Fast EMC Diagnostics of Complex On-Board Radio Systems with Use of Experimentally Refined Worst-Case and Conditionally Worst-Case Models of "Transmitter-to-Receiver" Interactions

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***Abstract*—An improved computationally efficient technique for EMC diagnostics of radio equipment of complex on-board radio-electronic systems is presented. The first improvement is based on the use of worst-case and conditionally worst-case mathematical models to describe unwanted electromagnetic (EM) interactions between transmitters and receivers of the system, which allows to detect all potentially dangerous interactions rapidly and avoid second-type errors when assessing the danger of these interactions. The second improvement concerns the iterative refinement of worst-case and conditionally worst-case models of potentially dangerous interactions (including models of transmitter radiation spectra, receivers susceptibility characteristics, amplitude-frequency characteristics of decoupling antenna filters and EM spurious couplings between antennas of on-board system) by the use of both numerical simulation methods and measurements to improve the accuracy of EMC diagnostics. The third improvement is associated with the use of an extremely effective technique of discrete nonlinear behavior simulation of radio receivers' operation in a severe EM environment formed by a set of powerful EM radiations from radio transmitters of the analyzed on-board system and a variety of external EM fields generated by various radio systems of different services.**

Keywords—EMC diagnostics, on-board system, receiver, transmitter, antenna, worst-case model, electromagnetic coupling, intermodulation

I. ABBREVIATIONS

AFC – amplitude-frequency characteristic
AP – antenna pattern
CLRS – complex on-board local radio system
DFC – double frequency characteristic
DFD – double frequency diagram
DLA – discrete linear analysis
DNA – discrete nonlinear analysis
EM – electromagnetic
EMC – electromagnetic compatibility
EME – electromagnetic environment
RR – radio receiver
RT – radio transmitter
SC – spurious coupling
STRI – spurious "transmitter-to-receiver" interaction

II. INTRODUCTION

Intrasystem and intersystem EMC diagnostics are an important parts of the design and ensuring normal operation of complex local on-board radio systems (CLRS), as these diagnostics can detect, identify and take actions to eliminate potentially hazardous spurious "transmitter-to-receiver" EM interactions (STRI) between CLRS radio transmitters and receivers, as well as promptly detect, identify and prevent the influence of undesirable effects of external sources of EM fields on the operational efficiency of these systems.

Typically, performing of such CLRS EMC diagnostic requires a multivariate STRI hazard analysis (taking into account useful and unwanted components of the transmitter spectra and receiver susceptibility characteristics in a wide frequency band, spurious EM couplings between antennas, characteristics of cables, frequency filtering systems and active components, for example, antenna amplifiers) for various options for the on-board location of antennas and modes of operation of CLRS radio equipment, and also for various protective technical and organizational solutions. In addition, intersystem EMC analysis is often required for a variety of application scenarios for the on-board system under consideration that differ in external electromagnetic environment (EME).

In practice, there are many choices (for how CLRS are implemented, configured, and operated) to be analyzed, so reducing the EMC analysis time for each case is especially important. With a large number of potentially dangerous STRIs and existing limitations on computing power, such an analysis is possible only using the IEMCAP technology [1], which assumes the use of simplified pessimistic models of amplitude-frequency characteristics (AFC) of potentially dangerous STRIs. In particular, this technique is implemented in [2, 3], its practical efficiency is confirmed by the results [4-7].

The most challenging problems of EMC computer diagnostics of CLRS are following:

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1) The lack of complete and reliable information about characteristics of CLRS equipment, for example, about characteristics of radiation spectra of radio transmitters (RT), susceptibility of radio receivers (RR), and AFC of antennas in a wide frequency range (up to 3 decades). An illustration of this circumstance, in particular, can be the data [8] and the results of measurements of the spectra of interference emitters [9], showing that the pessimism of models [1] of the RTs output spectra and RRs characteristics of susceptibility can reach 20-30 dB at all frequencies, except for frequencies of narrowband sputious components of RTs output spectrum and RRs spurious responses;

2) A sufficiently large number of STRI and external modulated EM fields (up to 10^3 ... 10^5) to be analyzed, and a large number of CLRS implementation options and operation scenarios for which EMC analysis is required, with significant resource constraints (computational, time, etc.).

