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Processing of Holographic Subsurface Radar Data

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***Abstract*— A backward propagation algorithm of reconstructing images is considered with experimental data obtained by holographic subsurface radars of RASCAN type. This family of radars uses stepped frequency continuous wave signals and can record in-phase and quadrature components of the reflected signal with a frequency bandwidth of 0.5 to 1 GHz with a center frequency ranging from 2 to 14.5 GHz (depending on radar modification). Among examined data acquiring scenarios were both contact and stand off measurements in media with different attenuation. The reconstructed images were shown to have high plan resolution and easy to interpret as the reconstructed microwave images preserve shape and other features of the optical images. Further modifications are suggested to improve the performance of the system.**

Keywords-ground penetrating radar; microwave holography

I. INTRODUCTION

At present time most of ground penetrating radars available on the market use pulsed signals and time-of-flight information to reconstruct disposition of subsurface objects and structures. They are heavily used in different application areas, manufacturers usually produce them in different modifications targeted to solve specific problems. The impulse radars may use several types of changeable antennas and bundled with dedicated software to process, display and annotate acquired data. It is possible to outline a situation where application of another type of radar is preferable. Such a situation emerges when detection of shallowly buried objects is required and approaching the experts, armed with expensive impulse radars and capable of interpreting the data, is unaffordable. For such situations, a radar that uses continuous wave stepped frequency signals was designed and manufactured at Bauman Moscow State Technical University [1]. With this radar, called RASCAN, one can easily get plan view images of subsurface objects. Special training is not required to interpret such images as they resemble optical ones, although with poorer resolution due to substantially larger wavelength. Until present no post-processing was used because of the fact that at shallow depths in real world lossy media the diffraction effects are relatively small and do not prevent identification of buried objects. In other situations, observation of objects at longer distances was more difficult due to increase of diffraction effects. To compensate the diffraction a reconstruction algorithm, described in Section II, was proposed to use with the data. The radar hardware, described in Section III, was modified to register both quadratures of the reflected signal to be used with the reconstruction algorithm. Preliminary experiments on data acquisition and processing were conducted. The results of these experiments are reported in Section IV. Section V suggests further improvements of the system and data processing algorithms.

II. BACKWARD PROPAGATION ALGORITHM

When registering optical holograms the interference pattern of the object wave and the reference wave is formed to register the phase of the object wave. At microwave frequencies forming the same geometry is not required as the phase can be obtained in a quadrature receiver. The phase is obtained by comparing the received signal with the signal that is guided by a transmission line from the transmitter to the receiver. This signal can be viewed as an analog to the reference wave in optics.

Subsequent reconstruction of an optical hologram involves illumination by the reference wave to obtain the image of the previously exposed object [2]. The same reconstruction algorithm can be implemented numerically on the data obtained at microwave frequencies. Here we consider only a plane sounding geometry, which is of most frequent occurrence and allows using computationally efficient algorithms to process the data. The plane sounding geometry is depicted in Fig. 1 where the sounding plane coincides with the ground surface and the focusing plane is a plane where the distribution of sources to be found. The planes marked as XZ-cut and YZ-cut dissect the volume of interest.

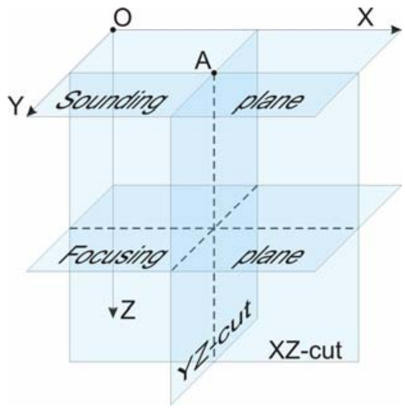

Figure 1. Geometry of sounding.

A point-sized transceiver moves in plane XOY and samples reflected by subsurface objects signal on a regular grid. The sensor is capable of registering I and Q quadratures of the signal, thus giving a complex signal with amplitude and phase (a complex hologram). The approach uses plane wave decomposition of the scattered field by the Fourier transform. The plane wave spectrum is propagated back to a focusing plane with the assumption that the space between the two planes is homogeneous. The inverse Fourier transform of the spectrum in the focusing plane gives a complex amplitude distribution with propagation effects eliminated. The following relationships summarize the method [3].

$$\hat{E}(k_x, k_y; 0) = \iint E^*(x, y, 0) e^{-ik_x x} e^{-ik_y y} dxdy \tag{1}$$

$$\hat{E}(k_x, k_y; z) = \hat{E}(k_x, k_y; 0) e^{i\sqrt{(2k)^2 - k_x^2 - k_y^2} z} \tag{2}$$

$$E(x, y, z) = \frac{1}{(2\pi)^2} \iint \hat{E}(k_x, k_y, z) e^{ik_x x} e^{ik_y y} dk_x dk_y \tag{3}$$

Equation (1) gives the plane wave Fourier spectrum in plane $z=0$. Complex conjugate of registered complex amplitude $E(x,y,0)$ is required if we want to obtain a complex distribution that gives converging waves toward positive z. Equation (2) relates plane wave spectra separated by distance z and expresses plane wave solution of the Helmholtz equation for the medium characterized by wavenumber k. The wavenumber is doubled because in such a geometry of sounding waves propagate twice the distance from the sensor to the subsurface object.

