Ground-Penetrating Radar for Fiber Duct Localisation

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Abstract

This paper treats a radar application, of ground-penetrating radar to be used in construction sites for locating ducts and identifying what they hold. We will start by going on a brief introduction about what are radar systems and ground-penetrating radars, as well as, its applications and the most commonly used metric for evaluating such systems, the radar range equation. Then we will cover the desired requirements for our application, such as, range resolution, depth penetration, form factor and some other functional requirements, and a general description of its workings. After defining our requirements, we will go on with the implementation of the application itself. We will adapt the radar range equation to our application's scenario and study various types of conditions in which the application will be used. Then we will calculate the radio noise ratio, taking into account all kinds of thermal resolution needed. For the final part of the implementation, we will briefly talk about power consumption. With the system complete, we will go on to the discussion, where we mainly address the challenges of actually locating targets and be able to distinguish them. Concluding our report, we will discuss how our system meets the desired requirements and compare it to the ones used on the market to see if they can be used on the field.

1 Introduction

Before going into detail about our application, we must first know what a radar is. A radar is a detection system that uses radio waves to determine the range, angle, or velocity of objects. It usually consists of a transmitter producing electromagnetic waves in the radio or microwaves domain, a transmitting and a receiving antenna, although it is often that the same antenna is used for both transmitting and receiving, and a receiver and processor to determine properties of the objects. The way a radio system works is that it transmits waves (pulsed or continuous) to the target that will be reflect off and return to the receiver, giving information about the object's location and speed.

To evaluate the performance of a radar system, it is often used an expression called the radar range equation:

$$P_r = \frac{P_t G_t G_r \lambda^2 \sigma F^4}{(4\pi)^3 R^4} \tag{1}$$

In the equation P_r stands for power received while P_t means power transmitted. G_t and G_r represent the gain of the transmitter and receiver, respectively, λ is the carrier wavelength, σ is the radar cross section of the target, F is the pattern propagation factor and R is the range from the radar to the target. Since our transmission will be in the ground, F will not be equal to 1. This equation represents the physical dependencies of the power transmitted by a propagating wave up to the receiving of target and then back propagation. Our system will be a ground-penetrating radar, or GPR, that will be used for locating fiber ducts in construction sites, which are usually buried around $2m$ below the ground. GPR is a geophysical method that uses radar pulses to image the subsurface. This method allows its practitioners to detect objects that are buried underground without the need to excavate the ground. In construction, being able to locate ducts without actually having to excavate is a huge benefit since there is a chance that the duct is in a slightly different place from where it was first placed or since you may not know where they are at all. Also, this method is non intrusive and it is among the cheapest methods working with almost any type of soil since it can penetrate most materials with ease. Like any radar, the principle it uses is to send some form of radiation, in this case electromagnetic radiation in the microwave band (UHF/VHF frequencies) of the radio spectrum, and then to detect the reflected signals from subsurface structures[1].

GPR has many other uses, from prospecting for gold nuggets and diamonds in alluvial gravel beds to study soils and bedrocks. It is also a method used in archaeological geophysics and to find unexploded ordnance and detecting tunnels by the military.

2 Application description and requirements

There are some requirements that this application needs to answer in order to be fully functional and operational.

2.1 Form Factor

The first requirement this application needs to fulfill is a practical and easy to use form factor. Since this system will be used in the field, which includes fields with rough soils or big fields that could take some time to locate the ducts, it needs to have a shape that allows its users to easily move it and handle it. Another reason for the friendly compact is that in order for the GPR to detect its target, it requires to be moved since it needs to detect the differences in the material return signal of its target. Taking that in consideration, it also needs all the elements to make it functional, such as an antenna, a power supply and also a control unit to make it easier to analyse the readings it gets from the ground.

