STEPPED FREQUENCY CONTINUOUS WAVE RADAR- DATA PREPROCESSING

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ABSTRACT

Radar systems have been paid a lot of attention since the end of the WWII. Along with performances improvement one has witnessed a diversification of their applications, which range from target detection and parameter measuring to navigation systems, anticollision systems and subsurface sensing. The last application has had a great importance for humanitarian demining purposes taken into account the number of landmines spread across the world and the danger they pose to humans. Both, continuous wave and pulse radar have been employed for landmine detection.

This paper deals with a stepped frequency continuous wave (SFCW) radar that operates from 400 MHz to 4845 MHz, in steps of 35 MHz. The novelty of the system, built at International Research Center for Telecommunication-transmission and Radar (IRCTR), consists in the fact that 8 frequencies are transmitted simultaneously, which drastically decreases the data acquisition time.

Because of the strong reflection from the air-ground interface one may face some difficulties to "see" the landmines, which are lying on, or just below of the surface. If the antenna system footprint is much more larger than the size of the mine, this is even more difficult as the signal from the mine will be buried into clutter signal. In order to remove the clutter signal and to improve signal to clutter ratio, average clutter subtraction and synthetic aperture radar have been investigated.

Keywords: SFCW radar, clutter subtraction, synthetic aperture radar.

INTRODUCTION

Many military conflicts that have occurred in different parts of the globe had left a dreadful inheritance: the antipersonnel landmines that are spread across the world. As the public awareness has grown the political factor took steps by banning the use of this kind of mines as well as by trying to help cleaning the affected areas. As a result a lot of funds from national as well as from international organizations have been directed towards humanitarian demining activities. Any demining activity supposes several stages: detection, identification and clearance/destruction. Of course, the detection is probably the most important phase in this process. Several types of sensors (metal detectors; infrared; ground penetrating radar (GPR), bulk explosive detection systems, etc.) have been investigated to be used for landmines detection. Among these a great importance is given to GPR because of several advantages: the ability to detect plastic mines, no need of direct ground contact, the potential use of target recognition techniques etc.

The GPR operates either in time domain or in frequency domain. The time domain systems could work either with a very short pulse, the shorter the pulse is the higher the range resolution is, or with a pulse train frequency modulated waveform or so-called "chirp radar". The frequency domain GPRs are continuous wave systems in which the carrier frequency is changed either continuously or with a fixed step.

The stepped frequency continuous wave radar has some advantages over the other types of GPRs: wider dynamic range, higher mean power, lower noise figure and, probably the most important one, the possibility of shaping the power spectral density. The last feature allows changing the level of the side lobes just by changing the "windowing" function. Of course there is a price to be paid and this regards the range resolution. Also, SFCW radar opens a lot of opportunities regarding single and multi frequencies processing, time-frequency analysis, polarimetric processing, in other words the SFCW can be seen like a step further towards a software GPR.
PRINCIPLE OF OPERATION OF SFCW RADAR

A set of 128 continuous wave signals with different frequencies are generated by up converting the output signals of a direct digital synthesizer (DDS), which walks from 115 MHz to 360 MHz through 8 steps [1]. These signals are transmitted towards the ground in 16 groups of 8 frequencies. The interface between the transmitter and the propagation media is made via an ultra wide band Archimedean spiral antenna. Any nonuniformity, which the radiated signal comes across, will produce a reflected signal that will be captured by the receiving antenna. In order to decrease the level of the coupling signal an Archimedean spiral with opposite sense of rotation has been employed for reception.

The signals backscattered by the objects buried into the ground as well as by the ground itself are attenuated and delayed proportional with the reflectivity properties of the backscatterer and with the distance to it. Inside the receiver the signals are down converted and applied to I and Q mixers. The outputs of the quadrature mixers will provide complex signals that have a phase shift proportional with the distances to different objects, which have scattered the transmitted signals. By applying an ifft to these signals a range profile is obtained.

The main parameters of any radar system are the unambiguous range and the range resolution. The unambiguous range, \( R_u \), of an SFCW radar is given by the formula:

\[
R_u = \frac{v}{2A_f},
\]

where \( v \) is the propagation velocity and \( A_f \) is the frequency step.

The range resolution, \( \Delta r \), depends on the bandwidth, \( B \), of the radar and can be calculated using the formula:

\[
\Delta r = \frac{v}{2B}.
\]

The frequency range and the frequency step of the SFCW radar, built by IRCTR, have been chosen as a trade-off of the resolution, the unambiguous range and the soil penetration. The bandwidth of the radar ranges from 400 MHz to 4845 MHz and the frequency step is 35 MHz. Replacing these values in (1) and (2) one gets \( R_u = 4.29 \text{ m} \) and \( \Delta r = 3.34 \text{ cm} \), in the air.

