RASCAN HOLOGRAPHIC RADARS AS MEANS FOR NON-DESTRUCTIVE TESTING OF BUILDINGS AND EDIFICIAL STRUCTURES

V.V. Razevig, S.I. Ivashov, T. Bechtel, L. Capineri
I.A. Vasiliev, A.V. Zhuravlev Franklin & Marshall College,
Bauman Moscow State University of Florence
Technical University Pennsylvania
Moscow, Russia USA
Moscow
vrazevig@rslab.ru capineri@ieee.org
tbechtel@fandm.edu

KEYWORDS: Holographic subsurface radar, non-destructive testing, microwave imaging.

ABSTRACT
A relatively new type of subsurface radar – holographic radar – is considered as means for non-destructive testing (NDT) of buildings and edificial structures. Principle of its operation, advantages and disadvantages are considered, and compared to those of traditional subsurface radars of impulse type. The RASCAN family of holographic radars is presented along with technical specifications and typical case of applications in edificial field. Civil and historic building surveys, NDT of dielectric materials are considered in row with others applications. Each application area is illustrated by relevant data acquired in laboratory experiments or field tests.

INTRODUCTION
A family of holographic subsurface radars, named RASCAN, has been produced following more than ten years of research and development. RASCAN radars are a completely unique and innovative type of subsurface radar that operates with continuous wave, discrete frequencies around 2 GHz, 4 GHz or 7 GHz depending upon the model. Images are recorded by sweeping the cylindrical horn antenna across an investigated surface, with the transmitter producing five discrete frequencies which are recorded at two receivers with parallel and cross polarization relative to the transmitter. The reflected signals are mixed with an internal reference signal to create a holographic image of the subsurface, with plan-view resolution of one half wavelength or better. The use of five frequencies and two polarizations ensures detection of targets with arbitrary orientation at depths up to about 2 wavelengths. RASCAN radars have previously shown great promise for shallow, very high resolution scanning of concrete, stone, wood, mortar, plaster, and other dielectric materials that are important in art and architectural preservation. A particular sensitivity to moisture, even at very low concentrations, has been demonstrated, and the knowledge of moisture presence is of critical importance in many antiquities. In addition, RASCAN can produce plan-view subsurface images in real-time even without post-processing. Subsurface targets are shown with their true plan-view shapes (as opposed to the time-of-flight hyperbolic reflection patterns typical of impulse radar images). These characteristics make RASCAN a tool readily applied and interpreted by users with no special geophysical training. Finally, RASCAN is commercially available, relatively low cost, and easy to use and interpret – making this device a potentially powerful tool for workers engaged in the preservation and restoration of artworks and architecture. It is worth to mention also that main advantage of subsurface radars of all types is the possibility in opposite of X-ray devices to record subsurface objects with one-side access to a detail under consideration.

DESCRIPTION OF RASCAN HOLOGRAPHIC SUBSURFACE RADAR
Traditionally, the type of the subsurface radar used in practice is impulse radar. In general, these repeatedly transmit one period of a sine wave signal, and record the amplitude and time of flight of reflected impulses (Fig. 1, left). Almost all subsurface radars now in commercial production are of this type. The main advantages of impulse radar are the high effective penetration depth into the surveyed medium due to the application of time-dependent gain which amplifies the weaker later/deeper reflected arrivals, and the ability to make direct measurement of reflector depths from the reflected signal time-of-
flight (Daniels, 1996). On the other hand, their main disadvantage is the ultra-wide spectrum of their signal. This can lead to interference with other microwaves devices (e.g. global positioning and navigation systems, communications, electronic switches, etc.), and conflict with existing norms – in particular, the USA Federal Communication Commission (FCC) regulations (FCC, 2002).