2.2 Range resolution and penetration depth

In terms of range, our application does not need a great range resolution since most ducts are usually buried 2m from the ground level. Although the range resolution is not one of the application's big requirements, penetration depth is one of them. Since some soils can be really moist or contain other high conductivity materials, materials that can absorb or attenuate GPR signals, the depth of the penetration will be heavily reduced or limited.

2.3 Efficiency and efficacy

The last requirement that our application needs to fulfill is the ability to distinguish between different targets and materials. Since its main purpose is to locate ducts, it also needs to interpret what material or substance is in it, be it water, fiber or even other materials. Besides the ability to distinguish materials, it also needs to make fast measurements in order to improve efficacy and efficiency.

3 Radar system implementation

For our implementation we first had to consider what were the main differences between a radar system which propagation medium is in air and ours would be through a solid. In the best case scenario this solid will be homogeneous and will be weakly absorbent so our electromagnetic radiation can propagate for a long distance giving of a good penetration depth. A critical factor is the size of the system since it need to be capable of being deployed in a convenient form factor out in the field so we can relay on making a large gain on a trade off between gain and power

4 Radar range equation in a medium

Our first concern is modeling our radar system, as was discussed previously the radar range equation is generally the mathematical description we use to get some type of understanding of what we should expect from the design system as is shown in Eq.1. In our case we cannot use this description since our radiation propagates through a solid medium which attenuates our signal. The model selected to describe our system was developed by the National Bureau of Standards (NBS) as presented by W.E Thain [2]. This model is based on the radar range equation but it takes into account the loss attributed to the medium by a medium absorption coefficient and a set of parameters to include a contribution of the air-surface medium change as show in Ref.2.

$$P_R = \frac{P_t G_t G_r \lambda^2 \sigma}{(4\pi)^3 R^4} ICDe^{-4\alpha R} \tag{2}$$

The parameters are the same as shown in Eq.1 the main change in this model is the factor $F^4 \approx ICDe^{-4\alpha R}$ where this factors play a role in modeling the boundary change and the absorption of the material as follows:

- I = two-way power transmission at the air/soil interface, accounting for dielectric differences.
- D = dispersion effect due to the medium resulting in pulse stretch and subsequent amplitude reduction
- C = factor accounting for the two-way refraction at the air/soil interface.
- α = the attenuation factor of the complex propagation constant.

It is also worth mentioning that the wavelength also changes with the change in refractive index in the medium making our wavelength $\lambda = \frac{\lambda_0}{n}$, where λ_0 is the wavelength in free space. Since our model has a large dependence on the material lets take an over view of how the refractive index and the attenuation factor are connected to the dielectric constant ϵ. Fundamentally in physics we describe a material mainly by its Dielectric constant which is a relative measurement compared to vacuum $\epsilon_r = \epsilon/\epsilon_0$. As deduced in Ref.[2] the attenuation constant is related to the dielectric constant, the permeability $\mu_r = \mu/\mu_0$ and the conductivity σ' as follows:

$$\alpha = \omega\sqrt{\mu\epsilon}\left[\frac{1}{2}\left(\sqrt{1+\left(\frac{\sigma'}{\omega\epsilon}\right)^2}\right) - 1\right]^{\frac{1}{2}} \tag{3}$$

Usually we assume that materials have low permeability $\mu_r \approx 1$ and have a well known conductivity so we focus more on the relative dielectric constant ϵ_r. In general one relies on experimental data for the attenuation factor that have been previously computed, some measured values for the dielectric relative constant in Table.1 for some of the materials we would be interested in studying with our radar system.

Material	ϵ_r
Air	1
Seawater	81
Dry Sand	5
Dry Granite	7
Soil	2-20
Dry Cracked concrete	4-5
Asphalt	12-16

Table 1: Typical relative Dielectric constant for selected materials [2].

Even though one can calculate the expected attenuation constant in a real implementation this will be set by an experienced operator that can do a good enough estimate of the soil and set it accordingly in our system to get a reliable range measurement. One can find a detail literature for large set of soils where we can determine the experimental value for the attenuation, for example Fig.1 is a measurement for black clay with some sand and rocks which was very cohesive.

