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QUANTITATIVE ANALYSIS OF TECHNIQUES FOR ACCURATE ESTIMATION OF ULTRASONIC ECHO-SIGNAL TIME-SHIFTS FROM BIOMEDICAL PHANTOMS

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ABSTRACT

The relative efficiencies of some digital time processing techniques to estimate small phase-shifts in ultrasonic echo-signals, acquired from phantoms emulating biological tissues, are analysed in detail. Cross-correlation, quadrature demodulation and phase shifting processing options are considered. The interest of these techniques resides in their great usefulness to investigate new non-invasive methods for accurate ultrasonic thermometry and measuring internal micro-movements in biological tissues. For every case, typical values in time-shift are obtained by degree of thermal elevation and millimeter of acoustic propagation. The echo-signals used for calculations were measured from phantoms elaborated for ultrasonic-thermal emulation of tissues, or well computer simulated.

RESUMEN

Se analiza la eficacia relativa de técnicas de procesamiento digital temporal basadas en correlación cruzada, de-modulación por cuadratura y desplazamientos de fase, para estimar pequeños time-shifts en eco-señales ultrasónicas adquiridas desde phantoms emuladores de tejidos biológicos. El interés actual de estas técnicas reside en su gran utilidad para investigar nuevos métodos no-invasivos de termometría ultrasónica precisa y medición de micro-movimientos internos en tejidos biológicos. Se obtienen, para cada técnica, valores típicos del desplazamiento temporal por grado de elevación térmica y milímetro de propagación acústica, usando eco-señales medidas desde phantoms elaborados para emulación ultrasónico-térmica del tejido, y también señales simuladas computacionalmente.

INTRODUCTION

Using short pulses of ultrasound, with a central frequency at the megahertz range, is an option very adequate to biomedical applications and in particular medical diagnosis purposes. This is so, because, among other interesting advantages, this pulsed energy provides a non-invasive measurement of inner zones with a very good penetration by using high-frequency acoustic beams that could be mechanically or electronically focused in order to obtain high-resolution in the inspection results. In addition, it has not ionising effects and presents a low relative cost.

Advanced signal processing procedures turn on a crucial stage to efficiently extract anatomical or physiologic information of interest from the ultrasonic echo-signals; for instance, a very well known and frequently used diagnosis tool is the processing required for displaying an image from the ultrasonic scan of a particular body region.
Nowadays there are a number of ultrasonic signal processing algorithms (USPA's) under research to determine their efficiency when they are applied for specific medical diagnosis or biological measurement requirements. The estimation of small time-shifts in an ultrasonic echo-signal, acquired from biological tissues under different tissue conditions, is an interesting field where biomedical researchers have been developed USPA's based on different principles.

In this work, a quantitative efficiency analysis of previously proposed techniques for small time shifts estimation is proposed, and the obtained analysis results are presented. An USPA for each of them was developed and the result of their applications, are analyzed for each case. Three of these methods are based on the phase change equivalent to the temporal displacement produced in the ultrasonic signal as a consequence of a change in the media (for example, a temperature rise, or a little movement). There are two important aspects of these alternatives procedures being indispensable to be taken into account for a reliable measure: precision and sensibility to noise; both aspects were evaluated in this analysis. Due to the great sensibility that is required in order to detect small changes in the signal phase, the estimation procedure becomes complex and, in consequence, it should be performed with caution to avoid obtaining incorrect results due to spurious undesired factors.

METHODOLOGY

Time-shift Estimation Techniques Analysis

Temporal displacements of several ultrasonic echoes (from different depths), produced by the temperature variation in the interrogated media, were analyzed. Four techniques for time-shift estimation were used for the analysis:

〉 Signals Correlation (SC). This technique uses the correlation function to measure the similarity between two ultrasonic signals acquired at two different conditions, each one formed by *N* sampling data. When the correlation function between the two signals, composed by 2*N*-1 data, reaches its maximum possible value, the signals become superposed totally and the measured displacement, in this concrete situation, will be the delay between both signals [1][2].

