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# Digital signal processing and numerical analysis for radar in geophysical applications

María G. Molina [a,b,c,*], M.A. Cabrera [b,c,d,1], R.G. Ezquer [c,d,e,2], P.M. Fernandez [a,3], E. Zuccheretti [f,4]

[a] *Dpto. de Ciencias de la Computación, Facultad de Ciencias Exactas y Tecnología (FACET), Universidad Nacional de Tucumán (UNT), Av. Independencia 1800, Tucumán, Argentina*

[b] *Laboratorio de Telecomunicaciones, Dpto. de Electrónica Electricidad y Computación, FACET, UNT, Av. Independencia 1800, Tucumán, Argentina*

[c] *Laboratorio de Ionósfera, Dpto. de Física, FACET, UNT, Av. Independencia 1800, Tucumán, Argentina*

[d] *Centro de Investigación de Atmósfera Superior y Radiopropagación, Facultad Regional Tucumán. Universidad Tecnológica Nacional, Rivadavia 1050, Tucumán, Argentina*

[e] *CONICET, Av. Rivadavia 1917, CABA, Argentina*

[f] *Istituto Nazionale di Geofisica e Vulcanologia (INGV), Via di Vigna Murata, 605 – 00143, Rome, Italy*

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**Abstract**

Numerical solutions for signal processing are described in this work as a contribution to study of echo detection methods for ionospheric sounder design. The ionospheric sounder is a high frequency radar for geophysical applications. The main detection approach has been done by implementing the spread-spectrum techniques using coding methods to improve the radar's range resolution by transmitting low power. Digital signal processing has been performed and the numerical methods were checked. An algorithm was proposed and its computational complexity was calculated.

The proposed detection process combines two channels correlations with the local code and calculates threshold ($V_t$) by statistical evaluation of the background noise to design a detection algorithm. The noisy signals treatment was performed depending on the threshold and echo amplitude. In each case, the detection was improved by using coherent integration. Synthetic signals, close loop and actual echoes, obtained from the Advanced Ionospheric Sounder (AIS-INGV) at Rome Ionospheric Observatory, were used to verify the process.

The results showed that, even in highly noisy environments, the echo detection is possible.

Given that these are preliminary results, further studies considering data sets corresponding to other geophysical conditions are needed.



*Keywords:* HF radar echo detection; Ionospheric virtual height determination; Time domain signal processing

## 1. Introduction

Modelling some stages and signals employed in digital radars design, using modern software tools such as Matlab©, is proposed. The simulation allows analysing the involved signals along the process, establishing qualitative and quantitative criteria over signal processing for echo detection (Mahafza, 2000; among others). This work deals with the signal processing simulation throughout the full detection process and numerical analysis of its results.

* Corresponding author at: Dpto. de Ciencias de la Computación, Facultad de Ciencias Exactas y Tecnología (FACET), Universidad Nacional de Tucumán (UNT), Av. Independencia 1800, Tucumán, Argentina. Tel.: +54 381 4364093x7765; fax: +54 381 4364093.

*E-mail addresses:* gmolina@herrera.unt.edu.ar, m.graciela@gmail.com (M.G. Molina), mcabrera@herrera.unt.edu.ar (M.A. Cabrera), rezquer@yahoo.com (R.G. Ezquer), enrico.zuccheretti@ingv.it (E. Zuccheretti).

[1] Tel.: +54 381 4364093x7818; fax: +54 381 4364093.

[2] Tel.: +54 381 4364093x7765; fax: +54 381 4364093.

[3] Tel.: +54 381 4364093x7734; fax: +54 381 4364093.

[4] Tel.: +39 06 51860324x274; fax: +39 06 51860397.

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Echo detection simulations in discrete time domain are presented.

The current trend in modern radars design for geophysical applications is to encode the transmitted signal using a proper kind of modulation. Signal coding methods are aimed to obtain a bandwidth as wide as the envelope detection technique with a narrow pulse. (Barry, 1971; Reinisch, 2000; among others). This is called "pulse compression" and makes possible to obtain high-range resolution to improve the signal to noise ratio (SNR) in received radio signals, with long transmitted pulses. This method is based on generating long duration waveforms, transmitting encoded carrier and processing the received signal by mathematical algorithms, particularly correlation (Rastogi, 1990; Ghebrebrhan et al., 2004).

