Potential of using holographic subsurface radars for mine detection

Sergei Ivashov¹, Nikolai Lichkov,² Adelina Tumbarska ²

¹ Bauman Moscow State Technical University, 2 Baumanskaya Str., Moscow, 105005, Russia, sivashov@rslab.ru
² Bulgarian Academy of Sciences, Institute of Metal Science, Equipment and Technologies with Hydro- and Aerodynamics Center “Acad. A. Balevski” (IMSETHAC-BAS), 67 Shipchenski prohod Str., 1574 Sofia, Bulgaria; niki0611@abv.bg; y.toubmarski@ims.bas.bg

Abstract

The use of holographic subsurface radars is a relatively new technology that enables the detection and recognition of non-metallic objects beneath the ground, including plastic explosives and mines with small or absent metal parts. The Moscow State Technical University (MGTU) “N.E. Bauman” has developed subsurface radars capable of registering such objects and determining their type using holographic methods for information processing. This article discusses the features and principles of operation of holographic subsurface radars. The capabilities of the radar holographic systems of the „Raskan” family developed by the MGTU are presented with a view to their use in the research activities within a joint scientific project carried out by the MGTU and IMSETHAC “Acad. A. Balevski”- BAS. The main results achieved by MGTU in using Raskan for mine detection and recognition are summarized and analyzed.

KEY WORDS: SUBSURFACE HOLOGRAPHIC RADARS; MINE DETECTION

Introduction

One of the most serious problems in local conflict zones and post-conflict areas is the large amount of installed anti-personnel and anti-tank mines, as well as improvised explosive devices (IEDs). The relatively low cost of such devices makes them widely used. Despite the ban on anti-personnel mines and international efforts in this regard, resulting in the continuous demining and destruction of available arsenal, huge quantities are still installed within the territory of many countries and there are considerable stocks of such mines. The combatants are well trained and have some means of detecting and neutralizing mines, however the civilian population, most often women and children, have been the main victims of these mines long after the conflict ended. According to statistics [1] 7,239 accidents caused by mines and other explosive remnants of war were recorded only in 2017 (2,793 people killed), 87% of them – civilians, nearly half of them were children.

At present, demining is done mostly by mechanical digging, trained dogs or rodents, and metal detectors. The metal detector is one of the most widely used short-range mine detection systems, however, currently landmines are made of plastic and other non-metallic materials, making them difficult to detect in areas contaminated with metal waste. The use of some sensors may increase the sensitivity of the instrument, however this will dramatically increase the number of false alarms triggered by pieces of metal such as grenade and cartridges fragments. The high frequency of false alarms and the inability to detect anti-personnel mines without or with a small metallic content make mine clearance operations dangerous, expensive and time-consuming. [2]

A relatively new technology that allows the detection of both metal and non-metal objects below the surface is Ground penetrating radar (GPR). The designs of subsurface radars are based on classical principles of radar technology. Signal emitted in a surveyed medium is reflected from heterogeneities if their permittivity or conductivity differ from that of the medium. The reflected signal is received by the radar antenna and amplified. After processing, the recorded information is visualized on a computer display.

In recent years, GPR has been subject of increased interest and research activity. Thanks to technological advances, significant improvements to key characteristics and the effectiveness of these systems have been achieved. New hardware and improved algorithms have been created, and modern computing resources enable the fast processing of large amounts of data. Humanitarian demining is among the many potential applications of these radars, thanks to their ability to detect underground objects of different sizes and shapes, including those made of non-metallic materials.

One of the recent achievements in this field is the family of ‘RASCAN’ holographic subsurface radars (HSRs) developed by the Bauman Moscow State Technical University. The wide practical applications have shown many advantages compared to devices using other methods, including real-time plan-view imaging and high lateral resolution in examination of low electrical conductivity media at shallow depths.

