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# TERAHERTZ RADAR OF IMAGE TO STUDY THE PROPERTIES OF MATERIALS

***The possibility of 3D radar calibration is studied in the exploring of material properties to the example of plexiglas, depending on the distance between the sample and the antenna using an absorber. The results of preliminary studies indicate the possibility of measuring the thickness of the material. On the calibration, a small metal plate and several measurement cycles for averaging the noise were used. It is shown that the accuracy of measurements is influenced by the width of the radiation pattern, the reduction in the number of measurement cycles at one point, the accuracy of positioning and moving the head during the measurements, and the time interval between the calibrations.***

**Keywords:** absorber; digital spectral analysis; electromagnetic simulator; horn antenna.

## INTRODUCTION

In the implementation of 3D scanning small objects is used FMCW radar at operating frequency 100 GHz and bandwidth about 10 GHz of terahertz frequency range (fig. 1).

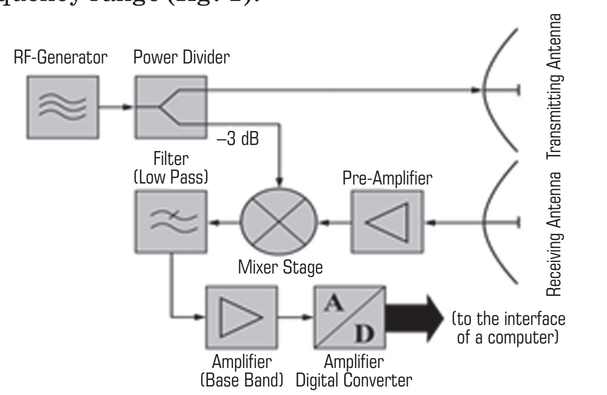


**Fig. 1. Microwave part of 3D FMCW terahertz radar**

We have developed algorithms and have obtained the required accuracy — less than 3 mm. In reality, we still cannot accurately assess the environment model to take it into account in processing. We will try to test the radar system, having previously calibrated it.

Before carrying out the measurements:

1) we set the horn and the sample close the absorber to reduce the reflections;

2) we measure the signal without a sample;

3) we place the sample (5-10 mm) and begin to measure;

4) very carefully a thin conductive film is pasted from above and measurements are taken;

5) very gently flip backed with a conducting medium and measure;

6) if all done carefully, there should be a shift of even a fraction of a millimeter. Scaner must be disabled. We will make a point of 50 measurements.

Then we measure (fig. 2).

1. We measure the signal without the sample (5 times).

2. We place the sample (plexiglas of 10 mm) on the absorber and repeat the measurement 5 times.

3. On the top of the sample we stick a thin conducting film (carbon fiber of 0,4 mm) and repeat the measurement 3 times.

4. We flip back the sample with the film conducting and measure 3 times.

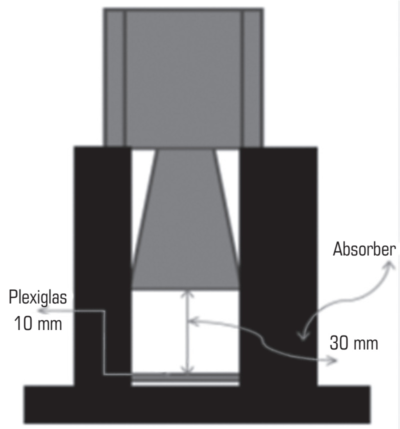


**Fig. 2. System for testing 3D radar**

## MAIN PART. COMPUTING AND MODELLING

### Some problems of estimation of sample thickness

1. Different materials have a different permittivity and different velocity of phase of electromagnetic wave. This property gives that real thickness between upper and lower plane of samples is equivalent to virtual thickness between real upper and virtual lower plane in air. We can to estimate equivalent virtual thickness between metal planes in air and then corrected result for real material [1].

2. In real materials we have a multiple reflection (fig. 3) what gives several spectral lines for one thickness of the sample.

3. Reflections from virtual metal planes do not fully correspond to reflections from real metal planes during calibration. There are numerous errors of discrepancy between virtual planes and the

nearest calibration levels. This gives multiple errors in the spectral lines and creates some difficulties in estimating the thickness.

