Holographic Radar as a Tool for Non-Destructive Evaluation of Structural Materials

Sergey Ivashov PhD, Vladimir Razevig, Anton Sheyko, Igor Vasilyev PhD
Institute of Applied Mathematics and Mechanics, Bauman Moscow State Technical University
5, 2nd Baumanskaya str., Moscow, 105005, Russia rslab@rslab.ru
Timothy Bechtel PhD, Enviroscan, Inc., 1051 Columbia Avenue, Lancaster, PA 17603, USA
email@enviroscan.com

ABSTRACT. One of the possible means of non-destructive testing and evaluation of structural materials is subsurface radar method. Up to now, its use was hindered by an insufficient resolution of commercial subsurface radars. For many practically important problems it is sufficient to have a sounding depth in the range of 10...20 cm, but the spatial resolution should be not less than 2...3 cm. Taking into account small sounding depths it's possible to use a continuous wave multifrequency signal. The device under consideration is a reflection mode radar, i.e. the transmitting and receiving parts of the antenna are located on the same side of the sounded surface. It operates in frequency range of 3.6 through 4.0 GHz. Some applications of holographic subsurface radars are discussed. Experimental results concerning the survey of an arch in a room wall are presented.

INTRODUCTION

The existing methods of non-destructive testing of structural and building materials or components have a number of disadvantages. X-ray devices, for example, require two-way approach to the observed detail. This is complicated sometimes and more often even impossible. X-ray devices are widely used in medicine, for hand-luggage control in airports and in technological processes where two-way approach to the object to be examined has no problems as a rule. Ultrasonic equipment has proved to be ineffective in media containing a great number of micro cracks and heterogeneities. Its main application is the examination of relatively homogeneous media with few defects and inclusions, for example, metal details of relatively large dimensions.

From this point of view, the microwave devices are the most promising as they make possible the use of reflective sounding, i.e. transmission and reception of electromagnetic waves is performed from one side of the sounded surface. It enables to examine walls, ceilings and decorative elements and so on in ready-for-service buildings. Thus, it is possible to control the quality of their construction and repair. When using a specially designed antenna, the proposed method also makes it possible to examine corners between walls. This is hardly possible otherwise. Another advantage of radar sounding is a relatively large wavelength λ in the used microwave band, at which there is no reflection from minor natural heterogeneities of media under investigation, for example, by cracks and small (compared to λ) technological hollows in bricks and other construction materials. However, taking into account that water has a very high permittivity of 80, cracks filled with moisture have high contrast. This effect can be used in practice. While constructing and reconstructing, concrete structures or their parts, which are under the level of the construction site ground, have to be sealed to prevent water intrusion. This type of structures includes underground garages, automobile parking places, underground pedestrian crossings, and etc. This problem becomes especially actual in spring and autumn when the soil water level is high. Any crack in structures or in joints between them results in infiltration of soil water into the underground part of the construction making it unfit for service. Things become worse when the external manifestation of the infiltrated water onto the structure surface does not often coincide with the real location of the crack through which water enters the underground part of the construction. Moreover, such manifestations may reveal after a time. It makes repair and crack sealing more difficult, increases the cost and reduces the quality of work.

The recent disastrous loss of space shuttle Columbia has aroused the great demand in new methods and devices for non-destructive testing and evaluation of the space shuttle Thermal Protection System heat protection tiles, as well as the external fuel tank insulation foam. Various approaches have been suggested for determining the integrity of the tiles and foam. However the Columbia accident indicates that the technologies currently in use cannot guarantee safe flights of the space shuttle. The radar under consideration was originally designed for producing non-destructive microwave images of construction details, buried targets, and etc. The preliminary investigations indicated that its high resolution and sensitivity to cracks or voids, and variations in the subsurface moisture content of materials under inspection could be useful in providing early warning of hidden, incipient problems in the shuttle protection systems.

This holographic radar method differs from traditional surface-penetrating radar (which typically uses impulse signals) in the simplicity of equipment design and the considerably smaller aperture of scanning antennae. These innovations allow improvement in the spatial resolution of surface-penetrating radar images. It is noteworthy that the effective detection depth of this method is less than that of traditional impulse radars. Nevertheless, for many applications, the holographic radar will provide sufficient detection depth. A good example is the space shuttle heat protection system, which has tile thickness in the range of 4.3 - 10 centimeters. Another extremely important advantage of this holographic radar technology is the possibility that it can image, without reverberation, dielectric materials that lie above a metal surface. Such materials cannot currently be inspected non-destructively with traditional time-domain impulse radar technology.

