kenyon meter was selected for calibration as the EM log was inoperative at the time.

The method used for calibration relies on speed-relative-to-ground data as measured on the ship's LORAN-C system. This report describes the technique developed for calibrating the knotmeter at sea and presents analysis of some of the statistical properties of the calibration measurements.

CALIBRATION METHOD

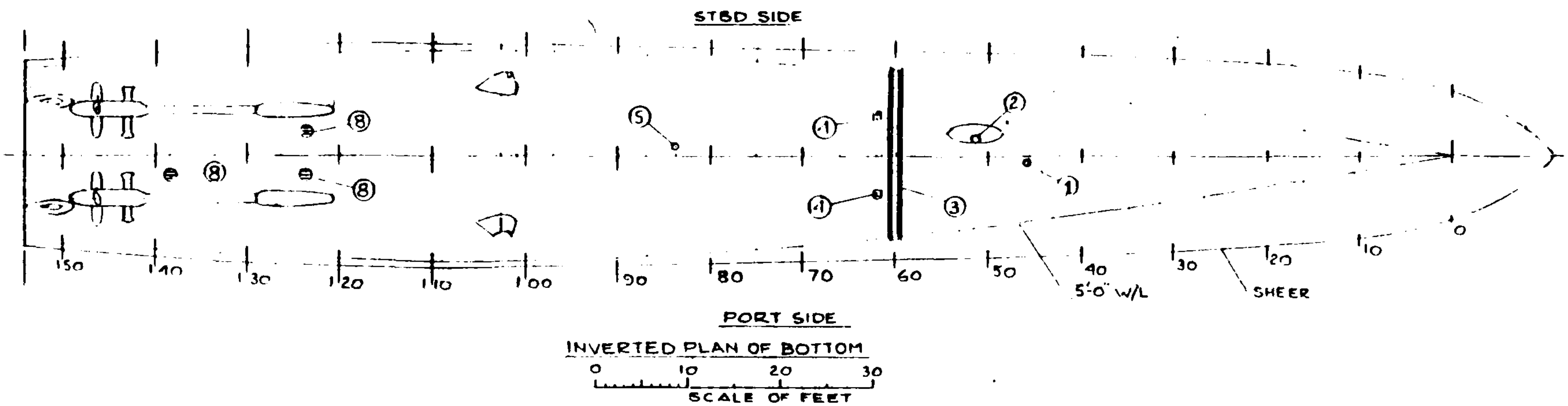
Calibration of ship speed sensors in a towing tank is not possible unless hull flow effects can be adequately simulated. On the other hand, in-situ calibration at-sea presents its own set of problems as a result of:

1. lack of precise knowledge of speed over ground because of ocean currents, and
2. difficulty of maintaining steady state conditions over a sufficient length of time.

The Kenyon knotmeter was calibrated at sea by a technique reflecting the above factors and based on the following methodology:

1. Ship speed relative-to-ground is measured by the ship's LORAN-C position indicator and the CC-2 computer.
2. By a proper selection of courses (reciprocal courses) current speed and direction can be resolved from the speed relative-to-ground measurement, and speed relative-to-water can be computed.
3. Statistical methods are used to resolve the uncertainties due to short-term fluctuations of the data.

The calibration technique is described in further detail below.



KEY

(1) Kenyon Log - FR 46 - 6' to port
(2) Fathometer - FR 51-3/4 - 2'3" to stbd.
(3) Band - FR 60
(4) Chesapeake Log (P&S) - FR 62 - 4'0" from ℄
(5) Yawmeter - FR 63-3/4 - 9" to stbd.

(8) Seachests

Figure 1 - Location of Underwater Appendages on R/V ATHENA

SPEED RELATIVE-TO-GROUND MEASUREMENT

ATHENA is equipped with a LORAN-C navigational system which computes and displays latitude and longitude, based on LORAN-C time differences. In an alternate mode of operation, the system computes and displays average speed over ground and track for the interval between successive fixes.

The latitude-longitude display may be used to duplicate the standard measured mile technique. The accuracy of the speed-over-ground determination depends on the accuracy of the measurement of the distance traveled and the time interval required. The error in LORAN-C position relative to a previous one is 50 ft (15 m) on ground wave. This introduces an error of only ±0.82 in a nautical mile (NM). However, the display is updated periodically so that the precision of this method depends on starting the exercise at the precise time of a position update and finishing the exercise at the precise time of some subsequent update. Also, unless the heading is due North or the trial is run at the equator, the computation of distance traveled is somewhat cumbersome. This method, like the standard measured mile technique, provides no information regarding variability of speed over ground or information regarding current, other than the component of the average current along the ship's heading. Also, sinuosity of the course resulting from the inevitable lag in correcting the helm results in an underestimate of distance traveled and a bias toward underestimating true speed through water (small though it may be).

The speed-relative-to-ground display, on the other hand, is reported to have an accuracy of ±0.25 knot. The data consist of the average speed (distance-to-time ratio) between fixes and, therefore, approximates the distance traveled over the course as a series of lines secant to the trace of the actual track, thus reducing the bias of errors on the helm. Previous observations indicate that the speed-relative-to-ground data vary and hence provide an indication of the expected variation in ship's speed under conditions of constant power. This variation is of interest as it may, for example, shed light on low frequency modulation of acoustic sensor self noise.

SPEED RELATIVE-TO-WATER CALCULATION

The procedure for calculating ship speed relative-to-water U is detailed in Appendix A. The ship course is run on four orthogonal legs (e.g., N, S, E and W) at constant shaft RPM. By measuring only speed relative-to-ground V, the relative direction of the current α can be computed by equation A.1:

$$\alpha = (\phi - \theta) = \tan^{-1}\left(\frac{V_E^2 - V_W^2}{V_N^2 - V_S^2}\right) \qquad (1)$$

With α, and forming ratios of the V's, the normalized current $C' = \frac{C}{U}$ can be computed using equation A.8. Finally U is computed by equation A.6.

Thus by selecting ship's runs to be reciprocal courses separated by 90^0, current speed and direction can be calculated and applied to the measurement of speed-relative-to-ground to obtain speed relative-to-water.

