Single-shot Doppler Velocity Estimation using double chirp pulse compression

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Coherent ultrasonic Doppler velocimeters provide precise and accurate measurements of velocity profiles in many applications. However, these instruments suffer from the well known range-velocity ambiguity, making this kind of instruments not well suited for velocity measurements in channels of several meters depth and water velocities of some meters per second. On the other side, incoherent ultrasonic Doppler velocimeters don't have such limitations but suffer from reduced spatial and temporal resolution. The known actual solutions to this compromise consist in using phase-coded repeated pulses composing one excitation ping. The performance of such a solution is mainly conditioned by the appropriate choice of the binary coding sequence. While longer codes reduce the variance of the velocity estimate, they limit both spatial resolution and measurable velocity range. We present in this paper an alternative pulse compression scheme using overlapping linear chirps. This method makes it possible to improve the estimation variance with respect to phase coding using minimum peak sidelobe level binary codes. The performances in term of both bias and variance with respect to various parameters including noise level, length of range-gated signal, velocity dispersion within a considered volume and number of particles will be addressed based on a model taking into account the Doppler effect on wideband transmitted pulses. These results will be discussed and compared with experimental measurements and theoretical predictions of performance limits (The Cramér-Rao lower bounds) for both wideband and narrow-band Doppler velocimeters. Furthermore, we will show that it is possible to extend the measurable velocity range without affecting spatial resolution and precision, all parameters otherwise unchanged.

Keywords: pulse-to-pulse coherent sonar, velocity-range ambiguity, pulse compression, precision

1 INTRODUCTION

Ultrasonic Doppler velocity estimation is the measurement of the amount of compression or expansion of the backscattered signal received after the transmission of an arbitrary ultrasonic signal. The principle of such an instrument is based on the existence of backscattering particles within the medium. Such medium consists generally either in oceanic or riverine waters where we need to make the measurement of long range velocity profiles (distribution of the velocity field along the ultrasonic beam) or simply estimating the relative velocity between the instrument referential and the medium for navigation purposes. The Doppler estimation is generally performed along several beams oriented toward the bottom and the projections of the velocity field vector on each ultrasonic beam axis provide a measure of the velocity mean radial vector in the considered range-gated volume. This measure is deduced by linear combination of the total single-beam projections estimated individually where the velocity field is supposed uniform throughout the volume containing all the ultrasonic beams.

We present in this paper a performance analysis by computer simulation based on a point scattering model for reverberation signal synthesis using wideband transmitted pulses. Pulse compression using both *Minimum Peak Sidelobe Level (MPSL)* binary codes and linear chirps will be compared and it will be shown that the latter technique permits the achievement of better performances since it appears to give more flexibility in designing highly correlated overlapping pulses.

2 PRINCIPLE OF OPERATION

The principle of operation of an instrument using short duration repeated pulses for the estimation of Doppler shift is depicted in figure (1). The excitation signal consists in a sequence of identical pulses of short duration transmitted in a single ping [4]. Like for the case of a coherent system, the problem consists in estimating the phase shift from the reverberation signal resulting from the summation of successive reflections of the two (or more) identical pulses on the ensemble of scatterers contained within the volume of interest.

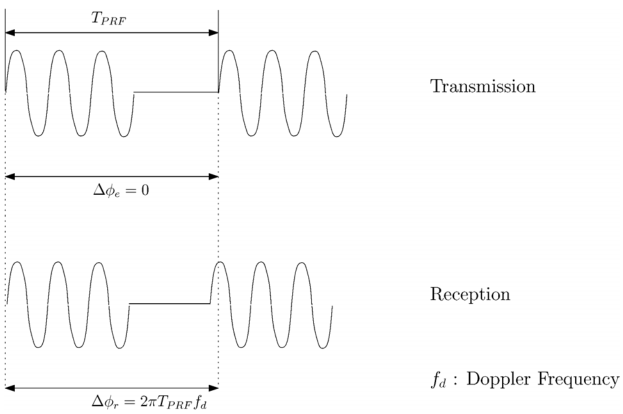

Figure 1: Principle of operation.

To alleviate the notation, we take in the following $T_{PRF} = T$ and the transmitted signal is given by:

$$e(t) = p\left(t - \frac{T}{2}\right) + p\left(t + \frac{T}{2}\right) \quad (1)$$

and

$$p(t) = \Re\left\{\Pi\left(\frac{t}{T_p}\right)e^{2j\pi f_0 t}\right\} \quad (2)$$

where $\Pi(t/T_p)$ is the unity rectangular window of duration T_p and $\Re$ denoting the real part.