While the RASCAN radar system is based on classical principles of radar technology, it is completely different from traditional impulse radars. Signal is emitted into the subsurface, which is reflected by heterogeneities with dielectric constant or conductivity different from the medium. The reflected signal is received by the radar antenna, amplified, processed, and displayed on a computer screen. RASCAN radars consist of a transmitting antenna, and two receivers, parallel and perpendicular to the transmitter polarization (Fig. 1, right).

![Fig. 1 Comparison of impulse and holographic radar schematics.](image)

During scanning, the transmitter emits a continuous wave at five discrete frequencies. The receivers record the reflections of these signals. The reflected signals are mixed with an internally generated reference signal that has not been transmitted to the medium. Both the reflected signal and reference signal have the same frequency, but the reflected signal has a phase shift that depends on the distance (depth) to the reflector. Thus, the reflected signal and reference signal interfere constructively or destructively depending on the reflector or target depth; thus, the need for five simultaneous frequencies that ensure that a target will be visible on at least one of the frequencies regardless of depth (Ivashov et. al. 2008).

The principle of image formation in RASCAN holographic radar is the same as in the simplest optical hologram. In Fig. 2, a flat monochromatic reference wave with a constant phase falls on a point object and is scattered by it. On a plane some distance behind the object, the reference and scattered waves create an interference pattern. If this plane is oriented perpendicular to the reference wave, the interference pattern is a Fresnel lens – the simplest hologram. In optics, the hologram has to be illuminated to reconstruct a virtual image of the object.

In RASCAN holographic radar, the reference wave is provided by direct coupling of the transmitter and receiver antennae. The scattered wave is recorded by the receiver, and the interference pattern is produce in the mixer. There are two important differences between optical and microwave holography: Firstly, because the signals are not in the visible waveband, the Fresnel lens cannot be directly illuminated to project a hologram – although numerical reconstruction algorithms have been developed (Chapursky et. al. 2002a). Secondly, an accurate true hologram cannot generally be reconstructed due to signal loss in most materials. That is, the full interference pattern is not recorded because the outer rings (for example for a point scatterer) are attenuated. However, these are not deficiencies for radar holography. In fact they are almost fortuitous since the loss of the outer rings produces an interference
pattern that typically strongly resembles the actual target object or feature. Thus, when RASCAN radars are employed for shallow targets, the natural loss of signal replaces the need for numerical image reconstruction, and high-resolution plan-view subsurface images appear in real time as the scanning is performed.

A comparison of parameters for impulse and RASCAN holographic subsurface radars is presented in Table 1. Impulse radars have a continuous frequency spectrum, while RASCAN holographic radar has a discrete spectrum which falls in the wavebands 1.6 to 2.0 GHz, 3.6 to 4.0 GHz, or 6.4 to 6.8 GHz depending on model (RASCAN-4/2000, RASCAN-4/4000, and RASCAN-4/7000 respectively). A parameter comparison for the three modifications of RASCAN radar is listed below in Table 2. The discrete frequencies make it easy to comply with electromagnetic spectrum regulations and norms. Impulse radars have better effective survey depth because of the possibility to apply time-varying gain. In contrast, RASCAN radar can only apply a constant amplification for objects at all depths, with the effective survey depth completely dependent upon signal attenuation in the medium or scattering of signal by shallow heterogeneities that may shade deeper objects. Maximum imaging depth of holographic radars rarely exceeds two or three wavelengths. This is less than that of impulse radars with the same central frequency. However, as will be shown below, it is sufficient for many important practical tasks. RASCAN has a distinct advantage in lateral or plan-view resolution over impulse radars because of the specific design of the radar antenna that combines transmitter and receiver antennae into one apparatus with small footprint. Another important advantage of RASCAN radar is the ability to image targets within dielectric materials which lie directly on a metal surface (Ivashov et. al. 2007). Such materials cannot currently be inspected non-destructively with impulse radar due to the reverberation of pulses between the radar antenna and strongly reflective metal. Targets in these constructions are typically lost in the multiple reflections or ghosts of transmitted impulse signals (Chapursky et. al. 2002b).