VARIABILITIES

The purpose of the experiment is to determine the average speed of the ship relative to water and correlate that measurement with the output of the water speed sensor. A number of factors affect the speed of the ship relative to water under conditions of constant power. Some of these are listed below:

1. sea
2. wind
3. heading relative to sea and wind
4. ship motion
5. variable rudder drag (from course corrections)
6. variation in shaft horsepower

Due to these factors, short term fluctuations occur in ship speed relative to water which are reflected in the speed sensor output. The Kenyon meter output consists of a voltage pulse for each revolution of the impeller. The pulses are counted for a specified interval of time to provide an average rotation rate over that interval, which in turn is directly related to speed through water as determined by other means.

As mentioned earlier, the independent means for resolving speed through the water is by calculation based on measurement of speed over ground. But the speed over ground within a given run (or measurement period) is subject to the same variabies that affect speed through water, plus a run to run variation due to current and wind. Moreover, the measurement interval and number of data points accumulated in a given time are not the same for each instrument. That is, readings are not obtained at identical times and the readings do not represent equal periods of time.

It is convenient therefore to regard the outputs of both the Kenyon meter and the LORAN-C as random variables that will tend to cluster more or less closely about the population mean during specific events. For our purpose, an event consists of a run on a constant heading with constant power settings of the ship's propulsive machinery.

The selected experiment design, therefore, consisted of obtaining sufficient data during each event to obtain an estimate of the population mean for both variables. The means of the over-the-ground speed records are used to compute the true speed through water. A linear regression analysis is performed that gives the relationship between the means of the Kenyon meter output and the means of the true speed through water. The correlation coefficient for this line of regression is computed together with the Standard Error (SE) of estimate of the mean.

The Kenyon meter output on ATHENA is converted from a frequency to D.C. voltage that drives a digital display. The electronic configuration is such that 100 c/s (counts/second) corresponds to a display output of 30 knots, or 0.3 knot/count/sec. On this time base, a count of ± 1 corresponds to an indicated speed change of ± 0.3 knot, so that under even ideal conditions a display variation of 0.6 knot would be expected. In a State 3 sea, fluctuations in the display on the order of 3 to 4 knots have been observed. It was desired, therefore, to accumulate Kenyon meter output in a format that would permit examination of smoothing techniques to reduce the extreme fluctuations in the one-per-second displays.

A time base of 10 seconds was selected for accumulation of the Kenyon meter output count, followed by a 10-second hold and display, another 10-second accumulation, etc. Thus, the Kenyon output was sampled for 10 seconds during every 20-second period. This permitted manual entry of data and reduced the impact of a single count to a nominal value of ±0.03 knot.

The LORAN-C system has an inherent accuracy of ±0.25 knot. The computer updates every 15 seconds to 60 seconds on a somewhat irregular basis, depending on detection of time differences. It thus displays average speed and track for the interval of time between successive updates.

EXPERIMENTAL PROCEDURES

Data were taken for six speeds, each run at constant shaft RPM to produce nominal ship speeds of 5, 10, 15, 20, 25 and 30 knots. For the 5- and 10-knot speeds, the runs were made over four legs separated by 90°, resulting in two sets of reciprocal courses at each shaft RPM setting. For the remaining runs, only the North-South legs were used.

Runs were identified as follows:

Run Number	1	2	3	4	5	6
Nominal Speed (kts)	5	10	15	20	25	30

Ship Heading (Degrees, True)	010	100	190	280
Designator	N	E	S	W

Thus 2E indicates a nominal speed of 10 knots on the eastbound or 100° leg.

The data runs were taken under conditions of constant power; i.e., at constant RPM on both shafts. All ships systems were given time to stabilize and settings were held constant during the various legs of each data run. The judgment that ship systems and speed were stabilized for a given run (and following turns within a given run) was based on the steadiness of the output of the Kenyon meter and the LORAN-C speed-relative-to-ground displays. In all cases, the LORAN-C display was allowed at least three updates prior to recording data from the run.

The trials were conducted on a NE and SW course line three to four miles offshore paralleling the coast in the area just north of the Port Everglades, Florida seabuoy, approximately between latitudes of 26°7' and 26°17' and longitudes of 79°55' and 80°2'30". The environmental conditions are listed in Table 1.

TABLE 1 - ENVIRONMENTAL CONDITIONS

Sea	State 1	½ ft to 1 ft (0.15 to 0.3 m)
Swell	State 1	(from S.E.)
Wind	6 knots	from 100°True
Ambient Temperature		78°F (26°C)
Ship Displacement		280 tons (2.5×10^6N)

Each leg of each run was conducted for a period of at least 5 minutes. The recorded data consisted of lists of the Kenyon meter output, referred to as counts, and the speed relative-to-ground and track as indicated by the LORAN-C display.

RESULTS

The data obtained on each run are summarized in Table 2 along with propeller pitch, shaft RPM, and, for the turbine runs, gas generator RPM, power turbine RPM and turbine inlet temperature.

The LORAN-C was operated on stations 7980W and 7980X with time delays of 30,000 μsec and 14,000 μsec, respectively. The included angle between these lines is about 15 degrees.

TABLE 2 - SUMMARY OF DATA

Ship Conditions	Speed Over Ground[a]					Kenyon Meter Count[b]			
	Leg	$\overline{V}$/knots	σ/knots	SE/knots	Samples	$\overline{N}$	σ	SE	Samples
Run No. 1: Propulsion: Diesel Prop. Pitch: 0.4 P; 0.4 S Shaft RPM: 240 P; 220 S	1N	7.87	0.61	0.16	14	170.27	16.67	4.30	15
	1S	5.79	0.64	0.17	14	201.75	8.73	2.11	16
	1E	6.35	1.60	0.38	18	186.53	14.21	3.69	15
	1W	7.61	0.93	0.24	14	159.09	13.63	3.92	11
Run No. 2: Propulsion: Diesel Prop. Pitch: 0.7 P; 0.7 S Shaft RPM: 280 P; 270 S	2N	12.47	0.54	0.15	14	329.39	1.86	0.44	18
	2S	10.31	0.84	0.21	16	336.53	3.26	0.79	17
	2E	11.14	1.11	0.28	16	338.37	4.77	1.09	19
	2W	11.93	1.56	0.38	17	325.67	4.23	1.00	18

[a]Arithmetical average (mean) speed for each leg, standard deviation and standard error of the mean.

[b]Arithmetical average (mean) of the 10 second counts, standard deviation and standard error of the mean.

