MICROWAVE IMAGING EQUIPMENT AND ALGORITHMS

Vladimir Semenchik [i)], Vasil Pahomov [ii)]

i) Department of Radiophysics, Belarussian State University, Belarus, Minsk, Baykalskaya str., 58, 321, e-mail:*semenchik@bsu.by*

ii) Department of Radiophysics, Belarussian State University, Belarus, Minsk, Kurchatova str., 8, V83, e-mail:*vasil_pahomov@tut.by*

Abstract. Microwave holographic imaging is set of methods for obtaining images of hidden objects and determining their electrical properties. The essence of these methods is image reconstruction from measurements of scattered electromagnetic field. The microwave holography is applied in medicine, industry, military, earth sciences etc. The paper presents the description of acting multifrequency microwave holographic experimental set-up.

Introduction

The microwave imaging is important in many applications such as medicine, science, industry, military etc. The problems where microwave imaging can be involved are non-invasive medical diagnostics, non-destructive testing, investigation of materials electromagnetic properties, determination of aircraft scattering characteristics, aerial and aerial cover design, detection of objects buried in soil such as mines, pipes or cables and so on.

There are two stages in active holographic microwave imaging. The first one is irradiation of object being investigated with monochromatic microwave field. Then the scattered field (transient, reflected or both) is measured. The measurements are taken on some limited surface called aperture. The second stage is object image reconstruction based on measurements taken.

There are different methods for image reconstruction, both optical and digital. Optical methods take care of reconstruction by performing some transformation of measurement data with optical system. They offer extremely fast reconstruction process and setup simplicity, but can be applied to limited set of problems only and are almost disused nowadays.

Digital methods base on numeric processing of scattered field measurement data. They allow reaching maximum flexibility in measurement configuration, investigated object properties and reconstruction algorithms. These methods are used in most recent microwave imaging applications. To implement digital reconstruction methods the scattered field measurement data has to be represented in digital form, the processing is performed usually by digital computer.

In general reconstruction task is inverse problem, and it is solved using some approximations. Due to its complexity, the microwave image reconstruction problem is often carried out with linear approximation. Approaches that deal with nonlinearity of problem require too much computational time and rarely used in practical applications.

The scattered field data acquisition is also important in image reconstruction applications. It’s necessary to measure both amplitude and phase of scattered field at sufficiently large number of aperture points. Additional condition is to take measurements with different frequencies of illuminating electromagnetic field. Reconstruction algorithms can achieve much more reconstruction accuracy using these multi-frequency data.

The imaging system construction is determined by measurement conditions. It is preferred to have measurements in as many points as possible to form aperture as closed surface surrounding investigated object. But there are technical difficulties to perform such measurement, and in some applications it is impossible to measure some data in principle – such as for buried objects, where we can measure only reflected wave.

The need for imaging system is felt particularly in experimental researches to test reconstruction algorithm against experimental data. Such testing helps to avoid so called “inverse crime” problem. The problem occurs when synthetic data used for testing is generated using same or similar approach than used for reconstruction. The problem results in qualitative numerical experiment results where results obtained by real measurements can be poor.

The microwave imaging set-ups are built for defectoscopy [1], for medical applications [2], and so on. These set-ups mostly use two-dimensional (cylindrical) approximation of investigated objects, which is inappropriate in some cases.

Microwave imaging set-up

To investigate three-dimensional microwave holographic imaging an experimental setup has been built. The setup is able to image hidden objects by measuring scattered electromagnetic field in 8-12 GHz frequency range. The setup currently adjusted to obtain images in reflected field in laboratory environment but it is planned to fit it for field experiment to investigate objects buried in soil and concrete.

The general setup diagram is shown on fig. 1.