Frequency domain EMC Discrete Linear Analysis (EMC DLA) technology developed by the IEMCAP [1] and based on the worst-case analytical models of spurious couplings (SC) in CLRS between RTs and RRs antennas and on the integrated interference margin (IIM) as the EMC system criterion, appears to be quite effective in solving EMC CLRS problems under the following conditions:

a) If it is implemented at the modern level [2, 3] using much more detailed frequency sampling of spectra and characteristics of susceptibility (10^5-10^6 samples and more), in comparison with [1];

b) If it is supplemented with the time domain EMC discrete nonlinear analysis technology (EMC DNA) [10-12], which provides high computational efficiency in the analysis of nonlinear effects (intermodulation, blocking, cross modulation, conversion of local oscillator noise, etc.) during radio reception in complex EME, including the use of specialized techniques [13, 14] for measuring parameters of the input nonlinearity of CLRS RRs.

An important way to improve the objectivity and accuracy of EMC DLA & DNA of CLRS is a sequential iterative refinement of worst-case models of potentially hazardous STRIs between CLRS equipment. In early stages of CLRS life cycle, this refinement is usually achievable only by detailed circuit-level mathematical modeling of RTs spectra and RRs susceptibility characteristics, as well as electrodynamic modeling of each of the options for the relative spatial arrangement of CLRS antennas [4-7]. At later stages, a more significant refinement of these models is possible based on the results of measurements of characteristics of CLTS equipment and SC.

The goal of this work is to improve the method of fast computer diagnostics of EMC of CLRS radio equipment (developed in [3-7] and based on the use of EMC DLA & DNA technologies) by using both pessimistic and conditionally pessimistic models of CLRS STRI, and also by refining these models using the measurement results.

III. Stages of Fast EMC Diagnostics of CLRS

The improved technique for the fast EMC diagnostics of CLRS is based on multi-variant EMC DLA & DNA of CLRS equipment operation in severe EME with the use of worst-case and conditionally worst-case models of STRIs. The technique includes the following main stages.

A. At CLRS designing

1) Develop a 3D geometric model of CLRS with help of CAD system. This model helps to consider different variants of allocation of RT and RR antennas and define all characteristics that affect EM SCs between the antennas (geometry and material of hull, characteristics of antenna placement, etc.).

2) Develop worst-case models of STRIs for different variants of CLRS implementation. This includes models of EM SCs between antennas, models of antenna patterns (AP) to analyze impact of external EME, models of main and spurious emission spectra for each RT in a wide frequency range (up to ten times exceeding the maximum working frequency), models of susceptibility characteristics of each RR via the main, adjacent, and spurious reception channels in a wide frequency range (up to ten times exceeding the maximum tuning frequency of RR), and models of frequency selectivity of feeder components (filters, preselectors, combiners, etc.).

3) Develop a model of external EME. The model has a form of an ensemble of external EMFs with predefined power characteristics, frequency spectra, direction of arrival and polarization. The model is developed based on data on allocation and operation of external RTs (ground-based, RTs of other CLRSs, of aircrafts, etc.); the radiomonitoring data could also be involved.

4) Perform the EMC DLA with the use of basic worst-case models [1] of STRIs and taking into account external EME for each variant of placement and elevation of CLRS antennas. The Integrated Interference Margin (IIM) is used as a criterion of EMC [1]; it is calculated for each receptor (i.e., RR) as follows:

$$IIM = 10lg\left(\sum_{i=1}^{n} IM\left(f_{Ai}\right)\right) \text{ [dB]},\quad IM = \frac{P_I}{S}, \qquad (1)$$

where P_I [W] is the level of unwanted signal at the receptor, S [W] is the receptor susceptibility to interference, f_A [Hz] is the analyzed frequency, n is the number of analyzed frequencies (called frequency samples in [1,10,11]), IM is the point Interference Margin at a fixed frequency.

As a result of this stage, the set of potentially dangerous STRIs that can cause radio interference in RRs of CLRS is detected.

5) Refine the models of potentially dangerous STRIs. Each potentially dangerous EM SC "Antenna-to-antenna" is analyzed by the use of numerical methods (FDTD, MoM, etc.). Such analysis is performed in the following order: models of AFCs of S-matrix elements which characterize the SC in predefined frequency ranges are developed and refined by small variations in values of antenna parameters and coordinates; the worst-case envelope of the AFC of "antenna-to-antenna" SC is constructed; AP models taking into account antennas' design features and orientation wrt the elements of CLRS hull structure and underlying surface are refined (for more accurate analysis of impact of external EME).

