Simulation of Nonlinear Interference in Aircraft Systems Operating in Complex Electromagnetic Environment Created by Land-Based and Air-Based Wireless Systems

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***Abstract*—Results of discrete nonlinear behavior simulation of aircraft wireless systems' operation in complicated electromagnetic environment (EME) created by electromagnetic radiations of wireless systems allocated on the earth's surface and in different surrounding airborne vehicles are presented. The simulation is performed with the use of technique of virtual testing area; this technique is based on implementation of geoinformation technologies for analysis of different scenarios of influence of unwanted signals on wireless systems of aircraft flying at low and medium altitudes. Results of simulation prove the presence of real danger of intermodulation interference in on-board VHF/UHF radio receivers of piloted aircraft in case of complicated EME at small and medium altitudes if unmanned aerial vehicles approach to the aircraft at distances which are acceptable from the viewpoint of air traffic control regulations.**

***Keywords*—EMC diagnostics, aircraft, nonlinear interference, UAV, behavior simulation.**

I. Introduction

Intensive development and expansion of unmanned aerial vehicles (UAV) equipped with radar, data transfer, control, navigation, retransmitting, and other radio systems essentially changes the conditions of operation of the traditional piloted aircrafts at small and medium altitudes. The main reason of this is the complication of an electromagnetic environment (EME) at such altitudes and the increase of danger of interference to operation of airborne electronic complexes, including nonlinear distortions - intermodulation, cross-modulation, etc. As a result of simultaneous growth of terrestrial density of land-based radio systems of various services, the EME complicating at the indicated altitudes happens as at the expense of obvious growth of a total number of electromagnetic fields (EMFs) the level of which exceeds the susceptibility threshold of airborne receivers, and also at the expense of extension of their dynamic range. The last increases the danger of a nonlinear interferences to airborne receiver operation and is connected with the growth of number of potential air-based EMF sources and increasing the probability of their short-term inadvertent approaching to the aircraft at a distance at which the occurrence of interference caused by intermodulation and receiver's spurious responses becomes possible.

The objective of this paper is an estimation of danger of nonlinear interference in aircraft radio receivers operating in severe EME if the aircraft approaches to an UAV (or dirigible) and/or land-based EMF sources at a distance admissible from the point of view of the air traffic safety.

II. Main Pecularities of the Problem

1) High complexity of on-board systems of modern aircrafts (both piloted, and pilotless), containing a lot of different radio systems operating in a wide frequency range (from MF to SHF), that is the reason of the significant number and high levels of EMF created by airborne radio transmitters on input ports of airborne receivers.

2) The major sizes of the area of potential interference interacting (line of sight area). That is specify a multiplicity of an EMF ensemble at aircraft altitude (to 104-106 radio signals created by the land-based radio transmitters of various services) which are exceeding the thresholds of an on-board receivers susceptibility

3) At rather high cruising altitude of modern jet aircrafts owing to their significant remoteness both from the ground surface, and from low-altitude vehicles (turbo-prop aircrafts, UAV, helicopters, dirigibles, etc.), the dynamic range of EMF levels at on-board receiving antennas, created by land-based and low-altitude systems is rather insignificant; excess of the dynamic range of aircraft receivers on intermodulation by input EME dynamic range, as a rule, is improbable.

4) Essentially other EME occurs in situations, inherent in mean and small altitudes of airplanes at their operation in conditions of

a) high terrestrial density of land radio systems of various services and under the complex relief when high-power land-based radio transmitters allocated on elevations up to 3-4 km above sea level;

b) mass application of different UAV; in these cases the air traffic management (ATM) limitations which eliminate the dangerous approaching of flight vehicles on distances and altitudes, do not eliminate approaching of radiating UAV to

DOI: 10.1109/EMCEurope.2017.8094819

low-altitude piloted aircrafts on distances at which creation of nonlinear radio interferences becomes possible.

5) In some cases the presence of radio monitoring equipment as a part of a number of aircraft on-board systems. This equipment is intended for the real-time analysis of external EME, including detection of presence of high-power signals. Usage of the radio monitoring data, of the nonlinear destruction threshold criteria of aircraft receivers, and the technique of EMC discrete nonlinear analysis (DNA) [1, 2] allows to perform the real time identification of external signals, which can be a cause of nonlinear interference, and the adaptation of on-board radio equipment to this interference (selection of frequency channels and modes of operation at which the nonlinear destruction of on-board receivers is eliminated).

