Project Report for NAG3-2091

Development of a Methodology for conducting Hall Thruster EMI Tests in Metal Vacuum Chambers of Arbitrary Shape and Size

by

Professor Alec D. Gallimore
The University of Michigan
Department of Aerospace Engineering
Ann Arbor, MI 48109-2118
alec.gallimore@umich.edu

Abstract

While the closed-drift Hall thruster (CDT) offers significant improvement in performance over conventional chemical rockets and other advanced propulsion systems such as the arcjet, its potential impact on spacecraft communication signals must be carefully assessed before widespread use of this device can take place. To this end, many of the potentially unique issues that are associated with these thrusters center on its plume plasma characteristics and the its interaction with electromagnetic waves. Although a great deal of experiments have been made in characterizing the electromagnetic interference (EMI) potential of these thrusters, the interpretation of the resulting data is difficult because most of these measurements have been made in vacuum chambers with metal walls which reflect radio waves emanating from the thruster. This project developed a means of assessing the impact of metal vacuum chambers of arbitrary size or shape on EMI experiments, thereby allowing for test results to be interpreted properly. Chamber calibration techniques were developed and initially tested at RIAME using their vacuum chamber. Calibration experiments were to have been made at Tank 5 of NASA GRC and the 6 m by 9 m vacuum chamber at the University of Michigan to test the new procedure, however the subcontract to RIAME was cancelled by NASA memorandum on Feb. 26. 1999.

1. INTRODUCTION

Survey of the known publications on EP secondary characteristics study [1-3] shows that these thrusters are the sources of electromagnetic emission having high enough value within the broad frequency range (from a few tens of kHz up to several tens of GHz). Taking into account that electric propulsions are currently considered as main engines for solving the tasks of modern communication satellite attitude control and orbit correction, it is necessary to know the characteristics of noises generated by EP within the operation ranges of onboard radio systems while designing the communication channels. This simple (on the face of it) research task faces definite difficulties at the test stage.

The main problem is connected with modeling of both space parameters and conditions for electromagnetic wave propagation though it under ground conditions. It should be noted in addition that there are currently no adequate enough physical and mathematical models explaining the properties and characteristics of electric propulsion emission.
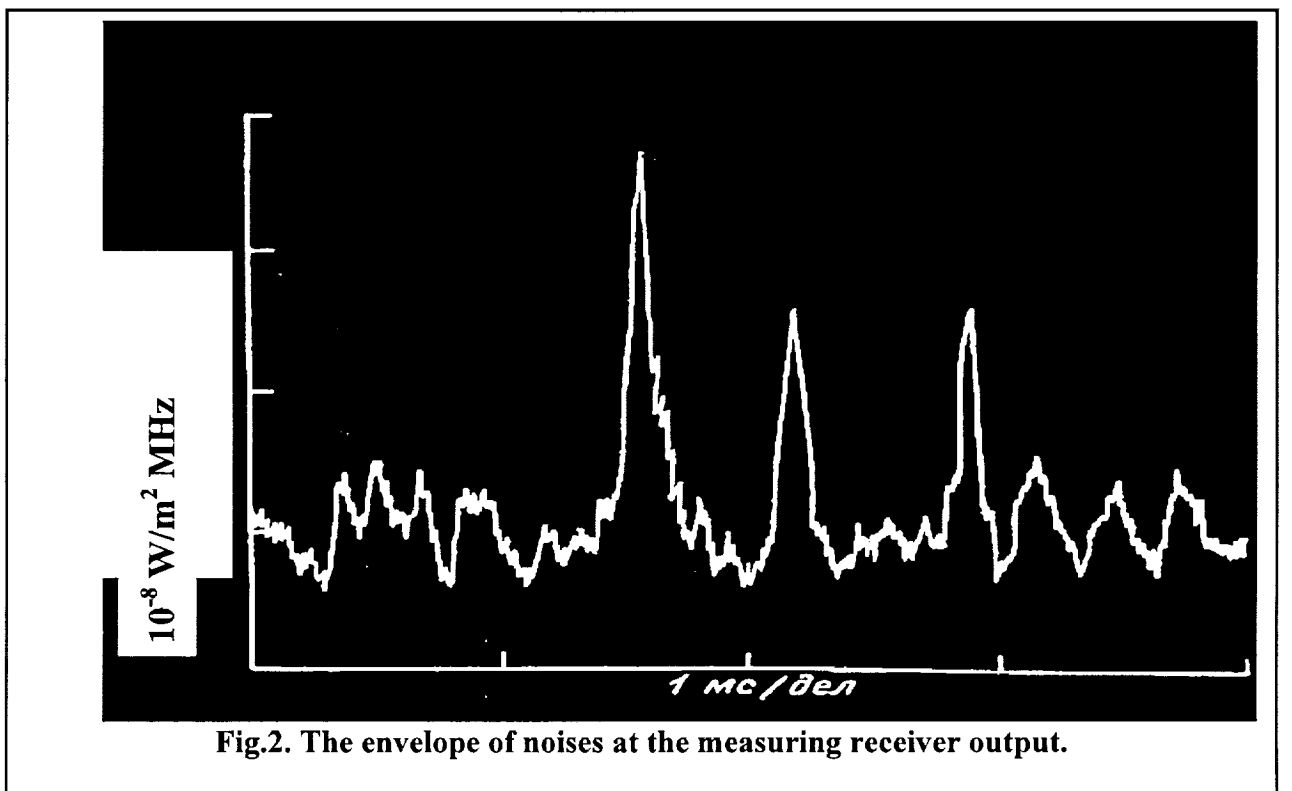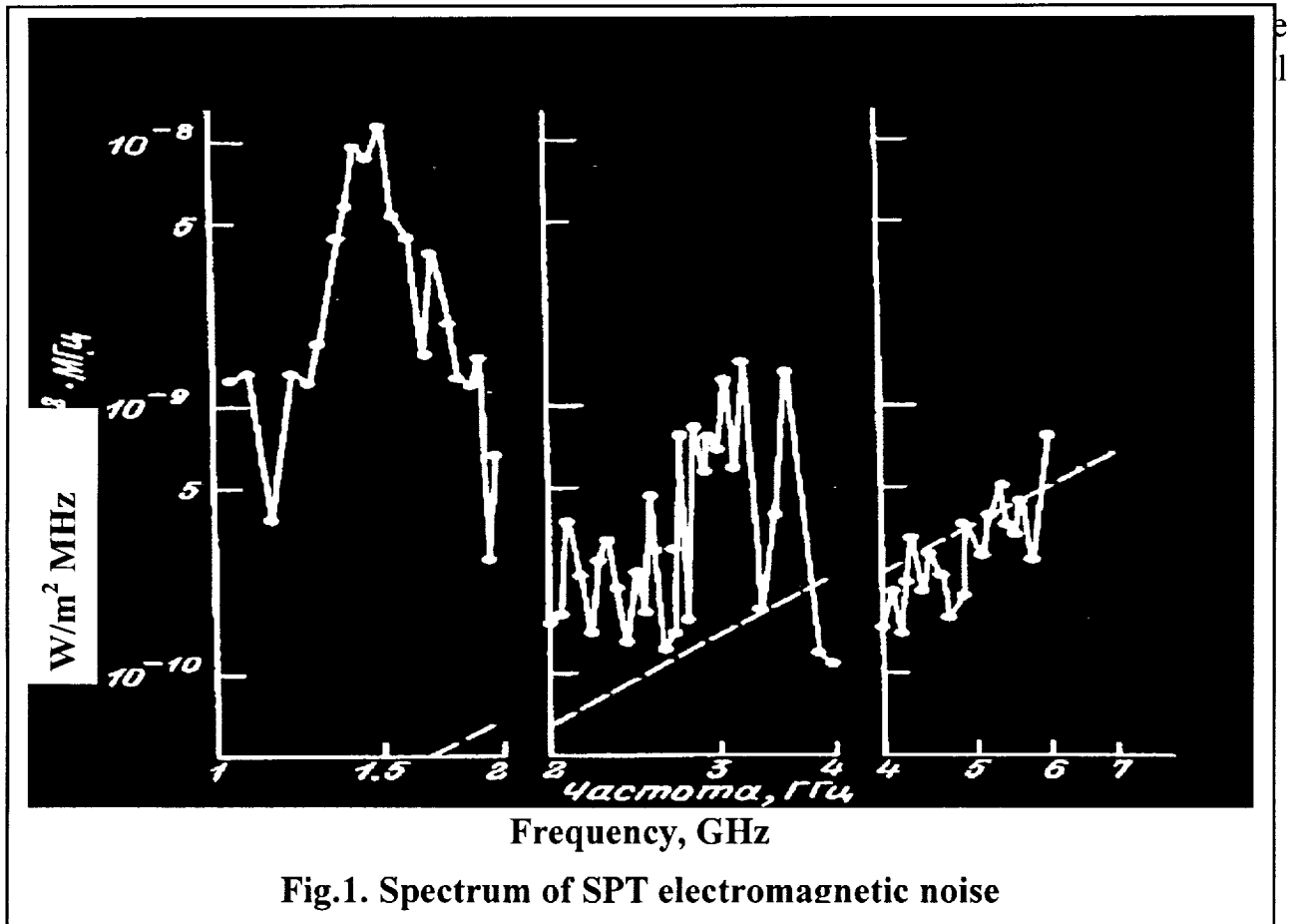
Let's consider the mentioned problem using the well-known thrusters of SPT type as an example.