$\overline{V}$ = mean speed over ground
$\overline{N}$ = mean count of the Kenyon meter
SE = standard error
σ = standard deviation

TABLE 2 (Continued)

Ship Conditions	Speed Over Ground[a]					Kenyon Meter Count[b]			
	Leg	$\overline{V}$/knots	σ/knots	SE/knots	Samples	$\overline{N}$	σ	SE	Samples
Run No. 3: Propulsion: Turbine Mode: High Speed Prop. Pitch: 0.9 P; 0.9 S Shaft RPM: 355 P; 355 S Gas Gen RPM: 6100 P'wr Turbine RPM: 3000 Turbine Inlet Temp: 580F (304C)	3N 3S	18.05 14.99	0.65 1.12	0.20 0.29	11 15	479.38 488.53	3.06 11.3	1.76 2.83	12 16
Run No. 4: Propulsion: Turbine Mode: High Speed Prop. Pitch: 0.89 P; 0.90 S Shaft RPM: 470 P; 470 S Gas Gen RPM: 6500 P'wr Turbine RPM: 3900 Turbine Inlet Temp: 750F (399C)	4N 4S	23.62 19.76	1.45 0.73	0.37 0.22	15 14	632.44 635.82	2.18 11.75	0.51 2.94	18 17

TABLE 2 (Continued)

Ship Conditions	Speed Over Ground[a]					Kenyon Meter Count[b]			
	Leg	$\overline{V}$/knots	σ/knots	SE/knots	Samples	$\overline{N}$	σ	SE	Samples
Run No. 5: Propulsion: Turbine Mode: High Speed Prop. Pitch: 0.89 P; 0.90 S Shaft RPM: 575 P; 580 S Gas Gen RPM: 7000 P'wr Turbine RPM: 4900 Turbine Inlet Temp: 950F (510C)	5N 5S	28.44 25.26	1.01 1.53	0.23 0.41	19 14	832.76 836.19	2.73 9.87	0.68 2.55	17 16
Run No. 6: Propulsion: Turbine Mode: High Speed Prop. Pitch: 0.89 P; 0.90 S Shaft RPM: 650 P; 665 S Gas Gen RPM: 7250 P'wr Turbine RPM: 5575 Turbine Inlet Temp: 1050F (566C)	6N 6S-1 6S-2	31.50 28.24 29.19	1.05 0.93 0.96	0.25 0.24 0.22	17 15 19	939.07 938.18 942.75	3.92 9.20 7.77	0.82 3.92 1.44	22 23 28

DATA ANALYSIS

Data analysis follows the method detailed in Appendix A to compute first the current direction relative to ship's heading α and then to solve for the current speed C and finally for the ship speed relative-to-water U upon which the Kenyon knotmeter calibration can be performed.

We first compute values for the direction of the current relative to ship's heading for leg 1N and then compute current-to-speed ratio C'. Using the data from Table 1 for Runs 1 and 2, values of current direction relative to ship's heading α are computed using equation (A.7) of Appendix A. The results are:

Run 1 = 31.76° (Port); = 338.23°

Run 2 = 20.32° (Port); = 349.68°

where 0 is the direction of current relative to earth.

Values for C' may now be computed using equation (A.8) from Appendix A. The results are listed below for Runs 1 and 2. Since α falls in the port quadrant, the negative value is used for computing the b_i defined in equation (A.8).

Run 1

i	α (deg)	Speed Ratio	b_i	C'_i
1	31.76	$(V_N/V_S)^2 = 1.8475$	2.8568	0.1807
2	31.76	$(V_N/V_E)^2 = 1.5360$	2.5681	0.2027
3	31.76	$(V_N/V_W)^2 = 1.0695$	4.1341	0.1228
4	31.76	$(V_S/V_E)^2 = 0.8314$	2.4475	0.2136
5	31.76	$(V_S/V_W)^2 = 0.5789$	2.7426	0.1888
6	31.76	$(V_E/V_W)^2 = 0.6963$	2.9396	0.1753

The mean value of C' for Run 1 is

$$\overline{C'} = 0.1807$$

Also, σ = 0.029 and SE = 0.012.

For Run 2, the following values are computed for C':

Run 2

i	α (deg)	Speed Ratio	b_i	C'_i
1	20.32	$(V_N/V_S)^2 = 1.4629$	4.9894	0.1012
2	20.32	$(V_N/V_E)^2 = 1.2484$	5.5202	0.0913
3	20.32	$(V_N/V_W)^2 = 1.0926$	6.0313	0.0835
4	20.32	$(V_S/V_E)^2 = 0.8565$	4.4634	0.1135
5	20.32	$(V_S/V_W)^2 = 0.7469$	4.7290	0.1069
6	20.32	$(V_E/V_W)^2 = 0.8719$	5.0764	0.0995

The mean value of C' for Run 2 is

$$\overline{C'} = 0.0993$$

Also, σ = 0.0098 and SE = 0.0040.

Next values of U and C for Runs 1 and 2 are computed using equation (A.6) from Appendix A.

The results of these computations are listed below:

Run	$\overline{U}_u$ (knots)	$\overline{C}'$	$\overline{U}$ (knots)	C (knots)
1 N-S	6.91	0.1807	6.80	1.2285
1 E-W	7.01	0.1807	6.90	1.2462
2 N-S	11.44	0.0993	11.39	1.1305
2 E-W	11.54	0.0993	11.49	1.1405

where subscript u indicates the uncorrected value of $\overline{U}$ and

$$\overline{U}_u = \left(\frac{V_x^2 + V_y^2}{2}\right)^{\frac{1}{2}}. \qquad (2)$$

The mean of means for C is

$\overline{C}$ = 1.1864 knots

σ = 0.0514 knot

SE = 0.026 knot

and the mean value of σ is 26 degrees.

Using the average values for C and the speed through water $\overline{U}$ may be computed for each leg. $\overline{U}$ and $\overline{N}$ are then assumed to represent estimates of the population means for each leg of the runs. The results are tabulated in Table 3. Note that the average of $\overline{U}$ for the legs 1N-1S, 1E-1N, 2N-2S, and 2E-2W agree with the values computed earlier.

