Subsurface Near-Field Microwave Tomography: some aspects of development.

Ye. Maksimovitch, Senior Member, IEEE,
V. Badeev
Institute of Applied Physics NASB, Minsk, Belarus

K. Gaikovich
Institute for Physics of Microstructures RAS, Nizhny Novgorod, Russia
Acknowledgments

This collaborative work has been supported by:

- the Belarusian Republican Foundation for Fundamental Research (grant № T12R-133);

- the Russian Foundation for Basic Research projects No. 12-02-90028-Bel, 13-07-97028_r, 13-02-97069_r, 13-02-12155_ofi_m.
Outline

• Introduction
• Simulations of the UWB planar dipole (design of balun and antennas arms)
• Experimental results
• Predictive analysis
• Imaging
• Conclusions
Introduction

• Simulation results for UWB bow-tie antennas had been presented:


Main conclusions:
- A combination of a tapered capacitive loading and a resistive loading leads to reduce unwanted reflections;
- The tapered capacitive loading is realized by an array of slots constructed on the antenna surface;
- For the resistive loading, absorbers block are used by placing them on the slotted surface of the antenna;
- The modified bow-tie antenna demonstrates similar behavior in GPR applications as compared to TEM horn, whereas dimensions and weight of bow-tie antenna are several times lower.
Introduction

UWB antennas

Dielectric media

Reflections between antennas

Reflections from surface

T

Own reflections

Rx

Reflections from boundary media-air

Object
Introduction

Problems

1. Own reflections;
2. Reflections between antennas;
3. Reflections from the first boundary (air/soil)

Solutions

1 – UWB impedance transformer (RF trans. Mini-circuits?);
   - distance between antennas plate and ground plane;
   - absorbers and R-cards;

2 - distance between antennas;
   - absorbers and R-cards;
   - free space;

3 - metal plane (a few different distances between plane and antenna);
   - matching layer between radiating part of the antenna and the studied media.
9 parts for theoretical modeling:
1- SCPW–symmetric coplanar waveguide;
2- Chebyshev impedance transformer;
3- asymmetric transformer;
4- TCPW– Coplanar waveguide tapered linearly in the lower slot;
5- ACPW– Asymmetric coplanar waveguide;
6- TACPW - Asymmetric coplanar waveguide tapered linearly in the upper ground strip;
7- TSLO– Unterminated slotline open;
8- TCPS–Asymmetric coplanar stripline tapered linearly in the upper strip;
9- SCPS– Symmetric coplanar stripline.
UWB antenna design
Balun design (50 Ohms to 100 Ohms)

Geometrical minimization of the balun. 20 cells per wavelength and edge cells were used, size of min.

UWB antenna design
Balun design (50 Ohms to 100 Ohms)

- For longer lines, there are not critical changes in lower frequencies, but at a frequency of 6 GHz the losses increase to -3dB.

- Restrictions in the higher part of frequency range taking into account properties of a substrate material are corrected by length reduction of CPS. Consequently, it’s necessary to use a short CPS line to connect balun and antenna, for obtaining a good bandwidth.

- Obviously, maximum losses value is higher for long lines. For short lines, maximum losses are lower and at higher frequencies.
UWB balun
UWB antenna design
Antennas flare design

Antenna width 56.4 mm
Antenna length 93 mm
Substrate FR-4 1 mm
Length of solid flare 34 mm
Slotline width 1 mm
Strip width 2 mm
The both flares are circular 90° sectors.
UWB antenna design
Antennas flare design
UWB antenna design
Electric field amplitude distributions

5 cm from dielectric surface
antenna with aperture matching

Dielectric permittivity of media 3.36
UWB antenna design

Electric field amplitude distributions

5 cm from dielectric surface

antenna with aperture matching

Dielectric permittivity of media 41.5
Test results

VNA E5071B

Box with sand
50cm

metal sheet

1 and 2 boundaries of the box with sand
2 boundary and metal sheet
Metal sheet in 10 cm from 2 boundary

Amplitude vs. Distance, cm
Experimental results

B-scan after performing inverse discrete Fourier transform with 6-th order Kaiser window to convert frequency data to the smoothed time-domain signal.