The so called "ionospheric sounder" is a high frequency radar for geophysical applications, used to obtain the critical frequencies and virtual heights of the ionospheric layers throughout vertical sounding by scanning a frequency band. The virtual height representation vs. frequency is the widely known ionogram.

The detection process is based on quadrature sampling, correlation and threshold analysis for several particular cases. The ionospheric virtual height is obtained from echo delay time and amplitude information (both involved in the detection process as will be explained in Section 2.1) for a particular selected sounding frequency value of 3.5 MHz. This experiment was performed by means of signals acquired from AIS-INGV at Rome Ionospheric Observatory. Particularly, the following cases have been examined: signals without electromagnetic noise (close loop circuit in the mentioned instrument), and signals from actual received echo (Zuccheretti et al., 2003).

The paper starts with the description of coding and echo amplitude detection methods in Section 2. In Section 2.1 echo detection considerations and threshold calculation are analysed. In Section 2.2 an algorithm for echo delay time and amplitude recovery is explained. In Section 3 data analysis and results are presented. Finally in Section 4 we provide conclusions regarding the signal processing as well as the importance of a good algorithm design.

## 2. Coding and echo amplitude detection

There are two basic ways to implement the pulse compression technique: coding the frequency or the phase of the transmitted pulses, resulting in frequency-coded or phase-coded waveforms, which are the basic types of waveforms used in modern radars.

The phase-coded waveform is used in this work, in particular the phase shift keying (PSK) that makes the carrier phase changing between 0 or $\pi$ according to a sequence of binary digits (Rastogi, 1990; among others).

When using binary encoded carrier, signal processing methods are necessary to extract information from the encoded received signals in order to obtain the echo delay time and energy amplitude (Reinisch, 2000, among others). Considerations on theoretical encoding process and practical aspects on radio signals management are needed, to detect weak and noisy signals, like those used in radar design. Inside the detection process, the correlation is the mathematical tool which allows extracting the echo information. This operation recovers the code from the carrier, and by correlation with local code (LC) the echo peak is obtained, thus its temporal position represents the transmitted–received signal delay time. Once this value is obtained the ionospheric virtual height can be estimated (Skolnik, 1980,1990; Rastogi and Sobolewski, 1990; Curry, 2005).

There are several codes used in radar applications (Ioannidis and Farley, 1972), the complementary code was selected in this survey as the carrier encoding scheme. Complementary code pairs have the important property that the sum of auto correlation functions of each sequence is equal to zero for all lags, except for zero lag (Golay, 1961). General criteria in high atmosphere radars design suggest the use of codes with autocorrelation functions with high principal lobe and minimum side lobes to get echoes from noisy received signals. Sultzer and Woodman (1984) specified that the total power in the correlations side lobes should be 20% or less than the main lobe. Radio signals are affected by noise, in this scenario the detection process efficiency may decrease. In order to improve the SNR tools such as coherent integration of multiple pulse, and filtering must be used (Reinisch, 2000; among others).

The complete detection process starts after a single frequency step is performed, and the received signal is sampled. The estimation of the virtual height of ionosphere for a given frequency involves the echo detection within noisy received signals. Because both, signal reflected by the target (ionosphere) and radar noise background, result from stochastic processes the detection is a statistical method (Curry, 2005). At the end, the detection is a decision problem to distinguish if a target is present or not.

In order to achieve this, a basic detection strategy called thresholding is needed. The returned signal amplitude is compared to rms noise value. According to this, a variable threshold is set for each signal; hence if the signal exceeds it, the presence of the target can be declared (Richards, 2005).

In order to analyze the involved radio signals, this particular radar target can be considered stationary for several minutes (Rishbeth and Garriot, 1969), this ionospheric feature allows us to consider different echoes coming from the same target at the same frequency, in order to improve the SNR, by coherent integration and allows design simple and efficient algorithms with a computational complexity of $O(n^3)$, where $n$ is the number of samples involved in the process.

The detection process validation has been done by implementing the detection algorithm, with actual echo samples as input. Discrete time domain simulations have been done using Matlab©.

