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THE PERFORMANCE OF A THREE AXIS ULTRASONIC CURRENT SENSOR WHEN INTEGRATED INTO AN OCEANOGRAPHIC DATA ACQUISITION SYSTEM

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Summary

The paper discribes the present status for the ultrasonic current sensor based on the travel time difference prinsiple. In particular reference is given to experiences with a 3 axis recording current meter.

Introduction

Since the 1930s various attempts have been made to obtain current measurements by means of a non-moving current sensor. Only since the 1960s, however, have electronic components reached the degree of perfection needed to produce reliable and stable ultrasonic current measurements.

Fig. 1 illustrates how an ultrasonic current measurement is made. Two piezoelectric transducers, denoted as A and B, are placed in a fluid of velocity $\vec{U}$ shown in the figure as a unidirectional field $\vec{V}(y)$ directed along the x-axis. Three different direct signal processing systems are now in general use: the 'travel time' or 'leading edge' system, the 'sing-around' system, and the 'phase difference' system.

In the travel time or leading edge system A and B are simultaneously excited by voltage steps from 100 to 400 V at a repetition rate f_r. For each excitation a burst of exponentially damped acoustic oscillations is generated at each transducer surface. The resulting acoustic wavetrains travel towards the opposite transducer with a velocity $C \pm \vec{U} \cdot \vec{S}$ where C is the sound velocity in the resting fluid, and $\vec{S}$ is a unit vector parallel to the sound propagation path $d\vec{l}$. The travel time of the leading edge of the signal from A to B is

$$T_{AB} = \int_A^B \frac{d\vec{l}}{C + \vec{U} \cdot \vec{S}}. \tag{1}$$

The travel time is

$$T_{BA} - T_{AB} = \frac{2\,L}{C^2}\,|\vec{U}_m|\,\cos\theta \tag{2}$$

where L is the straight line distance between A and B,
$\underset{\rightarrow}{U}_m$ is the mean velocity along the path between A and B,
and θ is the angle between $\underset{\rightarrow}{U}_m$ and the line between A and B.

To compensate for changes in the sound velocity, the average travel time $T_A \simeq T_B = T$ is simultaneously measured and a computation of

$$\underline{\Delta \tau} \simeq \frac{\Delta t}{(L/C)^2} = k_1 |\underset{\rightarrow}{U}_m| \cos \theta, \qquad (3)$$

where k_1 is a constant, is carried out for each ultrasonic burst. To get a continuous output, $\Delta T/T^2$ is converted to an analogue or digital signal which is updated in an output-storing circuit for each new ultrasonic burst. The repetition frequency is chosen to correspond to the needed bandwidth.

In the sing-around system bursts of ultrasonic signals are first sent from A to B. The reception of a leading edge at B causes the generation of a new burst of signals in the same direction. Thus an 'upstream' frequency $f_{AB} = 1/T_{AB}$ can be defined. Similarly a corresponding 'downstream' frequency $f_{BA} = 1/T_{BA}$ is determined by sending signals in the opposite direction, from B to A. Finally

$$f_{AB} - f_{BA} = k_2 \; |\underset{\rightarrow}{U}_m| \cos \theta \qquad (4)$$

Is calculated. Thus in the sing-around system, C cancels from the equation with no further calculations.

In the phase difference system continuous ultrasonic signals of frequency f_A are transmitted from A to B while similar signals of frequency f_B are simultaneously sent from B to A. By means of several possible signal processing methods the phase difference $\phi_B - \phi_A$ can be transformed into a signal proportional to

$$\frac{k_3}{C^2} |\underset{\rightarrow}{U}_m| \cos \theta$$

where k_3 is a constant.

For about 10 years the author has tried to develope current meters based on the havel time difference principle. When designing a current sensor, several properties are disirable. The most important of them are

- stable, low noise output signals
- high sensitivity
- wide dynamic range
- good linearity
- good long term zero point stability
- low power consumption
- small dimensions
- ease of operation
- mechanical strength

Current meters based on Equations 1 to 3 can now offer a noise level corresponding to less than 1 mm s^{-1}, sensitivity better than 1 mm s^{-1}, dynamic range from 0 to ±3 m s^{-1}, linearity better than 1%, a zero point long term stability better than 5 mm s^{-1} per month, a continuous power consumption from 50 to 500 mW, a bandwidth inexcess of 50 Hz, and the possibility of measuring 3 current components at the same time.

Instrument design

An acoustic current meter consists of a current sensor (probes) in combination with electronic circuits, batteries, and mechanical protection for the parts that cannot be directly exposed to the sea.

Acoustic design

Piezoelectric transducer elements are available in several frequencies and dimensions. A typical tranducer could be resonant at 3.5 MHz and have a diameter of 10 mm. Typical thickness is 0.5 to 1 mm.