Experimental results for antennas without (left) and with (right) aperture matching.
Experimental results

Brickwork image

Image of wooden block between concrete and gypsum slabs
Objects
Predictive analysis

Foam block 40*40*5mm in the box with sand

scattered field
Concrete block 40*40*30mm in the container with waste oil
Experimental setup
Experimental setup

Scanning region: $L_x = 30 \text{ cm}; \ L_y = 20 \text{ cm};$ dipole bow-tie antennas; measurements at 801 frequencies in the range 1.7 - 7 GHz
Pseudopulse Near-Field Subsurface Tomography

Initial data – 2D field distribution near surface of media with object under test

Development of method for obtaining tomographic image.

The transverse spectrum of the received signal in the Born approximation is presented as an integral of the depth profile of the transverse spectrum of irregularities (Fredholm equation of the first kind).

A regularizing algorithm based on the Tikhonov principle of generalized residual is developed for the desired functions in the complex Hilbert space. Three-dimensional image is found by the two-dimensional inverse Fourier transform.

Problem: strong distortions of the field caused by near-surface irregularities.

Modification of the method

Reduction of the Fredholm equation of the first kind to the equivalent problem in the time domain. Introduction of the equivalent pseudopulse to separate the contributions by surface scattering and scattering by irregularities.

Result

Possibility of determining the region of localization of irregularity and obtaining clear image.

Possibility of retrieving the shape of subsurface object with homogeneous internal structure (computer holography).

Pseudopulse Near-Field Subsurface Tomography

Current distributions on the bow-tie antenna at 1.7 GHz and 7GHz. (b), (c) Lateral spectra of these current distributions.

Images of measured signal at frequencies 1.7, 3.46, 5.23, and 7GHz.

Images of pseudopulse at effective depths $z = -4.0, -4.8, -6.4$, and $-9.6$cm.

Results of subsurface tomography. (a) Horizontals section at depth $z = -5$cm (retrieval without near-field components). (b) The same as in (a), but retrieved with near-field components. (c) Vertical section at $y = 10$cm. Dashed lines mark the position and boundaries of the real target.
Near-Field Subsurface Holography
Scattering of electromagnetic field

Reduction of Maxwell’s equation to the solution of the integral Fredholm equation of the 2nd kind using Green functions

\[
\begin{align*}
\text{rot } \mathbf{H} - i \frac{\omega}{c} \varepsilon \mathbf{E} &= \frac{4\pi}{c} \mathbf{j}^p \\
\text{rot } \mathbf{E} + i \frac{\omega}{c} \mathbf{H} &= 0 \quad \varepsilon = \varepsilon_0 + \varepsilon_1(\mathbf{r})
\end{align*}
\]

\[
\begin{align*}
\text{rot } \mathbf{H}_0 - i \frac{\omega}{c} \varepsilon_0 \mathbf{E}_0 &= \frac{4\pi}{c} \mathbf{j}^p \\
\text{rot } \mathbf{E}_0 + i \frac{\omega}{c} \mathbf{H}_0 &= 0
\end{align*}
\]

\[
\begin{align*}
\mathbf{E}_0(\mathbf{r}) &= \int_{V} \tilde{G}(\mathbf{r} - \mathbf{r}') \mathbf{j}^p(\mathbf{r}') d\mathbf{r}' \\
\mathbf{E}(\mathbf{r}) &= \mathbf{E}_0(\mathbf{r}) + \frac{i \omega}{4\pi} \int_{V} \varepsilon_1(\mathbf{r}') \tilde{G}(\mathbf{r}, \mathbf{r}') \mathbf{E}(\mathbf{r}') d\mathbf{r}'
\end{align*}
\]

