The Holographic Principle in Subsurface Radar Technology

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ABSTRACT. A relatively rare type of subsurface radar – holographic radar – is considered in this article. Its principle of operation, advantages and disadvantages are considered, and compared to those of impulse radars. The RASCAN family of holographic radars is presented along with technical specifications and typical case histories. Among the applications considered are civil and historic building surveys, non-destructive testing of dielectric materials, security applications, and humanitarian demining. Each application area is illustrated by relevant data acquired in laboratory experiments or field tests.

Keywords: Holographic subsurface radar, non-destructive testing, security applications, humanitarian demining.

INTRODUCTION

Impulse radar is the most common type of radar that is being produced commercially and used in practice. This radar uses time-of-flight 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 subsurface impulse radars, there is also a class of subsurface radars that employ continuous signals; including frequency modulated radar, stepped-frequency radar, and holographic radar [1]. 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 [1]. Stepped frequency or synthesized radar transmits consecutively a set of discrete frequencies registering the amplitude and phase of reflected 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 [4].

Holographic subsurface radar, operating at one or several discrete frequencies, is used to illuminate 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. It should be noted that this type of radar has been characterized as not capable of finding significant applications due to strong signal attenuation in typical media [1, 5]. However, in the rest of this paper, an attempt is made to highlight significant application areas and problem cases where this type of radar could potentially outperform traditional impulse radar.
I. RADAR’S DESCRIPTION

1.1 Design of the Holographic Subsurface Radar

The designs of subsurface radars are based on classical principles of radar technology. Signal emitted in a surveying 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 reflected on a computer display.

In Fig. 1 the simplest schemes of impulse and holographic subsurface radars are compared. There is direct amplification of the reflected signal in the impulse radar. Thus, considering the delay of the reflected signal and the lower electromagnetic wave speed in the dielectric medium, the time-of-flight for a reflected pulse is a measure of the depth of the subsurface object.

The holographic radar of RASCAN type consists of: antenna, transmitter and two receivers for parallel and cross polarizations [6]. RASCAN radars use continuous wave un-modulated signals, which are transmitted in a frequency band with a width of about 0.5 GHz at five discrete frequencies. The choice of operating frequency band and the number of frequencies is dictated by the necessity to provide a sufficient contrast between the object and medium for at least at one of the operating frequencies. It will be shown further, that in the case of a single frequency, for a given target depth there are “blind spots” at which the sensitivity of the holographic subsurface radar is minimal.

The comparison of parameters for impulse and holographic subsurface radars is presented in Table 1. The main distinction between them is the type of frequency spectrum. Impulse radar has a continuous frequency spectrum with the form of emitted signals being close to one period of a sinusoid. Holographic radar, instead, has a discrete spectrum. A time-varying amplification in the stroboscopic receiver of the impulse radar provides higher amplification for deeper objects and endows the radar with its main advantage of high penetration depth. In contrast, since it is continuous wave, holographic radar has the same amplification for objects at all depths. In this case, penetration depth depends on attenuation in the surveying medium, and the magnitude of heterogeneities at shallow depths (since shallow heterogeneities may shade deeper objects in recorded images).
Table 1. Comparison of Impulse and Holographic Subsurface Radars Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Impulse Radar</th>
<th>Holographic Radar</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency spectrum</td>
<td>Continuous</td>
<td>Discrete</td>
<td></td>
</tr>
<tr>
<td>Penetration depth</td>
<td>Up to 10 λ</td>
<td>1-2 λ</td>
<td>λ – wavelength in air</td>
</tr>
<tr>
<td>Resolution at shallow depths in plane of surveying</td>
<td>&gt; λ</td>
<td>~ 0.25 λ</td>
<td>λ – wavelength in air</td>
</tr>
<tr>
<td>Surveying over metal substrate</td>
<td>Hardly possible</td>
<td>Possible</td>
<td></td>
</tr>
<tr>
<td>Possibility of object's depth measurement</td>
<td>Directly from recorded signal</td>
<td>under investigation</td>
<td>This task for holographic subsurface radar does not yet have a proper solution</td>
</tr>
<tr>
<td>Adaptation to the FCC norms</td>
<td>Difficult</td>
<td>Easier</td>
<td>Frequency spectrum of holographic radar could be selected in advance while impulse radar has a UWB spectrum that can’t be changed or limited arbitrarily</td>
</tr>
<tr>
<td>Radar cost, USD</td>
<td>15,000-45,000</td>
<td>~ 5,000</td>
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</tbody>
</table>