SUBSURFACE RADAR METHOD

The designs of subsurface radars are based on classical principles of radar technology [1]. Signal emitted in surveying medium is reflected from heterogeneities if their permeability or conductivity differs. The reflected signal is received by the receiving radar antenna and then is amplified. After processing, the recorded information is represented on display. Fig. 1 presents a block diagram of subsurface radar system.

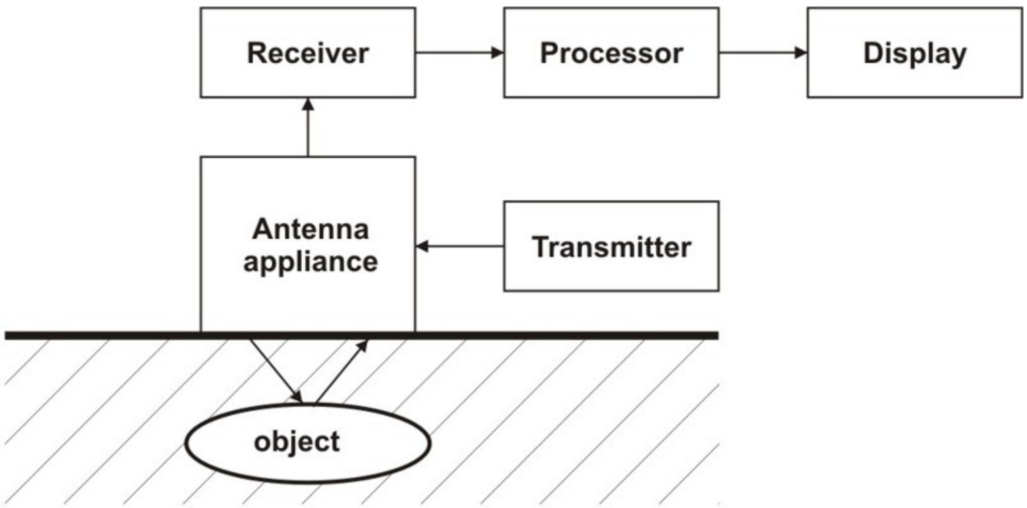


Fig. 1. Block diagram of subsurface radar system

The main difference between subsurface radars and ordinary radars intended for sounding of air or free space is high attenuation losses in surveying media (soils, construction materials and etc.) In some media the attenuation of an electromagnetic wave can achieve 100 dB/m or more. The properties of lossy dielectric media and materials in many respects define features of a radar design, frequency range and type of used signal. According to signal type, subsurface radars could be divided into several main types:

Time-domain. The radar of this kind radiates a super short pulse with duration from 1 up to 10 ns. Shorter pulses now are used also. The delay time of the reflected signal allows determining the depth of buried object.

Frequency-modulated continuous-wave. The radar transmits a continuously changing carrier frequency of sawtooth form. The received signal, which is reflected from an object, is mixed with a reference waveform and results in difference frequency. The frequency is related to phase of received signal and hence the range of the object. After processing, this allows also to find depth of the heterogeneity in material.

Stepped-frequency. The radars of this type radiate a coherent grid of frequencies. Definition of phases and amplitudes at all frequencies of the reflected signals enable to determine depths of objects in medium.

Nowadays time-domain radars are most frequently used subsurface radars.

As a rule, at a choice of frequency range it is necessary to search for the compromise between higher resolution at the higher frequencies and increased attenuation of micro waves that reduces depth of sounding. It is possible to formulate an empirical rule: The relation of maximal sounding depth to wavelength of signal is almost constant value, and this relation should not exceed 10. By one more difference from traditional radiolocation is that media and materials surveyed by subsurface radars are characterized by significant heterogeneity of dielectric properties and frequency dispersion of micro waves.

Subsurface radars have found wide application in many fields of science and applied engineering [1]. It is possible to list only some of them: surveying of grounds on construction sites and at archaeological excavation, detection of mines in a soil or overhearing devices in premises, and also inspection of road coverings and design details.

