Study the influence of intermodulation products on navigation signals

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Abstract. The work examines terrestrial radio broadcasting using frequency modulation (FM), which interferes with the ILS (Instrument Landing System), VOR (VHF Omnial Radio range) and VHF communications systems, which is a widespread problem among aircraft users. In the case of ground/air communication receivers, this interference problem involves disturbing of audio communications and distorted reception of signals from the RV range. In aircraft ILS locators and VOR receivers, the interference problem is associated with interference of audio communications and errors related to course deviation and flag modes of control. Interference in these navigation receivers is considered as a more serious problem than errors in course deviation or impaired communication, especially in the approach and landing phases.

1. Introduction

GNSS multipath propagation phenomena [1] and intermodulation distortion are unwanted combination of multiple signals into a nonlinear device that can cause interference to adjacent receivers located in radio relay objects. Most part of the intermodulation occurs in the transmitter's nonlinear power amplifier. The front end of the receiver is the next most common mixing point is.[2] It usually occurs in the unprotected first mixer of older radio receivers or in some cases in overloading the rear front of RF amplifiers. There are many methods for reduction, identification and filtration the noise signals. [3,4] Intermodulation may also be caused by corroded tower connections, safety cables, screw clamps and coupling rods or any metal objects located nearby which may serve as a non-linear "mixer/rectifier" [5].

Of interest to the practice is the case of "transmission" intermodulation, in which disturbances occur only when the two transmitters are simultaneously on air [6]. This intermodulation shall be observed in the event when transmitter "A" and transmitter "B" are located close enough to each other, at the same time are on air at frequencies of 150.00 MHz and 151.00 MHz respectively. Under these conditions, it is possible to be received the signal from one transmitter from the antenna to the other and cause interference with the operation of the final power amplifier, i.e. a mixing may occur in one or both of the transmitter's power amplifiers, creating several new frequencies at intervals of 1.0 MHz. (deviation). Parasitic signals will appear at frequency intervals of ±1.0 MHz to the side of each transmission frequency (figure 1). For example, for frequencies 146.00 MHz, 147.00 MHz, 148.00...
MHz, 149.00 MHz, 150.00 MHz, 151.00 MHz, 152.00 MHz, 153.00 MHz, 154.00 MHz, 155.00 MHz. The main frequencies are 150.00 MHz and 151.00 MHz and the intermodulation products (IMP) are as follows:

- for the third order are 149.00 MHz and 152.00 MHz;
- for the fifth order is 148.00 MHz and 153.00 MHz;
- for the seventh order are 147.00 MHz and 154.00 MHz;
- for the ninth order are 146.00 MHz and 155.00 MHz.

The common equation for the intermodulation product:

\[ IM = n_1A \pm n_2B \pm n_3C \pm \ldots, \] (1)

where A, B, C, etc. are the mixing frequencies and \( n_1, n_2, n_3, \ldots \) are harmonic or multiples of the mixing frequencies. For example, \( A+2B + 2C \) generates an intermodulation period of the fifth order (1 + 2 + 2). [8]

The greatest influence have the odd intermodulation disturbances of the 3rd and 5th order. Higher order intermodal products have lower power levels compared to third- and fifth-order products.

2. Methodology for measuring the intermodulation distortion

A single linear system can't produce intermodulation if the input signal of a time-invariant system is a single-frequency signal, then the output signal has the same frequency, only the amplitude and phase can differ from the input signal. [10]

Nonlinear systems generate harmonious constituents. Therefore, if the input signal from the non-linear system has a \( f_a \) frequency, then the output signal includes multiples of the input frequency. \( (f_a, 2f_a, 3f_a, 4f_a, \ldots) \).

Intermodulation occurs when the input signal in a non-linear system is composed of two or more frequencies. For example, for an input signal containing three frequency components of \( f_a, f_b \) and \( f_c \), can be described with the expression [8]:

\[ x(t) = M_a \sin(2\pi f_a t + \phi_a) + M_b \sin(2\pi f_b t + \phi_b) + M_c \sin(2\pi f_c t + \phi_c), \] (2)

where \( M \) and \( \phi \) are the amplitudes and phases of the three components.

