Utilizing the Vector Network Analyzer
To Work as a GPR for Detection of Hidden Objects

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Abstract:

Detection and subsequent imaging and classification of hidden objects can be done by the radar which transmits pulses and receives the reflections from the objects or targets. The radar that directs its energy to detect targets hidden under the surface of the ground or behind an obstacle such as a wall is called ground penetrating radar (GPR). There are many types of GPR's that work according to different theories. These are the pulse type, impulse, frequency modulated continues wave (FMCW) and synthetic pulse or stepped frequency ground penetrating radars. However, detection and classification of hidden targets is a very difficult task because they depend on the nature of the target and the environment surrounding it.

An experiment would involve variation the parameters of the target and those of the radar. The former is easy but the latter is difficult because one needs a radar, which is not available, and even that may not be adequate enough because a commercial radar's parameters may not be adjustable to allow for experimentation.

In this paper we utilize general-purpose laboratory equipment, namely, a vector network analyzer to operate it as a GPR. It has a wide operating frequency range and other controllable parameters. Vector network analyzers measure the magnitude and phase characteristics, these can be utilized to measure target parameters in the frequency domain and then they may be displayed in the time domain by application of the Inverse Fourier Transformation.

In this work many types of metallic and dielectric objects are placed within different types of soil and behind walls made-up of bricks and attempts are made to detect the targets.

1. Introduction

Electromagnetic energy is highly attenuated when propagating in the soil. The higher the frequency the greater is the attenuation. Nevertheless it is possible to employ radar to detect underground scattering objects if the distances are small. Radars for probing the ground beneath the surface are called Ground-Probing Radars " GPR " they have been used in a variety of applications including detection of buried gas pipes, water pipes, landmines, measurement of permeability and conductivity of coal, mapping of shallow geologic features and applications in groundwater.

Ground-Probing Radars are three types:

1. Impulse radar (VHF and UHF)
2. FM-CW radar (Microwave frequencies)
3. Stepped-frequency radar (VHF and UHF)

The impulse radar radiates a short pulse covering a wide frequency band. The FMCW radar sweeps the frequency between two limits and measures the distance depending on the difference in the frequency of the reflected signal and the frequency being transmitted. On the other hand the stepped-frequency radar transmits sequential pulses , increasing the frequency by a constant value "step" each subsequent pulse to cover the desired bandwidth. The range is obtained by measuring the phase of each step and then performing the inverse Fourier transform.

The basic principle in object or target detection is that the radar pulse reflects when strikes a boundary where there is an abrupt change in dielectric constant the range is determined by measuring the time delay between the transmitted and the received signal using the knowledge of the propagation velocity.

$$t = \frac{2R}{c} \tag{1}$$

where t is the delayed time, R is the range of the target and c is the propagation velocity.

The range resolution of closely spaced objects depends only on the signal bandwidth and is independent of the transmitted waveform, range and frequency. The equation that determines the limit of range resolution is:

$$\Delta R = \frac{c\,.\Delta t}{2} = \frac{c}{2\,.B} \tag{2}$$

where B is the system bandwidth. Also because the stepped-frequency transmits pulses in the frequency step Δf Hz, objects that extend beyond $1/\Delta f$ will cause ambiguous range responses. Mathematically, the unambiguous range can be derived as follows: The phase of a received signal due to a scatterer at range R is

$$f = {}^{4p\,.R}\!/_{l} = {}^{4p\,.f\,.R}\!/_{c} \tag{3}$$

The signal is totally described by its phase and amplitude or by its real and imaginary components:

$$\mathrm{Re} = A\ \cos(4.p.f.R/c) \qquad \mathrm{Im} = A\ \sin(4.p.f.R/c) \qquad (4)$$

The maximum alias-free range corresponding to a given frequency step size is obtained by solving (3) for a phase difference of $2p$ radians:

$$\Delta f = 2.p = 4.p.R_U.\Delta f / c \quad \text{since} \quad R_U = c/2.\Delta f \qquad (5)$$

R_U is the unambiguous range objects exceeding this value cause a folding of the true range into the unambiguous extent.

2. The Vector network Analyzer as a substitute for GPR

The vector network analyzer (VNA) can transmit signals over a wide range of frequencies to cover a specific bandwidth. The frequency step size can be changed through the available control features of the vector network analyzer. In this research we are planning to verify the ability of the VNA to work as a GPR by connecting two antennas to the VNA ports to detect the position of the buried objects.

