Development of an electromagnetic detection method for explosive materials

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Keywords: electromagnetic detection, explosive material, radar, dielectric constant, method algorithm, electromagnetic scanner.

Abstract. The main technical requirements for the development of an electromagnetic detection method for explosive materials are considered. The main elements of interference that increase the detection error are classified. The probability of detecting explosives at different soil depths is modeled. It was found that the frequency of the scanning signal has the greatest influence. Thus, reducing the scanning frequency increases the probability of detecting an object. However, reducing the irradiation frequency is limited by the resolution for objects of a given size. It is shown that reducing the dielectric constant of the soil does not lead to satisfactory detection probabilities even in the upper soil layer. In the size range of real explosives (0.1-0.5 m), the detection probability decreases by 10-25%. The analysis of the characteristic time signatures of explosives imitations showed that the development of a database of such signatures will reduce the number of false signals. An algorithm for the implementation of the method of electromagnetic detection of explosives consisting of 18 functional blocks and three logical blocks has been developed. The obtained results made it possible to describe the procedure for detecting explosive materials in a contaminated area. The use of the obtained results in humanitarian demining will increase the speed of surveying the territory, increase the probability of detecting explosive objects and reduce the risk of injury to personnel conducting humanitarian demining.

1 Introduction

The search for explosive materials has been relevant since the beginning of the active use of such items as weapons. Today, the use of mines by the military of various conflicts has become widespread, and the activity of armed conflicts unfortunately does not subside. The length of the combat line can reach thousands of kilometers, which, combined with the long duration of hostilities, leads to dense contamination of tens of thousands of square kilometers of territory with explosive objects. A vivid example of this is the military operations on the territory of Ukraine [1]. In such conditions, the issue of rapid and safe clearance of the territory from dangerous explosive devices becomes extremely relevant. Humanitarian demining is carried out by various structures and agencies around the world, but the main work is carried out by state rescue units and civilian volunteer organizations. The main problem in humanitarian demining is the detection of explosive materials due to their considerable diversity [2].

2 Problem formulation

The placement of anti-personnel and anti-tank mines is an effective way to defend the battlefield. Today, remote mining equipment is being actively developed, which has significantly increased the area of land contaminated with explosive materials. Of course, mine countermeasures face the classic problem of confrontation between destruction and defense systems. That is, along with the development of effective methods and techniques for detecting and neutralizing explosive materials, the latest solutions are being developed to keep such items hidden. The issue of clearing territories from explosive objects is further complicated by the wide variety of designs and materials used to make explosive objects. In addition to standard mines, other types of ammunition (grenades, shells, etc.) can be found. A separate class of explosive items is home-made items used by sabotage and terrorist groups. In such cases, the variety of designs and materials becomes almost unlimited.

So, there is a problem of detection and disposal of explosive objects with different design and material realization.

3 Analysis of publications

The humanitarian demining process has several main stages. First, planning and risk assessment are carried out, during which information about potentially dangerous areas is collected. Next, a non-technical survey is conducted, including interviews with local residents, analysis of maps and reports to identify possible mine sites [3]. After that, a technical survey is performed using special equipment to identify hazardous objects. The next stage is the clearance of the territories, which involves the neutralization or destruction of mines and explosive remnants. Upon completion of the work, quality control is carried out to ensure that the areas are completely safe. The final stage is the transfer of the cleared areas for safe use with the preparation of relevant documentation [4].

Drones are actively used for preliminary surveys of territories, which help to effectively identify dangerous areas [5]. Mechanical demining systems, such as robots, allow for remote work, minimizing risks to people. But usually, robotic systems only act as a carrier of detectors. However, given that humanitarian demining requires high quality clearance of the territory from explosive objects, it is necessary to control the quality of human clearance. In such cases, it is mandatory to use protective equipment, including special suits and helmets that ensure the safety of employees of pyrotechnic units [6]. A variety of equipment is used to search for explosive objects, including metal detectors to detect metal objects in the soil [7]. This method helps to determine the location of mines and explosive objects, but has a number of limitations related to the material of the object being detected and the limited detection distance.