4. The some calibration levels must be present lower then baseline to estimate positions of virtual metal planes.

5. We will try to fix existing mathematic problems and to get a mathematical tool for universal measurement device.

6. We check the additional measurement configuration. For calibration, we use a special sample with a higher accuracy — plexiglas (see fig. 2).

infinite ($M-1$)-layer medium with flat boundaries. The CRC $V(f, p)$ is related of the CRC of the structure in free space $V_S(f, p)$ through the scattering matrix **S** of the antenna, which is determined experimentally:

$$V = S_{11} + \frac{S_{21}V_S}{1 - S_{22}V_S}.$$

The CRC of the structure in free space depends on the thickness and electrophysical parameters of structure layers:

$$V_S = V_S(f, h_1, \ldots, h_{M-1}, \varepsilon_1, \ldots, \varepsilon_M, \mathrm{tg}\delta_1, \ldots, \mathrm{tg}\delta_M),$$

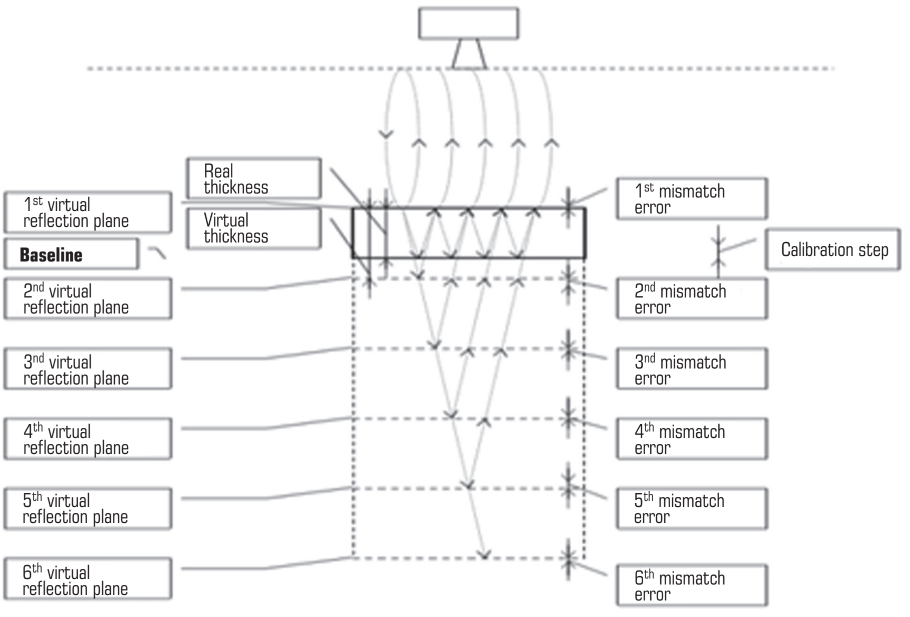


**Fig. 3. The reflections of an electromagnetic wave in a plexiglas sample**

As a result of the measurement cycle, a frequency dependence of the attenuation in the microwave channel $D(f) = U_{\mathrm{ref}}(f)/U_{\mathrm{inc}}(f)$ is obtained.

Unknown parameters of the dielectric structure are determined by procedure of global minimization of discrepancy between the measured attenuation in channel $D(f)$ and one calculated theoretically $D_{\mathrm{th}}(f, \mathbf{p})$

$$F(\mathbf{p}) = \sum_f \left| D(f) - D_{\mathrm{th}}(f, \mathbf{p}) \right|^2.$$

Here $D_{\mathrm{th}}(f, \mathbf{p})$ is defined according to the formula

$$D_{\mathrm{th}} = \left| k_0 + k_1 \frac{V - V_c}{(1 - k_3 V)(1 - k_3 V_c) - k_2 V V_c} \right|^2,$$

and $k_0(f), \ldots, k_3(f)$ are complex coefficients, which are determined experimentally using reference samples and describe properties of the microwave channel; $f$ is the frequency of sounding waves; $V_c(f)$ is the complex reflection coefficient (CRC) of the reference arm 3; $V(f, p)$ is a theoretically calculated CRC of the dielectric structure, which depends on a vector of the structure parameters $p$ (thickness of layers and electrical parameters of materials).

We consider that in free space extends a plane electromagnetic wave and normally incident on the

where $h_M$, $\varepsilon_M$, $\mathrm{tg}\delta_M$ is thickness, permittivity and loss tangent of $M$-th layer. The CRC of the plane wave from dielectric plane-layered medium $V_S(f, p)$ is determined by the known formulas:

$$V_S = \frac{W_0 - Y_1}{W_0 + Y_1},$$

$$Y_m = W_m \frac{Y_{m+1}(\exp q_m + 1) + W_m(\exp q_m - 1)}{W_m(\exp q_m + 1) + Y_{m+1}(\exp q_m - 1)}, \quad Y_M = W_M,$$

$$W_m = \sqrt{\varepsilon'_m / \mu_0}; \quad q_m = 2j \cdot 2\pi f \cdot h_m \sqrt{\varepsilon'_m \mu_0 \left(1 - \sin^2\theta\right)};$$

$$\varepsilon'_m = \varepsilon_0 \varepsilon_m (1 - j\,\mathrm{tg}\delta_m),$$

where $\varepsilon_0$ is permittivity and $\varepsilon_0$ is the permeability of free space.

