Mesure de la vitesse d'une cible sonar en utilisant des signaux émis tolérants au Doppler

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In conventional sonar approaches, the Doppler effect can be viewed either as a disturbing effect or as a support of information; transmitted waveforms are chosen accordingly. In this paper, we show that the bias due to Doppler can be easily compensated for any waveform by an appropriate definition of the emission date. A family of "naturally" Doppler tolerant waveforms is presented. With such waveforms, in addition to a non-biased estimation of position and a minimum contrast loss, we show that additional processing can be implemented and used to estimate target (or mobile) velocity using either a pair of signals or investigating the fine structure of the complex ambiguity function.

1 Introduction

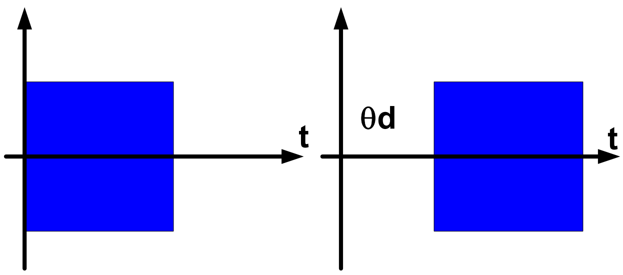
In conventional sonar approaches, the Doppler effect is viewed either as a spurious effect or as a carrier of information. In the first case, sonar designers look for Doppler insensitive (or tolerant) waveforms to transmit (linear period modulation, for instance [1, 2, 3, 4]) or for a Doppler sensitive (or resolving) waveforms (pure tone bursts or more complex waveforms such as Costas codes possessing dual resolution properties [5, 6]).

In this paper, we will show how Doppler insensitive waveforms associated to conventional pulse compression can be designed and associated to additional echo processing for estimating sonar target (or mobile) velocity.

2 Doppler-induced bias, just an illusion

As historically, sonar echo processing was inspired from radar processing (processing in the baseband), an important issue was the bias induced by Doppler and the "tilt" of the ambiguity function of the transmitted signal. Considering the processing power of DSP devices since the late eighties, and the low sampling rate required for conventional sonar signals, processing can be achieved, since then, on "RF signal" with no need of frequency shifting.

In his PhD thesis [8], M. Mamode has shown that for any signal, a so called "decoupling delay" can be defined that can then be used as a new reference for "time zero" and that allows decoupling the time delay estimation from the target velocity [9]. Although the concept is very simple, it has not been often used as processing was still achieved "the radar way": instead of starting counting time delay from the beginning of the signal, one can simply start counting θd seconds before (or after) that date (figure 1).



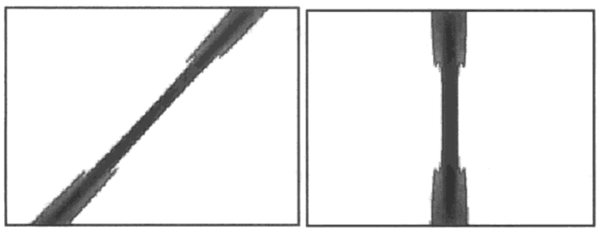
Figures 1: a simple re-definition of date t=0 for any transmitted signal.

The "new" transmitted signal contains a θd duration of zeroes that will be compressed or dilated by the Doppler effect. M. Mamode showed that this delay can be computed, for any signal to decouple arrival time from Doppler rate [8, 9].

This can be simply explained graphically:

- let's consider any signal with a given compression ambiguity function [7];
- the ambiguity function is tilted and bias is proportional to Doppler compression rate: b = η . θd;
- adding a delay θd to the signal will generate the same bias in the opposite direction: b = - η . θd;
- both delays cancel each other.

This concept is illustrated in figures 2, for a linear frequency modulated chirp. Figure 2a shows the conventional ambiguity function (Kelly-Wishner compression ambiguity function [7]) of a LFM chirp while figure b shows the same for a delayed chirp.



a- θd= 0 ms b- θd =45 ms

Figures 2: illustration of the use of a decoupling delay for compensating the Doppler effect. Ambiguity functions of a linear FM chirp (LFM: 110-90 kHz, duration: 10 ms). Scale: vertical η=1.1 to 0.9 (velocity: ±7.5 m/s); horizontal: ± 0.64 ms around arrival date, dynamic range: 12 dB.

Simulations have been achieved considering a processing around the carrier: no frequency shifting or heterodyning.

Having said that, the only residual effects of the Doppler on the output of matched filtering or pulse compression will be time spreading and loss of contrast.