Probing field \quad Total field is the sum of probing and scattered fields
Reduction of 3D inverse problem to 1D equation

\[
E_1(r) = \frac{i\omega}{4\pi} \int_V \varepsilon_1(r') \tilde{G}(x-x', y-y', z, z') E_0(r') dr'
\]

Scanning at the fixed source-receiver distance \( \delta r \) (\( \delta r = \text{const} \)):

\[
E_0(r', r, \delta r) = \int_{V'} j(r'' - r - \delta r) \tilde{G}^{13}(x' - x'', y' - y'', z', z'') dr''
\]

\[
E_{1i}(k_x, k_y, \omega, z, \delta r) = -4\pi^3 i\omega \int_{z'} \varepsilon_1(k_x, k_y, z') \left[ \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} e^{-ik_x \delta x - ik_y \delta y} 
\times \left[ j_i(k_x, k_y, z'' - z - \delta z) G^{12}_{ij}(k_x, k_y, z'', z') \right] G^{21}_{ji}(k_x + k_x, k_y + k_y, z', z) d\kappa_x d\kappa_y dz'' dz'
\right]
\]

This integral equation should be solved for each pair of \( k_x, k_y \)
to obtain profiles \( \varepsilon_1(k_x, k_y, z) \)


Integral equation for lateral components of spectrum

Multifrequency method:

\[ E_1(\kappa_x, \kappa_y, \omega) = 4\pi^2 \int_{-\infty}^{0} K(\kappa_x, \kappa_y, z', \omega) \varepsilon_1(\kappa_x, \kappa_y, z') dz' \]

\[ E_1(\kappa_x, \kappa_y, z, \omega) = \frac{1}{4\pi^2} \iint E_1(x, y, z, \omega) \exp(-i\kappa_x x - i\kappa_y y) dxdy \]

\[ \varepsilon_1(\kappa_x, \kappa_y, z, \omega) = \frac{1}{4\pi^2} \iint \varepsilon_1(x, y, z) \exp(-i\kappa_x x - i\kappa_y y) dxdy \]

\[ K(\kappa_x, \kappa_y, z, \omega) = \frac{1}{4\pi^2} \iint K(x, y, z, \omega) \exp(-i\kappa_x x - i\kappa_y y) dxdy \]

\[ \varepsilon_1(x, y, z) = \iint \varepsilon_1(\kappa_x, \kappa_y, z) \exp(i\kappa_x x + i\kappa_y y) d\kappa_x d\kappa_y \]
Integral equation for received signal

Received signal as a convolution of scattered field and instrument function:

\[ s(r_r, \omega) = \int E_1(r')F(x_r - x', y_r - y', z_r, z')dx'dy'dz' \]

Transversal spectrum of the signal:

\[ s(k_x, k_y, \omega) = \int_{z'} \varepsilon_1(k_x, k_y, z') K(k_x, k_y, z', \omega)dz' \]

\[ s(\kappa_x, \kappa_y) = \frac{1}{4\pi^2} \iint s(x_r, y_r, z_r) \exp(-i\kappa_x x_r - i\kappa_y y_r)dx_r dy_r \]
Transformation of equations in time domain

\[ s(x, y, t) = \int_{\Delta \omega} s(x, y, \omega) \exp(i \omega t) d\omega \]

\[ s(x, y, z_s) = s(x, y, t = -\frac{2z_s \text{Re} \sqrt{\varepsilon}}{c}) \]

\[ s(k_x, k_y, \omega) = \int_{z'} \varepsilon_1 (k_x, k_y, z') K(k_x, k_y, z', \omega) dz' \]

\[ s(k_x, k_y, t) = \int_{\Delta \omega} s(k_x, k_y, \omega) \exp(i \omega t) d\omega \quad s(k_x, k_y, z_s) = s(k_x, k_y, t = -\frac{2z_s \text{Re} \sqrt{\varepsilon}}{c}) \]

\[ s(k_x, k_y, z_s) = \int_{z'} \varepsilon_1 (k_x, k_y, z') K_1(k_x, k_y, z', z_s) dz' \]

Gaikovich K.P., Gaikovich P.K., Maksimovitch Ye.S., Badeev V.A.

