WHOI-75-44

VECTOR AVERAGING CURRENT METER SPEED CALIBRATION AND RECORDING TECHNIQUE

by

James R. McCullough

WOODS HOLE OCEANOGRAPHIC INSTITUTION
Woods Hole, Massachusetts 02543

September 1975

TECHNICAL REPORT

Prepared for the Office of Naval Research under Contract N00014-66-CO241; NR 083-004; N00014-74-CO262; NR 083-004; and IDOE/NSF Grant GX-29054.

Approved for Distribution L. V. Worthington

L. V. Worthington, Chairman
Department of Physical Oceanography

TABLE OF CONTENTS

I. ABSTRACT

Equations 1-4 summarize the rotor calibration used at WHOI for the VACM. A discussion of the instrumental and test details used to derive these equations follows. A list of other VACM documents and related bibliography is included.

II. INTRODUCTION

This report provides a discussion of the speed calibration equations used at the Woods Hole Oceanographic Institution (WHOI) for the WHOI-AMF vector averaging current meter (VACM) and the recording technique used in the instrument.

Discussion of the equations gives their relation to the VACM hardware and to the tow tank calibration procedures. Tow tank calibrations of the VACM rotor and associated cage were made by John Cherriman (1972) at the National Institute of Oceanography (NIO, now Institute of Oceanographic Sciences, IOS) in England. A second independent steady state calibration, i.e., uniform speed tows through still water, were made by Woodward and Appell (1973) at the National Oceanographic Instrumentation Center (NOIC) in the U.S.A. Ford and McCullough (1974) have data from additional steady state and dynamic calibration tests taken at the MIT tow facility. In these tests a full-scale plastic model of a VACM rotor-vane cage and pressure housing was used. Some steady tow data reported by Panicker (1973), however, appears to disagree with other tests; the reason is as yet unknown. Numerous studies (Refs. 4, 5, 7-12, 14-18, 21-23, 25, 27-29, 31) have been made but cannot be readily applied to the VACM since rotor cage designs differ and the cage configuration significantly alters the rotor calibration.

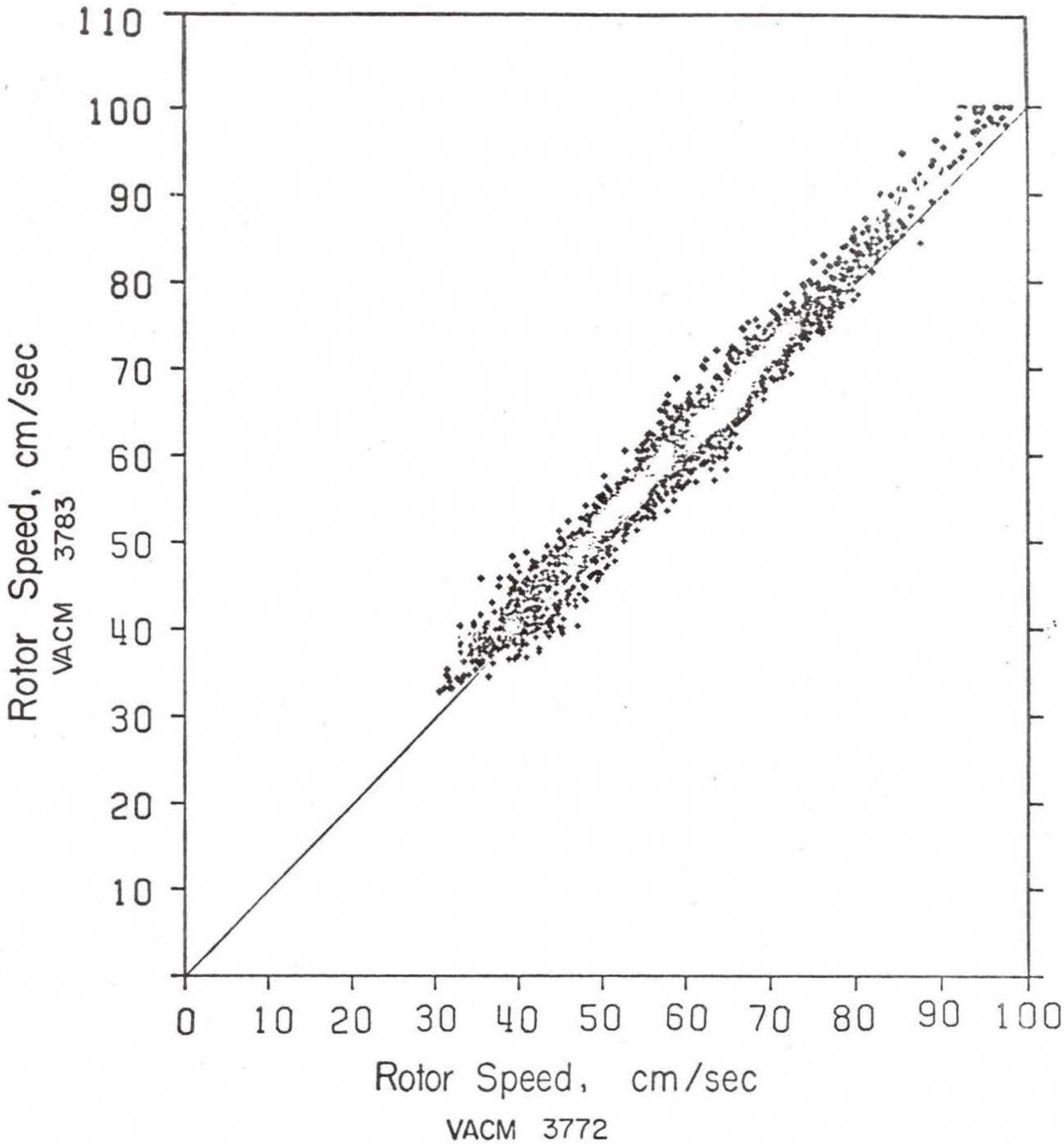
The NIO and NOIC results discussed below are in good agreement. There is no clear indication which calibration is more nearly correct. Consequently, WHOI continues to use the earlier Cherriman (1972) calibration data for its VACMs. Cherriman (1974) has extended his tests as discussed later.

Also, it is encouraging to note the excellent agreement Saunders (1975) finds between Aanderaa and VACM rotors tested at sea in the JASIN experiment. In this experiment, with rotors of different design and size, the results agree to within a few cm/sec during the 12.5 days of the test. The VACM and Aanderaa were at depths of 10 and 12 meters, respectively, below a surface toroid float moored in water of 3 kilometers depth 300 miles west of Ireland. The mean speed was 55 cm/sec, the difference in rotors speed did not exceed ±4 cm/sec at any time and the mean difference was less than 1 cm/sec. We found similar agreement in the 27-day sea trial of the first 4 VACMs constructed (McCullough, 1971). Halpern, et al. (1974) have compared the Aanderaa and VACM in shallow water.

Figure 1 shows a scatter diagram comparison of the mean rotation rates of the two VACM rotors (WHOI data numbers 3772, 3783) moored at a depth of 8 meters. The current meters were chained below two WHOI Site D surface toroids separated horizontally by 1.2 kilometers in a water depth of 2600 meters. The total number of 1/8 rotations for each rotor was recorded every 15 minutes. The plot contains 2600 points but due to the high correlation only a few hundred points are resolvable in the figure. Rotor speeds in the range of 30 to 100 cm/sec were recorded by each meter and a very high correlation is obtained. In the figure we see a maximum peak-to-peak scatter of about 10 cm/sec and a systematic offset of about 5 cm/sec. From analysis of other records from the same moorings it appears that the offset is real (not instrumental) and is caused by variations in mooring motion resulting from differences in the instrument load carried by the two moorings.

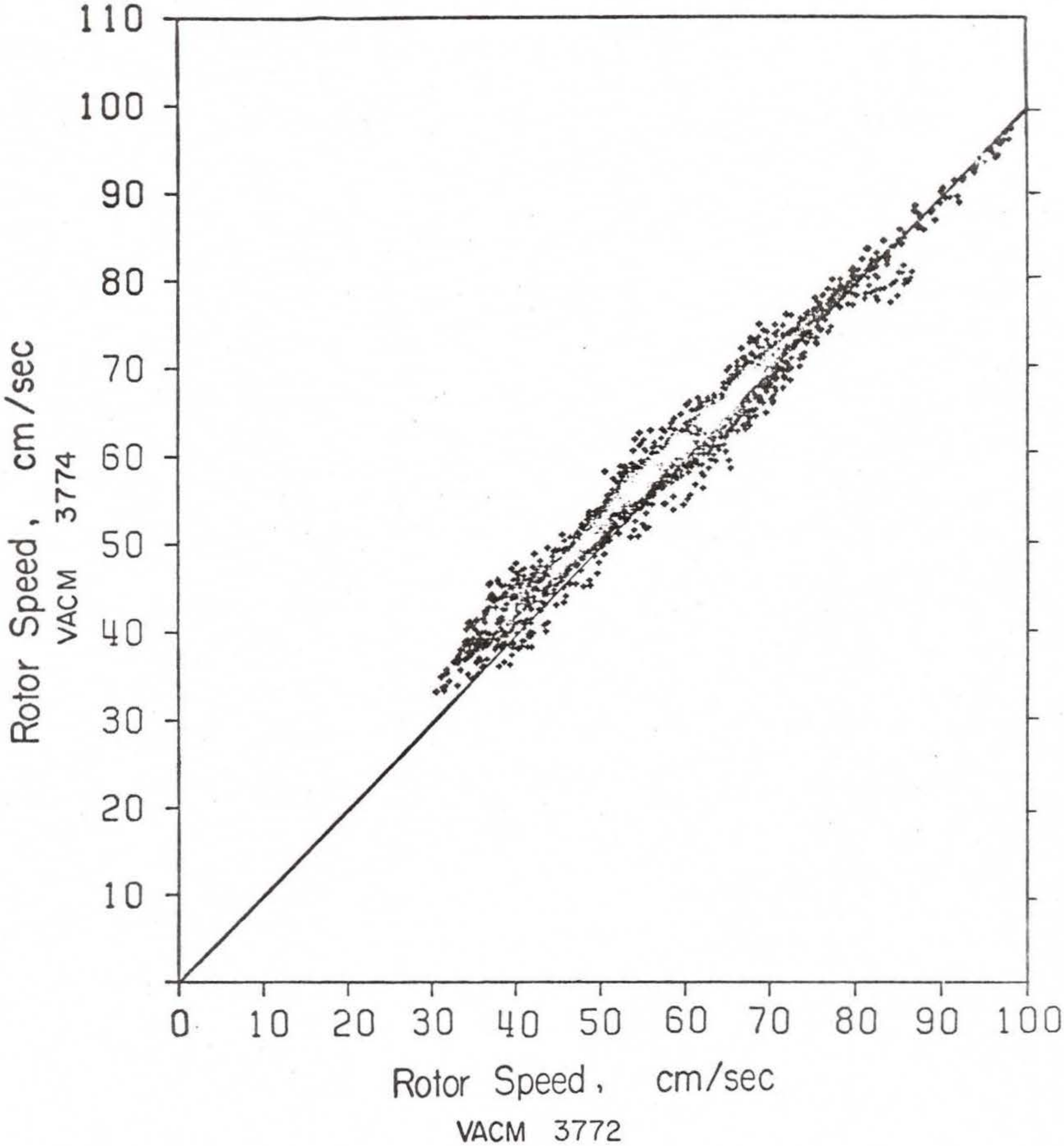
Figure 2 gives a similar comparison of two rotors (3772, 3774) on the same mooring at depths of 8 and 12 meters. Again there are 2600 points plotted and here the scatter is less than in Figure 1. No special care was taken to mechanically match the rotors; the same calibration was used for all three rotors.