According to theory, a presence of quazi-equilibrium component of electromagnetic emission connected with thermal mechanism of oscillation excitation should be expected for a stationary plasma thruster. But the experience of SPT life-time test and operation [4] testifies to the presence of non-equilibrium component of electromagnetic emission also, which appears after 200 hours of thruster operation, this component being by 3-5 orders of magnitude higher than the heat level. As an example, Fig. 1 shows the spectrum of SPT electromagnetic noise for different frequency ranges (dashed line corresponds to the spectral function for the noises of equilibrium plasma region).

Non-equilibrium emission component is of pulsed nature within the time region; its form is presented in Fig.2.

Analysis of known results shows that the highest level of oscillations is at frequencies of 1.5-2 GHz corresponding to the frequencies of electron Langmuir plasma oscillations in the external near-wall region of plasma flow being the region near the dielectric walls of acceleration channel. As an example, Fig. 3 shows the design of acceleration channel walls of a standard SPT to be used for the further discussion.

According to one of hypotheses [3], the instability pulsed component appears in the case of transition from the mode of ion spraying of dielectric walls to an abnormal erosion. In this case the broadening of excited oscillation spectrum and propagation of instability inside the acceleration channel take place at a developed erosion structure of walls.

Fig.1. Spectrum of SPT electromagnetic noise

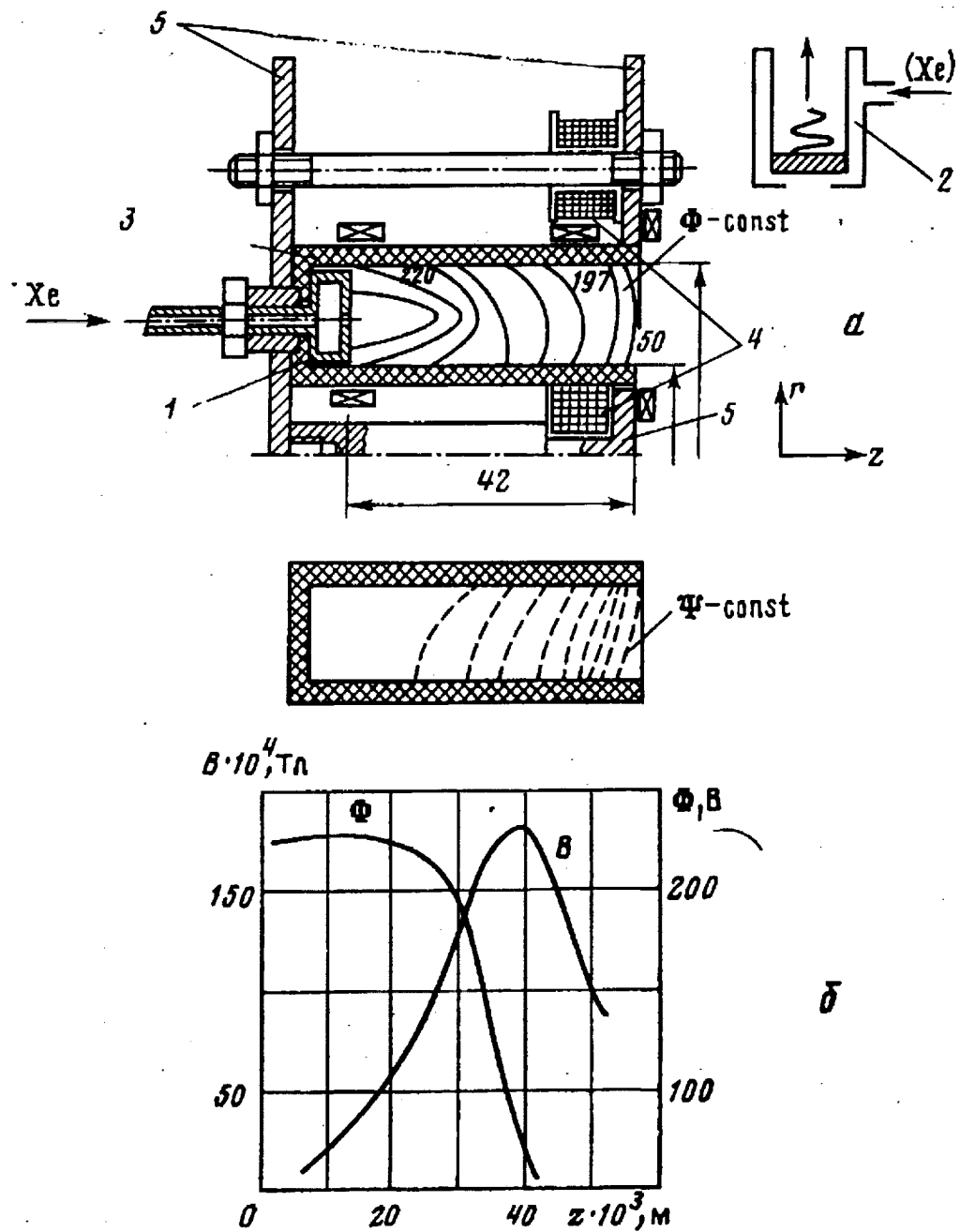Fig.2. The envelope of noises at the measuring receiver output.

Fig.3. Thruster design: 1-anode, 2-cathode-compensator, 3-dielectric channel, 4-magnetic coils, 5-magnetic guide.

sources in the plasma flow and the formation of electromagnetic emission field is one of the possible interaction mechanisms. The duration of emission process caused by abnormal erosion is defined by relaxation of non-equilibrium excited states at newly formed chips and cracks of erosion structure and does not exceed 1ms as a rule.

The above data testifies that in general case the electromagnetic emission of even stationary plasma thruster is far from stationary nature, its intensity and spectrum characteristics being changed during the life-time.

As applied to the repeater radio systems such emission may be considered as a broadband noise with unknown spectral characteristics and time responses. Its effect may be substantial depending on the intensity. Thus, the study of both spectral-temporal and spatial characteristics of EP self-emission is a rather actual task.

2. TEST ON STUDYING THE SPECTRAL CHARACTERISTICS AND TIME RESPONSE OF _P EMISSION

2.1. PROCEDURE FOR MEASURING THE SPECTRAL CHARACTERISTICS AND TIME RESPONSE OF EP EMISSION

Methods of received signal spectral analysis are mainly used for studying the EP emission characteristics [1-3]. We shall not present now the detailed description for the technical methods of extracting the EP self-emission (they will be presented later) and will discuss the general task statement.

Though the EP self-emission power spectrum, determined during the tests, provides data on the emitted process power distribution in frequency, it does not characterize the nature of phase relations inside the spectrum components. Otherwise, on the basis of power spectrum of emitted process it is impossible to make a definite conclusion on whether the process under study is a result of concrete mechanism of the EP power supply source energy conversion into the external self-emission or the mentioned emission is a superposition of many independent processes proceeding simultaneously in the discharge gap and in the outflowing EP plasma. In addition, the absence of phase data does not allow recovering the time response of the resultant signal on the basis of its spectrum. Answers to these questions would allow to make the available emission models substantially more accurate and to define the design parameters of EP responsible for the main characteristics of thruster self-emission.