The output signal \( y(t) \) is received after transmission of the signal through a non-linear function

\[ y(t) = G(x(t)), \] (3)

where \( y(t) \) contains the three frequencies of the input signal \( f_a, f_b \) and \( f_c \), as well as a number of linear combinations of the main frequencies, represented by (4):

\[ k_a f_a + k_b f_b + k_c f_c \] (4)

where \( k_a, k_b, \) and \( k_c \) are random integers.
Each of the mentioned frequency components has a different amplitude and phase, which depend on the nonlinear function. Therefore, when an input signal is set containing a random number \( N \) from frequency components \( f_a, f_b, \ldots, f_N \), the output signal will contain a number of frequency:

\[
k_a f_a + k_b f_b + \ldots + k_N f_N,
\]

where \( k_a, k_b, \ldots, k_N \) are random integers.

The order \( O \) of an IMP is the sum of the absolute values of the coefficients \([8,10]\):

\[
O = |k_a| + |k_b| + \ldots + |k_N|
\]

i.e. third-order intermodulation products appear, if the condition is met:

\[
|k_a| + |k_b| + |k_c| = 3
\]

\[
(f_a + f_b - f_c), (f_a + f_c - f_b), (f_b + f_c - f_a)
\]

\[
(2f_a - f_b), (2f_a - f_c), (2f_b - f_a), (2f_b - f_c), (2f_c - f_a), (2f_c - f_b)
\]

On figure 2 is shown the distribution of third-order intermodulation products. In blue are the main carriers, in red are the positions of the dominant intermodulation products, and in green - the positions of precisely defined intermodulation products.

![Figure 2. Distribution of third-order intermodulation products.](image)

Analysis of the distribution of intermodulation products shows that the main carriers have the greatest amplitude, and the intermodulation products have a lower amplitude level relative to the main frequencies, but occupy a wider frequency spectrum. The odd intermodulation disturbances of the 3rd and 5th order have the greatest influence, because the observed maximum levels are closer to the main frequencies.

3. **Common assessment method**

The objective of the CAM (Common Assessment Method) is to calculate all potential incompatibilities in the aircraft volume at multiple points. The maximum potential incompatibility, associated with the specific RV service, is defined as a protective distance. The CAM is based on the need to protect civil aviation radio services within the established minimum distances to the antenna systems of repeaters, etc., depending on the air service (ILS or VOR) and its activities. [11, 12]
3.1. Test points in ILS

Assessing compatibility with an ILS localizer, the CAM is based on a set of fixed test points, complemented by more test points for each designated operational coverage (DOC) transmission station of the ILS.

DOCs used in VOR services are big and therefore there are usually a lot of broadcast stations. The CAM assesses the compatibility regarding VOR, with test points selected above each broadcast station in the DOC and have in mind all stations outside the DOC.

Figure 3 shows the distribution of the fixed test points, and in table 1 - the minimum height, the distance from the location of the localizer and the navigation deviation dependent on the elongated axis line of the track. Fixed test points A, E, F, G have minimum heights of (0, 150, 300 and 450)m respectively, above the vertical section of the location where the ILS localizer is located. These values describe the descent trajectory with a slope of $3\pi$. All other fixed test points are at a minimum height of 600m.

![Figure 3. Location of fixed test points in the DOC zone of ILS.](image)