The designer usually tries to generate an acoustic beam with as high intensity as possible at the receiving end. In the leading edge type current meter non-perfect impedance matching between transducers and the surroundings causes a ringing which may modulate into the signal baseline. This ringing must be completely damped out before the received signal appears. Sufficient damping is normally obtained by backing the transducer with an absorbent material of characteristic impedance Z_B as close to the transducer impedance as possible. The transducers must always be protected by acoustic windows in the probe. The ideal protecting material must be strong enough to withstand the expected maximum ambient water pressutre without noticeable deformation and have a characteristic impedance as close to

$$Z_P = (Z_1 Z_W)^{\frac{1}{2}} \qquad (5)$$

as possible. Z_1 is the characteristic impedance of the transducer material, and Z_W that of the surrounding fluid. The thickness of the protecting material should ideally be chosen according to the formula

$$t_p = (2n - 1) \frac{\gamma}{4} \qquad (6)$$

where n is an integer and γ is the wavelength in the protecting material. Good results have been obtained by using protecting discs of ceramic materials which are both strong, non-absorbing, and have a characteristic impedance close to the optimum value of 6.6×10^6 m^{-2} s^{-1}. The rules given for the design of pulsing type transducers also apply to continuous signal instruments.

Hydrodynamic probe design

The probes must emit acoustic signals in the desired direction, protect the piezoelectric transducers, and have a physical shape that combines mechanical strength with a minium of interference of the flow field. Good mechanical probe design is the most difficult part of making good current meters.

A basic probe design, shown in Fig. 2a, is to mount the piezoelectric transducers in cylindrical prongs which are encapsulated in an acoustic window made from glass, ceramic or similar material. The wake behind the leading transducer may affect the velocity field and hence contribute to errors.

It has been found that the flow field along the acoustic path is virtually undisturbed if the current direction deviates from the acoustic path direction by more than about 25° (for the case of 15 mm thick prongs with L≃15 cm). This may be satisfied in four ways:

1) by using vertically-mounted prongs combined with a vane that makes the sound paths cross the current direction at an angle of approximately 45° (Fig.2a);

2) by using a reflector to obtain a 'V'-shaped acoustic path (Fig. 2b);

3) by using three pairs of transducers with acoustic path crossing each other at an angle of 60^o, sorting out the signals from the wake-distrubed path (Fig. 2c) during subsequent signal processing; or

4) by reducing the d/L ratio, either by decrasing the probe diameter d or by incrasing L until the disturbed part of the path length can be neglected.

Electronic design

The electronic circuits in acoustic current meters must generate the acoustic signals and convert the resulting travel time, frequency, or phase difference into an equivalent electrical signal in a suitable format for further processing or recording. Since most current meters operate on batteries, it is also important to keep power consumption low.

The basic problem with acoustic measurement is the very small time differences that must be detected. From Fig. 1, assuming $L=10$ cm, $C = 1500 \text{ m s}^{-1}$, and $|\underset{\rightarrow}{U}_m| = 1 \text{ mm s}^{-1}$, equation 2 gives

$$\Delta t \simeq 10^{-10} \text{ s.}$$

To get stable and low noise signals in the order of 1 mm s^{-1}, two basic problems must be solved:

1) precise detection of the moment when a specified part of the received signals arrive,

2) elimination of apparent changes in Δt due to drift in the electronic components.

Fig.3 illustrates the first problem. The figure shows the situation when the received signals arrive at A and B at the same time (the current is zero). The time-measuring circuits are adjusted to start when the signal's leading edges exceed

V_0. V_A and V_B are the peak amplitudes of the received signals. Assuming sinusoidal signals, the apparent travel time difference is:

$$\Delta t = \frac{1}{2\pi f} \left(\sin^{-1} \frac{V_0}{V_A} - \sin^{-1} \frac{V_0}{V_B}\right) \qquad (7)$$

With a typical ultrasonic frequency of 4 MHz, a resolution of 1 mm s^{-1} requires a stability in the phase angle detection of at least one-tenth of a degree. In travel time difference current meters this is solved by setting V_0 as close to zero as possible, and by making both V_A and V_B of equal and as high as possible amplitude. In continuous type current meters the best way is to beat the received signal with a stable oscillator and to detect the phase changes in the difference frequency.

Detecting time differences in the order of 10^{-10} s with electronic components that may have rise times in the order of several nanoseconds and in addition may vary by several nanoseconds with changes in temperature represents a basic problem. It can be satisfactorily solved by comparing the measured Δt with a known Δt_0 reference (Gytre 1976).

The power needed to run an acoustic current meter is a function of sampling rate, number of channels, and its integration into a recording system. Presently the travel time difference current meter has a power consumtion around 4-500 mW. New announced components will soon bring the power demand down to appr. 200 mW or less.

Use of the sensor in an oceanographic data acquisition system

Interesting as the design of a pure current sensor may be, the extensive use of it demands its integration into a data acquisition system where the outputs from the current sensors are combined with signals from other sensors like temperature salinity, pressure, direction etc.