The worst-case envelope of the AFC is calculated for each "antenna-to-antenna" SC as follows:

$$H_{ik}(f) = E_{nv}\{H_{1ik}(f), H_{2ik}(f), ..., H_{Nik}(f)\}, \qquad (2)$$

where f is the frequency, $H_{1ik}(f)$ is the AFC of S-parameter S_{ik} obtained for the SC between antennas with the numbers i and k for the first fixed set of antenna parameters and coordinates, $H_{2ik}(f)$ is AFC of S_{ik} obtained for the second set of antenna parameters and coordinates, etc.; $E_{nv}\{.\}$ denotes the worst-case envelope construction procedure described in [4-7]. Note that it is necessary to define the initial (reference) values of antenna parameters, based on information taken from technical specifications.

Then the discrete models of RT radiation spectra and of RR susceptibility characteristics are refined, e.g., by the use of numerical circuit-level simulation.

A useful technique is to use conditionally pessimistic models. By them we mean such models, the pessimistic nature of which is ensured when certain conditions are met.

As an example, we consider the VHF RR susceptibility characteristic's models synthesized based on data from the RR technical specification and shown in Fig. 1. Outside the main reception channel, the pessimistic model is the lower envelope of the susceptibility levels of the spurious reception channels, and the conditionally pessimistic model describes the susceptibility outside the spurious reception channels. Because the conditionally pessimistic model does not describe the spurious reception channels (image channel, spurious combination channels, etc.), then such a model is pessimistic, provided that, as a result of the selection of the operating frequencies of on-board RTs and the analyzed RR, the impact of RTs main and spurious oscillations on the RR spurious channels is excluded.

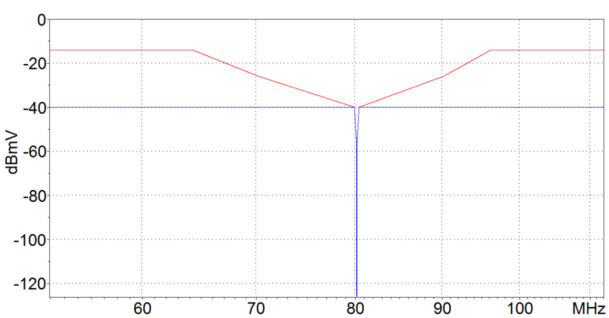

Fig. 1. Models of susceptibility characteristic RR of VHF transceiver tuned at 80.2 MHz: worst-case model (blue line) and conditionally worst-case model (red line).

Similarly, the model, which is the upper envelope of the spectrum of main, out-of-band and noise RT oscillations, but does not describe its narrow-band spurious oscillations, is conditionally pessimistic (i.e., pessimistic, provided that the interferences which are caused by impact of TR spurious oscillations through the main and spurious channels of on-board CLRS RRs are eliminated by selecting the operating frequencies of this TR and on-board RRs).

The use of conditionally pessimistic models of RTs spectra and RRs susceptibility characteristics, from which information about RTs narrow-band spurious oscillations and RRs spurious channels is purposefully removed, makes it possible to estimate the levels of unwanted effects from CLRS RTs at the inputs of CLRS RRs, subject to successful removal of interference caused by spurious RTs oscillations and RRs spurious channels, by frequency planning. The adequacy of this approach is determined by the fact that the probability of successful elimination of the indicated interference (as well as nonlinear interference) by frequency planning is rather high, since for each of the analyzed RT and RR several thousand frequency channels are available.

6) Repeat the EMC DLA (ref. stage 4) with the use of refined models of potentially dangerous EM SCs, RT radiation spectra, and RR susceptibility characteristics. This analysis refines the estimation of danger of STRIs detected earlier at stage 4.

7) Select the most promising variants of CLRS realization for further detailed analysis. This variants should be charectrized by the absence of interference via the main reception channels and the least possible levels of out-of-band input disturbances. If necessary, a set of measures to eliminate linear interferences between the RTs and RRs is developed for each selected variant of location of CLRS antennas (and then stage 4 is repeated taking into account the implementation of these measures).