In Figure 3 the speed of one of the rotors tested (3785) is shown as a function of time. The magnitude of the vector-averaged current from the same meter is also shown. The small mean variations of the rotor speeds seemed puzzling at first, particularly



Scatter plot of 15 minute rotor counts from 2 VACMs on separate surface toroid moorings separated horizontally by 1.2 kilometers. The meters were at 8 meters depth for 26 days at site D. 2600 pairs of rotor speeds are plotted but due to the high correlation only a few hundred points are resolvable. The systematic offset is believed to be caused by small differences in the mooring configuration.

Figure 1



Scatter plot of the same VACM as in figure 1 (3772 at 8 M) compared with a VACM at 12 meters depth (3774) on the same mooring. Again 2600 points are plotted.

Figure 2

since the rotor speeds of nearby 850 current meter varied considerably with time. To test this, Rory Thompson (1971) developed a numeric model and computer simulation to see if the steady rotor mean speeds were reasonable. His model gave rotor rates very similar to those observed. The model shows that if the number of samples taken is large (10,000 per quarter hour at 50 cm/sec in the VACM) the observed residual variance will be small. The variations seen then in the VACM records are due largely to slow changes in the average sea state and the associated instrument motion.

Note that rotor speed and magnitude of the vector are occasionally nearly equal but at other times may differ by as much as two orders of magnitude. In the figure the mean rotor speed is 64 cm/sec while the mean vector magnitude is only half as large.

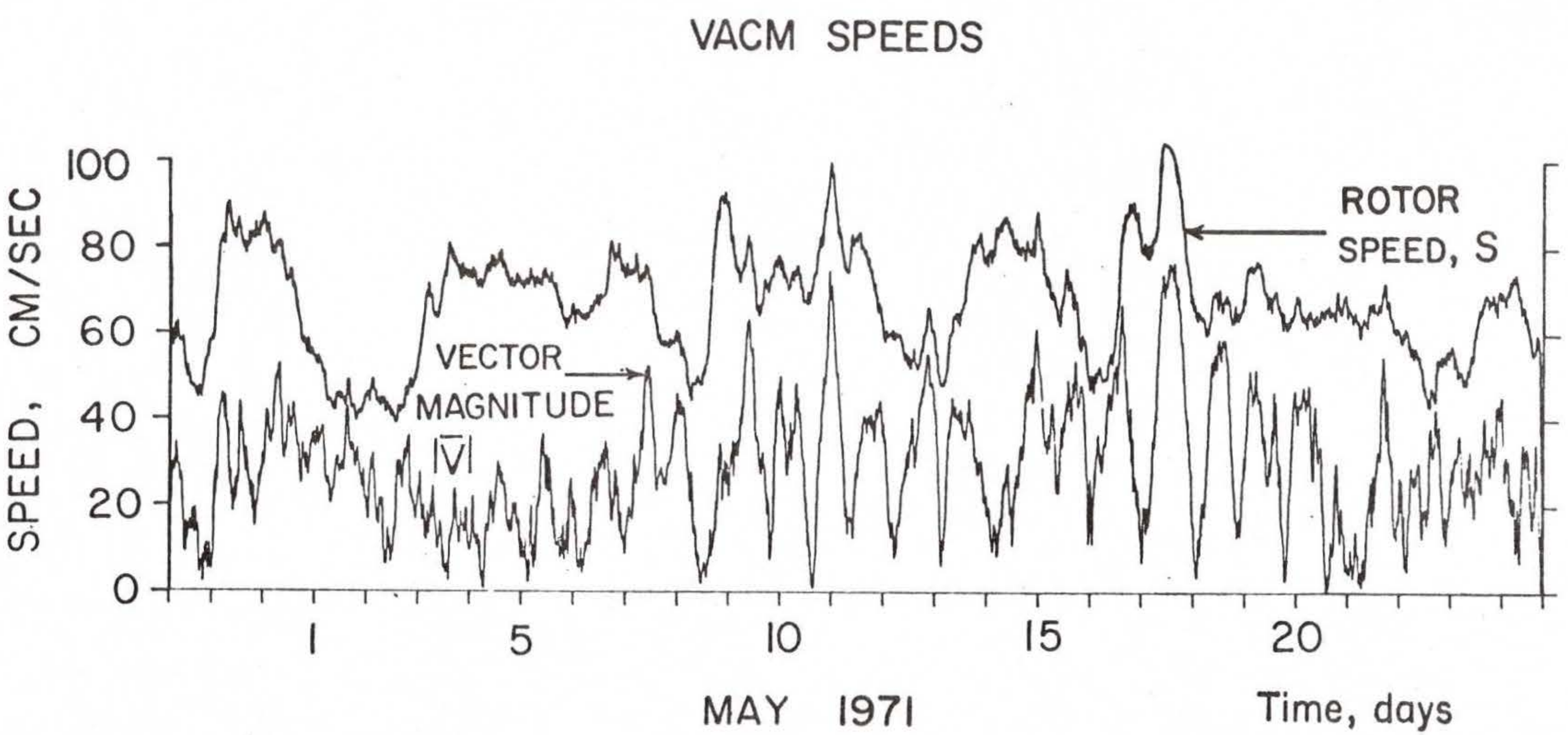
The general agreement in Figures 1 and 2 between the rotors is encouraging considering the range of speeds encountered, the length of the test and the large, uncorrelated mooring motions implied by the difference between the rotor speed S and the magnitude of the vector speed $|\overline{V}|$ shown in Figure 3.

In summary then it appears that:

1. VACM rotors of the same design give nearly identical rotation rates at sea and in steady tows.

2. VACM Savonius rotors and Aanderaa rotors give nearly equal speed indication at sea after the accepted calibration procedures for each are applied.

One should not infer from this, however, that the near surface mean currents can necessarily be accurately measured from surface moorings. The VACM sensors are non-linear at some surface gravity wave frequencies and the effects of turbulence caused by the rotor-vane cage end plates due to vertical heaving can be significant. Also, mismatches exist between the rotor and vane response times.



(3a)

Rotor speed and vector magnitude from VACM 3785 as a function of time. The total number of rotor rotations and the computed vector average were recorded every 15 minutes. Both values are scaled by the same constants to give speeds. As shown, the difference between the vector magnitude and the rotor rate is very large at times. The VACM was moored at 12 meters depth below a surface toroid float at Side D in 2600 meters of water.

Figure 3

III. CALIBRATION EQUATIONS

This section gives a summary of the VACM velocity calibration equations and constants used at WHOI. Their derivation is discussed in following sections. The equations are:

$$\bar{\omega} = \frac{R}{8T}, \qquad \text{rev/sec} \tag{1}$$

$$\text{EAST} = \frac{2E - R}{R}(a\bar{\omega} + b), \qquad \text{cm/sec} \tag{2}$$

$$\text{NORTH} = \frac{2N - R}{R}(a\bar{\omega} + b), \qquad \text{cm/sec} \tag{3}$$

where:

- R is the positive number recorded in the rotor field on the VACM tape, less one. (R-1 is the number of 1/8th rotor turns per recording interval.)
- T is the recording or sampling interval in seconds. (It is the time between consecutive VACM tape records, typically 15 minutes.)
- $\bar{\omega}$ is the mean rotor rotation rate in revolutions per second (not radians per second) in interval T.
- E and N are the positive numbers recorded in the east and north fields of the VACM tape.
- EAST, NORTH are the magnetic east and north components of the vector-averaged current, in cm/sec. (Note that EAST and NORTH can be negative, i.e., WEST and SOUTH components.)
- a,b are the empirical calibration constants derived from steady speed tow tank tests.

From the Cherriman (1972) tests they are:

$$\left.\begin{array}{l} a = 36.1 \text{ cm/rev, } b = 2.0 \text{ cm/sec for } \overline{\omega} < .915 \text{ rev/sec} \\ a = 32.6 \text{ cm/rev, } b = 5.2 \text{ cm/sec for } \overline{\omega} \geq .915 \text{ rev/sec} \end{array}\right\} \quad (4)$$

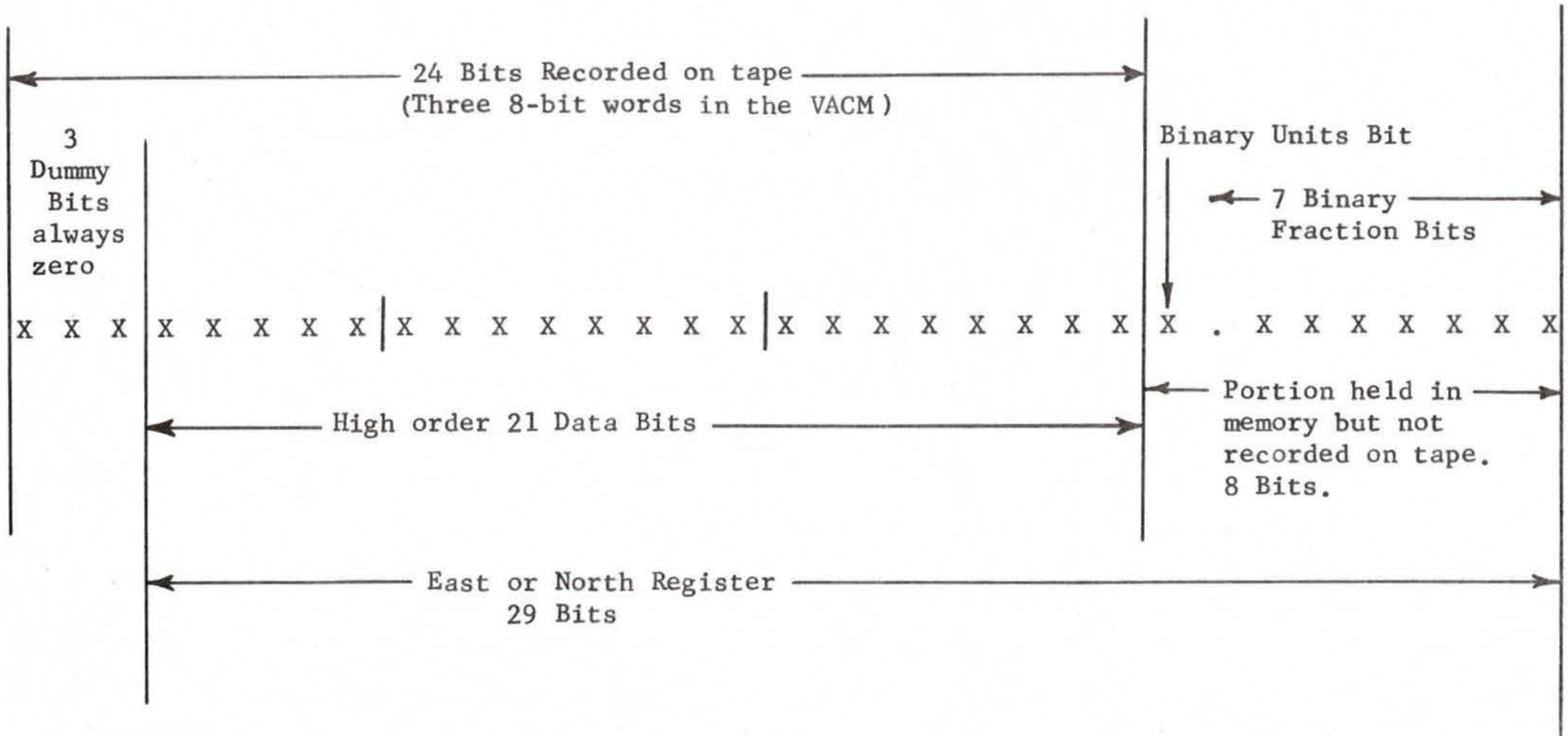
Estimates of the coefficient errors are discussed below. Some additional rotor calibration formula in present use are given in Appendix 3.