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 $\lambda$</td>
<td>1-2 $\lambda$</td>
<td>$\lambda$ – wavelength in air</td>
</tr>
<tr>
<td>Resolution at shallow depths in plane of surveying</td>
<td>$&gt; \lambda$</td>
<td>$\sim 0.25 \lambda$</td>
<td>$\lambda$ – 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 have a proper solution yet</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. Impulse radar has a UWB spectrum that can’t be changed or limited arbitrarily.</td>
</tr>
<tr>
<td>Cost of Radar technology</td>
<td>High</td>
<td>Low</td>
<td></td>
</tr>
</tbody>
</table>
In general, the advantages of RASCAN holographic radars are:

- High resolution in the plane-of-view; 1 to 2cm at shallow depths (Bechtel et. al. 2008)
- Ability to perform one-sided sounding, without requiring access to both sides of a medium as in X-ray devices
- Ability to detect not only metal objects in a dielectric medium, but also dielectric materials with dielectric constant or conductivity different from that of the medium
- Ability to image targets in dielectric media above, or directly on, metal surfaces
- Microwave emission levels of 10mW or two orders of magnitude less than the emitting power of an ordinary mobile phone that provides complete operator safety (Russian sanitary certificate, 2005).

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<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></td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>Number of recording signal polarizations</td>
<td></td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Emitting power, W</td>
<td>6·10⁻³</td>
<td>10⁻⁹</td>
<td></td>
</tr>
<tr>
<td>Sensitivity of the receiver, W</td>
<td></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>
</tbody>
</table>

RESULTS

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 so critical as detection and classification of the object on its recorded microwave image. In the following sections, plan view microwave images will be presented that demonstrate the advantage of a direct interpretation of buried objects by detecting their shape. Imaging of the buried object shape is one of the main advantages of the holographic method. Difficulties with depth estimation for RASCAN radars are connected with the fact that restoration of holograms is possible only for environments with low attenuation of electromagnetic waves (Razevig et. al 2010). In the majority of practically important cases, sounded media have high attenuation and the wave nature in registered images is not visible.

Some examples

In this series of experiments a sheet of paper with embedded letters was constructed. The letters were cut from thin aluminum foil. Dimensions of the word ‘RASCAN’ are 44 cm by 11.5 cm. The paper sheet with aluminum lettering was placed on a plaster sheet, and was covered by other plaster sheets one-by-one. After addition of each new sheet to the stack, the hidden paper sheet was scanned by hand using the RASCAN-4/4000 radar. The dimensions of scanned area were equal to 65 cm by 28 cm. Dry plaster sheets have very low level of attenuation in microwave range. So holographic nature of recorded image is clearly visible, see right image in Fig. 2.

![Fig. 2 RASCAN holograms recorded through the stack of plaster sheets: depth is 2 mm (left); depth is 98 mm (right)](image-url)
In Fig. 3 some examples of the microwave images of various walls are presented. All images were obtained by a RASCAN-4/4000. In these cases, attenuation was high and recorded images resemble X-ray images without waviness on them.