HOLOGRAPHIC SUBSURFACE RADAR

Up to now the use of subsurface radars for nondestructive testing was hindered by an insufficient resolution of commercial subsurface radars, which, as a rule, were designed for ground sounding, where, as it is known, resolution and frequency band requirements are quite different. To solve construction industry tasks it is necessary to develop dedicated high-resolution radars with relatively small sounding depths. For many practically important problems it is sufficient to have the maximum depth of penetration in the range 15...20 cm, but the space resolution should be not less than 2...3 cm. Preliminary estimate shows that a frequency range of 4GHz is optimal. Considering small sounding depth it turned out possible to use a continuous wave signal. The main task of the design was to obtain a maximum resolution at shallow depth even at the expense of radar capability to detect objects at larger depths.

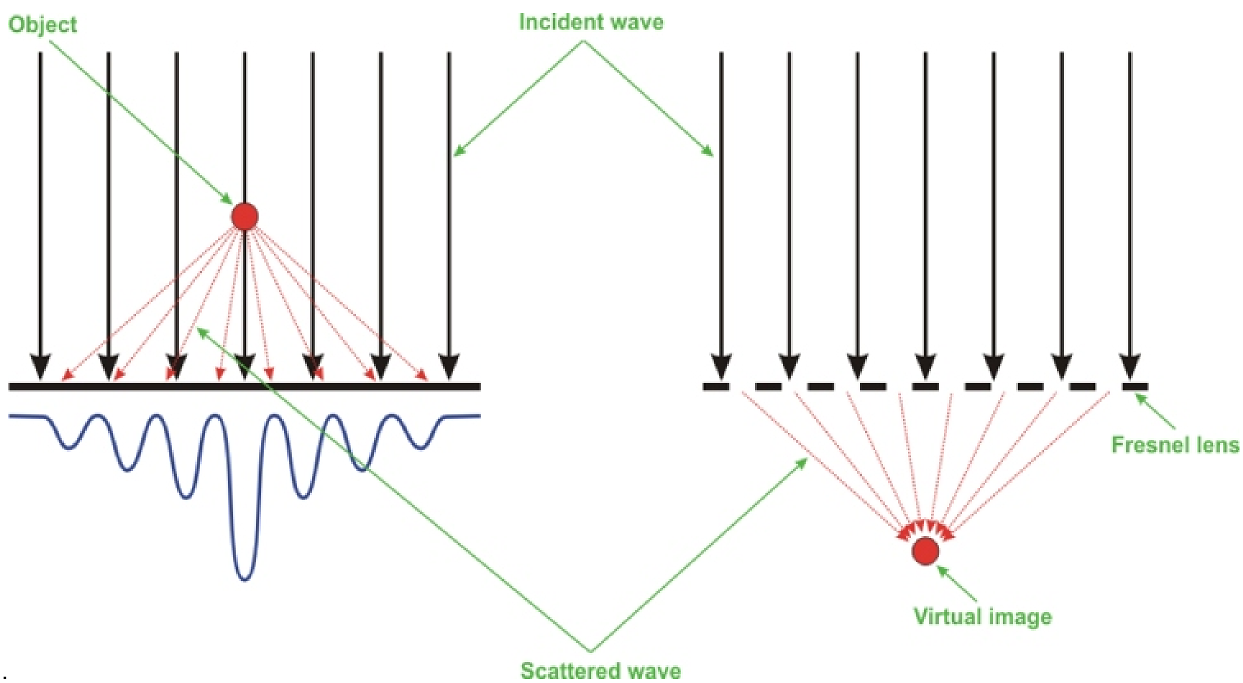
Subsurface holographic radar of the RASCAN type uses continuous wave unmodulated signals, which are transmitted in single-frequency or multi-frequency modes [2]. The radar is intended for surveying building structures and works. The characteristic feature of this device is the possibility of obtaining in a sounding plan the microwave images featuring a high resolution attaining 2...3 cm.

In the radar antenna, signal reflected from the object mixes with reference one. To obtain holographic images the radar antenna scans two-dimensionally along the surface of lossy material. The amplitudes of received signal are recorded in discrete set of surface points. Measured amplitudes of the radar signal are displayed as microwave holograms on a computer display.

The antenna with cylindrical waveguide, which is used in the radar, has about one and a half wavelength diameter, which corresponds to 7.5 – 8.3 cm for the frequency range of 3.6 - 4.0 GHz. The antenna operates as the gauge of the electromagnetic waves in the near and reactive fields for object depths from zero level up to 20 cm.