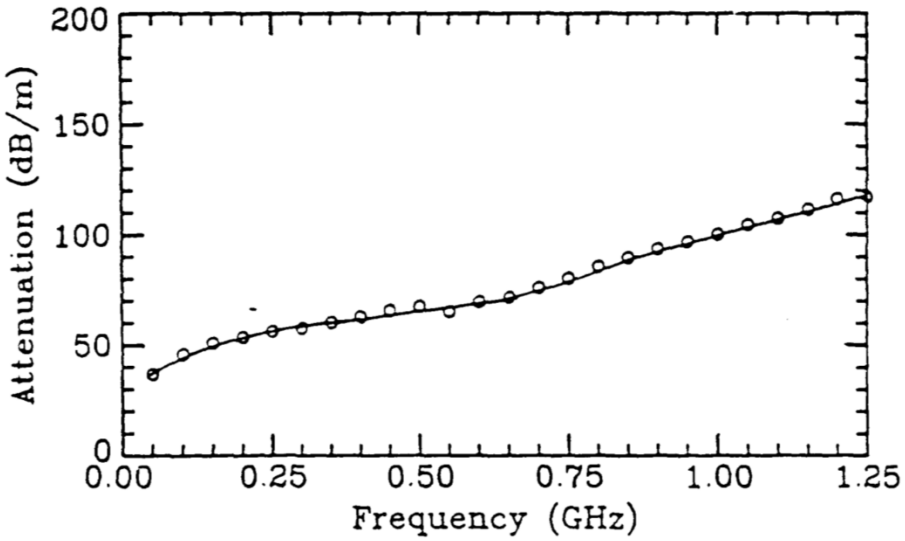


Figure 1: Attenuation coefficient for black clay with some sand and rocks, very cohesive for different frequencies [2].

Now that we can describe the attenuation of our material we are interested in the the losses associated with the air/soil interface. We are going to simplify the assumptions for our GPR analysis by assuming a mono-static system $G_t = G_r$ and will neglect the factors C and D. These parameters can be neglected since their overall contribution did not have much impact on the analysis.

The main objective is to construct a radar system that can help identify ducts that potentially have cabling that potentially could be optical fiber for example. Therefore, we have information about our target and can make an estimate of the cross section assuming that it is an infinite cylinder with radius a. We take a geometric optics approximation[3] and consider that Radar Cross Section is given by:

$$\sigma \approx R\pi a \tag{4}$$

4.1 Signal Noise Ratio

Now that we have most of our parameters defined our interest is to make a numerical estimation for the antenna gain to determine its effective area. To do this we need to determine what would be a tolerable signal to noise ratio SNR if we consider the receivers thermal noise given by :

$$P_n = kT_sB \tag{5}$$

where k is the Boltzmann's constant ($1.38 \times 10^{-23} \frac{Ws}{K}$), T_s is the noise temperature and B is the band width. We can take some expected values for our band width from other GPR systems as the one in Ref.[4] and as also discussed in the radar design segment in Ref.[2] a Pulse Repetition Frequency of 5 MHz which gives a Pulse Repetition Frequency Interval of 200 ns . The air/soil interface change acts as a low-pass filters to electromagnetic radiation, also due to the soils attenuation characteristics, for a good depth penetration a low-frequency RF energy is required. In contrast high resolution requires high-frequency energy. In our case the resolution and penetration depth are known since ducts are mainly in a range of 350 $mm - 3$ m under ground and our resolution can be in the order of magnitude of centimeters. A first estimate for the pulse width taking into account what was discussed and implemented by Ref.[2][4] would be a sine monocycle of a pulse width of 1 ns. We can compute the bandwidth of this pulse to be the inverse of the pulse width giving $B = 1\ GHz$ which is a fair trade off implemented in current GPR systems.