| Table 1. Distances of test points. |
|------------------------------------|
| Points on or above the Extended Centre Line | Points outside the Extended Centre Line |
|------------------------------------|------------------------------------|
| Points on or above the Extended Centre Line | Points outside the Extended Centre Line |
| (all at a height of 600m) | (all at a height of 600m) |
| ID | Distance (km) | Minimum height | ID | Distance (km) | Navigational deviation, according to the Extended Centre Line |
|----|----------------|----------------|----|----------------|-------------------------------------------------|
| A  | 0              | 0              | B,C| 31.5           | -35, 35                                        |
| E  | 3              | 0              | X0,Y0| 7.7           | -35, 35                                        |
| F  | 6              | 150            | X1,Y1| 12.9           | -25.5, 25.5                                    |
| G  | 9              | 300            | X2,Y2| 18.8           | -17.25, 17.2                                   |
| H  | 12             | 450            | X3,Y3| 24.9           | -12.9, 12.9                                    |
| I  | 15             | 600            | X4,Y4| 31.5           | -10, 10                                        |
| J  | 21.25          | 600            | X5,Y5| 37.3           | -8.6, 8.6                                      |
| K  | 27.5           | 600            | X6,Y6| 43.5           | -7.3, 7.3                                      |
| L  | 33.75          | 600            | X7,Y7| 18.5           | -35, 35                                        |
| M  | 40             | 600            | X8,Y8| 24.0           | -27.6, 27.6                                    |
| D  | 46.3           | 600            | X9,Y9| 29.6           | -22.1, 22.1                                    |
If the emitting station is inside the area shown in figure 3, an additional test point shall be created when the geographical coordinates of the emitting station are known and located at the same height as the emitting antenna. If the emitting station is within or below the ILS DOC, but outside the hatched area in figure 3, an additional test point shall be created having the geographical coordinates of the emitting station. The height of the test point is at least 600m above the ILS zone; or 150m above the emitting antenna.

3.2. Test points for VOR

The VOR test point is located at geographical coordinates of a emitting station, at a minimum height, which is at least 600m above the terrain (approximated as 600m above the location of the broadcasting station), or 300m above the broadcasting antenna, or at height to which the height of the VOR plot has been added. Additional test points in the DOC can be used to ensure the specific operation of the VOR. For example, when used as a landing assistant, or when service is required at an elevation angle less than 0°.

3.3. Selection of test points

Broadcasting stations shall be included in analyses at a test point if there is a direct line of sight from the broadcasting antenna to the test point. If the calculated signal level is greater than the B1 cut-off value threshold or the field intensity in a free space is at least equal to the value that may cause TYPE Al, A2 or B2 incompatibility and are not more than 125km away for cases A1 and B2.

In order to assess the compatibility of a set of broadcast stations at each selected test point, it is necessary to:

- calculate the field intensity in the free space for each of the broadcasting stations at the test point, taking into account the slope distance, the maximum effective radiated power (EIRP) and the characteristics of the antenna;
- calculate the signal level of the ILS or VOR;
- calculate the incoming power at the inlet of the aircraft receiver.

The impact of frequency and type (ILS or VOR) of the RV compatibility assessment office for each interference type A1, A2, B1 and B2 must be taken into account.

4. Measurement results for the presence of IMP type A1

A measurement was carried out on the radio relay and TV station “Frangata” Varna to establish the presence of IMP type A1, created by mutual penetration of signals, when working on more than one transmitter on one object or in close proximity to different objects. The main objective is to establish whether VHF-FM radio stations, operating in the 87.5 ÷108 MHz range, located on a single site or on nearby sites can be a source of mutual intermodulation products. They may pose a threat to the security of the operation of civil aviation radio services within the scope of 108÷137 MHz. [10, 11, 12, 13, 14]

In table 2 are shown the basic technical parameters and characteristics of the measurements:

- Intensity of aircraft systems ILS, VOR, COM
  - ILS intensity - 32 dB(μV/m);
  - VOR intensity - 39 dB(μV/m);
  - COM intensity - 38 dB(μV/m).
- Altitude - 306.0 m;
- Frequency of radio stations;
- Maximum EIRP;
- Height of the antenna.

IMP in the frequency band above 108MHz are examined, since only they fall within the 108÷137 MHz frequency band assigned to civil aviation radio services:

- $2f_1 - f_2$ double-signal IMP; $f_1 > f_2$
- $f_1 + f_2 - f_3$ three-signal IMP; $f_1 > f_2 > f_3$
Table 2. Basic technical parameters.