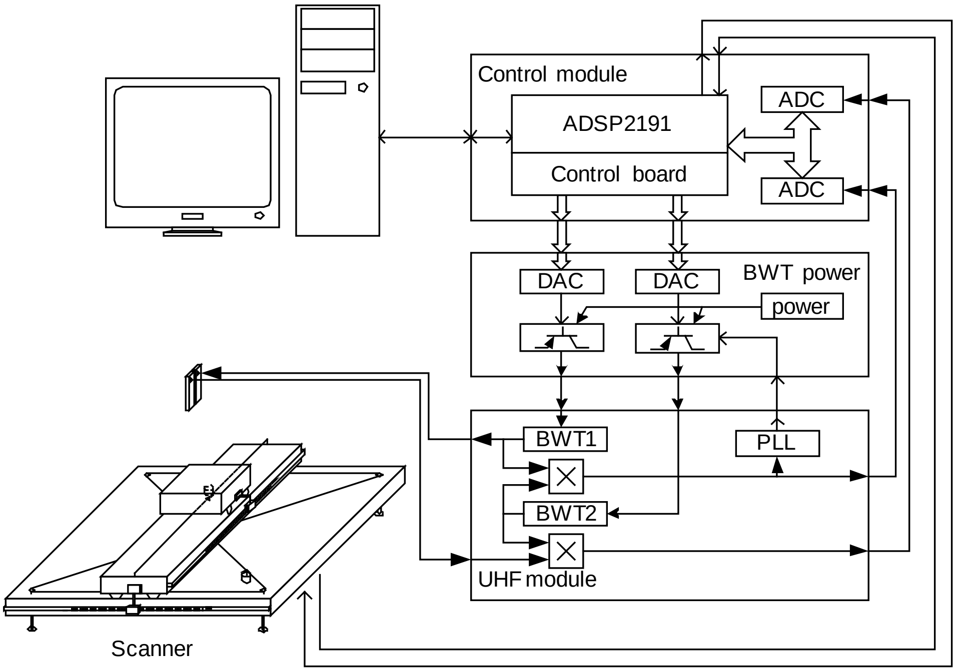


Fig. 1. The setup diagram.

The transmitting antenna is illuminating wave source. The antenna is fed by generator backward-wave tube BWT1. The scattered wave is registered with receiving antenna. The received signal comes to UHF-module. The open-end waveguide antennas are used to provide hemispherical directional diagrams both for receiving and transmitting antennas. These directional diagrams are important to provide uniform coverage for all the investigating area.

The high-frequency part of the setup (the UHF module on the diagram) is built based on heterodyne principle. The heterodyne in second backward-wave tube BWT2, and its frequency is maintained at 6,5 MHz below the generator (BWT1) frequency with phase-locked loop (PLL). Signals from both tubes are mixed to form reference signal. The object signal is formed by mixing signals coming from receiving antenna and heterodyne signal. So, both reference and object signals are at 6,5 MHz intermediate frequency regardless to true illuminating frequency.

The PLL consists of internal 6,5 MHz crystal oscillator and digital phase comparator that compares oscillator and reference signals phase. The comparator forms series of pulses with off-duty factor dependent of phase difference. These pulses are low-pass filtered to form difference voltage that is used to adjust heterodyne frequency. So the heterodyne frequency is kept to phase, and phase relation between basic and object signal at intermediate frequency are proportional to one between signals at true illuminating frequency.

The backward-wave tubes operating frequency is adjusted by varying tubes' supply voltage. This voltage is generated in BWT power module. The module has two 12-bit DACs receiving digital frequency controlling code from control module.

The supply voltage is produced by high-voltage power supply and is adjusted in range of 600-1300 volts by two voltage regulators for generator and heterodyne tubes correspondingly. The regulators use composite high-voltage transistors, which are controlled by low control voltage coming from DACs.

The controlling circuits are spanned by feedback to provide high stability of tubes' supply voltage. The feedback spans high-voltage and low-voltage part of circuits. The total illuminating frequency instability achieved is 10^{-3}, including supply voltage instability and tube's generation rate instability.

The heterodyne tube supply voltage is also adjusted by difference voltage coming from PLL phase detector. So the rough tuning of heterodyne frequency is taken with controlling code, and when PLL locks the frequency is slinghty adjusted with PLL to compensate incindental changes in generator and heterodyne frequencies.

The scanner performs aperture synthesis. The scanner moves the object stage in two perpendicular directions in the aperture plane. The movement happens relative to antennas, which are stationary. The aperture plane is normal to antennas direction and is situated at approximately 20 centimeters from the antennas. This configuration with moving object is chosen to avoid phase errors occurring due to antennas' cables bending. Investigations show that this error can achieve up to 20 degrees, which can introduce too large measurement error.

The object stage is moved by two reversible electric motors. The stage is moved rectilinearly along the caret by "line" motor, and the caret moves by "frame" motor in perpendicular direction to stage movement. The stage position is controlled by six photosensors – they signal of initial, final and intermediate positions of stage and caret positions. Three photosensors controlling stage position are attached to stage and are moved with the stage, and three remaining photosensors controlling caret position are attached to caret. The caret intermediate positions marks lines of the frame while stage intermediate positions marks points in which measurements are taken. The photosensors react on transparent areas in films stretched along the caret (for stage sensors) and along the "frame" side (for caret sensors). There are 64 marks on both films providing up to 4096 points in the aperture. In both cases the physical aperture dimensions are 31x31 centimeters.