On the other hand, the ultra-wide spectrum of the emitted time-domain impulse is the main disadvantage of impulse radar. This can lead to interference with other microwaves devices (global positioning and communications systems, electromagnetic switches or electroexplosive triggers, etc.), and as a consequence, also leads to conflict with existing standards for electromagnetic compatibility. In particular, it is worth mentioning the conflict that emerged in the USA in connection with the Federal Communication Commission (FCC) requirements that actually forbade the use of subsurface radars [2, 3]. However, holographic radars are much easier to adapt to the US FCC regulations and demands, and also have the advantage that they are much cheaper to produce than impulse radars.

In addition, at shallow depths, the holographic radar of RASCAN type has a distinct advantage in resolution over impulse radars because of the specific design of the radar antenna that combines transmitter and receiver antennae into single housing. Another extremely important advantage of holographic radar technology is the possibility to image without reverberation heterogeneous inclusions in dielectric materials that lie above, and even directly on, a metal surface. Such composite materials cannot currently be inspected non-destructively with traditional time-domain impulse radar technology. The reverberation of pulses between the impulse radar antenna and metal substrate obscures the actual location and shape of heterogeneities, defects, and other inclusions in the dielectric medium. Here, the object of interest is lost in multiple reflections (often called ghosts or phantoms) of transmitted impulse signal [7]. Therefore, the unique ability of holographic radar to image objects on metal surfaces could be very important for inspection of the heat protection system of space vehicles. Experiments that support this application area are considered later in the paper.

Three models of RASCAN holographic radar, with operating frequencies in range of 3.6 through 4.0 GHz; 1.6-2.0 GHz; and 6.4 – 6.8 GHz respectively, are now being produced. The choice of a frequency range, and hence radar model, is determined by the conditions of a particular task and by the trade-off between spatial resolution and penetration depth. For higher operating frequency ranges the spatial resolution improves but penetration depth falls. However, this is a common problem for all types of subsurface radars, and for all non-destructive testing or geophysical methods.

It is necessary to point to an essential distinction of the term “spatial resolution” when applied to impulse and holographic subsurface radars. For impulse radars, as a rule, the resolution is understood as the depth resolution and is defined by the duration of the emitted impulse. For holographic radars this term is determined by the resolution at shallow depths in the plane of view. The resolution in the latter case is defined by the operating frequency.

The antenna of holographic subsurface radar operates as the gauge of the electromagnetic waves in the near and reactive fields for object depths from zero level to a maximum sounding depth of 15-35 cm. To record a microwave hologram, the operator scans the surface of the location under inspection line-by-line. The scanning head is swept directly by hand, or using a special handle for the 1.6-2.0 GHz device. A parameter comparison for the three modifications of RASCAN radar is listed below in Table 2. The high resolution in the plane of view for
holographic subsurface radars of RASCAN type is explained by the focusing properties of the antenna at shallow depths.

Table 2. Parameters of RASCAN holographic radars

<table>
<thead>
<tr>
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<tbody>
<tr>
<td>Frequency range, GHz</td>
<td>1.6 - 2.0</td>
<td>3.6 - 4.0</td>
<td>6.4 - 6.8</td>
</tr>
<tr>
<td>Number of operating frequencies</td>
<td>5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of recorded signal polarizations</td>
<td>2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Emitting power, W</td>
<td>6·10⁻³*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sensitivity of the receiver, W</td>
<td>10⁻⁹</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Resolution in the plane of sounding at shallow depths, cm</td>
<td>4</td>
<td>2</td>
<td>1.5</td>
</tr>
<tr>
<td>Maximal sounding depth (depends on medium permittivity), cm</td>
<td>35</td>
<td>20</td>
<td>15</td>
</tr>
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</table>

1.2 Theoretical Analysis and Explanations

It was indicated earlier that radars of RASCAN type operate in a five-frequency mode because, when working at a single frequency, there are “blind spots” at some depths where the signal from an object vanishes or is insufficient. Let us consider a mathematical model of the simplest monochromatic holographic subsurface radar. It can be presented as follows.