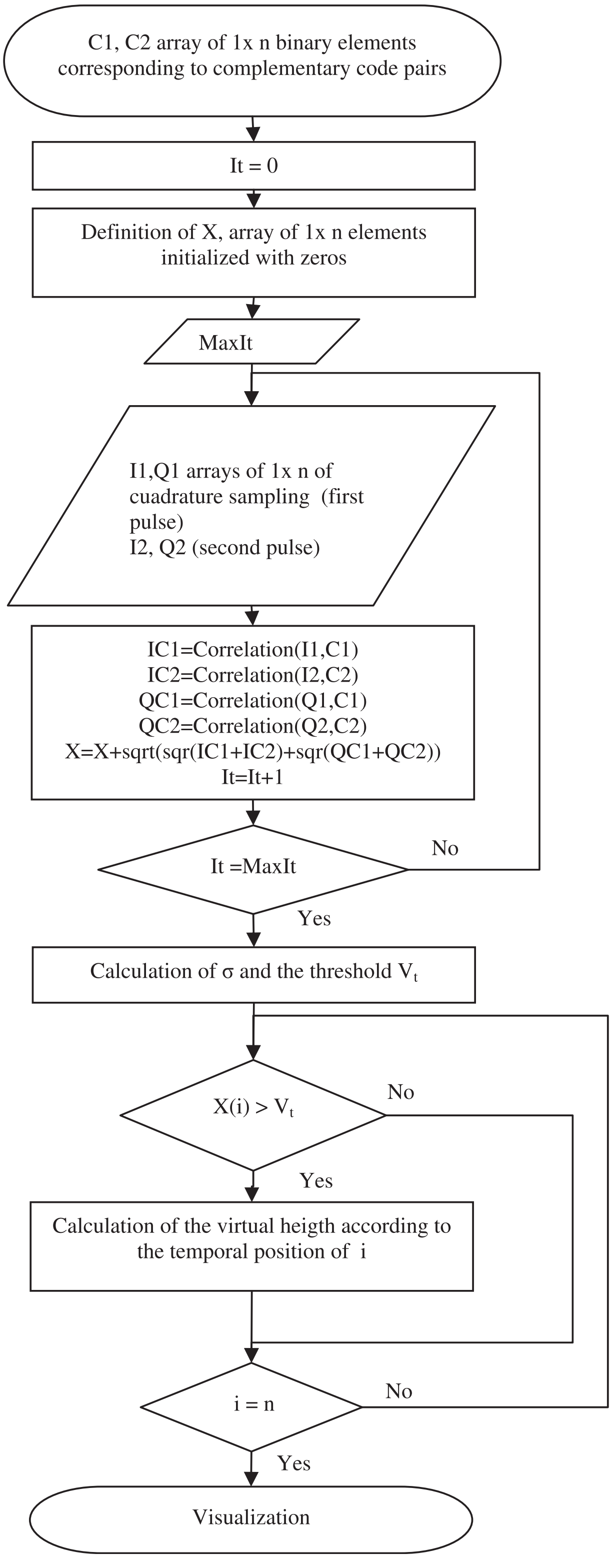


Fig. 1. Flowchart of algorithm described in this paper.

### 2.1. Echo detection considerations

Detection process involves, from a global perspective, signal encoding, correlation process and finally automatic detection; in this scenario some special considerations have to be made. The decision whether a given measurement is the result of an echo from the target or simply the effect of interference, leads to the concept of threshold (Richards, 2005). Thus, two definitions are needed, false alarm probability ($P_{fa}$) and detection probability ($P_d$). Since radar signals are best described statistically, the probability whether a target is present and could be detected ($P_d$) and the false presence of a target ($P_{fa}$) have to be estimated. Many authors (Skolnik, 1980, 1990; Barton and Leonov, 1998; among others) have shown that, if $P_d$ rises, the $P_{fa}$ rises as well. Then, the main goal is to maximize $P_d$ in a way that $P_{fa}$ does not exceed a tolerable value. In fact, the most accurate approach is to have a constant false alarm value ($P_{fa} = \alpha$) (Richards, 2005). Hence, a threshold ($V_t$) value is required to achieve the desired $\alpha$. When a given sample exceeds the threshold, a target is declared. The general idea behind thresholding involves the knowledge of the statistics for both signal and noise. In practice, and according to the sounder design, the received signal has zero-mean Gaussian distribution, and after intermediate frequency (IF) conversion the signal plus noise has a Rayleigh distribution (Skolnik, 1980; Wirth, 2001).