In the simplest case the transmitted pulses will be generated with a specified frequency band which is proportional to the desired resolution. The transmitted pulse is expressed by

$$x(t) = \sum_f \cos(2.p.f.t) \qquad (6)$$

Where the quantity $(2.p.f.t)$ express the temporal variations due to the transmitted signal, the received pulses are shifted with a phase angle f relative to the transmitted pulses

$$f = 2.b.l = \frac{4.p}{l}.R \qquad (7)$$

Where R is the distance to boundary where there is an abrupt change in dielectric constant in the propagation medium, thus the received pulses are expressed by

$$y(t) = \sum_f \cos(2.p.f.t - f) \qquad (8)$$

Worth mentioning that the degree of desired target discrimination in this paper is detection and location of targets also we will attempt to estimate the dielectric constant of the propagation media through the knowledge of traveled distance and time delay of the received signal.

3. Measurements and Results:

The vector network analyzer and the two horn antennas shown in figure (1) are used to measure the phase of the transmission coefficient (S_{21}) of different objects placed at certain distance from the antennas.

The following arrangements are considered in the measurements:

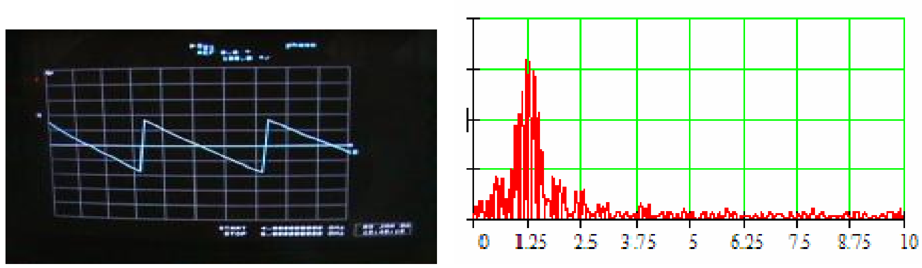
1. To have the required range resolution which 7.5 cm, a bandwidth of 2GHz or higher is used.

2. To satisfy the minimum required bandwidth of 2 GHz and a frequency step size of 40 MHz the number of points used by the VNA is 51 points, which permits an unambiguous range of 375 cm.
3. Using the "gating" property of the VNA in some results to cancel the directly leaked signals between the antennas.
4. The frequency range is from 4 GHz to 6 GHz.

Fig (1) Equipment setup: two horn antennas connecting to the VNA ports

Using Mathcad software to calculate the Inverse Fourier Transform and providing the phase of the transmission coefficients (S_{21}) to obtain the signal in the time domain. This is done for different materials such as bricks, sand and clay with reflectors and without. From time domain results of reflections the range of the target is estimated.
The following experimental cases give details of the materials used and their arrangements. The figures below show the time domain signals after the application of the IFT in nano seconds.

Case 1: The two antennas are placed face to face without any targets, the results in figure (2-a) and figure (2-b) show the insertion phase and the time delay due to the presence of the antennas. From figure (2-b) the time delay is ~1.25 nsec. This equivalent to antenna length of 18.75 cm.



a b

Fig (2) the insertion phase response and the time domain signal case 1

Case 2: The metallic reflector is placed behind a wall of single bricks having a width of about 15 cm which is at a distance of 32 cm from the antennas. The separation distance between the two antennas is 17 cm. Figure (3) shows the leakage signal at 1.56 nsec, reflections from reflector placed behind the bricks being at 5.6 nsec. The reflection at 3.1 nsec is from the front side of the wall.