〉 Quadrature Demodulation (QD). The principle of this analysis is to consider the echo signal as a signal modulated by phase quadrature, where the carriers are signals with central frequency equal to the one of the echo and the envelope is the modulating signal. In order to estimate the echo time displacement, it means, the for obtaining the phase angle between two signals acquired at different conditions (for instance, for distinct temperatures), it is necessary to consider the phase of each echo signal with respect to a reference signal, and to apply the quadrature demodulation [3][4].

〉 Phase difference (PDf) & Phase displacement (PDs). Both methods analyze the temporal displacement of the echoes by means of the calculation of the phase changes that the ultrasonic signal suffers with a situation change, based on the calculation of the analytic signal:

$$\aleph = s(n) + i s_{Hi}(n) \quad , \tag{1}$$

where the phase of the original signal is defined as:

$$\rho(n) = \tan^{-1}\left({s_{Hi}(n)}/{s(n)} \right) \quad , \tag{2}$$

When the relation between phases of the echo signals and the echo depth is lineal (Phase difference), the temporal displacement is determined multiplying the subtraction of both phases by a coefficient, which represents the relation between phase difference and time displacement.

In the case, when linearity between the phase signals and the echo depth does not exist (Phase displacement), the time displacement between the phase curves has to be determined in a different way. Once phase curves are obtained, by means of the equation (2), the time displacement of the echo is calculated by means of a bi-dimensional interpolation of the phase values and the points corresponding to the echo depth of the phase second signal to the phase values of the first phase signal. In this way, the points corresponding to the echo depth of the second signal are modified, and the time displacement between both signals can be determined by means of the subtraction of both values of echo depth (its equivalent in the time domain) for the same value of phase [3].

Our quantitative efficiency analysis in the present work, was divided on two examination stages:
A) The first objective was to measure the precision of the results obtained by each USPA, applied to four groups of multi-echo signals (two experimental and two simulated), with regard to an established reference. This reference, for the simulated cases, was the time delays calculated by the algorithm that simulated the signals produced by successive temperature changes; and for the experimental cases, was the time delays measured during the signals acquisition at different temperatures. Once defined the references, a comparison between them and the results obtained by the four techniques was made for the 4 groups of signals. The data of the time displacements were graphed with respect to temperature rise and an average error with respect to its reference was calculated for each case.
B) To evaluate the sensibility to the noise present in an ultrasonic signal, a simulated noise signal, with an average power such that the SNR was equal to I) 3 dB y II) 6 dB, was added to one group of the simulated signals (composed by 7 echoes). The noisy signals were processed by the four time-shift techniques, and the obtained data with each of them were graphed versus temperature rise, to observe their behavior and evaluate the performance of each technique in presence of a high level of noise. For techniques that show a great sensibility to noise, a wide sweeping was carried out, from a signal with a SNR of 60 dB to a signal with a SNR of 120 dB (in steps of 2 dB), focusing on the minor amplitude echo (i.e. the most affected by the noise) in order to determine an immunity threshold for each one of these methods. All multi-echo signals were segmented in data windows that contained an echo each one before the processing.

Ultrasonic Echo-signals

Four sets of signals were generated for the analysis: two of them were acquired by means of a experimental pulse-echo interrogation set up (Figure 1) of a biological tissue phantoms (based on a mixture of agar, tri-distilled water and glycerol [5-7] to mimic ultrasound velocity on tissue) submitted to a controlled and uniform temperature conditions. A transducer with a central frequency of 2.25 MHz (I2C-0204-S Harisonic, Staveley NDT Technologies) was used, and far field conditions in its radiation was considered for signal acquisition.

The first phantom contained four layers of glass mini-spheres regularly spaced, and it was submitted to a temperature rise from 25°C to 50°C in steps of 1°C. The second phantom contained nylon threads uniformly distributed in seven layers, and it was interrogated in a temperature range from 30°C to 50°C in steps of 2°C.