The threshold estimation depends on the desired $P_{fa}$ for a given problem. Since both $P_d$ and $P_{fa}$ vary together, a trade-off between them must be set. The first step is to set a desired value of time between false alarms ($T_{fa}$). This value in our case was settled at 10 s, because the ionosphere can be seen as stationary target for this period of time. Then $P_{fa}$ can be calculated as follows,

$$P_{fa} = \frac{1}{T_{fa} B_{if}} \tag{1}$$

where $T_{fa}$ is set at 10 s and $B_{if} = 60$ kHz is the IF bandwidth at the AIS-INGV (Zuccheretti et al., 2003). A typical frequency (1–20 MHz) scanning period for ionospheric soundings is 5 min. It is an usual time between consecutive soundings. But a single frequency reception and integration, as considered in this work, is few seconds long: there we want the ionosphere stability and we currently integrate pulses along 1 s and in that time interval we consider the ionosphere stable, not creating unstable targets (that are false alarms). This means that during that 1 s, false targets are generated only by noise. So 1 s coherence integration normally is enough to maintain the noise at a level so that true echoes are generally well evident. In that sense we select a new value of time $T_{fa} > 1$ s, let's suppose 10 s that is closer to a possible value for the ionospheric coherence time. This means that during this time false targets are generated only by noise. The calculated value for $P_{fa}$ is $1.6 \times 10^{-6}$.

The time between false alarms can be calculates as follow,

$$T_{fa} = \frac{1}{B_{if}} \exp\left(\frac{V_t^2}{2\psi_0}\right) [s] \tag{2}$$

where $V_t$ is the voltage of the threshold and $\psi_0$ is the mean-square value of the noise voltage. From Eq. (2) the threshold can be estimated as follow,

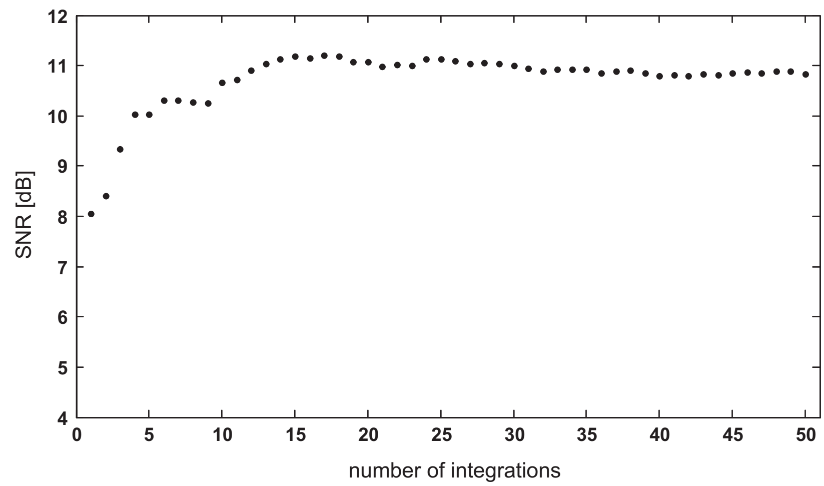


Fig. 2. SNR according to pulses used in coherent integration.

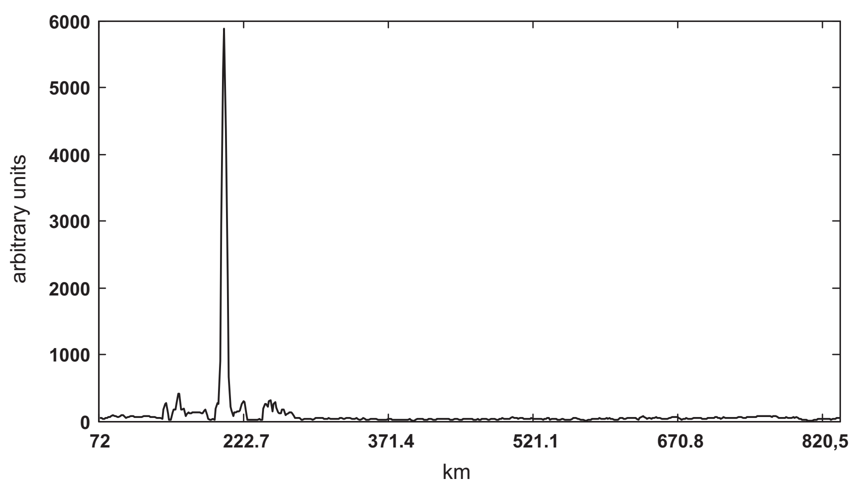


Fig. 3. Close loop signal. The virtual height at 202 km is the corresponding to the delay time obtained using the detection software.