Let us approximate a subsurface object by a plane that is perpendicular to the incident electromagnetic wave. The radar radiates electromagnetic waves at a constant frequency \( \omega \) whose amplitude and phase do not depend on time. The reflected wave has constant amplitude \( A_r \), but the phase of the reflected wave \( \phi_r \) depends on the range to the object

\[
\phi_r = 2\sqrt{\varepsilon} \frac{l\omega}{c} + \Delta\phi, \tag{1}
\]

where \( \Delta\phi \) is the phase shift which arises upon reflection of the electromagnetic wave from the object, \( \varepsilon \) is the dielectric permittivity of the medium, \( l \) is the distance to the object, \( \omega \) is the cyclic frequency, and \( c \) is the speed of light. Thus, the reflected signal depending on time \( t \) can be written as

\[
A_r \cos(\omega t + \phi_r) \tag{2}
\]

Reflected wave (2) mixes with a constant-phase radar reference signal in form of

\[
A_o \cos(\omega t + \phi_o), \tag{3}
\]

where \( A_o \) and \( \phi_o \) are the amplitude and phase of the reference signal respectively. Then, the reflected signal (2) is mixed with the radar reference signal (3) in the mixer. The amplitude of signal in the mixer output at the difference frequency is given by

\[
A_rA_o \cos(\phi_o - \phi_r). \tag{4}
\]

From this relation one can conclude that, if the phase shift between the reference signal and reflected one is close to

\[
\phi_o - \phi_r = (k+1/2)\pi, \quad k=0,1,2,\ldots \tag{5}
\]

the level of recorded signal from the object is low, and at

\[
\phi_o - \phi_o = k\pi, \quad k=0,1,2,\ldots \tag{6}
\]

* Low emitting power guarantees full safety for personnel while using RASCAN radars, Russian sanitary certificate on October 19, 2005 # 77.01.09.650.П.041358.10.05.
the recorded signal level is maximal. The latter circumstance was observed experimentally. To avoid "blind" depths it was proposed to use multifrequency signals with a bandwidth providing inversion of the object contrast with background for scanning within the chosen frequency range. This guarantees high contrast of displayed object for at least on one of the working frequencies.

The microwave holograms in Fig. 2 show just two (4.0 and 3.6 GHz) of the five simultaneous frequencies recorded by a RASCAN-4/4000. The holograms illustrate well the wave nature of recorded images. These holograms were recorded over a stack of dry plaster sheets in which several metal coins of 25 mm in diameter and two thin wires were placed at different depths. One coin, in the top left corner of the image, was placed under a wire at some distance below it.

![Image of holograms](image)

**Fig. 2.** Microwave images of coins and wires recorded by holographic radar RASCAN-4/4000 at two operating frequencies

Due to the difference in phase shifts between the reference and reflected signal from objects located at different depths, it possible to achieve higher contrast for one object or another by switching through frequencies in the selected bandwidth. In the first case, the frequency was chosen so that the contrast of the coin located at a greater depth was higher than the contrast of the wire. In the second case, at a different frequency, the wire shades the coin more strongly. For a better representation of images at all five working frequencies, a computer animation in which the image at one frequency transforms smoothly into the image at the next frequency, and so on, is used [17]. So, the operator can evaluate the results of his work with the radar simultaneously at all frequencies.

To explain the principle of image formation in the holographic radar, an optical analogy is presented in Fig. 3. Let a flat monochromatic wave, referred to as the reference wave, with a constant phase fall on a point object and be scattered by it. As a result of the interference of the reference and scattered waves on a plane located at some distance behind the object, an interference pattern is formed. If the interference plane is located perpendicular to the direction of the reference wave propagation, the interference pattern represents a Fresnel lens. Thus, after illuminating the recorded interference pattern with the reference wave, a virtual image of the point object appears behind it.

In holographic subsurface radar of RASCAN type, the reference wave is provided by direct receiver-to-transmitter antenna coupling. It is also important to note that the interference pattern is only visible in media with low attenuation, e.g. the plaster sheets of Fig.2.