III. Composition of Simulation Technique

Main peculiarities mentioned above specify an application of the following simulation technique:

1) The "Virtual Testing Area" (VTA) technique [3] for EME simulation ЭМО at the altitude of considered aircraft. EME model is represented in the form of EMF ensemble (set) in the considered points of aircraft flight path; each EMF is specified by the set of power (power flux density, field strength) and non-power (frequency, polarization, azimuth and viewing angle of arriving, modulation, etc.) parameters. Owing to the problem main peculiarities No.2,3,4 given above, this EME model must be created with the use of geoinformation (GIS) technique and systems, and appropriate databases for potential interference sources.

2) The technique of EMC discrete linear analysis (DLA) EMC [4-7] for preliminary analysis of possible on-board radio receiver's destruction by linear interference through adjacent channels and receiver's spurious responses, in particular with the use of radio monitoring data.

3) The DNA EMC technique [1, 2] under its outstanding computational efficiency entirely satisfying the to the problem main peculiarities No.1,2 specified above (extra wide frequency range, very large quantity of input EMF) and making it possible

a) to create and use the high-quality models of front-end nonlinearity of radiofrequency ports susceptible to nonlinear effects, on the basis of experimental data, in particular, received with the use of 3D measuring technique [8,9], and also

b) the direct usage of on-board radio monitoring data for execution of DNA EMC procedures.

IV. Description of Simulated Typical Aircraft On-Board System

Typical configuration of the model of onboard radio electronic system, utilized at the simulation of nonlinear radio interferences using VTA & DNA-technology, is developed on the base of analogues – onboard systems of different aircrafts (piloted and unmanned), helicopters, dirigibles, etc., equipped with complicated set of instrumentation and radio communication equipment, data communication and control equipment [10-13 et.al.]. Radio systems of this aircraft (radio communication systems of different frequency ranges, radars, radio navigation systems, radio altimeter, radio compasses of UHF and HF-bands, etc.) in several situations may be affected by nonlinear interference (intermodulation, cross-modulation, desensitization, etc.

V. Basic Algorithm of Simulation

The following algorithm of estimation of unintended linear and nonlinear interference at the on-board radio receivers, representing the development of conventional algorithms of EMC analysis with the implementation of capabilities of techniques [1-3,6-9], is used:

1) Creation of EME models in the input radiofrequency ports of each of on-board receivers:

a) Estimation of levels of signals of M on-board radio transmitters in N input ports of on-board receivers. Result is N subsets $\{E_{n1}(f_{11}), E_{n2}(f_{12}), \dots, E_{nM}(f_{1M})\}$, $n = 1 \dots N$ of values of levels of signals on frequencies $f_1, \dots, f_M$ of on-board transmitters for each of N input radio receiving ports.

b) Creation of mathematical model of the external EME in considered point of aircraft flight path as a set of K values $\{\Pi_k(\alpha_k,\beta_k,\phi_k,f_k)\}$, $k = 1, \dots K\}$ of K external EMF intensities with corresponding non-power EMF parameters: frequencies f_k, polarizations ϕ_k, azimuths α_k and viewing angles β_k. This model can be obtained by computational technique (with the use of database of land-based and air-based radio systems, results of simulation of aircraft flight scenarios and adequate ITU-R models of radio waves propagation [14]), and also with the use of radio monitoring results.

c) Reduction of model of external EME created on the previous stage, to the each of N input radiofrequency ports of aircraft receivers to the corresponding set of voltages $\{U_{n1}(f_{21}), U_{n2}(f_{22}), \dots, U_{nK}(f_{2K});\}$, $k = 1 \dots K$, $n = 1 \dots N$, and

d) Integration it with corresponding sets of levels of signals of M on-board radio transmitters specified above on stage "a" for each input radiofrequency port. Result is N sets of values $\{\{E_{n1}(f_{11}), E_{n2}(f_{12}), \dots, E_{nM}(f_{1M}); U_{n1}(f_{21}), U_{n2}(f_{22}), \dots, U_{nK}(f_{2K})\}$, $n = 1 \dots N$, $k = 1 \dots K\}$ of levels of signals of on-board transmitters on their operating frequencies $f_{11}, \dots, f_{1M}$, and of external signals on frequencies $f_{21}, \dots, f_{2K}$ for each of N input radiofrequency ports of on-board receivers.