| Radio station | Frequency (MHz) | Max. EIRP (dBW) | Height (m) |
|---------------|----------------|-----------------|------------|
| VESELINA      | 106.30         | 28.0            | 38.0       |
| HR. BOTEV     | 104.80         | 37.8            | 62.0       |
| BNR           | 103.40         | 37.8            | 59.0       |
| RADIO 1 ROCK  | 101.50         | 34.8            | 72.0       |
| HORIZONT      | 100.90         | 44.6            | 62.0       |
| DARIK         | 99.30          | 37.6            | 62.0       |
| CITY          | 98.60          | 34.8            | 72.0       |
| BG RADIO      | 97.80          | 34.8            | 78.0       |
| VERONIKA      | 97.30          | 34.8            | 72.0       |
| RADIO 1       | 93.80          | 34.8            | 78.0       |
| RADIO ENERGY  | 91.20          | 34.8            | 72.0       |
| FOCUS         | 89.50          | 32.1            | 40.0       |

In the calculations are included:
- ILS systems located up to 125 km from the research site: Varna airport – 109.9 MHz; Burgas airport - 110.3 MHz. The requirement for electromagnetic compatibility (EMC) is ±200 kHz of frequency.
- Intermodulation products within the ILS range (108MHz ÷ 112MHz) using channels 108.10, 108.15, 108.30, 108.35MHz, etc. up to 111.70, 111.75, 111.90 and 111.95MHz do not comply with the EMC requirements:
- Intermodulation products within the VOR range (108MHz ÷ 112MHz) using channels 108.05, 108.20, 108.25, 108.40, 108.45 MHz, etc. up to 111.60, 111.65, 111.80, 111.85 MHz, also VOR frequencies occupying channels located at intervals of 50 kHz in the 112 ÷ 118MHz frequency band, as follows: 112.00, 112.05 ... 117.95 MHz do not comply with the EMC requirements.
- VOR systems located up to 278 km from the research VHF site - Varna airport - 109.9MHz, Burgas airport - 110.3MHz, Gorna Oryahovitsa airport - 113.6MHz, Ruse airport - 115.55MHz.

The measurement are carried out in accordance with the test staging presented in figure 4. IMP are measured after the output of the summing device (filter combiner) and before the feeder and antenna system.

![Figure 4. Test staging](image-url)
The scheme consists of three transmitters, but the number may vary \((n=2\) or \(n=3)\), depending on whether a two or three signals A1 IMP are measured and perhaps other transmitters included in the same filter combiner, which are not involved in the product measured and may not be taken into account. An IMP can be measured from the interaction of few radio stations operating on two or three different filter combiners. In such as, the measurement of one A1 IMP shall be carried out sequentially in the outputs of the two or three filter combiners.

For the purposes of the study, a directional deflector, a selective band filter and a standard spectrum analyzer Keysight model “E4407B”, with a frequency range from 9 KHz to 26.5 GHz, a power sensor Keysight type “U2000H”, with a frequency range from 10 MHz to 18 GHz and equivalent loads are used.[15, 16]

The directional deflector emits a proportional portion of the energy supplied to the antenna. The band filter is set to the frequency of the A1 IMP, defined as incompatible, corresponding to the frequency of a particular VOR, ILS or COM for which the measurement is carried out. The filter achieves suppression of the main radiation of the transmitters to achieve the necessary measurement dynamics. Suppression of A1 IMP shall be determined by adding to the variance recorded by the spectral analyzer screen between the levels of a radio transmitter and the A1 IMP and the correction factors for the filter decay and the directional deflector "A" for the operating frequencies of the concerned transmitters.

For each IMP established, an amplitude frequency response (AFR) of the pass filter shall be made, including the transmitters that cause it. When setting the filter, the aim is to ensure minimal IMP suppression and maximum transmitted power.

Some of obtained results are presented in figures 5, 6, 7 and 8. On figure 5 is presented AFR for IMP frequency 112.40 MHz (marker 1), a combination of frequencies: marker 2 – 106.30 MHz, marker 3 – 103.4 MHz, marker 4 – 97.30 MHz, antenna 1 and antenna 2

![Figure 5. AFR for IMP frequency 112.40 MHz.](image1.png)

![Figure 6. AFR for IMP frequency 112.40 MHz.](image2.png)
Conclusion
IMP have an influence on the work of Instrument Landing System. A methodology has been proposed and a testbed for measuring IMP of type A1 has been proposed and studied. The experimental studies, carried out on-site, and the 3 antennas indicate that, there is no reported presence of IMP type A1 for the frequency range from 109.9MHz to 120.2MHz. The presence of type A1 IMP was recorded for only the 123.1 MHz frequency belonging to the COM range. The IMP levels for frequency 123.1 MHz meet the criteria of the EMC standards.