TABLE 3 - CORRESPONDING MEANS OF U AND N

RUN	1N	1S	1E	1W	2N	2S	2E	2W
$\overline{U}$ (knots)	6.786	6.833	6.780	7.015	11.393	11.363	11.609	11.362
$\overline{N}$ (knots)	170.27	201.75	186.53	159.09	329.39	336.53	338.37	325.67

RUN	3N	3S	4N	4S	5N	5S	6N	6S-1	6S-2
$\overline{U}$ (knots)	16.974	16.047	22.548	20.819	27.368	26.321	30.429	29.302	30.252
$\overline{N}$ (knots)	479.38	488.53	632.44	635.82	832.76	836.19	939.07	938.19	942.75

Using the data from Table 3 the regression of $\overline{U}$ on $\overline{N}$ is found to be

$$\overline{U} = 1.4481 + 0.030616\ \overline{N} \qquad (3)$$

which is taken as the best estimate of the functional relation between ship speed U and Kenyon meter count per 10 seconds, N. The coefficient of determination is

$$r^2 = 0.9946$$

and the correlation coefficient is

$$r = 0.9973$$

which indicates that the variance of the data is almost completely due to the linear relation between U and N. The standard error of estimate of U on N is 0.677 knot, and the standard errors of the regression coefficients are 0.342 knot and 5.81×10^{-4} knot per 10 second count, respectively.

The graph of equation (3) is shown on Figure 2. The 95% confidence band is shown as the upper and lower dashed lines.

The relation between actual speed and speed indicated by the Kenyon meter prior to the calibration reported here (12 December 1979) is shown on Figure 3.

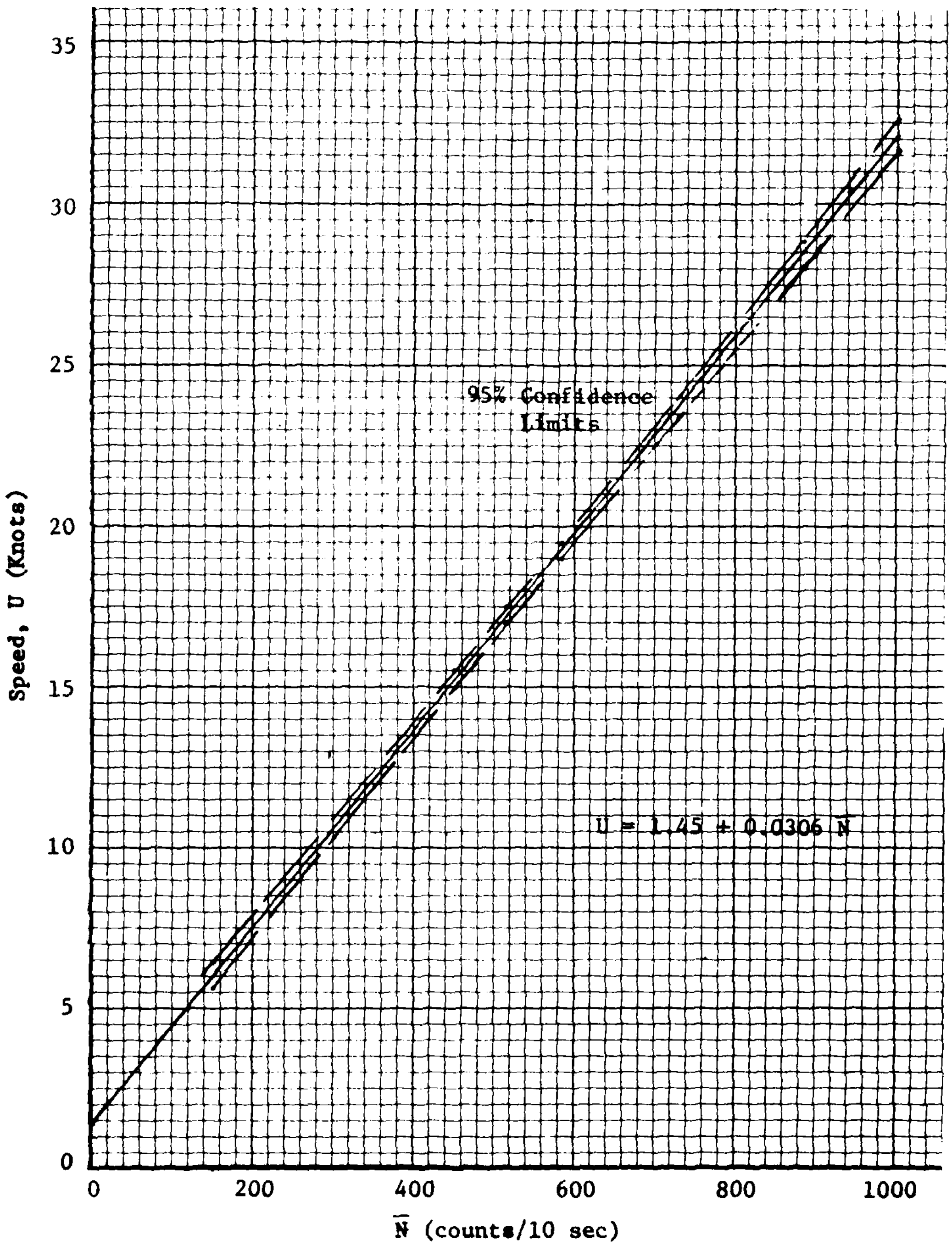


Figure 2 - Regression Line of Speed Relative to Water U on Kenyon Meter 10-Second Count $\bar{N}$

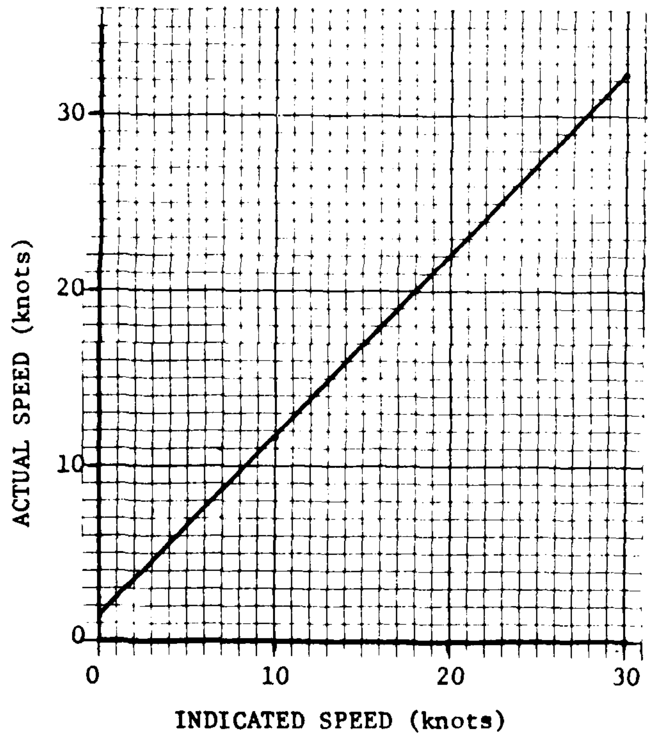


Figure 3 - Chart for Correction of Speed Indications from Kenyon Meter on R/V ATHENA Prior to December 15, 1979