2) To be convinced of absence of linear interference to on-board equipment operation, the diagnostic of danger of linear interference through each of N input radiofrequency ports with the use of DLA EMC technique [4-7] is executed.

3) Preliminary diagnostic of danger of nonlinear interference at each of N input radiofrequency ports is made: comparison of level of each signal included in the corresponding set of values noted above on previous substage "1d", with the accepted standardized threshold values of an appropriate port susceptibility to each of nonlinear effects (intermodulation, cross modulation, desensitization), or with susceptibility values on an intermodulation of various orders detected in receivers with the use of technique [8,9] is executed. Result is a list of input radiofrequency ports which can be affected by nonlinear interference:

a) If levels of all input signals (both external, and created by on-board equipment) are less than threshold susceptibility to intermodulation, the decision concerned an absence of danger of unintended interference through the given port, is made;

b) If level of any input signal defined for the given port on substage "1d" exceeds the threshold susceptibility to intermodulation (with allowance for a guard space), decision concerned the presence of danger of nonlinear interference through the given port, is made, and

- Estimations of the possible highest levels of input signals (taking into account the expected changes of aircraft flight path) are executed,
- The necessary order of a polynomial model of a port nonlinearity is determined, according to the maximum order of an intermodulation the susceptibility threshold to which is exceeded by levels of input signals, and, if necessary, specification of a model of input nonlinearity of the given port is effected.

4) Detailed analysis of nonlinear interference at each of input radiofrequency ports for which the potential danger of nonlinear interference on substage "3b" is detected. For each of ports under the stage "3b"

c) Creation of set of input signals, capable to be a reason of nonlinear interference, is made by exclusion from the integral signal ensemble created on stage "1d", those signals which cannot cause an intermodulation owing to their small levels, or because of their suppression by input port frequency-selective units;

d) Execution of the DNA EMC with the use of a model of the port front-end nonlinearity gained at execution of the stage "3b", and of a set of input signals created on the stage "4a"; the analysis of presence and danger of nonlinear interference in frequency channels of considered input ports. In the most complex cases caused by intermodulation interference

- The analysis of levels of an intermodulation components in corresponding frequency channels, the estimation of SNIR value in considered port and a degree of degradation of it characteristics;
- Identification of EMF sources producing the detected intermodulation, and
- Selection of option of adapting of the on-board radio system to the nonlinear interference on basis of the analysis of time-behavior and probabilistic characteristics of intermodulation, selection of frequency channels, free from intermodulation (for multichannel systems), etc.

VI. Description of Simulated Scenario

Model of spatial environment of examined aircraft (helicopter) is represented by area topographical map on Fig. 1.

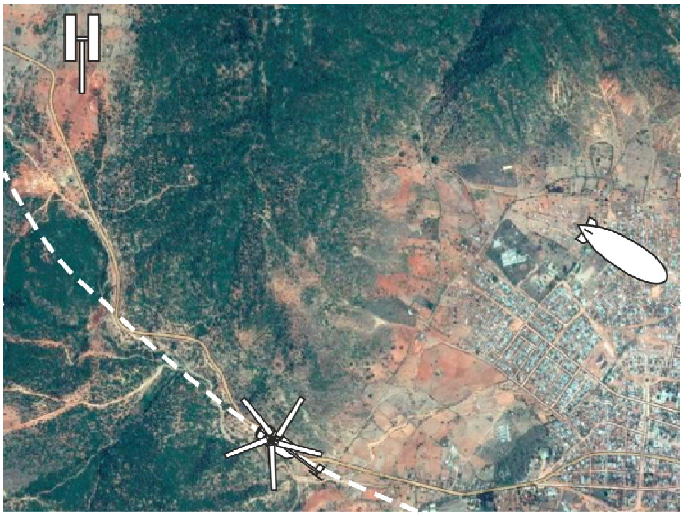

Fig. 1. Allocation of examined helicopter.

Main features and elements of simulated situation are listed below.

1) Region of aircraft (helicopter) operation is characterized by

a) compound relief of ground surface (strongly irregular terrain) with occurrence of uplands (mountains, hills) and lowlands with general level difference up to 0.5-1.0 km and height above sea level up to 1.0-1.5 km, and

b) high terrestrial density of land-based radio systems of different radio services (mobile and fixed communications, radar, etc.).

2) Scenario of helicopter spatial movement (marked by corresponding sign on Fig. 1), accomplished over mountain plateau on actual altitude 0.3-1.0 km over ground surface.