References
[1] Iliev TB, Stoyanov IS, Sokolov SA and Beloev IH 2020 The influence of multipath propagation of the signal on the accuracy of the GNSS receiver, 43rd International Convention on Information, Communication and Electronic Technology (MIPRO), Opatija, Croatia, pp 508-511, doi: 10.23919/MIPRO48935.2020.9245409
[2] Hegarty CJ, Bobyn D, Grabowski J and Van Dierendonck AJ 2020 An overview of the effects of out-of-band interference on GNSS receivers. NAVIGATION, 2020, 67, pp 143–161. https://doi.org/10.1002/navi.345
[3] Balabanova I, Georgiev G and Kostadinova S 2018 Artificial neural network for identification of signals with superposed noises, Advances in Intelligent Systems and Computing, 679 Springer, Cham., pp 488-495, https://doi.org/10.1007/978-3-319-68321-8_50
[4] Kogias P, Balabanova I, Malamatoudis M, Georgiev G and Sadinov S 2019 Reduction and identification of noise signals using artificial neural networks with various activation functions. Journal of Engineering Science and Technology Review Special Issue on Telecommunications, Informatics, Energy and Management, Kavala, Greece, 2019, pp. 89-93, ISSN: 1791-2377
[5] Wang Q, Su D, Jiang M and Xie S, 2006 A study on RF frequency optimization design system related to intermodulation interference, 4th Asia-Pacific Conference on Environmental Electromagnetics, Dalian, pp 616-619, doi: 10.1109/CEEM.2006.258030.
[6] Handbook on radio frequency spectrum requirements for civil aviation, 2018 ICAO spectrum strategy, policy statements and related information I, 2nd edition, International Civil Aviation Organization
[7] Radio frequency interference best practices guidebook 2020, Cybersecurity and infrastructure security agency
[8] Maury microwave corporation, Theory of intermodulation distortion measurement (IMD), 1999, pp 1-3, Available at: https://www.maurymw.com/pdf/datasheets/5C-043.pdf
[9] Handbook on radio frequency requirements for civil aviation, Fifth Edition, 2009 (Doc 9718-AN/975), Available at: https://www.icao.int/safety/acp/ACPWF/AACP-WGF-22/ACP-WGF22-IP11-9718_5ed_unedited_version_en.pdf
[10] Methodology for measuring intermodulation products of type “A1”, occurring during the operation of closely situated VHF-FM radio broadcasting stations, Available at: https://crc.bg/files/_en/Metodika_IMP1.pdf

[11] ITU-R SM.1009-1, Compatibility between the sound-broadcasting service in the band of about 87-108 MHz and the aeronautical services in the band 108-137 MHz, 10/1995, Available at: https://www.itu.int/dms_pubrec/itu-r/rec/sm/R-REC-SM.1009-1-199510-I!!PDF-E.pdf

[12] Rohde & Schwarz, Aeronautical radio navigation measurement solutions Application Note, Available at: http://www.rohde-schwarz.com/appnote/1MA193

[13] Acakpovi A, Tefutor I, Quist-Aphetsi K, Nwulu N, Sowah R and Abubakar R, 2019 Impact analysis of induced FM radio interferences on aeronautical radio navigation systems: case study of Kotoka international airport, Accra-Ghana, International Conference on Computing, Computational Modelling and Applications (ICCMA), Cape Coast, Ghana, 2019, pp 19-197, doi: 10.1109/ICCMA.2019.00011

[14] Skrypnik O 2019 Radio Navigation Systems for Airports and Airways, Springer Aerospace Technology

[15] https://www.keysight.com/us/en/assets/7018-01953/data-sheets/5989-9815.pdf

[16] https://www.keysight.com/us/en/assets/7018-01515/data-sheets/5989-6278.pdf