*Physical Review Letters*, 2012, **108** (16), 163902
Method of generalized discrepancy for complex-valued function in a Hilbert (Sobolev’s) space $W_{21}$

$$M^\alpha (\varepsilon_1) = \|K\varepsilon_1 - s\|_{L_2}^2 + \alpha \|\varepsilon_1\|_{W_{21}^1}^2$$

$$\rho(\alpha) = \|K_h\varepsilon_1 - s\|_{L_2}^2 - \delta^2 = 0$$

$$\|\varepsilon_1\|_{W_{21}^1}^2 = \frac{1}{\Delta z} \int_{z_{\text{min}}}^{z_{\text{max}}} \left\{ \varepsilon_1^2(z) + \left[ \Delta z \frac{d\varepsilon_1}{dz} \right]^2 \right\} dz,$$

$$\varepsilon_1(x, y, z) = \iiint \varepsilon_1(\kappa_x, \kappa_y, z) \exp(i\kappa_x x + i\kappa_y y) d\kappa_x d\kappa_y$$

Holography equations

Left: \( \epsilon_1(k_x, k_y, z) = \frac{1}{4\pi^2} \int_{y_1}^{y_2} \int_{x_1(y)}^{x_2(y)} \epsilon_1^0 e^{-ik_xx - ik_yy} \, dx \, dy = \frac{\epsilon_1^0}{4\pi^2} \int_{y_1}^{y_2} \exp(-ik_yy) \frac{1}{ik_x} \left( e^{-ik_x x_1(y)} - e^{-ik_x x_2(y)} \right) \, dy. \)

\[ \epsilon_1(k_x, y, z) = \frac{\epsilon_1^0}{2\pi ik_x} \left( e^{-ik_x x_1(y,z)} - e^{-ik_x x_2(y,z)} \right) \]

Right: \( \epsilon_1(k_x, y, z) = \frac{\epsilon_1^0}{2\pi ik_x} \left( e^{-ik_x x_1(y,z)} - e^{-ik_x x_2(y,z)} \right) + \frac{(\epsilon_1^{02} - \epsilon_1^0)}{2\pi ik_x} \left( e^{-ik_x x_3(y,z)} - e^{-ik_x x_4(y,z)} \right) \)
Near-Field Subsurface Holography

Foam sample in sand

samples $4 \times 4 \times 1 \text{ cm}^3 \ (1 \times 1 \times 0.25\lambda_{\text{min}}^3)$

Near-Field Subsurface Holography

Upper row: images of signal amplitude $|s(x, y, z)|$ for epoxy sample at $z = -5$ cm at $z = -4, -5, -6, -10$ cm in sand. Lower row: holography Images of target expressed by functions $x_1(y,z), x_2(y,z)$. Insertion: target.

Conclusions

Experiments confirmed conclusions derived from simulations that matched UWB dipole improves directivity due to suppression of sidelobes rather than main lobe.

Signal collected by transmitting-receiving antenna pair becomes more regular with matched antennas that makes GPR signal processing more effective.

The proposed methods of subsurface tomography and holography of dielectric targets in the near zone is effective enough, providing as ubwavelength resolution for targets of typical natural materials in various media.

We hope that the developed approach can be used in various applications of electromagnetic or acoustic diagnostics, including biomedical diagnostics of tumors, nondestructive testing in defectoscopy, civil engineering, and underground remote sensing.
REFERENCES


• Гайкович К.П., Максимович Е.С. Ближнепольная томография и голография слабоконтрастных диэлектрических объектов. *Изв. вузов. Радиофизика*, 2015, т.58, №2, с. 142-156.

Thank you for your attention