3) Presence of retransmitting dirigible (marked by corresponding sign on Fig. 1) on actual altitude 0.5-1.0 km over ground surface equipped with retransmitting radio system for VHF land-based mobile communications.

4) On the observed surface patch on the tops places a set of base stations (BS) of cellular and trunk (TETRA, APCO-25, MPT-1327) radio communication systems are disposed. Also a great number of mobile radio stations of various types and frequency ranges (HF, VHF, UHF) are distributed on this territory.

VII. Results of Preliminary EMC Diagnostics

As a result of preliminary EMC diagnostics with the use of [6,7] (phases 2,3 of simulation algorithm) the following potentially dangerous situation was detected (Fig.2):

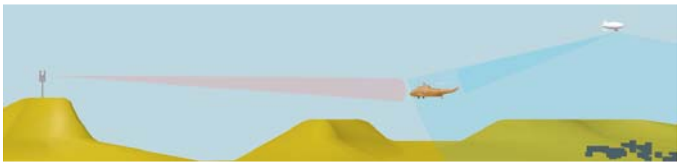

Fig. 2. Layout of interference emitters and receptor.

1) Considered helicopter is equipped with the VHF radio communication system (air mobile service, 118-144 MHz); BS of land-based VHF trunk radio communication system (marked by corresponding sign on Fig. 1) and dirigible retransmitting system (land mobile service, 146-174 MHz) can be a reason of nonlinear interference in on-board VHF receiver at its remoteness from these BS on distances up to 2-6 km.

2) Levels of BS and dirigible signals in helicopter receiver input can exceed a threshold of its intermodulation susceptibility on 10-15 dB, that defines the necessity of specification of a model of front-end nonlinearity of this receiver.

VIII. Specification of a Model of Front-End Nonlinearity

Refinement of a model of an on-board receiver front-end nonlinearity is executed with the use of the results of testing of its clone with the use of double-frequency test technique (ADFTT) [8,9]; some of these results are given below in Fig.3-Fig 6 and in Table 1.

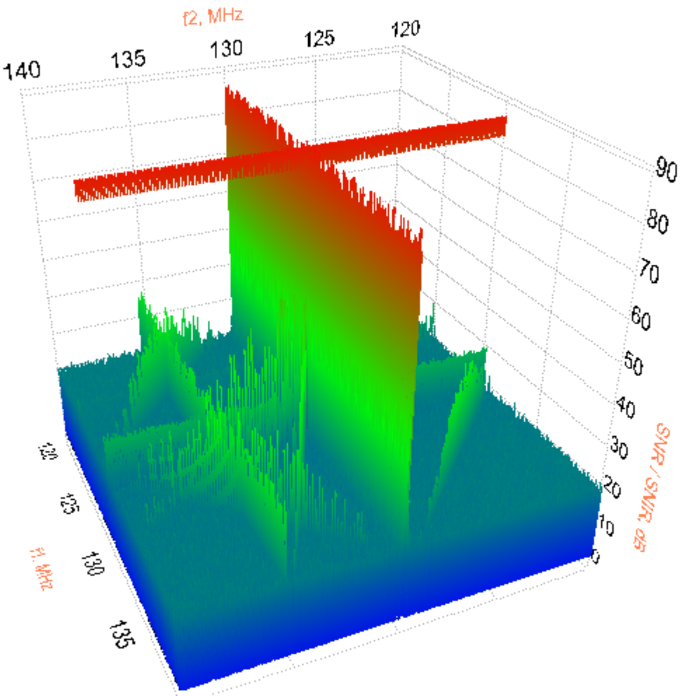

Fig. 3. VHF Receiver Double-frequency characteristic measured with the use of ADFTT.

Polynomial model of the front-end nonlinearity (Fig. 6, Table 1) is synthesized on the basis of the measured receiver's spurious-free dynamic range (IDR) for 3-rd-order intermodulation (56 dB); the synthesis technique is based on the use of the intermediate theoretical model [15]. The gain of the nonlinearity model is taken equal to unity, therefore the levels of signals and spectra at all points of the receiver model are referred to the receiver input.