**Surveying of building structures**

To demonstrate the capabilities of holographic radar technology, survey work in one of Saint-Petersburg’s historical buildings is described. The historic former Russian Senate building in Saint Petersburg was designed by the outstanding architect K.I. Rossi, and constructed in 1829–1834 (Fig. 4). As part of a renovation project, it was necessary to precisely delineate a system of subfloor heating tubes. At the outset of the work there was concern that the non-metallic heating pipes could be obscured or shadowed by metal reinforcing mesh in the concrete floor, or that the pipes may not have sufficient dielectric contrast with surrounding medium. In addition, the contrast of a subsurface target depends not only on the dielectric contrast and phase shift that depends on depth but for elongate targets such as pipes or wires and on the orientation of the target relative to the radar signal polarization. A RASCAN-4/2000 (Fig. 5) was used to scan a 16.7 m² room in individual sections of 1.7 by 2.0 m, with the sectional images stitched together to produce a complete image. As expected, the pipes and metal mesh could not be discriminated on the parallel polarization images. However, in cross polarization (Fig. 6), the plastic pipes were clearly visible, and can be made even more apparent by numerical filtration of the digital image based on the regularity of the mesh (Razevig et. al. 2008). In addition, numerous power and communication and electricity cables are visible on the RASCAN radar images. These can be discriminated because they lead to visible pull boxes. The RASCAN radar images allowed marking of the heating tubes and utilities directly on the floor so that they could be avoided during intrusive renovation activities (Fig. 7).
Fig. 6 RASCAN-4/2000 holographic scanning of a 170 cm by 804 cm floor of the Russian Senate Building reveals curvilinear heating tubes and metal reinforcing mesh (left). The regular spacing of the mesh allows numerical filtration to suppress the mesh and enhance the tubes (centre), allowing accurate marking of the tubes as well as previously undocumented power and communication conduits beneath the floor (right).

( - heater pipes; - communications)
Another example of investigations is the scanning of the concrete floor at Leningradskaya hotel in Moscow, Russia, Fig. 8. According to the reconstruction plan of the hotel, an automatic fire-fighting system was installed in the building. According to the design of the fire-fighting system each room of the hotel has the main pipe of 63 mm in diameter from which by means of smaller pipes water is directed to sprinklers. Due to the presence of other objects (mainly power cables) at the installation stage of the fire-fighting system the actual layout of pipes was different from that was planned according to the design. The following nailing of plywood sheets for parquet could damage the pipes and the actual layout had to be known precisely.

It turned out that in acquired images the places where horizontal pipes bent to the sprinklers of the lower floor ceiling were easily seen. Given this, only the areas where sprinklers were supposed to be about were
inspected. On acquiring such fragment of image the operator analyzed it and mapped a piece of pipe or sprinkler on the floor. The overall picture was interpolated given a typical layout of pipes, Fig. 9 and 10.

![Acquired images mapped to the layout of a room (left); reconstructed from radio images layout of pipes and sprinklers (right)](image)

**Fig. 9** Acquired images mapped to the layout of a room (left); reconstructed from radio images layout of pipes and sprinklers (right)

![Map of concealed pipes is drawn on the floor in the Leningradskaya Hotel as result of inspection](image)

**Fig. 10** Map of concealed pipes is drawn on the floor in the Leningradskaya Hotel as result of inspection

**CONCLUSIONS**
In this work a summary of the holographic subsurface radar technology and its applications has been presented. The main advantages and limitations in respect to the commonly used impulse radars are also reported. In general, it is worth mentioning that the 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. Typical field of application for the holographic subsurface radar is the sounding of opaque media at shallow depths resulting in imaging that has high plan-view resolution. In these cases it is possible to define the form of targets and clutter objects, and to formulate reasonable assumptions concerning their nature. The interpretation of grey-scale plan-view images is straightforward even for non-radar expert users and does not necessitate specialized reconstruction software to convert time of flight data into tomographic imaging as is common for impulse radars.

ACKNOWLEDGEMENTS
Support for this work was provided by the President of Russian Federation Grant #MK-694.2009.9, and grants of Russian Foundation for Basic Researches.

REFERENCES
Daniels, D.J. (1996), Surface-Penetrating Radar, Pub. by IEE. London.
Chapursky, V.V. et. al. (2002a), Microwave Hologram Reconstruction for the RASCAN Type Subsurface Radar, Proceedings of the Ninth International Conference on Ground Penetrating Radar, GPR’2002, April 29 - May 2, 2002, Santa Barbara, California USA, pp. 520-526.
Russian sanitary certificate (2005) # 77.01.09.650.Π.041358.10.05, October 19, 2005.