DISCUSSION

The linear regression of $\bar{U}$ on $\bar{N}$, equation (3) and Figure 2, is almost perfectly correlated with a slope of 0.3062 knot/count/second. The nominal calibration for the Kenyon meter is 0.3 knot/count/second. This indicates either a small decrement in water velocity due to the ship's boundary layer and/or a friction drag on the meter. The meter, as installed on ATHENA, is subject to static friction as it appears not to turn until some break-away speed is reached between zero and 6 knots.

The values resolved for speed and direction of the current are in general agreement with values shown on charts for the area in which the calibration data were acquired.

The variability of both V and U are indicated by the data from Table 1. In particular, it would be expected that U, as indicated by the Kenyon meter count, would be nearly constant during a run under conditions of constant power. This was not the case, however, as indicated by the extremes between the high and low readings listed in Table 3.

In almost all cases the extremes and the variance (see Table 1) in both sets of data occur at the lowest speeds and when running into or quartering into the sea (the S and E legs of the runs). Some of the extremes are surprisingly large. Also, from Table 1 and Table 3, it is seen that the mean of the Kenyon count is consistently smaller on the down-sea legs of the runs (N and W).

Time series plots of the indicated speed relative to water may be constructed as each reading from the Kenyon meter represents a 10-second count taken at 20-second intervals. Each reading, therefore, indicates the average speed U for the 10-second period immediately preceding the display. No such plot is possible for V due to the irregularity of the updates.

To examine the effect of averaging, run 6S-2 was analyzed to obtain indicated water speed on the basis of accumulating the 10-second counts for a given number of cycles and thence updating by dropping the oldest sample and adding the last. The results are shown in Figure 4 for run 6S-2 for the unsmoothed data (10 second count), 2 cycle updating (20 seconds) and 3 cycle updating (30 seconds). As

TABLE 3 - EXTREME VALUES OBSERVED DURING RUNS

Run	Kenyon Meter 10 sec Count		Differences Kenyon		Speed over Ground Differences (knots)
			Counts	Knots	
1 N	High	187			
	Low	131	56	1.72	1.90
1 S	High	217			
	Low	183	34	1.05	2.06
1 E	High	211			
	Low	162	49	1.51	4.75
1 W	High	180			
	Low	145	35	1.08	3.02
2 N	High	332			
	Low	325	7	0.22	2.01
2 S	High	344			
	Low	331	13	0.40	3.16
2 E	High	351			
	Low	332	19	0.58	3.93
2 W	High	334			
	Low	317	17	0.52	5.12
3 N	High	486			
	Low	475	11	0.34	2.28
3 S	High	518			
	Low[1]	464	54	1.66	4.21
	Low[1]	472	46	1.42	
4 N	High	638			
	Low	630	8	0.25	4.24
4 S	High	655			
	Low	610	45	1.38	2.89
5 N	High	839			
	Low	829	10	0.31	3.93
5 S	High	850			
	Low	819	31	0.95	3.92
6 N	High	947			
	Low	932	15	0.46	3.79
6 S-1	High	950			
	Low	918	32	0.98	3.42
6 S-2	High	955			
	Low	927	28	0.86	3.23

[1] Rudder change larger than normally applied was used to effect a course correction. The reading from the Kenyon showed a drastic decrease. Otherwise the low reading was 472 counts. Both, however, indicate a significant variation.