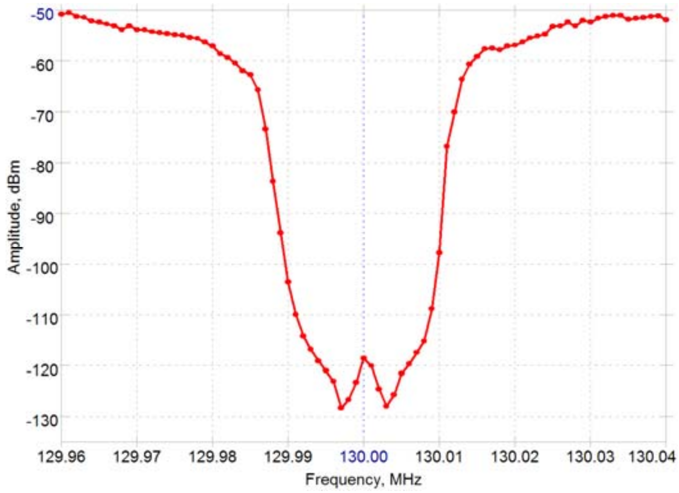

Fig. 4. Measured characteristic of susceptibility of VHF AM receiver to AM interference (receiver tuning frequency is 130 MHz.

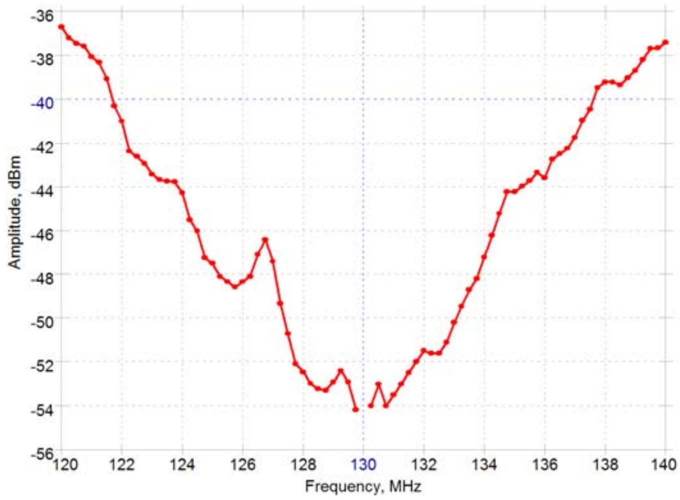

Fig. 5. Two-signal 3-order intermodulation selectivity characteristic of VHF AM receiver at tuning frequency 130 MHz (measured).

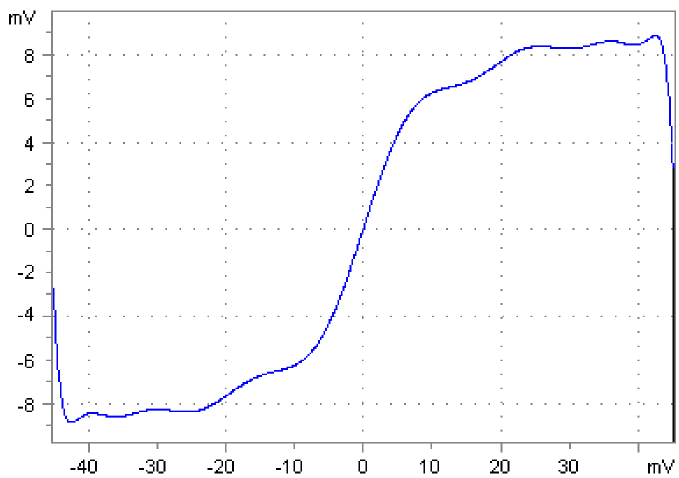

Fig. 6. Normalized instantaneous transfer characteristic of equivalent nonlinearity of VHF AM receiver front-end at tuning frequency 130 MHz (synthesized).

TABLE I. COEFFICIENTS OF THE SYNTHESIZED POLYNOMIAL MODEL OF THE RECEIVER FRONT-END NONLINEARITY

Degree	Calculated IDR, dB	Polynomial coefficient
1	0	9.90223575843484E-01
2	99.97	2.48478867233772E-14
3	**56** [1)]	-5.24601649120399E+03
4	100.21	-3.10170719637256E-10
5	67.74	1.94670184786138E+07
6	100.62	1.21310044086772E-06
7	73.57	-3.88959949702330E+10
8	101.22	-1.90437674678915E-03
9	77.36	4.33301062789320E+13
10	102.06	1.58820998596040E+00
11	80.17	-2.70508239695165E+16
12	103.2	-6.20875117941448E+02
13	82.43	8.84932626148319E+18
14	104.82	9.49294014793969E+04
15	84.41	-1.18051511592990E+21