The control algorithm moves the object in zigzag path – every odd line of frame is scanned in forward direction and every even – in reverse direction. The algorithm allows skipping intermediate marks to reduce aperture size twice. At the stage's intermediate positions the measurements are taken. The aperture is represented as complex value matrix, where each element is related to amplitude and phase of measured scattered field in given point.

It is planned to construct another scanner that carries antennas and whole UHF module over the ground. So the problem of cable bending will be avoided, and it would be possible to perform measurement in soil and in large heavy objects (such as concrete blocks) which current scanner cannot carry.

The whole set-up operation is handled by controlling module based on ADSP2191 signal processor. The photosensors and PLL status signals are acquired by control board (CB) and transferred to DSP. Control board also forms frequency control and scanner motors control signals. The control board contains low-level logic that prevents turning on motors in both directions simultaneously (for example, due to DSP program errors) which can result in motors' power circuit damage. The board also has shaping and triggering circuits for photosensors' signals and buffering circuits for frequency control singals.

The control module has two 10-bit ADCs, which are used to digitise reference and object signals. The ADCs' sampling frequency is 20 MHz. The ADC board has its own memory to accumulate samples during measurement, which are initiated by DSP at aperture points. Then the samples are processed by special algorithm to obtain object signal amplitude and phase. The algorithm extracts quadrature components of object signals. These quadrature components become real and imaginary parts of aperture point. The block diagram of algorithm is shown on fig. 2.

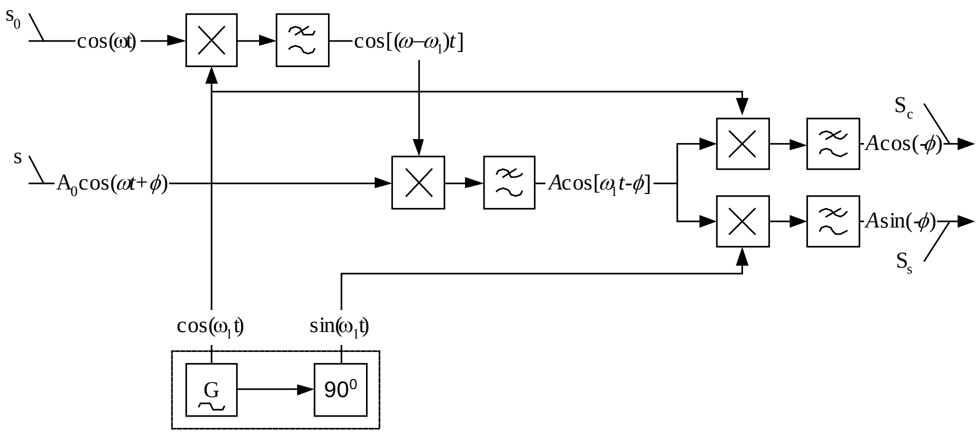


Fig. 2. Measurement algorithm block diagram.

The algorithm uses "virtual" heterodyne to form two reference signal shifted by 90 degrees in phase. Then these signals are multiplied by object signal and low-pass filtered thus extracting quadrature components.

The “moving average” low-pass filters [3] are used to improve algorithm’s performance. The algorithm processes 5000 reference and object signal samples for each aperture point in real time.

The measured data in form of quadrature components is stored in DSP board memory buffer and transferred to the PC via asynchronous serial interface placed on DSP board. This interface is also used to load DSP code, to set up measurement conditions – the aperture size and illuminating frequency, to lock the PLL by adjusting heterodyne frequency and to control the setup during. The scanning should be performed at each illuminating frequency. This disadvantage results from large time needed for backward tube to change frequency, which does not allow switching between frequencies during scanning.

The PC has the software running that receives aperture data and stores it in a buffer. This software also performs image reconstruction from measured data.

Image reconstruction

The simplest reconstruction algorithm is used based on homogenous approximation of space between antennas and object and neglecting mutual reflections. The distribution of electric intensity vector is reconstructed and the amplitude of this vector is taken as reconstructed object. The electric intensity distribution at the aperture plane is convolution of such distribution at the object plane and the free-space impulse response. So to reconstruct desired distribution in object plane it is necessary to deconvolve the aperture data knowing free-space impulse response, which depends on distance to the object.

It is well-known that convolution of two signals in space domain results in multiplication of signals’ spectrums in frequency domain. So deconvolution is performed as division of Fourier-transformed aperture data by free-space frequency characteristic.

