Experimental Study of Scattering at Large Radio Anechoic Chamber

Yuri I. Belov

Abstract - **The reflectivity level for frequencies 12 and 35 GHz were measured by the Voltage Standing Wave Ratio (VSWR) technique, in purpose of preliminary estimate the new large radio anechoic chamber at Nizhny Novgorod. Experimental results and its analysis are presented. A modeling interferometric technique was used for to determine the scattered signal areas.**

Keywords – **Radio Anechoic Chamber, Reflectivity Level, the *VSWR* Measurement Technique.**

I. INTRODUCTION

A common estimate for quality of radio anechoic chambers (RAC) is the reflectivity level. It is determined as a ratio of the power flux densities: one scattered by the chamber surface and (or) its internal facility is referred to the power, radiated from antenna under test (AUT); both are in the area of receiving antenna aperture [1].

Analysis of locations and values of reflected signals in a RAC is difficult, but necessary task for any type measurements: low level side lobes of antenna pattern, radar cross sections (RCS) and some other.

Recent progress of radio measuring technics permitted to radiate the shortest picosecond pulses in purposes to analyze a scattering in RAC by means of evaluating of received signal delays [2]. Short pulses also can be artificially synthesized, if to measure and Fourier transform the complex (phase and magnitude) received signal in a broad frequency range [3].

To measure vector signals, which could be synthesized as a short pulse in the case of multi frequency technique or be used for data processing algorithm similar to the MUSIC [4], one need to arrange an additional reference channel of measurement facility. The reference channel presence could bring some serious problem for large RAC, particularly at millimeter wavelength range.

We do not discuss any advantages or disadvantages of these vector type measurement techniques, but any case an investigator should interpret the measurement results with the aim to determine the mostly intensive and also weak scattering sources. By analogy with radiolocation a complete knowledge on a scattering target consists of a delay (distance) and direction (angles) in a coordinate system.

To separate an arrival direction of scattered signal in limits of antenna main beam the high gain antennas with low level side lobes must be used. Of course difficulties for measurements of reflectivity level at meters and decimeters wavelengths arise because of great sizes of the high gain antennas.

A possibility to determine a source of scattered signal by the analysis of amplitude modulation periods of received signals during the procedure of RCS study was marked in [5]. The modulation is a consequence of the radar target linear shifts. We used a similar approach to the problem.

It should be mentioned, that an investigation of "quietness quality" for the large RAC, which are intended to operate in broad frequency range, is a very long lasted process.

To accelerate a process of the quality evaluating, to simplify the procedure as well as a set of used facility it is desirable to employ the broad band test antennas and amplitude only measurements. Also it is needed an easy interpreting technique for measurement results. This objective are urgent for every developer of a RAC, because of necessity to obtain an effective tool for improving the reflectivity level by a simple designing technique during the RAC evaluation process.

We have tested experimentally an influence of reflection sources placement at the large RAC $(15 \times 10 \times 45\,\text{m}^3)$ in studying of its interference processes by use of similar receiving and transmitting antennas. It were broadband antennas of 0.1 – 12 GHz frequency range and parabolic reflectors and horns of range near 35 GHz having enough low level of side lobes. A use of a low level side lobes antenna at the test facility makes some re-calculation problems for received power in data processing of experimental signal records. On the other hand high gain antennas produce more intensive received signals.

The studied RAC has a specific feature of measurement facility units: the transmitting AUT changes its orientation along azimuth angle contrary to "classic" structure, when it is immovable [1]. Automated system of trailing the AUT along special trusses, oriented along the horizontal axis of the antenna polarization rotation, supplies to arrange the reflectivity level measurements very fast and effectively with amplitude data only (phaseless).

In the presented work for data processing we have based on a human eye ability to separate a periodical process from noise, even, when the process amplitude is not statistically valuable. This fact was formulated in the article [6], which analysis was concerned of quasi-periodical changes of the sky stars brightness: the most recognizable by human eye oscillations are these, which have its period of 1/3 part of the observation records duration. The argument of processed data, which we received during our reflectivity level study, was a shift of the transmitting antenna position along specially oriented directions of it in RAC. For all these we a priori had evaluated the interferometric oscillation periods on a base of mutual antenna positions and the RAC sizes.

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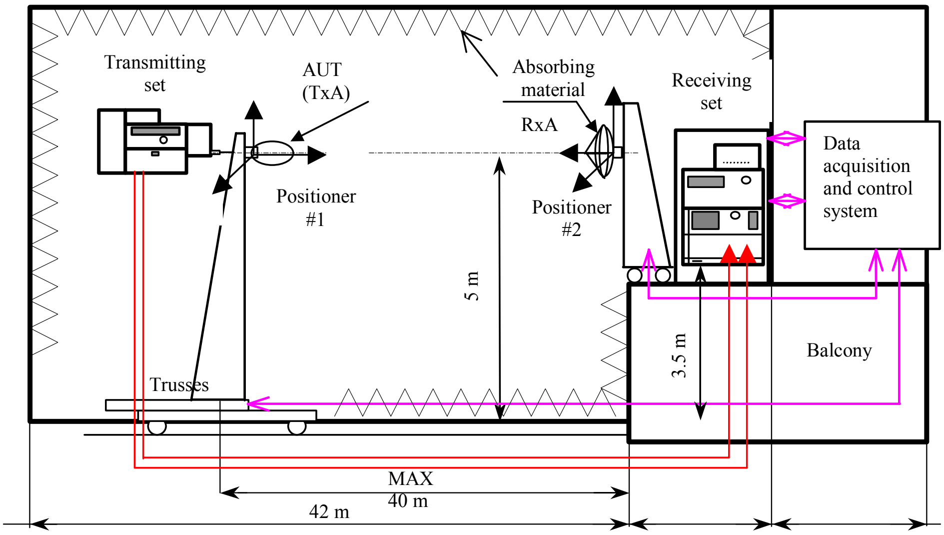

Fig.1

We present here results of the reflectivity level measurements at frequencies 12 and 35 GHz by technique of "VSWR"[1], which is named so, because of similarity the signals received by the test facility to the phenomenon of "standing wave". The empirical analysis of experimental results was performed on a base of understanding the interference of scattered wave, from the a priory determined area, and direct wave radiated by a transmitting antenna.

The measurement results verification was implemented partly by a comparison of it with the reflectivity level values obtained with another, but similar technique – "Antenna Pattern Comparison" (APC), which is described in [8] in details.

Comparison is satisfactory for a purpose of preliminary estimate of the RAC reflectivity level. The performed study has permitted to recommend the RAC design modification for to improve its quality.

