

Detection of Groundwater by Ground Penetrating Radar

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Abstract—The application of ground probing radar (GPR) to detection of groundwater from relatively deep aquifers in a desert environment is addressed and processing techniques to improve the detectability of a weak signal in noise and interference are reported. The study is based on simulated images from structures that have the potential of storing groundwater one of which is the buried valley structure.

To increase the signal to noise ratio to achieve a reasonable probability of detection and false alarm, various processing schemes are possible, typically employing analogue, binary (double threshold) and digital processing. Different system architectures are compared to improve detectability. Automatic detection and classification by artificial neural networks is tried to classify geologic subterranean features for aiding and speeding the process and to overcome lack of experts on the field.

1. Introduction

Figure 1 shows how losses increase with depth. Losses include attenuation, spreading losses and loss due reflection coefficient from the buried interface. The bottom layer is considered to be saturated soil giving a reflection coefficient of 0.25. Losses that depend on external influences and not on system parameters are lumped together and called external losses, they are expressed as follows.

$$Loss = \frac{\lambda^2 \sigma |\rho|^2 e^{-4 \alpha R}}{(4 \pi)^3 R^4} \quad (1)$$

where λ is the wavelength, σ is the scattering cross section, ρ is the reflection coefficient and R is the interface depth. For a planar interface the scattering cross section is given as $\sigma = \frac{\pi \lambda R}{4}$, which is the first Fresnel zone [1].

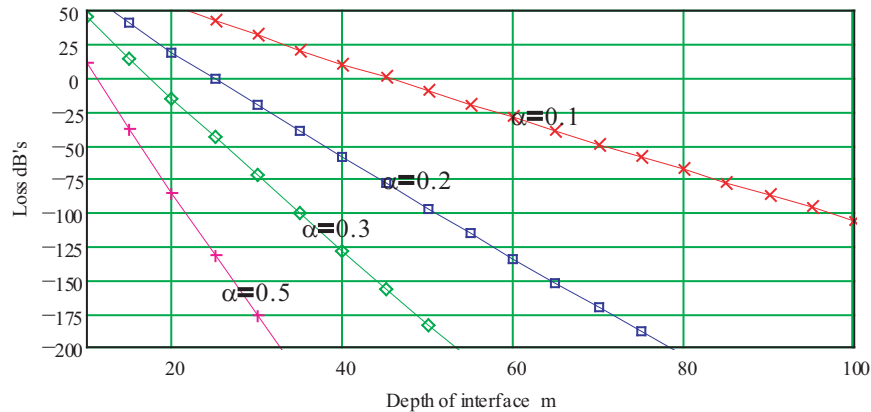


Figure 1: A monogram showing how losses increase as functions of depth and attenuation.

2. System comparison

Different detection techniques are compared. The processors that are compared are digital, binary and step frequency.

2.1. Digital Pulsed System

This is a pulsed radar having a digital processor assuming the use of swept gain amplifier which compensates for attenuation due to the range of each scatterer.

The system gain before digitisation is chosen so that interference and noise would not exceed the input range of the ADC full scale ratio (FSR) for an acceptable time duration (implying a large probability that the interference is within the FSR). Assuming that the input to the ADC is Rayleigh distributed. If the FSR to be equal to 10σ implies saturation for only 1% of the time. The amplification factor satisfying the 1% saturation criterion is 48 dB (for a FSR=10 V) and 23 dB (for a FSR of 0.54 V).

The noise level without amplification is -64 dBm and the interference power is -34 dBm and if the bandwidth is increased to 20 MHz (a pulse duration of $0.05 \mu\text{s}$) the noise will be -61 dBm and interference will be -31 dBm. It is seen that interference is the dominant factor and therefore the time required to increase the output signal to noise ratio for the digital processing would be equivalent to that of an analogue system. Therefore, an 8 bit ADC would probably be adequate.

Table 1: Quantisation noise and amplified input noise and interference.

FSR, V	Quantisation noise for an ADC with the number of bits in dBm			applied gain dB	amplified noise dBm	amplified interference dBm
	8 bits	10 bits	12 bits			
10	-9	-21	-33	48	-16	13.2
0.54	-34.3	-46	-58	23	-41	-12.3

2.2. Pulsed Radar System with Binary Integration

The binary integrator has a threshold device that generates 1's or 0's depending on whether the input to the device has exceeded a certain threshold voltage or not. After detection noise alone has a Rayleigh probability density function and the sum of the signal and noise has a Rician probability density function.