When $R \leq 16$ the direction of the current should be computed from the compass and vane follower fields. The need for this arises from quantizing errors associated with VACM data truncation discussed next and in Appendix 5.

IV. VACM REGISTERS AND TAPE FORMAT

The VACM records on four-track digital magnetic tape. At the end of each interval T the following numbers are recorded: the 21 high order bits in the east current component register, the same for the north register, the number of 1/8 rotor turns plus one in the interval T, one compass reading, one vane follower reading, a time word from the quartz oscillator clock, the value in the temperature register, a tape gap, preamble and track parity bits. A tape record is physically about 1/16 inches long on the cassette tape. Calling the fields E, N, R, C, V, t, and τ the lengths are 3, 3, 3, 1, 1, 2, and 3 eight-bit words, respectively. Redundant check information is included in all 7 fields and in the parity bits for each of the 4 tape tracks. No lateral or character parity bit is recorded. Further details of the tape format are given in Appendix 1.

Figure 4 shows the structure of the 29-bit VACM electronic east and north data registers and their relation to the data recorded on the VACM tape. The high order 21 bits of the registers as marked on the diagram are recorded on the tape each sample period (length T). As shown in the figure, the data are grouped in 8-bit words in the VACM. They are recorded on tape in 4-bit



Format of the VACM East-North registers in the current meter computer memory and on the VACM tape. The 8 low-order bits are retained in memory but are not recorded on tape.

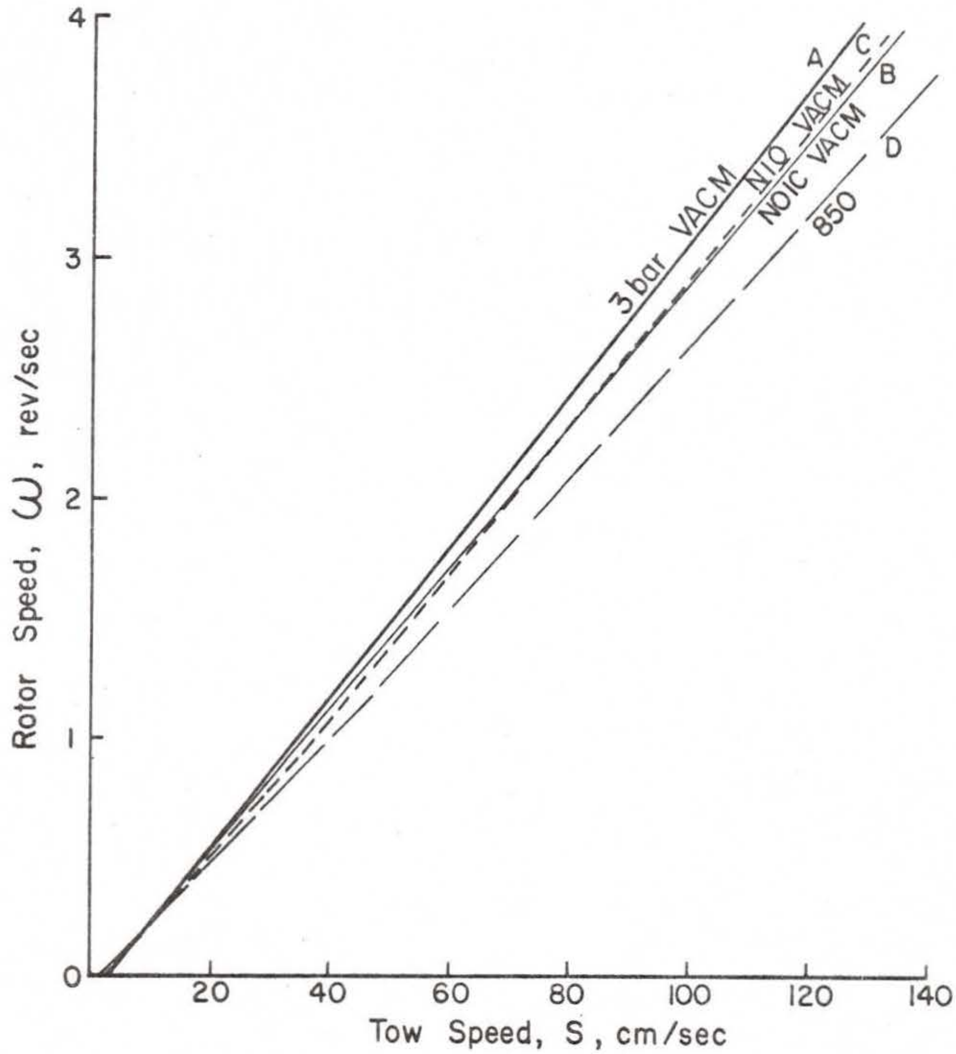
Figure 4

tape characters. The east and north values recorded on tape each use three 8-bit VACM words with three high order zeros added to fill out the 3-word field. These zero bits can be used for check purpose since they have a fixed value. The 8 low-order bits of the VACM east and north registers are not recorded on tape and are not reset at any time but are carried over to the next interval. They represent a water length of about 4 cm. This rather peculiar data format resulted from the limited variety of integrated circuit (IC) components available in the early days of low power (COS/MOS) IC technology. It introduces an unfortuante quantizing problem (discussed in Appendix 5) when rapid recording of samples is desired. A redesign of the dual 8-bit memory electronics card is required to eliminate the problem. There is a single IC now available that could replace most of the functions of that card. COS/MOS microprocessors could be used to replace many of the other cards as well.

V. DISCUSSION OF CALIBRATION EQUATIONS

The VACM calibration function used by WHOI (given by Equations 1-4) is shown in Figure 5C and is replotted in Figure 6 together with the NIO data from which it is derived.

Figure 5 illustrates the effect of cage construction on rotor response. Rotor rotation rate ω is plotted as a function of tow speed S. Equations for curves B, C, and D are given in Appendix 3. Line A (Figure 5) is for a VACM with three cage stand-off bars. Lines B and C are standard VACMs calibrated by NOIC and NIO and line D is for the Geodyne model 850 style cage. The rotors are of the same general design and size in all cases. There is about a 10% difference in the 850 and VACM rotor response due to different cage construction. The difference is in the sense that the VACM rotor is better coupled to the water, that is, it revolves faster at a given tow speed. The difference is attributed to the slightly wider spacing of the VACM cage bars which are also farther from the



Effect of rotor cage design on rotor response. Rotor rotation rate is shown as a function of tow speed. Response changes are caused by differing rotor cage construction. (a) 3-bar VACM cage, (b) and (c) standard VACM, (d) Geodyne 850. All rotors are of the same general design and size.

Figure 5

rotor. Such effects have also been noted by Woodward and Appell (and others) for other rotor-cage configurations.

We have no information on rotor response during rotation of the cage about the vertical rotor axis such as is found on moorings. The complex hydrodynamic interaction between rotor and cage precludes any reasonable estimate of rotor response variation under cage rotation or vibration.

In Figure 6, K is the number of centimeters of water required to cause one rotor revolution (in a steady tow) plotted as a function of tow speed. The distance "constant" K (distance of water moved to cause one rotor turn) has the value

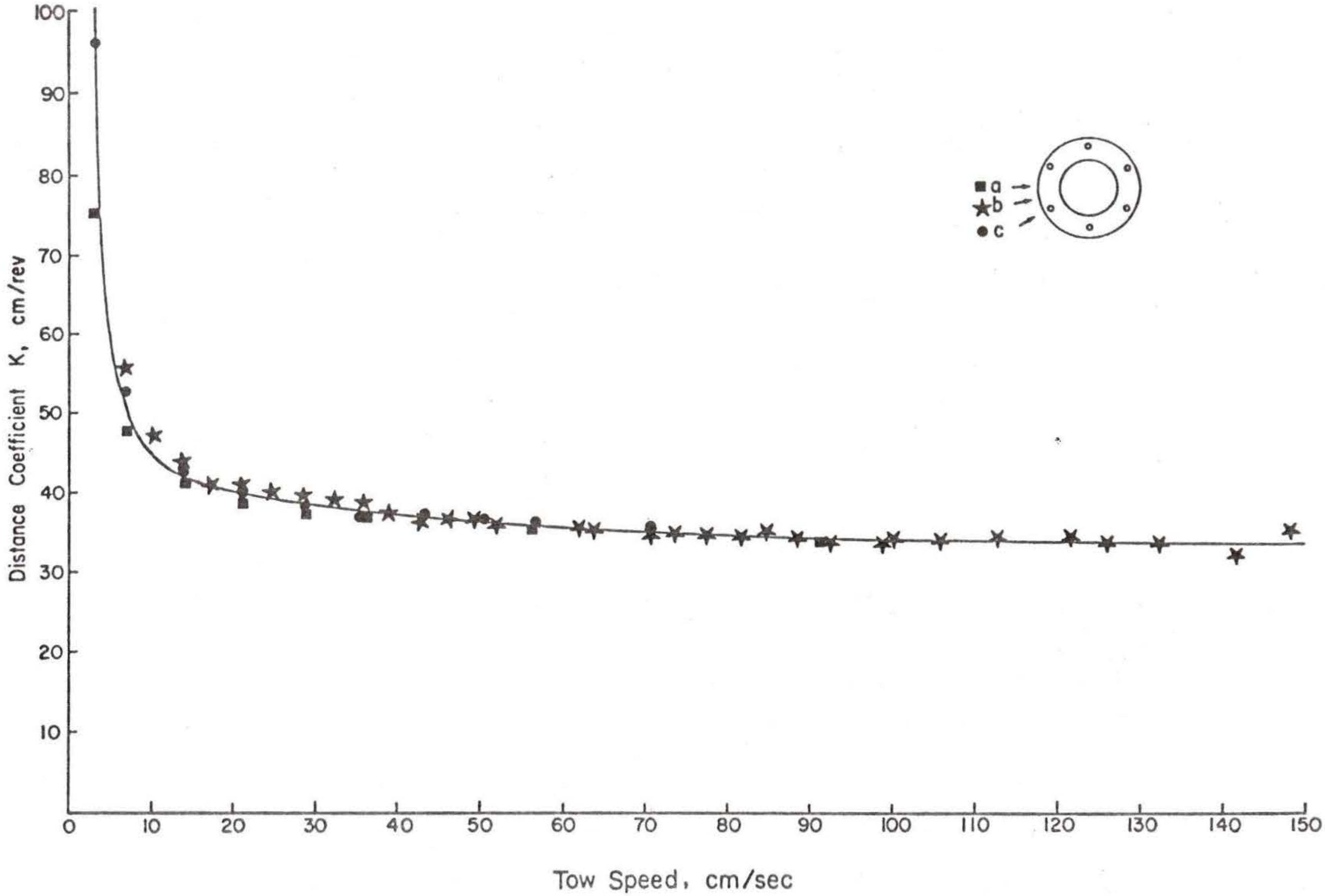
$$K = \frac{a\omega + b}{\omega} \; . \tag{5}$$

Alternately, one can think of K as being the reciprocal of the rotor conversion coefficient G which is:

$$G = \frac{\text{OUTPUT}}{\text{INPUT}} = \frac{\omega}{S} = \frac{\omega}{a\omega + b} = \frac{1}{K} \; .$$

It can be seen from Figures 5 and 6 that the rotor stalls at about 2 cm/sec (large distance constant) and that above about 20 cm/sec K is nearly constant. Ideally, K would be constant at all speeds, i.e., a linear rotor (gain independent of input signal). In that case each revolution of the rotor would correspond to the same length of water regardless of the water speed, analogous to a wheel moving on a road without slipping.

The VACM actually measures water displacement not speed (i.e., it acts like an odometer not a speedometer). The length of water moving past the meter is continuously summed in the two separate 29 bit east and north data registers.



Calibration data and best fit function for the standard VACM. The distance coefficient K (steady state tow distance required to cause one rotor rotation) is shown as a function of tow speed. The data is the same as shown in figure 5b.