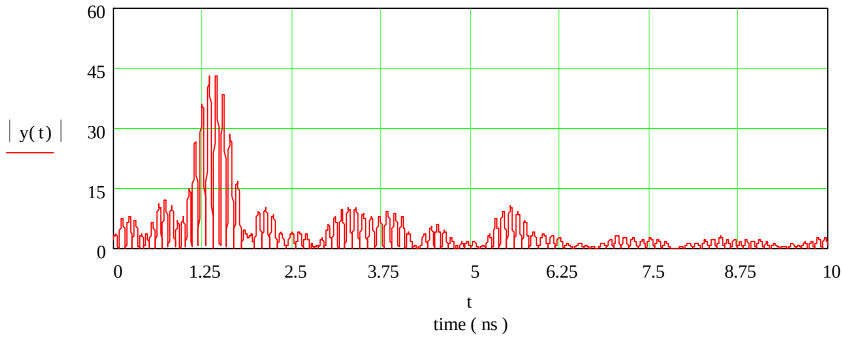


Fig (3) time domain signal, case 1

Case 3: The target is double-brick target, it is made of two adjacent bricks hence the width is ~30 cm. Its distance from the antennas is 30 cm. The antennas are placed very close to each other. Figure (4) shows the reflections from the bricks at ~3.4nsec emanating from the front face of the wall and at 5.5 nsec from the gap between the two bricks. The reflection from the back of the wall does not appear. The approximate space distance of the blocks from the antennas is ~32.25 cm. There is no metallic reflector.

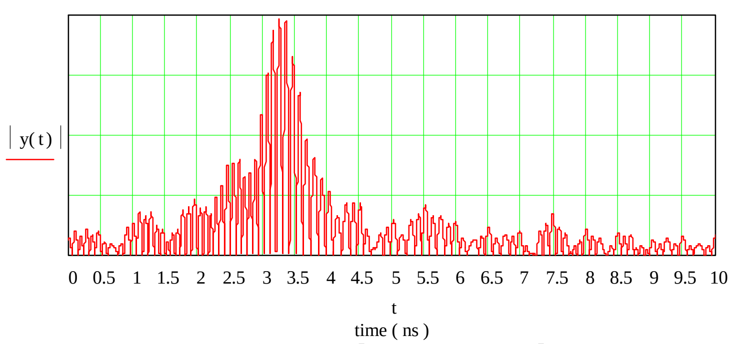


Fig (4) time domain signal, case 3

Case 4: A metallic reflector is placed at a distance of 16 cm behind a single brick wall situated a distance of 30 cm from the antennas. The leakage between the antennas has been gated out. Figure (5) shows the reflection at 3.25 nsec is from the face of the wall and the reflection at 7 nsec is from the metallic reflector.

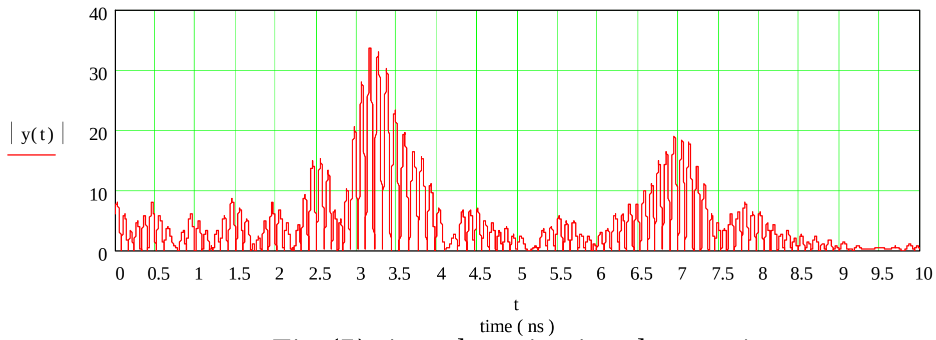


Fig (5) time domain signal, case 4

Case 5: A metallic reflector is placed at the end of the sand container of depth 18 cm, the height of the antennas is 20 cm from the upper surface of the sand. Figure (6) shows the reflections at 1.3 nsec being the leakage and reflection from the surface of the sand is at 2.6 nsec. The approximate space distance from the antennas~20 cm. The next reflection is at 4.3 nsec is from the metallic reflector which shows that the signal traveled a distance of ~25.75 cm to the position of the reflector.

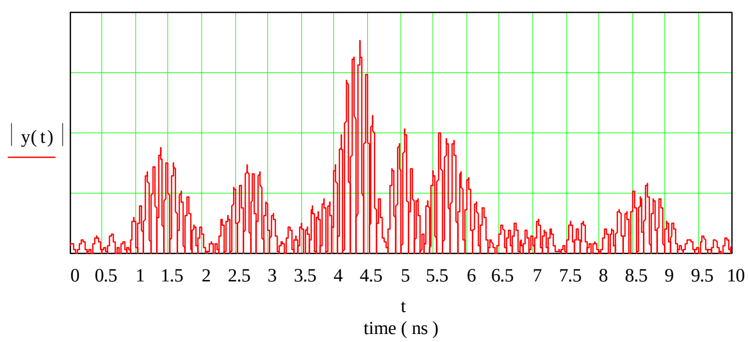


Fig (6) time domain signal, case 5

Case 6: A metallic reflector is placed a depth of 9 cm from the sand surface, the height of the antennas is 24 cm from the upper surface of the sand. Figure (7) shows the reflections from the upper surface of the sand at 2.8 nsec corresponding to approximately 24 cm, and the other reflection is at 3.75nsec which is from the metallic reflector. In this case the bandwidth has been increased to 3 GHz.