The next summing device taking the input from the threshold device will count the number of 1's obtained from a collecting a set of pulses. If the total exceeds a certain number (k out of m) which is a type of (digital) threshold, a target is declared. The input to the threshold device has a signal to noise ratio defined as the ratio of signal voltage to standard deviation of the noise and is given the symbol a , [1].

The signal to noise ratio of the quantised video is defined as $\rho = \frac{p_s - p_n}{\sqrt{p_n(1-p_n)}}$, where p_n is the probability of obtaining a quantised pulse (binary 1) due to noise alone and p_s is the probability of obtaining a quantised pulse when the signal is present. The signal to noise ratio of integrated video is $SNR_{out} = \sqrt{m} \rho$ where m is the number of integrated pulses. For an input signal to noise ratio of -37 dB (this is when assuming the radar has a transmitted power of 10 W and a pulse duration of $0.05 \mu\text{s}$) $\rho = 8 \times 10^{-5}$ for input $SNR = -37$ dB, $m = \left(\frac{SNR_0}{\rho}\right)^2$, making the number of pulses that are needed for integration to be about 4×10^9 . The output SNR being 7 dB. The time to collect data is about 22 hours for a prf of 50 kHz.

The choice of the second threshold k out of m is

$$k = SNR_{out} \sqrt{m} p_n (1 - p_n) + m p_n + \frac{1}{2} \quad (2)$$

Therefore, k is 8×10^8 and so if the number of 1's exceeds 8×10^8 then a target is declared.

2.3. A Step Frequency Processor.

The radar system transmits a sinusoid and measures the magnitude and the phase angle of the received signal. It does this for a group of sinusoids forming the spectral components of the time domain signal that we want to synthesise and then an IDFT is performed to obtain the reflected signal in the time domain. This must be the point of comparing data obtained by the step frequency and the pulsed radar systems. At the input to the display device the value of signal to noise ratio must 7 dB to have the same probabilities of detection and false alarm as that of the pulsed system. The step frequency (SF) radar can be operated with an instantaneous narrow bandwidth making the input noise and interference to remain low and therefore quantisation noise may become dominant.

2.3.1. A radio Frequency Digitising System

Figure 4 presents a step frequency system digitising the signal at radio frequency.

A step frequency radar system with a system noise factor of 10 is considered, a transmitted power of 1 W, a bandwidth of the preselector filter of 1 kHz, a pulse duration of 1 ms and a burst repetition frequency of 1 kHz. The number of frequency spectral samples is 40 (20 MHz effective bandwidth with a frequency step of 0.5 MHz). The signal to noise ratio at point A is the thermal noise is $kTfB = -134$ dBm and the atmospheric noise (being 30 dB above thermal) is -104 dBm. Interference power is -75 dB (not allowing for low interference bands) and if low interference bands are utilised, it would be about -115 dBm (the power spectral density of interference in these bands is about -145 dBm/Hz).

The number of bursts that has to be collected and integrated is determined by the need to bring the signal to noise ratio at point C to that is required at point D. Considering an ADC having 8 bits and an FSR of 10 V,

the signal to noise ratio at point C would be -71 dB. The number of bursts that are needed for integration is about 6.4×10^6 . The integration is coherent and so it is assumed to have an improvement that is $\propto N$. If the FSR is made 0.54 V with an 8 bit ADC and no gain is applied, the number of bursts that are needed for integration are 2×10^4 and the total time to collect all the data is about 13 minutes.

The signal to noise, interference and quantisation ratio at point B is $SNIQR = \frac{Pr \cdot G}{(Na+I) \cdot G + Nq}$.

where Na is atmospheric noise power, I is interference power, Nq is quantisation noise power and G is gain.

For $FSR = 10$ V, the gain that may be applied before clutter saturates the ADC is about 7 dB. The signal to total noise ratio (total including noise interference and quantisation noise) is -63 dB, the number of pulses to be integrated is about 9×10^5 . If the ADC has 10 bits, the time would be about 40 minutes and for a 12 bit ADC the time would be about 3 minutes. It seems that quantisation noise is higher than input noise and interference in the case of a SF radar.