The method of scanning the earth's surface with electromagnetic waves can eliminate the disadvantages of the magnetic method [8]. This method has no fundamental restrictions on the material of the object to be detected and can detect at a considerable distance from the explosive object. Such systems have proven themselves in engineering work during construction, where they are used as ground penetrating radar. However, this method has a number of limitations that need to be taken into account when using it for humanitarian demining. Significant losses during the propagation of electromagnetic waves in the ground result in a wavelength that is larger or commensurate with the size of a landmine [9]. This significantly distinguishes GPR from conventional radar systems operating in bands where the size of targets is much larger than the wavelength (e.g., in the optical range). Radars operate in the range from the Rayleigh region to the resonant region (Mi), where wavelengths and target sizes are close in scale [10].

The total energy loss in the ground can be as high as 100 dB over several wavelengths, depending on the material. As the overall gain of GPR is typically less than 120 dB, this requires detection of landmines in very short time intervals, typically around 20 ns. GPR can only operate effectively at a distance of a few wavelengths from the antenna, especially in cases of high lossy soils [11].

The peculiarity of GPR is that it often operates in the near field, where energy is transferred mainly by induction, or in the far field, with traditional wave propagation. As a result, the devices face high levels of interference and low signal-to-noise ratios, which is a major technical challenge. All of these factors pose significant challenges to the development of effective GPR for landmine detection.

In our previous work, we modeled the process of electromagnetic wave propagation in soil with an explosive object [12]. The processes of reflection and absorption of waves by multilayer surfaces of the EO at an arbitrary angle of incidence were taken into account. Particular attention is paid to determining the dielectric properties of the EWP materials [13], which allows to improve the detection accuracy and sort out false signals. However, the unresolved part of the problem is to determine the technical limits of the electromagnetic method of detecting explosive materials and evaluate its effectiveness.

4 Aim of Paper

The purpose of this research paper is to determine the probability of detecting explosive materials at different depths under the influence of electromagnetic radiation and to develop a method for electromagnetic detection of explosive materials.

5 Main part

The main difficulty in the operation of electromagnetic detection systems is the presence of interference inside and on the surface of the material. The side and rear lobes of the antenna constitute a separate area of interference [14]. Interference is defined as unwanted sources of reflection that occur within the effective bandwidth and search window of the detector and are represented as spatially coherent reflectors. Examples of interfering objects include animal burrows, cracks in the ground, and stones. Careful identification and understanding of these objects is crucial for selecting and operating the best processing systems and algorithms. Interference can completely hide buried targets. An important problem is the impact of uneven terrain on the detection system. This leads to a change in the irradiation angle of the ground surface and, accordingly, the reflection angle. Radar signal processing methods that “smooth” the radar signal by adjusting the delay time relative to the ground surface do not always produce good results. This is because it is impossible to predict these changes, and uncontrolled signal adjustment only increases errors. Sharp discontinuities can also cause multiple reflections, which are then superimposed on the incoming reflected energy.

When forming an electromagnetic radiation signal, it is necessary to achieve selective reflection from such obstacles as

- small pieces of metal, shrapnel, shell casings (defined as small, with a surface area of no more than 1.5 cm^2);
- changes in the terrain, puddles, animal burrows, cracks and crevices in the soil
- tufts of grass, rocks and stones.

When estimating the received signal power, it is necessary to take into account the coefficients of reflection and wave transmission through the dielectric and reaching the target, and Snell's law defines the corresponding angles of incidence, reflection, transmission, and refraction [12]. For detection at close distances, the efficiency of the process is high. Detecting explosive materials hidden in the ground is a difficult problem for radar systems, and their effectiveness is highly dependent on terrain conditions. For vertically polarized waves at incident angles below the Brewster angle, the losses at the air-ground interface are relatively small, but increase rapidly at incident angles above the Brewster angle. Since the dielectric constant and transmission loss depend on the angle of incidence, this angle should not exceed 85 degrees. Therefore, to maximize the operating range, radars should be installed as high above the ground as possible. Consequently, at a given altitude, the radar's efficiency depends on the dielectric constant of the ground. In addition to the problem of energy matching with the ground, the effective cross-sectional area of all targets decreases as they are buried.