In typical media (concrete, bricks, wet soils, etc.) for most subsurface radar applications, the attenuation is much higher than in dry plaster. In this case, recorded images still appear, but they are shadow pictures reminiscent of X-ray images. It can be easily seen that to form a complete interference pattern, a buried object must reveal its presence to the antenna not only in nadir but also in some area away from nadir where the distance to the object increases and the amplitude of received signal drops due to attenuation. In a lossy medium, the signal extinction along such slant paths away from nadir is large enough to not reveal any interference pattern. The interference pattern effect is best observed in air, but this problem does not concern subsurface radar applications, although mathematical algorithms for reconstruction of microwave holograms from subsurface radars have been developed in [11, 14].
Sounding of media with high attenuation is the main objective in subsurface radiolocation. In some media, the attenuation of electromagnetic waves can achieve 100 decibels per meter or even more. Other media are notorious for their high dispersion and attenuation that distort the emitted pulse form and add to the problem. The properties of lossy dielectric media and materials in many respects dictate the features of radar design, selected frequency range, and the type of used signals.

The high attenuation of electromagnetic waves in many media to be sounded results in maximal penetration depth for holographic subsurface radars of less than two or three wavelengths. This is much less than that of impulse radars with the same central frequency. However, as will be shown below, it is quite sufficient for many important practical problems. The RASCAN radar advantages can be summarized as follows:

- High resolution in the plane-of-view, that can achieve 1.5-2.0 cm at shallow depths
- Ability to perform one-sided sounding, instead of double-sided sounding as in X-ray devices
- Ability to detect not only metal objects, but also objects made from any dielectric materials provided that their permittivity is different from that of the medium
- Ability to image targets in dielectric media above, or directly on, metal surfaces. This can be very important when surveying composite materials, i.e. heat protection of space vehicles
- RF emission level for RASCAN radars (10 mW) is two orders of magnitude less than the emitting power of an ordinary mobile phone, and is completely safe for the operator.

II. APPLICATION FIELDS OF THE HOLOGRAPHIC SUBSURFACE RADARS

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 this case, there is commonly no special requirement to measure the depth to an object. Estimation of object depth in the medium may be desirable, but not as critical as detection and classification of the object from its recorded microwave image. As examples, we refer to the tasks of mine detection for humanitarian demining and detection of overhearing devices or “bugs” in buildings. In these cases, the main goal is detection of a concealed object, and knowing its depth is not so important. Imaging of the buried object shape is one of the main advantages of the holographic method. In any case the detected object has to be eliminated. For mine clearance, if necessary, mine depth can be estimated with a sapper spike. Difficulties with depth estimation for RASCAN radars are connected with the fact that restoration of holograms (by the algorithms offered in [11]) is possible only for environments with low attenuation of electromagnetic waves. In the majority of practically important cases, sounded media have high attenuation and the wave nature or interference pattern in registered images is not preserved.
2.1 Surveying of Building Structures for Determining the Position of Defects, Reinforcement, Voids and other Heterogeneities

To demonstrate the capabilities of holographic radar technology, survey work in one of Saint Petersburg’s historical buildings is described. The former Senate building was being renovated for use by the Constitutional Court of the Russian Federation. The building was designed by the outstanding architect K.I. Rossi in 1829-1834 and has great value for Russian culture. According to the restoration project, a radiant heat system was installed in the building, with the heating pipes being under cement covering. The lack of specific knowledge about the positioning of the pipes presented a risk of accidental damaging when laying a proposed parquet floor covering.

The following installation technology of sub-floor heating system is usually used. First, metal mesh is laid on the sub-floor. The size of the mesh cells is typically 15 cm × 15 cm square. Then, the pipes are fastened to the mesh by plastic clips. Various types of pipes are used, including cross-linked polyethylene (PEX), multi-layer (a composite of PEX, aluminum and PEX) and polybutylene (PB): copper pipes are not used now. The spacing of the pipes is around 30 cm. The pipes are then covered by finishing layer of cement. The depth of the cement above the pipes is typically about 3 cm.

There was concern that the plastic pipes of the heater system would be invisible against the background of the metal mesh because plastic has lower permittivity contrast with the cement than does the metal mesh. It has been mentioned that the object contrast on holographic radar images depends on reflectivity of the object as well as phase shift – which is a function of the distance to the object. For extended or elongate objects, the orientation of the received signal polarization also has great influence on the resulting image contrast. At improper polarization, a long metal bar or wire can be invisible.