The sensor signals must be standardised to within say ± 2.5 V of analogue range, multiplexed into an A/D-converter and stored on digital tape at programmable time intervals. After the observation period has ended the data tapes need a readout unit and computer facilities.

The design of a field usable data acquisition system also demands that great care is taken in the design of mechanical details like probes pressure tube, way of mooring, protection against mechanical shocks and protections against corrosion. An important feature in the design is also possible feedback to the user after the instrument has been closed for use in the sea. Before putting the instrument into the sea, it should therefore be possible to get simple signals from the instrument which tell whether the instrument probably functions or not.

Fig. 4 shows the basic underwater building blocks of such a data acquisition system which has been developed in cooperation with the Chr. Michelsen Institute, Bergen. The left unit is a combined battery packet and tape recorder section. The tape recorder is a digital cassette type which can store appr. 2.2 million bits. On top of the left unit is an optical data feed-through plug which emits short flashes of light each time data are recorded on the cassette. The optical signals come from two sources. One emits each time a logical '1' is recorded and the other emits each time a logical '0'is recorded.

Flashing from the optical plug tells the user that the instrument timer works. If the flashing from the '1' and '0' - sources seems to be evenly distributed, also the complete instrument probably works well. Excact information on the data quality can be readily obtained by connecting an optical decorder combined with a printer or a display to the optical plug.

The middle unit contains the sensor part of the system with the neccessary electronics needed to shape the sensor signals. The middle unit also includes a programming unit which makes possible both single and burst samplings of all sensors at variable intervals from 1 to 256 minutes.

The pressure tube is shown to the right. The tube diameter has been made identical to that of all Aanderaa Instruments current meter (=4½") to enable use of the same mooring equipment if so wanted.

Readout

To read the tapes several readout units have been made. The most sophisticated readout unit continuously shows the data on digital displays during readout, presents them on analogue output terminals and also transfer them to 9 track IBM computer compatible tape.

Results with the complete system

The complete assembled instruments equipped with a 3 axis current sensor is shown on Fig. 5 . In addition to the first instrument which has been used by the author, Chr.Michelsen Institute has made several duplicates. The duplicates are now in general use at scientific institutions both in Norway and abroad. In particular the Continental Shelf Institute of Trondheim has put much effort into the evaluation of the instrument performance, both close to the bottom and close to the surface.

Calibration

Fig.6 shows results from a calibration of 3 instruments owned by IKU at the towing tank of SMHI at Norrköping. The calibration was done by moving the instruments in the velocity range from 0 ± 50 cm both in upright and in inclined positions, continuously printing the signals from the optical plug, which are numbers from 0 - 4095. 0 corresponds to velocity components of appr. -2.5 m/s and 4095 to velocity components of + 2.5 m/s. (Zero is ideally at 2048, but all instruments have a permanent ofset of a few bit.)

The regression analysis from the calibration show that the reflector based current sensor has a very close to perfect linearity in the range 0 - 50 cm/s, with a recording resolution of between 1 and 2 mm/s.

Practical use

The instrument has been used in the field for about a year. After having modified some details in electronics and in the tape recorder driver, the instrument seems to collect data very reliably.

Fig.7 shows the results from a measurement at Tromsöflaket made by the IKU. In this experiment an Aanderaa current meter was used for reference. In order to test its ability to work under fouling conditions, the author has used the current meter at 2 meters depth at Svanøy, close to a fish farm. The results showed that the instrument was unharmed by the vegetation which fixed to the probes.

Computer processing

By transferring the cassette data to a 9 track IBM-tape, the data become available for a general computer processing.

Fig.8 shows a randomly selected page from Audunson et al. 1979 showing typical computer processed information from the data acquisition system.

Concluding remarks

The ultrasonic current sensor has now been developed to a level where it can be generally used. Probes can be designed to physical shapes that are convenient for work close to the bottom, close to the surface or in intermediate layers. The sensor is capable of measuring current speeds from less than 1 mm/s to several meters per second with a high degree of stability.

Pending work, not yet published, shows that it is also possible to design 1 MHz ultrasonic transducers for use in air - thus enabling the standard current meter electronics to measure wind velocities as well. As the sound velocity c in air is 5 times less than in water, an improvement of 25 in theshold detection is automatically obtained. Wind velocities from 1/25 mm/s and up can thus be measured. The author plans to exploit this in a planned air/sea interaction instrument.

The data acquisition system described probably represents a fianl stage in the tape recorder technology. During the next five years solid state memories will offer a data storing capasity which will become comparable to that of the tape recorders, enabling the design of very versatile instruments of dimensions no greater than the one described by Gytre 1979.

References

Gytre, T. 1976. The use of a high sensitivity ultrasonic current meter in an oceanographic data acquisition system. The Radio and Electronic Engineer, 46:617-623.

Audunson, T. et al. 1979. Bunnströmsmålinger på Tromsöflaket september 1978, Datarapport. IKU-report no P-080/1/1979.