For the noise temperature there is literature that covers the subject, we get some experimental values for our system from Ref.[5] where they find that $T_s = 111K$ for a detection system temperature of $303K$. Know that we have some estimates of the thermal noise we can find the SNR [6], which is given by taking the ratio of Eq.2 and Eq.5 which gives:

$$SNR = \frac{P_tG^2\lambda^2\sigma}{(4\pi)^3R^4kT_sB} Ie^{-4\alpha R} \tag{6}$$

An assumption that we are going to make is that the SNR should be effectively around 20 dB and that is numerically demonstrated by Thain [2] where they also give a value for $I = 0.458$. The refractive index is related to the dielectric constant as $n \approx \sqrt{\epsilon_r}$ and from Table.1 we select a value of 12 giving us $n \approx 3.46$. The RF frequency that we are going to choose for our implementation is 400 MHz is based on what can be found in the market of GPR systems currently in the range specified previously and as is demonstrated in Ref.[4] and shown in Table.2. Considering the band width the GPR system outputs a range of frequencies from 400 MHz to 1.4 GHz, to model this system we will look at the this set of frequencies. From this we can determine the range of wavelengths from 21 cm to 6 cm which is quite a large spectrum.

Frequency	Depth
400 MHz	2.5m
270 MHz	3.5m
200 MHz	7.5m

Table 2: Typical penetration depths for different frequencies in a homogeneous medium [4]. This will change slightly depending on the material.

At this point we have defined all the parameters needed to get information about the product of antenna gain and emitted power, so we continue to make our numerical estimate. For the RCS we know that the average diameter of a duct is $a = 32\ mm$ giving $\sigma = 0.2\ m^2$, and we used a $\alpha = 2.3\frac{dB}{m}$. Plugging all this to Eq.6 we get:

$$PG^2 = 43.13 \rightarrow G = \frac{4\pi A_e}{\lambda^2} = \sqrt{\frac{43.13}{P}} \tag{7}$$

Now the average power of a commercial antenna and GPR system at 400 MHZ is 40 mW so that is what we are going to use also. Therefore, we can estimate the effective area A_e for the upper limit of our wavelength range needed, which gives an area of $0.275\ m^2$ thus making it a simple antenna to construct with an approximate size of 10 cm by 2.72 cm which is what we need for our implementation since both dimension of the antenna are large than a complete wavelength of all the frequency range. At this point we have our system completely characterized except what could be its total power consumption.

For duct detection it is not necessary to have a high resolution since we know that they are at certain depth we just need to know their location in the scan plane. We can find the minimum range by the following expression:

$$Resolution > \frac{v}{2B} \tag{8}$$

the speed v is the speed of propagation inside the medium. Our resolution is theoretically limited to around 1 cm, experimentally we actually find that the resolution would be about 15 cm. This is a good resolution for the objective needed.

4.2 Power Consumption

An estimate of the power consumption is done by looking at similar radar system with small form factor. In general the power consumption is in a range of 6 W to 8 W depending on the penetration depth and frequency[7]. Since our proof of concept has been carried out by looking at the commercial components available, we consider that a power consumption of 8 W is a choice that is cost effective and has commercially available components to build the system. For this type of power supply we would require it to be a high-power with a High DC voltage output, which in general as mentioned in Ref.[3] this type of systems have a 20% to 40% efficient.

5 Discussion

With our GPR system now our interest shifts to what we can actually detect and how to distinguish between different targets. We looked at examples of images collected by similar GPR system that are available on the market that have close specification to our system[4]. Our main interest is to detect ducts but we need to be able to distinguish between ducts that have a liquid flowing and metal bars or ducts that have cables running through them.

