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LIMITATIONS ON THE PERFORMANCE OF DOPPLER SONAR SYSTEMS FOR VEHICLE VELOCITY ESTIMATION

J G Boulton

Cambridge Consultants Limited

1. Introduction

The performance of a doppler sonar system to be used for vehicle velocity estimation is limited by the nature of the environment in which it must operate. For example, variations in the velocity of sound through the insonified water column, and changes in sea bed scattering strength with angle, lead to inaccuracies in the estimation of vehicle velocity. The factors affecting system performance, and their relative importance will be considered in detail.

First, consideration will be given to effects which limit the coherence time, and related problems will be discussed. Secondly the importance of variations in the velocity of sound with position and time will be investigated, and finally noise sources, and pitch and roll problems will be considered.

In order to put the problem into perspective, the operational modes of a doppler sonar will next be described.

2. Operational Modes of a Doppler Sonar

A narrow conical sonar beam is directed at an angle to the ship's velocity as shown in Figure 1.

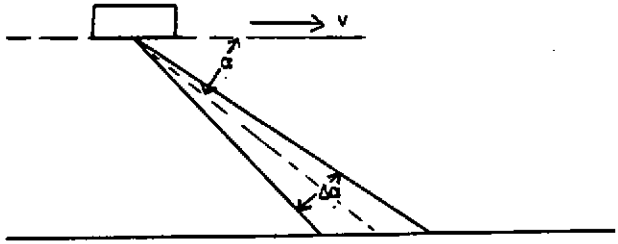

Figure 1

Short pulses of acoustic energy of a single frequency are transmitted. These are scattered by either the sea bed or the water itself and the return pulses are detected in general by the same transducer. The frequency of the return pulse is measured. The ship velocity, v, is given by

$$v = \frac{\Delta f \, c}{f \, 2 \cos \alpha} \qquad (1)$$

where

Δf is the change in signal frequency on scattering (i.e. the doppler shift),

f is the transmitted frequency,

c is the velocity of sound,

and α is the angle of inclination of the beam.

Providing the range is not too great, the strongest signal obtained is that from the sea bed. If the bottom return is used for velocity estimation, the system is said to operate in bottom track mode. In deep water the bottom return signal is weak and is lost in noise. In that case many doppler sonar system switch to water track mode. The signal backscattered from water ten to twenty metres below the ship is chosen by range gating and processed to give the ship's velocity relative to the chosen surface of water.

3. Coherence Length and Fluctuation Error and Calibration Error

The coherence length of a signal is inversely proportional to its bandwidth. A return signal of finite bandwidth will restrict the accuracy with which the doppler shift, Δf, can be detected. The finite bandwidth may be due to three principle causes. First, the length of the transmitted signal pulses, being finite, will cause a spread in frequency. For a pulse length of 20 ms, for example, the associated frequency spread is 50 Hz. If this is the dominant effect, it can be compensated for as the nature of the spectrum is then a known function of the transmitted signal.

Secondly, changes in the refractive index with position give rise to variations in path length experienced by different longitudinal sections of the beam, henceforth referred to as beam elements. The result is that the beam elements are phase shifted with respect to each other and interference effects will occur as they recombine at the receiver. This leads to a broadening of the return frequency. The spectral density function due to such broadening has been measured by Coates (1981) at 600 kHz, and the highest spectral components was found to be 0.5 Hz, consistent with a coherence time of two seconds. Other evidence (Farmer and Crawford, 1983) obtained at 100 kHz, suggest a value of the same order.

The final effect leading to frequency broadening occurs because the sonar beam is finite in width. Each beam element subtends a slightly different angle with the sea bed, and is frequency shifted by an amount varying in proportion to cos γ, where γ can vary between α and $\alpha + \Delta\alpha$, where α is the angle of inclination and $\Delta\alpha$ is the beamwidth, as shown in Figure 1. The spread in frequency $\delta(\Delta f)$ is given by

$$\delta(\Delta f) = \frac{2 f v \sin \alpha \Delta\alpha}{c} \qquad (2)$$

For a frequency of 500 kHz, an angle of inclination of 60^0, a beamwidth of 10^0 and a velocity of 1 ms^{-1}, the spread in frequency is 70 Hz. The spread in frequency due to the finite beamwidth will, in fact, dominate the other two effects, other than at very low velocities.

The spread in doppler frequency leads to three major effects. First, it limits the coherence time, that is, it limits the time over which phase information within the return signal is related to previous phase information. As this coherence time, 14 ms in the example, is short relative to a typical ping return time (53 ms for 20 m depth, 60° angle of inclination), coherent pulse processing, whereby phase information is compared from ping to ping to estimate frequency, cannot be used. Incoherent pulse processing, whereby a separate frequency estimate is made for each separate return, must be adopted in most operational situations.