The thickness of each step was increased in 50 micron increments from the desired minimum to the desired maximum. The horizontal size of each step was at least 20×20 mm, to prevent artifacts from borders. During the setup process, we do not need to change the distance between the signal and the base line, but we need to will move the device and perform a calibration at the center of each step. This calibration process is simpler and can be performed in automatic mode without an additional table with a micrometer (fig. 4).

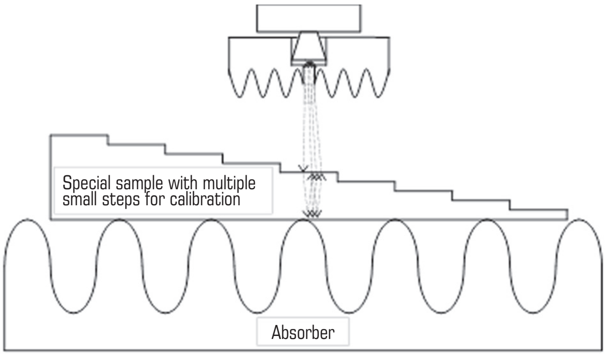


**Fig. 4. Calibration of the system using absorber and plexiglas plates of different thicknesses**

### About radar system configuration (fig. 5–14)

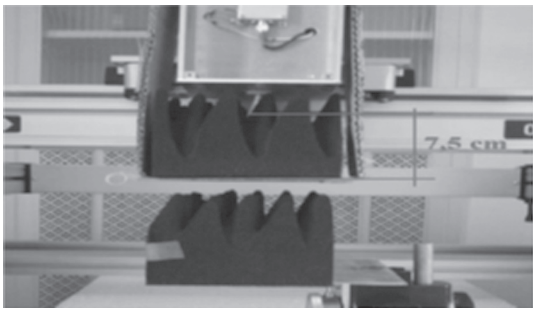


**Fig. 5. The configuration of the measurement of a radar system with two absorbers**

This configuration is not very good, since the bottom surface of the upper absorber acts as a reflector. The signal, which is reflected from the sample and extends to the horn, is partially reflected from the lower surface of the upper absorber and returns back to the sample. Thus, it can have several reflections. Increasing the distance between the sample and the absorber reduces the effect of this effect, but also reduces the level of the desired signal.

We carried out the configuration using the special hole in the upper absorber.

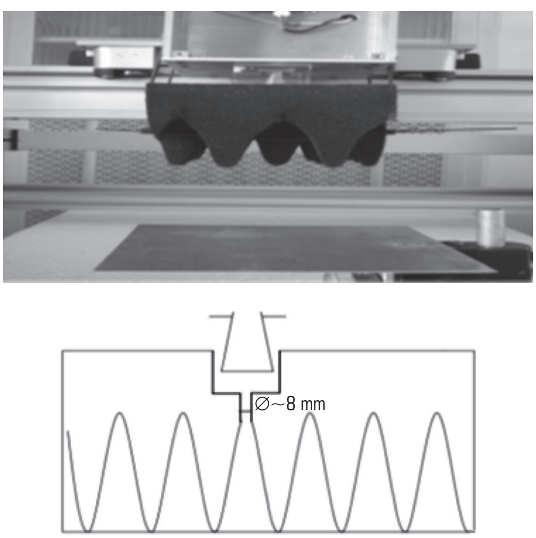


**Fig. 6. The configuration of system using the special hole in the upper absorber**

We used hole of size 8 mm to make calibration with 5×5 mm metal fragment between $D$max = 10,5 cm and $D$min = 9,5 cm.

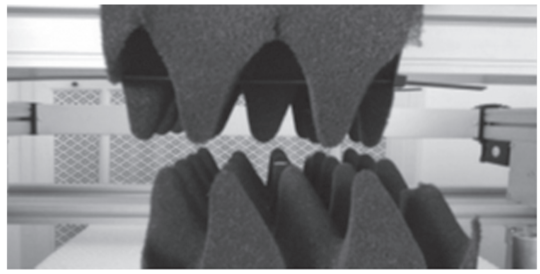

**Fig. 7. The configuration of system using the special hole of size 8 mm to make calibration with 5×5 mm metal fragment**

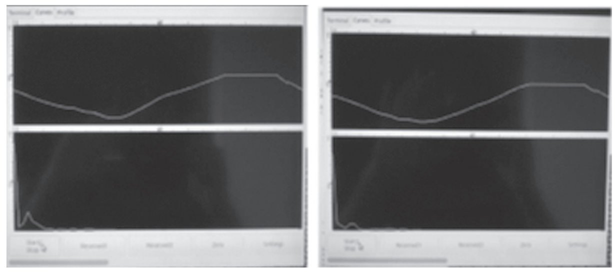

**Fig. 8. Calibration signal: in *D*min in the left; in *D*max in the right**

After calibration, we performed some experiments with a sandwich of two metal fragments, arranged one above the other.

