Sensing Groundwater in the Desert by Ground Penetrating Radar

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Abstract: - This paper addresses the application of ground probing radar (GPR) to detection of groundwater from relatively deep aquifers in a desert environment. An interesting aquifer is the buried valley aquifer due to its potential for storing good quality water and its being common in the Sahara desert. The radar system must be capable of detecting the signal being reflected by relatively deep subterranean surfaces. The reflected signals have very low signal to noise ratio which is improved by integration. The system also combats defects in the electronic components.

Keywords- ground penetrating radar, remote sensing and groundwater.

1 Introduction
Because of the relative depth of aquifers that may be as deep as 100 m, the signals reflected are degraded by the effects of the environment. These effects include attenuation, filtering (selective attenuation of higher frequencies), dispersion and clutter. The signals are also contaminated by external noise and interference [1] and [2]. Other problems are pertinent to the system components where errors and nonlinearities inherent in electronic components limit the capabilities of the system.

A radar system based on the concept of synthesized pulse or stepped frequency technique is proposed and its operation is simulated. The system has the advantage of overcoming the difficulties detecting a weak signal in the presence of noise and interference [3]. It performs coherent integration and nonuniform sampling for reduction of noise and interference effects. It combats the low-pass filtering by the ground by performing deconvolution. Some properties of the radar such as the tolerated harmonic levels and the performance of nonuniform sampling are examined. The ray tracing method is used for the simulation of reflections of signals from the buried valley structures.

Selection of the frequency of operation is a compromise between two opposing trends. As the frequency is increased the signal suffers more attenuation but the resolution is increased, but since but depth of penetration is more important so selection of lower frequencies in the HF region is a better choice as figure 1 presents how attenuation varies with frequency of operation.

2 The Radar System
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 synthesize and then an IDFT is performed to obtain the reflected signal in the time domain. 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 signal being transmitted, figure 2. Figure 3 shows the proposed architecture.
The magnitude and the angle of a sinusoid are found from:

\[
\text{Magnitude} = \sqrt{I^2 + Q^2}\quad (1)
\]

\[
\text{Angle} = \tan^{-1}\left(\frac{-Q}{I}\right)\quad (2)
\]

where \(I\) is the value of the sum of samples taken at instants \(T_A\) minus the value of the sum of samples taken at instants \(T_C\) and \(Q\) is the value of the sum of samples taken at instants \(T_B\) minus the value of the sum of samples taken at instants \(T_D\). \[4\].

Figure 3 presents the signal to noise ratio depending on the attenuation constant of the soil and depth of the reflector and how the signal to noise improves with the averaging of the reflected signals depending on the bandwidth of the receiver.

The simulated system has an ADC with 8 bits and the FSR (full scale ratio) is 5 V and hence the quantizing step is 0.02 V. The amplitude is varied to include values that are much smaller than the quantizing step and other values that are larger. In all cases the phase angle of the sinusoid is 60 degrees since angle has no effect on the system performance testing. The simulated bandwidth is 1 kHz. The distribution of the results of simulated experiments depends on the received amplitude of the sinusoid and the number of averaged samples listed below. The improvement in the SNR due to averaging is calculated and compared with what is theoretically achievable with coherent integration. The improvement is also close to theoretical coherent. Figures 5 and 6 present how standard deviation of the simulated reflected magnitude and angle decrease with increase in averaging. The reflected signal has an amplitude of 0.01 volt and an angle of 60 degrees. With added noise the measurements vary around these figures.
Fig. 5. Distribution of the measured magnitude of a sinusoid depending on the number of averaged samples, A) Number of samples is 100, B) Number of samples is 500.

The measured improvement in the SNR due to extra averaging is 7 dB which is equal to the theoretical coherent value.

3 Low-pass Filter by the Ground

Low-pass filtering by the ground is a major problem. It reduces the resolution and a process called deconvolution is applied to deal with [5]. The solutions to be investigated are; more integration at higher frequencies, transmitting more power at higher frequencies and the application of frequency dependent gain to the data before IDFT, coupled with more integration to detect these signals since they would have lower signal to noise ratios.

A signal reflected from a buried interface where the ground has a frequency dependent loss is simulated. The reflected signal from an interface at a depth 40 m will be considered. Figure 7 shows the reflected signal without noise being added to it.