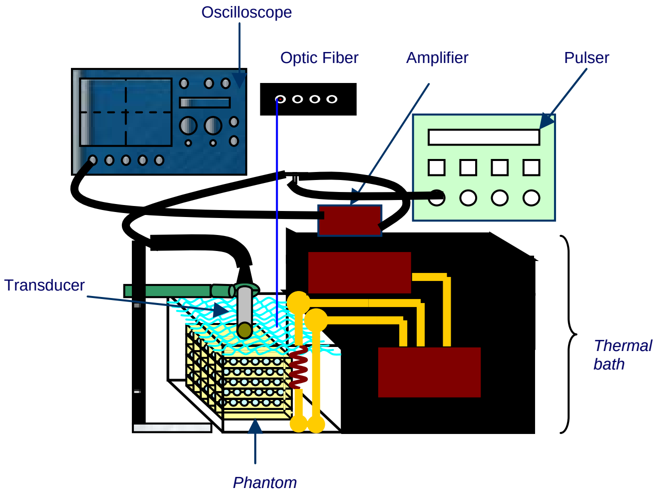

Figure 1. Experimental pulse-echo interrogation set up

The other two sets of signals were numerically simulated by means of a computational algorithm and considering to reproduce the conditions of the experimental signals sets. The acoustic modeling of biological tissue consider that it can be represented as a semi-regular lattice of scatters spaced by a uniform distance "d" [8-10] and that the echoes coming from this type of structures could be considered as a delayed sum of the elemental echoes from scatters. This basic modelling [10] of the elemental echo-signals is employed in this analysis, because the interest of our analysis is exclusively focused on time displacement of echoes phenomena, and acoustic diffraction effects can be neglected.

The simple pattern of the ultrasonic pulse used for an elementary echo coming from a punctual reflector is calculated for far-field conditions, by an expression very usual in this type of applications:

$$\xi(t) = -e^{-4(\beta\omega)^2 t^2} \times t \times sen(\omega_0 t) \quad , \tag{3}$$

where $\beta\omega$ is the bandwidth of the ultrasonic pulse, ω_0 is the central angular frequency of the pulse band, and *t* is the time.

Finally, the whole signal received from the irradiated medium, by an ultrasonic transducer, could be considered as an overlapping of all the echoes produced by each one of the reflectors contained in the involved zone.

RESULTS AND DICUSSION

Precision Analysis

Time displacements were obtained applying the 4 USPA's for each set of signal. Data was graphed versus temperature rise. Figures 2-5 show temporal displacements obtained with SC, QD, PDf and PDs techniques, respectively. The displayed time-shifts represent the "echo delay", nevertheless, the echo has a positive displacement (an advance in time), which can be interpreted as a negative delay; for this reason, time displacements are negative. A practically linear relation between echo time-shift and temperature can be appreciated in the graphics for simulated echoes, but there is a notorious quadratic trend, in the behaviour of echo time displacement with respect temperature rise, in the experimental signal cases (C) & (D).