Secondly, the spread in frequency leads to fluctuation error. This can be explained as follows. The sea bed, or the water volume, in water track mode, approximates an array of point scatterers. Each beam element will intersect a different set of scatterers. The scattering strengths of these point sources, and the phase shifts they cause, will vary in a random fashion. Thus some elements will return a strong signal and others a weak signal, in any particular return pulse, due in part to amplitude variations, and in part to interference effects. As the frequency shift of each beam element depends on its angle of inclination, and thus on its position in the footprint, certain frequencies will be enhanced in a particular return, and some suppressed. Thus the centre of gravity of a return pulse in frequency space, is not, as expected, at the centre frequency, but will fluctuate around the centre frequency from ping to ping, depending on the particular characteristics of the ground covered by the footprint at a given time.

Kayton and Fried (1969) show that the standard deviation of the velocity estimates relative to the mean velocity due to fluctuation error, ϵ_f, is given by

$$\epsilon_f = \frac{1}{\Delta f} \; \frac{\delta(\Delta f)}{2 \quad n^{\frac{1}{2}}} \qquad (3)$$

where n is the number of independent measurements, and is equal to $\tau \cdot \delta(\Delta f)/2$, where τ is the pulse length.

For the values previously quoted, and for a pulse length of 20 ms ϵ_f is equal to 15% for one ping. The error, a zero mean error, is reduced, however, by averaging velocity estimates over several pings. It can be reduced to 0.5% by averaging over 1000 pings, in this case.

The above example shows that, providing a sufficient number of estimates can be averaged, errors due to fluctuation error are small. The third effect related to the finite beamwidth is potentially more serious, however. This is known as calibration error, and occurs only in bottom track mode. Its occurrence is due to the fact that backscattering strength from the sea bed varies as a function of angle, and, furthermore, the nature of this change is dependent on sea bed type. Thus each beam element, intersecting the sea bed at a particular angle, and gaining a particular doppler shift, will have a different return strength with respect to neighbouring elements. As, in general, scattering strength increases with increasing angle of inclination, and thus decreasing doppler shift, the total return signal will be biased by the lower frequency returns. That is, the doppler spectrum will be skewed towards the lower frequencies, and the system will tend to underestimate velocity. Correction for this bias error is non trivial as, even if the degree of change in scattering strength with angle were known for a given sea bed type, the particular sea bed type over which a ship is travelling is not known.

The size of the error is hard to estimate, due to the lack of information regarding scattering strength changes with angle. What information is available (Urick, 1967, Smailes, 1978) suggests that, over a 10^0 beamwidth, the scattering strength is unlikely to change by more than a factor of three. Assuming this change is linear with angle, and assuming the incident beam has a Gaussian profile, then the position of the centre of gravity within the return beam will be modified by 1^0. For the values of frequency, speed etc used previously, there results a bias error of 3% in the velocity estimate, which is clearly not reduced by any averaging techniques.

In conclusion, it can be seen that the finite beamwidth of doppler sonar systems results in the use of incoherent pulse processing, and leads to fluctuation errors in velocity estimates. Furthermore, in bottom track mode, the finite beamwidth, together with changes in sea bed scattering strength with angle, lead to a bias error in velocity measurement, which is significant and cannot easily be corrected from.

4. Effects due to Variations in Sound Velocity with Position and Time

4.1 Refraction

Variations in water temperature, salinity and density cause variations in sound velocity with depth and position. As sound travels through the medium, it is refracted as it passes through these regions of varying refractive index. This causes the beam path to deviate from a straight line. If the angle of inclination of the beam is modified at the point where the beam intersects the seafloor, or sample water volume, then the velocity estimate will be inaccurate by an amount proportional to sin $\alpha\delta\alpha$ where $\delta\alpha$ is the cumulative deviation in α at the point of intersection (see Fig 2).

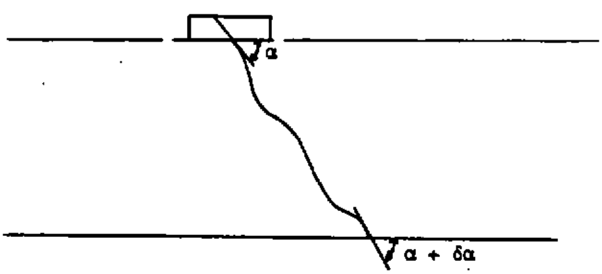

Figure 2

If the effect is random, that is, as the vehicle moves, the mean value of $\delta\alpha$ is zero, then the error will be reduced by $\sqrt{n}$, if n frequency estimates are averaged together. If the effect has a bias, that is, the sound velocity profile is stationary over a region of sea, so that the angle of inclination has a mean value greater or smaller than α, then a bias error is inherent in the system.