Our radar system can give us this type of information, but it requires a trained user to be able to distinguish the differences. We give some examples that were taken form Ref.[4] where they studied a controlled homogeneous soil with different types of ducts. First we look at solid metal pipes under ground in Fig.2, all the pipes are the same but we can see that they are set at different depths, one can observe that the lower the pipe the larger the parabola is. Thus, the size of the hyperbola gives us information about the depth of the target. With this we can distinguish between different targets that might be at a close range from each other.

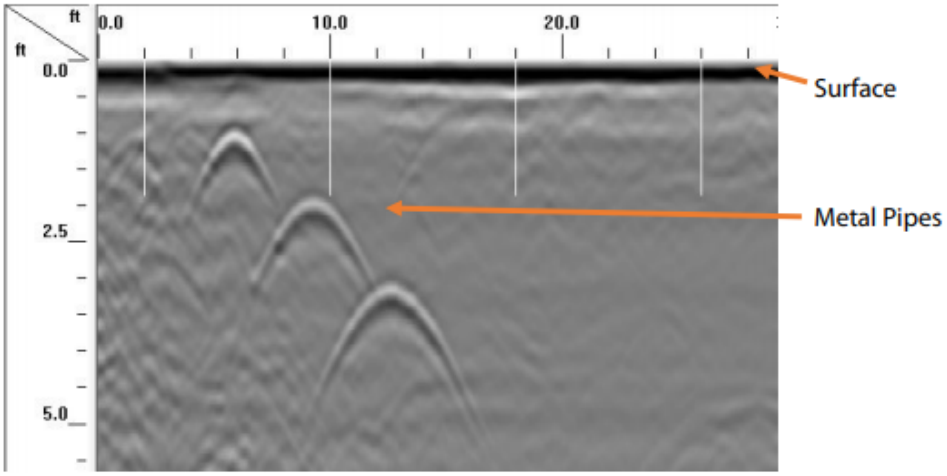


Figure 2: GPR signal for three metal targets of the same diameter. Note how the deeper the target is, the larger the hyperbola is [4].

One can interpret range from our system by the collected data, now how do we determined the content that is inside. In Fig.3 we have a comparison between a metal pipe and an empty PVC duct, first this system is similar to what we are interested in since the fiber ducts are commonly made from PVC and are in most part empty since the cables inside do not fill in all the space. The metal pipe gives us a target that is solid with large reflection which is similar to what could be found near a fiber duct water tubing, etc. Now how can we distinguish between this two systems, again a trained eye is needed but in general we can see that there is a slight difference in opacity. This is because a PVC pipe or non-metallic conduit in soil produces low-amplitude hyperbolas of the same shape as hyperbolas from metal targets. PVC is nearly transparent for RADAR, so targets inside or underneath a PVC pipe can still be visible. This means that we do not directly detect the PVC, we detect whatever is inside of the PVC. This is preciously what we need, but then how does a PVC duct look when it has multiple cables inside

would be our next question.

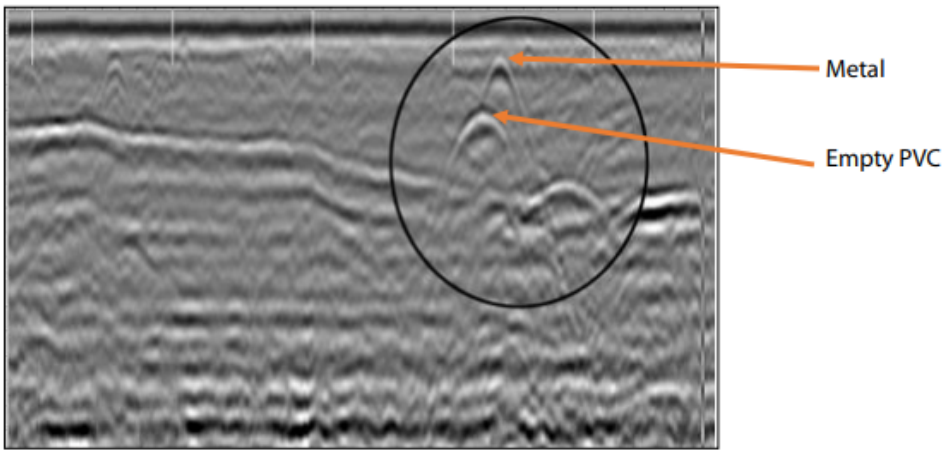


Figure 3: A metal and PVC pipe giving off signals with different opacity where the PVC has small amplitude [4].