3 Naturally optimal waveforms

Optimal waveforms are the one that minimize the residual disturbances to Doppler effect. For this purpose, a linear-period modulation (i.e. hyperbolic frequency modulation, HFM), have been traditionally used. Again, it can be shown graphically that compression of a hyperbola can be achieved by shifting on the same hyperbola; i.e. modulation law is the same for normal and compressed signal and only starting and ending frequencies will be changed. In fact, this can be also demonstrated in the frequency domain. For large time-bandwidth product (stationary phase approximation [10]), the group delay of a HFM will possess the same expression that period modulation in the time domain.

If we now consider the general family of signals with a hyperbolic group delay, they can be expressed by their spectrum (analytic complex signal):

$$Z(\nu) = A(\nu).e^{i.\alpha.\log(\nu)}$$

Where A(ν) is any positive real function and α is a real parameter.

For a constant radial speed, the compressed version can be expressed as:

$$Z(\eta.\nu) = {}^{1}\!/_{\sqrt{\eta}}\,.A(\eta.\nu).e^{i.\alpha.\log(\eta.\nu)}$$

The ambiguity function of signal z(t) can thus be expressed as:

$$B(\nu).e^{i.\alpha.Log(\eta)}$$

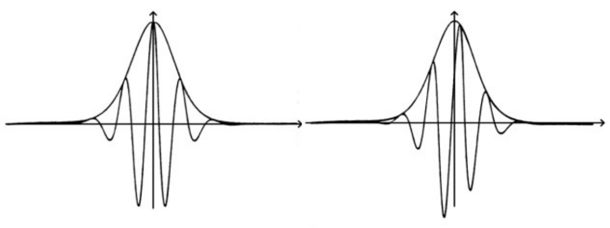
Where: $B(\upsilon) = {}^{1}\!/_{\sqrt{\eta}}\,.A(\upsilon).A\,(\eta.\upsilon)$ is a positive real function (power density).

Its inverse Fourier transform possesses the structure of an autocorrelation function: its envelope is maximal in zero (or at t_0 for a delayed echo) and it is symmetric with respect to the central date.

$e^{i.\alpha.Log(\eta)}$ is a pure phase term factor that will generate a phase shift between the autocorrelation envelope and its real part.

In short, for this family of signals, the envelope is only slightly affected by the Doppler effect (loss of contrast of η and equivalent time spreading). In addition, the phase of the real part at the unbiased arrival date carries an information on the velocity.

Figures 3 illustrate the properties of such transmitted waveforms.



a: η = 1 (v = 0 m/s) *b: η= 1.004 (v = 3 m/s)*

Figures 3: cross sections (envelope and real part) of the complex ambiguity for waveforms with a linear period modulation of group delay (log normal amplitude modulation). [11, 12, 13].

4 Velocity estimation

Despite the fact that we consider Doppler insensitive waveforms (in term of contrast loss), we see that the information on the velocity is still present. Three ways can be envisaged for velocity estimation:

- Method 1 [14], [15]: Transmit two waveforms simultaneously, one Doppler-unbiased, S1, and one Doppler-biased (with a delay Δ), S2, and estimate the relative delay (η.Δ).
- Method 2: Fine observation of the complex ambiguity function: estimate the position from the envelope and velocity from real part.
- Method 3: combination of methods 1 and 2.

For the first method, the second signal can be either in a separate band or "orthogonal" to the first one in the same band. For instance, one can use signal and time reversed signal (orthogonality = time-bandwidth product). The second signal can be delayed (by Δ seconds). In order to increase the accuracy of the estimation: the longer the delay Δ, the better the accuracy (Doppler induced delay is proportional to Doppler compression rate). The maximum delay admissible is given by a priori information on target velocity (as must remain in the observation beam at both dates time 1 to time 2).

The method is described in figure 4.

The estimation error on η is twice the estimation of arrival date after pulse compression, i.e. the error σ provided by conventional Woodward formula:

$$\sigma = \frac{1}{B^2.\rho_s}$$

where B is the effective bandwidth and ρs is the signal to noise ratio after pulse compression.