Figure 6

Equation 1 gives the mean rotor rotation rate in units of revolutions per second during the sampling interval T. R is divided by 8 since there are 8 magnetic pairs on the rotor giving 8 counts per rotor revolution.

In Equations 2 and 3, R is subtracted from 2E and 2N to remove the bias which has been introduced in the VACM computer to eliminate negative number computations. If θ is the current bearing the VACM uses, $1 + \sin \theta$ and $1 + \cos \theta$ instead of $\sin \theta$ and $\cos \theta$ to find east and north components, respectively. The total rotor count, R, is also recorded in order to have the mean rotor speed available for each record period.

In Equations 2 and 3, E and N are multiplied by 2. This is necessary since the units bit and seven binary fraction bits of the east and north components held in the VACM memory are not recorded on tape. Multiplying by 2 shifts the recorded east and north binary bits left one binary place thus restoring the appropriate weight to each bit. The fact that the resulting numbers always end in binary zero (due to the shift) seems to suggest some possible systematic error. This is not the case, however, since the unrecorded 8 bits are retained in VACM memory (see Appendix 5) and no overall error is introduced. In other words, full precision is retained in the 29-bit VACM east and north computer registers but only the high order 21 data bits are read to tape. The 8-bit remainders in the VACM are not cleared and thus contribute to the next record.

Continuing with Equations 2 and 3, let θ again be the magnetic bearing of the current, then the number added to the east register each 1/8 rotor turn is

$$1 + \sin \theta$$

and that added to the north register is

$$1 + \cos \theta \ .$$

These sums are performed continuously every 1/8 rotor turn and are recorded on tape every T seconds. We have:

$$2E - \Delta E = \sum_{n=1}^{R} (1 + \sin \theta_n) \qquad (6)$$

where the 2 and the ΔE result from the VACM truncation discussed above and shown in Figure 4. Ignoring ΔE and simplifying the right hand term, we have:

$$2E - R = \sum_{n=1}^{R} \sin \theta_n \;. \qquad (7)$$

The desired east component of displacement X is:

$$X = \sum_{n=1}^{R} \frac{K_n}{8} \sin \theta_n \qquad (8)$$

(The 8 is from 8 rotor pluses per rotor revolution.)

If we assume K is a constant, $\overline{K}$, then

$$X = \frac{\overline{K}}{8} \sum_{n=1}^{R} \sin \theta_n \qquad (9)$$

from (7)

$$X = \frac{\overline{K}}{8} (2E - R) \qquad (10)$$

and from (5 and 1)

$$\frac{\overline{K}}{8} = \frac{a\overline{\omega} + b}{8\overline{\omega}} = \frac{a\overline{\omega} + b}{R/T} \;. \qquad (11)$$

Thus the east component of current from 10 and 11 is:

$$EAST = \frac{X}{T} = \frac{2E - R}{R} (a\overline{\omega} + b) \quad \text{cm/sec}$$

which is Equation 2 above. Equation 3 is found in the same manner.

From (7) the term

$$\frac{2E - R}{R} = \frac{1}{R} \sum_{n=1}^{R} \sin \theta_n$$

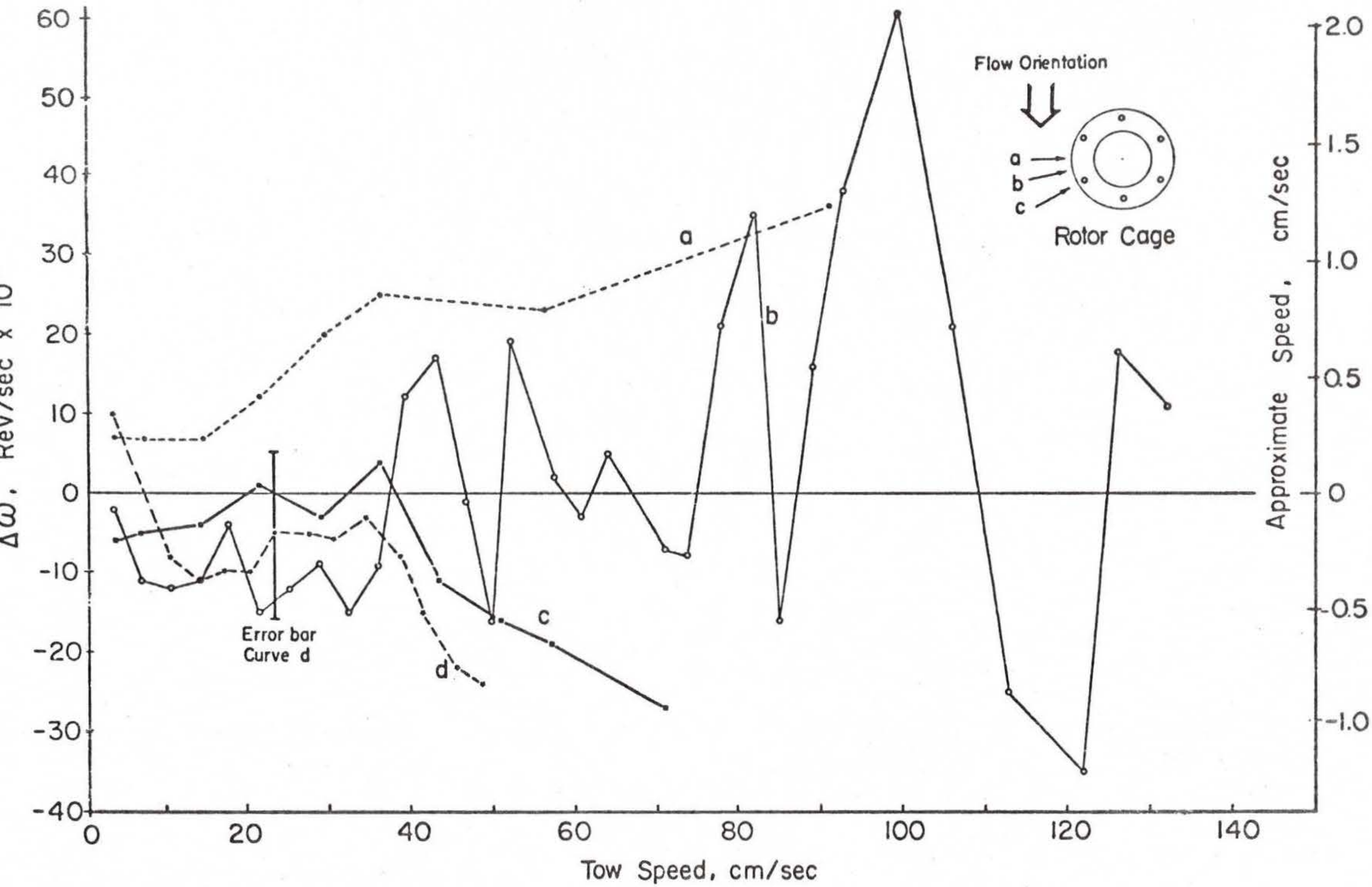
is the mean of the angle terms, $\sin \theta_n$, which forms a coefficient dependent on direction, while $a\overline{\omega} + b$ gives the magnitude of the flow vector.

VI. DISCUSSION OF CALIBRATION CONSTANTS

Figure 7 shows the observational scatter of the 49 tows (Cherriman, 1972) compared with the derived calibration coefficients. The figure shows the residuals or differences between the observed rotor rotation rate and that calculated from the constants in Equations 4 plotted as a function of tow speed. An approximate speed scale is shown at the right. The systematic difference between curves a, b, and c of about 1 cm/sec is caused by the relative orientation of the cage bars to the flow as indicated in the insert.

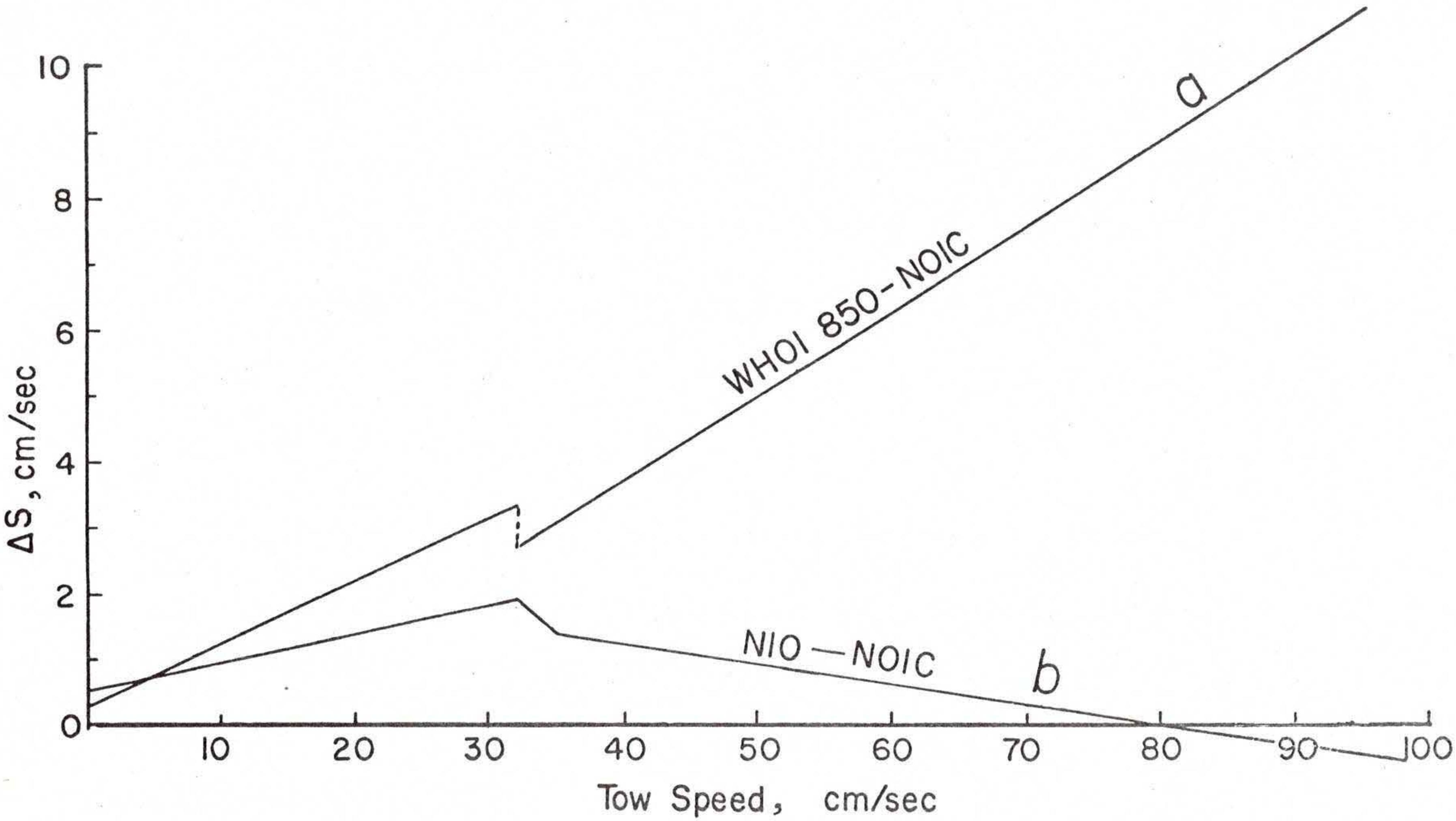
In a third set of VACM rotor calibration tows Cherriman (1974) at NIO tested 7 AMF VACMs at 14 equally-spaced speeds from 3 to 48 cm/sec for flow on a bar and midway between two bars. Figure 7d shows the residuals for these 196 tows. Each point represents the 14-point mean of 7 instruments each towed once with a bar leading and once with a gap leading. The error bar shows a mean standard deviation equavalent to about ±0.3 cm/sec. The maximum peak-to-peak difference in all the tows shown in the figure corresponds to about 3.6 cm/sec.