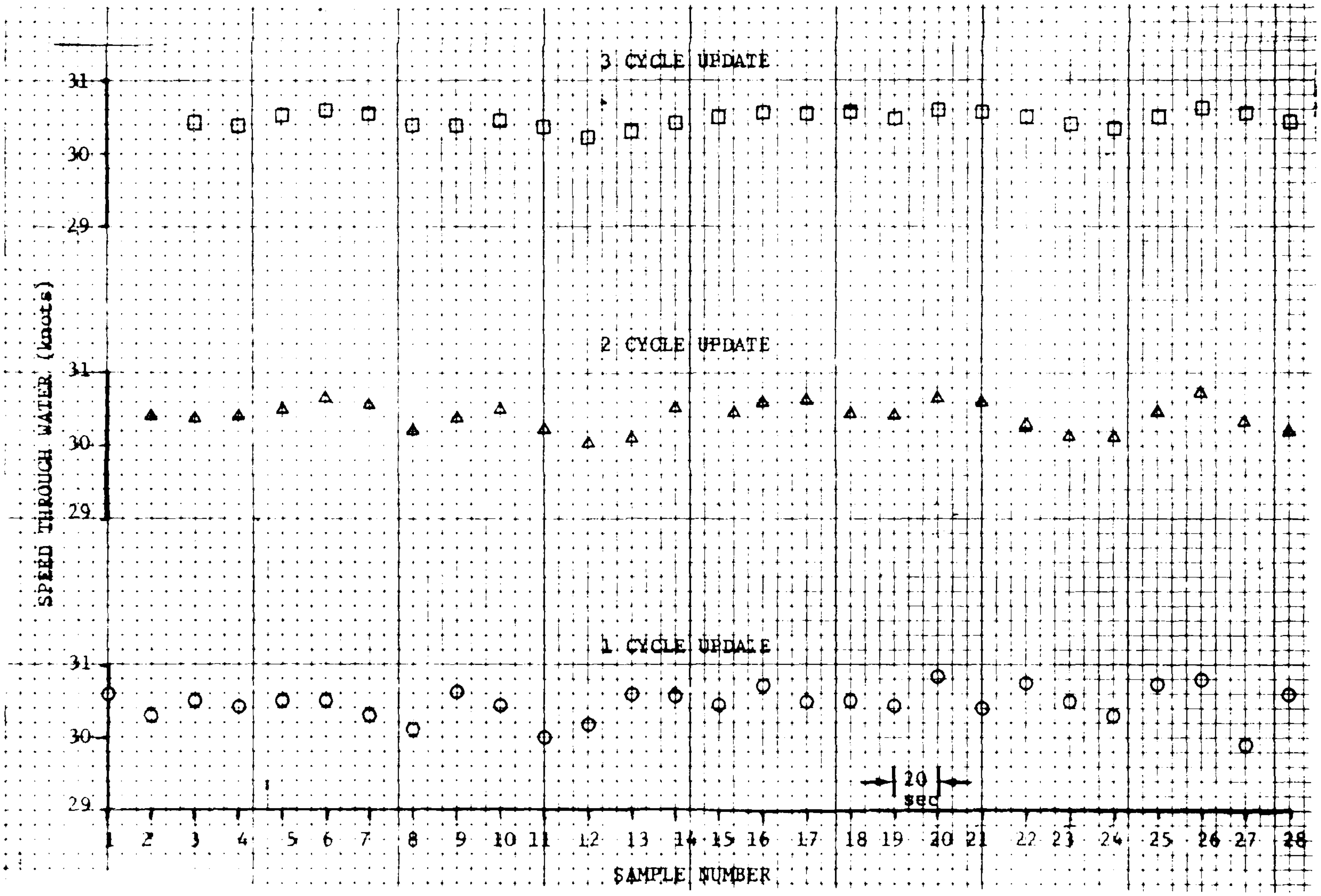


Figure 4 - Effect of Averaging on Speed as Indicated by the Kenyon Meter for Run 6S-2

expected, the fluctuations are significantly reduced as the averaging period is increased. Figure 5 compares the effect of 3-cycle smoothing on the data from runs 1N and 1W.

These data indicate a long term, fairly smooth variation having a period on the order of 80 to 120 seconds. The long period variation is apparently real and is probably related to the action of the helm as the period of the variation is roughly the same for all samples examined and roughly corresponds to the swinging of ship's head about the course line as subjectively observed on the bridge. The extreme excursions (as seen in run 1W) correlate with the ship's rolling motion as indicated by notations on the raw data and, therefore, probably do not reflect actual changes in the ship's speed. As the data do not allow us to firmly distinguish fact from artifact, some smoothing is necessary to minimize the effect of short-term extreme fluctuations in indicated speed.

The effect of 3-cycle sampling on indicated speed for conditions of periodic rolling is illustrated on Figure 5 for run 1W. Note that the effect of the heavy rolls was far from eliminated, but a significant degree of smoothing is achieved. It also should be noted that the underlying long-term periodicity persists, even though the indicated amplitudes are substantially lower than for the unsmoothed (10-second) data.

Finally, it is noted that where current speed is small relative to ship speed, a good estimate of ship speed through the water can be obtained from one set of reciprocal course runs and using LORAN-C measurements. Briefly it is found that:

$$U_u = \sqrt{(V_x^2 + V_y^2)/2} \qquad (4)$$

provides a good estimate of U under conditions of moderate current (one knot or less), but is always on the high side. Here subscript 'u' designates the uncorrected estimate of U, and V_x and V_y are mean values of V obtained on reciprocal headings of the ship.

The exact value of U may be found by multiplying equation (4) by the quantity $(1 + C'^2)^{-1/2}$, where C' is the ratio of current C to speed through