The work of floor inspection was carried out with the aid of a RASCAN-4/2000 holographic subsurface radar (see Fig. 4). The total area of scanned surface was 16.7 square meters. The overall time of work (disregarding the time for equipment deployment) was about 5 hours. More than half of that time was spent on scanning while the rest was spent on plotting the layout of pipes and cables directly on the floor. While inspecting the floor, a tangle of power and communication cables was also found. This added to the complexity of interpreting the radar images.

The surveyed area was divided into sections with the size of 1.7 by 2.0 m. After recording a radar image of each section, the operator analyzed the image and drew the results on the floor with chalk. The position of heater tubes was marked by blue chalk, with red chalk used for cables and wires, see Fig. 5. As it was assumed before investigation, there was no difference between pipes and metal mesh in the radar images at parallel polarization. In the radar images at cross polarization, the plastic pipes were clearly visible. An interesting part of a radar image is shown on Fig. 6. In this fragment, one can clearly see how the heater pipes are bending over the cable.

![RASCAN-4/2000 radar head](image1.png)  ![Position of heater tubes was marked by blue chalk, and red chalk was used for cables](image2.png)  ![Part of radar image.](image3.png)

Fig. 7 presents three images: a) raw cross polarization radar image at the frequency of 2.0 GHz; b) image "a" after numerical filtration; c) plan of water tubes (black lines) and communications (hatched areas). The observable horizontal lines in image "a" are reflections from the metal mesh in the cross polarization radar channel. The elements of the grid in another direction can be clearly seen only in the parallel polarization channel (this image is not presented here). The overall dimensions of the radar image in Figure 7 are 1.70 m by 8.04 m. An FFT-based numerical algorithm was proposed to suppress reflections from the periodic structure of metal mesh in the radar images [12]. Fig. 7 b) demonstrates the effectiveness of this algorithm.
Fig. 7. Interpretation of the radar image:
   a) raw radar image at the frequency of 2.0GHz (cross polarization);
   b) image "a" after Fourier-based numerical filtration;
   c) layout of pipes and communications on results of the radar’s surveying
   (— heater pipes; — communications)

One more example of using the RASCAN holographic radar technology was an inspection of a church in Toscana, Italy. The Church of S. Biagio was built near the town of Montepulciano by Antonio da Sangallo the Younger more than 500 years ago (Fig. 8). An international team of Italian, American, and Russian scientists conducted inspection of the floor in the Church of S. Biagio in September of 2007. One of the inspected areas of floor was an inlaid marble medallion as pictured in Fig. 9. The marble decoration dates to about of 1590 AD, and
according to documentary sources, it was laid during the burial ceremony of a church man (*Prelatio in Latin*) belonging to the family Cervini. During the project in the Church of S. Biagio, the subsurface holographic radar RASCAN-4/4000 was used. This radar is small and is operated by hand scanning (Fig. 9). A radar image of the marble medallion in Fig. 10 reveals a complex subsurface structure of the object, the origin of which is not clear without additional information.

To interpret the obtained images a series of additional experiments involving marble plates, wooden bars, and bricks was conducted as well as an historical investigation. Combining results of the auxiliary experiments and historical research, it was found that under the marble stone there is probably an empty area with wood or brick elements to support the medallion. Thus, the cavity under the medallion is probably none other than Vincenzo Cervini’s burial chamber.

Fig. 8. The Church of S. Biagio in Montepulciano, Italy.  
Fig. 9. Inspection of a marble medallion in the church by RASCAN-4/4000 radar  
Fig. 10. Radar image of the medallion at a frequency of 3.9 GHz

2.2 Non-Destructive Testing of Dielectric Construction Details

The disastrous loss of the US Space Shuttle Columbia forced researchers to find new possible methods and devices for non-destructive testing and evaluation of the space shuttle thermal protection system, as well as the external fuel tank insulation foam. Such methods of diagnostics could be useful not only for current space vehicles, but also for proposed new spacecraft such as the Orion manned exploration vehicle.

The main problem in nondestructive testing of heat protection systems for space vehicles is that the task requires surveying a layer of a dielectric material that lies directly on the metal load-bearing shell. If similar composite designs were sounded using impulse subsurface radars, reverberations of a radiated impulse between the metal surface and radar antenna would considerably complicate detection of heterogeneities and defects in dielectric heat protection materials [7]. Holographic subsurface radars are free from this drawback since the signal reflected from the metal surface parallel to the surface of heat-shielding material has constant phase and is thus invisible in the recorded radar images.