The reflection of $e(t)$ on a single scatterer moving with radial velocity v relatively to the transducer will produce $r(t)$. Assuming that the effect of the acoustic backscattering coefficient of the particle as well as the amplitude propagation loss is represented by the coefficient a, the received signal is given by:

$$r(t) = ae\left(\beta\left(t - \frac{2\mathrm{R}_0}{c+v}\right)\right) \quad (3)$$

where $\beta = c - v / c + v$ is the Doppler compression/expansion factor and c is the sound velocity in the medium. The relative radial velocity is assumed constant during both the signal duration and the round-trip travel time and R_0 is the distance between the particle and the transducer at the emission instant.

The autocorrelation function argument of the complex baseband signal at a time lag equal to the inter-pulse spacing gives a measure of the Doppler frequency. The autocorrelation of the received signal can be calculated as:

$$\Gamma_r(\tau) = \Gamma_{pp_\beta}\left(\tau + \frac{T}{\beta}\right) + 2\Gamma_{pp_\beta}(\tau) + \Gamma_{pp_\beta}\left(\tau - \frac{T}{\beta}\right) \quad (4)$$

with $\Gamma_{pp_\beta}(\tau)$ being the autocorrelation of $ap(\beta t)$.

Therefore, the Doppler effect can be seen as a translation of the lateral peaks of the baseband auto-covariance function by a time delay $\Delta T = (\beta - 1)T / \beta$. An estimate is calculated by evaluating the phase shift equal to the argument of the autocorrelation function at a time lag equal to the pulse pair spacing [2]:

$$\Delta\varphi_r = arg\left[\Gamma_{pp_\beta}(\Delta T)\right] = 2\pi(\beta - 1)f_0 T = 2\pi f_d T \quad (5)$$

3 PULSE COMPRESSION

Pulse compression is a widely used technique in RADAR and SONAR technology [3]. The main advantages are an improved spatial resolution and a better immunity to both ambient and electronic noise. In that context, frequency modulated signals and pseudorandomly biphase-modulated signals are the most used methods. Since the former has gained less attention in the past, the aim of this study is to characterize the performances of each technique both by simulation and experimentation. Phase modulation using binary codes provide the advantage of its simplicity since it consists in simply changing the sign of the carrier frequency, the main drawback is the necessity to find optimal codes whose autocorrelation function have minimized sidelobes. Some of these codes are provided in the literature and the most known among them are the Barker codes with PSL=1 (Peak Sidelobe Level). Longer codes have been discovered but having PSL greater than one. Frequency modulated signals or chirps (linear or hyperbolic) on the other side are more complicated to generate but provide the advantage of being more flexible to adapt by modifying their bandwidth and duration. Furthermore, overlapping two or more chirps gives the possibility to extend the unambiguous velocity range without affecting the estimation variance simply by better filling the transducer bandwidth.

4 REVERBERATION SIGNAL SIMULATION

Performance comparison using various kinds of excitation signals and pulse compression schemes can be compared under the same conditions using a repeatable and easily parameterizable synthetic reverberation signal.

By invoking superposition, the reverberation signal $r(t)$ is the sum of echoes from many discrete scatterers:

$$r(t) = \left[\sum_i a_i D^2(\vec{r}_i)(s * h_T)(\beta_i(t - t_i))\right] * h_T(t) + w(t) \quad (6)$$

with $\beta_i = (c - v_i)/(c + v_i)$. The echo from each scatterer, indexed by i, is delayed by t_i corresponding to the two-way travel time between the scatterer and the transducer as well as the phase of the scatterer acoustic impedance considered to be uniformly distributed random variable on the interval $[0, 2\pi]$. The gain factor $D^2(\vec{r})$ is used to modelize the effect of ultrasonic beam pattern and h_T the transducer transfer function. The individual amplitude factor a_i is representing the modulus of the acoustic impedance of each scatterer as well as the two-way propagation loss. The SNR is adjusted by varying the power of $w(t)$ which is a zero mean additive white Gaussian random noise of variance σ_n^2. The velocity dispersion is varied as a Gaussian random variable with mean v_m and variance σ_v^2.

The resulting synthetic reverberation signal is range-gated to obtain the windowed signal corresponding to a cell of arbitrary length. Finally, the signal is passed through an analog quadrature demodulator and subsequently decimated. The output of the simulator is a dual digital data stream representing the inphase and quadrature components forming together the complex baseband output of the system.

5 SIMULATION RESULTS

The simulations were conducted using a binary code of 51 bits length (4 wavelengths per bit) and PSL=3 repeated two times. The central frequency was $f_0 = 1.25 Mhz$. Two chirps of equal length centered on f_0 and with spectral width equaling two times the equivalent bandwidth of the binary code were used for comparison. One thousand estimations using the same random parameters in each case were performed. The default values were 0dB for the SNR, 100cm for the cell size, no velocity dispersion and 200 particles per a volume equivalent to 200cm range.

