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ON ESTIMATING THE QUALITY OF DOPPLER SONAR DATA

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ABSTRACT

This paper describes efforts to determine the accuracy (bias) and precision of water velocity measurements obtained with the MPL Doppler Sonar System. Precision is well quantified by comparing velocity estimates from similar sonars pointed in parallel. It is found that 2-5 cm/sec rms precision is possible after averaging over only 15 returns (~ 30 seconds). The smaller velocity errors are associated with longer pulses, which have poorer range resolution. Bias in Doppler measurements has been investigated by intercomparison of Doppler and electromagnetic estimates of the vertical profile of horizontal velocity. For the relative velocities present during the intercomparison, which were less than 30 cm/sec, no bias was detectable. Further tests are necessary at higher, known, relative velocities to quantify bias errors.

INTRODUCTION

Doppler sonar is becoming a useful method of remotely sensing currents in the sea. In this technique, sound is transmitted in a narrow beam. The sound scatters off plankton and nekton in the beam. From the Doppler shift of the returning echo the component of scatterer velocity parallel to the sonar beam can be determined as a function of range.

During 1978-80, a four-sonar Doppler system was built at Scripps for use in internal wave research. The sonars operate at frequencies between 67 and 85 kHz. Velocity estimates have been achieved to a range of 1.5 km, with range resolution of 15-30 m. The system was operated from the Research Platform Flip during a data collection cruise in May 1980. An eighteen day continuous series of Doppler data was obtained. These data are currently being analyzed. This paper documents efforts to determine the quality of the ocean velocity estimates obtained from the Doppler sonars.

Estimating Accuracy and Precision

When considering the quality of Doppler measurements it is useful to distinguish between measurement precision (variance) and measurement accuracy (bias). For pulse to pulse incoherent systems which scatter from a large number of randomly positioned targets, the ultimate precision is limited by a fundamental uncertainty principle. One cannot specify the motion in an arbitrarily small volume to an arbitrary precise velocity in a finite length of time. In contrast, there is no fundamental limit on estimate bias. Measurement bias results from poor system design, poor system use (e.g., significant echo energy being received from side lobes of the transducer) or inadequate processing of the returns to estimate Doppler. Two experiments to determine the precision of Doppler measurements will be presented below. This discussion is followed by a description of an intercomparison experiment which was designed to detect bias errors in the MPL system.

Measurement Precision

The expression which approximates the limit on measurement precision in a random scattering situation is:

$$\frac{\Delta V_{rms} \; \Delta x}{\sqrt{N}} = F(c,\omega) \qquad (1)$$

ΔV_{rms} is the rms uncertainty in velocity measured after N pulses of length $T = 2\Delta x/c$ have been transmitted and the resulting returns are properly processed and incoherently averaged. The derivation of this expression is discussed in Thierault (3) and, for a particular Doppler processor, by Miller and Rochwarger (1).

Two different approaches were used in an attempt to investigate the precision of the MPL system. In theory, motions in the sea are restricted to frequencies below the so-called Väisälä or stability frequency:

$$N = \left[\frac{g}{\rho}\left[\frac{\partial\rho}{\partial z} - \frac{\rho g}{c^2}\right]\right]^{\frac{1}{2}} \qquad (2)$$

where g is the acceleration of gravity, ρ the density of water and c the speed of sound. In the ocean, N varies from 5-15 cycles per hour in the upper thermocline down to 0.5 cph near the sea floor. Motions detected by the sonar at frequencies above N can be defined as spurious, evidence of the finite precision of the measurement. This can be seen in data taken on a January 1977 cruise, during which a sonar was mounted on Flip's hull at a depth of 50 m and directed 7° down from horizontal. Twenty-four hour data series were formed at discrete ranges. The series are Fourier transformed in time, resulting in spectra of slant velocity as a function of frequency and range (depth) (Fig. 1). The nearest spectra represent