Equation (3) gives complex amplitude distribution at z and considered as the microwave image of a buried object located in immediate vicinity. Values k_x and k_y in (1)–(3) are spatial frequencies reciprocal to x and y. These spatial frequencies have physical sense of x and y components of wavenumber k in reference frame XOZ in Fig. 1.

III. RADAR PPROTOTYPE

The functional diagram of the developed radar is presented in Fig. 2. The transmitter of the radar is based on an integral frequency synthesizer coupled with a voltage controlled oscillator (VCO). The reference frequency to the synthesizer is provided by a 20 MHz crystal resonator. The directional coupler is used to split the VCO output to the transmit antenna and the receiver, which employs frequency direct conversion technique.

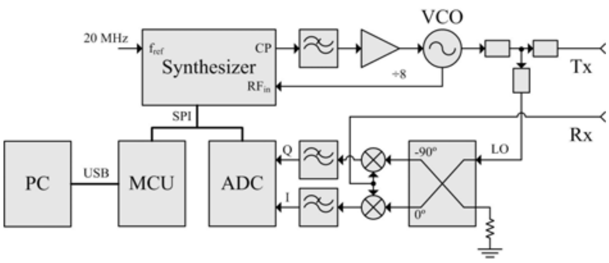

Figure 2. Radar schematics.

To control radar components a microcontroller control unit was developed. It uses SPI to initialize and control the synthesizer and analog-to-digital converter as well as maintain data buffering. The microcontroller unit gets commands from a PC and streams back collected data via USB. Switching between frequencies is accomplished by programming internal registers of the synthesizer. Three different radar prototypes sharing the same principle diagram were designed to operate in 3.6–4.0, 6.4–6.8, and 14–15 GHz frequency bands. The PC-side software is capable of acquiring, displaying, and storing the data. Post-processing is accomplished in a software module written in Matlab.

The transmitter and receiver modules mounted on an open waveguide antenna are shown in Fig. 3. The radar can be placed in a housing equipped with a marching wheel to measure the position from the beginning of scan lines at manual scanning.

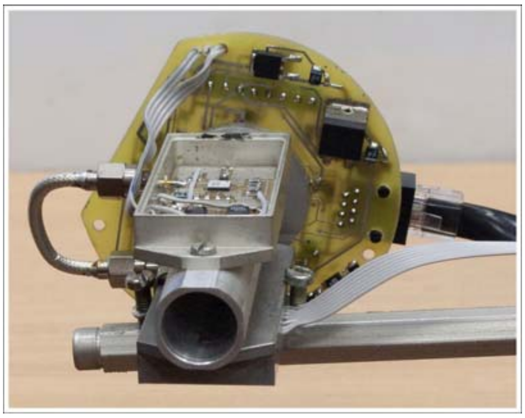

Figure 3. Radar prototype for 14–15 GHz frequency bandwidth.

IV. EXPERIMENTAL RESULTS

A series of experiments was conducted to assess the possibilities of hologram reconstruction. The hologram of two crossed metal rulers placed under a stack of dry plaster sheets of 14.7 cm thick is shown in Fig. 4. The sizes of the rules were 32 by 2 and 32 by 5 cm. The sounding was done at 3.75 GHz with immediate contact with the sounding surface. As it is seen in Fig. 4, the microwave hologram does not have many interference ridges compared to optical holograms. The strength of only the first order interference extremum is significant and it is still possible to discern two elongated objects. The picture is deteriorated by evident diffraction effects, which can be compensated by the considered algorithm.

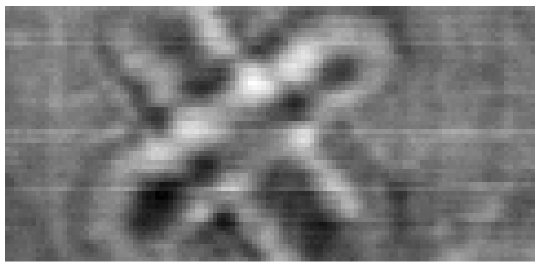

Figure 4. A microwave hologram of two metallic rulers behind a stack of plaster sheets, 3.75 GHz.

On the reconstructed image of the rulers (Fig. 5) the visible size of the objects reflects their actual size while in the interference pattern the size ratio is reversed.