The simplest model for estimating signal strength is derived from the long-range radar range equation, which, however, has limitations in correctly reflecting the actual operation of a very short-range system. However, it allows us to estimate the expected first-order signal levels. The model is based on the equation for the receiver voltage as a function of the range r and the target radar cross-section σ, which has the form:

$$V(r) = \frac{V_0}{\tau} \cdot \frac{1}{c} \cdot \frac{A_e}{\sqrt{4\pi}} \cdot \frac{1}{r^2} \cdot \sqrt{\sigma} \cdot \tau_g \cdot \sigma_\tau \cdot m \cdot e^{-k2r}, \quad (1)$$

where V_o – peak radiated voltage;
τ – pulse duration, s;
c – speed of light, m s^{-1};
Ae – antenna effective aperture, $м^2$;
σ – target cross section, $м^2$;
m – number of averages;
τg – transmission coefficient into ground;
σt – reflection coefficient from target;
r – range, m;
k = α+jβ – the propagation constants.

In the absence of any obstacles on the ground and provided that the reflection from the front surface is completely eliminated, the probability of detecting explosive material under the ground can be calculated. Taking the signal-to-noise ratio of the electromagnetic receiver to be 15 dB and the relative permeability of the soil to be $e_r = 10$, for an explosive object with dimensions of 0.2 m, the dependence of the detection probability on the depth of the target is shown in Fig. 1. The distance from the antenna to the ground surface is 10 cm.

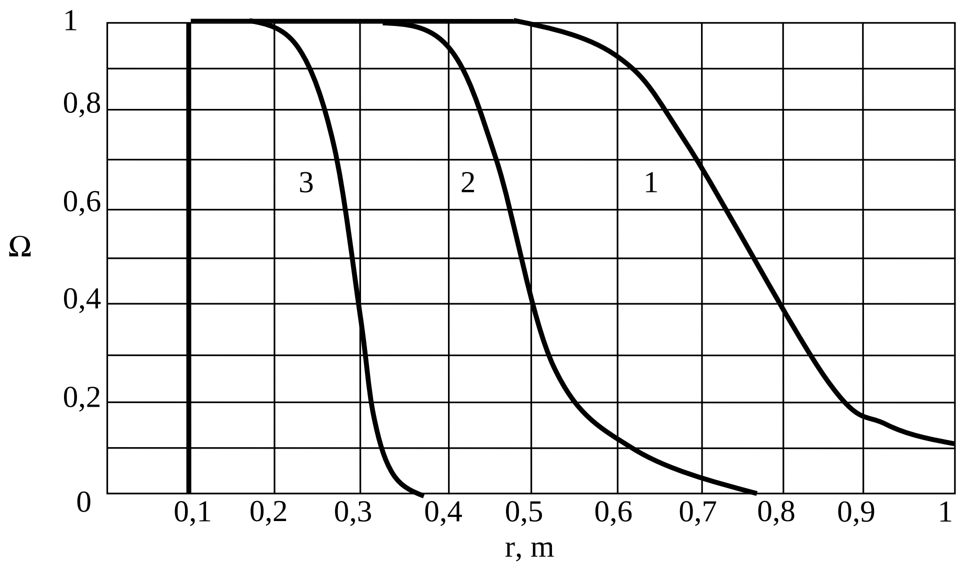

Fig. 1. Dependence of the probability of detecting explosive material on its immersion depth at different radiation frequencies: 1 – 1 GHz; 2 – 2 GHz; 3 – 3 GHz.

Figure 1 shows that the frequency of the electromagnetic signal during scanning significantly affects the probability of detecting an explosive object (EO). While it is no longer possible to find an object 10 cm in size deeper than 25 cm from the ground surface with a 3 GHz signal, a stable reliable signal can be obtained even at a depth of more than 50 cm with a scanning frequency of 1 GHz. However, when the frequency is lowered, there is a significant limitation in the resolution, i.e., it is always necessary to match the frequency to the size of the search object. If the wavelength exceeds the size of the object, the signal is completely lost due to the fact that electromagnetic radiation passes through the object without reflection.