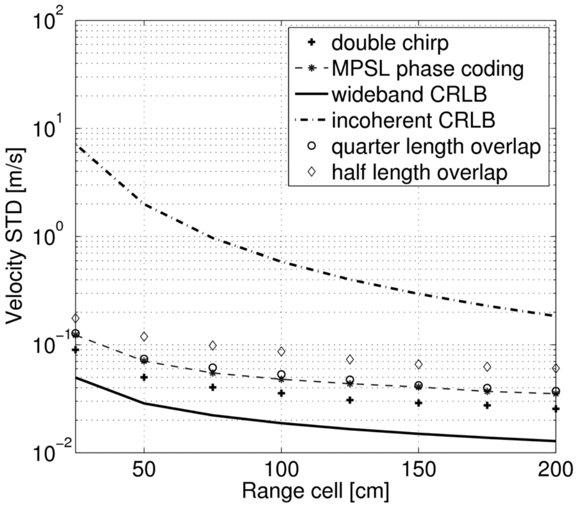

Figure 2: Velocity standard deviation for various cell sizes.

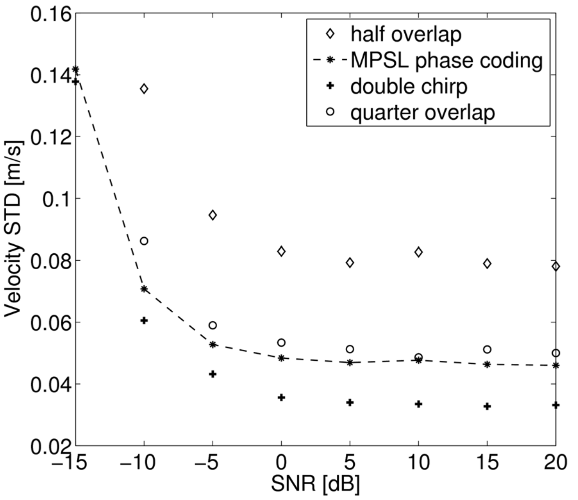

Figure 3: Velocity STD for various SNR values.

The influence of the cell size on the estimation variance is reported in figure (2). For comparison, we give the obtained STDs by using double pulse with MPSL binary phase coding, double chirp with same duration and inter-pulse spacing (same ambiguity velocity), double half length overlapping chirps with same total duration (ambiguity velocity augmented with 100%), and double quarter length overlapping chirps with same total duration (ambiguity velocity augmented with 50%). Both CRLBs (Cramér-Rao Lower Bounds) for incoherent [5] and wideband [1-2] cases are plotted for reference. In figure (3), the effect of SNR is plotted and using wideband linear chirps is clearly advantageous. Particularly, using double chirp with quarter length overlapping gives almost the same STD (except for very low SNRs), but with the advantage of increasing the maximal unambiguous velocity by 50%. The bias comparison on figure (4) shows no significant difference between the two methods.

As would be expected, the number of particles per volume unit does not have any direct influence on

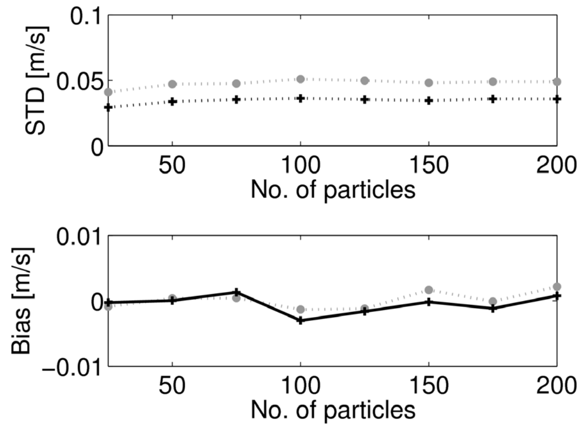

Figure 4: Influence of the number of particles on the measurement precision (Top), and the bias (Bottom). (Grey: Phase Coding, Black: Double chirp).

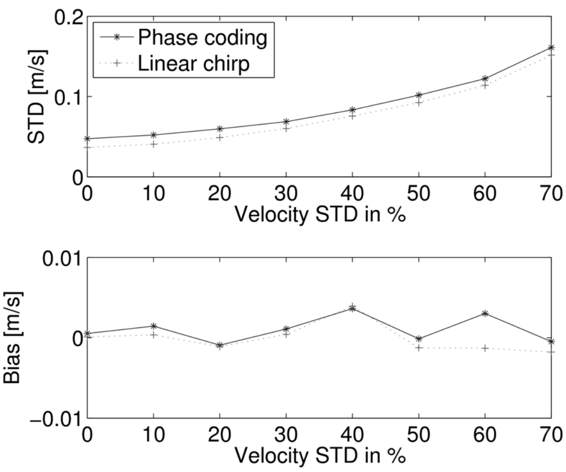

Figure 5: Influence of velocity dispersion on standard deviation and bias of velocity estimate.

the precision of the measurement (see figure (4)), however, in real situations, since the concentration is related to the power of the backscattered signal, the consequence will be a variation in the SNR.