Gytre, T. 1979. A simple field instrument for measuring and recording up to 16 observations of current speed and direction. ICES C.M. 1979/C:53.

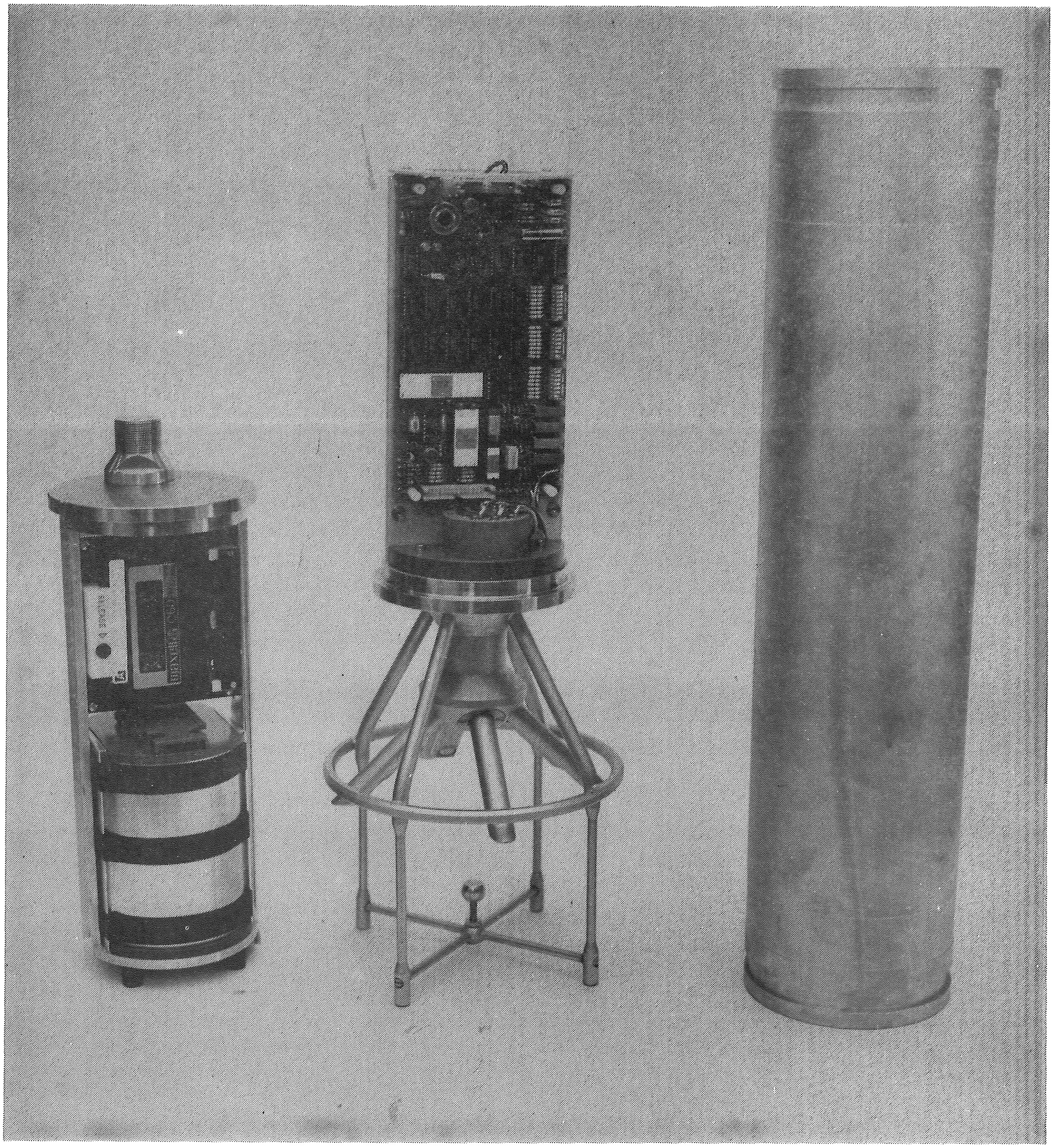

Fig. 4. Main parts of the data acquisition system. From left: Recorder and battery, sensor and programming electronics, and pressure tube.