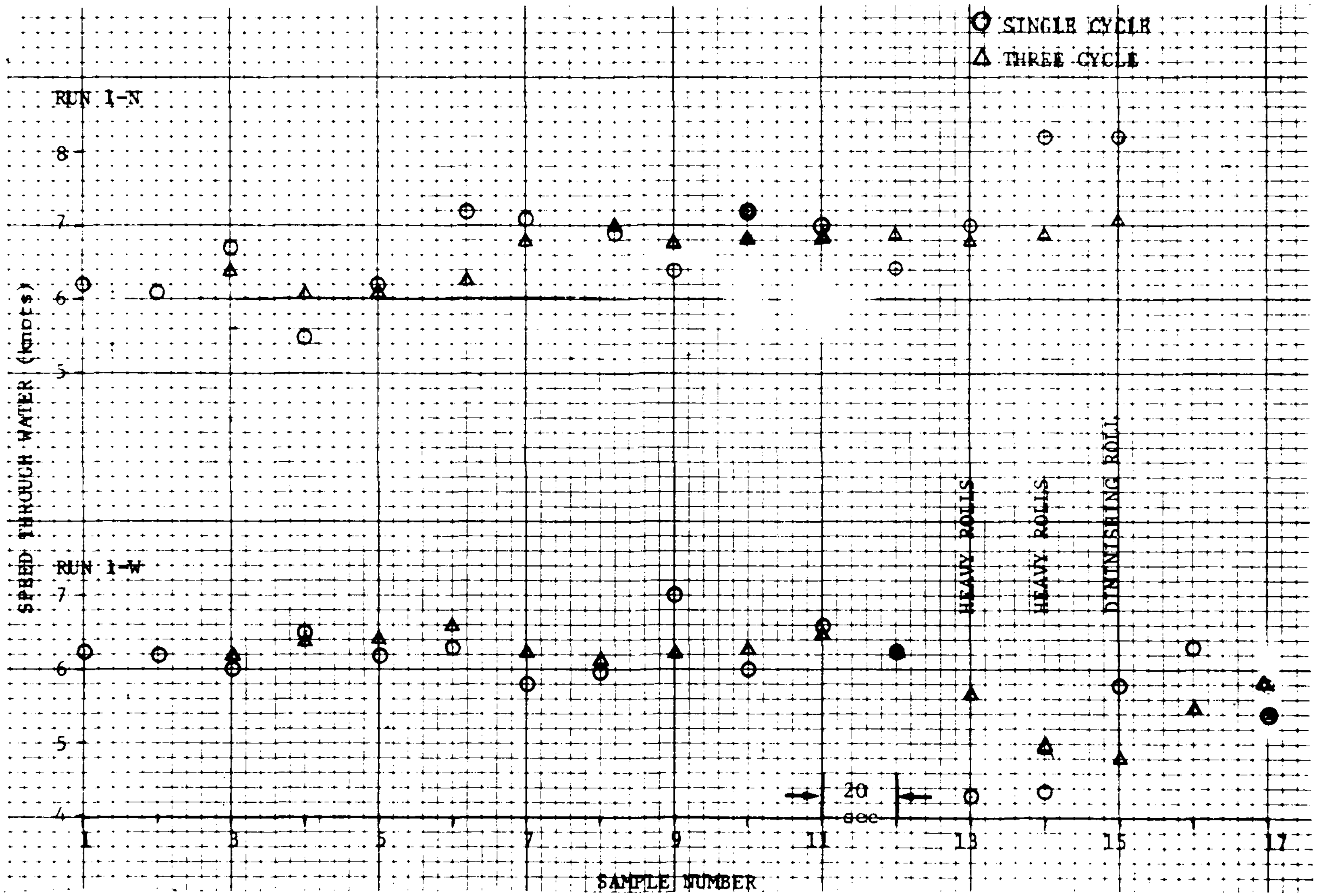


Figure 5 - Effect of 3-Cycle Averaging on Indicated Speed for Runs 1-N and 1-W

water U. For small values of C', this quantity may be put in the form $1 - \frac{1}{2}C'^2$. Defining the error as

$$e = C'^2/2 \qquad (5)$$

we may write

$$U = U_u(1 - e). \qquad (6)$$

The error is small at high speeds. For example, for C = 1 knot and ship's speed of 10 knots, e = ½%, and the error in U is 0.05 knot if the correction is neglected.

Since currents rarely exceed one knot, equation (4) may be used to estimate speed relative to water during trials at any time it is convenient to run reciprocal courses.

CONCLUSIONS

On the basis of the data presented herein, it is tentatively concluded that:

1. The indicated long term (80 - 120 second) variations of ship's speed through water are real and are related to the use of rudder to effect course corrections.

2. The Kenyon meter is seriously affected by ship motions. Rolling motion at low ship's speeds apparently has the greatest effect and leads to an underestimate of speed through water. It is speculated that the large angles of flow induced by the roll (relative to the axis of the meter) results in partial stalling of the rotor vanes.

3. The Kenyon meter as installed on ATHENA is subject to excessive static friction thus requiring a "break-away" torque developed at a speed below 6 knots.

4. The calibration curve as reported herein provides the best estimate (in the statistical sense) of ATHENA's true speed through water. The

confidence limits for the calibration curve vary from ±0.5 knot at 6- and 30-knots to ±0.25 knot at 17 knots. We may thus be confident that 95% of the time the true speed is in error by not more than ±0.5 knot.

RECOMMENDATIONS

It is recommended that:

1. The electronic Kenyon meter speed display on ATHENA be adjusted to reflect the data presented herein. A constant offset voltage is required to provide accurate outputs.

2. The time base for the speed measurement be increased to at least 60 seconds with 10-second updates using latest data.

3. Consideration be given to assessing the research community's requirements regarding ship speed to assess the adequacy of the equipment installed on ATHENA.

APPENDIX A

ESTIMATION OF CURRENT AND SPEED RELATIVE TO WATER

Let C, U and V respectively stand for current speed, speed of ship relative to water and speed of ship relative to ground. Also let ϕ stand for ship's true heading and θ for the direction of the current. The ground speed V on any given heading is given by

$$V^2 = \left[U + C\cos(\phi - \theta)\right]^2 + C^2\sin^2(\phi - \theta) \qquad (A.1)$$

We seek to deduce U, C and θ from an appropriate set of measurements of V.

For given U and C, the value of V is affected only by a change in ship's heading.

Let $\qquad \alpha = \phi_1 - \theta$.

where ϕ_1 is a selected heading relative to which other headings (ϕ_2, etc.) are taken.

Equation (A.1) then takes the values:

$$V_N^2 = (U + C\cos\alpha)^2 + C^2\sin^2\alpha$$

The value of V on the opposite head, $\phi_1 + 180^o$, is

$$V_S^2 = (U - C\cos\alpha)^2 + C^2\sin^2\alpha$$

The value on a heading of $\phi_1 + 90^o$ is

$$V_E^2 = (U + C\sin\alpha)^2 + C^2\cos^2\alpha$$

and for $\phi_1 + 270^o$,

$$V_W^2 = (U - C\sin\alpha)^2 + C^2\cos^2\alpha$$

These equations could be written for any arbitrary set of headings. The mathematics is simplified by selecting increments of 90° for ship's head, however, and the equations are thus presented in that form. We now put the above equations in the form

$$V_N'^2 = 1 + 2C'\cos\alpha + C'^2 \qquad (A.2)$$

$$V_S'^2 = 1 - 2C'\cos\alpha + C'^2 \qquad (A.3)$$

$$V_E'^2 = 1 + 2C'\sin\alpha + C'^2 \qquad (A.4)$$

$$V_W'^2 = 1 - 2C'\sin\alpha + C'^2 \qquad (A.5)$$

where the prime denotes division by U.

On adding equations (A.2) and (A.3), we obtain

$$\Delta_{N+S}/U^2 = 2(1 + C'^2)$$

where $\Delta_{N+S} = V_N^2 + V_S^2$.

Thus
$$U^2 = \frac{\Delta_{N+S}}{2(1 + C'^2)} \qquad (A.6a)$$

Also,
$$U^2 = \frac{\Delta_{E+W}}{2(1 + C'^2)} \qquad (A.6b)$$

Taking differences, we find

$$\tan\alpha = \frac{\Delta_{E-W}}{\Delta_{N-S}} \qquad (A.7)$$

where the subscript N-S indicates the difference $V_N^2 - V_S^2$, etc. Note that a negative value of α indicates the direction of the current is to the left of the heading ϕ_1.

Given α, C' may be computed from any of the ratios of the V's. Six ratios may be formed, as follows:

(1) $V_N^2/V_S^2 = A$

(2) $V_N^2/V_E^2 = B$

(3) $V_N^2/V_W^2 = D$

(4) $V_S^2/V_E^2 = E$

(5) $V_S^2/V_W^2 = F$

(6) $V_E^2/V_W^2 = G$

The solutions for C' are of the form

$$C_i' = b_i - \sqrt{b_i^2 - 1} \quad \text{(A.8)}$$

where

$$b_1 = (A + 1)\cos\alpha/(A-1)$$

$$b_2 = (B\sin\alpha - \cos\alpha)/(B-1)$$

$$b_3 = (D\sin\alpha + \cos\alpha)/(D-1)$$

$$b_4 = (E\sin\alpha + \cos\alpha)/(E-1)$$

$$b_5 = (F\sin\alpha + \cos\alpha)/(F-1)$$

$$b_6 = (G + 1)\sin\alpha/(G-1)$$

For purposes of this computation the b_i's are to be taken as positive, i.e., the absolute value of b_i is to be used, but the appropriate sign for α is required.