II. Basic features of the RAC facility set

The "classic" VSWR technique to measure the reflectivity level of a RAC is described [7] as: a transmitting antenna (TxA) of low gain (like a short horn) more or less smoothly radiates on the chamber walls and a receiving antenna (RxA) of high gain and low level side lobes is trailed along a straight line and receives the vector sum (interference fringe) of direct and scattered signals in some points of the chamber. A receiver of the test facility registers the interference signal; a computer processes the recorded files accordingly to the next section algorithm, and evaluates the reflectivity level value for a fixed receiving antenna angular position. Further the RxA is re-oriented to another part of RAC and so on. Thus the antenna directivity permits to determine the angular direction of reflection wall area and evaluation procedure gives a ratio of the scattered signal to direct one.

Some development requirements have led to that the facility transmitting equipment with a TxA (AUT) were settled on the polarization rotation positioner, which is placed on a top of 5 meter height tower. The tower can to be trailed automatically along the two trusses and rotated together with it along azimuth (positioner #1) ± 180°. A receiving part of the facility with RxA (used like a reference standard antenna) are immovable, but can together to be rotated along a horizontal axis (polarization) and adjusted in a small range of azimuth and elevation, see Fig. 1.

A study of "black" disks diffraction patterns presented at [9] has shown an asymmetry of the patterns against incident and observation (scattering) angles $(\vartheta_{in}, \vartheta_{sc})$ in the sense, that $S(\vartheta_{in}, \vartheta_{sc}) \neq S(\vartheta_{in}, \vartheta_{sc})$, if $\vartheta_{in} \neq 2\vartheta_{sc}$. But it is not a point do not use the VSWR technique for our variant of measurement facility. As it will be shown in the next subsection, we measure the same reflectivity value: the flux density ratio of scattered by the RAC area signal to the incident directly to the RxA aperture signal.

Automation of precise shift of the TxA along the trusses as well as both antennas rotation has permitted us to use two identical standard broadband ridge horns for its whole band (1- 12 GHz) for purpose of fast measuring the reflectivity level. The antenna gain is 10 – 27 dB in operation frequency range.

Nevertheless, the broadband antennas bring over the specific measurement features: in the part of high frequency range the scattered by the RAC walls signal is received by a RxA via enough low level side lobes; and in low frequencies of the range, where the antennas pattern broadens, some ambiguity of pointing to the reflecting area appears. The last circumstance is clear in view of Fig. 2.

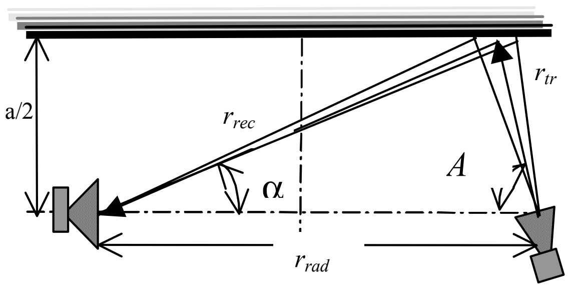

Fig. 2

The RxA power density decrease apart of its main beam direction, when it illuminates the RAC wall (ray 1), could be compensated by an increase of the RxA directive gain (ray 2) in that shifted direction. Computer simulation of both antenna patterns with the Gaussian shape for the antennas separation distances, which we used for our experiments, has shown the angular size of ambiguity 1° – 2°, for frequencies 1 – 1.5 GHz (broad main beams) and the TxA azimuth angles in a vicinity ~ 40° – 60°. One can take into account this value by an averaging the RxA antenna pattern in re-calculation of the reflection levels to constant receiving gain, see Eq. (6), below.

For narrow beam antennas which are very typical at centimeter and millimeter wavelength range, the scattered signal is suppressed by the RxA pattern, really, but one must take into account, that the TxA azimuth angles are used in a range 30°– 90°, as it will be shown in Section IV. Thus the interfering, direct and scattered by the RAC signals, are of approximately the same value, so if one has a good sensitivity receiver, the signals could be registered.

All discussed problems were overcame in our experiments, and we convinced that for purposes of a preliminary or express assessment the reflectivity level it is possible to use broadband and narrow beam antennas, both as receiving or transmitting one, in the case of sensitive receivers usage.

III. EVALUATING OF THE RL BY VSWR TECHNIQUE

Briefly an essence of the VSWR technique for reflectivity measurements consist of the next evaluation procedure.

A ratio of the power flux density scattered by the RAC in aperture of the RxA to power directly radiated there by the TxA is named the reflectivity level of RAC. It is a characteristic of RAC evaluated for chosen orientation (azimuth) of the TxA (AUT) relatively to the pointing it to the RxA.

$$RL = \rho = \frac{\left|\vec{E}_{sc}\right|^2}{\left|\vec{E}_{dir}\right|^2} \text{ or } \rho = 10 \cdot \lg \frac{P_{sc}}{P_{dir}} \text{ [dB]}. \qquad (1)$$

The *RL* is used as a function of the AUT orientation angles for measurements of antenna pattern with low level side lobes, otherwise as a limit for various the AUT positions to estimate a maximal error input of the RAC been brought to a measured antenna pattern.

The ratio of maximal to minimal signal power in receiving antenna $\eta = \frac{P_{\max}(r_{rec}, r_{tr1})}{P_{\min}(r_{rec}, r_{tr2})}$, (the formula values are determined on Fig. 2), is measured as a function of the TxA shift along its polarization rotation axis. The ratio could be transformed to the reflectivity level function as:

$$\eta = \frac{\left|\vec{E}_{dir}\right|^2 + \left|\vec{E}_{sc}\right|^2 + 2 < \vec{E}_{dir}\vec{E}^*_{sc} >}{\left|\vec{E}_{dir}\right|^2 + \left|\vec{E}_{sc}\right|^2 - 2 < \vec{E}_{dir}\vec{E}^*_{sc} >} = \frac{1 + \rho + 2\sqrt{\rho}}{1 + \rho - 2\sqrt{\rho}} \qquad (2)$$

where the brackets <…> denote the vectors dot product, and * is a complex conjugate value. The *RL* as a solution of Eq. (2) is equal to

$$\rho = \left(\frac{\sqrt{\eta} - 1}{\sqrt{\eta} + 1}\right)^2 = \left(\frac{\sqrt{P_{\max}} - \sqrt{P_{\min}}}{\sqrt{P_{\max}} + \sqrt{P_{\min}}}\right)^2. \qquad (3)$$

This expression can be presented in more convenient form:

$$\rho = \left(\frac{\dfrac{\Delta P}{2P_{av}}}{1 + \sqrt{\dfrac{P_{\max}P_{\min}}{P_{av}^2}}}\right)^2, \qquad (4)$$

where $\Delta P = P_{\max} - P_{\min}$, $P_{av} = \frac{P_{\max} + P_{\min}}{2}$, and $\frac{\Delta P}{2}$ – the amplitude of interfering signal. All values, as it's told, are function of the TxA position on the horizontal trusses. An algorithm of choice one or another value in data records is detailed in Section VI.