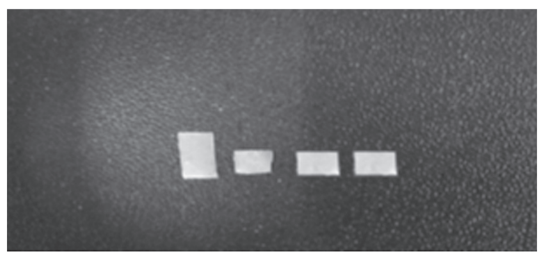

**Fig. 9. Metal fragments**

Fig. 9 showes in order:

1) metal fragment 10×5 mm and thickness 500 μm;

2) metal fragment 5×5 mm and thickness 500 μm;

3) sample made with aluminum foil folded repeatedly to obtain a thickness of about 250 μm;

4) sample made with aluminum foil folded repeatedly to obtain a thickness of about 400 μm.

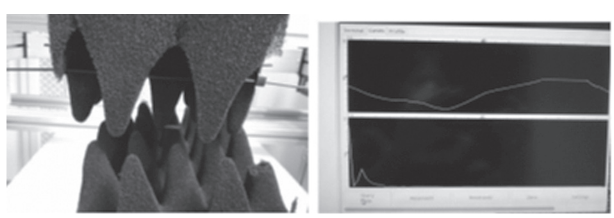

**Fig. 10. Controlling the presence of the reflected signal from the lower fragment 10×5 mm**

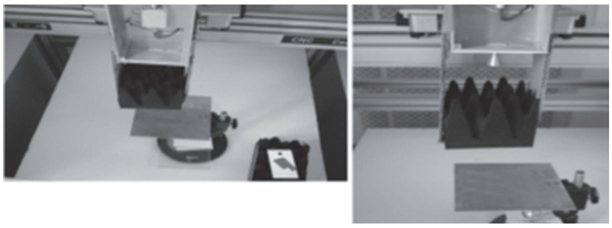

**Fig. 11. Measurement configuration with the absorber which has a hole of size of about 1 cm**

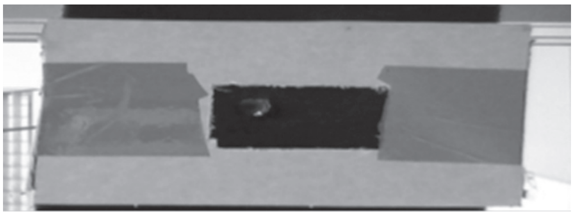

**Fig. 12. Measurement configuration which has a hole under the absorber**

The beam enters the hole through the absorber and enters the material under the horn. Most of the beam coming from the horn is protected by an absorber. Only power beams pass through the material.

With this configuration, a new calibration was performed. In this case, the power that affects the material is reduced. Thus, the maximum reflection for the metal plate is obtained in the position shown in the fig. 13.

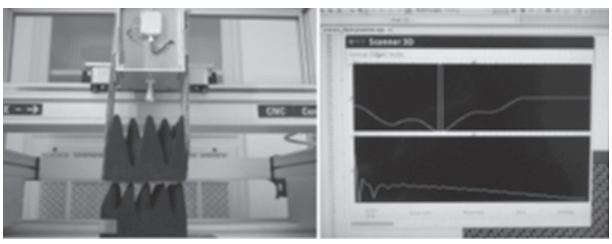

**Fig. 13. The maximum reflection (*D*max) for the metal plate position**

From this position the metal plane is turned down of 10 mm.

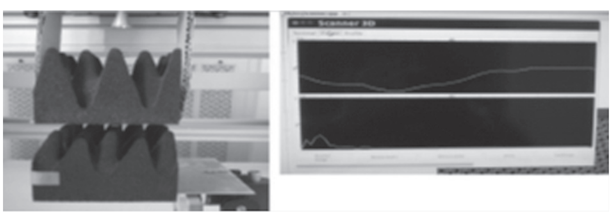

**Fig. 14. The minimum reflection (*D*min) for the metal plate position**

From Dmin to Dmax the acquisitions are made for every step of 250 μm.

### About the configuration measuring system of the radar (fig. 15–20)

The horn is at 80 cm from the absorber and the sample holder that we use to put the samples to test can be moved along the length between the horn and the absorber.