Pilot experiments have been conducted to investigate various types of anomalies within a rigid 5 centimeters thick foam plastic layer placed over an aluminum sheet. The anomalies presented by voids in the foam, some of which were water-filled, were easily detected by a RASCAN-4/4000 radar [10]. Further experiments with the same type of radar were conducted in cooperation with NASA Jet Propulsion Laboratory, CA and NASA Johnson Space Flight Center, TX. In these tests, real Space Shuttle heat protection tiles were glued to an aluminum sheet similar to the aluminum body of the shuttle using the same RTV adhesive as is used on the shuttle (Fig. 11).

In Fig. 12, the results of tile inspection are presented [13]. Areas on the surface of the aluminum sheet, in which the glue under the tile was absent, are seen as white spots. The reverberation effect, intrinsic in this situation to the impulse radar, is absent in the images. Further research to define capabilities of such diagnostics, and to determine a proper frequency range for such a radar is necessary in the future.
2.3 Detection of Water Infiltration in Underground Parts of Building

Because of the abnormally high dielectric permittivity of water, areas with increased level of moisture should have high contrast on microwave images. This assumption was confirmed in experiments with RASCAN radars. Such an experiment took place in an underground garage with the purpose of finding places of ground water intrusion, Fig. 13. As a result of radar inspection of a garage ceiling bench, the microwave image presented in Fig. 14 was recorded. Two inclined, bright, elongated spots in the upper part of the image were interpreted as voids through which water advanced vertically down. To test the assumption a hole was drilled at one of the spots through which water immediately revealed itself. Builders concluded that the cracks had to be sealed to prevent further moisture intrusion.

3.4 Security Applications

One important applications for holographic radars is detection of listening or bugging devices intended for clandestine recording of confidential information in government, business, or residential buildings. Due to high resolution of RASCAN radars, it is possible not only to find suspicious areas in different parts of a building but also identify the type of a bugging device on a recorded microwave image.

Although resolution of RASCAN radars is inferior to X-ray devices, their essential advantage is the ability to record images with one-side access to the surveyed object. In many cases, the required two-side access makes impossible application of X-ray imaging. Moreover, RASCAN radars emit less than 10 mW of power, and are
absolutely safe for the operator and nearby personnel. This is not the case when operating X-ray devices, which require strong safety precautions to mitigate hazards to human health. The RASCAN radar could also be an effective tool to complement non-linear junction detectors in searches for bugging devices. That is, RASCAN radar could be used to examine suspicious places found by non-linear junction detector, and thus significantly lower the level of false alarms produced by the latter when it is operated solo.

Fig. 15 shows a wall model made of chipboard plates with built-in bugging devices: two microphones and a tiny TV camera. From above, the model was covered by two other layers of chipboard, with total thickness of 5 cm. The result of scanning this model by a RASCAN-4/4000 radar is pictured in Fig. 16. The recorded microwave image precisely represents the form of the hidden objects beneath the chipboard plates. This allows discrimination of bugging devices from innocuous objects that may be present naturally in building designs (nails, reinforcements, etc.).

To improve radar resolution, a new model, RASCAN-4/7000, was developed. This radar operates in the frequency range of 6.4-6.8 GHz. Experiments conducted with the device have shown that its sensitivity is enough to detect fiber-optic cables even without any metal content.

3.5 Humanitarian Demining

Unexploded ordnance (UXO) remediation is the number one environmental concern on millions of square kilometers of local war conflicts and formerly used defense sites all over the world. While subsurface radar is not a perfect tool for detecting and mapping UXO over large areas, many experts have proposed that radar could be used for small area studies, or for interrogation of anomalies identified by other geophysical methods (e.g. magnetometry or electromagnetic induction) to discriminate UXO from clutter, or even identify UXO types prior to excavation [15]. While considerable progress has been made in developing equipment and algorithms for discriminating UXO using conventional impulse radars, a basic limitation of impulse radar is that signal spreading causes all targets to appear in subsurface images as non-unique sets of parabolic reflections that do not generally resemble the actual target [16]. Research on recording of microwave images of mines in the ground began at the end of 1980's with the use of the standard continuous-wave MMP mine detector which operated at a frequency of 600 MHz [8].