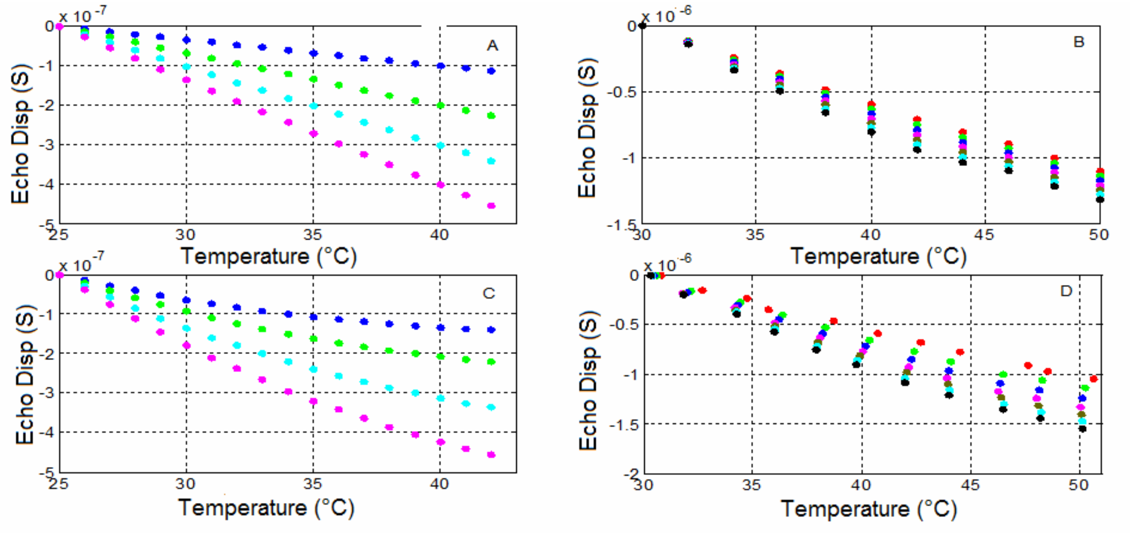

Figure 2. Temporal displacements obtained with SC technique. A) 4 echoes simulated signal, B) 7 echoes simulated signal, C) 4 echoes experimental signal (mini-spheres phantom), D) 7 echoes experimental signal (nylon threads phantom).

The errors of the resultant displacements were calculated for each one of the four techniques (applied to each group of signals) with regard to a reference, initially for each window, and later they were averaged to obtain a final error. The average errors obtained for the simulated signals containing four and seven echoes are shown in Table 1 and Table 2 respectively; and averaged errors obtained for the experimental signals (containing 4 and 7 echoes) are shown in Table 3 and Table 4. The smaller error, in all cases, is the obtained by the signal-correlation technique, followed by the phase difference technique and the phase displacement technique. The bigger error, in all cases too, was obtained by quadrature demodulation technique.

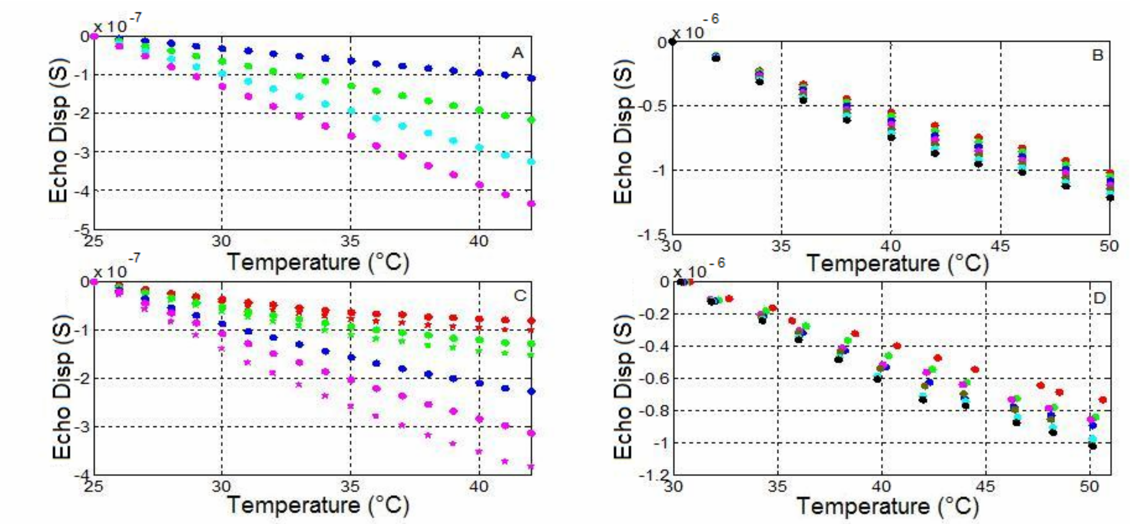

Figure 3. Temporal displacements obtained with QD technique. A) 4 echoes simulated signal, B) 7 echoes simulated signal, C) 4 echoes experimental signal (mini-spheres phantom) D) 7 echoes experimental signal (nylon threads phantom).