Referring to the equations in Appendix 3, Figure 8 gives a comparison of (a) the speed given by the 850 equation (4) minus the speed given by the NOIC equations (2), and (b) the speed given by the NIO-WHOI equations (1) less that given by the NOIC equations (2). The difference in speed is shown as a function of



Residuals of NIO VACM calibration data and best fit linear function used at WHOI. (a) cage, gap leading (30°), (b) flow axis 15° from bar, (c) bar leading (0°), and (d) 14 point mean residuals for 196 tows with 7 VACMs. An approximate speed scale is shown at right. Error bar curve d shows a standard deviation of about ±0.3 cm/sec.

Figure 7



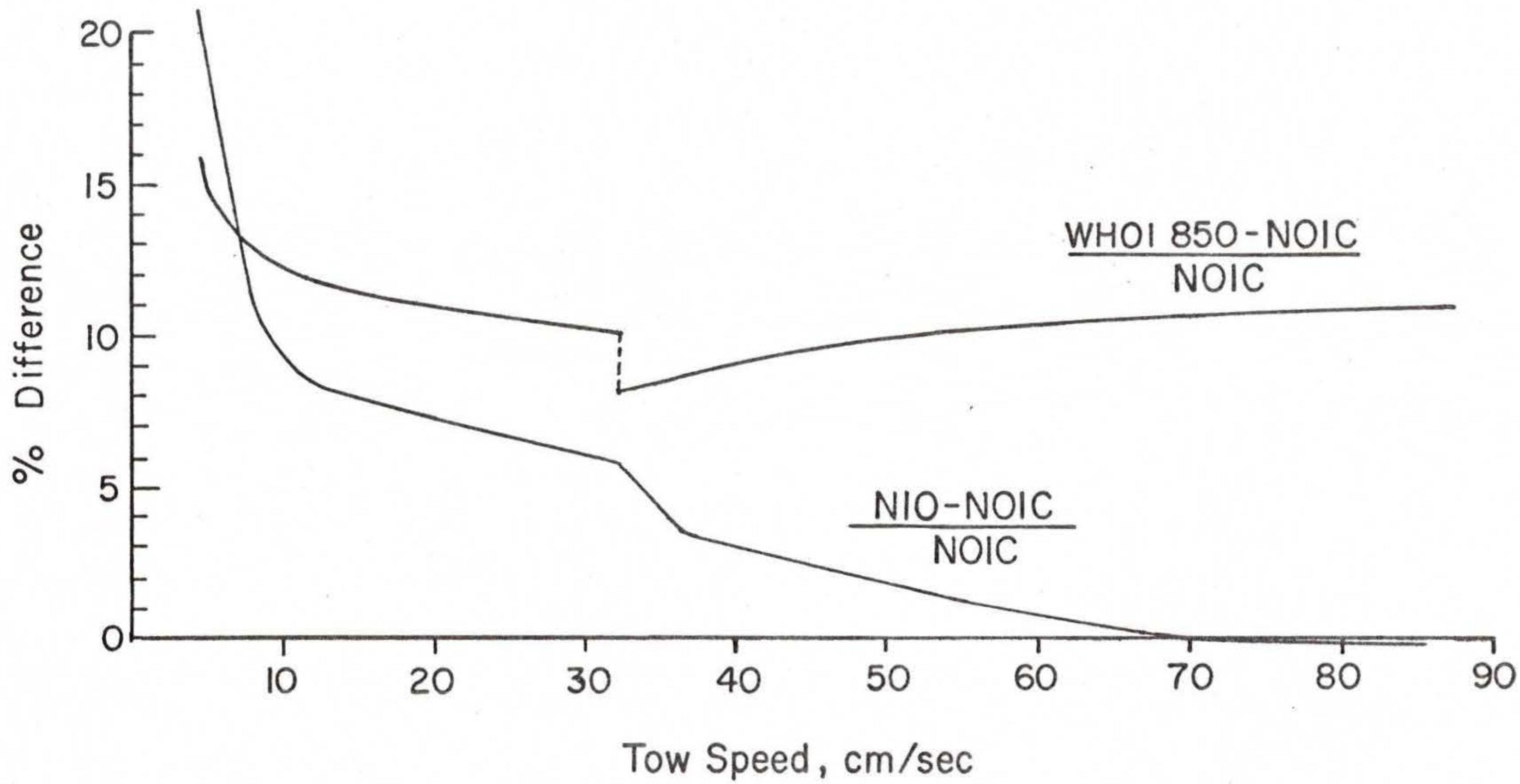
Comparison of calibration functions (a) WHOI 850 less NOIC VACM, (b) NIO VACM less NOIC VACM shown as a function of tow speed.

Figure 8

the speed given by the NOIC equations (2). (There is no intention of suggesting that NOIC data is more nearly correct, it is simply being used here for comparison.) It can be seen that below about one knot (51 cm/sec) a systematic difference of about 1 cm/sec exists between the NOIC and NIO calibrations. The systematic difference for the 850 is much larger.

Figure 9 shows the percent difference when the same sets of equations are compared. Above 57 cm/sec the NOIC and NIO equations agree to better than 1% while at 9 cm/sec there is a 10% difference in the sense that the NOIC calibration gives a lower speed for a given rotor rotation rate. That is, the NOIC rotor turned faster at a given tow speed. The NIO VACM rotor bearings had been used at sea for a month at the speeds shown in Figure 3 prior to testing and may have slowed the rotor slightly in the NIO tests. Alternately the small difference in response between new (NOIC) and used (NIO) bearings indicates the bearings can run well for a month at sea with mean speeds in excess of a knot.

At 5 cm/sec in Figure 9 there is a 20% difference. As seen in the previous figure, however, the magnitude of the low speed error is less than 1 cm/sec and if we share the difference, the NOIC and NIO data agree to within about 0.5 cm/sec below 10 cm/sec. Actually, this is very good agreement when we consider that the calibrations were made in different facilities, by different experimenters, using different rotors, with different pressure housing configurations. (NOIC used a complete VACM while NIO towed just the rotor-vane cage portion.) The rotors came from different manufacturers and the bearing styles may have differed. Speed calibrations below 10 cm/sec are in fact difficult to make. The agreement gives one estimate of the similarity of rotor response under well controlled test conditions.



Similar to figure 8 with speed difference shown as a percentage of the tow speed.

Figure 9

VII. SOME CALIBRATION ASSUMPTIONS

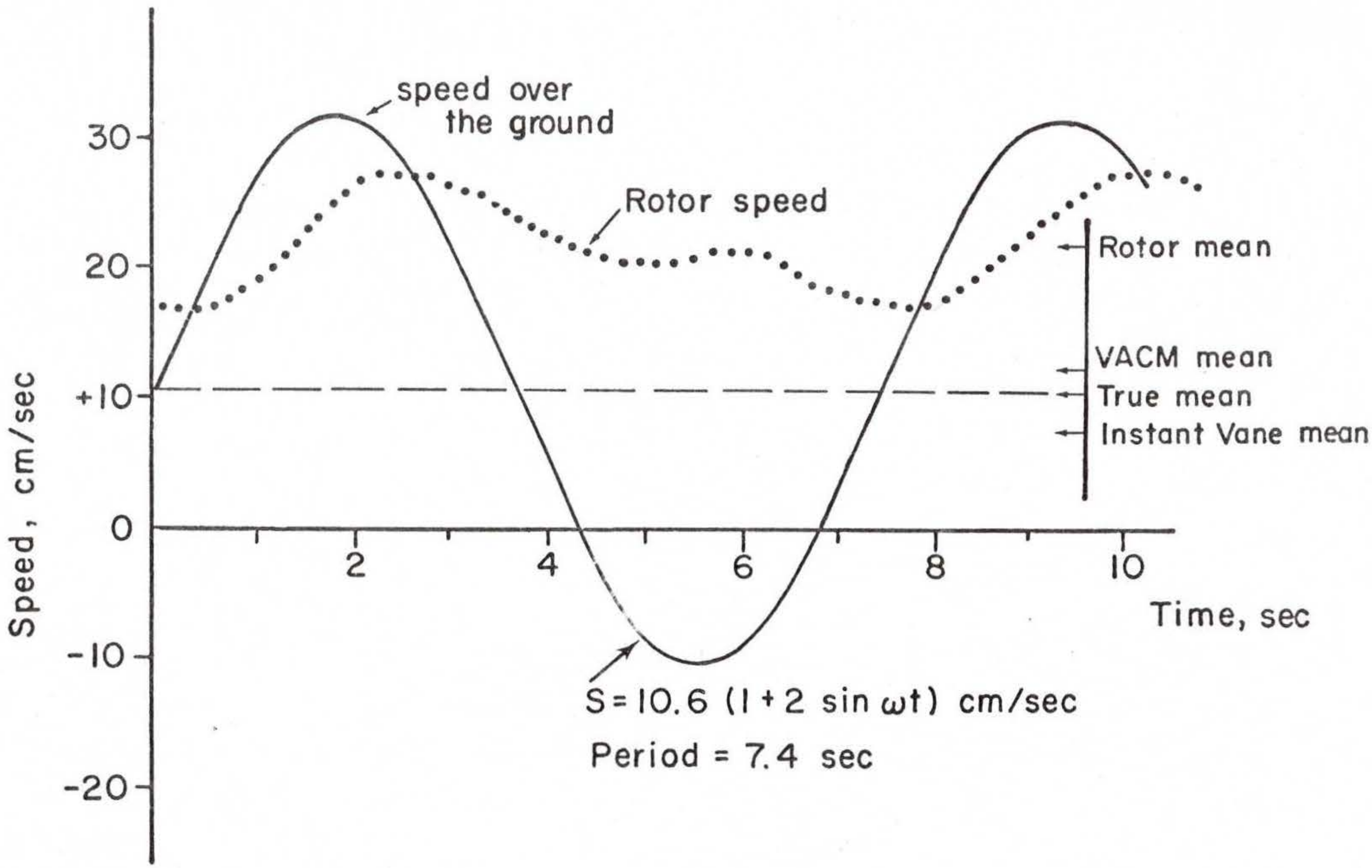
It is clear from Figure 6 that K is not a constant but is a function of speed. The key assumption is that the individual coefficients K_n in Equation 8 can be represented by some mean value $\overline{K} = f(\overline{\omega})$. For typical speed distributions above about 30 cm/sec the approximation should be good. Further, if the speed distribution is symmetrical about the mean and the speeds are not correlated with the direction terms sin θ_n then K need only be locally linear. It would seem reasonable, however, that on a moving mooring the speed and direction might well be correlated. The error introduced is probably masked, however, by the highly non-linear dynamic response of the rotor discussed in the next section.

Near or below the stall speed the rotor reading is totally meaningless and a threshold speed is arbitrarily substituted. The error introduced by the assumption that the response is linear, therefore, depends on the distribution of rotor speeds and their absolute value.

VIII. DYNAMIC RESPONSE

The rotor calibration technique assumes non-rotating, steady, non-turbulent flow. When the flow is not steady the rotor response is quite different and very complex. We have demonstrated in the laboratory that the rotor can run faster *or* slower than predicted by the steady speed calibration depending on the nature of the oscillating and steady flow components.

By way of illustration, Figure 10 shows the rotor speed as a function of time when the meter is being towed at a steady speed of 10.6 cm/sec and is simultaneously being moved sinusoidally ahead and back on the tow carriage. The period of oscillation is 7.4 seconds. As is shown at the right side of the figure, the lag and overrun in the rotor response give a mean rotor speed that is



Observed rotor response to collinear steady and oscillatory motion.