An important factor in the detection of explosive materials in the soil is the properties of the soil itself. The dielectric constant of the soil varies in a wide range depending on geological features and water content. The dependence of the probability of detecting an explosive material with the properties indicated above at a radiation frequency of 2 GHz is shown in Fig. 2.

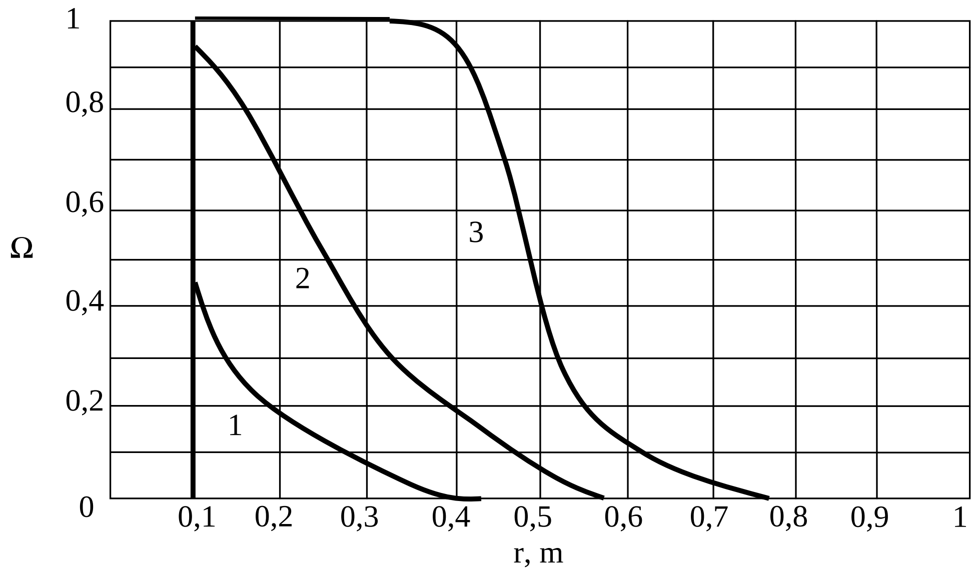

Fig. 2. Dependence of the probability of detecting explosive material on the depth of its immersion at different dielectric constant of the soil: 1 – e_r = 3; 2 – e_r = 5; 3 – e_r = 10.

Fig. 2 shows that a decrease in the soil permittivity e_r to 3 leads to a significant decrease in the reliability of detecting explosive materials even near the ground surface and is less than 45%. That is, before starting the process of detecting a certain area, it is necessary to find out the geological features of the surface layer. It is also important to assess the water content of the soil. That is, it is advisable to choose the time period of the detection process.

Of course, the size of the explosive material also affects the probability of detection. At a radiation frequency of 2 GHz and a soil permittivity of e_r = 5, the dependence of the probability of detecting explosive material on its size is shown in Fig. 3.