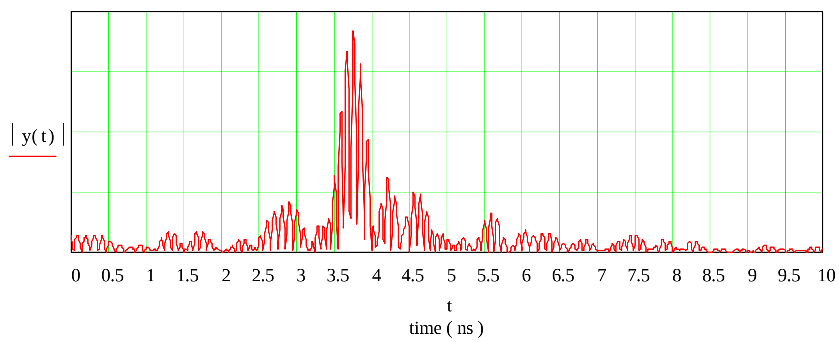


Fig (7) time domain signa, case 6

Case 7: A metallic reflector is placed at a depth of 7 cm in clay material, the antennas are at a height of 17 cm from the upper surface of the clay material, the result is shown in figure (8). Another experiment is done using a reflector at a depth of 10 cm from the surface of clay shown in figure (9) and the antennas are at a height of 15 cm from the clay surface. Even though the bandwidth was increased to 3.8 GHz but there were no apparent clearly distinguishable reflections from the metallic reflector.

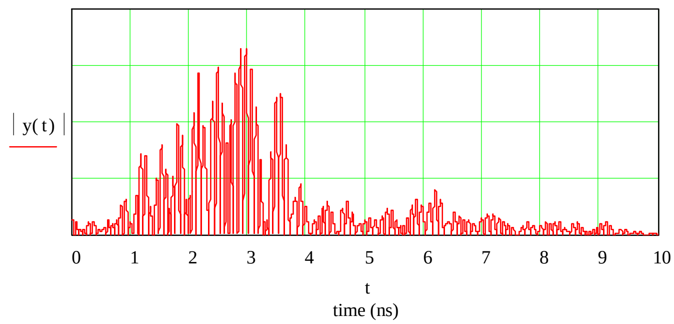


Fig (8) time domain signal, case 7

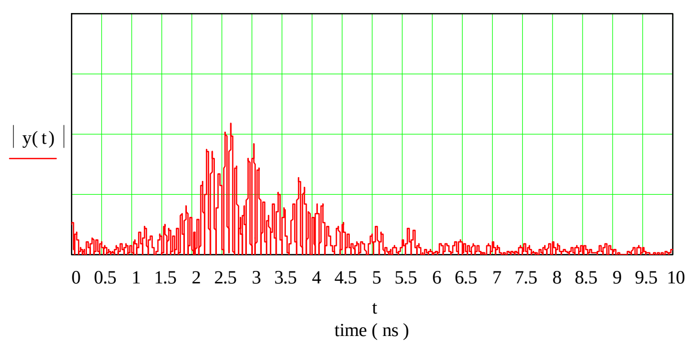


Fig (9) time domain signal, case 7

4. Conclusions and future work

From this work we can draw the following conclusions:

- The vector network analyzer can be used as a stepped frequency ground probing radar
- The "gating" property of this network analyzer is a very convenient feature because it removed the directly leaked signal between the antennas which is big problem in detection of small and close targets to the antennas such as landmines. They can easily masked by the leakage signal.
- The target buried in sand can be detected without difficulty.
- Clay has high attenuation property, especially when wet. We expect that it has a high moisture content since it was collect few days after the rain. In our case we were not able to estimate the moisture content of the clay nor the other materials.

Further work can be done by including more natural and industrial materials with controlled moisture content. It is not too difficult to estimate the relative permittivity and conductivity of the materials from the experiments.

5. References

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