$$V_t = \sqrt{2}\sqrt{\ln(T_{fa}B_{FI})}\sigma \quad [V] \tag{3}$$

where $\sigma$ is equal to the square root of $\psi_0$. After applying these equations, in our case, the threshold is,

$$V_t = 5.16\sigma \quad [V] \tag{4}$$

and the only parameter to be estimated is the standard deviation $\sigma$ (Skolnik, 1980). When $\sigma$ increases the threshold rises. If the threshold value is high, the target can be masked and not be declared. This situation can be improved by multiple pulse coherent integration. The $\sigma$ calculation has been done considering all the available samples in the listening time.

### 2.2. Detection algorithm

As a contribution to study signal detection for geophysical applications Cabrera et al. (2010) have used I and Q channels and correlated them with the code separately, and the signal module amplitude was obtained at the end of the process. Using the mentioned method in discrete time domain and adding a threshold ($V_t$) obtained by Eq. (4) it is possible to design a detection algorithm.

This detection algorithm estimates the delay time since a signal is transmitted to its reception and virtual height is obtained as follow,

$$h_v = \frac{c\tau}{2} \tag{5}$$

where $\tau$ and $c$ represent the delay time and light speed respectively.

After correlation between the received signal and the local code the result will produce, ideally a distinctive peak in the output that will represent the delay time ($\tau$).

The detection algorithm is shown in Fig. 1.

This algorithm uses a pair of encoded pulses with complementary sequences, thus two simultaneous pulses have to be processed. Then, for a frequency step, four arrays of $1 \times n$ elements at the input are needed, that are I1, Q1 (first complementary sequence) and I2, Q2 (second

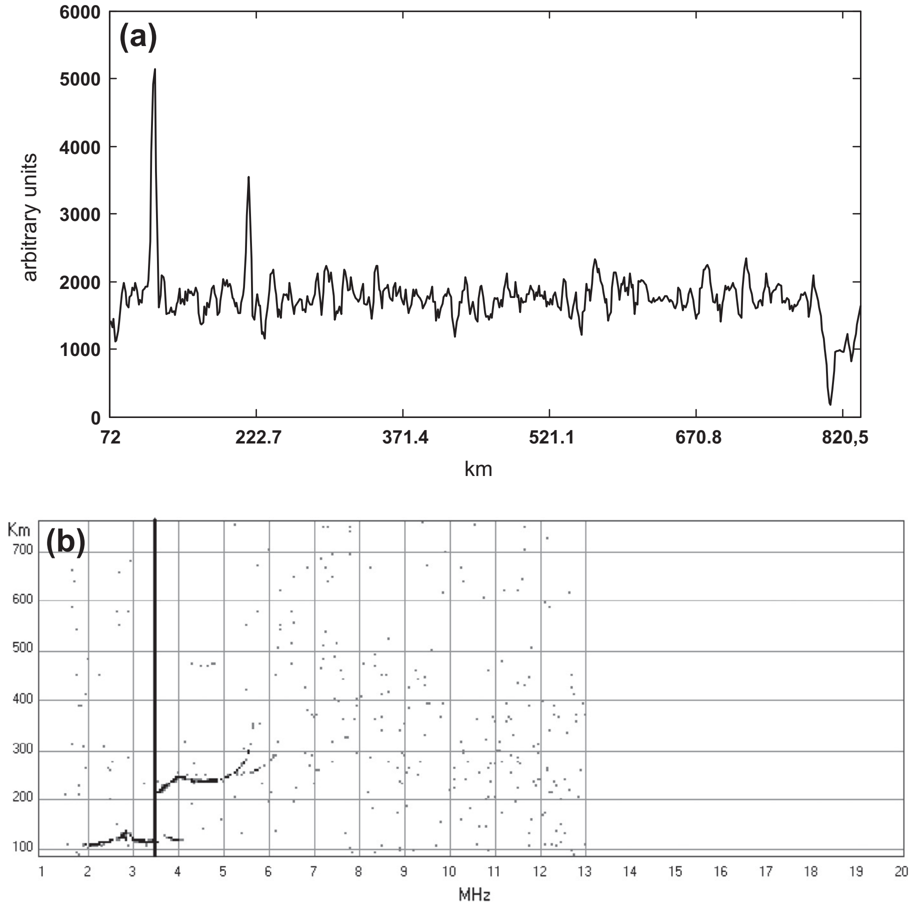


Fig. 4. a and b Actual echo sounding performed at 3.5 MHz and its corresponding ionogram from the Rome ionospheric station October 16th of 2008 at 12:20UT.

complementary sequence). The number n represents samples obtained at the analogic to digital converter (ADC) at a sample rate of 10 μs (Zuccheretti et al., 2003).