A wide variation of Savonius rotor-vane speeds are possible in such flow. Period shown is 7.4 sec, true mean is 10.4 cm/sec. At right, the rotor rectifies the signal above the true mean. If combined with an instantly reversing vane the vector mean is *below* the true mean because the long backward motion in the tank is combined with overly large rotor speeds. The VACM vane requires time to assume negative value, giving a mean slightly larger than nominal. If the flow did not reverse, the vane direction would be constant and the mean speed values would equal that of the rotor or more than twice the true value.

Figure 10

more than double the mean speed over the ground. The vane response further complicates the total vector response but brings the mean more nearly to the correct value. If the flow did not reverse the indicated magnitude of the flow vector would be the rotor mean (because the vane would not reverse) or more than double its true value.

This and other rectification properties of the non-linear rotor-vane sensors have been recognized for over a decade but it is only in the last few years that we have begun to identify moored configurations in which the errors become significant. The response is influenced in a complex way by the relative values of the mean flow, Vo, and the amplitude of the fluctuating flow, V_f, as well as the magnitude of Vo + V_f, the spectral content of V_f, the linear bandwidth of the sensors and relative strength and spectral content of the vertical current component (Refs. 8 and 17) seen by the instrument. The extent of amplified resonances, signal leakage from one frequency band to another, non-linear parametric amplification at low frequencies by frequencies outside the linear pass band of the sensors, the influence of the instrument package on the sensors, etc. will depend on these unknown factors.

Comparing the Aanderaa and the VACM, it appears that both rotors give nearly the same indicated mean speed near the surface on surface moorings over a range of ocean conditions. If the flow is non-reversing and collinear ($Vo > V_f > 0$), however, both meters will read high, i.e. over estimate Vo.

If the flows are not collinear or the fluctuations are larger than the mean speed (reversing currents), then instruments with large vanes will necessarily give high readings while the smaller VACM vane may or may not track the oscillations (Saunders, 1975). At some frequency (wave number) of interest, however, the VACM will no longer respond properly and readings may contain large errors (Ford and McCullough, 1973, Figure 10 above).

At mid-depths on surface moorings all meters tested give erroneously high, noisy readings (Ref. 26). Energy levels 2 to 7 times too large have been observed and are attributed to vertical heaving of the instruments in a weak mean horizontal flow (see for example McCullough, 1974).

On subsurface moorings with the float below the wave field ($z > \sim 20$ meters) the errors are thought to be small. Bryden (1975) finds, for example, that the low-frequency instrument errors for 11 closely spaced (6 to 1600 m) VACM pairs on the subsurface IWEX tri-moor to be 0.35 cm/sec and 3.0 degrees for the vector magnitudes and directions, respectively. He notes that errors are due more to the direction than to the speed measurements.

Clearly interpretation of rotor data in unknown oscillatory flow is difficult at best.

IX. OTHER VACM DOCUMENTS

1. <u>AMF Technical Manual (1973)</u>

Basic VACM Technical Manual (SLS 106-11419) prepared by WHOI and AMF and containing:

a. General description
b. Theory of operation
c. Test and alignment procedures
d. Wiring diagrams
e. Circuit schematics
f. Printed circuit card layouts
g. Electronics parts lists, and
h. Read only memory contents
(Items a and b provided by AMF. Other items originated by WHOI.)

The manual has evolved from WHOI prototype drawings to its present form. Additional information in the Theory of Operation section would be useful. (56 pages, 26 diagrams, 32 pages of tables, sold by AMF.)

2. VACM Checkout Procedure Manual (1974)

Complete detailed list of digital and analogue laboratory test used by WHOI for VACM preparation. (No text. About 20 pages of tests, WHOI current meter laboratory document, publication in preparation.)

3. NOIC VACM Evaluation (1973)

Woodward and Appell report extensive test on VACM static and dynamic response. Steady tow calibration with rotation and tilt are included as are dynamic tests from tows in a large wave tank. Compass test calibration, temperature sensor calibration, environmental tests (temperature, vibration, tensile load, pressure, tensile load plus pressure), and quantizing errors are discussed. (51 pages, 13 figures, 13 pages of tables, bibliography, NOAA-TM-NO3-NOIC-1.)

4. Patent Disclosure (January 1973)

Koehler and McCullough. General instrument description in patent jargon. (22 pages, 10 figures, Navy Case 55,686.)

5. EG&G-WHOI Technical Manual (September 1971)

Superseded by AMF Technical Manual. Contains theory of operation, signal flow, board functions, checkout procedures, wire lists, circuit diagrams, printed circuit layouts, timing diagrams. (49 pages, 3 tables, 12 figures, prepared by WHOI and EG&G, published by EG&G, 1971.)

6. AMF Mechanical Drawings

Detailed manufacturing drawings of all VACM parts. AMF proprietary (perhaps available on special request from AMF). (Several hundred pages, 1972-74.)

7. Delta Temperature Option (1975)

Description of the high accuracy dual thermistor circuits developed at WHOI. Report in preparation by R. Koehler.

8. Pressure Option

One electronic card pressure option for the VACM. Sea Data Corp., Newton, Massachusetts.

9. Precision AC Bridge Option

Koehler and McCullough. WHOI prototype circuit diagram.

10. Multiplexor Option

Koehler and McCullough. WHOI prototype sensor multiplexor circuit diagram.

ACKNOWLEDGEMENTS

It is a pleasure to acknowledge the assistance given in the preparation of this report by: J. Cherriman and G. Tupper for the tow tank tests; W. Woodward and G. Appell for numerous related conversations and tests; M. Chaffee for the graphic arts and text editing; J. Dean, R. Koehler, R. Payne, P. Saunders, and S. Tarbell for technical and editorial advice and L. Lawday, D. Haight, and A. Williams for typing.

The financial support and encouragement of the Office of Naval Research and National Science Foundation is gratefully acknowledged.

REFERENCES

1. Bryden, H. (1975). Precision of Low Frequency Estimates of Current and Temperature of VACMs on the IWEX Mooring. Private communication. WHOI internal memo.

2. Cherriman, J. (1972). VACM Steady State Rotor Calibration. Private communication. Letter to J. McCullough dated 7 March 1972.

3. Cherriman, J. (1974). VACM Rotor Calibrations. Private communication. Letter to J. McCullough dated 24 January 1974.

4. Dacy, R. F. (1967). Deep Ocean Current Meter Test Report, University of California.

5. Fofonoff, N. P. and Y. Ercan (1967). Response Characteristics of a Savonius Rotor Current Meter. WHOI Ref. 67-33 (unpublished manuscript).

6. Ford, E. and J. McCullough (1973). VACM Rotor Studies at the M.I.T. Tow Tank (unpublished).

7. Gaul, R. D. (1962). The Savonius Rotor Current Meter. Texas A&M Department of Oceanography and Meteorology, Tech. Rep. 62-2T.

8. Gaul, R. D. (1963). Influence of Vertical Motion on the Savonius Rotor Current Meter. Texas A&M, Project 329, Ref. No. 63-4T.

9. Gaul, R. D., J. M. Snodgrass, and D. J. Cretzler (1963). Some Dynamical Properties of the Savonius Rotor Current Meter. ISA Marine Sci. Inst. 2.

10. Goss, B. and R. Knox (1965). Some Response Characteristics of the Sävonius Rotor: Technical and Experimental. (WHOI internal report)

11. Gould, W. J. (1972). The Oceanographer's Current Meter. Proc. Soc. Underwater Tech. 1, 4, pp. 50-58. N.I.O. #854.

12. Gould, W. J. and E. Sambuco (1975). The Effect of Mooring Type on Measured Values of Ocean Currents. Deep-Sea Res. 22 55-62.

13. Halpern, D., R. D. Pillsbury, and R. L. Smith (1974). An Intercomparison of Three Current Meters Operated in Shallow Water. Deep-Sea Res. 21, pp. 489-497.

14. Hankins, T. L. (1963). Report on the Performance of the Savonius Rotor. EG&G Geodyne report, Waltham, Mass.

15. Horrer, P. L. (1968). Comments on the Measurement of Currents in the Presence of Waves. Bendix Application, Note 101, Baltimore.

16. Kalvaitis, A. N. (1972). Survey of the Savonius rotor Performance Characteristics. Jour. Mar. Tech. Soc. Vol. 6 (4), pp. 17-20.

17. Kalvaitis, A. N. (1974). Effects of Vertical Motion on Vector Averaging (Savonius rotor) and Electromagnetic Current Meters. NOAA Tech. Memo, NOS,NOIC 3.

18. Karweit, M. (1974). Response of a Savonius Rotor to Unsteady Flow. J. Marine Res. 32, 3.

19. McCullough, J. R. (1971). The Woods Hole Vector Averaging Current Meter (VACM). Soc. Underwater Technology, NIO England, October 1971 (unpublished).

20. McCullough, J. R. (1974). In Search of Moored Current Sensors. MTS 10th Annual Conf., Washington, D. C. September 1974.

21. NOIC (1974). Vector Averaging Current Meter, AMF, Inc. NOIC Fact Sheet IFS-74008.

22. Panicker, N. (1973). Strumming Frequency of a Pendulus VACM. WHOI Memo to N. Fofonoff, March 6, 1973.

23. Richardson, W. S., P. B. Stimson, and C. H. Wilkins (1963). Current Measurements from Moored Buoys. Deep-Sea Res. 10, (4), 369-388.

24. Saunders, P. M. (1975). Near-Surface Current Measurements. Deep-Sea Res. (in press). WHOI Cont. No. 3486.

25. Savonius, S. J. (1931). The S-Rotor and Its Applications. Mech. Eng. 53, No. 5.

26. SCOR Working Group 21 (1969). An Intercomparison of some Current Meters. UNESCO Tech. Pap. in Mar. Sci., 11, 70 pp.

27. Sexton, R. (1964). Some Tow Tank Calibrations of the Savonius Rotor. Lamont Geophysical Observatory. Columbia University Technical Report No. CU-11-64.

28. Smoot, G. and R. Carter (1968). Are Individual Current Meter Ratings Necessary? Jour. of the Hydraulics Div., Proceedings of the American Society of Civil Engineers.

29. Snead, E. (1969). The Relative Effects of a Savonius Rotor's Turnrate when Coated with Antifouling Paint. In-House National Instrumentation Report.

30. Thompson, R. (1971). A Computer Model of the VACM Rotor Rotation Rate (private communication).

31. Woodward, W. and G. Appell (1973). Report on the Evaluation of a Vector Averaging Current Meter. NOAA, TM, NOS NOIC-1, NSF, AG-263.

APPENDIX 1

VACM Tape Format

The VACM data is stored internally in a "write only" Phillips cassette digital magnetic tape recorder designed by WHOI and Harvard and manufactured by Sea Data, Inc., Newton, Massachusetts. Data is recorded simultaneously on four tracks at 800 4-bit characters per inch giving a maximum tape capacity (less record gaps) of 11×10^6 bits. Each track uses non-return to zero phase encoding for data and return to zero format for record gaps. The tape must be properly degaussed before use.

Each tape write request initiates a zero flux (no write current) record gap followed by one data record written at 100 characters (400 bits) per second. Each track of a record starts with a 2-bit preamble (for playback synchronization) and ends with a track parity bit for error detection. The return to zero gap preceding each record allows the VACM recorder to advance the tape before writing in order to reduce problems of unwanted tape motion caused by vibration or tape creep during periods of no recording. The recorder draws no power when quiescent. Typically a moored VACM does not record data for 15 minutes before writing a 1/16-inch long record in 1/2 second.

Data is presented to the miniature recorder one binary bit at a time (bit serial format). The recorder electronics generates the tape gap, generates the two-character track preamble code, provides shift pulses for the serial data input stream, assembles the 4-bit tape characters, generates an odd parity bit for each track, records the parity character and stops ready to generate the next record when requested.