For every fixed azimuth of the TxA it should to search the maxima and minima, which are repeated with a priory evaluated period, depending on the antenna azimuth, see Eq.(9) below, as well the maximal deviation from averaged power records of these adjacent "vrai" maximum and minimum $-P^{\max}_{\max}$, $P^{\max}_{\min}$. After that it is evaluated:

$$\rho = 20 \cdot \lg \frac{\Delta P}{2P_{av}} - 20 \cdot \lg\left(1 + \sqrt{\frac{P_{\max}P_{\min}}{P_{av}^2}}\right). \qquad (5)$$

The *RL* value should be re-calculated to constant power level of direct signal and with taking into account a diminution of reflected signal from illuminated wall area by side lobes of the RxA. Thus the weighting influence of the RxA effective area, which depends on the observation angle, is excluded. So, from the ratio of measured interfered power to averaged power ρ_{test} one shall get the ratio of the scattered by RAC power flux density in aperture of the RxA to the power directly radiated there by the TxA, i.e. commonly used the *RL* value. This correction by directivities of both antennas is described by formula:

$$RL = \rho_{test} + 10\lg\frac{P_{avr}(A)}{P_0} - 10\lg\frac{P_{av}(\alpha)}{P_0}, \qquad (6)$$

where it are denoted

$-10 \cdot \lg\frac{P_{av}(A)}{P_0}$ – the TxA pattern level for its azimuth angle "*A*";

$-10 \cdot \lg\frac{P_{av}(\alpha)}{P_0}$ – the RxA pattern level for its azimuth angle "α";

- α is the observation angle from view of the RxA aperture side to a point of crossing by the TxA main beam the RAC side wall.

The angles "A, α", the RAC width "a", and separation distance "r_{rad}" are jointed with obvious relation, which is easy to get from view Fig.2:

$$ctg\ A = \frac{2r_{rad}}{a} - ctg\ \alpha . \qquad (7)$$

This correction formula is true only for an assumption, that the area of the RAC wall illuminated by the main beam is the most significant in scattering signals. But corrected value the RL does not depend on the antennas directivity gains.

IV. The VSRW technique restrictions

Follow to the assumption, that in the RxA aperture the direct and scattered by the area illuminated the main beam signals are mainly interfered, both positioners and other construction of the RAC facility must be accurately covered by absorbing materials, also the TxA side lobes are of low level. Trying to avoid the last requirement we additionally surrounded the TxA aperture by a flat sheet of absorbing material of 1 square meter size. Also large sizes of the RAC naturally diminish the second order reflections. Being measured at the RAC facility the broadband ridge horn antennas have far side lobes – 40 dB at the frequency 12 GHz, and the 35 GHz horn's far side lobes are less than – 50 dB.

Therefore the received power in data records is proportional to the sum module:

$$P_{rec} \propto P_{tr}\left|G_{tr}^{1/2}(A)G_{rec}^{1/2}(0)e^{i\varphi 1} + G_{tr}^{1/2}(0)G_{rec}^{1/2}(\alpha)\hat{S}^{1/2}e^{i\varphi 2}\right|^2$$

$$= P_{tr}[G_{tr}(A)G_{rec}(0) + G_{tr}(0)G_{rec}(\alpha)\hat{S} \qquad (8)$$

$$+ 2\,\mathrm{Re}(G_{tr}^{1/2}(A)G_{rec}^{1/2}(0)G_{tr}^{1/2}(0)G_{rec}^{1/2}(\alpha)\hat{S}^{1/2}e^{i\varphi 12}]$$

where the functions G_{tr} and G_{rec} are directive gains of the TxA and RxA, correspondingly. $\hat{S}(A,\alpha)$ depends on the reflection coefficients of the RAC absorbing material. It is two-dimension function of A as an incident angle of main beam radiation connected by Eq. (7) with scattering angle α.

Dependence of phase difference $kdl = 2\pi dl/\lambda$ (λ is a wavelength) between the direct and scattered by the illuminated area signals in the RxA aperture against of the TxA shift "dr" along its axis is expressed by the next formula:

$$kdl = \frac{4\pi}{\lambda} dr \sin^2(A/2) . \qquad (9)$$

The spatial period of interference signal determined by the condition $kdl = n \cdot 2\pi$ is large enough ($\geq 7.3\lambda$) for the TxA azimuth angles $\geq 30°$. This circumstance makes difficult, or even impossible, the *RL* measurements by the *VSWR* technique for small azimuth angles, exceptionally in decimeter wavelength range, because of two reasons.

First of all, the length of the trusses to shift the TxA is ~ 2 m, that is equal to 10 wavelengths only for the frequency 1.5 GHz, but we need (7.3 x 3) λ for the TxA azimuth angle A=30°, as it was mentioned above and shown in Table 1.

Second problem arises, when the TxA azimuths are $A \leq arctg(a/2r_{rad})$; this limit corresponds to the TxA main beam being directed to the front wall corner of the RAC and the scattered signal of illuminated wall area being observed from angle α ~ 90°. In this case the signal scattered by the RAC front wall is received by back lobes of the RxA, which we can not measure in its real surrounding, because of immobility of the antenna at its installation point. Consequently, we are not able to correct measured data records by the RxA gain directivity accordingly to Eq. (7).

TABLE 1. Interference period (IP)

TxA azimuth *A* [deg]	0°	30°	45°	60°	90°
IP [wavelengths]	∞	7.46	3.42	2	1

When the TxA has been rotated more than 90° along azimuth, the mechanical units for its rotation and transmitting sub-system which are placed on a top of the positioner tower could shade the illuminated wall area. Moreover, even an appearance of any obstacle in the RxA main beam could distort its pattern and consequently *RL* correction results in compliance to Eq. (6). Follow to this arguments we used the TxA azimuth angles *A* in limits ±90° only.

If one knows the antennas gain directivity as well the reflection coefficient of the RAC absorbing material, it is possible to estimate a requested sensitivity of receiving sub-system from the Eq. (8). For a good absorber the ratio of the interfered power to the averaged power proportional to expression:

$$\frac{P_{\mathrm{int}}}{P_{avr}} \sim \frac{\sqrt{\hat{S}G_{rec}(\alpha)G_{tr}(0)}}{\sqrt{G_{rec}(0)G_{tr}(A)}} . \qquad (10)$$

In the case of bad absorption of radiated waves for some areas, the ratio (10) should to inverse.