After coherent integration, the threshold $V_t$ is calculated by the Eq. (4) using standard deviation for all available samples. Each element $X_i$ is tested against $V_t$, where $X_i$ is the *i*th component in the $X$ correlation sample vector. If $X_i$ exceeds the threshold, a target is declared for the *i*-th sample which represents the echo temporal position. Finally, by Eq. (5), the virtual height is calculated.

The heaviest computational work is due to correlation function executed MaxIt times corresponding to the number of integrated pulses (see Fig. 1). MaxIt is smaller than the number $n$ of samples, so that the computational complexity of the detection algorithm can be expressed by $O(n^3)$.

Big –Oh notation allows measuring the complexity of an algorithm in the worst possible scenario. The idea is to evaluate the time complexity of the algorithm underlying the program, to estimate its behaviour as the input grows. In that case we define $T(n)$ to be the worst case running time, that is, the maximum, over all inputs of size $n$, of the running time on that input. For example, when we say the running time $T(n)$ of some program is $O(n^3)$, read “big oh of $n$ cubic” or just “oh of $n$ cubic,” we mean that there are positive constants $c$ and $n0$ such that for $n$ equal to or greater than $n0$ ($n \geqslant n0$), we have $T(n) \leqslant cn^3$. Finally the idea is to settle a bound independently of some proportionality constant.

In the proposed algorithm and using Big-Oh properties the estimation of its complexity was calculated as follow, each assignation or decision statement can be computed as O(1), but each iteration depending on n, has a cost of O(n) (Aho et al., 1987).

The final detection depends on many variables, the coding scheme used to encode the carrier, the correlation, the coherent integration and the variable threshold estimation. The number of pulses to integrate coherently was estimated regarding two main aspects, the ionosphere can be considered stationary for about 5 min and by SNR empirical evaluation on multiple samples shown in Fig. 2. Regarding the first considered aspect, it is well known that there are daily and hourly ionospheric plasma variations depending on many contributors (Rishbeth and Garriot, 1969).

Fig. 2 shows how the SNR is improving as the number of pulses increases in the integration. Ideally, if this number is large the SNR become better. This is true while the target remains stationary, but in an actual environment this hypothesis is seldom accomplished (Bianchi et al., 2003). Thus, for few pulses (under10 iterations) the SNR is unsta-