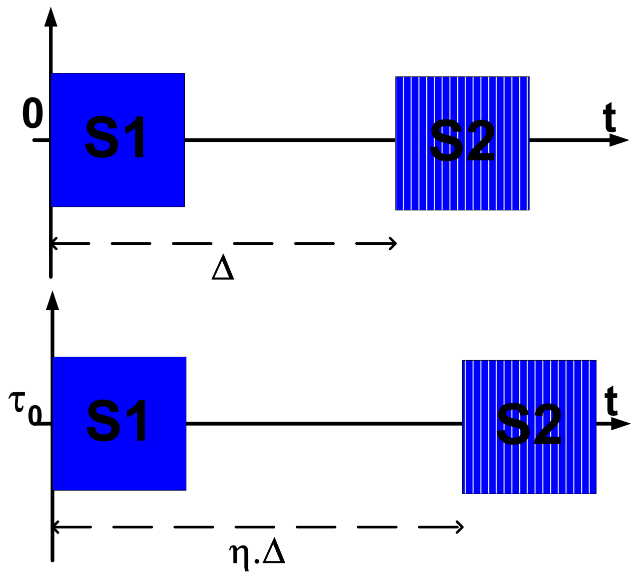


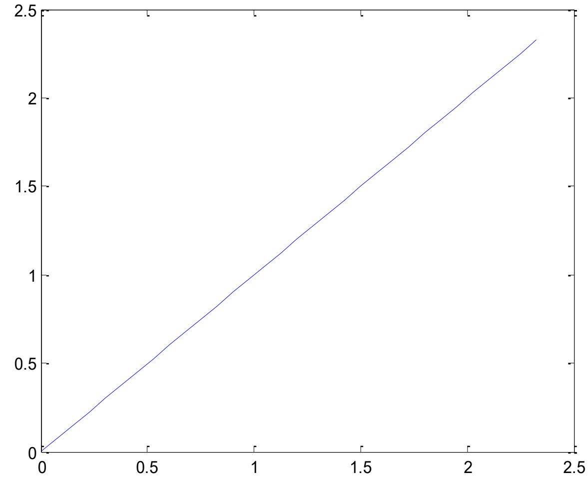
Figure 4: Illustration of method 1 for estimating both position and velocity. Method 1 using a pair of waveform; S1, Doppler insensitive and S2 Doppler sensitive one.

The second method is based on the observations made on figure 3. It is achieved in three steps:

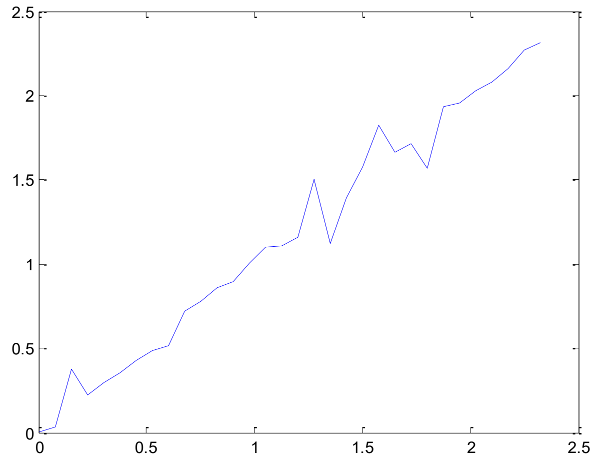
1. Estimating the unbiased arrival date using the envelope of complex ambiguity function.
2. Estimating the value of the real part of this function at this date.
3. Compute η.

Figures 5 show the velocity estimation for 2 cases: input signal to noise = 20 dB. and -30 dB.

Test signal possesses a hyperbolic modulation of group delay with a gaussian envelope with an effective bandwidth of 8.8 kHz around 10 kHz and an effective duration of 11.4 ms. Pulse compression gain is 20 dB.



Input S/N ratio= 20 dB



Input S/N ratio= -30 dB

Figures 5: estimated velocity (in m/s) as a function of real one.

For large velocities one will be faced to the periodic structure of the output phase as illustrated in figure 6.

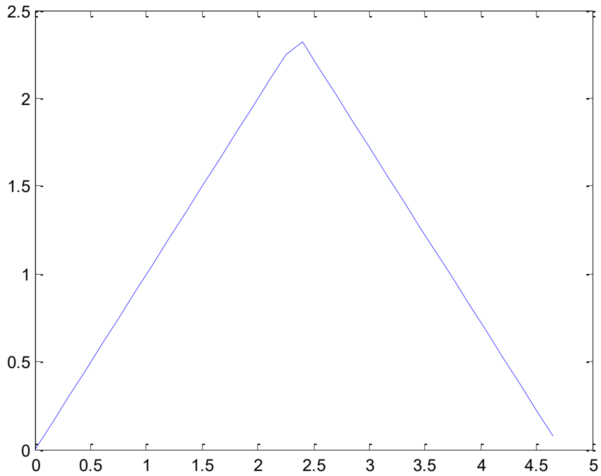


Figure 6: estimated velocity (in m/s) as a function of real one. Same test signal as figure 5. S/N ratio: +20 dB

5 Conclusion

This paper shows that any Doppler-induced bias can simply be cancelled by an appropriate definition of the date of emission. For a given family of naturally Doppler-tolerant signals (linear modulation of group delay, $\theta d=0$), the phase of the complex ambiguity function (compression) can be used to estimate the velocity. Due to the periodic nature of the phase, the estimation will be difficult for large velocities. In this case, either an a priori information can be used (rough trajectory), or a pair of transmitted signals can be used (instead of a single Doppler insensitive one). The second signal can then be delayed and the effective delay after pulse compression will be used to give a first estimate of the velocity that can then be combine with a fine phase analysis.

6 References

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