CLUTTER SUBTRACTION

A stepped frequency radar has to operate in a harsh environment. The electromagnetic waves that are transmitted by the radar have to propagate through the air and, of course, through the ground. At any interface between any two media having different electromagnetic parameters, part of the electromagnetic energy is reflected backwards to the receiver and part is transmitted into the second media. The same thing happens when the transmitted signal comes across an object buried into the ground. The portion of the signal, which is reflected, depends on the reflectivity properties of the object and the ratio between the size of the object and the wavelength. Unfortunately the same phenomenon happens while electromagnetic waves come across any nonuniformity within the propagation path. As a result, beside the useful signals that come from the objects we are looking for, reflected signals from air-ground interface as well as from any other nonuniformities inside the ground (stones, layers having different electromagnetic parameters, etc.) will be received. All these returns have no use for landmine detection and are called clutter. These clutter signals, especially the one that comes from the air-ground interface will worsen the parameters of the radar. There are several techniques for clutter removal but in this paper we will address only average clutter subtraction.

In order to see how this technique works a so-called C scan has been made at IRCTR's facility. The facility consists of a wooden box, 2x2x1.3m size, 83 cm height, filled with dried sand. The antenna system moves above the sand at a distance of 60 cm in steps of 2 cm. The measurements are carried out with no objects lying on the sand. The signals received while the center between the transmit and receive antenna is over the center of the wooden box, in time domain, before and after average clutter subtraction are compared. In figure 1, the signal in time domain, after averaging is presented. The peaks of the signal are numbered as follows:

1-coupling signal;
2-the first reflection from the sand;
3-the second reflection from the sand;
4-the first reflection from the ground floor supporting the wooden box;
5-reflection from an object under the ground floor;
6-the second reflection from the ground floor.
Fig. 1 Average clutter in time domain, with no objects on the scene.

In figures 2 and 3 the signals, measured in the center of the scene (x=0, y=0), before and after average clutter subtraction, are pictured.

For SFCW radar the main contribution to the clutter signal comes from the break through signal and the reflection from the ground. The coupling signal depends on the separation between the two spiral antennas, the height of the antenna system above the ground and the relative position between the two antennas. For the configuration that has been used for this measurement although the coupling signal is quite high it is decreased by an important amount by average clutter subtraction. The main concern is the clutter that comes from the ground, which does not correlate too well from one point to another, and, at the same time, it overlaps the signals, which may come from shallow buried object, or surface laid objects, which is the case for antipersonnel landmines.

SYNTHETIC APERTURE RADAR

Formulation

In order to detect the positions of the landmines or other objects that could be hidden in the ground, the antenna system scans the area at a certain height above the ground. The separation between the ground and the antenna system as well as the position of the two antennas is a matter of trade-off between the footprint of the antenna and the coupling between the ground and the antenna system. Being an ultra wide band antenna the Archimedean spiral has a large beam width [2] and, as a result, the transmitted power is spread across a large area. As the dimensions of the landmines are much more smaller than the size of the footprint, the signal backscattered by them is much more weaker than the signal reflected by the ground. For instance, taken into account the transmitting and receiving antenna separation, the beam widths as well as the distance
to the ground, the antenna footprint can be approximate with a 68 cm diameter circle (in real life the footprint is not circular but elliptic and it changes as frequency changes [2]). Let us suppose that a 5 cm diameter plastic landmine lies on the ground, then the ratio between the powers that comes from the ground and from the landmine will be:

$$P_G = 10 \log \left( \frac{r_n^2 \pi R_{p}^2}{r_g^2 \pi R_g^2} \right),$$

where $P_G$ and $P_n$ are the signal power received from the ground and the landmine, respectively; $R_{p}$ and $R_{g}$ are the radius of the footprint and of the landmine, $r_g$ and $r_n$ are the reflections coefficients of the ground and of the landmine. If we assume that the reflection coefficient of the ground and of the landmine are close enough to be simplified and replace the above mention values in (3) we will get that the signal from the ground is 22.6 dB higher than the signal from the landmine. Therefore, along with clutter subtraction other signal processing techniques, like synthetic aperture radar (SAR), should be applied. Another reason for advanced processing is the need to accurately localize the objects and find features (e. g. shape) to support their classification.

As the antenna system moves above the ground any backscatterer can be "seen" as long as it stays within the footprint of the system, so the signal from this backscatterer will be present in several positions of the antenna system. Therefore, an improvement of the quality of the image can be got by focusing it.

Assume $N$ and $\Delta f$ to be the number of frequencies and the frequency step size, respectively. Then, the frequency of the $k$th step will be:

$$f_k = f_0 + (k-1)\Delta f,$$

where $f_0=400$ MHz and $1 \leq k \leq N$.

Consider a scanned area having $L_x$ and $L_y$ the dimensions along Ox and Oy axis. If we denote with $Ax$ and with $Ay$ the measurement steps along the two axes then the number of points, which correspond to each dimension, will be:

$$M_x = \frac{L_x}{Ax},$$
$$M_y = \frac{L_y}{Ay}$$

Let us suppose, just for simplification, that $X$ and $Y$ dimensions of the scanned area along Ox and Oy equal the footprint dimensions along the two axis (in real life the footprint is not rectangular but elliptic). In this case, if an isotropic backscatterer is placed in the middle of the scanned area, it will be "visible" in all $M_x \times M_y$ points of measurement. Also, it is assumed that the reflected signal does not depend on the relative position between the antenna system and the backscatterer and that the space is homogeneous (surface laid mines).