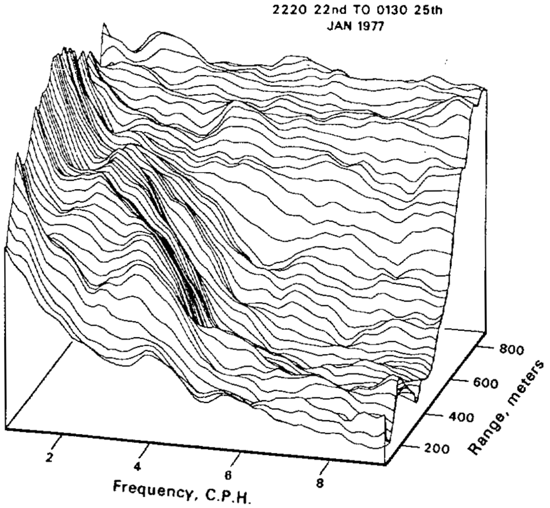


Fig. 1. Slant velocity power spectra $(cm/sec)^2$/cph as a function of frequency and range.

mixed layer motions. These decay irregularly with increasing frequency. The spectral slope is approximately $\omega^{-5/3}$. At greater ranges (~ 300 m), the spectral slope increases to approximately ω^{-2} and a sharp cutoff is observed at the Väisälä frequency. The spectral level at frequencies above the Väisälä cutoff is an indicator of the precision of the velocity estimates. An rms noise of 1 cm/sec is indicated for ranges 2-600 m. At greater ranges, the strength of the returning echo is diminished, and the precision in the velocity estimate is degraded. This is seen in the increase in spectral noise level with increasing range, beyond 600 m.

A second, more ambitious test of sonar precision was conducted off the coast of San Diego in Nov. 1981. Two identical sonars were mounted side by side on Flip (Fig. 2). The sonars were pointed downward 45°. The beams were parallel to within 2°. In a series of four 20-minute tests, 10, 20, 40, and 80 rms pulses were transmitted every 2 seconds from both sonars simultaneously. One sonar was operated at 70 kHz, one at 75 kHz. Velocity profiles were estimated every 30 seconds. The rms velocity difference was estimated on the range interval 220 to 410 m and averaged over the twenty minutes of each test. These rms differences are presented in Fig. 3 for the four transmitted pulse lengths. Velocity estimates were calculated using the complex covariance technique first suggested by Rummler (2). Using this technique the velocity is estimated at a given range from the average rate of change of phase of the return at that range. This rate of change is determined by comparing the phase of the echo at successive times separated by an interval τ which should be small compared to the length of the transmitted pulse. In Figure 3, precision is given as a function of this time lag, normalized