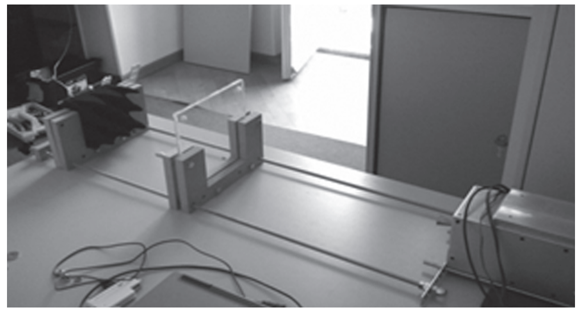

**Fig. 15. Measuring device for radar**

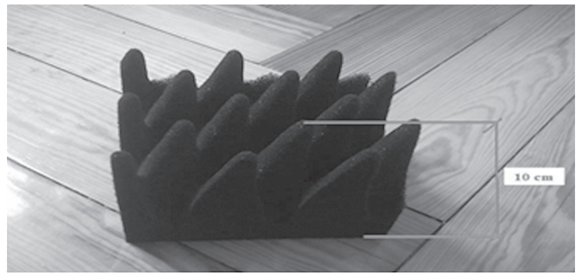


**Fig. 16. The absorber for measurement to radar system**

The absorber is with height 10 cm as showed in fig. 16. Our system characterized by the following parameters: $D = 80$ cm; $d = D/2 = 40$ cm.

This setup is the start setup in all test. We need to do three kinds of test.

**Test 1**

In the test 1 the measurements are made on a single material at a time. We'll do measurements using plexiglas. The thickness is not important; the procedure of measurement is as follows.

1. We put the system in the condition of start setup. This means that at the bottom is present the absorber ($D$ = 80 cm) and the sample is put at $d = 40$ cm. This is the first measurement.

2. Then we move the sample by increasing the distance from the horn of 1 mm at a time. We repeat this operation 10 times. After each movement we record the spectrum. So the measurements correspond at these distances from the horn: 401, 402, and so on until 410 mm.

3. From this position (41 cm), we move the sample by increasing the distance from the horn of 1 cm at a time. For each position we record the spectrum. We repeat this 10 times. So the measurements correspond at the distances from the horn: 42, 43, 44, and so on until 50 cm.

**Test 2**

In the test 2 the measurements are made using the same samples — plexiglas. The sample is kept in stop at $d = 40$ cm and the absorber is made move from the back of the sample to the bottom of the system ($D = 80$ cm).

1. The sample is at the distance $d = 40$ cm. Behind it and adherent its surface, is put the absorber. We record the spectrum.

2. From this position (40 cm), we move the absorber by increasing the distance from the sample of 1 cm at a time. For each position we record the spectrum. We repeat this in different times. These measurements are necessary to understand if and how the absorber influences the measurements.

**Test 3**

When performing tests, we take into account the following.

1. Now we use two plates and make the «sandwich». The first one (in front the horn) must be homogeneous and weakly absorbing (we use plexiglas). The second one is behind and adherent the first (fig. 17, 18).

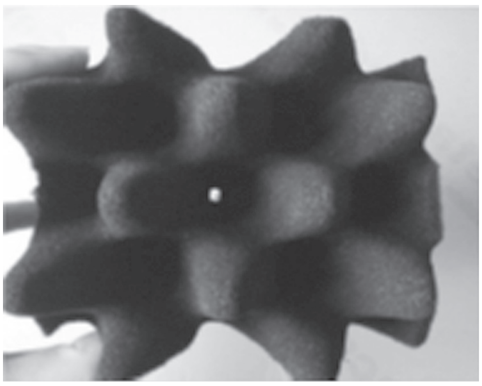

**Fig. 17. This side must be top (as a worked side of absorber)**

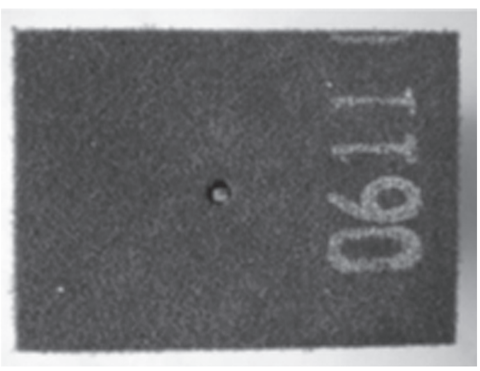

**Fig. 18. This side must be bottom**

Some previous experiments proved, that this side works as reflection plane.

The new system is shown in the fig. 19 and the maximum distance at which the absorber can be placed with respect to the antenna is $D = 80$ cm.