In the thermocline, the variation of sound velocity with depth is great, and furthermore is stationary. Typical values of $\partial c/\partial z$ where z is the depth are of the order of 0.1 s^{-1}. The variation in angle of inclination over 200 m depth for an initial angle of inclination of 60^0 is equal to 0.4^0. This gives an error in the velocity estimate of 1.2%. Thus it can be seen that if such refraction effects are not accounted for, a significant bias error results. The effect is less likely to be significant in shallow coastal waters, however, as a value for $\partial c/\partial z$ will be less systematic. Furthermore, in deep water, the system is likely to operate in water track mode, where the depth of water for which backscattered signals are processed is of the order of 10 - 20 m. Such an effect would be negligible in that case.

4.2 Fluctuations due to Variations in Sound Velocity

Fluctuations due to variations in sound velocity between the paths traversed by separate elements of the beam have already been shown, in section 2.2.2, to lead to a spread in the return frequency.

A further effect of importance with long range doppler sonars is due to a time change of sound velocity along the acoustic path during the return time of a single pulse. Such a time change, due to current, or due to an advection of the sound velocity field by internal waves, has the effect that the leading edge of the pulse travels with a different mean velocity than the trailing edge. The pulse is thus gradually distorted, and its frequency altered. This can be a significant effect in the thermocline, where depth variations in sound velocity are great.

The magnitude of the effect can be estimated from the expression for the phase of the return pulse, ϕ, relative to its phase as it was emitted.

$$\phi = \frac{2\pi f . 2\underline{r}}{\underline{c}} \qquad (4)$$

where $\underline{r}$ is the range

$\underline{c}$ is the mean sound velocity in the direction of the beam.

Thus

$$\frac{\partial\phi}{\partial t} = \frac{2\omega}{c^2}\left(cv - r\frac{\partial c}{\partial t}\right) \qquad (5)$$

where $v = \frac{\partial r}{\partial t}$, $\omega = 2\pi f$

Now,

$$\frac{\partial c}{\partial t} = \frac{u\,\partial c}{\partial z}, \qquad (6)$$

where u is the vertical water velocity,

$\frac{\partial c}{\partial z}$ is the gradient of sound velocity in the vertical direction.

A typical value of $\frac{\partial c}{\partial z}$ is $0.1\ s^{-1}$.

Thus, for a range of 200 m, and a vertical water velocity of $1\ ms^{-1}$, $\frac{r}{c}\,u\,\frac{\partial c}{\partial z}$ is equal to $1.3 \times 10^{-2}\ ms^{-1}$. Thus, for a ship velocity of $1\ ms^{-1}$, an error of 1.3% is introduced into the measure of rate of change of phase, and thus into the estimated velocity, for a change of velocity with depth of $0.1\ s^{-1}$, and a vertical water velocity of 1 ms^{-1}. Such an effect is clearly significant in long range, deep water operations, but, again, will be less important in shallow water, and negligible in water track mode.

4.3 The Importance of an Accurate Knowledge of Sound Velocity

As can be seen from equation (1), in order to obtain an estimate of v from a measurement of the doppler shift, Δf, the value of the sound velocity, c, must be known. The value of the velocity of sound which determines the value of Δf is that local to the ship which can thus be measured and incorporated within equation (1).

Changes in the velocity of sound within the water volume do not represent an error in this respect.

4.4 Conclusion

Effects due to variations in sound velocity in cases where the velocity of sound changes with depth in a marked way can lead to bias errors of the order of 1%. These changes do not affect the value of the velocity of sound required in equation (1), however. The value required here is that local to the ship. This can either be measured or compensated for, and as such does not represent an insurmountable problem.

5. Signal to Noise Ratio

If noise, either background noise or system noise is high with respect to the return signal strength, then the accuracy of estimation of the return frequency will be degraded. Background noise is caused by traffic within or upon the ocean, by life within the ocean, for example, snapping shrimps, by ocean waves, and, at high frequencies, by Johnson noise. Flow noise due to the ship itself can cause problems. The noise level will set the operational range of a system for a given power level, although improvements can be made using signal processing techniques. For example, noise is in general broadband, so that filtering of the return signal to eliminate all frequencies other than those around the expected return frequency, will eliminate much of the noise.