Principle of operation of the holographic radars

Ground penetrating radar (also known as subsurface radar) utilize powerful burst of electromagnetic energy pulses send into the ground from a transmitter antenna located on the surface. Subsurface structures, such as bedding, cementation, changes in moisture and clayey content, cavities, voids, fractures, intrusions, man-made objects and many others, possessing a contrast in dielectric properties, cause some of the pulse energy to be reflected back to the surface, while the rest of the energy continues to penetrate deeper. The reflected pulse energy is picked up by a receiver antenna on the surface. These signals are then processed and plotted in a distance versus time-depth display. Thus, as the radar antenna is slowly towed across the surface, continuous cross-sectional “picture” of subsurface conditions is generated. [3]

Impulse radar is the most common type of radar that is being produced commercially and used in practice. This radar uses real time measurements of short emitted pulses to reconstruct an image of the subsurface, and to measure the distance to buried objects (based on electrical properties of the media). Apart from impulse radars, there is also a class of subsurface radars that employ continuous signals, including frequency modulated radar, stepped-frequency radar, and holographic radar. [4] Frequency modulated radar transmits a continuously changing carrier frequency known as a chirp pulse. Reflected signal from the object is mixed with a reference signal to produce an intermediate or difference frequency, which in turn depends on the range to the reflector. [4] Stepped frequency or synthesized radar transmits consecutively a set of discrete frequencies registering the amplitude and phase of reflected signals.
signal at each frequency. Obtained in such manner, the frequency response function can be converted to time domain by Fourier transform to yield range information. [5]

The holographic radar (HSR) is a special kind of GPR that uses unmodulated continuous-wave signals. This holographic subsurface radar differs from other GPR types in that it records plan-view subsurface holograms. Penetration depth of this kind of radar is rather small (20–30 cm), but lateral resolution is enough to discriminate different types of landmines in the soil, or cavities, defects, bugging devices, or other hidden objects in walls, floors, and structural elements. Holographic subsurface radar, operating at one or several discrete frequencies, illuminates a sufficiently extensive area of a surface to be inspected to register the signal phase and amplitude distribution reflected from objects beneath the surface. Obtained in such a manner, the dataset can be used to mathematically synthesize a large effective aperture, and eventually reconstruct the subsurface image by methods analogous to those used in optical holography.

Unlike pulse radar measurements, single point measurements using monochromatic holographic radar do not produce informative results, so the reflected signal must be detected on a specific fragment of the surface to obtain a microwave hologram. Scheme of the subsurface holographic radar measurements is presented in Fig. 1 - (x, y, z) are the Cartesian coordinates, and z₀ is the depth of the object relative to the radar plane. [6]

![Fig. 1. Scheme of the subsurface holographic radar measurements.](image)

The signal emitted by the transmitting antenna is reflected from the subsurface object (object wave) and is mixed in the detector with a reference wave that is obtained from a generator. The signal that is directly transmitted from the transmitting to the receiving antenna may also serve as the reference wave. Such a configuration is used in the measurements of amplitude holograms. A specific feature of the holographic subsurface radar under study lies in the fact that the transmitting and receiving dipole antennas are located in a unit that represents an open-end circular waveguide. The waveguide diameter, antenna positions, and the remaining parameters are optimized with respect to the radar sensitivity. [7]

The algorithm of hologram reconstruction can be generally described by the following equations:

$$F(k_x, k_y) = \frac{1}{(2\pi)^2} \iint E(x, y) e^{-i(k_xx+k_yy)} \, dx \, dy$$

$$S(k_x, k_y, z_0) = F(k_x, k_y) e^{i \sqrt{\frac{4(\omega \varepsilon_0)c^2}{c^2-k_x^2-k_y^2}} z_0}$$

$$E_R(x, y, z_0) = \int S(k_x, k_y, z_0) e^{i(k_xx+k_yy)} \, dk_x \, dk_y,$$

where:

- $E(x, y)$ is the registered hologram, i.e. the complex amplitude distribution registered by the radar receiver on the scanner aperture at $z = 0$;
- $F(k_x, k_y)$ is the plane-wave spectrum of hologram;
- $S(k_x, k_y, z_0)$ is the plane-wave spectrum at parallel plane at $z = z_0$;
- $E_R(x, y, z_0)$ is the image reconstructed for plane $z = z_0$;
- $\omega$ is the angular frequency;
- $\varepsilon$ is the dielectric permittivity of the medium;
- $c$ is the speed of the electromagnetic wave in the medium

$k_x$ and $k_y$ are the spatial frequencies corresponding to $x$ and $y$, respectively.

Based on principle briefly described above, variety of models of “RASCAN” family radars has been created at the MGTU that have different operational frequency ranges and different applications. Two representatives of the “RASCAN” family are presented in Fig.2 and Fig.3.