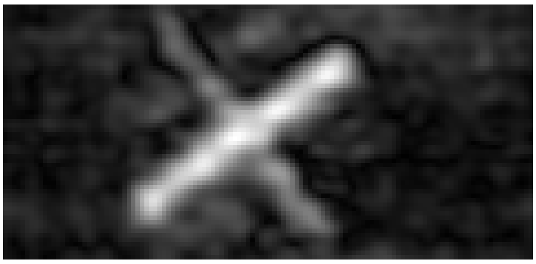

Figure 5. A reconstructed image of two rulers.

Fig. 6 shows a PMN-2 antipersonnel mine that was placed in air at the distance of 13 cm from the sounding plane in another experiment. This mine has a round plastic body of 120 mm in diameter and features a small-scale structure, an X-shaped pressure plate.

Figure 6. A photograph of PMN-2 antipersonnel mine.

Fig. 7 shows the amplitude of the scattered field with subtracted background at the sounding frequency of 14.4 GHz. Sounding in air increases the number of visible interference ridges due to antenna wider directivity pattern and much lower than in a condensed medium attenuation. Fig. 8 gives a reconstructed image of the microwave hologram at the depth of 12.4 cm. The image has high resolution that clearly exposes the X-shaped pressure plate. Fig. 9 and 10 demonstrate XZ and YZ cross-sections of the reconstruction volume, which are marked in Fig. 7 by two intersecting perpendicular lines and explained graphically in Fig. 1. The place of scattered field focusing is clearly visible at the expected depth.

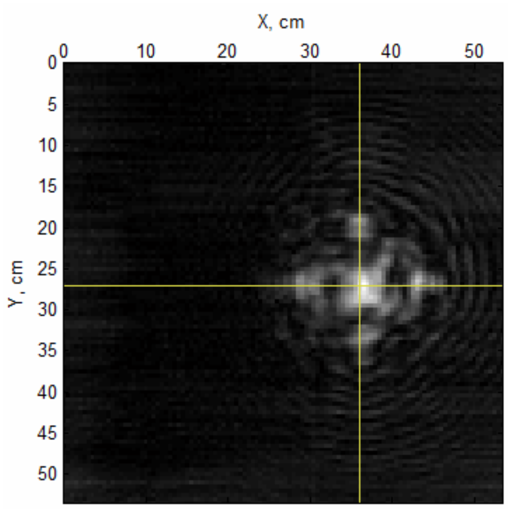

Figure 7. Amplitude hologram of a PMN-2 mine with background subtracted.

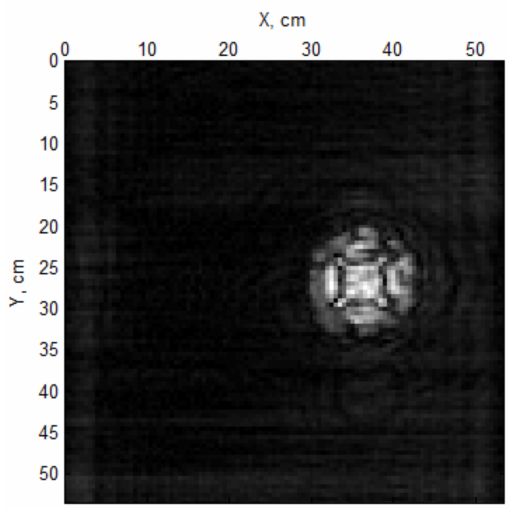

Figure 8. Reconstructed image of PMN-2 mine.

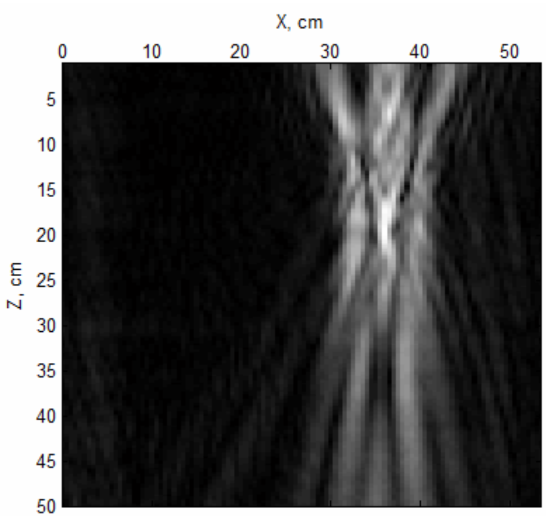

Figure 9. XZ-cut of reconstructed volume.