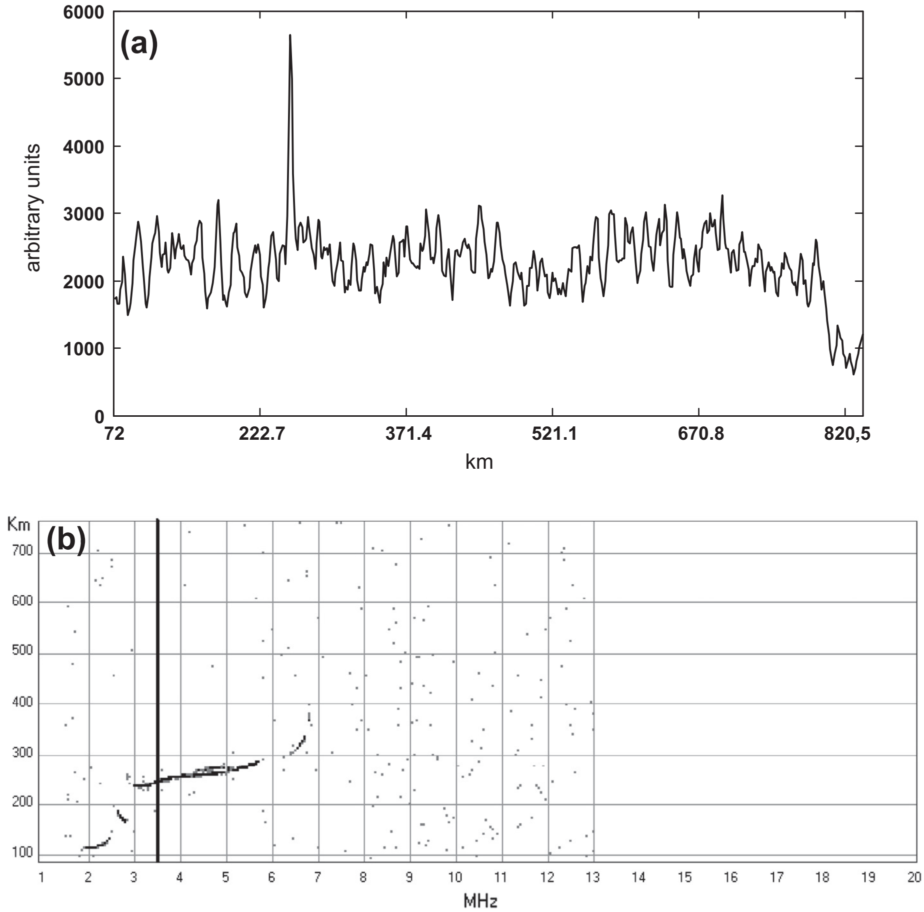


Fig. 5. a and b Actual echo sounding performed at 3.5 MHz and its corresponding ionogram from the Rome ionospheric station October 16th of 2008 at 14:20UT.

ble but after the tenth pulses the SNR is improved. After 20 iterations, the detection does not improve significantly but is almost steady, and even begins to decrease. This behaviour would suggest that the ionosphere is moving in height.

## 3. Data analysis and results

One of the key points to perform good variable threshold estimation is associated to the data reliability. The samples can be seen as time series that are often contaminated with outliers or bad measurements. These outliers appear mainly because the hypothesis of independence and equal distribution of observations is not often satisfied in practice. The effect of outliers on statistical quantities can be quite significant, so that, some decisions have to be made. The raw data was pre-processed and the outliers were identified and dismissed to avoid inaccurate statistics.

There are numerous methods to treat outliers, some of them statistically rigorous (Rastogi, 1990). In our case an algorithm consist in eliminating a number of values near the minimum. The reason for such algorithm lies in the source of the data. After correlation, the time series has two important features, (1) the values near the minimum cannot be the target because after correlation the points under the average value are those originated by noise. Those can be considered as outliers, (2) the values on the top, near the maximum, could be the target as a result of the coherent integration and cannot be treated as outlier. This criterion was checked with an exploratory visual inspection of the data sets and it is quite suitable in our case. After correlation, the simulations yielded in positive echo detection as result.

The simulations outcomes are presented for close loop circuit in the instrument and actual target echo samples in the received signals. Measurements were performed by sounding at a fixed frequency of 3.5 MHz.

The ideal detection case is to have a “clean” signal without any interference, so the echo detection is almost immediate and the estimated virtual height can easily be found. This kind of signal is useful to evaluate the simulation performance. The system, through an internal programmable pattern of delay time and attenuation has the possibility to emulate the echo signals. The result is an IF signal, called close loop signal. There is no electromagnetic noise present which allows a clean detection showed in Fig. 3 as a distinctive peak. This peak represents the delay time ($\tau$) and its corresponding ionospheric virtual height (assuming the radio waves propagation with light speed).