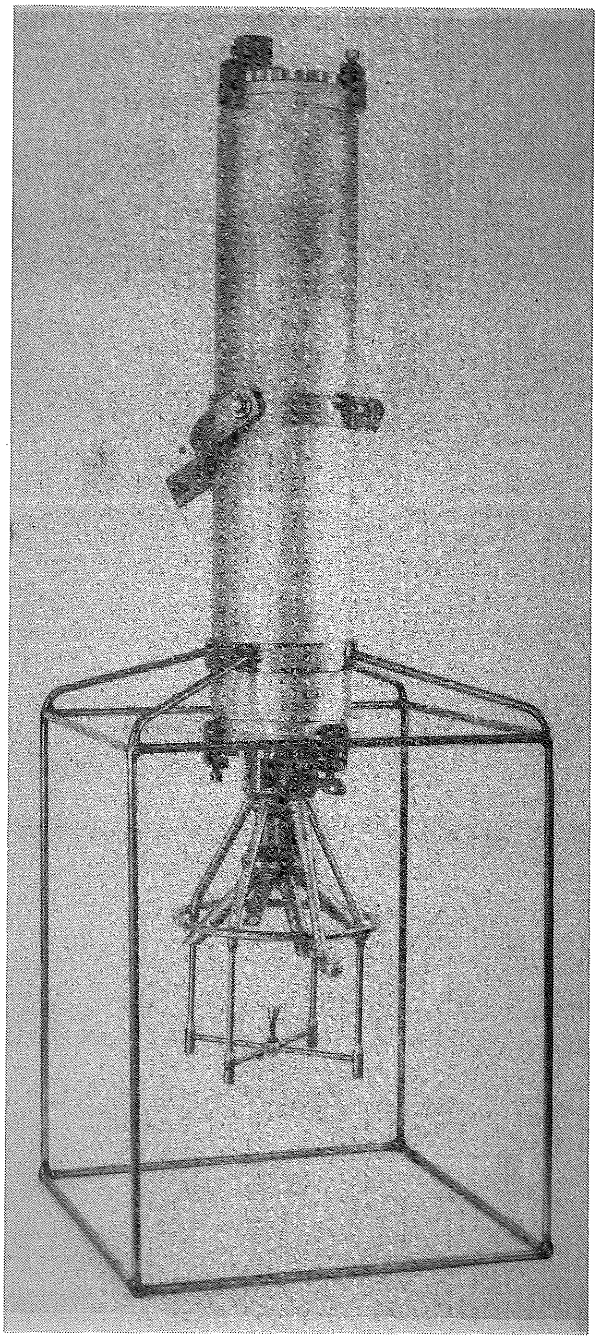

Fig. 5. Complete assembled system with protection for the 3 axis current probe.

Måler nr.	Akse+	Regresjons-koeffisient	Helning*	Nullpunkt	Antall punkter
	x	0.99968	0.10797	2041.1	9
1	y	0.99964	0.10529	2053.8	9
	z	0.99527	0.15887	2052.4	6
	x	0.99973	0.17823	2053.6	10
2	y	0.99967	0.17576	2057.0	8
	z	0.99649	0.18635	2005.5	3
	x	0.99976	0.18221	2051.4	8
3	y	0.99952	0.17850	2046.2	9
	z	0.99990	0.26839	2051.9	3

* cm/sek pr. digitalverdi

\+ lokal z-akse er den vertikale akse.

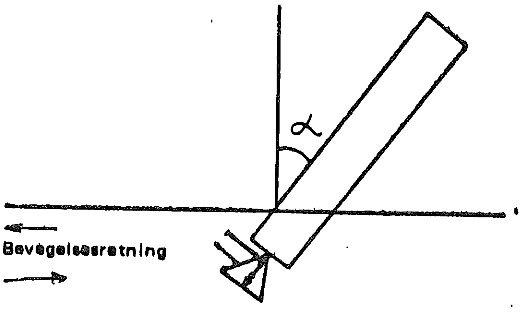

Fig. 6. Calibration of 3 ultrasonic current meters owned by IKU. Vertical axis was calibrated by tilting the instrument an angle and measuring a component of the current speed. As all signals are multiplexed through the same electronics in sequence small differences in the "Helning" (cm/s per bit) most probably is caused from a slight misalignment referred to the towing direction. The instruments were towed in the range 0 - ± 50 cm/s.