Thus, while stating the test it is necessary to foresee a possibility for assessing the EP self-emission amplitude-phase characteristics in advance. In the simplest case, it is quite enough to obtain the studied process realization and corresponding energy spectrum in synchronism within correlation interval of this process. Theoretically, this may be made by corresponding synchronization (for the moment of the scan start) of spectrum analyzer and oscilloscope used in the mode of "manual" scanning with corresponding parameters. The required statistics both for the time realizations and for their spectra may be obtained as a result of a set of repeated tests. But definite problems appear in the case of technical realization of these measurements. This is connected with the fact that such studies are realized most successfully for the narrow

band processes (processes the spectrum width of which is much less than the central frequency) because in this case both input process quadrature processing and extraction of its amplitude and phase at subsequent defining of their statistic characteristics are made easily. In the case of EP, characterized by broadband electromagnetic emission, it is impossible for us (at this stage of studies) to state definitely that it is a superposition of independent processes that form corresponding regions of spectrum. Thus, theoretically the measuring equipment should overlap the whole spectrum of the process. Otherwise, we shall assess the process characteristics at the output of the filter being the measuring equipment. This may be definitely taken into account if you know the amplitude-frequency and phase-response characteristics of the measuring section, but it is a rather difficult engineering task to provide the operation of equipment within the broad frequency range. In addition, while studying the time characteristics of the process it will be necessary to record its realization (or envelop). It will be difficult to use the oscilloscopes "with memory" for this, because the process is not periodic and special measures should be taken for starting the sweep with the given time characteristics for obtaining a set of statistic data.

Methods and equipment mentioned above operated on analog processes, but the use of high-speed A/D converters allows to use efficiently their digital representation and specialized digital procession methods.

2.2. PROCEDURE FOR MEASURING THE SPECTRAL CHARACTERISTICS AND TIME RESPONSE OF EP EMISSION AND THEIR SUBSEQUENT PROCESSING

Bispectral assessing in the digital signal processing

While assessing the signal power spectrum the process under study is currently considered to be a result of superposition of statistically uncorrelated harmonic components, and assessment is made for the power distribution among these frequency components. In this case, linear mechanisms defining the process progress are studied only, because the phase relations between the frequency components are excluded [8]. Data contained in the power spectrum essentially coincides with the data available in the autocorrelation sequence; it is quite enough for complete description of Gaussian process with the known mean value.

However, in practice in a number of cases it is insufficient to know the power spectrum only for obtaining data on deviation from gaussness and presence of nonlinearities. Such data may be obtained from the spectra of higher orders (the so-called polyspectra) defined for this process by its semi-invariants (cumulants) of high

orders. The spectrum of the third order (called bispectrum also) and spectrum of the forth order (trispectrum) defined as Fourier transform for a sequence of semi-invariants of the third and forth orders, correspondingly, for a stationary random process are the particular cases of such spectra. In this case, usual power spectrum is the spectrum of the second order.

Background

Advisability for using the high order spectra while processing the signals is generally substantiated by the following necessity:

- To extract data caused by the deviations from gaussness (or normality). Such possibility is provided by a known property consisting of the following: all polyspectra of the order higher than 2 identically go to zero for a Gaussian process ([5], [8], [12]). Thus, a non-zero spectrum of high order testifies to the deviation from normality;

- To assess the phase of non-Gaussian parametric signals. This possibility is provided by a known property that the spectra of high orders keep information on the phase of non-Gaussian parametric signals;

- To reveal and characterize non-linear properties of mechanisms resulting in the time series connected with the phase relations of their harmonic components.

Numerous publications are known on the practical application of high order spectra, in plasma physics for example [9, 10].

Such cases are possible in practice when a part of power is released at the sum (difference) frequencies of these components due to the interaction of two harmonic components of the process. Such phenomenon, which may be connected with square-law non-linearities, causes definite phase relationships called square-law constraint in phase. In some practical cases it is necessary to determine whether the peaks in the harmonically connected points of the power spectrum are really connected. As in the case of power spectrum all phase relationships are suppressed, it is impossible to answer this question on the basis of this spectrum. But bispectrum makes it possible to reveal and assess quantitatively the constrains in phase [9, 10, 13, 14, 15].

Ordinary methods of bispectral assessments

There are two main methods for assessing the bispectrum:

- Fourier type method;

- Parametric method based on the autoregression models.

Problems of assessing the bispectra are discussed in detail in [6 ,7, 9, 10, 11,

14, 15, 16].

One of the possible representations for a bispectrum of stationary random process $X(t)$ has the following form:

$$B(f_1, f_2) = \lim \frac{1}{T} X_T(f_1; t) X_T(f_2; t) X_T *(f_1 + f_2; t) \ ,$$

where: $X_T(f; t) = \int_{t-T}^{t} X(\pi) \exp(-i2\pi f \tau) d\tau$, *- complex conjunction.

In this case, bispectrum describes the statistical interrelation for the triplets of spectrum components at the harmonically connected frequencies $f_1, f_2, f_1 + f_2$.

Principally new property of bispectral procession consists of the following: if random process contains, for example, the harmonically connected spectrum components with independent randomly distributed phases, then the usual power spectrum will contain all three components at corresponding frequencies, while the bispectrum will be zero. If the phase of one of three spectrum components is a sum of phases of two other spectrum components, the power spectrum will not change and bispectrum will differ from zero at two forming frequencies. In particular, this testifies to the fact that the analyzed random process is a result of some initial process progressing in a non-linear system.

In view of the above presented, the mentioned properties of bispectra are considered as perspective while assessing the spectral characteristics of EP self-emission and might be recommended for the digital signal processing.

It is obvious that test procedure and procession of its results will be finally defined by the potentialities of available equipment.

In this case, a principally new condition for the proposed test (independently on the procession type – analog or digital) is a due account of EP self-emission phase characteristics in any of possible forms. This will make it possible to develop adequate mathematical models for the processes of EP emission and use them effectively in practice. We consider this as the most important aim of this run of possible tests.

2.3. PROCEDURE FOR DEFINING THE DIRECTIONAL PATTERN OF THE EP PLUME SELF-EMISSION

Test aim

It is supposed to study the following generalities during the test:

• Mechanism of the directional pattern formation for a EP-PLUME system emission within the given frequency range including the determination of boundaries for the near and far zones;

• The form of the directional patterns of EP-PLUME system self-emission for the characteristic frequencies of the range.
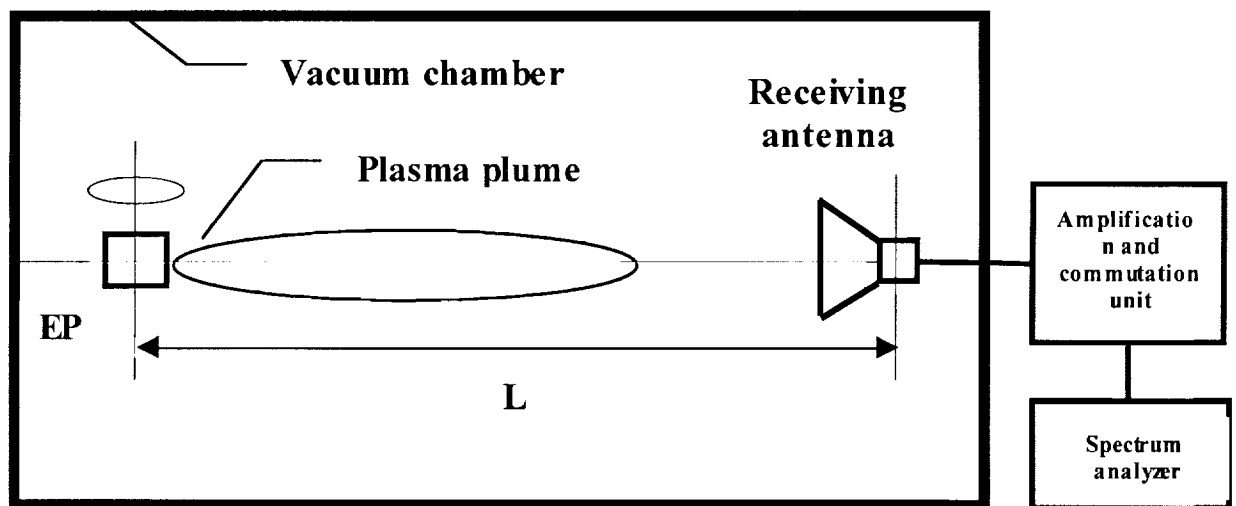

Fig.4. Block diagram of the test

Test procedure: EP and receiving antenna (or a set of receiving antennas overlapping the given frequency range) are located at a distance **L** from each other along the axis of cylinder vacuum chamber. Antenna output is connected to the spectrum analyzer input through the commutator and a set of low-noise amplifiers (overlapping the entire frequency range). It is possible to rotate EP remotely relative to the vertical axis (horizontal axis) to an arbitrary angle within ± 90⁰ relative to the initial position. Fig. 4 shows the block diagram of the test.