Velocity dispersion was varied and the results on both standard deviation and bias are reported on figure (5). As expected there is a degradation in the estimation of the mean velocity as the dispersion increases. On the other side there is no significant influence on the estimate bias.

6 EXPERIMENTAL VERIFICATION

The comparative results obtained from measurements carried out on a turbulent flow contained in a laboratory channel are presented on figure (6). For the two cases, double chirp pulse compression (top) and phase-coded excitation (bottom), we present the spectrogram of one transmitted and received signals (left), 100 successive velocity profiles (middle), and the mean profile as well as the standard deviation as a measure of the precision in each case.

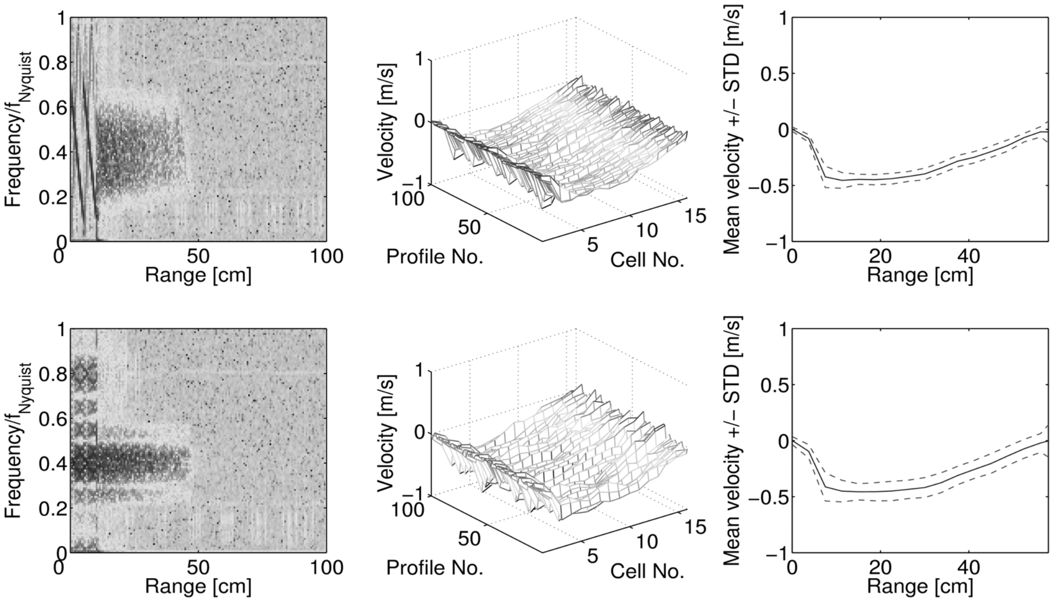

Figure 6: Experimental verification (see text for details).

The excitation signal with central frequency $2Mhz$ (0.4 as normalized by the Nyquist frequency), is repeated with a frequency equivalent to one meter exploration depth. The phase coded signal was modulated with 51 bits code, 4 wavelengths per bit, and the chirps having $3Mhz$ bandwidth. By comparing the two spectrograms, it can be seen that while the double chirp have a wide spectrum, the phase-coded signal is characterized by a relatively narrower spectral main lobe despite the fact it have been coded using MPSL binary sequence. The result is a reduced variance using wideband double chirp pulse compression.

7 CONCLUSION

We presented in this paper some comparative results concerning the use of two pulse compression techniques for the improvement of velocity estimation using an hybrid excitation scheme. This method allows the measurement of velocity profiles along one ultrasonic beam using a single transmit-receive cycle. It has been shown through computer simulation and by measurements conducted in a laboratory controlled water flow that using wideband overlapping chirps permits a valuable improvement in the measurement precision. This achievement is made possible because of a better usage of the transducer bandwidth. Moreover, the flexibility in using frequency modulated chirps also permits the extension of the unambiguously measurable velocity range. This is made possible since overlapping two chirps reduces the inter-pulse duration. Therefore, by augmenting the bandwidth at the same time, it is possible to extend the maximal unambiguous velocity without affecting the estimation variance. The spatial resolution and effective exploration range being unchanged since these quantities are only related to the total transmission duration.

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