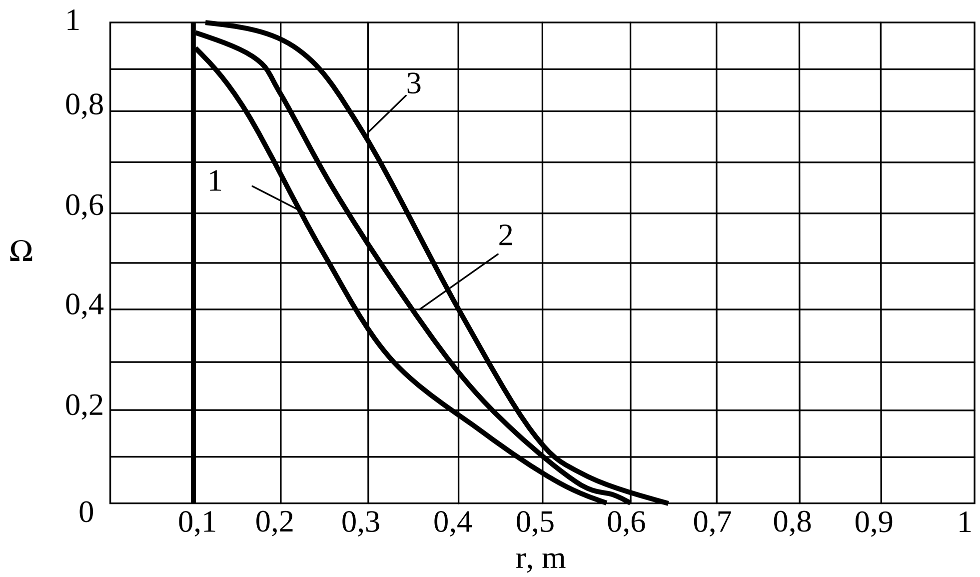

Fig. 3. Dependence of the probability of detecting explosive material on the depth of its immersion: 1 – 0,1 m; 2 – 0,25 m; 3 – 0,5 m.

From Fig. 3 shows that the size of the scanned object has the least influence of all the parameters considered. In the range from 0.1 to 0.5 meters, which corresponds to most existing standard and home-made EOs, the detection probability changes by 15-25%. This is a positive result, as it allows to search for EOs in a wide range of design versions with virtually no adjustment of the electromagnetic radiation characteristics.

It is expected that in very dry soils and at shallow depths, the scattering coefficient of a metal-sheathed EO will decrease by about 10 dB. Under the same conditions, the cross-sectional area of a plastic-sheathed EO will decrease to a greater extent due to a decrease in the dielectric contrast between the sheath material and the surrounding soil. Therefore, such a EO is better detected in wet sandy soils than in dry ones. However, due to the fact that plastic-cased EOs have larger gaps for the movement of the casing before detonation, their presence in loose soils is safer.

Electromagnetic explosive detection systems must have a signal-to-noise ratio of at least 20 dB to detect buried objects in all weather conditions. Therefore, to detect buried plastic targets with gaps, the corresponding signal-to-noise ratio should be at least 12 dB in dry conditions and 18 dB in wet conditions. Conventional radar systems are believed to be able to separate two identical targets with a pulse width of 0.8 between them. In the field of optics, Rayleigh suggested that the resolution should be defined so that the main intensity of one component coincides with the first minimum of the other component's intensity.

Electromagnetic energy is scattered due to the difference in impedance of explosive materials. The most common shapes of objects (cube, sphere, cylinder) have well-studied radiation properties that can vary depending on the dielectric constant of the soil [15]. Explosive materials can have several scattering centers, each with its own angular radiation pattern, and in the case of plastic shells, additional scatterers can be generated by the internal structure of the object. Most plastic-sheathed explosive objects can be viewed as multilayer dielectric cylinders, each interface of which causes reflection. The time characteristics of the latter can be modeled using a simple transmission line model representing the case when the angle of incidence and the angle of reflection are equal (Fig. 4).