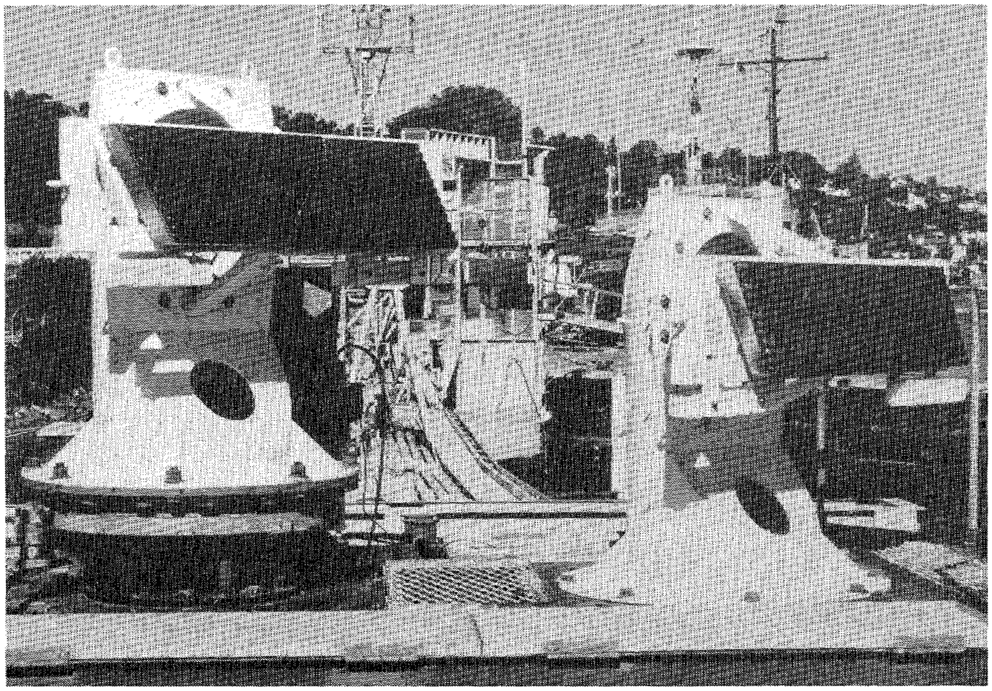


Fig. 2. The MPL scattering sonars used in the intercomparison experiment.

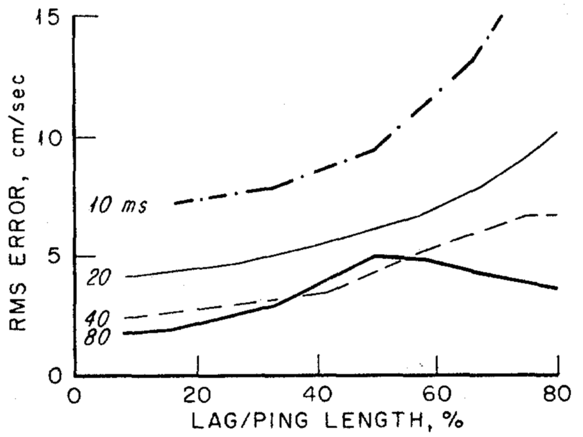


Fig. 3. The RMS disagreement in water velocity sensed over ranges 220-410 m by the sonars in Fig. 2. The error is given as a function of the ratio of the time lag during which phase progression is estimated to the transmitted pulse length.

by the ping length, for the different lengths of pulse. It is clear that precision improves as the time lag is decreaseed, in contrast to a prediction by Miller and Rochwarger (1). The rms uncertainty in the 10, 20, 40, and 80 ms pulses is 12, 6, 3, and 2 cm/sec after averaging over 15 pings in time and over a pulse length in range. Note that for the shorter pulses, the rms error is halved as the pulse length doubles, in concert with equation (1). This pattern is not maintained with the longest pulse, at 80 ms. When the transmitted pulse length is increased much beyond 40 ms, range resolution is lost without the expected improvement in velocity precision. This phenomenon is tentatively attributed to the random motion of the scatterers within the scattering volume. As a result of this random motion, the spectrum of the return echo from the 80 ms pulse is significantly broadened. Since velocity precision is set by the return spectral width, the expected improvement in precision is not attained.

It should be emphasized that these results include errors other than just estimator uncertainty. They represent a bound on measurement repeatability from all sources relevant in Doppler experiments.

BIAS ERRORS

While differences in measurements from different instruments are easily quantified, there is no guarantee that either system accurately tracks the motion of the water. A standard means of determining the accuracy of Doppler systems is to mount the transducer on a movable platform, move it at a fixed speed, and establish the range of speeds in which the velocity estimates are accurate. This is difficult to do with large transducers.

At present, the most successful attempt to establish the accuracy of the MPL system has been an intercomparison test between the sonars and expendable temperature velocity probes (XTVP) developed by Dr. Tom Sanford of the University of Washington. On 10-11 May 1980, Sanford rendezvoused with Flip on a conventional ship 400 km west of San Diego. During a several hour period, a series of expendable probes were dropped through a 45° downward slanting sonar beam. Results of a typical comparison are presented in Fig. 4. The slant velocity measured by the sonar was converted