2.3.2. A Proposed System

The radar system presented in Figure 4 digitises at the radio frequency which is possible at HF but if the radar operates at higher frequencies it may be difficult. There are many designs to make the ADC's work at lower frequencies by implementing a mixer to down convert the frequency either to DC or to other IF's higher than zero, all of which suffer from the inherent drawbacks of the analog components. A proposed system avoiding these problems and does not require the ADC's to work at excessively high frequencies is given in Figure 5. The system is composed of four ADC's working in an interleaved manner. The timing of sampling between the samplers is $T/4$, T is the period of the received signal.

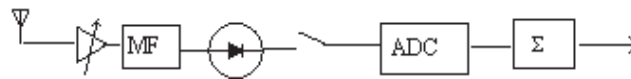


Figure 2: A pulsed digital processor.

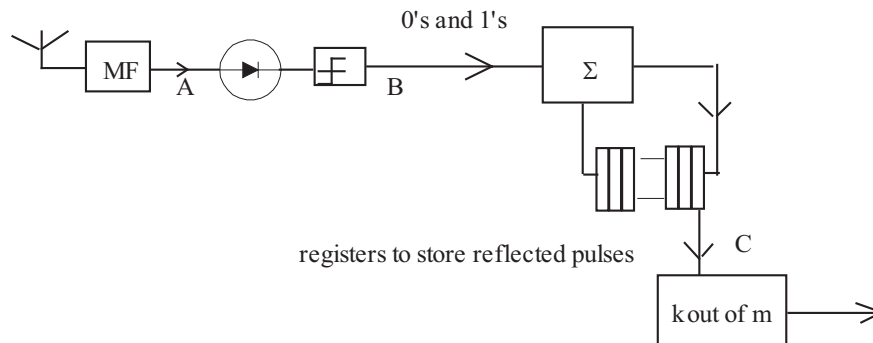


Figure 3: A pulsed system with a binary integrator.

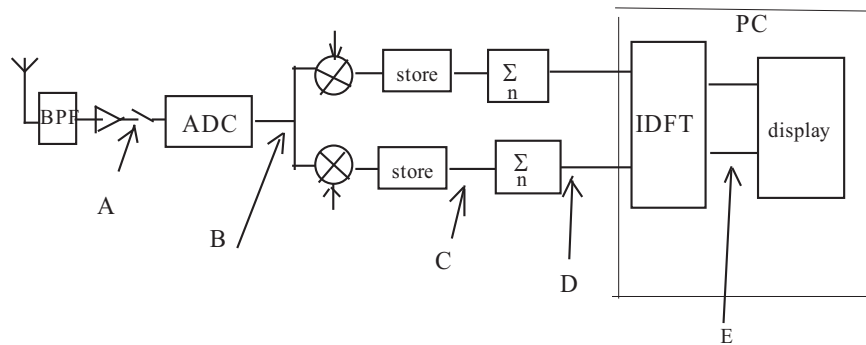


Figure 4: A step frequency processor with RF digitisation.

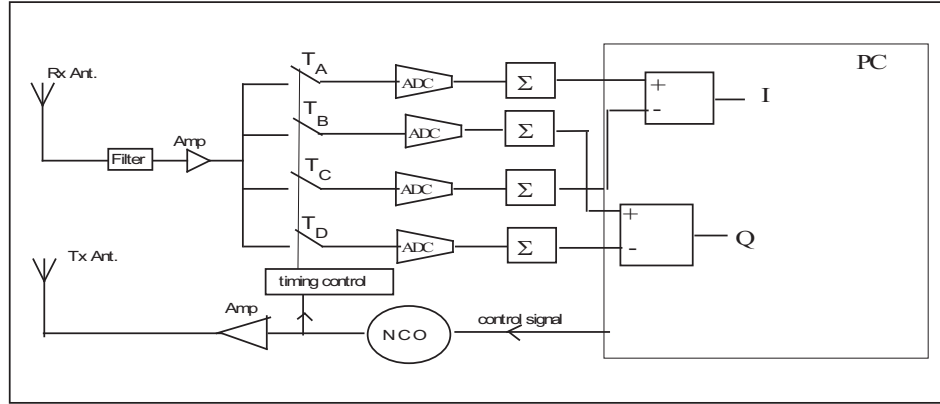


Figure 5: Schematic diagram of the proposed radar system.