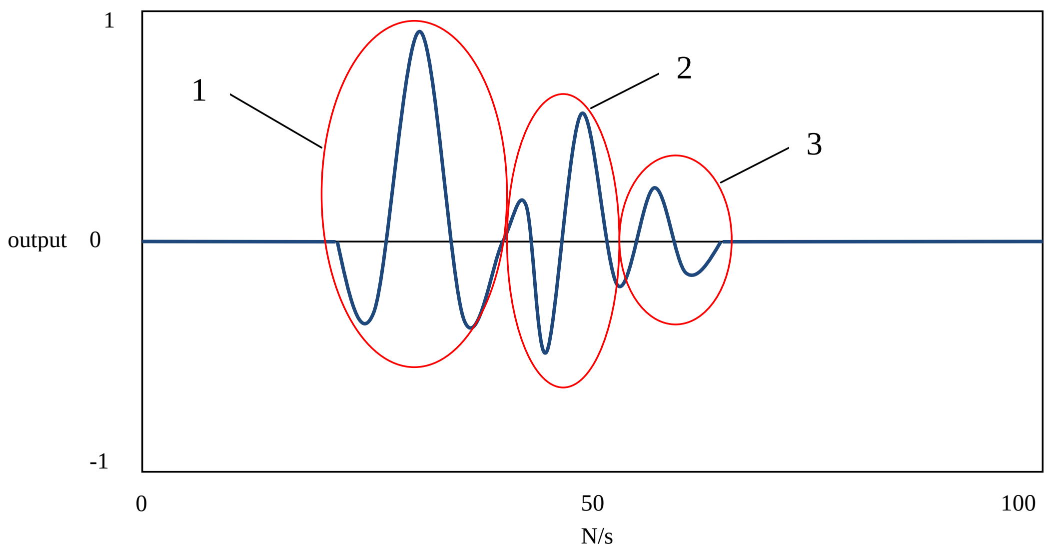

Fig. 4. A characteristic signature of the time domain of explosive ordnance simulation

As can be seen from Fig. 4, the time domain signature of the signal when detecting explosive materials in the soil can be divided into separate regions. Each region has its own interface. In Fig. 4 shows 3 areas, but there may be more depending on the design features of the explosive object. Area 1, Fig. 4 corresponds to the reflection of the signal from the ground surface. Area 2, Fig. 4 demonstrates the reflection from the surface of the EO case. The height of the peaks in area 2 can be used to recognize the shell material. In the case of a metal shell, the peaks will be clearly defined and significantly higher than in the case of a plastic shell. Peak 3 allows you to identify the type of explosive. Usually, the 3rd peak will be the weakest due to signal attenuation by reflection from the ground surface and the shell material. However, the main reason for the weak signal of area 3 of Fig. 4 is the low permittivity of most explosive materials. Of course, safe objects (stones, seals, etc.) also produce reflection signals. However, such objects usually do not have a multilayer structure, so the number of signature peaks will be smaller. In addition, the development of a database for the characteristic peaks of the relevant areas will improve the quality of EO recognition.

Based on the results obtained above, the paper proposes an algorithm for implementing the method of electromagnetic detection of explosive objects (Fig. 5).