[1)] Measured IDR value for 3-order intermodulation

IX. DETAILED ANALYSIS OF NONLINEAR INTERFERENCE

Detailed analysis of nonlinear interference in helicopter radio receiver of VHF radio communication system, created by radio signals of BS of land-based VHF trunk radio communication system and dirigible retransmitting system is performed with the use of DNA EMC Technique [1,2,7-9] and of the specified model of receiver front-end nonlinearity (Fig.6, Table 1) as a part of the Wiener-Hammerstein receiver model presented in Fig.7 below:

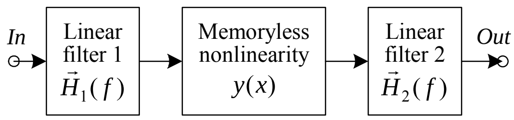

Fig. 7. The Wiener–Hammerstein model of receiver:

In this model $H_1(f)$ is an amplitude-frequency characteristic (AFC) of front-end receiver frequency selectivity, $y(x)$ is instantaneous transfer characteristic of front-end nonlinearity, $H_2(f)$ is an AFC of the main frequency selectivity of receiver (presented in Fig.4). Receiver noise factor is 6 dB, so susceptibility level reduced to its input is -126 dBm for SIR=16 dB, and threshold sensitivity is -110 dBm. Receiver tuning frequency is 130 MHz, its discrete nonlinear behavior simulation is performed at frequency range [1 kHz, 1 GHz].

The following parameters of the land based and air-based sources of high-power VHF signals which are capable to be a cause of intermodulation in helicopter receiver, are used:

- Operating frequency of land-based BS is 146.5 MHz, equivalent isotropic radiated power is 53 dBm (radiated power 50W, antenna gain 6 dB);
- Operating frequency of air-based retransmitter is 163 MHz, equivalent isotropic radiated power is 43 dBm (radiated power 10W, antenna gain 3 dB).

Results of this analysis are illustrated by spectrograms given below in Fig. 8-12.

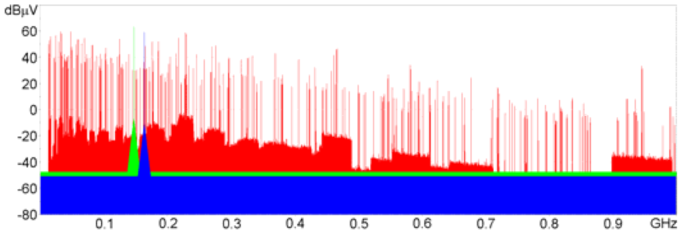

Fig. 8. Main components of EME at receiver input: the set of 250 sigmals of land-based systems of different radio services (red), signal of land-based BS of VHF trunking radio communication system (green), and signal of dirigible retransmitting system (blue), frequency range [1 kHz, 1 GHz]

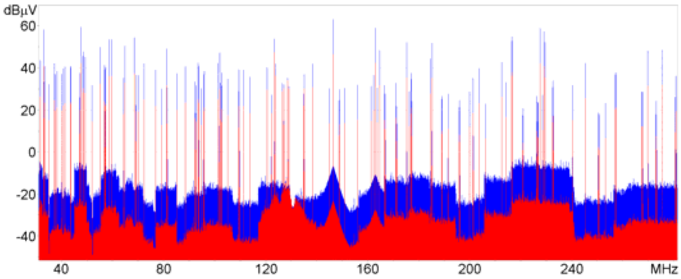

Fig. 9. Spectra of aggregate signal at the receiver input (blue) and at the output of receiver front-end selectivity model (red); segment [30 MHz, 280 MHz] is displayed

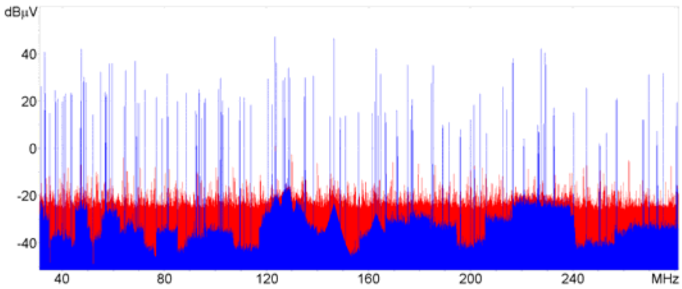

Fig. 10. Spectra of aggregate signal at the input (blue) and output (red) of the receiver front-end nonlinearity model, segment [30 MHz, 280 MHz]