Both antennas patterns in vertical plane are enough narrow, the antennas were installed on a height 5 m, consequently level of reflected signal of ceiling and floor was neglected. Also after first experiments of the *RL* measurements we distributed some blocks of absorbing material by chaotic style in Fresnel zone of the RAC floor to diminish reflected signals.

V. Analysis of experimental results

We present the result of measurements at frequencies 12 and 35 GHz on Figs. 3 and 4. Spatial periods of interference caused by directly radiated and scattered by the wall area which was illuminated by the TxA signals are clear visually recognized for both frequencies at the 45°, 60°, 90° azimuth angles. The periods comply with the evaluated one accordingly to (9). We used as the data with 3 oscillation periods (A = 45°) per a record as well more than it (A = 60°, 90°). If periods more long than 4λ the difficulties to separate them are growing, because of additional signals always presented in the RAC, see Fig. 4 e, where the TxA was shifted along the trusses on 28 wavelengths. These "disturbances" could be referred to non-ideal covering the cart of positioner #1 in preliminary measurements.

A remarkable feature of all records is the modulation with period of half wavelength λ/2, similar to standing wave could do it. For the shorter interference periods (between 2λ – λ),

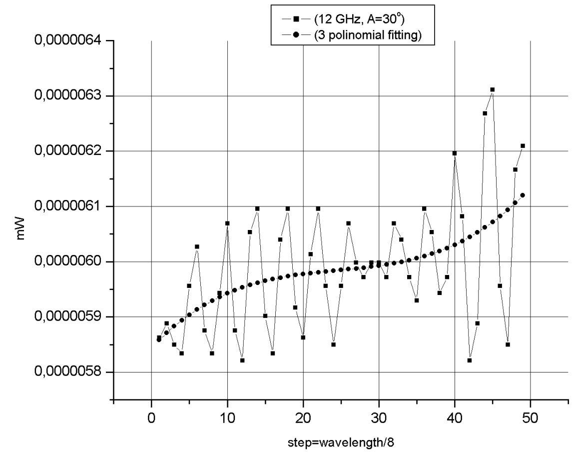

Fig 3 a.

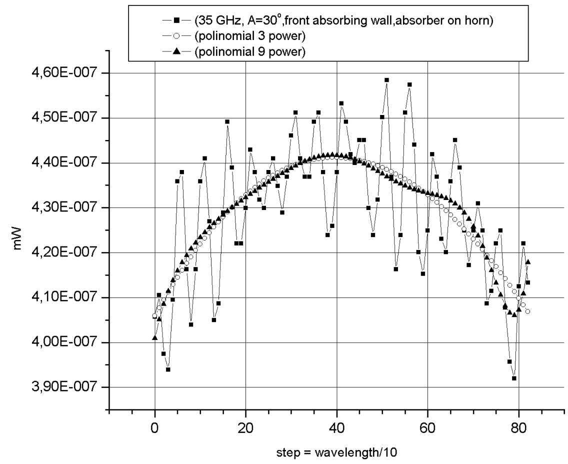

Fig. 4 a

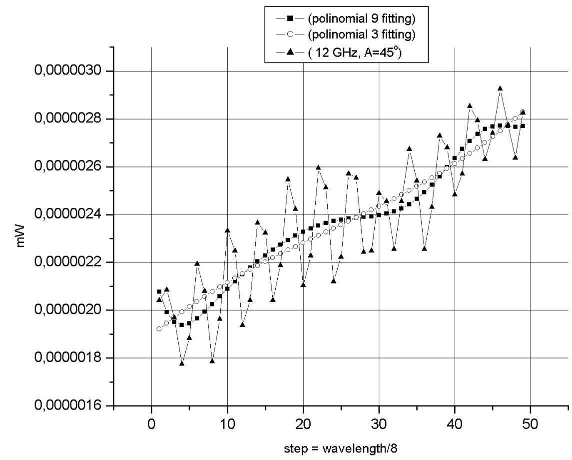

Fig. 3 b

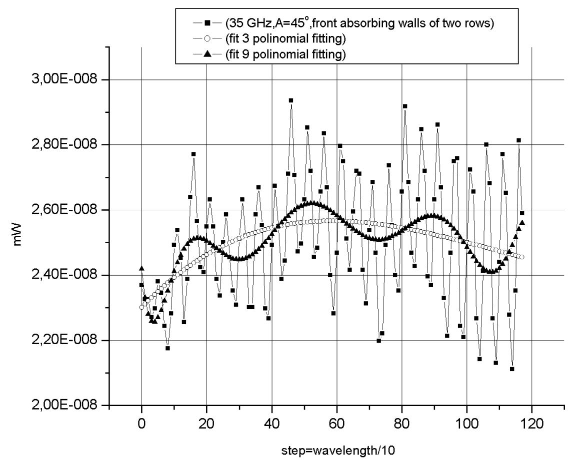

Fig. 4 b

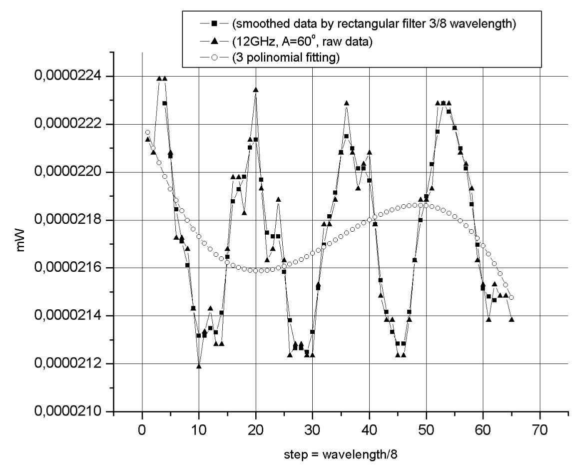

Fig. 3 c

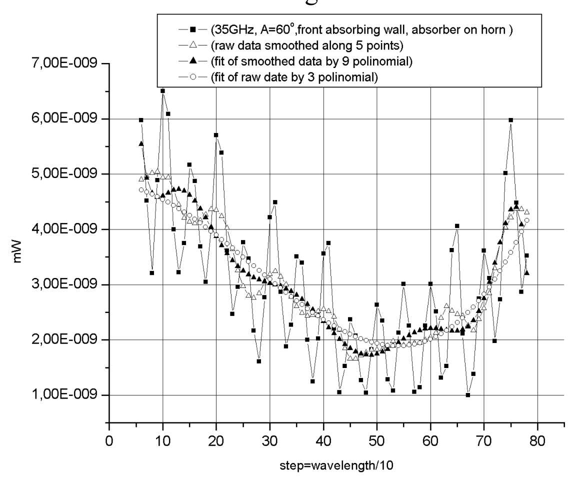

Fig. 4 c

which are relevant for the 60° – 90°azimuth angles interval, it is more complicated to separate visually the λ/2 period modulation, see Fig. 4 d.