In order to test the suitability of holographic radar of RASCAN type for discriminating UXO, several inert UXO items, ranging in diameter from 40 to 81 mm, were buried in a sand test bed, and scanned with a RASCAN-4/4000. All items were buried horizontally, just under the surface. For these large, complex objects, the depth to the upper surface ranged from near zero to about 8 cm. For example, the fins on the rocket were nearly exposed, but the cylindrical body part laid at about 7 cm. The wrench was a nearly uniform 3 cm, with the adjustment collar nearly exposed. The thickest part of the body of the 80mm shell was at the surface, with the fins at about 4 cm, and the thinnest part of the body at 7 or 8 cm. The 40mm shell was just barely covered by sand.
The RASCAN holographic image of each buried item is shown next to a photograph of the item in Fig. 17. Note that the figures clearly illustrate the interference pattern nature of RASCAN images. However, all of the images strongly resemble the actual item - even without reconstruction of the hologram from the recorded interference pattern. This preliminary study emphatically supports the opinion that the radar - in particular holographic radar - could be used to interrogate/identify potential buried UXO items [15].

Object photo | Microwave hologram of buried object
--- | ---
40mm shell casing
50mm rocket
80mm shell
Pipe wrench

Fig. 17. Microwave hologram images recorded by RASCAN-4/4000 subsurface radar

A more advanced prototype of a holographic radar that automatically performs electromechanical scanning of ground surface, and is equipped with an additional induction metal detector channel was created under the International Science and Technology Center (ISTC) Project #2541 in 2007 [9]. This radar is presented in Fig. 18.
Technical specifications of the holographic radar channel of the prototype are close to that of the RASCAN-4/2000 radar.

Scanning of a line in this radar is performed by automatically sweeping the radar head across the device chassis, perpendicular to the travel direction of the entire system. The metal detector coil is placed on the radar antenna’s lower face. This allows registration of the same area both in the radar and metal detector channels simultaneously. The images of various objects recorded by the radar, developed under ISTC project # 2541, are presented in Fig. 19. The objects were buried in sand at a depth of 5 cm. The left column has photos of the objects, the middle column shows radar images and the right column presents coincident images recorded in the metal detector channel.

The metal detector channel reveals an anti-tank mine in metal case. In this channel the image of an entirely plastic mine is absent (all metal details including the detonator, were removed). A thin wire of 25 micron diameter is also not visible for the metal detector due to the characteristically poor coupling between metal detector coil loops and highly elongate, thin targets. Were the same wire looped, it would give a powerful signal in the metal detector channel. The contrast of wires in radar images depends strongly on channel polarization, but does not depend on the diameter and form of a wire

![Fig. 18. Holographic radar with electro-mechanical scanner. ISTC project #2541.](image)

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. In this sense, the task of sounding building construction details or bugs by holographic radars is much easier. Here, most cases involve surveying over a smooth surface and a priori assumptions about concealed objects are frequently present.

CONCLUSIONS

In this work we have presented a summary of the theory, technology and applications of the holographic subsurface radar. The main advantages and limitations relative to the commonly used impulse radars are also reported. In general, it is worth mentioning that subsurface radar is not a universal method of opaque media sounding. In many practically important cases, the penetration depth is not sufficient, and quality of recorded images does not allow reliable identification of detected objects. However, appropriate choice of the type of probing signal and its frequency range can lead to useful results that may be impossible to achieve with other non-destructive diagnostic methods. The typical field of application for holographic subsurface radar is the sounding of opaque media at shallow depths when images with high plan-view resolution are required. In these cases it is possible to define the form of targets and clutter objects, and to formulate reasonable assumptions concerning their nature.
<table>
<thead>
<tr>
<th>Object photo</th>
<th>Microwave image of the object when buried under the surface</th>
<th>Metal detector channel under the same conditions</th>
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<tr>
<th>Buried metal wire of 0.25μm diameter placed at an angle to the direction of radar motion</th>
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<th>Russian metal-body TM-62M antitank mine buried in sand</th>
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<tr>
<th>Russian plastic-body TM-62P3 antitank mine buried in sand</th>
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Fig. 19. Images recorded by subsurface radar and metal detector

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