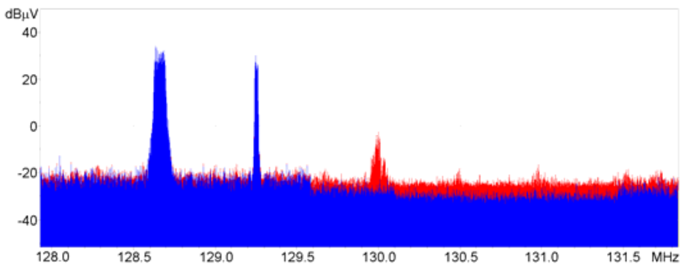

Fig. 11. Spectra of aggregate signal at the input (blue) and output (red) of the receiver front-end nonlinearity, segment [128 MHz, 132 MHz]

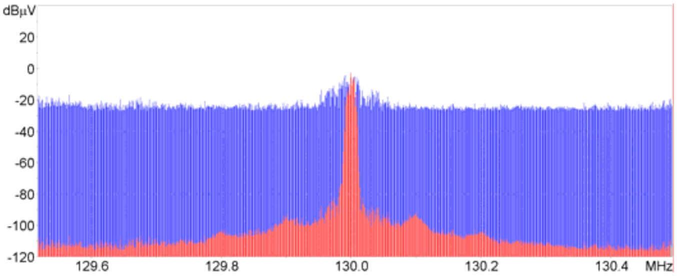

Fig. 12. Spectra of aggregate signal at the input (blue) and output (red) of the receiver's main selectivity model (which is the receiver model output – ref. Fig.7); noise of spectrum analyzer is not modeled; segment [129.5 MHz, 130.5 MHz] is displayed.

As expected, aggregate signal passing through linear filters (i.e. through models of the front-end and main receiver selectivity) does not lead to occurrence of new spectral components but only changes the relative levels of presented spectrum components (see Fig.9 & Fig.12). Contrary to it, as a result of aggregate signal nonlinear conversion in its spectrum there is a great number of new components (intermodulation components – see Fig.10 & Fig.11), many of which, however, are of low levels and consequently are masked by receiver internal noise.

Estimations of the separate power interference margin (i.e. a frequency dependence of the ratio of a noise level to susceptibility level) on a receiver output testify to the following:

- Total (for all spectrum components) integral power interference margin in considered point of flight path (in definition of [4-6]) TIIM = 19.1 dB.
- Positive (in dB) TIIM value indicates the presence of interference on a receiver output (this conclusion also follow from the comparison of spectrums resulted on Fig.12). As the given interference (on 130 MHz) is absent in an input spectrum of the front-end nonlinearity (see Fig.11), it has a nonlinear nature and correspond to the 3-order intermodulation.

X. Conclusion

Results given above confirm the presence of real danger of intermodulation interference in on-board VHF radio receivers of piloted aircraft in case of complicated EME at small and medium altitudes if an UAV approaches to the aircraft at a distance which is acceptable from the point of view of air traffic control regulations.

The conclusion concerned the danger of nonlinear interference for aircraft receivers is confirmed also by simulation of other scenarios of aircraft operation at small and medium altitudes: 1) by behavior simulation of UAV control channel of 915-928 MHz range in case of UAV usage over the hilly urban area with developed GSM-900 radio network; 2) by behavior simulation of on-board receiver of air mobile service (300-400 MHz) if the aircraft operates over such area with high-power BS of mobile communication service (401,6-430 MHz, 440-470 MHz) and transmitters of broadcasting service (TV channels in the lower end of 470-790 MHz range).

By our estimations, intermodulation interference in the simulated airborne receivers of air radio navigation and air mobile services can be dangerous if the airplane operating at small or medium altitude above the hilly area approaches to above mentioned BS of VHF/UHF land mobile service and/or digital TV transmitters of broadcasting service at a distance less than 3-4 km, or to BS of GSM-900 at a distance less than 1.5-2 km, or to an UAV equipped with radio equipment (of data transmission, control, retransmitting, command link, etc.) at a distance less than 1-3 km.

The executed research confirms very high efficiency of the involved technique [1-3] intended for behavior simulation of radio receivers in a very complicated EME: the simulation of the considered scenario (more than 250 modulated signals – ref. Section IX) with the use of 15-order polynomial model of the front-end nonlinearity (ref. Section VIII) takes less than 1 minute on usual personal computer.

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