The half wavelength period modulation is well known phenomenon at antenna measurements theory: it could be observed as a feed reaction to its antenna reflector [10], when the feed is shifted along its axis.

But there are two antennas in the *RL* measurement case – the TxA and RxA, so we try to investigate the modulation reason from another point of view.

Let's admit an ideal matching of TxA to open space and radiating of it to the RAC side wall (*A* = 90°). The back scattered signal from illuminated wall area and then intercepted by effective the TxA aperture should to form a standing wave in the antenna feed. The intercepted power P_{int} is estimated like it has been done at [10] for the reflector feed reaction in geometrical optics approximation:

$$P_{\text{int}} = P_{tr} \frac{G|F|^2}{4\pi(2r_{tr})^2} \frac{G\lambda^2}{4\pi}, \quad (11)$$

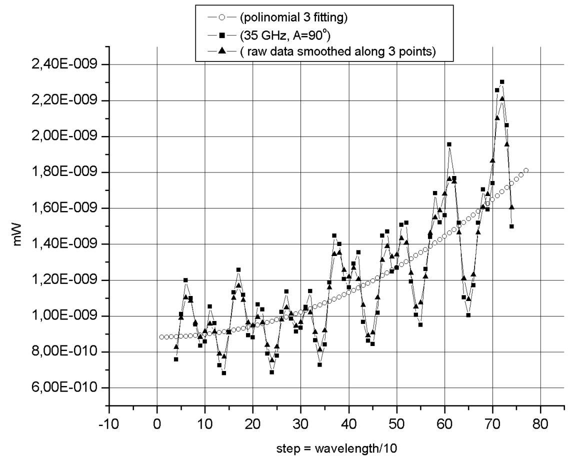

Fig 4 d

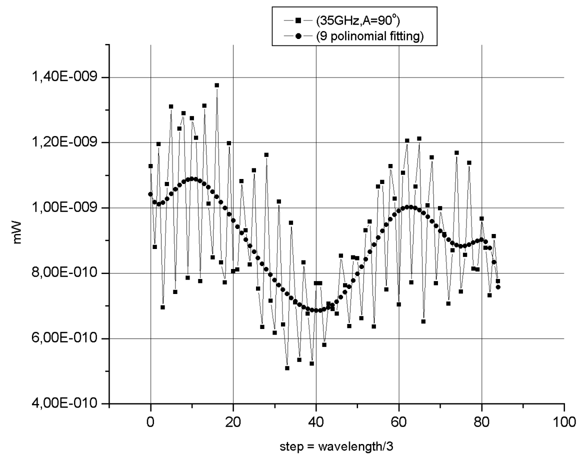

Fig. 4 e

where r_{tr} is a distance from TxA to the RAC wall, G is the antenna gain, $A^{(eff)}$ is its effective area, commonly expressed via the gain value as $G = \frac{4\pi A^{(\text{eff})}}{\lambda^2}$, $|F|^2$ is the RAC absorbing material reflection coefficient. These Fresnel reflection coefficients could be taken out from the RAC absorbing material specifications. For the broad band antennas $|F|^2 \approx 5 \cdot 10^{-5}$) the ratio is $\frac{P_{\text{int}}}{P_{tr}} \approx 2{,}2 \cdot 10^{-7}$.

This is a value, which leads to a negligible distinction from unity of the *VSWR* in the TxA feed. We mean, that in the formal *VSWR* definition − $VSWR = \frac{1 + |\Gamma_{\text{equ}}|}{1 - |\Gamma_{\text{equ}}|}$ − a role of $|\Gamma_{\text{equ}}|$ is played by the value: $|\Gamma_{\text{equ}}| = \sqrt{\frac{P_{\text{int}}}{P_{\text{tr}}}}$, equivalent reflection coefficient, which depends on both the antenna input and its load impedance [11], further shown as $|\Gamma\ |$. Thus we shall specially mark this circumstance by the sign "equal". In accordingly to the estimate made above, $VSWR_{equ} \approx 1.001$, it is very near of unity.

For the case of illuminating the RAC front wall (A = 0°) by an ideally matched TxA, the power scattered forward by the RxA (let's assume, it the same antenna as the TxA) aperture, which further, we suggest, is completely reflected by the front wall and collected by the effective area of the TxA, could be approximately evaluated (as an upper limit) by means of the radar formula [9]:

$$P_{\text{int}} = P_{\text{tr}} \frac{G}{4\pi R^2} \frac{4\pi A^{(eff)2}}{\lambda^2 4\pi R^2} \frac{|F|^2 G\lambda^2}{4\pi} = \left[\frac{|F| G^2 \lambda^2}{(4\pi R)^2}\right]^2 \quad (12)$$

where for RCS of the RxA the value $\frac{4\pi A^{(eff)2}}{\lambda^2}$ was taken from [12].

The equivalent input reflection coefficient for the experiment parameters shown above (λ, $G, |F|^2$, $R \approx r_{tr}$= 12.8 m) is a value of 4.3 $\cdot 10^{-5}$, i.e. less than one for A = 90°. Respectively, the $VSWR_{equ}$ is more near to unity. But experimental results for A = 0° shows the $VSWR_{equ} \approx 1.06$, which value is relevant to the ratio $\frac{P_{\text{int}}}{P_{tr}} \approx 2.2 \cdot 10^{-4}$. This value is more than evaluated on the Eq. (12). The comparison performed for the TxA azimuth 90° shows the same tendency, but with more inaccuracy of the $VSWR_{equ}$ evaluation, because of impact the half wavelength modulation, see experimental record curves.

The main infer of these estimates is a small influence to the radiated power, caused by back scattering of the RAC absorbing material. Of course the intermediate TxA azimuth angles could produce more significant back scattering power. We used the simulation results [9] for to limit asymptotically the RAC wall scattering areas by some Fresnel zones and for modeling the scattering. There were no significant changes of estimates. Preliminary experiments on additional covering of some positioner details have shown a remarkable decrease of jittering in antenna patterns records performed in the RAC. This is an indirect evidence also of weak influence the back scattering to power radiated by the TxA.

Now we'll estimate a possible rise of the half wavelength period modulation in received signal for a reason of non-equity the *VSWR* to unity in receiving antenna feed. This problem is very similar to an origin of standing wave due to a shift of the reflector antenna's feed [10].