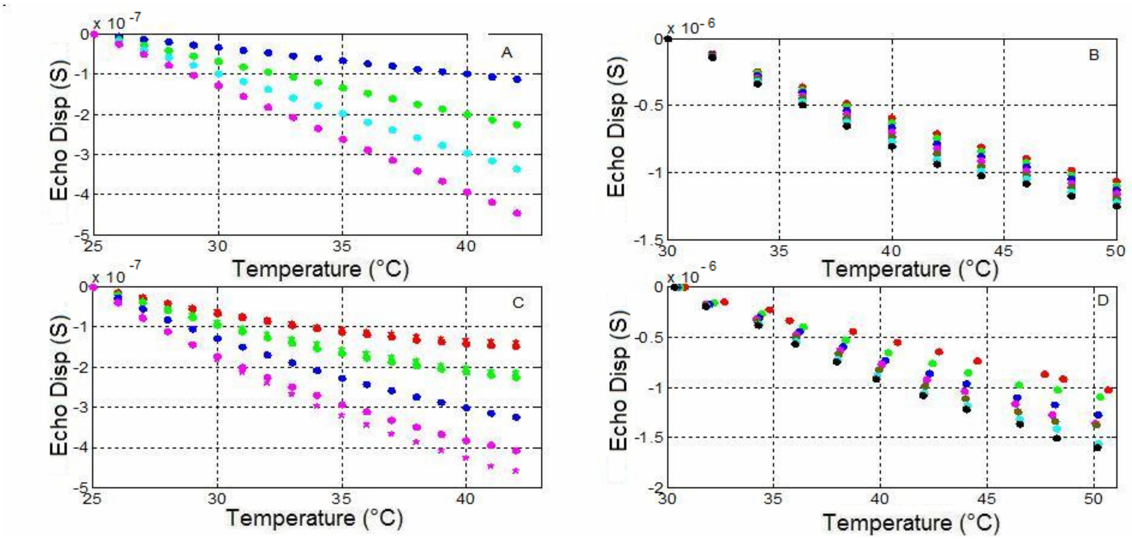

Figure 4. Temporal displacements obtained with PDf technique. A) 4 echoes simulated signal, B) 7 echoes simulated signal, C) 4 echoes experimental signal (mini-spheres phantom) D) 7 echoes experimental signal (nylon threads phantom).

From the data presented in the four previously mentioned tables, it can be concluded that the most precise technique, due to the smallest error values obtained in all cases is the signals-correlation technique. In the other hand, the quadrature demodulation technique presented the largest errors in all the cases, attaining values that become not acceptable for our purpose.

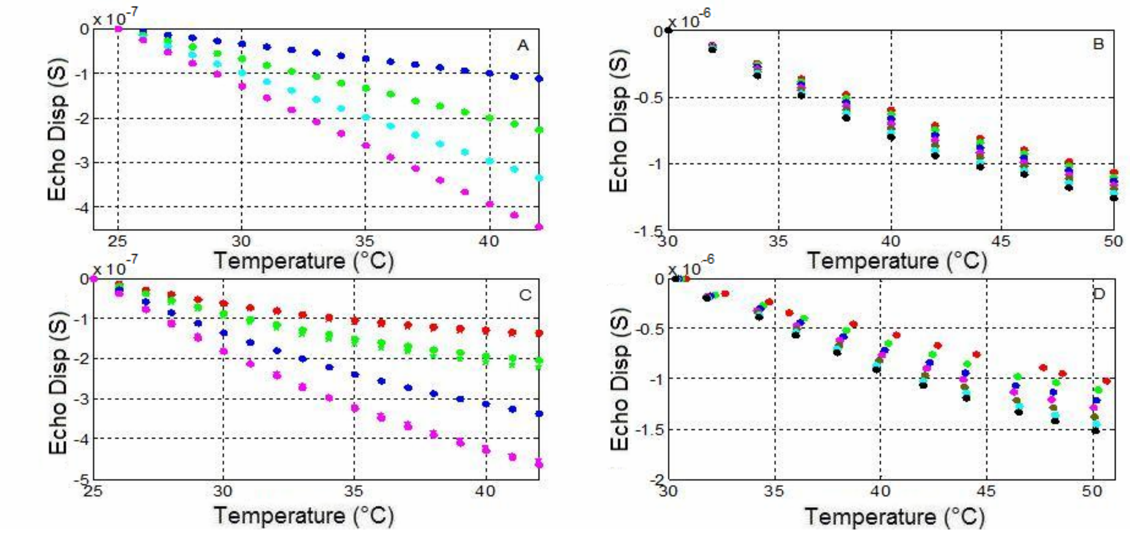

Figure 5. Temporal displacements obtained with PDs technique. A) 4 echoes simulated signal, B) 7 echoes simulated signal, C) 4 echoes experimental signal (mini-spheres phantom) D) 7 echoes experimental signal (nylon threads phantom).