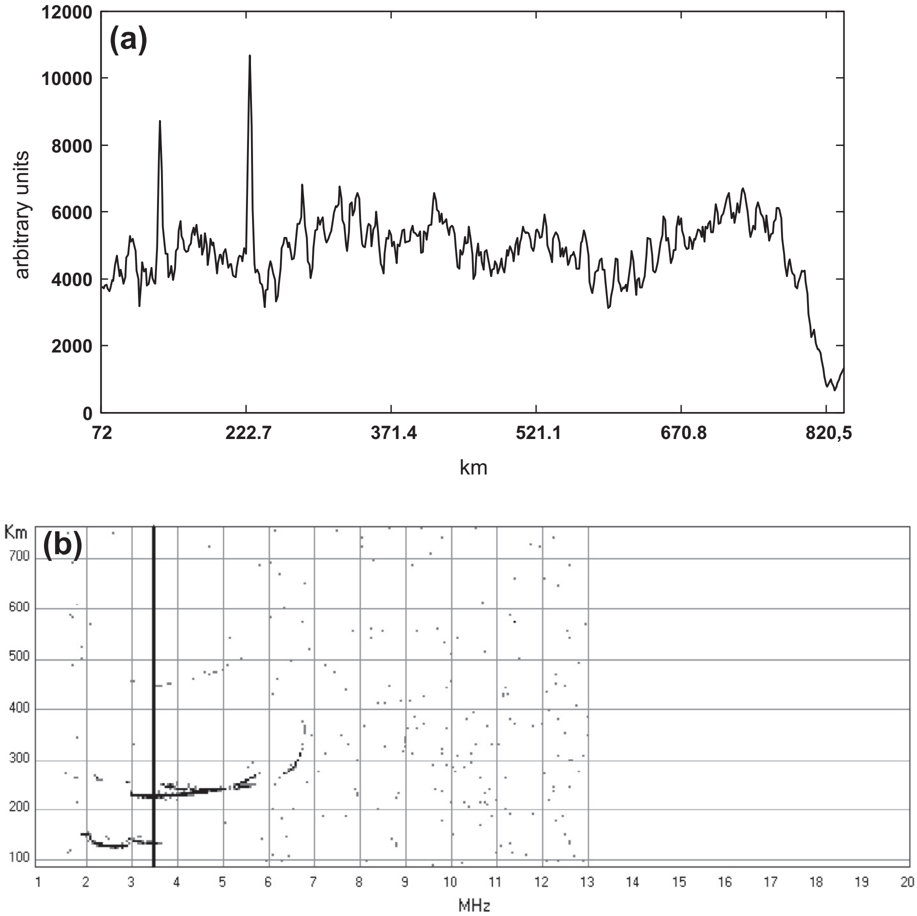


Fig. 6. a and b Actual echo sounding performed at 3.5 MHz and its corresponding ionogram from the Rome ionospheric station October 16th of 2008 at 15:35UT.

The single artificial echo was adjusted at 200 km and the simulation fits this value quite good (Fig. 3). The obtained SNR is 12 dB, which agrees with the theoretical value for encoded noiseless signals correlation (Bianchi et al., 2003).

A more realistic scenario was considered, and actual data was used as input and the simulations have been tested against measurements using ionograms images to assess target's position.

Figs. 4–6a show the echo signals after the correlation process with ten echo integrations. The corresponding ionograms are shown in Figs. 4–6b.

Fig. 4a shows the results obtained with the signal detection simulations for the first considered case. It can be seen two echoes, one at 118 km and other at 214 km. The first echo has a signal to noise ratio (SNR) close to 12 dB and the second one 10 dB. The corresponding ionogram, displayed in Fig. 4b, shows that for the 3.5 MHz frequency the virtual heights are 118 km and 214 km.

The results for the second considered case and the corresponding ionogram are shown in Fig. 5a and b, respectively. A single echo at 253 km is observed and its SNR value is close to 11 dB.

Fig. 6a and b display the results for the last case and its ionogram. It can be seen the presence of two echoes, one at 133 km and the other at 226 km. For the first echo, SNR is approximately 9 dB and for the second one 10 dB.

It can be seen in Figs. 4 and 6a two echoes coming from ionospheric layers with different amplitudes. Considering Fig. 4a the first echo amplitude is higher than the second one. This suggests that the electromagnetic wave has been partially reflected, refracted and absorbed by sporadic Es layer and finally reflected by F layer. In Fig. 6a the second echo is higher than the first one. This suggests that Es layer is more transparent compared to the situation in Fig. 4a. This phenomenon would indicate more energy refracted towards F layer than reflected by Es layer.

## 4. Conclusions

In this work a numerical solution for radar echo detection in geophysical applications was described, as a contribution to the study of echo detection methods. Signal processing for a digital ionospheric sounder was simulated using Matlab© by implementing quadrature sampling, correlation process, coherent integration and variable threshold estimation. Geophysical characteristics of involved signal had to be considered in order to implement numerical algorithms.

The proposed detection process combines two channels correlations with the local code and calculated threshold ($V_t$) by statistical evaluation of the background.

Computational and storage capability of modern computers allows a reliable design tool. Furthermore, in geophysical radar design, software development is growing in relevance. Thus, efficient algorithm design has become possible to implement in radar systems such as the proposed detection algorithm.

The preliminary simulations results obtained, for the considered AIS-INGV echo signals, show that it is possible to extract amplitude and delay time information from noisy signals using discrete time domain signal processing techniques.

Other cases with different levels of noise, single and multiple echoes in the listening windows are necessary to be considered for a more complete detection method performance analysis.

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