The averaged signal looks noise-free but is still is not becoming narrower. Before averaging, it had a SNR of -20 dB. Therefore, it is observed that there is no improvement in the resolution due to averaging alone. Frequency dependent averaging is tried and it did not improve the resolution [4]. One technique is applying frequency dependent gain to a signal that has suffered low-pass filtering by ground.

The restoration of resolution due to low-pass filtering by the ground cannot be improved by frequency dependent averaging only. It is the application of frequency dependent gain that would combat low-pass filtering by the ground. Frequency dependent averaging, however can be used to reduce the time spent on averaging since lower frequencies have higher SNR and do not need as much averaging as the higher frequencies.
4 Non-Uniform Sampling

Due to interference by communication systems and broadcasters, some parts of the electromagnetic spectrum are occupied. It is possible to avoid the occupied portions of the spectrum by taking nonuniform measurements. There could be two solutions to the problem of sampling being nonuniform. The first approach is by using a transform that allows for nonuniform samples, the IDFT is such a transformer provided that the largest gap does not exceed some limit. The second approach is by using interpolation to obtain the value of the signal at the uniform frequency values where the data is missing. Simulated results are presented here of a signal obtained from uniform frequency sampling where the frequency steps are 1 MHz apart, and a signal obtained from samples deviating from a uniform frequency interval. The random variation is changed to see how much deviation from the uniform steps can be tolerated. If the frequency steps are shifted by a random shift away from the place of the uniform spot, the result of the IDFT is presented in figure 10.

Fig. 10: Frequency steps are shifted randomly by as much as a) 50 kHz, b) 100 kHz, c) 300 kHz and d) 500 kHz. The Dotted curve is the result of nonuniform sampling.

The operation of the radar in nonuniform sampling manner to avoid interference is possible according to the above graphs using IDFT. Nonuniform sampling produces false target when the gaps are large. The random step or the random deviation from a uniform step requirement is not very stringent. If it is necessary to leave large gaps, they could be filled by interpolation.

5 Harmonics

Harmonics are introduced by the transmitter and by active components in the front-end of the receiver. The effect of harmonics on the accuracy of
measurement of the magnitude and the phase angle of the received sinusoid are investigated. Suppose the received signal contains harmonics that were introduced by the transmitter and active circuits in the receiver input such as amplifiers and filters, we want to see how much error in measuring the magnitude and the phase are obtained by the receiver.

Assuming a signal is reflected from a buried interface that is 40 m deep and the distance between the two radar antennas is 20 m. The received signal with harmonics and the pure are plotted in Figure 12.

![Figure 12: Signals with varying harmonic level contents in dB's, (a) pure (no harmonics), (b) -20, (c) -16, (d) -14, (e) -6, (f) 0](image)

It seems that harmonic levels between -20 dB or perhaps even as high as -16 dB can be tolerated. Harmonics can be reduced by transmitting a signal with low enough harmonic content and by filtering the input signal. The requirement stated above is not stringent so that having a source with adequate harmonic purity is not a problem. A filter of third order is adequate to reduce the level of harmonics to an acceptable level, however, the introduction of a filter would cause some variable phase shift to the different frequency components. The low pass filtering by ground would also help in reducing the harmonics that were transmitted along the fundamental signal.

6 Simulated Buried Valley Aquifer

An interesting structure is the buried valley aquifer due to its potential for storing good quality water and it is being common in the Sahara desert. The ray tracing method is a common technique to simulate ground penetrating radar propagation into the ground, [6] and is used in this work. Radar images of the radar with and without groundwater are presented in Figures 3 to 5. The simulated GPR is based on the stepped frequency concept and it works from the frequency of 10 MHz to 30 MHz. The depth of the banks of the valley is at 40 m and the images span a width of 150 m. Figure 13 shows a sketch of a cross section of buried valley. Its image is presented in Figure 14. An aquifer containing groundwater is also simulated its image is shown in Figure 15.

![Figure 13: Another geological model representing an alluvial structure. The depth of the banks are 40 m below earth surface](image)

![Figure 14: An image of a dry buried valley aquifer.](image)

![Figure 15: An image of a buried valley aquifer containing groundwater.](image)
inferred from the ground penetrating radar images [7].

7 Conclusion
It can be concluded that a suitable radar design based on the stepped frequency concept and appropriate signal processing techniques would make a system that is capable of detecting relatively deep groundwater in the desert.

References