In general, only three of equations (A.2) through (A.5) are required to obtain a solution. For example, assume measurements of V_N, V_S and V_E are available. Equation (A.6a) applies, but the values of α and C' must be deduced from the equations

$$\left.\begin{aligned} A &= (1 + 2C'\cos\alpha + C'^2)/(1 - 2C'\cos\alpha + C'^2) \\ \text{and} \quad B &= (1 + 2C'\cos\alpha + C'^2)/(1 + 2C'\sin\alpha + C'^2) \end{aligned}\right\} \quad \text{(A.9)}$$

The family of solutions for equations (A.9) are given in Figure A-1 for values of α between 0^{o} and 90^{o} and for C' from 0 to 0.6.

Closed solutions also may be obtained by taking the ratio of the differences between equations (A.2) and (A.3) and between (A.2) and (A.4). This leads to, for example,

$$\tan \alpha = 1 - 2 \Delta_{N-E}/\Delta_{N-S} \qquad (A.10)$$

Actually ten such ratios may be formed based on the total combinations of differences. The values of C' then may be found from equation (A.8), as previously described, and the values of U from equations (A.6).

Under field conditions, the quadrant in which α falls is known after the first set of values for V become available. The equations have been developed on the assumption that α lies in the range 0^{o} to 90^{o} relative to ship's head. Thus to apply the equations we need only designate as V_N the value of V that has a component of the current in the direction of the ship's heading. For example, suppose four values of the V's are obtained; V_A, V_B, V_C and V_D where V_A and V_B are taken on reciprocal headings and V_C and V_D are obtained from reciprocal headings on a course normal to V_A and V_B. If $V_B > V_A$, designate $V_B = V_N$ and $V_A = V_S$. The current set relative to ϕ_1 (corresponding to V_N) may be determined from comparison of V_C and V_D. It is evident that any consistent grouping may be used. For example, if $V_D > V_C$, we could set $V_D = V_N$, in lieu of V_B.

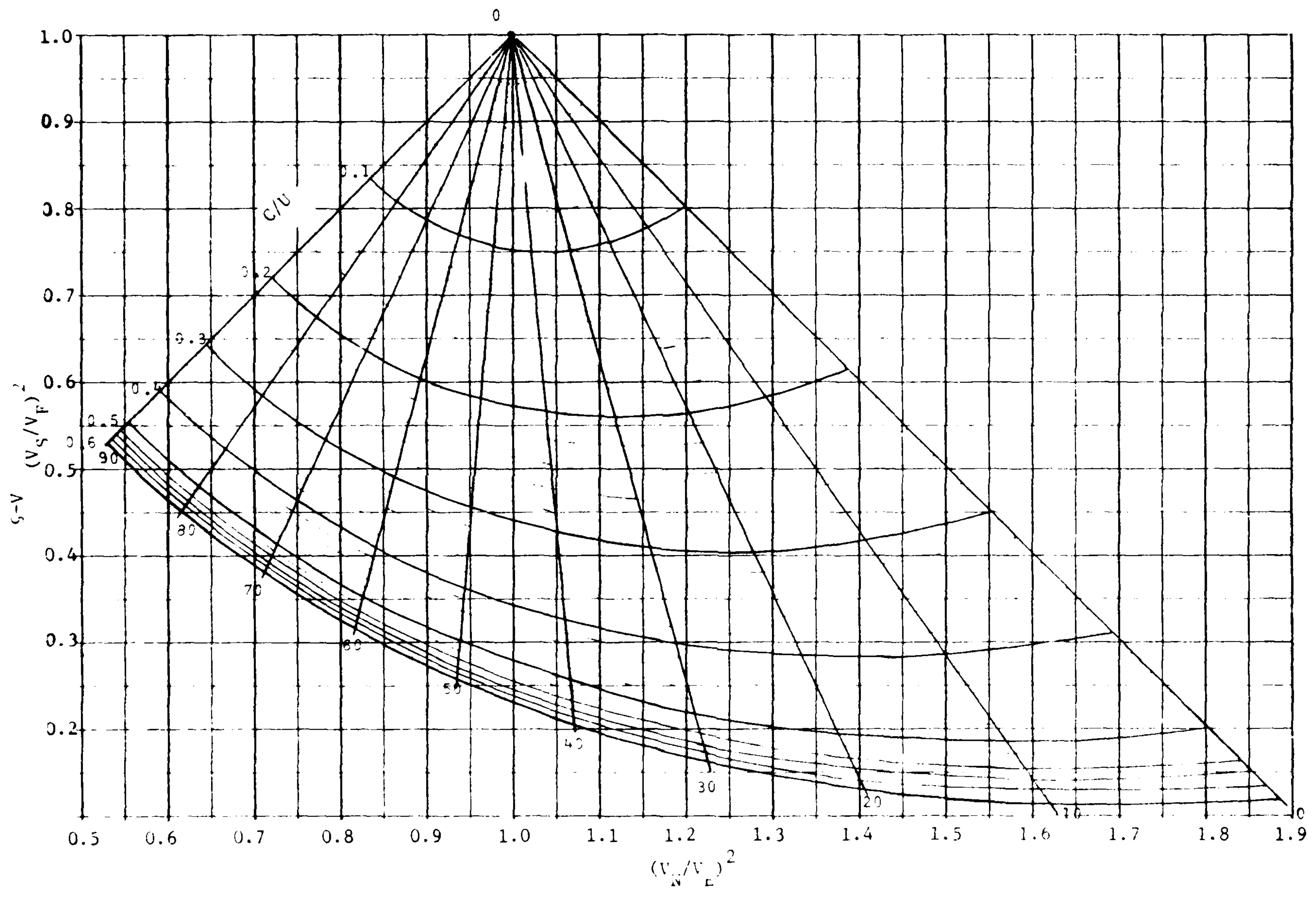


Figure A.1 - Chart for Determining Ratio of Current C to Water Speed and Direction of Current Relative to Ship's Heading

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