The following measurements will be made during the test:

• Receiving antenna is mounted at a minimum distance L from EP (defined by its guaranteed operation in the far zone). The thruster is started and discrete angular

displacement of its plume axis in space within ± 90^0 relative to the receiving antenna axis is made using the remote drive. Angular patterns of the plume self-emission are measured simultaneously at the selected characteristic discrete frequencies using the spectrum analyzer. The results obtained are fixed to the definite distance L. After that, distance L is increased by steps and all measurements are made again. Collection of EP self-emission patterns for different frequencies and different distances from the emitter is obtained as a result. Having chosen one of the most characteristic (from the self-emission intensity point of view) frequencies of the EP self-emission spectrum, one may analyze the behavior of the self-emission angular patterns depending on the distance to the emitter. In accordance with the general theory of antennas it may be expected that starting from some distance L the form of emission angular patterns will not change. This is the evidence of the measuring antenna transition to a far zone of electromagnetic field for the EP-PLUME system self-emission. A conclusion on spatial dimensions of the EP-PLUME system effective aperture for the given frequency may be made on the basis of measured value of the near and far zones boundary;

- Repeating the above measurements for various frequencies of the range it is possible to determine the boundaries of the far zone for the EP-PLUME emitting system for all studied frequencies;
- After these measurements the receiving antenna is mounted at a distance L, ensuring the operation in the far zone for all frequencies of the range. After that, measurements are repeated for angular patterns of EP-PLUME system self-emission for all frequencies of the range.

Conclusions: Results obtained during this test will allow:
- To make a conclusion on geometric dimensions of effective aperture (spatial dimensions of emission area) of the EP-PLUME emitting system for different emission frequencies;
- To define optimum geometry for the location of measuring equipment for obtaining adequate measurement results in the far zone of emitter exactly;
- To obtain spectrums of noise emission for EP-PLUME system within the range of angle of view from 0 to 90^0 and to compare them with each other in intensity. 2-D distribution for the power of signal emitted by EP-PLUME system in angle and frequency may be obtained as a result;
- The results obtained will give a principally new possibility for the designers of onboard radio devices, connected with due account of the level of noise signal reaching the antennas of onboard devices at any orientation of their axes relative to the EP plumes.

In the case of technical difficulties connected with providing the thruster rotation it is possible to use separated reception, presented in Fig. 5.

In this case a set of the same antennas may be used, located in the same plane, at the same distance L from EP center and under different angles to its axis. The following angles are proposed: 0^0, 30^0, 60^0 and 90^0.

While choosing the L distance the following condition should be obligatory taken into account: operation of pick-up antennas should be provided in the far zone both for their directional patterns and for the emitter.

Fig.5. Block diagram of separated reception
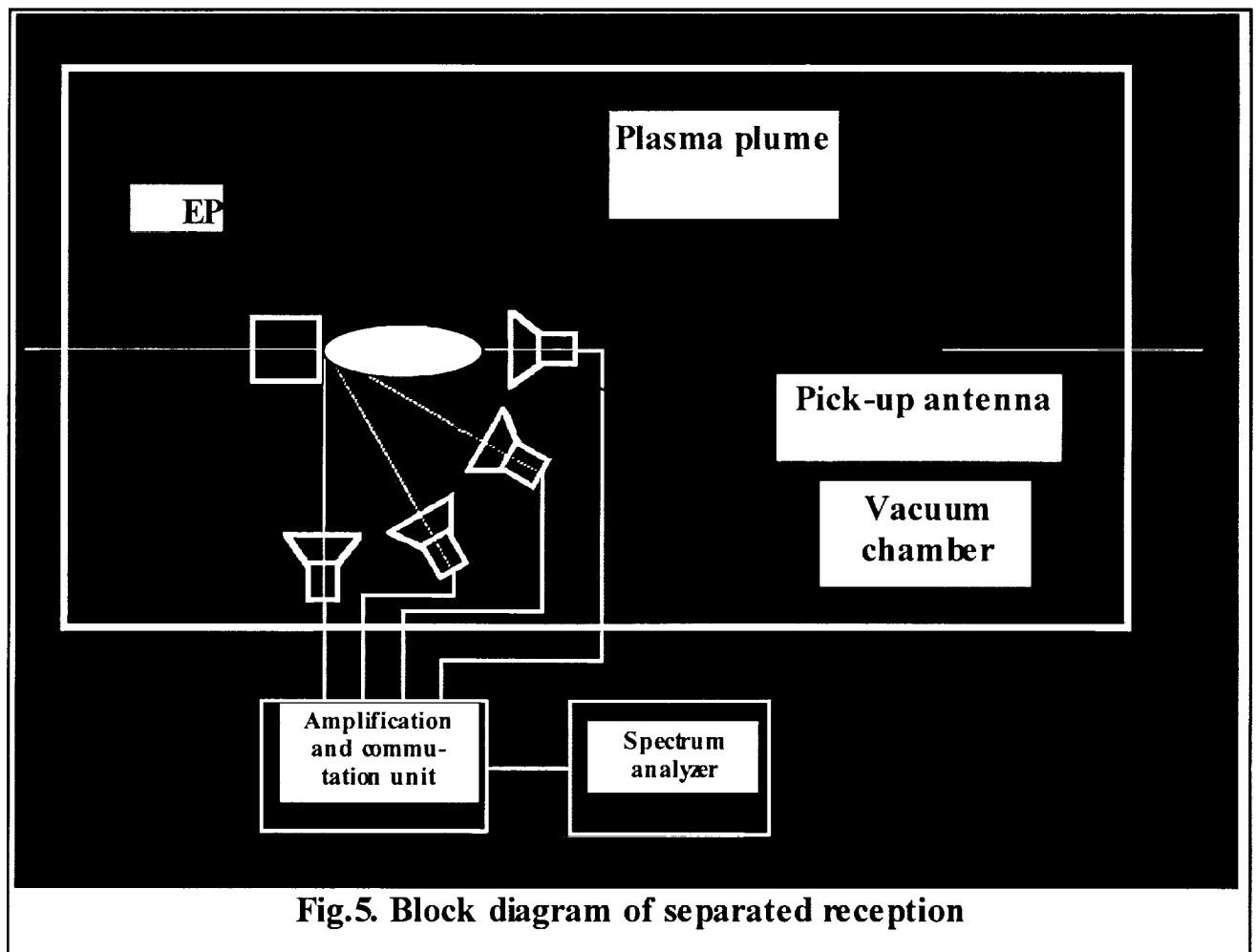
Parameters measured during the test.

Result of the noise signal recalculation from the spectrum analyzer output (for each frequency under study) to the input of aperture of the corresponding pick-up antenna, in the form of absolute values for the power (intensity) of the signal electric field (for the known distance from EP center) for example, may be considered as a test result.

Results may be presented in the form of plots for the absolute values of power (intensity) of the electric field of signal (in dBW/Hz or dBµV/m·MHz, for example) as functions of frequency in the pick-up antenna aperture, with which the allowable level of interference specified by the onboard equipment designer will be compared.

In this case, angular distribution for the power (amplitude) of signal emitted by EP at a distance L may be plotted for each of the selected frequencies (directional patterns of EP self-emission in the environment).

3. PROCEDURE FOR THE MEASURING EQUIPMENT CALIBRATION

3.1. GENERAL PRINCIPLES FOR THE MEASURING SECTION CALIBRATION.

Potential accuracy of the proposed measurements will be defined by the following two factors:

- Accuracy in defining the gain factor for the whole measuring section for each of the studied frequencies;
- Degree of influence of the interference reflections from the walls of metal vacuum chamber.