8) Perform the EMC DNA of CLRS for the situations remaining potentially dangerous in terms of nonlinear interference [10-12]. In order to perform the EMC DNA, the nonlinearity and selectivity characteristics of RR through the antenna input must be determined taking into account peculiarities of structure, components, and frequency conversions in RR. The best result of the determination can be achieved by involving the DFT technique [13,14] that makes it possible to detect, identify, and measure parameters of all existing linear and nonlinear paths of probable RR damage by disturbances through the antenna input, as well as to measure the RR input nonlinearity rather accurately.

9) Develop measures to eliminate nonlinear radio interferences. Technical (filtering, shadowing, cancellation, etc.) and organizational (time division, frequency planning, etc.) measures not related to change in location of antennas are considered.

Note: In the course of EMC diagnostics of on-board CLRS, it is often essential to take into account not only antenna-to-antenna SCs but also other kinds of EM SCs (antenna-to-cable, cable-to-cable, antenna-to-equipment case, external EM field-to-cable, etc.). For this purpose, procedures 1…7 are carried out as a part of the EMC analysis based on simulation of these SCs.

B. *At CLRS physical implementation*

After performing the above EMC diagnostics at the CLRS design stage, its results were refined during the CLRS physical implementation (CLRS prototype development). At this stage, the following was performed.

1) Measurements of output spectra of all RTs of CLRS are performed (similar to how it was done in [9]); at different RT tuning frequencies, the levels of out-of-band and spurious oscillations, as well as their frequency bands, are determined.

2) Measurements of susceptibility characteristics of all RRs of CLRS are performed (for example, using technique [13, 14]) at different RRs tuning frequencies; frequencies and susceptibility levels of all spurious channels detected in the RRs are determined, as well as all types and orders of intermodulation channels of RRs nonlinear interference.

3) Measurements of AFC of SCs "Antenna-antenna" are performed.

4) AFCs of all elements of feeders (antenna filters, decoupling unit and other elements used to suppress interference) are measured.

5) AFCs worst-case mathematical models for antenna filters, decoupling units and SC "Antenna-antenna" are specified based on the measurement results.

6) *EMC DLA & DNA procedures are repeated* in order to eliminate those STRIs, the danger of which turned out to be overstated due to the pessimistic nature of their theoretical mathematical models.

7) Undesirable combinations of RTs and RRs tuning frequencies are determined, at which interference through the main and spurious RRs channels from narrowband spurious RT oscillations and intermodulation interference generated by RTs signals and strong signals of external EME is possible (on this stage only those STRIs are considered, the danger of which is confirmed by the previous stage).

8) The set of conditionally worst-case models of RTs output spectra and the RRs susceptibility characteristics are refined, from which the RTs narrowband spurious oscillations and the RRs spurious channels are deliberately removed (since the interference caused by these oscillations and channels is eliminated by frequency planning by eliminating the unwanted combinations of RTs and RRs working frequencies).

9) EMC DLA & DNA procedures using refined conditionally worst-case models of RTs output spectra and RRs susceptibility characteristics at different tuning frequencies are performed (in order to confirm that the measures taken will eliminate interference to CLRS RRs from CLRS RTs at CLRS operation in given external EME).

IV. Practical Implementation

The technique of fast EMC diagnostics of complex on-board radio systems with the use of experimentally refined worst-case and conditionally worst-case models of "transmitter-to-receiver" interactions was tested at the development of a specialized communication and control vehicle, the 3D geometric model of which (with antenna's layout adopted after the STRI and EMC DLA simulations at the CLRS design stage) is shown on Figure 2. Figure 3 shows the structure of its airborne CLRS.

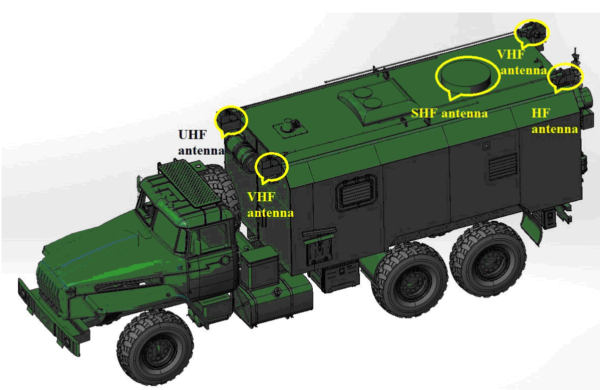

Fig. 2. 3D CAD model of location of CLRS antennas on vehicle body.