Direct and scattered by the RAC wall interfering signals are registered in output of a receiver. It has been assumed that only the illuminated by main beam area forms the scattered signal. So from Eq. (8) it follows, that power in a load of receiver is:

$$P_{rec} = \left|\{G_{tr}^{1/2}(A)e^{-ikr_{dir}} + G_{tr}^{1/2}(0)G_{rec}^{1/2}(-\alpha)\hat{S}^{1/2}(A,-\alpha) \quad (13)$$
$$\cdot e^{-ik(r_{tr}+r_{rec})}\} + \Gamma\{...\}\right|^2$$

- r_{dir}, r_{tr}, r_{rec} are functions of the TxA and RxA geometrical positions, the RAC sizes, the TxA azimuth, and linear shift of the TxA along the positioner trusses *dr*. The common connections of this parameters are easy determined from geometry shown in Fig. 2;
- third item is the same as in {…} brackets multiplied by reflection coefficient of the receiving antenna load.

If to define for brevity the complex factors of exponents as U_1 and U_2, we shall obtain an expression similar to one of [10]:

$$P_{\rm rec} = |U_1 + U_2|^2[1 + |\Gamma|^2 + 2\,{\rm Re}\,\Gamma^*] \quad (14)$$

But the phase of its reflection coefficient is different of the mentioned solution for reaction of a feed to reflector and looks like:

$$tg\varphi = \frac{|U_1|\sin[2k(d + dr\cos A)] + |U_2|\sin[2k(r + dr)]}{|U_1|\cos[2k(d + dr\cos A)] + |U_2|\cos[2k(r + dr)]}, \quad (15)$$
$$r = (r_{\rm tr} + r_{\rm rec}).$$

This phase function against of the TxA shift along trusses depends on a ratio $\frac{|U_1|}{|U_2|}$, which in its turn is determined by both antennas gain directivities as well as a reflection function of anechoic material $\hat{S}(A,\alpha)$ for various incidence and observation angles. We modeled the phase function, which determines the interference phenomena in received signals, against the TxA shift for the ratio $\frac{|U_1|}{|U_2|}$ as a parameter in 0.03 – 1.0 limits. Both antennas assumed of equal gain $G = 500$. For azimuth angle near 30° and 90°, when a direct signal prevails $\left[\frac{|U_1|}{|U_2|} << 1\right]$, the interference spatial period is near of half of wavelength. For intermediate azimuth angles of the interval the beatings are observed, which period is evaluated accordingly to Eq. (9). When $\frac{|U_1|}{|U_2|}$ moves to 1, more "exotic" beatings arise. View of the experimental curves in Fig 3 a, probably, is due to this condition.

To a certain extent degree the analysis for azimuth angle $A = 0°$ presented here is similar to suggested technique in [13] for a division of signals reflected by non-matched aperture antenna. There the scattered field was presented as a sum of scattering field by matched antenna itself and radiation antenna field multiplied by equivalent input reflection coefficient.

VI. Detailed RL evaluation technique

Module sum of the complex signals U_1 and U_2 depends on its phase shift produced by difference of propagation paths of direct and scattered by illuminated area rays. The difference is evaluated accordingly to Eq. (9). Oscillations in received signal records against of the TxA shift along its axis (see its spatial periods in Table 1) are clear recognized for azimuth angles 60° (12 GHz) and 90°(35 GHz) without any additional processing.

Using jointly Eqs. 13, 14 a received signal is presented as

$$P_{\rm rec} = [1 + |\Gamma|^2 + 2|\Gamma|\cos\varphi][P_{\rm 0dir}(A) + P_{\rm 0sc}(A,\alpha) + 2\sqrt{P_{\rm 0dir}(A)P_{\rm 0sc}(A,\alpha)}\cos kdl], \quad (16)$$

where subscripts denote direct $P_{\rm 0dir}$ and scattered $P_{\rm 0sc}$ power undisturbed by standing wave.

A ratio of maximal received power to minimal one, commonly used[1] for evaluation of the *RL* [1,8], depends on the reflection coefficient phase φ as well on a phase shift of direct and scattered by illuminated by main beam signals:

$$\eta' = \frac{P_{\max}}{P_{\min}} = \frac{[1 + |\Gamma|^2 + 2|\Gamma|\cos\varphi_1]}{[1 + |\Gamma|^2 + 2|\Gamma|\cos\varphi_2]} \cdot \frac{[P_{\rm 0dir}(A) + P_{\rm 0sc}(A,\alpha) + 2\sqrt{P_{\rm 0dir}(A)P_{\rm 0sc}(A,\alpha)}]}{[P_{\rm 0dir}(A) + P_{\rm 0sc}(A,\alpha) - 2\sqrt{P_{\rm 0dir}(A)P_{\rm 0sc}(A,\alpha)}]} \quad (17)$$

Otherwise it is

$$\eta' = \left[\frac{1 + |\Gamma|^2 + 2|\Gamma|\cos\varphi_1}{1 + |\Gamma|^2 + 2|\Gamma|\cos\varphi_2}\right]\frac{1 + \rho + 2\sqrt{\rho}}{1 + \rho - 2\sqrt{\rho}} = \left[\frac{1 + |\Gamma|^2 + 2|\Gamma|\cos\varphi_1}{1 + |\Gamma|^2 + 2|\Gamma|\cos\varphi_2}\right]\eta \quad (18)$$

If a spatial period of interfered signal is longer than wavelength, (azimuth angles $A < 45°$), then it is possible to use small variations of second co-factor of Eq. (18) along the $\frac{\lambda}{2}$ scale. This leads to take for experimental data processing the oscillating power amplitude ΔP as an arithmetical mean of peak-to-peak neighboring oscillations with the half of wavelength period. The oscillations are taken in vicinity of $P_{\max}^{\max}$ and $P_{\min}^{\min}$, see Eq.(5):

$$\Delta P = \frac{1}{2}\{[P_{\max}^{\max}(R) + P_{\max}^{\max}(R \pm \frac{\lambda}{2})] - [P_{\min}^{\max}(R') + P_{\min}^{\max}(R' \pm \frac{\lambda}{2})]\} \quad (19)$$

where R and R' are coordinates of minimum and maximum power for the TxA positions shifted apart with evaluated accordingly to Eq. (9) period of spatial oscillation. An average power should be evaluated as:

$$P_{av} = \frac{1}{4}\{[P_{\max}^{\max}(R) + P_{\max}^{\max}(R \pm \frac{\lambda}{2})] + [P_{\min}^{\max}(R') + P_{\min}^{\max}(R' \pm \frac{\lambda}{2})]\}. \quad (20)$$

These operations exclude an impact of reflection coefficient Γ. We omits some details of power correction

[1] Equation (17) is a base of nomograms for measurement data processing [1].

due to change of a distance between the TxA and RxA.