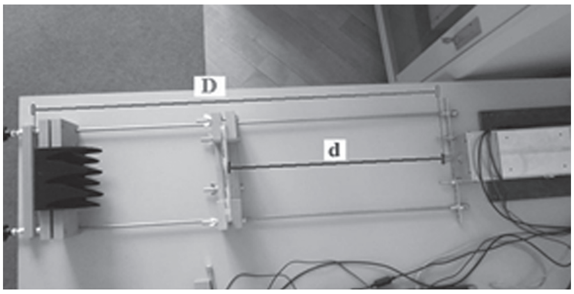


**Fig. 19. New system head 3D image radar**

The measurements were made as following.

1. Measuring without sample moving the absorber from 10 to 80 cm with 5 cm step.

2. Using a single material at the same time: plexiglas (see fig. 20).

3. Putting the sample at $d = 30$ cm and making measurements increasing the distance from the horn beginning in 1 mm at a time until reaching the distance of 31 cm.

4. From this position (31 cm), moving the sample increasing the distance from the horn of 1 cm in the same time until reaching the distance of 40 cm.

5. Repeating paragraphs 1–3 using two plates like a «sandwich» (plexiglas+PVC). The first one (in front the horn) must be homogeneous and weakly absorbing (we use plexiglas). The second one is behind and adherent the first.

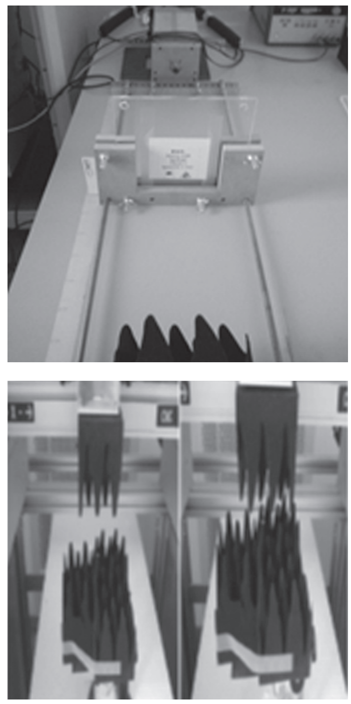

**Fig. 20. Setup using plexiglas and PVC sample. Reflection plane is a 6x6 metal plane**

**Measurement of plexiglas properties (fig. 21–28)**

The system is shown in the fig.21 and the maximum distance at which the absorber can be placed with respect to the antenna is $D = 80$ cm.

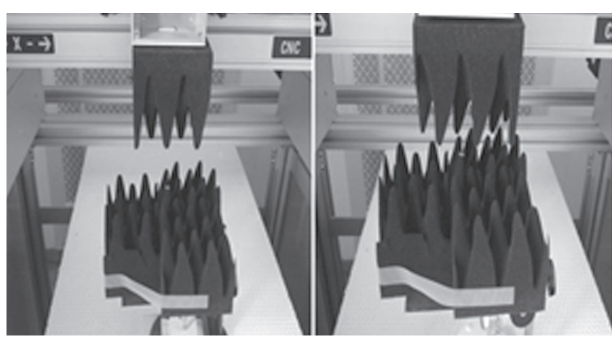

**Fig. 21. Reflection plane is a 6x6 metal plane**

Width of emission beam in this case maybe a larger then 6 mm diameter, but only when 6×6 mm square (see fig. 21). This is proof, that emission beam with 6 mm diameter must produce a results. In next measurements we have a less distance from horn to samples and must have a bigger signal. This is proof, that center of hole is not in focus of beam in the following measurements (fig. 22, 23). The larger of the series size, the smaller of the approximation error is 4×10 mm.