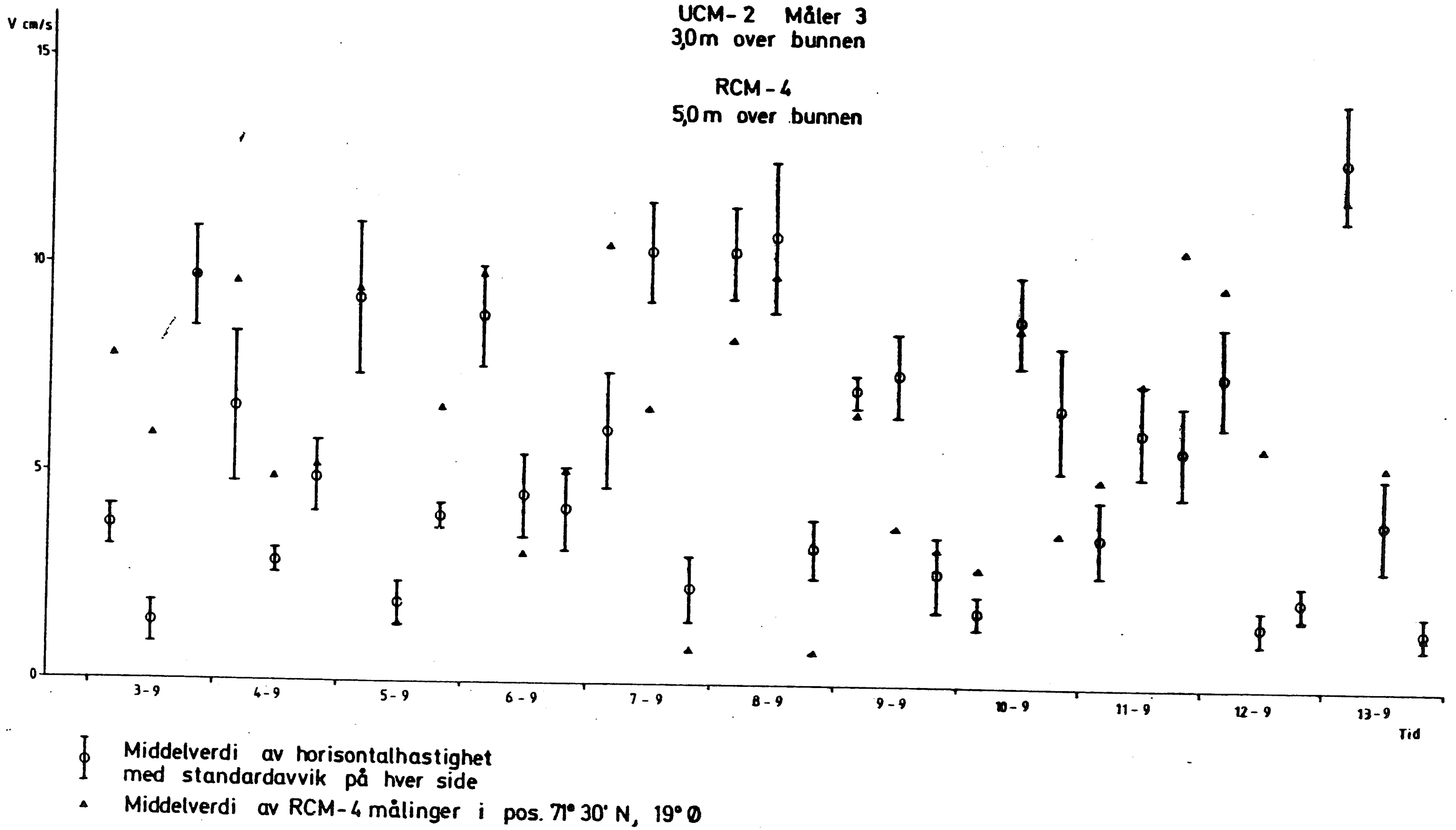

Fig. 7. Ultrasonically measured mean horizontal velocities at 3 meters above the ocean floor of Tromsöflaket Sept. 3 - 13 1978 compared with recordings of an Aanderaa RCM-4 (measured by IKU) at 5 meters.

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TABELL C35:  TROMSOEFLAKET - 1978, MAALER NR. 3, 3.00 M OVER BUNNEN
*********************************************************************
PERIODE NR.  19:   START   78- 9- 8 KL. 18.40
**********************************************

                    VN        VE        VV        VH        VA        AH        AV        TEMP.
   MIDDEL  (S):   -2.680    1.870     0.179     3.319     3.482                         9.003
   ST.AVVIK   :    0.674    0.637     0.998     0.723     0.666                         0.008
   MIDDEL  (V):                                 3.268     3.273   145.098     3.137


***FORDELINGER, REGISTRERINGSPERIODE NR.   19:

   FORDELINGER MHP. RETNING I HORISONTALPLANET:

   NR.     ...SEKTOR...     ANTALL   VH-MID   VH-MAX   REL.FLUX   VA-MID   VA-MAX   REL.FLUX
    1       0.0    15.0       0       0.0      0.0       0.0       0.0      0.0       0.0
    2      15.0    30.0       0       0.0      0.0       0.0       0.0      0.0       0.0
    3      30.0    45.0       0       0.0      0.0       0.0       0.0      0.0       0.0
    4      45.0    60.0       0       0.0      0.0       0.0       0.0      0.0       0.0
    5      60.0    75.0       0       0.0      0.0       0.0       0.0      0.0       0.0
    6      75.0    90.0       0       0.0      0.0       0.0       0.0      0.0       0.0
    7      90.0   105.0       0       0.0      0.0       0.0       0.0      0.0       0.0
    8     105.0   120.0       1       2.64     2.64      0.10      3.10     3.10      0.11
    9     120.0   135.0     130       3.37     5.13     16.48      3.53     5.25     16.46
   10     135.0   150.0     396       3.29     5.32     49.14      3.47     5.48     49.38
   11     150.0   165.0     255       3.39     4.93     32.56      3.53     5.04     32.29
   12     165.0   180.0      18       2.53     4.20      1.71      2.73     4.42      1.77
   13     180.0   195.0       0       0.0      0.0       0.0       0.0      0.0       0.0
   14     195.0   210.0       0       0.0      0.0       0.0       0.0      0.0       0.0
   15     210.0   225.0       0       0.0      0.0       0.0       0.0      0.0       0.0
   16     225.0   240.0       0       0.0      0.0       0.0       0.0      0.0       0.0
   17     240.0   255.0       0       0.0      0.0       0.0       0.0      0.0       0.0
   18     255.0   270.0       0       0.0      0.0       0.0       0.0      0.0       0.0
   19     270.0   285.0       0       0.0      0.0       0.0       0.0      0.0       0.0
   20     285.0   300.0       0       0.0      0.0       0.0       0.0      0.0       0.0
   21     300.0   315.0       0       0.0      0.0       0.0       0.0      0.0       0.0
   22     315.0   330.0       0       0.0      0.0       0.0       0.0      0.0       0.0
   23     330.0   345.0       0       0.0      0.0       0.0       0.0      0.0       0.0
   24     345.0   360.0       0       0.0      0.0       0.0       0.0      0.0       0.0
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Fig. 8a.   Excample on computed horizontal current velocities.