Nevertheless for azimuth angles more than 45° this type of averaging is impossible, the reason is clear of view Fig. 4 d, so we use another technique of evaluating the oscillating power amplitude and average power estimates.

Maximal difference of η' and η is determined by the first co-factor of Eq. (18):

$$\eta' = \frac{(1+\Gamma)^2}{(1-\Gamma)^2}\eta . \qquad (24)$$

A solution of Eq. (18) to obtain "non-corrected" for the half wavelength modulation value of the *RL* is presented as

$$\rho' = \left[\frac{\sqrt{\eta'}-1}{\sqrt{\eta'}+1}\right]^2 = \left[\frac{\sqrt{\eta}\,(1+|\Gamma|)-(1-|\Gamma|)}{\sqrt{\eta}\,(1+|\Gamma|)+(1-|\Gamma|)}\right]^2 . \qquad (25)$$

Otherwise, it may be arranged to more compact form:

$$\rho' = \frac{(\sqrt{\rho}+|\Gamma|)^2}{(1+|\Gamma|\sqrt{\rho})^2} \qquad (26)$$

Neglecting by relative systematic error $\Delta = |\Gamma|\sqrt{\rho}\,/(\sqrt{\rho}+|\Gamma|)$, we shall obtain an approximate formula:

$$\sqrt{\rho'} \approx \sqrt{\rho} + |\Gamma| . \qquad (27)$$

Relative error performed by neglected term for $\sqrt{\rho'} \approx \sqrt{\rho}$, $VSWR_{equ} = 1.5$ is a value 4.4 %.

In Table 2 we present a processed (averaged along the TxA shift = 7 wavelengths, to avoid the half wavelength oscillation) the $VSWR_{equ}$ evaluated as a ratio of maximum received power to the neighboring minimum one. The extremes alternation period were selected accordingly to Eq. (9) for some the TxA azimuth angles.

TABLE 2

The TxA azimuth	0°	30°	45°	60°
$VSWR^{av}_{equ}$	1.024 ± 0.003	1.022 ± 0.003	1.096 ± 0.03	1.014 (макс)

These values are more realistic to be compared with real *VSWR* of the RxA input (≤1.3 in range of 1.0 – 17.44 GHz).

Based on the above estimates and experimental data processing a conclusion of this section is that a mostly probable reason of half wavelength oscillations is a non-ideal matching of the RxA input. To improve the *RL* accuracy measurements it is needed to match better the input.

A remarkable difference the $VSWR_{equ}$ processed value in Table 2 for A = 45° could be explained as a total impact of reflected waves – one made by the RxA input, another by the TxA output. For this case the total equivalent $VSWR_{equ}$ is determined by multiplying of complex reflection coefficients – Γ_{equ} and Γ_{out}.

The approximate solution (24) permits to modify the data processing algorithm to evaluate the *RL* with taking into account the half wavelength modulation in records.

VII. Data processing errors

Data processing of received signal records should use any software ("ORIGIN", for example) supplied a polynomial fitting of the records, evaluation of the RMS estimates, recognizing of maximal and minimal deviations of signal records from it. Two main features should be taken into consideration in data processing: first – smooth alternating of mean power against a distance between of the Tx and Rx antennas and its mutual orientation; second – oscillations of the records with half wavelength period. First reason, i.e. change of the records mean value is described like a fitting procedure of records by 3-d power polynomial. Third power is used to describe a possible asymmetry of the antenna lobes. The antennas been used for described experiments showed a neglect difference with use of second power polynomial for data processing. The length of horizontal trusses admits to record three or more oscillation of mean power with periods evaluated accordingly to Eq. (9) for both frequencies and the TxA azimuth angles 45°, 60°, and 90°, see Table 1.

The half wavelength oscillations could be taken into account by evaluating the RMS estimate of records deviation *S* from its fitting polynomial accordingly to correlation

$$S^2 / P_{av}^2 = \int_{L\,\min}^{L\,\max} [P_{rec}^2 - \langle P_{rec}\rangle^2]dl \approx 2\Gamma^2 \pm \delta_{fluct} , \quad (25)$$

which further is used to exclude Γ in Eq. (24). Designations of Eq. (25) are:

- $\langle P_{rec} \rangle$ is a function against the TxA shift along trusses, which is evaluated as a fitting polynomial or by some another technique will be described below;
- $L_{\min}$, $L_{\max}$ – the TxA positions along trusses correlated to maximal and minimal scattering signals are determined by received signal analysis;
- $-P_{av} = \frac{1}{2}[P_{rec}(L_{\max}) + P_{rec}(L_{\min})]$;
- δ_{fluct} – relative error limits evaluated as a sum of hardware error of power measurements and an error caused by discrete argument (the TxA positions) of the power records.

The hardware error limits are δ_{hdw} = ±11 % for 12 GHz and ±9 % for 35 GHz. The estimate of discreteness relative error in determination of maxima and minima of power values in "standing wave" (half wavelength modulation) was evaluated on a base of [15] and given by formula:

$$S_d^2 \approx \frac{1}{12}\xi^3 , \qquad (26)$$

where $\xi = \frac{2\pi}{N}$, N – is amount of discretes along the wavelength, RMS estimate $S_{\text{d}} \approx 14.4\%$, if N = 10.

Consequently, for correction the RL accordingly to procedure (24), we use for to estimate the $|\Gamma|$ a value evaluated in data processing under Eq.(25):

$$|\Gamma| \approx \frac{S}{P_{av}\sqrt{2}} \approx 0.707S \;/\; P_{av}\,. \qquad (27)$$

Also an estimate of systematic measurements error was taken on recommendations [13] as

$$\delta_{fluct} = \pm\sqrt{\frac{1}{4}\delta_{hdw}^2 + \delta_d^2\left[\frac{1.96}{1.645}\right]^2}\text{, where } \delta_d = 1.645\frac{S_d}{\sqrt{2}} =$$

±16.8%. A use of the Eq. (20) diminishes δ_{hdw} two times, because of its averaging.

The main result of this estimating is that the value of equivalent reflection coefficient $|\Gamma|$ restricts minimal value of measured *RL* as

$$\rho_{\lim} > |\Gamma|^2 \cdot (\delta_{fluct})^2\,, \qquad (28)$$

otherwise the correction procedure leads to negative values of the *RL*. We would remind, that we are able to estimate the $|\Gamma|$ by means of the $VSWR_{equ}$ evaluating. For example, for the maximal $VSWR_{equ} \approx 1.1$, see Table 2, the correction procedure could be used for *RL* > –40 dB.