![Fig.2. Holographic subsurface radar of RASCAN type 4/7000.](image)

![Fig.3. Holographic subsurface radar of RASCAN type 5/15000.](image)

Extensive research and experimentation, including comparison of results obtained by other methods, has shown that the main applications for “RASCAN” radars are connected with tasks in which sounding to great depths is not required, i.e. sounding of shallow layers is sufficient. In these cases there is usually no specific requirement to measure the depth at which the object is located. Depth estimation may be desirable but not as critical as detecting and classifying an object from its recorded microwave image. For example, when searching for buried mines or “bugs” in buildings, the primary purpose is to find the hidden object, and the depth to which it is placed is not essential. Therefore, imaging the shape of a hidden object is one of the main advantages of the holographic method. [8] Observation of shallow subsurface objects, defects, or inhomogeneities is an increasingly proven area of these radars application, including in civil engineering, preservation and restoration of cultural heritage objects, security, humanitarian demining, etc. [8-12]

**Use of holographic radars in mine detection**

Existing detection systems for “inconspicuous” mines installed in the ground in plastic cases, as a rule, use radio sensors. The principle of detection in these systems is associated with measuring changes in the dielectric properties of the soil at the site of the installation of the mine. Given the low contrast of the mine, with a
sufficient level of detection, the probability of false alarms per unit of the investigated area is unacceptably high. This is primarily due to reflections of radio signals from natural inhomogeneities in the soil and its surface. This drawback is due to the low information content of traditional mine detectors that identify mines using only the amplitude of the signal reflected from it.

An approach to overcome the difficulties is the use of broad size mine detection systems. The advantages of radio frequency countermine system with broad size detector are their higher performance and the possibility of increasing the information content of mine detection due to spatial selection and, as a result, reducing the likelihood of false alarms during mine clearance. The image obtained in this way is recognized even at high levels of background reflections. Thus, knowing the characteristic size of a mine, it can be distinguished against the background of the heterogeneity of the ground in its shape and size. [13]

This method has been realized by developing the “MiRaskan”- combined GPR and metal detector system, which makes it possible to detect and identify shallow (up to 20 cm) objects by their shape. The radar design is based on the principle of multi-frequency sounding of condensed matter (building structures, soils, etc.), Fig.4. [14]

The radar has 5 operating frequencies in the range from 1.5 to 2.0 GHz, and the signal is received in two polarizations. The radiated power of the generator at each of the successively switched frequencies is 10 mW, which ensures complete safety for the operating personnel. In the process of scanning over the earth’s surface, signals are sequentially received at each of the frequencies and in both polarizations. The frequency switching provides spatial coincidence of radio images at individual frequencies. Experimental results has shown that proposed method for obtaining radio images of objects in the soil with the possibility of their subsequent recognition can serve as the basis for creating promising mine detectors. [14]

As a result of the active scientific and experimental work, several systems have been developed, which allow obtaining high-resolution images of shallowly buried objects suitable for application in humanitarian demining. Fig.5 shows microwave hologram images of 50 mm rocket and 80 mm shell recorded by „RASCAN-4/4000“ subsurface radar. [8]
Fig.6. Images of Russian anti-tank mines TM-62M (metal body) and TM-62P3 (plastic body) recorded by subsurface radar and metal detector. [8]

In general, studies results show that the main obstacle that complicates the use of subsurface radars, irrespective of their type, in humanitarian demining operations, is the presence of different heterogeneities on the ground surface or at shallow depths. Reflections of electromagnetic waves from such heterogeneities and other objects of anthropogenic origin create a cluttered background difficult for detection and identification of mines. [8]

Conclusions

The paper presents the principle of operation of the holographic subsurface radars and the basic characteristics of the “Rascan” family radars developed by the MGTU. Main experimental results obtained by using these radars for detecting mines with low metal content are also presented. Experimental data show an extremely high efficiency of the holographic subsurface radars in recognizing various types of mines. At the same time, their use is limited to relatively shallow buried mines and in dry soils. It is therefore appropriate to use sub-surface radars to detect and identify landmines and improvised explosive devices located in dry soils at depths of up to several tens of centimeters. Subsurface holographic radars can also be used as complementary means of demining to identify suspected objects detected by other devices.

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