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********************************************************************************
TABELL C36:  TROMSOEFLAKET - 1978, MAALER NR. 3, 3.00 M OVER BUNNEN
********************************************************************************
***PERIODE NR.    19


   FORDELINGER MHP. VINKEL MED HORISONTALPLANET:

   NR.      ...VINKEL...        ANTALL     VA-MID    VA-MAX    REL.FLUX
    1      -90.0    -80.0          0         0.0       0.0        0.0
    2      -80.0    -70.0          0         0.0       0.0        0.0
    3      -70.0    -60.0          0         0.0       0.0        0.0
    4      -60.0    -50.0          0         0.0       0.0        0.0
    5      -50.0    -40.0          1         2.96      2.96       0.11
    6      -40.0    -30.0         30         3.14      3.72       3.38
    7      -30.0    -20.0         56         3.21      4.20       6.46
    8      -20.0    -10.0        109         3.34      4.74      13.05
    9      -10.0      0.0        154         3.53      4.88      19.51
   10        0.0     10.0        173         3.67      5.11      22.81
   11       10.0     20.0        134         3.84      5.48      18.48
   12       20.0     30.0         79         3.18      5.18       9.03
   13       30.0     40.0         44         3.08      3.92       4.86
   14       40.0     50.0         19         3.25      4.36       2.22
   15       50.0     60.0          1         2.34      2.34       0.08
   16       60.0     70.0          0         0.0       0.0        0.0
   17       70.0     80.0          0         0.0       0.0        0.0
   18       80.0     90.0          0         0.0       0.0        0.0


   HASTIGHETSFORDELINGER:

   NR.     ..INTERVALL.      ...ANTALL REGISTRERINGER...
                                 VH         VV         VA
    1       0.0     1.0           0        510          0
    2       1.0     2.0          19        265          8
    3       2.0     3.0         253         24        178
    4       3.0     4.0         384          1        443
    5       4.0     5.0         140          0        163
    6       5.0     6.0           4          0          8
    7       6.0     7.0           0          0          0
    8       7.0     8.0           0          0          0
    9       8.0     9.0           0          0          0
   10       9.0    10.0           0          0          0
   11      10.0    11.0           0          0          0
   12      11.0    12.0           0          0          0
   13      12.0    13.0           0          0          0
   14      13.0    14.0           0          0          0
   15      14.0    15.0           0          0          0
   16      15.0    16.0           0          0          0
   17      16.0    17.0           0          0          0
   18      17.0    18.0           0          0          0
   19      18.0    19.0           0          0          0
   20      19.0    20.0           0          0          0
   21      20.0    21.0           0          0          0
   22      21.0    22.0           0          0          0
   23      22.0    23.0           0          0          0
   24      23.0    24.0           0          0          0
   25      24.0    25.0           0          0          0
   26      ENDA STOERRE           0          0          0
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Fig. 8b. Excample on computed vertical velocities 3 meters above botton floor.

C.M. 1979/C:52
Fig. 1 - 3.
(T. Gytre)