Table 1. Average errors for simulated signals with four echoes

Window	SC	PDf	PDs	QD
1	1.11E-10	2.39E-10	1.22E-09	2.53E-09
2	0	3.38E-10	1.17E-09	4.95E-09
3	5.56E-11	3.34E-09	4.39E-09	7.39E-09
4	1.67E-10	7.11E-09	8.06E-09	9.88E-09
Average	**8.33E-11**	**2.76E-09**	**3.71E-09**	**6.19E-09**

Table 2. Average errors for the simulated signals with seven echoes.

Window	SC	PDf	PDs	QD
1	3.09E-10	4.87E-09	3.09E-10	4.41E-08
2	2.55E-10	7.04E-09	1.93E-09	4.62E-08
3	3.45E-10	7.41E-09	1.33E-09	4.75E-08
4	3.09E-10	8.43E-09	1.36E-09	4.94E-08
5	2.73E-10	9.73E-09	1.40E-09	5.17E-08
6	2.73E-10	1.13E-08	1.65E-09	5.39E-08
7	2.91E-10	1.27E-08	1.78E-09	5.60E-08
Average	**2.94E-10**	**8.78E-09**	**1.39E-09**	**4.98E-08**

Table 3. Average errors for the experimental signals with four echoes

Window	SC	PDf	PDs	QD
1	2.00E-10	1.59E-09	2.81E-09	3.61E-08
2	1.09E-09	1.57E-09	1.09E-08	5.69E-08
3	6.89E-10	4.72E-09	8.67E-10	6.55E-08
4	2.14E-09	1.44E-08	1.71E-09	9.43E-08
Average	**1.03E-09**	**5.56E-09**	**4.07E-09**	**6.32E-08**

Table 4. Average errors for the experimental signals with seven echoes

Window	SC	PDf	PDs	QD
1	6.84E-09	3.01E-08	2.12E-08	1.75E-07
2	5.93E-09	1.66E-08	1.71E-08	1.81E-07
3	4.58E-09	5.22E-09	1.93E-08	1.93E-07
4	3.47E-09	7.95E-09	2.13E-08	2.72E-07
5	4.62E-09	8.93E-09	1.75E-08	2.73E-07
6	5.33E-09	1.60E-08	1.53E-08	2.87E-07
7	3.07E-09	1.52E-08	1.45E-08	3.02E-07
Average	**4.83E-09**	**1.43E-08**	**1.80E-08**	**2.40E-07**

Sensibility to Noise Analysis

In order to perform this analysis about the sensibility of the distinct methods with regard to the noise, the noisy simulated signals with 7 echoes were processed by means of the four methods. The behavior of the displacements of the first echo in the time domain, obtained with each method of estimation, for a SNR= 3 dB, is shown in the Figure 6.