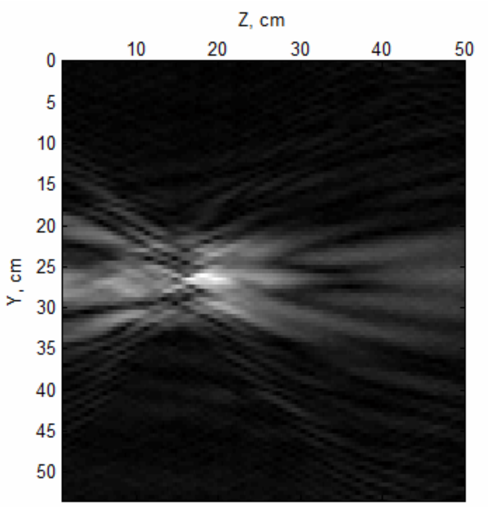

Figure 10. YZ-cut of reconstructed volume.

The following experiments were performed to test the ability of the described reconstruction algorithm to restore holograms obtained by providing a gap between the scanning plane and the interface. A succession of letters cut from aluminum foil forming word RASCAN was used as a test object. The letters were glued to the bottom side of a 12 mm plaster sheet which was placed on a stack of other plaster sheets as it is shown in Fig. 11.

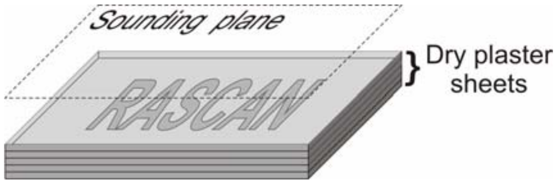

Figure 11. Measurements with a gap between the sounding plane and the interface.

The distance between the sounding plane and the top of the stack was equal to 13.3 cm. The sounding frequency was equal to 14.7 GHz. The acquired hologram and the result of its reconstruction are shown in Fig. 12 and 13 correspondingly. Although diffraction effects for such a distance are already significant resulting to an unrecognizable initial pattern, the reconstruction renders a sharp image with readable letters.

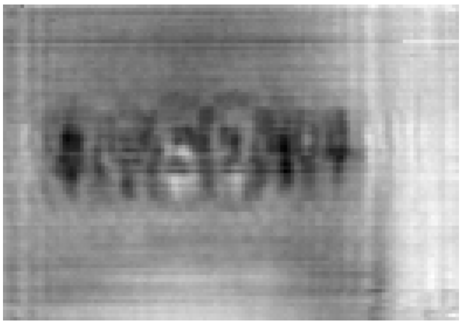

Figure 12. A hologram of aluminum foil letters behind a plaster sheet obtained from the distance of 13.3 cm to the top of the sheet.

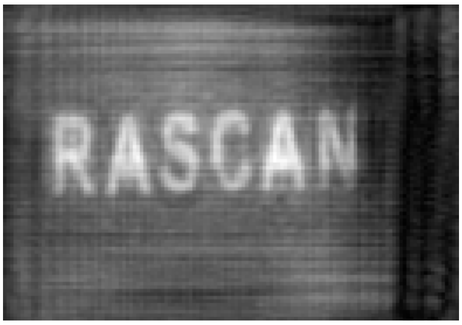

Figure 13. A reconstructed image of aluminum foil letters behind a plaster sheet.

The above experiments were conducted under favorable conditions when the sounding medium was homogeneous, had low attenuation and the sounding object had a flat surface oriented parallel to the interface. Inhomogeneous media having rough interface and high attenuation can make reconstruction impossible. A wide-band frequency signal is desirable to extend operating condition range by adding range resolution.

Numerical implementation of reconstruction algorithms on the basis of fast Fourier transform gives convenient interactive representation of reconstructed data, when an arbitrary focusing depth is selected interactively and the result of reconstruction is obtained immediately.

V. Future Work

Further development of the system can be achieved by employing wideband frequency signals and implementing a wideband reconstruction algorithm. In this algorithm range resolution will be achieved by a wide frequency bandwidth and plan resolution will be achieved due to synthetic aperture.

When collecting data with the considered system the situation where the background is present along with the object of interest is very frequent. These areas on images are easily recognized and can be used to evaluate the wavenumber relevant to the medium at hand. This can be achieved by considering a half-space homogeneous medium model characterized by a constant wavenumber value to match the experimental complex amplitude over a free region on hologram with that of predicted by the model. The development of such self-calibration technique is another object for our future research.

Acknowledgment

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References

[1] S. I. Ivashov et al., “Holographic subsurface radar of RASCAN type: Development and applications,” IEEE J. Sel. Topics Appl. Earth Observ. Remote Sens., vol. 4, no. 4, pp. 763–778, Dec. 2011.

[2] J.V. Goodman, Introduction to Fourier Optics. New York: McGraw-Hill, 2005.

[3] Sheen D.M., McMakin D.L., Hall T.E., “Three-dimensional millimeter-wave imaging for concealed weapon detection,” IEEE Trans. Microwave Theory Tech., vol. 49, no. 9, pp. 1581–1592, Sep. 2001.