Since the images recorded by radar are microwave holograms, it is impossible to determine the objects depths under the scanning surface without the appropriate processing. Moreover horizontal resolution is deteriorated with the increase of depth. This effect is typical for all types of subsurface radars.

The diagram which illustrates schematically the principle of recording and reconstruction of microwave hologram is presented in Fig. 2. The role of the incident wave in the RASCAN radar is performed by the reference signal, which has constant phase. Mathematical algorithm that was elaborated for reconstruction of microwave hologram is described in the paper [3].



[3].

(a) (b)

Fig. 2. Recording (a) and reconstruction (b) of a hologram

However, there is important distinction between the holograms recorded in microwave and visible spectrum. So, holograms obtained in optics allow obtaining image of objects only after the image-reconstruction procedure, while in many cases subsurface radar holograms give the image close to the real location of objects in the sounding plane without resorting to this algorithm [4]. This effect is explained by high attenuation of microwaves in lossy media. So only the signals reflected from the objects up to maximum depth of penetration and lying in the relatively narrow beam of the antenna pattern could be recorded.

In this case the object's contrast is determined by a phase difference between the reference and reflected signals of the radar. The phase of the reference signal is substantially constant, while both the depth of location and a phase shift at reflection from the object determine the phase of the reflected signal.

RADAR INVESTIGATION OF ARCHED WALL APERTURE

While performing repair and reconstruction works in buildings having great historical and cultural value, there are problems connected with the determination of load-carrying ability of building constructions [5, 6]. Primarily, these problems are determined by the lack of building documentation and presence of construction elements, which appeared as a result of preceding restorations and repair works. At that, in the initial body of a building construction additional details as well as dimensional changes of wall apertures often appear. Subsequent time-induced changes can result in lowering of construction bearing capacity and cracks in walls or even can cause their collapse.

Scanning technique of the radar antenna is mechanical; data input in the computer is performed automatically via a dedicated interface connected to a computer parallel port. At that, the computer itself needs no elaboration. Data display is performed at the computer's screen in real time scale in form of gray scale images, in which specific tone gradation corresponds to each level of received signal. In hard-to-reach places the surface scanning can be performed manually. Image of an operator with the RASCAN radar during the sounding of the investigated arch is presented in Fig. 3.

The object of examination was a wall aperture made in a form of an arch. The brick-build wall was covered by two-centimeter layer of plaster and painted. The purpose of examination was the detection in the wall of an expected ∏-form metallic bearing construction, which was needed for the strengthening of the arched aperture and transfer of a loading to a ferroconcrete slab in the floor of premises. The form and dimensions of the wall aperture are shown in Fig. 4.

Fig. 3. An operator with the RASCAN radar
during the sounding of the investigated arch

Numbers in this figure indicate the sounding spots of the investigated surface and obtained microwave images. The images 1 and 5 relate to the straight parts of the aperture. The brickwork of the aperture is seen on them under a plaster layer with rows of stretcher and header bricks as well, as joints between bricks. From these images one can make a conclusion that there are no vertical metal posts. The sounding of flank parts of the arch had corroborated this.

The microwave images 2 and 4 were obtained in the area of the arch aperture on its internal side. A rectilinear object (supposedly, metal beam) embedded in the vault with the right end going by 8-10 cm behind the rectilinear arch generatrix is seen at the image 4. Another end of the beam rests against an object at the level of the rectilinear arch generatrix. This object is seen as white spot and marked by an arrow in the image 2.

The image 3 was obtained on the external side of the arched aperture and it is like a pair to the image 2. A second beam, which also rests against the object, marked by the arrow, is seen in this image also. From the images 2 and 3 it follows that the object, marked by the arrows, is oriented with its butt to a wall plane. One can assume that the object is a side-bar, embedded in the wall, to which beams are welded.

The amplitude of radar signal was measured in the upper part of the vault (see line A-A in Fig. 3). The result of this measurement is shown in Fig. 4. The arrows at this plot indicate the positions of external and internal beams. They mark by numbers 1 and 2 respectively. It is not unlikely that a central beam marked with the number 3 with the interrogation sign "?" was also embedded. But, taking into account the fact that this beam was revealed in one place only, namely in the upper point of the vault, it is impossible to affirm its existence for sure.