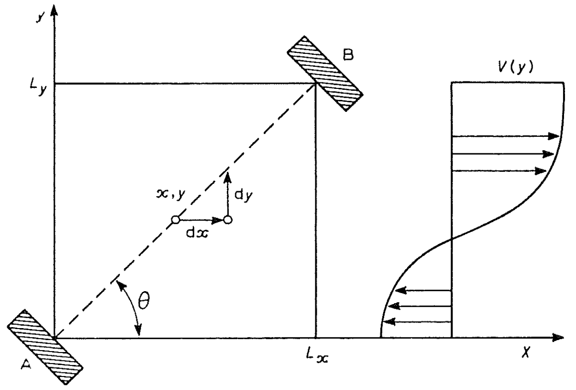
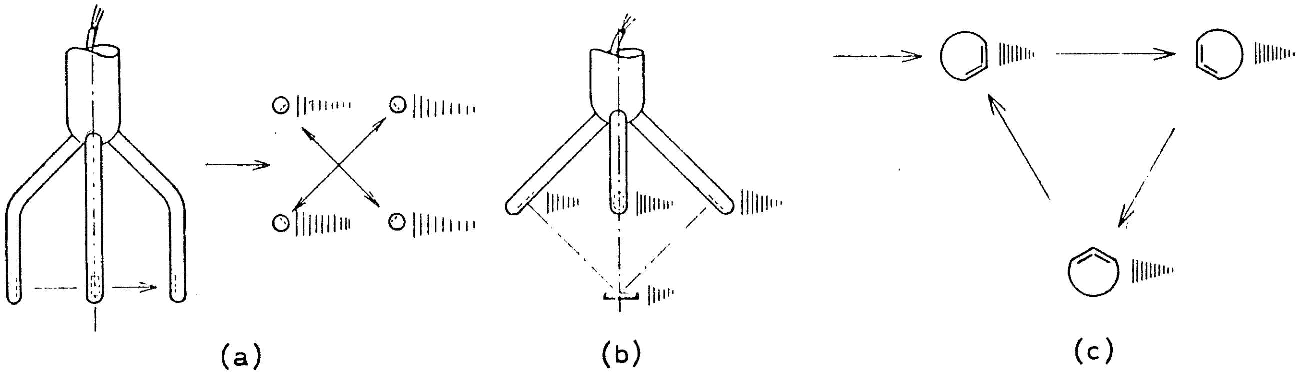


Fig. 1. Travel time difference principle.



(a) By orientating the acoustic path away from the current direction.

(b) By using a reflector.

(c) By using 3 paths and neglecting signal from the one that is disturbed.

Fig. 2. Principles for reducing effect of circulation and separation behind the transducers.

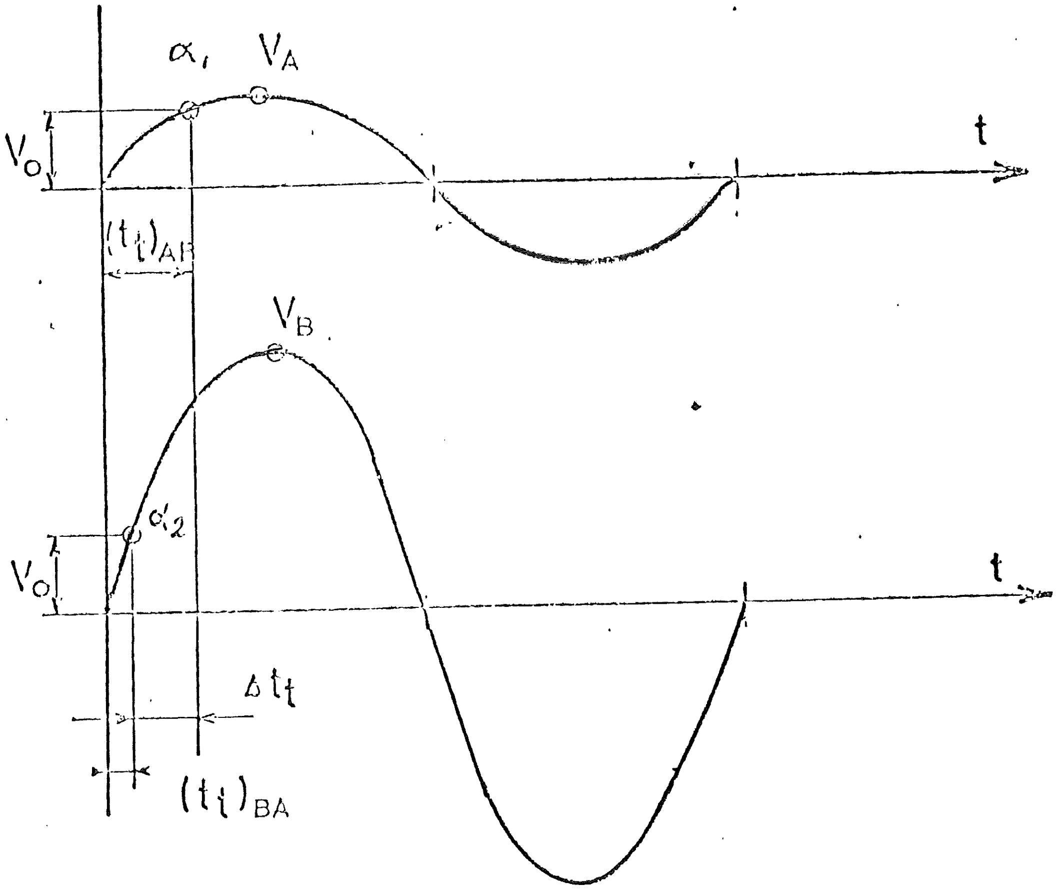


Fig. 3. Effect of non - even received acoustic signals.