The tape reader reverses the operation to recreate the initial binary bit sequence for each record together with parity error flags where indicated. Redundant bits in the data plus the record parity checks greatly facilitate automatic error detection. Track skew difficulties associated with multiple track, high density recording and inexpensive miniature transports are resolved by the self-clocking feature of phase encoding, track preambles, and asynchronous detection (electronic deskewing) in the tape reader.

The VACM data fields in the order recorded are:

		Bits
1)	East Component, E	24
2)	North Component, N	24
3)	1/8 Rotor Revolutions, R	24
4)	Compass Sample, C	8
5)	Vane Follower Sample, V	8
6)	Time, t	16
7)	Temperature, τ	24
	Total	128

For checking purposes it should be noted that the leading three high-order bits of E, N, R, and τ are always zero as are the single high-order bits of the C and V fields. The time field, t, is inherently redundent.

The record length is:

		Bits
1)	Gap (19 characters × 4 bits each)	76
2)	Preamble (2 × 4)	8
3)	Data (32 × 4)	128
4)	Parity (1 × 4)	4
	Total	216

The gap can be shortened to about 8 characters if greater data capacity is desired.

The tape capacity is:

Sample Period	Standard Gap (19 Characters)	Short Gap (8 Characters)
Continuous	7.65 hours	7.65 hours
56.25 sec	33 days	41 days
112.5	66	82
225	132	165
450	265	333
900	530	666
Record Length	54 Characters	43 Characters
Capacity	51,000 Records	64,000 Records

APPENDIX 2

Rotor Calibration Technique and Data

The Cherriman (1972) tests were made in the NIO fresh water tow tank whose size is 6' × 6' × 176' long. Rotor pulses (1/8 turn), one meter distance pulses, and a 0.5 second sine wave were recorded on a strip chart recorder at a rate allowing time resolutions to better than 0.1 sec. Only the rotor and vane cage was towed. No pressure case was attached. The cage was built by ORE, Falmouth, Massachusetts and fitted with EG&G, Waltham, Massachusetts, rotor, vane, and bearings. Hydrodynamically the ORE cages appear to be identical to the AMF cages.

The cage was mounted rigidly to the hydraulically-driven NIO tow carriage which runs on rails fitted to the top of the tank walls. Three orientations of the cage bars relative to the flow were made; (1) flow on the leading bar (0°), (2) flow centered in the gap between two bars (30°), and (3) flow midway between cases 1 and 2 (15°). Tows were made in one direction only with about a 15 minute settling wait between tows. The constants given in Equations (4), page 5, were derived at WHOI from least squares fits to the 3 orientations of the cage bars. No corrections for tank blocking or edge effects were applied.

Woodward and Appell (1973) show a worst case VACM horizontal angular rotor response difference (due to the cage bars) of 7% at 20° (speed = 27.3 cm/sec). Their mean values show a 6% peak-to-peak difference. Cherriman (NIO) was unaware of this asymmetry when his calibrations were made and it is not clear which case 3 (orientation relative to the pitch of the rotor blades) he tested. (Some of our rotors rotate in one direction, others in the opposite direction.) When the magnitude of the variation shown in Figure 7 is compared with the NOIC results it appears that the NIO tests did not include the angle of lowest response (50°). If true, the NIO speeds would read slightly high which is in the wrong sense to explain differences discussed above between the NIO and NOIC calibrations.

Tilt does not appear significant. According to Woodward and Appell (1973) tilting the VACM away from the flow by 10 degrees causes the rotor to run 2% faster at 35 cm/sec. Sexton (1964), however, gives a 2% error per degree tilt with a different cage design.

Sexton found changes ranging between about 0 and 8% with and without a pressure housing. Adding the pressure housing made the rotor turn faster for tow speeds in the range 10 to 230 cm/sec. This has the proper sense and magnitude to account for the NOIC-NIO differences. The effect should be demonstrated directly with a VACM, however, before considering any changes in the WHOI calibration procedure. Sexton notes, "It is unknown whether the pressure case has such an extreme effect on the rotor or whether the differences are artifacts of the experiment." Tank edge effects and pressure housing differences are one possible source of the calibration differences noted. Bearing effects may also be significant at low speeds and are being evaluated. In all the general agreement is encouraging.

Cherriman Calibration Data

The following data was supplied to WHOI by John Cherriman of NIO (now IOS) in a letter to J. McCullough dated 7 March 1972. The VACM tested was a WHOI prototype not an AMF instrument. The VACM-rotor-calibration used at WHOI, 1971 to date, is based on these 49 tow tests. The data is plotted in the text in Figures 5, 6, and 7.

Table 1

FLOW AXIS ON THE LEADING CAGE BAR

V	ω	Δω
Carriage Speed cm/sec	Rotor Speed Rev/sec	Residuals to W.H.O.I. Equations × 10^{-3}
3.7	0.038	-7
6.9	0.130	-5
14.0	0.329	-4
21.2	0.531	+1
28.7	0.736	-3
35.9	0.944	+4
43.2	1.153	-11
50.4	1.367	-16
56.8	1.562	-19
70.9	1.984	-27

Table 2

FLOW AXIS BETWEEN TWO CAGE BARS

V	ω	Δω
3.4	0.045	+7
7.1	0.148	+7
14.2	0.344	+7
21.5	0.522	+12
29.0	0.767	+20
36.1	0.971	+25
56.1	1.580	+23
91.5	2.677	+36

Table 3

FLOW AXIS MIDWAY BETWEEN CASE 1 AND 2 ABOVE

Carriage Speed cm/sec	Rotor Speed Rev/sec	Residual × 10^{-3} to W.H.O.I. Equations
3.2	0.030	-2
6.8	0.122	-11
10.4	0.220	-12
14.1	0.322	-11
17.5	0.425	-4
21.3	0.519	-15
25.0	0.625	-12
28.8	0.726	-9
32.1	0.819	-15
35.7	0.926	-9
38.8	1.040	+12
42.6	1.163	+17
46.4	1.259	-1
49.6	1.344	-16
51.9	1.448	+19
57.0	1.587	+2
60.2	1.679	-3
63.9	1.801	+5
70.8	2.002	-7
73.6	2.086	-8
77.5	2.234	+21
81.4	2.367	+35
84.9	2.422	-16
88.6	2.567	+16
92.5	2.709	+38
98.9	2.927	+60
105.9	3.103	+21
113.0	3.274	-25
121.8	3.534	-35
126.0	3.715	+18
132.3	3.900	+11

APPENDIX 3

Various Calibration Equations in Use

1. Cherriman - McCullough (1972) (NIO-WHOI, VACM)

$S = 36.1\omega + 2.0 \qquad \omega < .915$ rev/sec

$S = 32.6\omega + 5.2 \qquad \omega \geq .915$ rev/sec

2. Woodward - Appell (1973) (From extensive NOIC VACM tests)

$S = 34.6\omega + 1.4 \qquad \omega < .887$ rev/sec

$S = 33.6\omega + 2.9 \qquad \omega \geq .887$ rev/sec

3. Fofonoff - Ercan (1967) (850 style rotor calibration, Ref. 5)

$S = 38.9\omega + 1.3 \qquad \omega < 1.2$ rev/sec

$S = 36.5\omega + 4.2 \qquad \omega \geq 1.2$ rev/sec

4. WHOI 850 (Used by WHOI for 850 current meters. Very nearly the same as Fofonoff - Ercan.)

$S = 37.9\omega + 1.8$

Alternately the above equations can be written:

1. Cherriman - McCullough (VACM NIO)

$\omega = .0277S - .056 \qquad S < 35$ cm/sec

$\omega = .0307S - .160 \qquad S \geq 35$ cm/sec

2. Woodward - Appell (VACM NOIC)

$\omega = .0289S - .0405 \qquad S < 32.1$ cm/sec

$\omega = .0298S - .0863 \qquad S \geq 32.1$ cm/sec

3. Fofonoff - Ercan (850)

$\omega = .0257S - .0334$ $\quad S < 48.0$ cm/sec

$\omega = .0274S - .115$ $\quad S \geq 48.0$ cm/sec

4. WHOI 850

$\omega = .0264S - .0475$

APPENDIX 4

VACM "Rotor One Bit" Modification

When R = 0 the compass and vane follower fields in the VACM are meaningless. Since the direction can be useful even if there are no rotor data (rotor is below threshold, stuck, rotor circuit is broken, etc.) all WHOI instruments have been modified to electronically introduce one extra rotor count at the start of each tape record cycle. The change is called the "rotor one bit mod."

The extra count can, if desired, be removed in the data reduction since the compass and vane angles for the extra count are known. The compass and vane values of one tape record are those used in the computation of the vector east and north components of the following record.

With the "mod" the VACM compute cycle can be initiated asynchronously by either the rotor circuit or by the tape recorder. Once started the compute cycle continues uninterrupted until it is completed at which time the compute program resets the compute request flip-flop allowing a new compute request. This means that if the recorder requests the extra rotor count while the compute cycle is in operation the request will be ignored and the extra rotor count will not be made.

In a one knot current rotor pulses occur at a rate of 11 per second or one every 91 milliseconds. The compute cycle is .33 milliseconds long so the probability of the extra rotor count not being recorded is 0.36% or one in 280 records (about 3 days with the 15 minute record rate). One count is equal to 1/8 rotor turn or about 4.7 cm of water. For normal use then the error due to the missed extra computation is insignificant.

APPENDIX 5

Rapid Sampling and Data Quantizing

As in all finite length digital computations errors introduced by round-off or quantizing of numbers need to be evaluated. The various quantizing schemes in the computation performed by the VACM include:

1. Every 1/8 rotor turn (about 4.7 cm of water) is computed as a unit distance (resolution). The size of the unit distance is not a constant but depends on the speed of the rotor. It is estimated from the mean rotor rate $\overline{\omega}$ for each record period T.

2. Compass and vane follower readings are in 7-level gray binary code. These are converted to a 7-level binary code in the VACM. The two values are subtracted to get a 7-level binary magnetic flow bearing, i.e., $360°/2^7 = 2.81°$ is the least count of the indicated direction for each 1/8 rotor turn.

3. For each of the 128 possible bearing angles, θ,8 bit values of $(1 + \sin\theta)$ and $(1 + \cos\theta)$ are assigned, giving $\sin\theta$ and $\cos\theta$ values rounded to 7 binary places or to within $\pm 2^{-8} = \pm 0.00391$ of the true value.

4. The E and N components are accumulated in two 29 bit registers having 22 whole bits and 7 binary fraction bits each. The low order 8 bits (units bit and 7 fraction bits) are not stored on the VACM magnetic tape.

The VACM east and north registers have the form:

MSB		LSB
$2^{21} + 2^{20} + \cdots + 2^2 + 2^1$	+	$2^0. + 2^{-1} + \cdots + 2^{-7}$
Recorded (21 bits)		Not Recorded (8 bits)

The unrecorded portion is not reset, the recorded portion is reset. The size of the quantizing error introduced by ignoring the low order 8 bits depends on the total number of rotor counts in the time NT.

If rapid sampling is used and/or the currents are small, the number of rotor counts per record interval may be small and the resulting stability of individual estimates of the vector speed will be degraded. Longer period averages formed from the shorter samples will not be degraded, however, since the low order bits of the east and north registers in the VACM are not reset. Further, as shown in Appendix 4, it is not likely that an appreciable number of rotor counts will be lost during the VACM compute cycle associated with the record process.

The following table gives some representative error values, assuming the bearing is constant, for R rotor counts. The first data column gives the extreme range of angle errors while the next column gives the RMS error over all 128 possible bearings. The last two columns give the extreme and RMS speed errors. (Where the positive and negative extreme values differ slightly an average is listed. The values were determined numerically by computer simulation of the VACM.)