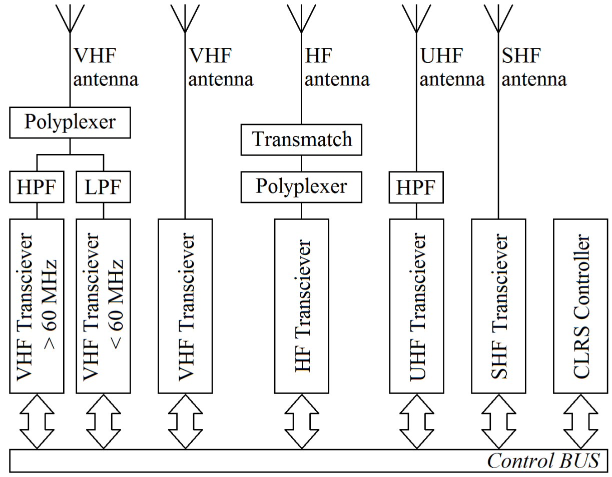

Fig. 3. CLRS primary block diagram.

After completing procedures 1-8 in Section B above, a refined EMC analysis of the CLRS equipment using the measurements was performed in the following sequence:

1) EMC DLA using models refined based on the results of measuring the output spectra of all RTs, the susceptibility characteristics of all RRs and AFCs of all potentially dangerous SC. Refined models of phenomena that are subject to strong variability during the CLRS operation, it is advisable to make pessimistic, i.e. to find the envelopes of the measurement results (an example of such a model is shown in Fig. 4). As other models, it is possible to use the measurement results directly (an example of such a model is shown in Fig. 5).

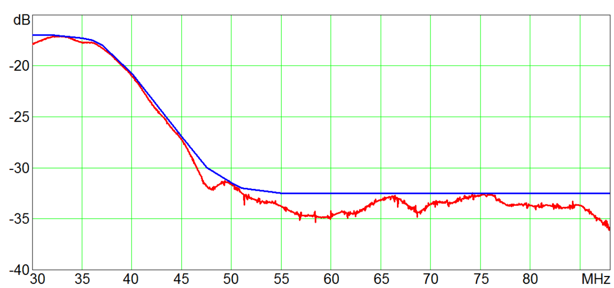

Fig. 4. AFC of the SC between VHF antennas of CLRS: red line - measurement result, blue line - refined pessimistic (worst-case) model

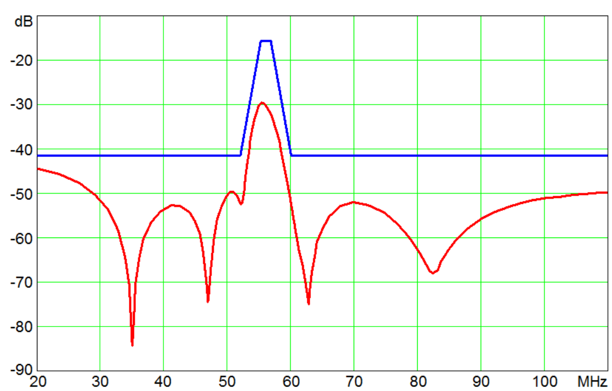

Fig. 5. AFC of the SC through an antenna filter unit (AFU): blue line - pessimistic model based on data from technical specification; the red line is the refined model obtained from the measurement results.

In fig. 6 the image of the double frequency characteristic (DFC) [13,14] of RR of the first VHF transceiver is given; fig. 7 shows the image of its double-frequency diagram (DFD) - a map of DFC levels (levels below the standard response corresponding to the real RR sensitivity are not displayed on the DFD). In fig. 6 and 7, the RR spurious channels, as well as intermodulation channels up to the 7th order inclusive, are detected. In fig. 8, the measured RR susceptibility characteristic of the first VHF transceiver is shown as an example, on which the corresponding RR spurious channels are also observed.

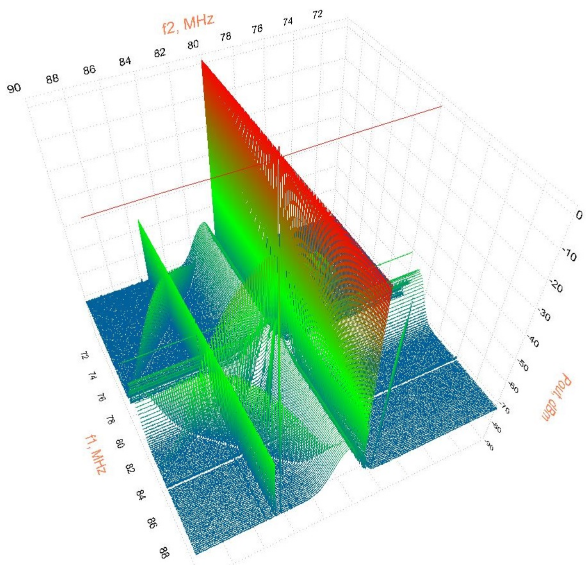

Fig. 6. DFC of RR of VHF transceiver.