Fig.6. Block diagram for the measuring equipment calibration
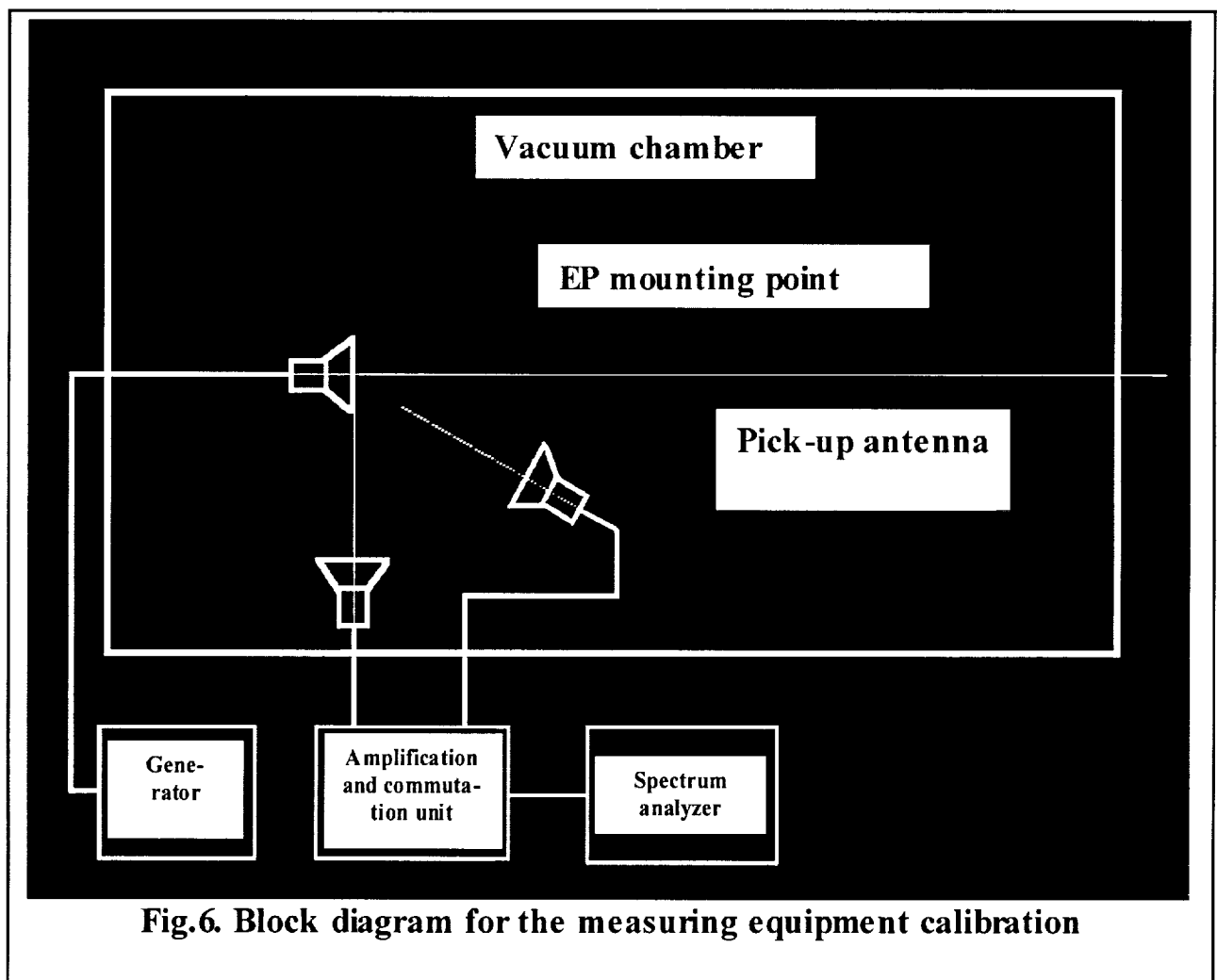
These two tasks are independent, so let's discuss them separately.

For the guaranteed obtaining of adequate results it is proposed to solve the task of the whole measuring passage calibration (gain factor definition) in three steps:

- At the first stage, all measuring channels are calibrated using the standard generator and standard antenna with broad directional pattern located in the point of subsequent EP mounting and simulating its emission. In this case, each frequency of the signal of standard generator (with the known radiation power) is brought into correspondence with the signal level at the spectrum analyzer output. Having obtained the calibration amplitude-frequency characteristic for each section, one may assess the level of emission in the aperture of corresponding pick-up antenna on the basis of signal at the spectrum analyzer output for each of the studied frequencies. As a result of measurements this will allow to obtain the absolute power spectrum of EP emission within the measuring equipment bandwidth. General configuration and location of equipment for the case of calibration of two pick-up antennas are presented in Fig.6.

- At the second stage it is proposed to use all known calibration data for the separate elements of measuring section (table data for the gain factor of each antenna, data on attenuation for each connecting cable and corresponding switch and data on the gain factor of entire section of amplification and commutation unit within the studied frequency band) at subsequent mathematical recalculation into the parameters of entire section.

- At the third stage, calculated and measured amplitude-frequency characteristics for each measuring channel are compared with each other and a final decision is made on the reliability of calculations and measurements. In the case of availability of definitely accurate calibration data for each element of measuring section, noticeable disagreement of test and calculation data may be caused by the influence of interference reflections from the vacuum chamber walls only; this will require additional tests (corresponding procedure will be presented below).

The final form of functions for recalculating the values of signal at the spectrum analyzer output to absolute values of intensity (power) in the aperture of pick-up antennas is formed as a result of the fulfilled preparatory work.

3.2. GENERAL PRINCIPLES FOR ASSESSING THE DEGREE OF INFLUENCE OF INTERFERENCE REFLECTIONS IN THE METAL VACUUM CHAMBERS

For assessing the degree of metal vacuum chamber influence upon the accuracy of measurements it is proposed to use modified approaches known from the theory and practice of anechoic chambers. In this case, it is proposed to characterize

the quality of vacuum chamber anechoicness by an anechoicness factor K_{ae}, which is defined by the ratio of total power for all reflected waves that have reached the operation zone to the power of direct wave.

A number of methods is known currently allowing to assess the degree of interference reflections influence for anechoic chambers [17]. They include the following:

• Method of standing wave ratio (SWR);
• Method of scattered power direct measurement;
• Method of directional patterns superposition;
• Method of two receiving antennas;
• Method implying the use of generator with tunable frequency.

Let's briefly consider the essence of methods mentioned above using the SWR method as an example. Indicator antenna with low side and back lobes is used for this test method. This antenna is transported inside the chamber along different directions (along three mutually perpendicular axes, for example). As a result of interference of direct and reflected signals during the antenna movement an interference pattern appear, as in Fig. 7, for example (a and b plots correspond to different directions of transportation).
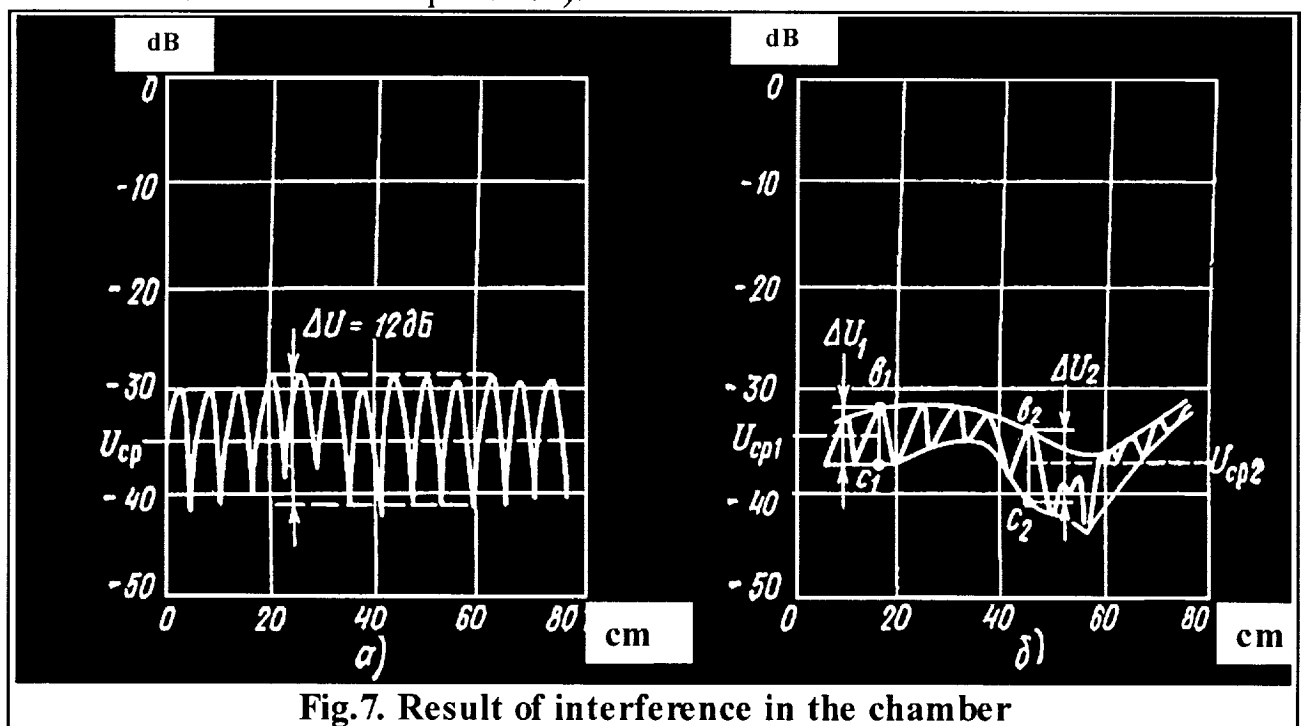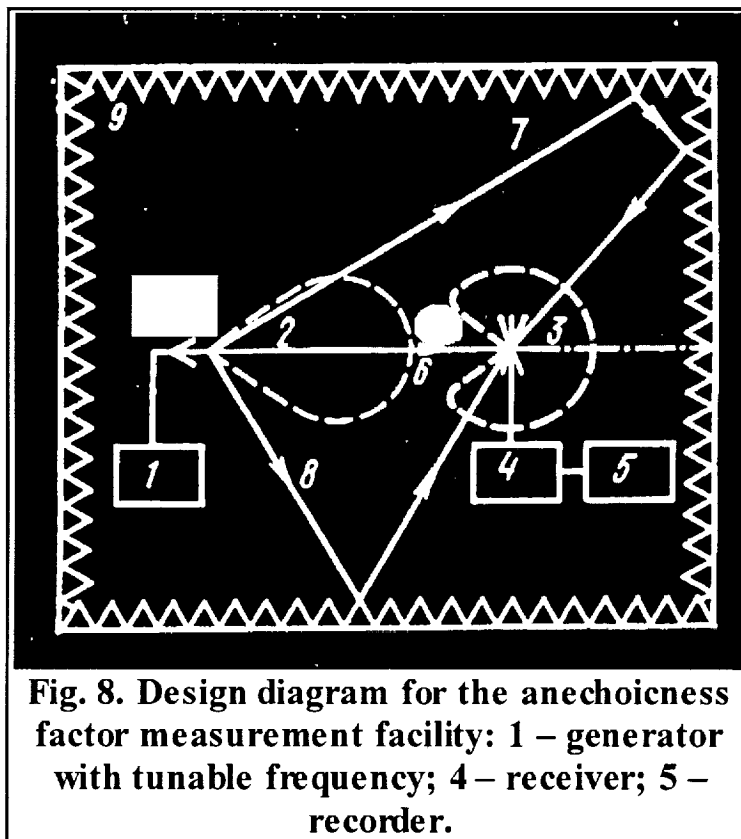