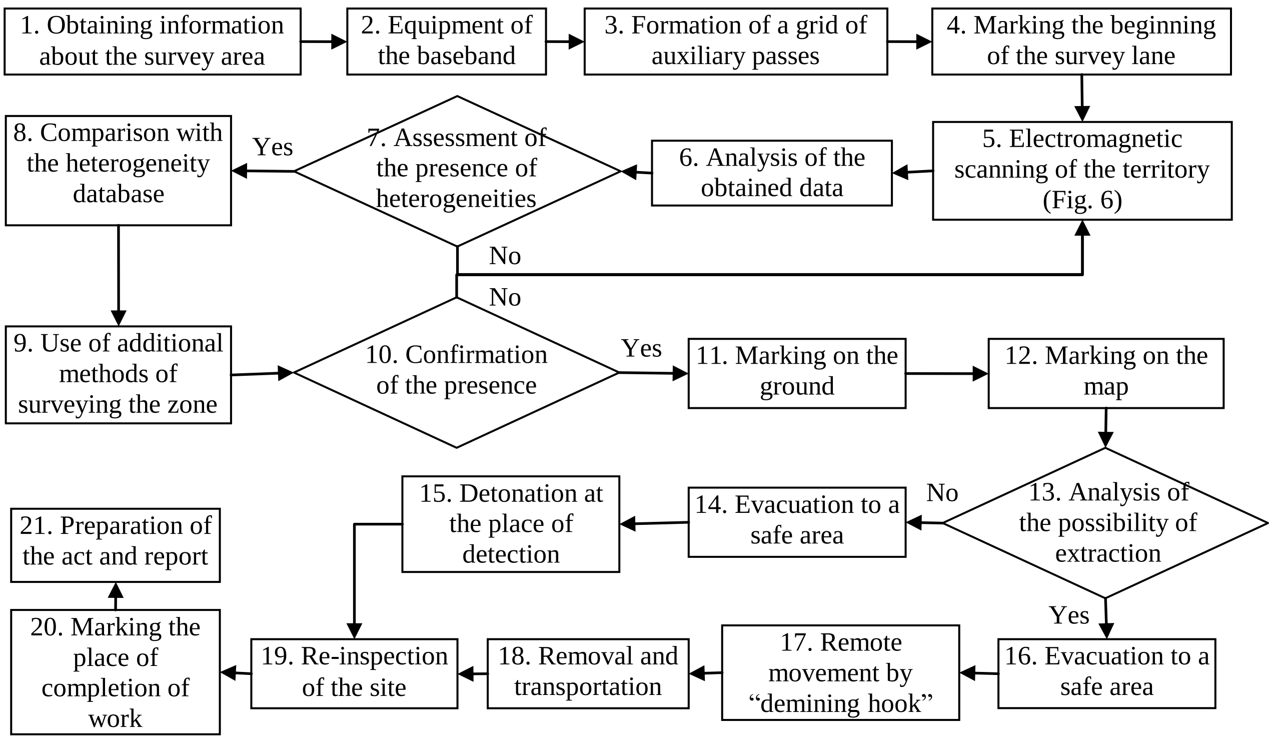

Fig. 5. Algorithm for implementing the method of electromagnetic detection of explosive objects.

On the basis of the task and the information certificate, the demining supervisor determines the area to be cleared of explosive materials. Prior to the commencement of work on clearing the territory from explosive ordnance, a safety strip is arranged in front of the edge of the hazardous area. A grid of auxiliary passages is formed in the hazardous area, which must be cleared of EOD and marked.

The search for EOs starts from the safe lane. When conducting work using the electromagnetic ground scanning method, the safety strip may be located at a certain distance from the defined boundary of the hazardous area, which allows to detect EO outside the defined hazardous area. The area of the territory where explosive materials are searched may be increased if they are found along the edges of the defined hazardous area or if additional direct evidence of the presence of ERW is found. The area shall be cleaned within a radius of at least 25 meters from the ERW or direct evidence of their presence found near the edge of the defined hazardous area.

At the command of the work supervisor, the operator of the first detector located on the left flank starts moving along his working lane. The next operator starts moving in his working lane only after the distance between him and the previous operator is at least 5 meters, to maximize the exclusion of mutual interference of detectors.

When using unmanned electromagnetic detector carriers, operators first visually assess the survey area for the possibility of unmanned detector movement (presence of pits, debris, clutter, etc.).

The electromagnetic scanning of the territory is realized according to the algorithm of Fig. 6. The reflected signal from the explosive material is received by the receiving antenna, after which this signal is amplified and digitized. The key role in signal processing is played by a digital processor that analyzes the received signal and reformats it into a visualized form. The obtained data can be stored in memory and displayed on the screen for analysis by the operator. In order to clarify the obtained data and reduce the error, it is necessary to correct the frequency and amplitude characteristics of electromagnetic radiation. This is done either automatically by the processor or manually by the operator.

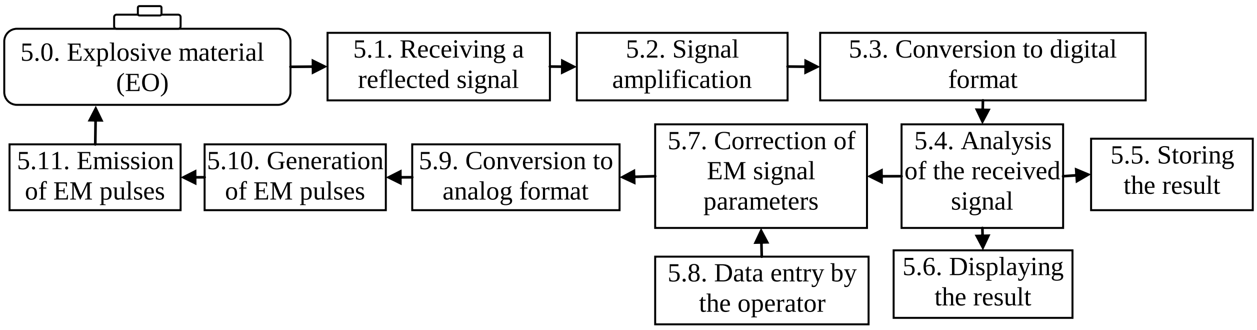

Fig. 6. Algorithm of the electromagnetic scanner for detecting explosive materials.