A further problem is caused by air bubbles, in particular those caused by ship's wakes. These often exist for a significant time at significant depths, and can cause spurious signal returns which can be interpreted by the sonar as sea bed returns, or will swamp the water volume reverberation of interest in water track mode.

6. Effects Due to Movement of Ship or Platform

Pitch, roll and heave of the ship will introduce velocity components along the beam direction, and will thus cause errors in estimation of ship velocity. That is, the doppler system measures velocity in the ship's coordinate system. If a global velocity estimate is required, then the effects of pitch, roll and heave must be corrected for. Pitch and roll can be measured by accelerometers and their effects thus taken into account.

A further consideration is that large values of pitch and roll will affect the range of a signal, and will thus affect the strength of the signal return and its position in time. An ideal system would thus detect the degree of pitch and roll and then adaptively correct the gain of the system and the position of the observation window, if range gating were used, in order to optimise system operation.

A simpler solution in order to minimise the effects of pitch, roll and heave is to use three or four beams in a Janus arrangement. One such arrangement is to have one beam pointing fore, one aft, and two in a similar arrangement perpendicular to the ship or platform. Consider the fore and aft beams, as shown in Fig 3.

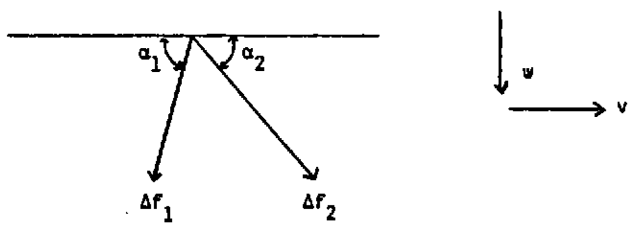

Figure 3

Consider that there is a horizontal velocity, v and a vertical velocity, w. The frequency shift, Δf_1, is proportional to $w \sin\alpha_1 - v \cos\alpha_1$, that of Δf_2 proportional to $w \sin\alpha_2 + v \cos\alpha_2$. Thus, if

$$\alpha_1 = \alpha_2, \tag{7}$$

then $$\Delta f_1 - \Delta f_2 = 2\, v \cos\alpha \,.\, \frac{2f}{c} \tag{8}$$

and $$\Delta f_1 + \Delta f_2 = 2\, w \sin\alpha \,.\, \frac{2f}{c} \tag{9}$$

Thus, if the ship is horizontal, and is known, v and w can be calculated exactly. If a certain degree of pitch and roll exists, and α_1 is not equal to α_2, the system is nevertheless more robust in the presence of such variation than if a Janus arrangement is not used. Kayton and Fried (1969) state that the fractional velocity error, ϵ_v, for an error of δP in the pitch angle is equal to

$$\epsilon_v = \tan \alpha \delta P, \tag{10}$$

for the non-Janus case

and

$$\varepsilon_v = 1 - \cos \delta P, \qquad (11)$$

for the Janus arrangement.

For 10^0 of pitch, this leads to an error of 30% in the non-Janus case, and 1.5% in the Janus case.

Thus, if no pitch and roll measurements are available, or their accuracy is limited, the fluctuation error due to pitch and roll can clearly be reduced by the use of a Janus arrangement.

7. Conclusion

Limitations on doppler sonar performance are due to several effects, which can be summarised below.

Fluctuation error in velocity estimates occurs because of the finite size of the footprint and the nature of random scattering. Its effect can be reduced by averaging over successive estimates, but then the time constant over which sudden changes in velocity can be detected, increases. Calibration error, related to changes in scattering strength with angle in bottom track mode, would seem to be significant, and is not easy to compensate for. In either case, a narrow beamwidth is clearly an advantage.

Effects due to variations in sound velocity with position and time are significant in cases where there is a systematic change of sound velocity with depth, and in cases where the operating depth is large. In general, they can be neglected, however.

The major causes of concern are due to difficulties in detecting the sea bed return. This may be due to pitch and roll increasing the range, or be due to spurious signals from bubbles or other noise sources masking the return. Range gating is clearly an advantage, as the spurious signals are likely to be detected at a different time than the sea bed return and can then be rejected. The range of the sea bed could be detected by a separate sonar.

Operation in water track mode, does not have the disadvantage of calibration error, and the effect of sound velocity variations is negligible as the water depths of interest are so shallow. It must be remembered however, that velocity will only be measured relative to the water velocity, and any water currents will affect the results.

The effects of pitch and roll can be significantly minimized by the use of a Janus beam arrangement.

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PERFORMANCE OF DOPPLER SONAR SYSTEMS FOR VEHICLE VELOCITY ESTIMATION

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