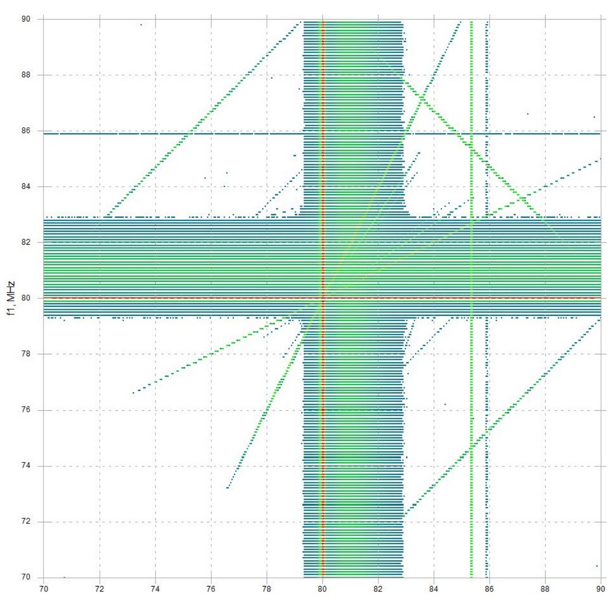

Fig. 7. DFD of RR of VHF transceiver.

The results of this stage made it possible to establish the absence of interference for the operation of UHF & SHF transceivers, as well as to determine all channels of on-board RRs affected by the narrowband spectra components of on-board RTs, and to clarify the set of unwanted combinations of RT and RR tuning frequencies, at which interference for RRs from narrow-band spurious RTs oscillations is possible.

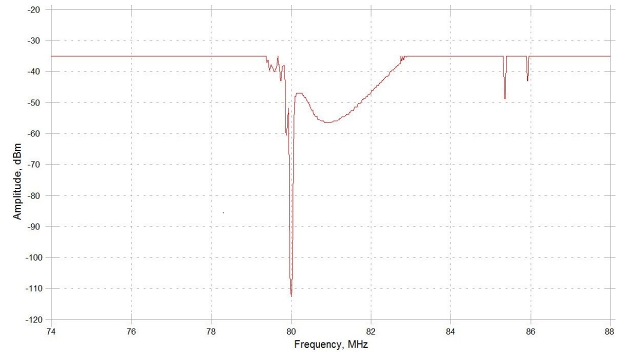

Fig. 8. Measured RR susceptibility characteristic of the first VHF transceiver.

2) EMC DLA using conditionally pessimistic models of RTs output spectra and RRs susceptibility characteristics in order to performing of intrasystem EMC diagnostics of CLRS after the introduction of restrictions on the RTs and RRs operating frequencies (accepted at the previous stage of the analysis). At this stage, an additional unacceptable combinations of frequency channels of RTs and RRs operation may be revealed, due to the effect of wideband (out-of-band and noise) components of the RTs spectra on the main and spurious channels of RRs reception. Based on the results of this stage of the analysis, a decision is made on the effectiveness of the measures taken to ensure EMC and on the need for additional measures to protect RR from intrasystem interference. Fig. 9 shows an example of the results of DLA of EMC of transceivers, located on vehicle body, using conditionally-pessimistic models of RTs output spectra and RRs susceptibility characteristics.

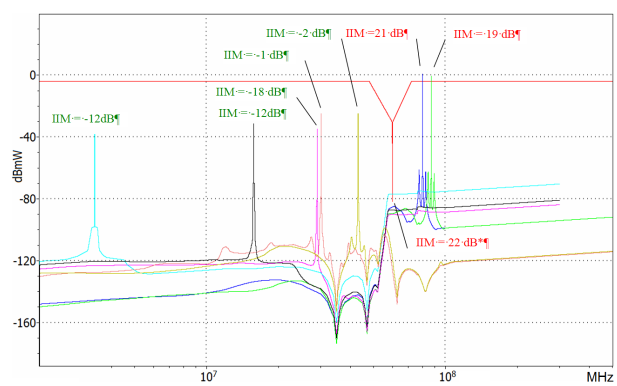

Fig. 9. Results of the EMC DLA of CLRS using conditionally pessimistic models: red line - characteristic of receptor susceptibility (RR of VHF transceiver), lines of other colors - spectra of signals of RTs of HF and VHF transceivers at the antenna input of the receptor (An example).