Now, as would be expected if we have a PVC duct full with cables, the return signal can be distinguished since the PVC is almost transparent to RF signals what we detect would be the cables inside. As is seen in Fig.4 the signal is multiple hyperbolas coming form the same place, this would be the return signal of all the cables inside. One with enough training could give an estimate on how many cables are inside and if they could be fiber cables that is the target that we are interested in.

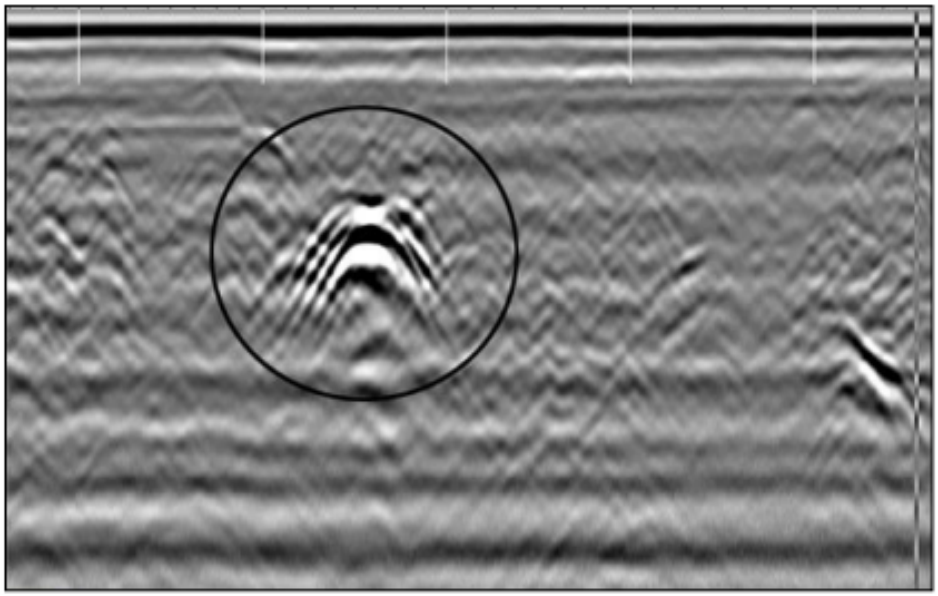


Figure 4: Return signal form a PVC duct with multiple cables running threw it. We detect the return signal of all the cables inside the PVC duct [4]

There are multiple trade offs that were taken into account threw out our design of this system one could look for a longer penetration depth by selecting a higher RF frequencies, or a better transmission between air/soil interface by having a larger bandwidth. But we

believe our system has a good trade off between these parameters for the detection of our intended target. There are also many other applications this technology could be implemented on, as it is now we can detect a wide range of underground targets, but by changing the frequencies we could have a longer penetration depth and could be used as a tool to detect the changes in soil in a terrain we are interested in or if you select a shorter frequencies one can detect the inner cabling of a building where most of the target as metal rods inside concrete.

6 Conclusions

The radar system designed can effectively fulfill the task that we set out to complete. By comparing to what can be found in the GPR market our system could be made to have a small and compact form factor. This is due to the size of the antenna and the power consumption of the device making it a suitable candidate for field deployment with ease. We also gave examples on the expected signal from a duct field with cables Fig.4, it is implied that a trained operator could determine what was being observed. Therefore, it can be a useful tool for the proposed task, reducing the amount of digging needed to be done to find the correct duct.

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