The $k$th radiated signal, $u_k(t)$, if the transmitted power is equalized, will be:

$$u_k(t) = Ae^{j2\pi ft_k},$$

where $A$ is a constant.

The received signal that corresponds to the $k$th frequency is:

$$s_k(t, t_i) = rAe^{j2\pi k(t-t_i)},$$

where $r$ is the reflection coefficient and $t_i$ is the propagation delay, $0 \leq t_i \leq 1/\Delta f$. If the antenna system is placed $z$ m above the scatterer and $d_{mn}$ is the separation between the transmitting and receiving antennas then:

$$t_i = \frac{2z^2 + (d_{mn}/2)^2}{v},$$

where $v$ is the propagation velocity.

After down conversion the signal at the output of I and Q mixers will be:

$$s_k(t_i) = rAe^{-j2\pi ft_i}$$

Now let us suppose that the isotropic scatterer is located at $x$ and $y$ coordinates and the antenna system is aligned along the y axis. This scatterer will be 'seen' from all points which are within a footprint centred on $x$ and $y$. So, in order to focus the image of this point these signals should be phase compensated and added. The phase shift is due to different propagation path lengths. If the antenna system is located at $x_m$ and $y_m$ then the difference between the propagation times will be:

$$\tau(m, n) = \frac{\sqrt{z^2 + (x_m - x)^2 + (y_m - y)^2} - t_i}{v} + \frac{\sqrt{z^2 + (x_m - x)^2 + (y_m - y + d_{mn}/2)^2} - t_i}{v},$$

and the focused signal will be given by:
\[ s_n(t) = \sum_{m=1}^{M} \sum_{n=1}^{N} r_{m,n} e^{-j2\pi f_{m,n} t} e^{j2\pi \phi_{m,n}}, \]

where \( t_{\text{prop}} \) is the propagation delay that corresponds to the position of the antenna system defined by \( x_m \) and \( y_n \).

Applying this procedure for each frequency we will get the focused images for the scatterer located at \( x_i \) and \( y_j \).

**Experimental results**

In order to check how the above algorithm works a C scan at 60 cm above the sand has been made. There are 5 metallic objects (20 cm diameter disc, 7x7 cm plate, 3x3 cm plate, 5 cm diameter tennis ball covered with tinfoil, 23x45 cm strip) and 2 plastic landmines (12 cm diameter and 5 cm diameter) filled with paraffin laid on the sand. The signals, in time domain for \( x=0, y=0 \), before and after average clutter subtraction as well as clutter average are presented in figures 4-6. The meaning of the numbers associated with signal peaks in figure 5 is the same like in figure 1.

![Fig. 4 A range profile (A scan), before clutter subtraction, 5 objects and 2 mines.](image1)

![Fig. 5 Average clutter, in time domain, 5 objects and 2 mines.](image2)

![Fig. 6 A range profile (A scan), before clutter subtraction, 5 objects and 2 mines.](image3)

As can be seen in figures 4 and 5 the signal that is measured in the middle, which corresponds to 60 cm separation (the second peak), is about 5 dB above the average clutter. This is the contribution brought by the objects that are laid in the middle of the scene. Also the reflection from the ground floor (the fourth peak) is decreased of about the same amount because the objects shield the ground floor. After clutter subtraction (figure 6) the coupling signal (the first peak) is decreased 5 dB less than in figure 3 where no objects are on the sand. This could be due to the close distance between the antenna system and the sand and the influence of the last one the coupling signal.

Also, if we compare the second peaks in figures 3 and 6 we can say that the signal that comes from the objects is about 15 dB.

In figure 7 a slice through a C scan, after average clutter subtraction, is displayed. It can be seen that only the disc is perfectly visible and that the image is unfocused. The synthetic aperture radar procedure described above has been applied to this data. The processed data are presented in last two figures. The signal that corresponds to \( x=0 \) and \( y=0 \), in time domain, after SAR processing is pictured in figure 8. Figure 9 shows a slice through a C scan after SAR processing, at the same distance like in figure 7.
Fig. 7 Five metallic objects and 2 mines without SAR processing.

If we compare the shape of the signals from figures 6 and 8 it can be easily seen that the signal reflected by the objects is completely changed after SAR processing.

CONCLUSIONS

Average clutter subtraction and synthetic aperture radar for a SFCW radar have been analysed. We get a reduction of about 15 dB by average clutter subtraction, with no objects on the scene, but we expect in real life the value to be less because of the ground nonuniformity and anisotropy. The synthetic aperture radar procedure does produce image focusing, after SAR the shapes of the objects are clearly visible. The SAR procedure that has been presented in this paper does not account for the amplitude variation of the signals due to the antenna pattern. However, taken into account the width of the antenna beams, the authors do not expect to get much improvement by adding the amplitude information to the procedure.

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REFERENCES