3) EMC DNA using technology [10-11] and nonlinear RR models obtained using the results of measurements of the parameters of front-end nonlinearity of RRs using ADFT technology [13,14]. As an example, Fig. 10 shows the total spectrum of unwanted signals observed at the output of the RR nonlinear model of VHF transceiver. This spectrum contains both signals of RTs of HF and VHF transceivers, and intermodulation components of 3 ... 7 orders.

Based on the results of the last stages of the CLRS intrasystem EMC diagnostics, a decision is made on the sufficiency or insufficiency of organizational measures (automatic control of the simultaneous operation of CLRS radio equipment and the exclusion of the use of dangerous combinations of operating frequencies using the created corresponding database) and technical (frequency and spatial filtering, blanking, etc.) to ensure EMC.

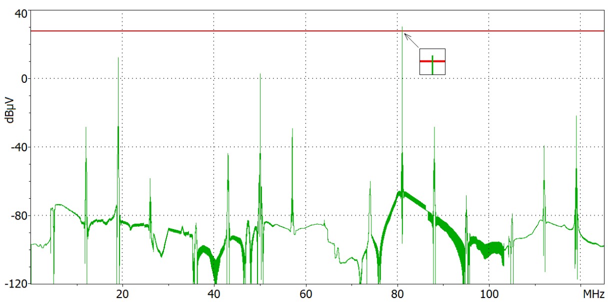

Fig. 10. Results of EMC DNA for RR of VHF transceiver tuned to 81 MHz: spectrum of unwanted signals at the output of the RR nonlinear model (green line) and the susceptibility characteristic of the receptor connected to the output of the nonlinear model (red line). The Hammerstein-Wiener model with 15th order polynomial model of RR front-end inertialess nonlinearity is used.

In particular, after analyzing the results of this stage of computer diagnostics of intrasystem EMC of the considered CLRS, the LPF and HPF (see Fig. 3) were replaced with appropriate bandpass filters, which made it possible to exclude intermodulation interference created by output signals of on-board RTs, and also essentially decrease levels of interference specified by broadband components of the RTs output spectra in the main and spurious RR frequency channels, as well as somewhat reduce the number of prohibited combinations of RTs and RRs tuning frequencies of on-board VHF transceivers.

V. Conclusion

The presented testing results (see section IV) allowed us to come to the following conclusions about the effectiveness of the fast EMC diagnostics technology of complex on-board radio systems with the use of experimentally refined worst-case and conditionally worst-case models of "transmitter-to-receiver" interactions:

1) Execution of EMC DLA & DNA using "worst-case" models [1], obtained on the basis of technical specifications of CLRS equipment, when developing and providing EMC of vehicle CLRS, gives too pessimistic results of diagnostics of intrasystem EMC, far from reality, despite the use of much more detailed frequency sampling of spectra and characteristics of susceptibility compared to [1].

2) Execution of EMC DLA & DNA using "worst-case" models, refined by detailed electrodynamic modeling of SC with variations in technical parameters, characteristics of placement and matching of on-board antennas [4-7], provides clarification of characteristics of SC between antennas, which is necessary for the adoption of design solutions. However, the accuracy of such EMC diagnostics is significantly limited due to the lack of complete and reliable information on the RTs oscillation spectra, RRs susceptibility characteristics and AFCs of the decoupling filters.

3) Refinement of the models of "Transmitter-to-Receiver" interactions based on measurements of RTs oscillation spectra, RRs characteristics and frequency responses of the decoupling filters provides improved accuracy of the EMC DLA & DNA results, allowing to predict the CLRS performance characteristics, confirmed by testing its prototypes.

4) In case of insufficient repeatability of the characteristics of some samples of CLRS on-board equipment (transceivers, antennas, filters), its replacement requires repeating the last stages of EMC diagnostics with the correction of the list of prohibited combinations of operating frequencies of on-board RTs and RRs.

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