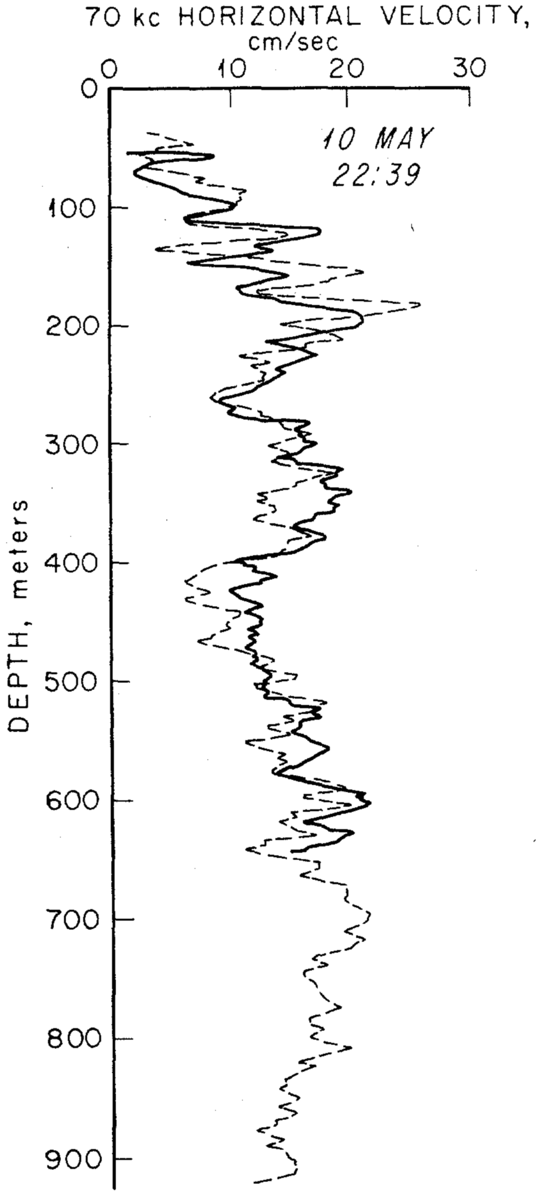


Fig. 4. The 45° slant profile of slant velocity as measured by a 40 kH Doppler sonar as compared with the equivalent component of horizontal velocity measured with a Sanford XTVP. Note that much of this difference can be attributed to a slight mismatch in depth scales.

to an "equivalent horizontal velocity" by multiplying by $\sqrt{2}$. Sanford rotated the north and east components of velocity produced by his instrument to components parallel and perpendicular to the sonar beam. The agreement between the estimates is striking. The rms difference is of order 2 cm/sec. It should be emphasized that these results come from an instrument falling vertically through a 45° slanting sonar beam. At some depths the information is coming from positions separated horizontally by ~ 0.5 km.

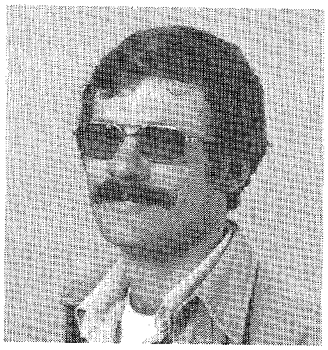
CONCLUSIONS

Further tests are needed to quantify the accuracy and precision of the sonars. It is particularly desirable to check the performance as a function of scatterer velocity. It might be that, when Doppler shifts are sufficient to shift the echo by a large fraction of the sonar passband, a high-speed bias will result. Perhaps intercomparisons between Loran C data showing Flip's drift and bottom scattered Doppler velocity will be adequate to check out this potential problem. There is some hope of improving velocity precision at fixed range and time resolution by transmitting coded pulses or by using nonlinear processing on the sonar echoes. The techniques described in this paper should be useful in determining the performance of these new approaches.

1. Miller K. S., and M. M. Rochwarger (1972). A covariance approach to spectral moment estimation. IEEE Transactions on Information Theory, IT-18, 5, 588-596.

2. Rummler, W. D. (1968). Introduction of a new estimator for velocity spectral parameters. Tech. Memo MM-68-4141-5. Bell Telephone Laboratories.

3. Thierault, K. B. (1981). Bounds on pulsed Doppler current profiler performance. Technical Memorandum 634. Bolt, Beranek and Newman, Inc.



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