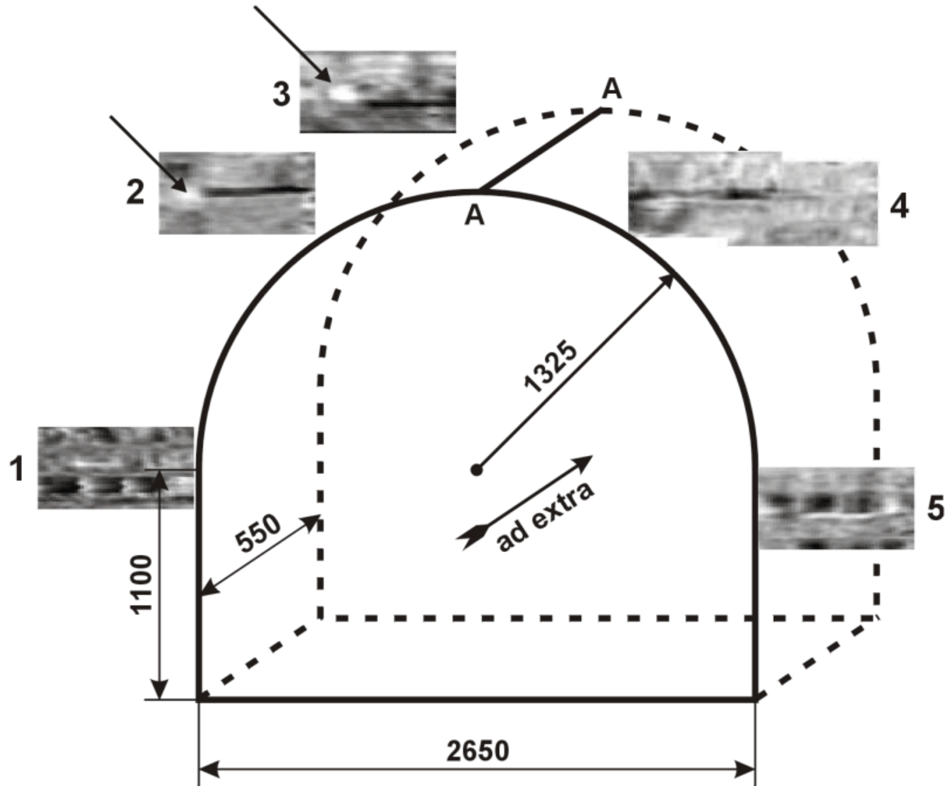


Fig. 4. Geometrical parameters of the investigated arch and the results of radar sounding. The arch dimensions are presented in centimeters

The analysis of this set of images obtained by the sounding of the arched aperture in the wall allows one to make the following conclusion: horizontal metal beams, resting against the niches of the wall brickwork, are embedded in the vault of the arched aperture, and supporting vertical posts are absent.

Close-ups of microwave images obtained during sounding experiment are shown in Fig. 6. We can see more details in this case. The numbering of these images corresponds to the microwave images in Fig. 4. The image 4 is compound, as it was received as a result of imposing two microwave images. It was made to find the right end of beam.