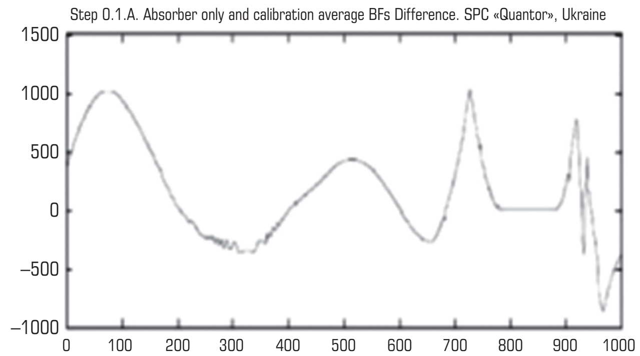


**Fig. 22. Estimation of calibration result**

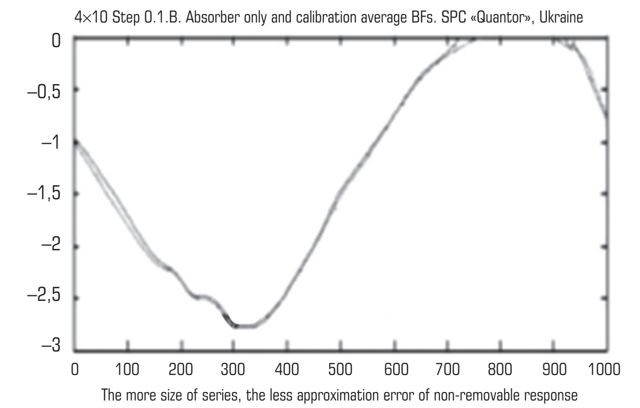


**Fig. 23. Estimation of calibration results**

We see an average basic function (BF) of 40 response signal from 6×6 mm metal at 40 different distance — estimation of non removable response from constructive elements (horn and others), and average BF of 40 response signal from absorber only without metal plane [2]. We can see a small difference between absorber only average BF and calibration (by metal) (see fig. 24).

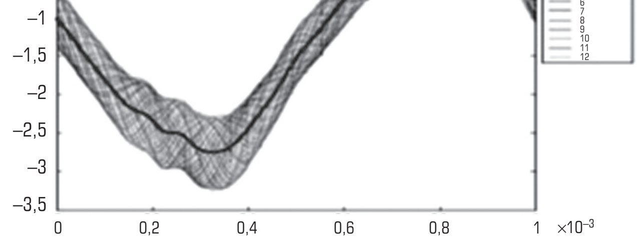


**Fig. 24. Comparing of calibration average BF between response signal from absorber only without metal plane and only metal plane**

Curve bold — average BF (non-removable response). Curve 1–40 — series of BF for different 40 distances. It is a good result (see fig. 25).

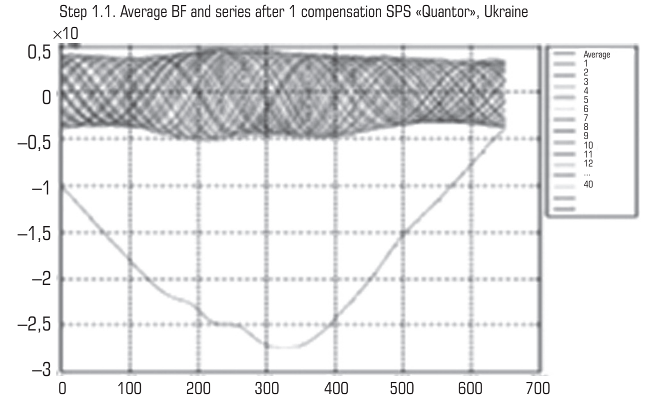


**Fig. 25. Results of compensation of average BF of non-removable response signal response for series measurements**

The new series of compensated BF is estimation of elementary responses from 40 different distances. We see that the recovery error is very small. Total result for calibration is OK [3].

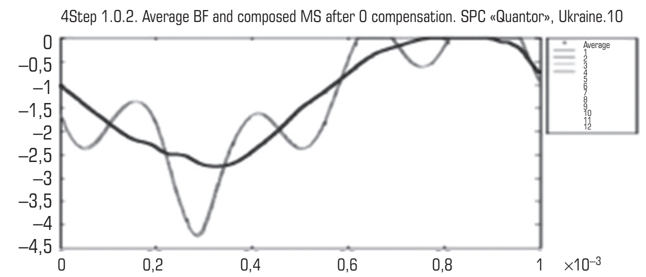


**Fig. 26. Average BF of response signal from non-removable constructive elements and response useful signal from plexiglas 100×100×10 mm**

Curve bold — average BF of 40 response signal from 6×6 mm metal at 40 different distance — estimation of none removable response from constructive elements (horn and others), curve 1–4 — mix of non-removable response from horn and large (good!) useful signal from plexiglas 100×100×10 mm (see fig. 26).

Thickness of 10 mm give a composed mixed signal (MS) with 2 elementary responses, that according to BF #1 and BF#40 (approximately) (see fig. 27). Really we can see 1-st maximum for BF #39 (the last BF #40 has been removed from analyze to protect matrix singularity) and 2-nd maximum for BF #1 and BF#2 (that corresponding to case, when reflection plane is between distance #1 and #2):

BF # 01.085535 — part of composed MS by non-removable response (average BF).

BF # 39-1.180438 — part of composed MS by 1-st reflection plane of sample with 10 mm thickness.

BF # 1-2.276038 — part of composed MS by 2-nd reflection plane of sample with 10 mm thickness.

BF # 2-2.502144 — part of composed MS by 2-nd reflection plane of sample with 10 mm thickness.

All 4 composed MS for plexiglas 100×100×10 mm gives very similar distance spectrum.