2.3.3. Measurement of Amplitude and Phase Angle of a Sinusoid

The magnitude and phase of the received signal is gives by the following equations.

$$\text{Magnitude} = \frac{\sqrt{I^2 + Q^2}}{2} \quad \text{and the} \quad \text{Angle} = \tan^{-1} \left(\frac{-Q}{I} \right) \quad (3)$$

Figure 6 show a simulated traces and an image as obtained by the radar.

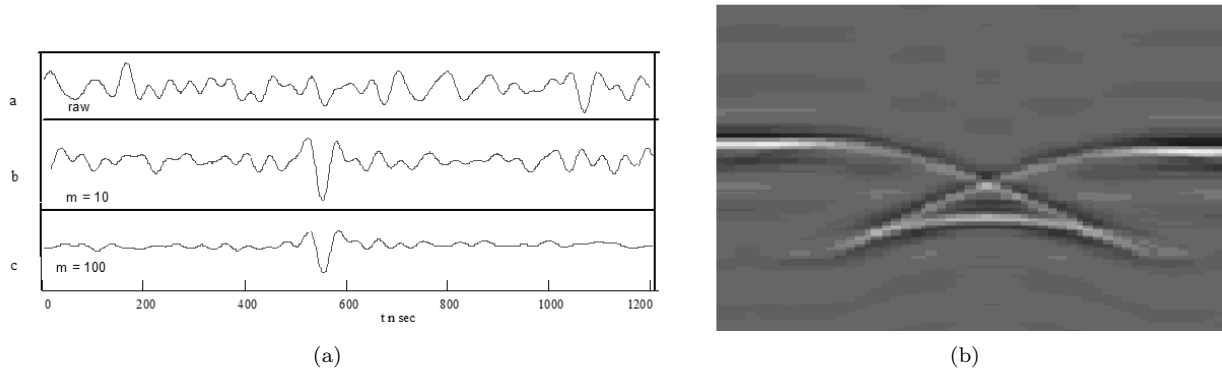


Figure 6: a) Signals after averaging repeated samples. (m is the number of averaged samples) and b) The radar image of a buried channel.

3. Artificial Neural Networks

Samples of the simulated images that were fed to the ANN's for classification are shown in Figure 7. The size of the images is 80 by 50 pixels. The structures are those of, mostly, a buried valley having different cross section shapes one of which is having a saturated zone. Another image is of a buried dome structure.

A backpropagation artificial network is used for image classification. Results provided are for the conditions of number of neurons in the middle layer being 10, sum square error is 0.1 and the SNR is 10 dB. It is found that the ANN classifier gives very high success rate.

4. Summary and Discussion

It is seen that binary integration takes longer time than analogue but it has a small word length making it simpler to implement and being low cost. Because of its simplicity, it may be possible to operate the binary integration scheme at higher prf's, allowing the time of data collection to be reduced. The Step frequency radar may operate with powers that are lower than those needed for a pulsed radar and takes shorter time to acquire the data. For SF radar, the averaging of many samples of the signal increases the SNR coherently. ANN's are useful in classifying the subterranean images.

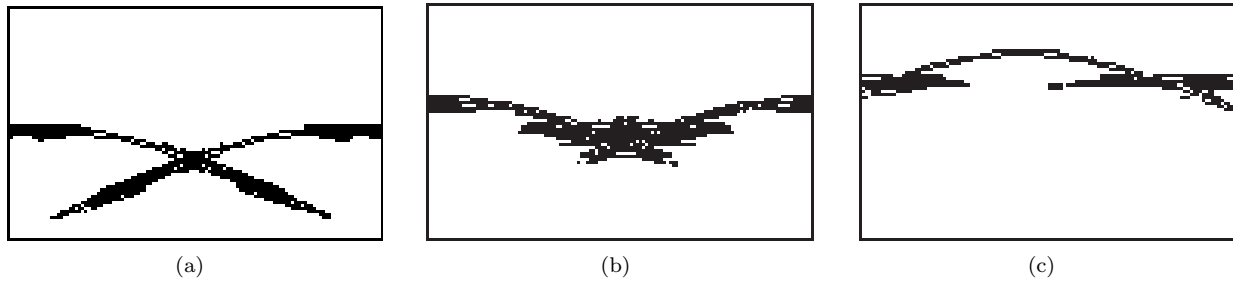


Figure 7: Samples of some images of the geological features that are used for the ANN's.

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