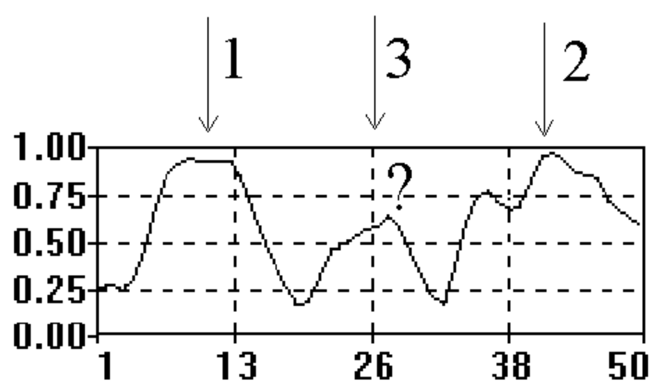
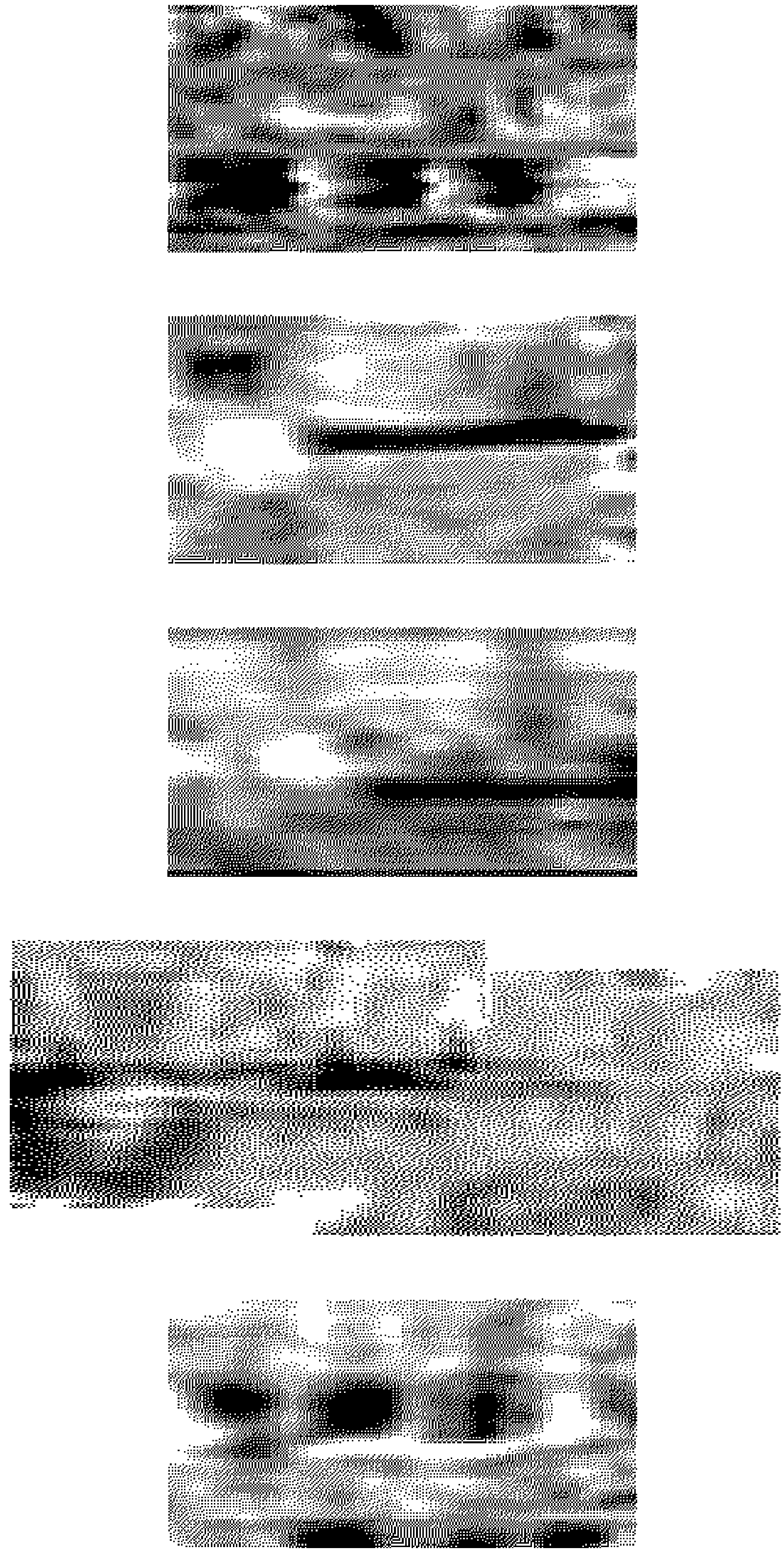


Fig. 5. The amplitude of radar signal measured in the upper part of the vault along line A-A in Fig. 4



1

2

3

4

5

Fig. 6. The microwave images obtained by sounding of the arched wall aperture

CONCLUSIONS

The development of dedicated radar designed for sounding of building constructions permits the transition to the practical use of subsurface radar techniques in repair works. The use of the holographic principle in the RASCAN radar design affords the opportunity for improvement of image quality and resolution in the sounding plane relative to the traditional time-domain impulse radars. To improve even further the resolution of subsurface images it is possible to design holographic radar operating at a higher frequency range of 8 to 10 GHz. Such radar could be used in technological processes for quality control of different dielectric details, for example, space shuttle Thermal Protection System heat protection tiles and external fuel tank insulation foam.

ACKNOWLEDGEMENTS

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