Fig.7. Result of interference in the chamber

With the knowledge of the field spread and its average level it is not difficult to define the degree of anechoicness for a given chamber. As a rule, all above methods for defining the anechoicness factor K_{ae} have one substantial disadvantage (as applied

to the planned tests) connected with the fact that while making measurements it is necessary to transport the indicator antenna inside the chamber, and special equipment and considerable time are required for this.

Hardware options

The interference pattern may be obtained not by antenna transportation only, but by varying the signal frequency also [18]. Application of generator with tunable frequency eliminates a number of engineering difficulties and allows recommending it for subsequent use in the planned test.

The essence of this method is illustrated by Fig. 8, which shows the measurement equipment and the vacuum chamber under study.

Fig. 8. Design diagram for the anechoicness factor measurement facility: 1 – generator with tunable frequency; 4 – receiver; 5 – recorder.

For the receiving antenna to receive all reflected waves and not to receive direct wave, its directional pattern (in the ideal case) should be isotropic and have deep crevasse in the direction of direct wave. Such pattern of cardioid type may be formed in different ways, by specially phased dipoles and frames, helix antennas with shields, quasi-nondirectional antenna with absorbing dowel directed towards the direct wave, for example.

Electric length of direct beam 6 and of the reflected beams, 7 and 8 for example, will change with generator frequency, and the interference curve similar to the curve of SWR method (Fig. 7) will be recorded by the recorder as a result.

In view of the exact form of receiving antenna directional pattern (not of cardioid type obligatory), the anechoicness factor K_{ae} will be defined by the following formula:

$$K_{ae} = 20Lg \frac{\sqrt{Pa\,min}}{\sqrt{Pa\,max}} +20Lg \frac{\sqrt{P\,max} - \sqrt{P\,min}}{\sqrt{P\,max} + \sqrt{P\,min}};$$

where:

$Pa\,min$ - power received in the direction to transmitting antenna;

Pa max - power in the maximum of receiving antenna pattern.

The following conditions should be satisfied in order to provide correct measurements by sweep generator:

- The product of transmitting antenna gain factor $G_{tr}(\lambda)$ and receiving antenna effective surface $S_{rec}(\lambda)$ should be constant within the tuning range of sweep generator used for measurements:

$$G_{tr}(\lambda)S_{rec}(\lambda)=const;$$

- Ratio of receiver sensitivity to the transmitter power should be constant within the tuning range:

$$P_{rec}(\lambda)/P_{tr}(\lambda) =const$$

If both conditions are satisfied approximately, the facility should be calibrated before the test and results of this calibration should be taken into account while processing the measurement data. In this case, high enough requirements in the output signal stability in time are imposed for the generator with tunable frequency.

3.3. PROCEDURE FOR THE EXPERIMENTAL DETERMINATION OF THE DEGREE OF VACUUM CHAMBER INFLUENCE UPON THE ACCURACY OF RADIO PHYSICAL MEASUREMENTS MADE INSIDE IT.

Test aim: Quantitative assessment for the degree of metal vacuum chamber influence upon the accuracy of radio physical measurements made inside it, of characteristics of EP electromagnetic emission, in particular.

Test essence: For the test determination of the degree of vacuum chamber influence upon the accuracy of radio physical measurements made inside it, the same test facility and equipment (antennas, feeder section, measurement and other equipment) are used as for the main test consisting of the EP emission characteristics measurement.
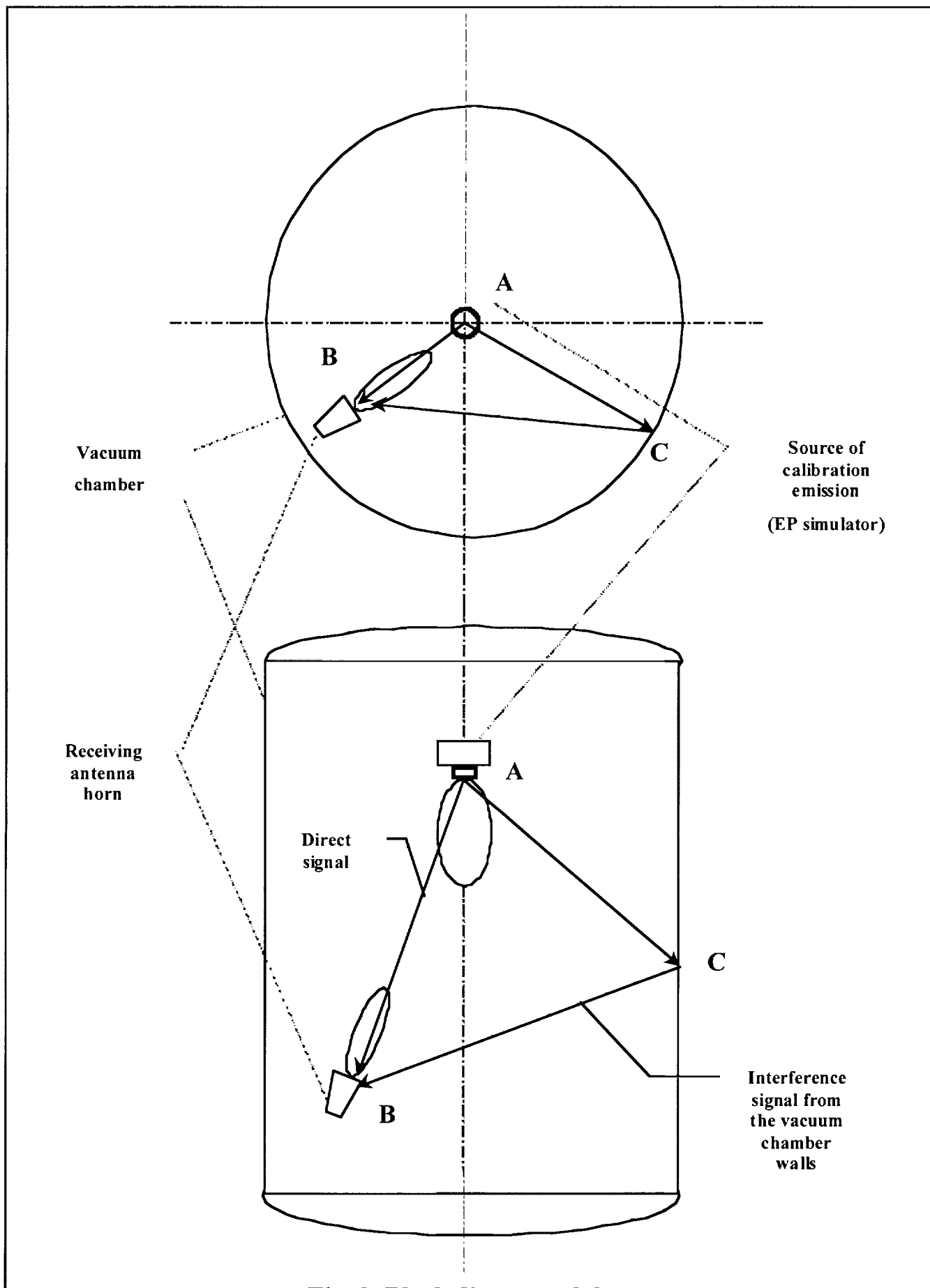
A source of harmonic signal operating within the EP emission range is mounted instead of EP (as in the case of pick-up antennae calibration). It is necessary in this case that the form of directional pattern of the antenna of this source be similar to a maximum extent to the directional pattern of EP emission within the selected range.