The corrected signal is converted to analog format and sent to the electromagnetic pulse generator. The pulse generator emits electromagnetic waves with the appropriate duty cycle and pulse length through the radiating antenna. The electromagnetic radiation hits the interface, from which it is reflected. Accordingly, the electromagnetic scanning algorithm is a closed loop.

The resolution is determined by the characteristics of the antenna and the signal processing method used. In general, to achieve acceptable resolution, electromagnetic detection systems require antennas with a high gain. This requires a sufficiently large aperture at the lowest transmission frequency. Therefore, to achieve a high gain with a small antenna size, it is necessary to use a high carrier frequency, which may not penetrate the material to a sufficient depth. When choosing equipment for a particular application, a trade-off must be made between planar resolution, antenna size, signal processing capabilities, and material penetration. The resolution improves with increasing attenuation if there is sufficient signal to identify the interference in the overall stream. In low attenuation environments, the resolution achieved by horizontal scanning is poorer, but only under these conditions can in-plane resolution be improved by synthetic aperture techniques.

If a signal is received from the detector, the operator visually inspects the location of the signal. In the absence of any EOs on the soil surface at the signal detection site, the operator continues to carry out the work, while marking the signal detection site is not carried out. Other technical methods of detecting explosive materials may also be used to verify the received signal.

When confirming the presence of EO, the operator assesses the possibility of safe removal of EO and its transportation to a safe place. If a decision is made to destroy the explosive item at the place of detection, all personnel with equipment and tools are withdrawn to a safe distance, except for persons involved in the preparation of blasting operations. After the destruction of an explosive item at the detection site, its remnants and fragments shall be searched for and removed, and the resulting craters and trenches shall be filled in.

Before the detected EO is removed, it is dislodged with the help of a “demining hook”. Next, the detected EO is removed from the soil and transferred to a vehicle or to a specially designated place.

Upon completion of the work, the work supervisor marks the results of the work performed on the Working Scheme for the territory clearance and draws up the Act of work performance on clearing the area from explosive hazards and the Daily Report.

6 Conclusion

The basic technical requirements for the construction of the method of electromagnetic detection of explosive materials are considered. The boundary environmental conditions under which the use of the proposed method will give a minimum error are determined. Modeling of the probability of detecting explosive objects at different depths in the soil showed that the scanning signal frequency has the greatest influence. Thus, when the scanning frequency is reduced from 3 GHz to 1 GHz, the reliable probability of detecting an object measuring 0.1 m increases from 0.2 m to 0.5 m, respectively. However, the reduction of the irradiation frequency is limited by the resolution for objects of the corresponding size. It is shown that when the soil permittivity is reduced from 3 to 3, it is impossible to achieve a satisfactory detection probability even in the surface soil layer, while at e_r = 10 a satisfactory probability is observed even at a depth of 0.3 m. It was also found that in the size ranges of real explosive objects (0.1-0.5 m), the detection probability decreases by 10-25%. The analysis of the characteristic signature of the time domain of explosive ordnance simulation showed that the development of a database of such signatures will reduce the number of false signals. An algorithm for implementing the method of electromagnetic detection of explosive objects has been developed, which consists of 18 functional blocks and 3 logical blocks. On the basis of the developed algorithm, the procedure for electromagnetic detection of the territory contaminated with explosive objects is described. Additionally, an algorithm for the operation of an electromagnetic scanner for detecting explosive materials, which has a cyclic structure, has been developed.

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