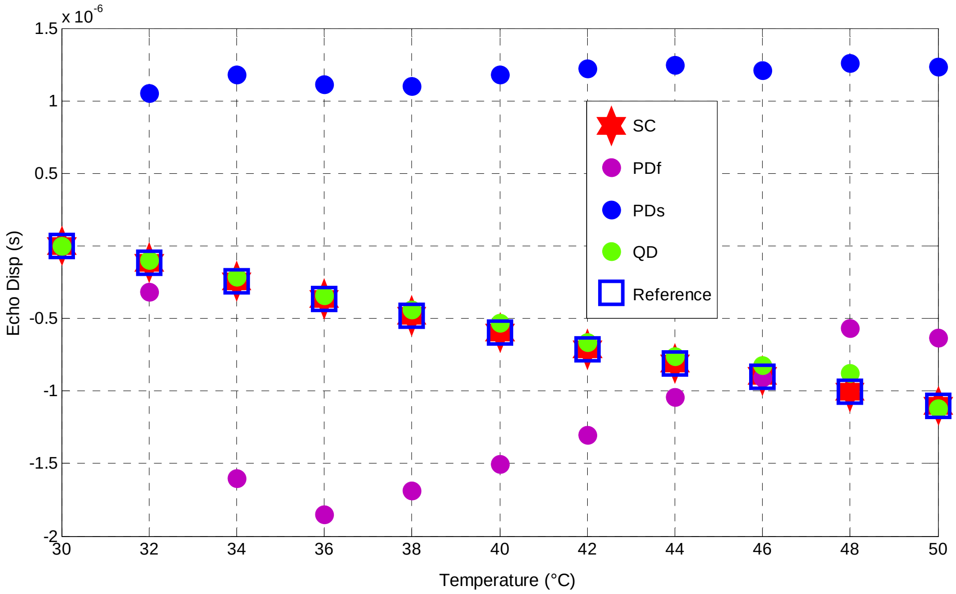

Figure 6. Echo time-shifts obtained with the 4 estimation methods
for the simulated signal with seven echoes.

The averaged errors of the displacements of the first echo with respect to the reference displacement, obtained for the SC and QD methods applied to ultrasonic signals with SNR = 3dB, SNR = 6dB, and without noise (0 dB) are shown in Table 5.

Table 5. Averaged errors for SC and QD methods

Average Error (ns)			
SNR	Without noise	6 dB	3 dB
Signal-Correlation	00.30	00.70	00.78
Quadrature Demodulation	44.37	48.90	45.00

The PDf and PDs methods were the most affected by the presence of noise. For these reason both methods were submitted to a specific analysis, in order to determine an immunity threshold for each one of them. A sweep was performed from a signal with a SNR = 60 dB to a signal with SNR = 120 dB in steps to 2 dB. The analysis focused in the smaller amplitude echo.

According to the described clinical protocol in [11], the temperature precision required in a thermometry system for certain kind of treatments (temperature elevation of 37 °C - 46 °C) must be of 2 °C, which (based on the observed displacements of the reference echo and considering a linear relation between displacement and temperature) corresponds to a displacement of 13.2 ns into the seventh window of our echo-signals. The phase difference method presents an average error of a) 12.7 ns for the signal without noise, b) 25.9 ns for the signal with a SNR = 80 dB, and c) 12.8 ns for the signal with a SNR = 120 dB, for the seventh window.
The method of phase displacement, present an average error for the seventh window of: a) 1.7 ns in the case of the signal without noise, b) 15.2 ns in the case of the signal with SNR = 80 dB and c) 11.8 ns in the case of the signal with a SNR = 82 dB.

CONCLUSIONS

In all the cases, analyzed here, the signal-correlation method was the most precise technique for time-shift estimation, providing the smallest temporal errors with regard to a reference, for the four different groups of signals analyzed.

The temporal technique based in the quadrature demodulation provided an error of more tan 50 times of that produced when cross-correlation technique is used.

Phase difference and phase displacements techniques presented error values situated between those associated to these two abovementioned methods.

With regard to the noise sensibility, signal-correlation and quadrature demodulation showed the best results, preserving their behavior even when signals with a SNR of 3 dB are processed.

With regards to the robustness in presence of noise, the techniques based on phase difference and phase displacement present the higher sensitivity to noise. The phase difference method present an immunity threshold of a SNR =120 dB, and the phase displacement, of a SNR =82 dB; both SNRs represent a very low noise level, as opposed to the typical grain noise registered in the echoes obtained from a real tissue.

Based in the obtained results, it can be concluded that the most precise and less-sensitive-to-noise technique was that based in the signal-correlation. On the other hand, the temporal technique based in the quadrature demodulation, was robust in presence of noise; nevertheless the error obtained in its measurements is too great, even with absence of noise.

Finally, the techniques based in the phase difference and phase displacement did not originate significant errors; however, in these cases, the previous treatment must be given to the ultrasonic signals (to eliminate the initial noise), has to be very rigorous, since these two techniques lose the coherence in their results due to small oscillations in the signal amplitude, as those produced by the noise. For this reason, they are not recommendable as trustworthy estimators of temperature for noisy signals from a determinate level of noise.

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