Fig. 9 shows the generalized schematic diagram for the location of equipment inside the vacuum chamber. Signal emitted by the source **A** comes to the input of receiving antenna **B** both along the direct path **AB** and after the reflections from the metal walls of the chamber, along the path **ACB**, for example.

As a result, there is signal U_Σ being a vector sum of direct (valid) signal $U\_$ and interference signal $U\_\_$ in the input of receiving antenna (Fig. 10). In reality, the interference signal $U\_\_$ may represent by itself a composition of many signals reflected from different parts of vacuum chamber.

Let's use the above-presented method of frequency tuning for assessing the level of interference signal relative to the valid signal. In the case of frequency variation for a signal, emitted by the source of calibration emission, the variation of their relative phase shift takes place due to different phase paths for the valid and interference signals. In this case, vector $U\_\_$ starts to rotate relative to the vector $U\_$ (Fig. 10). By changing the level of total received signal U_Σ as a function of frequency, it is possible to obtain dependence similar to the presented in Fig. 11. Relative level of the received signal fluctuations

$$\delta = \frac{U_{\text{АÑÂ}_{max}}}{U_{\text{ÀÂ}}} = \frac{U_{max} - U_{min}}{U_{max} + U_{min}}$$

Vacuum chamber

Source of calibration emission

(EP simulator)

Receiving antenna horn

Direct signal

Interference signal from the vacuum chamber walls

Fig. 9. Block diagram of the test

characterizes the degree of influence for the signals reflected from walls and uniformities of the chamber upon the accuracy in measuring the level of valid signal, i.e. the vacuum chamber anechoicness factor.

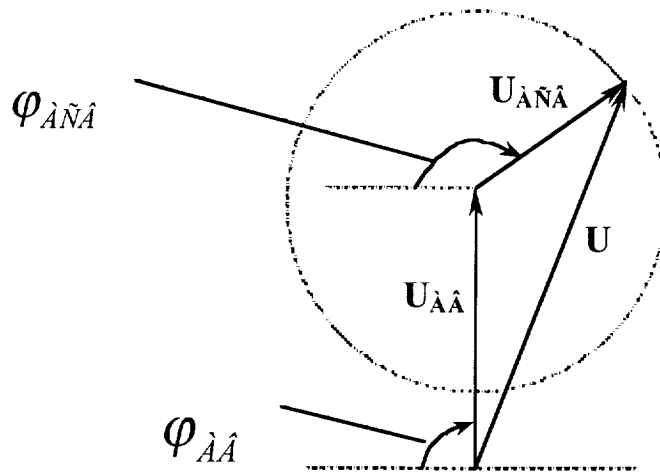Let's define the required range for the frequency tuning for obtaining reliable
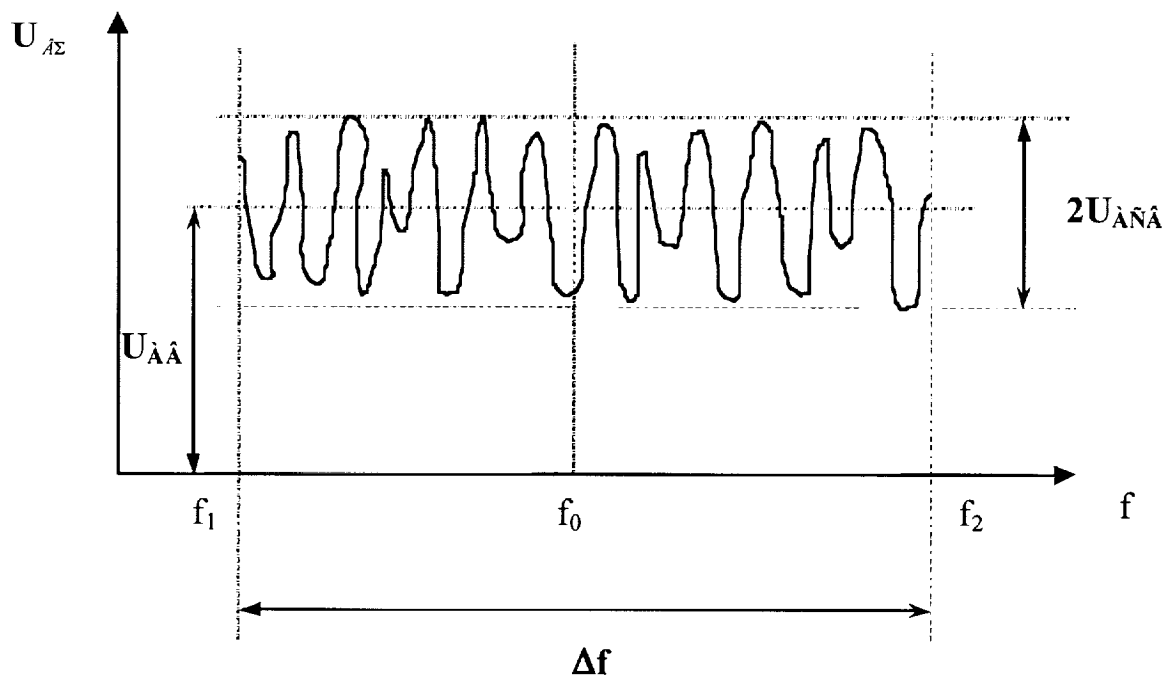

Fig. 10

Fig.11.

metrologic estimates for the degree of vacuum chamber influence.

The phase of signal $U\_$ is defined as $\varphi_{\dot{A}\hat{A}} = 2\pi\dfrac{\dot{A}\hat{A}}{\lambda}$, and phase of the signal $U\_\_$ -

as $\varphi_{\dot{A}\hat{A}\tilde{N}} = 2\pi\dfrac{\dot{A}\tilde{N}+\tilde{N}\hat{A}}{\lambda}$. This phase difference defining the location of $U\_\_$ vector

relative to the vector $U\_$ is:

$$\Delta\varphi = \varphi_{\dot{A}\hat{A}\tilde{N}} - \varphi_{\dot{A}\hat{A}} = 2\pi\frac{\dot{A}\tilde{N}+\tilde{N}\hat{A}}{\lambda} - 2\pi\frac{\dot{A}\hat{A}}{\lambda} = \frac{2\pi}{\lambda}(\dot{A}\tilde{N}+\tilde{N}\hat{A}-\dot{A}\hat{A}) \ .$$

In the case of frequency variation, the vector $U\_\_$ rotation relative to some initial position at f_1 frequency is defined by the following relationship:

$$\Delta = {}_\Delta\varphi_{f_2} - {}_\Delta\varphi_{f_1} = (\frac{2\pi}{\lambda_2} - \frac{2\pi}{\lambda_1}) * (AC+CB-AB) = \frac{2\pi}{c}(f_2 - f_1) * (AC+CB-AB) \ ,$$

where:

$\_$ – velocity of electromagnetic wave propagation in free space;

f_1 and f_2 – initial and final frequencies of generator tuning.

In view of the fact that under real conditions there are several independent signals, reflected from the chamber walls, the total signal level variation with frequency is of stochastic nature, as a rule. For providing the required accuracy in assessing the anechoicness factor it is necessary to obtain large enough number (10-50) of "periods" in the variation of received signal level.

The range of frequency tuning required for obtaining one "period", i.e. for the rotation of $U\_\_$ vector about $U\_$ for 2^π , is defined as:

$$_\Delta f^{(1)} = \frac{c}{AC+CB-AB}$$

Example: Let the diameter of the typical vacuum chamber be 4 m, $AC \cup 2m, CB \cup 2.6m, AB \cup 1.3m$. This corresponds to one of the variants of antennae location. Then the range of frequency tuning, required for obtaining one period of signal level fluctuations, is:

$$_\Delta f^{(1)} = \frac{3*10^9}{2+2.6-1.3} \cong 91 MHz \cup 100 \ MHz \ .$$

The tuning range will be as broad as 1 GHz for obtaining 10 periods.