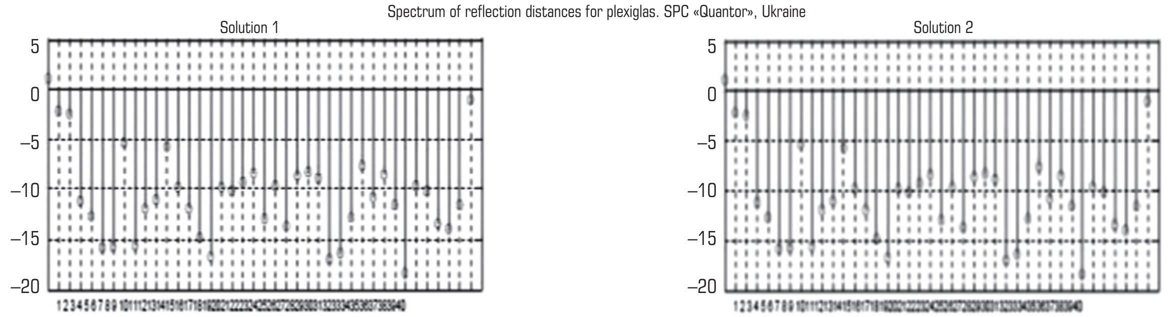


**Fig. 27. Dependence of the spectrum on distance for plexiglas 100×100×10 mm**

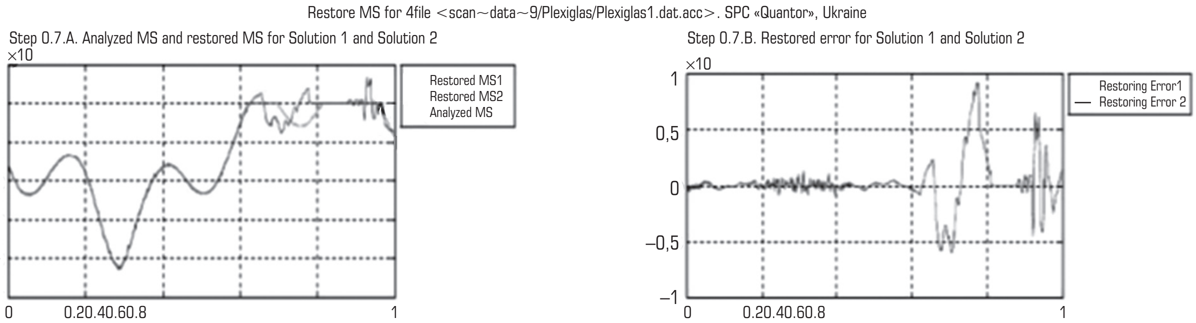


**Fig. 28. Attempt to restore source composed MS from calculated distance spectrum**

We can see a good restoring (from 0 to 0,6 mm, where error was been minimised), that is proof that distance spectrum is true [4].

## CONCLUSION

The work was performed on the equipment of scientific and production enterprise «Quantor» in cooperation with the Taras Shevchenko National University in Kyiv of the «Modeling and Optimization» laboratory and the Institute of Cybernetics of the Academy of Sciences of Ukraine.

To increase accuracy of distance spectrum estimation we can try to decrease size of distance step up to 50 mm. We must make revision, if the centre of hole is in the focus of beam. We can try to repeat every measurement a sometimes, for base distance $D1$, $D2 = D1 + 1000$ mm, $D3 = D1 + 2000$ mm, for example. A good measurement techniques is to make an additionally calibration with absorber only with step 1 mm [4].

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**ТЕРАГЕРЦОВИЙ РАДАР ЗОБРАЖЕННЯ ДЛЯ ДОСЛІДЖЕННЯ ВЛАСТИВОСТЕЙ МАТЕРІАЛІВ**

*Висвітлено можливість використання 3D радара для вивчення властивостей матеріалів на прикладі плексигласу з використанням поглинача. Досліджено залежність розглядуваних властивостей од відстані між зразком та антеною.*

**Ключові слова:** поглинач; цифровий спектральний аналіз; електромагнітний симулятор; рупорна антена.

*Н. Косовец, Л. Товстенко*

**ТЕРАГЕРЦОВЫЙ РАДАР ИЗОБРАЖЕНИЯ ДЛЯ ИССЛЕДОВАНИЯ СВОЙСТВ МАТЕРИАЛОВ**

*Показана возможность использования 3D радара для изучения свойств материалов на примере плексигласа с использованием поглотителя. Исследована зависимость рассматриваемых свойств от расстояния между образцом и антенной.*

**Ключевые слова:** поглотитель; цифровой спектральный анализ; электромагнитный симулятор; рупорная антенна.