The multifrequency data are used to improve radial resolution of setup. This is done by summation of reconstruction results (field distribution at the object plane) for all frequencies involved. It is necessary to adjust reconstructed distribution by empirically determined coefficient so that same object points will have same phase of reconstructed distribution. When summing such adjusted distributions, amplitude of object points increases due to coinciding phase and amplitude of other points (lying in front of or behind object) decreases.

The reconstruction algorithm is as shown on fig.3.

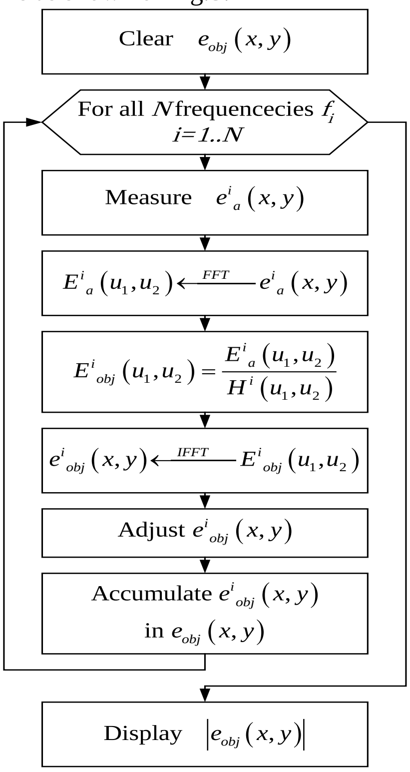
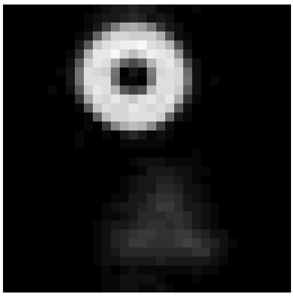


Fig. 3. Reconstruction algorithm flowchart

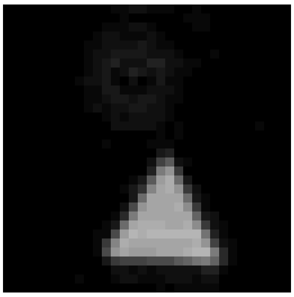
Here i is frequency index, $e^i_a(x,y)$ and $E^i_a(u_1,u_2)$ are field distribution in aperture plane and its Fourier transform respectively, $H^i(u_1,u_2)$ is frequency response of free space, $e^i_{obj}(x,y)$ and $E^i_{obj}(u_1,u_2)$ are field distribution in object plane, and $e_{obj}(x,y)$ is accumulated object distribution.

There are more sophisticated algorithms under development now, which take care of reconstruction problem nonlinearity.

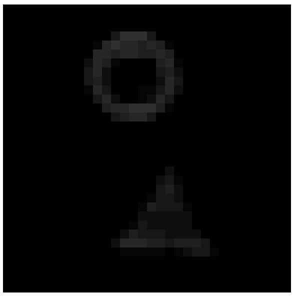
Some simplest examples of images reconstructed with setup are shown in fig.4. The object is composed of metallic triangle situated at 17,5 cm distance from aperture plane and compact-disc at 12,5 cm. Eight frequencies in range between 8 GHz and 11,5 GHz were used. The aperture is 32x32 point and 31x31 centimeter. Three images shown on fig. 4 are obtained when focusing on different distances (shown in captions).



d = 12,5 cm



d = 17,5 cm



d = 15 cm

Fig.4. Reconstructed image examples

Conclusion

Microwave imaging techniques are considered to be of great importance for different applications, and are extensively studied. One of the biggest problems of microwave imaging investigation is lack of experimental investigations what holds off practical implementation of these techniques. The description of acting microwave imaging setup developed for microwave image reconstruction investigations is presented in this paper. The setup is currently operational and able to perform reconstruction. The work is underway on setup enhancement to improve reconstruction quality and extend its imaging capabilities.

References:

[1]. Yoo Jin Kim, Luis Jofre, Franco De Flaviis, Maria Q. Feng, “Microwave reflection tomographic array for damage detection of civil structures,” IEEE Trans. of Antennas and Propagation, vol. 51, no. 11, pp. 3022-3032, November 2003

[2]. Paul M. Meanley, Margaret W. Fanning, Dun Li, Steven P. Poplack, Keith D. Paulsen, “A clinical prototype for active microwave imaging of the breast,” IEEE Trans. on Microwave Theory and Techniques, vol. 48, no. 11, pp.1841-1853, November 2000

[3]. Steven W. Smith, The scientist and engineer’s guide to digital signal processing. California Technical Publishing, San Diego, California, pp. 277-284, 1999