A search of relevant to Eq. (9) formula spatial oscillations is performed by mean of 9 power polynomial approximation included in the used data processing software, see Figs.3 and 4. But some difficulties arise in evaluating of the RMS estimate to determine $|\Gamma|, P_{av}$ and $\langle P_{rec}\rangle$ for the TxA azimuth angles from 60° up to 90°, when received interfering signal alternates with period from 2 to 1 wavelength against of the TxA shift. The polynomial approximation is not adequate for short periods.

To evaluate the $\langle P_{rec}\rangle$ function as well as RMS deviation of records we convoluted the records with rectangular filter of half wavelength width, see the results in Figs. 3 c, 4 c, d. This operation leads to an appearance of additional term in comparison with Eq. (25) expression:

$$\sigma^2 / P_{av}^2 \approx 2\Gamma^2[1 - 2\sqrt{\rho}tg^2(A/2)]\,. \qquad (29)$$

This term brings over an additional systematic error of value ±2.0% for the TxA maximal azimuth angle and the *RL* = –40 dB, shown above as a limit for the admitted $|\Gamma|$.

VII. PRELIMINARY RL VALUES OF THE RAC

Preliminary results of the *RL* evaluating are shown in Table 3, where all included values are re-calculated to equal incident power to the RxA aperture by adding the term of the TxA directivity gain in Eq. (6) for every azimuth shown in the table as argument. Correction procedure Eq. (24) was used also. The receiving antenna pattern was convoluted with a rectangular filter of the angular size equal to 3 dB beamwidth. This smoothing is performed for to take into account a finite size of a scattering source – illuminated wall area. Also we evaluated the minimal *RL* values admitted by Eq. (28). The $VSWR_{equ}$ were evaluated with use of received power records and relevant to it the *RL* are shown in brackets.

We have marked by sign "?" these *RL* values, which are less than limits conditioned by the measurement error and equivalent reflection coefficient $|\Gamma|$ (evaluated with the processed records). The limiting *RL* is shown in brackets.

TABLE 3
MEASUREMENT RESULTS

Freq. (GHz)	TxA azimuth (deg)	30°	45°	60°	90°
12	ρ'/ρ =*RL*; (ρ_{lim}) [dB]	-36/49; (-46)	-35?; (-34)	-48/51; (-52)	-34/36 (-40)
35	ρ'/ρ =*RL*; (ρ_{lim}) [dB]	-11/11.7; (-40)	-21/38; (-36)	-44?; (-20)	-43? (-33)

A verification of evaluated in our measurements of the RAC reflectivity level has been conducted by means of the Antenna Pattern Comparison (APC) technique [8] partly: three patterns of the TxA for its different positions along the positioner trusses in range of 2.4 wavelength (frequency 12 GHz, Fig. 5 a), and three patterns of another antenna for its positions in range of 2.66 wavelength (frequency 35 GHz, Fig. 5 b,c) were compared. Evaluated accordingly to special nomograms of [5] the reflectivity levels are – 30 dB (deviation 1.0 dB on the pattern level – 5 dB) at the frequency 12 GHz, and – 40 dB (deviation 0.7 dB on the pattern level – 10 dB) at the frequency 35 GHz. It is satisfactory coincidence with our experiments, if to take in view, that the deviations are normal for the APC technique, as shown in [8].

For frequency 35 GHz we have performed measurements of the horn patterns and the reflectivity level for the TxA azimuth A = 45° in two cases: both the TxA and RxA were sunk into absorbing material up to apertures and when they were out of the material on a length of the horns.

The patterns obtain less jitter, when the antennas are sunk into absorbing material (Fig. 5 b), but the measured *RL* are the same in the evaluated error limits. This is an indirect evidence of correctness the technique of excluding the half wavelength modulation.

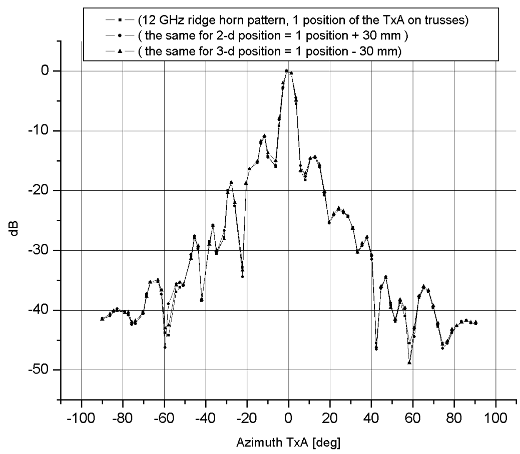

Fig. 5 a

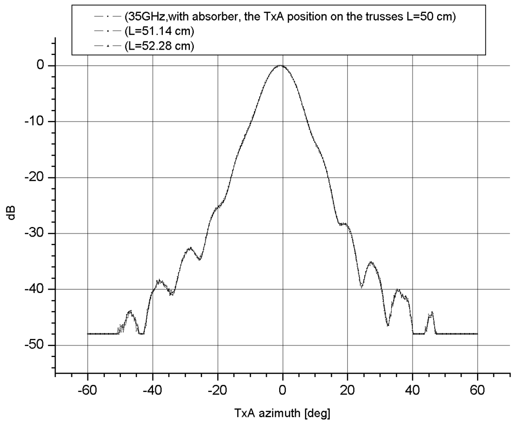

Fig. 5 b

.

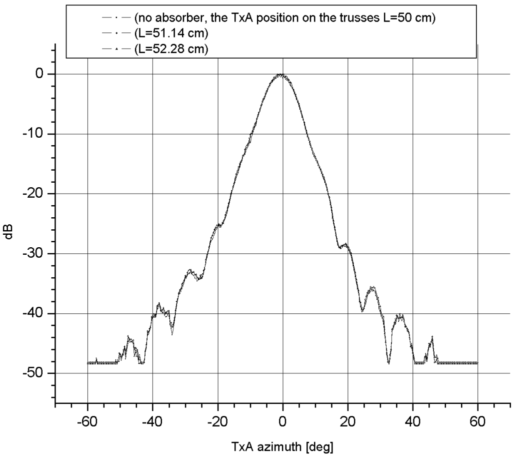

Fig. 5 c

Large deviation of the *RL* for 35 GHz and A=30 is a specific case, because all data were recorded at the equal shift range, thus the length of record was insufficient for a correct analysis.

VIII. CONCLUSION

The conducted modeling analysis of experimental data has shown its ability for to find the basic area of scattered signals in the large RAC, also to evaluate the reflectivity level. A good sensitivity of receiving facility permits to realize the reflectivity level phaseless measurements by use of wide band aperture antennas with low side lobes. The preliminary measurement results were used for to re-design of absorbing material configuration into the RAC, thus to reach the more effective chamber operating.

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