Test procedure: As it was noted already, the same hardware will be required for this test as for the main one. One of the options for its realization is shown in Fig.6.

Tuning range and step for changing the generator frequency are to be calculated before the test in accordance with geometric characteristics of given vacuum chamber and geometry of mounting points for pick-up antennas.

For the obtained values of frequency range the characteristics of frequency attenuations in all segments of feeder section are recorded during the test. Frequency characteristics for the gain factors of transmitting and receiving antennas are defined on the basis of data sheets or by making tests in the anechoic chamber.

The signal level (in dB) measured by spectrum analyzer for a given frequency is defined as:

$$P_{meas} = P_{gen} + K_{f1} + K_{f2} + K_{At} + K_{vc} + K_{Ar} + K_{f3} + K_{f4} + K_{U} ,$$

where:

P_{meas} – level of received signal (in dB) measured by spectrum analyzer;

P_{gen} – generator signal level;

K_{f1} – feeder section transfer coefficient from external generator to the pressurized junction of vacuum chamber;

K_{f2} – feeder section transfer coefficient from the pressurized junction of vacuum chamber to the transmitting antenna;

K_{f3} – feeder section transfer coefficient from the receiving antenna to the pressurized junction of vacuum chamber;

K_{f4} – feeder section transfer coefficient from the pressurized junction of vacuum chamber to spectrum analyzer;

K_{vc} – vacuum chamber transfer coefficient specifying the variation of signal level between the transmitting antenna output and receiving antenna input;

K_{At}; K_{Ar} – gain factors for the transmitting and receiving antennas, correspondingly;

K_{U} – spectrum analyzer gain factor.

By measuring the level of received signal for different frequencies within the given range and knowing the amplitude-frequency characteristics of the above elements of the section, it is possible to define the frequency dependence for the vacuum chamber transfer coefficient:

$$K_{vc} = P_{meas} - (P_{tr} + K_{f1} + K_{f2} + K_{At} + K_{Ar} + K_{f3} + K_{f4} + K_{U}).$$

Taking into account the definition for anechoicness factor it is not difficult to obtain the interrelation of K_{vc} and δ :

$$\delta_{max} = \frac{U_{\text{ÀÑÀ}_{max}}}{U_{\text{ÀÀ}}} = \frac{U_{max} - U_{min}}{U_{max} + U_{min}},$$

$$K_{vc} = \frac{U_B}{U_A} \cup \frac{U}{U_{AB}} = \frac{U_{AB} + U_{ACB}}{U_{AB}} = 1 + \delta \ .$$

From the point of view of providing the acceptable accuracy of measurements, the anechoicness factor should not exceed 0.2 – 0.3, but in each case this value may be specified more accurately and the development of corresponding metrologic specifications is necessary in future.

3.4. CONCLUSIONS ON THE CALIBRATION

While making real hardware calibration it is necessary to pay attention to the following factors:

- The standard calibration antenna together with generator should be preliminary calibrated in the antenna hall for measuring the power (intensity) of its field at a given distance L (L is a distance from receiving pick-up antennas to the EP center) within the entire frequency range and the range of deviation angles from the main axis. In each case, the form of its directional pattern should correspond to the emission diagram of real EP to a maximum extent.

- It is natural that when calibration and pick-up antennas will be mounted inside the metal vacuum chamber, their directional patterns will change. It is impossible to assess the directional pattern deformation by simple methods, but the introduced error may be estimated qualitatively on the basis of the value of anechoicness factor measured earlier. At this stage it is difficult to define strict boundary, but if the level of interference pattern fluctuations (for the given point of pick-up antenna mounting) referred to its mean level does not exceed 20%, the calibration may be considered to be adequate.

- From the very beginning of calibration it is necessary to go to physical values that will be used during the main test; for example, to define the parameters of the field in the input of aperture of corresponding pick-up antenna in the form of absolute values of power (intensity) of the electric field of signal. Absolute values of power (intensity) of electric field (in dBW/Hz or dBμV/m·MHz, for example) may be used as dimensional representation.

- The values of vacuum chamber anechoicness factor in the places of pick-up antennae mounting will be the main criterion for the potential accuracy of conducted measurements. If the values obtained are beyond the acceptable level, it is necessary to optimize the spatial location of pick-up antennas inside the vacuum chamber.

- The proposed procedure allows not only to assess the level of interference reflections from the walls of metal vacuum chambers, but also to certify them for the degree of anechoicness. Thus, a principal possibility appears for providing unified metrologic conditions and comparability of results during the investigation of EP self-emission in different vacuum chambers under the condition of ensuring the same anechoicness characteristics in them.

4. REFERENCES

1. C.J.Sarmiento, J.M.Sankovic, J.Freitas and P.R.Lynn "RHET2/EPDM Hall Thruster Propulsion System Elecromagnetic Compatibility Evaluation", IEPC-97-108, 25th International Electric Propulsion Conference, August 24-28, 1997, Cleveland, Ohio
2. A.P.Plokhikh, N.A.Vazhenin, C.J.Sarmiento, J.M.Sankovic "Study of the Hall Thruster Self-Emission Effective Center Location Within the Radio Frequency Band". The 25th International Electric Propulsion Conference, IEPC-97-193.
3. V.I.Brukhty, K.P.Kirdyashev, V.L.Zarembo, O.E.Svetlitskaya "Non-stationarity of Electron Wave Processes in Plasma Accelerator", Journal of Technical Physics (JTP), 1996, Vol.66, No.2.
4. V.I.Brukhty, K.P.Kirdyashev "Evolution of High-Frequency Instability of Stationary Plasma Thruster", Letters to JTP, 1997, Vol.23, No.10.
5. D.R.Brillinger "An Introduction to Polyspectra", Ann.Math. Statist., vol. 36, pp. 1351-1374, 1965
6. K.Hasselman, W.Munk, and G.MacDonald "Bispectra of Ocean Waves" in Time Series Analysis, M. Rosenblatt, Ed. New York, NY: Wiley, 1963, pp. 125-130
7. M.J.Hinich and C.S.Clay "The Application of the Discrete Fourier Transform in the Estimation of Power Spectra Coherence and Bispectra of Geophysical Data", Rev. Geophys., vol. 6, no. 3, pp. 3-363, 1968
8. P.J.Huber, B.Kleiner, T.Gasser, and G.Dumermuth "Statistical methods for investigating phase relations in stationary stochastic processes", IEEE Trans. Audio Electroacoust., vol. AU-19, pp. 78-86, 1971
9. Y.C.Kim, J.M.Beall, E.J. Powers, and R.W.Miksad " Bispectrum and nonlinear wave coupling" Phys. Fluids, vol. 23, no. 2, pp. 258-263, Fb. 1980
10. Y.C.Kim and E.J.Powers "Digital bispectrum analysis of self-excited fluctuations spectra", Phys. Fluids, vol. 21, no. 8, pp. 1452-1453, 1978
11. K.S.Lii and K.N.Helland "Cross-bispectrum computation and variance estimation", ACM Trans. Math. Software, vol. 7, pp. 284-294, 1981.

12.	C.H.McComas " Bispectra of internal waves", Woods Hole Tech. Note 02543, Woods Hole, MA, 1978

13.	M.R.Raghuveer "Bispectrum and multidimensional power spectrum estimation algorithms based on parametric models with applications to the analysis of ECG data", Ph.D. dissertation, Univ. Of Connecticut, Storrs, Dec. 1984

14.	M.R.Raghuveer "Bispectrum estimation: A parametric approach", IEEE Trans. Acoustics, Speech, Signal Processing, vol. ASSP-33, no. 5, pp. 1213-1230, Oct. 1985

15.	"Bispectrum estimation via AR modeling", Signal Processing (Special Issue on Modern Trends in spectral Analysis), vol.9, no.1, pp. 35-48, Jan. 1998

16.	J.W.Van Ness "Asymptotic normality of bispectral estimates", Ann. Math. Statist., vol. 37, pp. 1257-1272, 1966

17.	Galagan S. "Understanding Microvawe Absorbing Materials and Anechoic Chambers:

Part1 - Microwaves, 1969, v.8, N 12, p. 38-41

Part2 - Microwaves, 1970, v.9, N 1, p. 44-49

Part3 - Microwaves, 1970, v.9, N 4, p. 47-50

Part4 - Microwaves, 1970, v.9, N 5, p. 69-73

18. Author's Certificate 345451 (USSR) – Device for Measuring the Anechoic Chamber Parameters, Torgovanov V.A., 1972