R	RMS Angle (°)	RMS Angle (°)	Speed Max %	Speed RMS %
4	±43.6	19.5	±46	29
8	18.2	8.6	27	15
16	8.2	4.0	16	7
32	3.9	1.7	12	5
64	1.8	0.8	3	2

Whether the single bearing given by the compass and vane follower samples is a better estimate of the direction than that derived from the east and north components of current will depend on R and the distribution of bearings in the sample. If we assume some normally distributed sample then the stability of the estimate should improve by roughly $R^{-\frac{1}{2}}$ and for R = 16 we would expect extreme errors of the order of $8°/\sqrt{16} = 2°$, hence the arbitrary selection (page 5) of R = 16 for the transition from E - N to C - V data for determing the current direction value in a given sample.

APPENDIX 6

Ideal Speed Sensor Response in Oscillatory Flow

This appendix gives some simplified demonstrations to illustrate that even with an ideal or perfect speed sensor the correct mean current cannot be found unambiguously in the presence of oscillatory flow *unless the flow vector direction is accurately known and vector averaging in fixed Cartesian coordinates is applied.* This is true of any speed sensor not just the omnidirectional type rotor which has an additional rectification effect since it doesn't sense the sign of the flow component. The error arises not from imperfection in the sensor or its calibration but from the fact that the average speed, $\overline{S}$, and the magnitude of the vector-averaged velocity, $|\overline{V}|$, are not in general equal. Figure 3 in the text illustrates this inequality.

Consider then a speed sensor that gives exactly the true speed (positive or negative) at every instant of time. It is linear and unbiased. Now apply a steady flow V_o in the positive x direction together with a linear sinusoidal motion at an angle θ to the mean flow. The velocity components u and v in the x and y direction are:

$$u = V_o + A \sin \omega t \cos \theta \qquad (1)$$

$$v = A \sin \omega t \sin \theta \qquad (2)$$

At any instant of time, t, the true speed S squared is:

$$S^2 = u^2 + v^2 \, . \qquad (3)$$

Substituting for u and v and simplifying we get

$$S^2 = V_o^2 + 2V_o A \sin \omega t \cos \theta + A^2 \sin^2 \omega t \qquad (4)$$

or

$$S^2 = V_o^2 + 2V_o\ A \sin \omega t \cos \theta + \frac{A^2}{2} (1 - \cos 2\ \omega t). \qquad (5)$$

From Equation (5) we see that by averaging over an integral number of cycles the mean of the squared speed is

$$\overline{S^2} = V_o^2 + \frac{A^2}{2}. \qquad (6)$$

This might be used as a consistency test since it is not a function of θ. (In passing, the variance of S is Var $= \overline{S^2} - \bar{S}^2$ while the rms $= \left(\overline{S^2}\right)^{\frac{1}{2}}$.)

Now consider some special cases of Equations (4) and (5).

1. For $\theta = 0$, i.e., collinear or longitudinal oscillation, we have from (4) that

$$S^2 = V_o^2 + 2V_o\ A \sin \omega t + A^2 \sin^2 \omega t$$

$$= (V_o + A \sin \omega t)^2$$

$$S = \pm (V_o + A \sin \omega t)$$

and ignorning the extraneous root, the mean speed $\bar{S}$ is

$$\bar{S} = V_o .$$

In the mean we get V_o for longitude oscillation. (For the not so ideal Savonius rotor response shown in Figure 10 of the text, of course, not even this is true. For reversing flow, $A > V_o$, it is not even true of ideal omnidirectional rotors which will "full wave" rectify the signal.)

2. For $\theta = 90°$ (cross or lateral oscillation)

$$S^2 = V_o^2 + \frac{A^2}{2} (1 - \cos 2\ \omega t) \qquad (7)$$

$$\overline{S^2} = V_o^2 + \frac{A^2}{2}$$

Suppose that $A = V_o$, then from (7)

$$S = \pm[V_o^2 + \frac{V_o^2}{2} (1 - \cos 2\,\omega t)]^{\frac{1}{2}} \tag{8}$$

$$\overline{S} = \pm\sqrt{1.5}\ V_o = 1.22\ V_o$$

That is not so good. Even with a perfect speed sensor the reading is 22% higher than the true mean.

3. Try circular motion plus a steady flow.

$$u = V_o + A \sin \omega t$$

$$v = A \cos \omega t$$

$$S^2 = (V_o + A \sin \omega t)^2 + (A \cos \omega t)^2 \tag{9}$$

$$= V_o^2 + 2V_o A \sin \omega t + A^2$$

$$\overline{S^2} = V_o^2 + A^2$$

again for $A = V_o$

$$\overline{S} = \sqrt{2V_o} = 1.41\ V_o. \tag{10}$$

The reading is 41% high.

If we think of the speed sensor as moving through stationary water (or as a bicycle wheel moving on a road), then in Case 1 all motion is in the same line but in Case 2 the motion would be S-shaped and the distance travel per unit time would be greater than the total distance down the tank (road) per unit time. In Case 3 moving at a constant rate in a circle even without any steady motion, V_o, would result in some net steady speed, $\overline{S}$.

Without belaboring the point, we reach the conclusion that even an ideal speed sensor may very well give substantially erroneous readings of the mean current in the presence of oscillatory flow. There is no way to allow for the difference in the calibration since the magnitude of the oscillatory flow is not known. Again a perfect speed sensor, a perfect direction sensor and vector averaging in a fixed Cartesian coordinate system are required to correctly extract the mean in the presence of oscillatory flow. It is not sufficient to average speed and record some "average" direction as is done in the majority of ocean currents in use today. (Such meters include the Aanderaa, Alexaev, Braincon, Hydrowerkstatten, Plessey, etc.)

Typically, the speed sensor counts turns of a rotor or propeller and periodically records the number of turns and some estimate of the direction. Unfortunately the fundamental limitations of such techniques are frequently overlooked. Saunders (1975) finds Aanderaa meters in near surface measurements reading 2 to 5 times higher than drogue measurements of the mean near surface currents. Such large differences clearly overshadow the errors of a few percent found in tow tank calibrations of rotors.

MANDATORY DISTRIBUTION LIST

FOR UNCLASSIFIED TECHNICAL REPORTS, REPRINTS, & FINAL REPORTS
PUBLISHED BY OCEANOGRAPHIC CONTRACTORS
OF THE OCEAN SCIENCE AND TECHNOLOGY DIVISION
OF THE OFFICE OF NAVAL RESEARCH
(REVISED JAN. 1975)

1 Director of Defense Research
and Engineering
Office of the Secretary of Defense
Washington, DC 20301
ATTN: Office Assistant Director
(Research)

Office of Naval Research
Arlington, VA 22217
3 ATTN: (Code 480)
1 ATTN: (Code 460)
1 ATTN: (Code 102-OS)
6 ATTN: (Code 102IP)

1 LCDR David Cacchione, (USN)
ONR Representative
Woods Hole Oceanographic Inst.
Woods Hole, MA 02543

1 Office of Naval Research
Branch Office
495 Summer Street
Boston, MA 02210

Director
Naval Research Laboratory
Washington, DC 20375
6 ATTN: Library, Code 2620

1 National Oceanographic Data Center
National Oceanic & Atmospheric
Administration
Washington, DC 20235

12 Defense Documentation
Center
Cameron Station
Alexandria, VA 22314

Commander
Naval Oceanographic
Office
Washington, DC 20390
1 ATTN: Code 1640
1 ATTN: Code 70

Woods Hole Oceanographic Institution
WHOI-75-44

VECTOR AVERAGING CURRENT METER SPEED CALIBRATION AND RECORDING TECHNIQUE by James R. McCullough. 35 pages. September 1975. Contracts N00014-66-C0241; NR 083-004; N00014-74-C0262; NR 083-004; and IDOE/NSF Grant GX-29054.

Equations 1-4 summarize the rotor calibration used at Woods Hole Oceanographic Institution for the VACM. A discussion of the instrumental and test details used to derive these equations follows. A list of other VACM documents and related bibliography is included.

1. Current Meter
2. Rotor
3. Calibration

I. McCullough, James R.
II. N00014-66-C0241; NR 083-004
III. N00014-74-C0262; NR 083-004
IV. IDOE/NSF Grant GX-29054

This card is UNCLASSIFIED

Woods Hole Oceanographic Institution
WHOI-75-44

VECTOR AVERAGING CURRENT METER SPEED CALIBRATION AND RECORDING TECHNIQUE by James R. McCullough. 35 pages. September 1975. Contracts N00014-66-C0241; NR 083-004; N00014-74-C0262; NR 083-004; and IDOE/NSF Grant GX-29054.

Equations 1-4 summarize the rotor calibration used at Woods Hole Oceanographic Institution for the VACM. A discussion of the instrumental and test details used to derive these equations follows. A list of other VACM documents and related bibliography is included.

1. Current Meter
2. Rotor
3. Calibration

I. McCullough, James R.
II. N00014-66-C0241; NR 083-004
III. N00014-74-C0262; NR 083-004
IV. IDOE/NSF Grant GX-29054

This card is UNCLASSIFIED

Woods Hole Oceanographic Institution
WHOI-75-44

VECTOR AVERAGING CURRENT METER SPEED CALIBRATION AND RECORDING TECHNIQUE by James R. McCullough. 35 pages. September 1975. Contracts N00014-66-C0241; NR 083-004; N00014-74-C0262; NR 083-004; and IDOE/NSF Grant GX-29054.

Equations 1-4 summarize the rotor calibration used at Woods Hole Oceanographic Institution for the VACM. A discussion of the instrumental and test details used to derive these equations follows. A list of other VACM documents and related bibliography is included.

1. Current Meter
2. Rotor
3. Calibration

I. McCullough, James R.
II. N00014-66-C0241; NR 083-004
III. N00014-74-C0262; NR 083-004
IV. IDOE/NSF Grant GX-29054

This card is UNCLASSIFIED

Woods Hole Oceanographic Institution
WHOI-75-44

VECTOR AVERAGING CURRENT METER SPEED CALIBRATION AND RECORDING TECHNIQUE by James R. McCullough. 35 pages. September 1975. Contracts N00014-66-C0241; NR 083-004; N00014-74-C0262; NR 083-004; and IDOE/NSF Grant GX-29054.

Equations 1-4 summarize the rotor calibration used at Woods Hole Oceanographic Institution for the VACM. A discussion of the instrumental and test details used to derive these equations follows. A list of other VACM documents and related bibliography is included.

1. Current Meter
2. Rotor
3. Calibration

I. McCullough, James R.
II. N00014-66-C0241; NR 083-004
III. N00014-74-C0262; NR 083-004
IV. IDOE/NSF Grant GX-29054

This card is UNCLASSIFIED

UNCLASSIFIED 9/75

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER: WHOI-75-44	2. GOVT ACCESSION NO.
3. RECIPIENT'S CATALOG NUMBER	
4. TITLE (and Subtitle): VECTOR AVERAGING CURRENT METER SPEED CALIBRATION AND RECORDING TECHNIQUE	5. TYPE OF REPORT & PERIOD COVERED: Technical
	6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s): James R. McCullough	8. CONTRACT OR GRANT NUMBER(s): N00014-66-C0241; N00014-74-C0262; IDOE/NSF GX-29054
9. PERFORMING ORGANIZATION NAME AND ADDRESS: Woods Hole Oceanographic Institution, Woods Hole, MA 02543	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS: NR 083-004
11. CONTROLLING OFFICE NAME AND ADDRESS: Office of Naval Research, Code 480	12. REPORT DATE: September 1975
	13. NUMBER OF PAGES: 35
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)	15. SECURITY CLASS. (of this report): Unclassified
	15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

1. Current Meter
2. Rotor
3. Calibration

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Equations 1-4 summarize the rotor calibration used at Woods Hole Oceanographic Institution for the VACM. A discussion of the instrumental and test details used to derive these equations follows. A list of other VACM documents and related bibliography is included.

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE
S/N 0102-014-6601

UNCLASSIFIED 9/75

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)