COMINT Solutions Developed for the Modern PET/PCL Passive Netted Radars – Features, EA Immunity and the Passive Radar System Protection Capability

Roman Jażdżewski
AM Technologies
Al. Jerozolimskie 146C
02-305 Warszawa
POLAND

E-mail: roman.jazdzewski@amt.pl

ABSTRACT

The paper focusses on the description of modern Communication Intelligence (COMINT) solutions employed by the Passive Emitter Tracking (PET) system, integrated with the Passive Coherent Location (PCL) system within the passive netted radars. COMINT geolocation capabilities, applied for the airborne radiocommunication transmitters, are described in particular. Graphical interpretation of the PET/PCL heterogeneous data fusion for the 3D hybrid geolocation is given as an illustration of systems integration. COMINT elements immunity against the Electronic Attack (EA) and its potential capability to find the direction of arrival and locate the jammer, to protect the PET/PCL system, are shown.

1.0 INTRODUCTION

According to the classical EW (Electronic Warfare) definition: COMINT (Communications Intelligence) and ELINT (Electronic Intelligence) are parts of SIGINT (Signal Intelligence), that is a counterpart of ES (Electronic Support) next to EP (Electronic Protection) and EA (Electronic Attack) that are the main components of EW. In other approach the COMINT is one of the intelligence information gathering ways, among ELINT, FISINT, IMINT, OSINT, MASINT, HUMINT and GEOINT. In a wider context COMINT is a part of a complex mixture of Spectrum Operations, Computer Network Ops, Cyber Ops and Network Centric Ops, all performed by the C6ISR (Command, Control, Computers, Communications, Cyber, Combat, Intelligence, Surveillance, and Reconnaissance) class systems to which the contemporary GBAD (Ground Based Air Defence) systems, incorporating passive and active netted radars information, belong too.

From the technical point of view, the area of the COMINT operation is the passive monitoring (detection, recognition, location) of signals emitted by the military radiocommunication transmitters (transceivers, radio-relays, video and data links, satellite terminals, etc.) used by the adversary forces. Among them, there are airborne transmitters also.

As far as the airborne transmitters and their platforms are considered, the COMINT system distributed sensor network can provide the information of detected, located, recognized and tracked emitters/targets to the GBAD systems, playing the role of more than passive radar, in addition to the ‘classical’ passive radar systems employing the PCL (Passive Coherent Location) technologies. Opposite to the PCL systems, that locate the reflected signal coming from the target platforms, the COMINT system exploits the primary signal sources coming from emitters installed on airborne platform. This is the reason why the COMINT systems are classified as a PET systems (Passive Emitter Tracking or Passive ESM Tracking, where the ESM stands for the Electronic Support Measures, classical part of the EW what reflects better the true nature of the PET).

The essence of the Air Defence PET/COMINT system is to locate and track airborne objects, that are usually fast moving in the 3D space (its longitude, latitude, altitude and the velocity vector are to be established). This is a little more demanding and challenging then it takes place in most typical land based COMINT systems, designed to recognise terrestrial transmitters placed on the Earth (i.e. in the 2D space), where most of them are stationary (with fixed position) or moving with relatively low velocity. The main limitations of the PET/COMINT include: the lack of the capability to easily average elementary measurements (bearings, time differences, frequency differences) and the estimated location results, in order to increase their final accuracies (because the recognised objects are in motion with not known velocity and trajectory). The evaluation of the recognized object altitude, that is usually not known, is also demanding. It requires Direction Finders with the elevation measurement additional capability, or extra TDOA/FDOA sensors, deployed in the area, to gather more data.

This article focuses mainly on the COMINT solutions applied for the passive location of radiocommunication RF signal sources in the 3D space. Resulting object location accuracy enhancement in 3D space can be achieved by elementary hybrid heterogeneous data fusion from PET/COMINT with those coming from the PCL system. Synthetic comparison of the PET and PCL systems main advantages and limitations, proving their complementarity, is presented in Table 1.

Graphical comparison of geolocation results of the hybrid configuration of the PET and PCL systems, as the superposition and surfaces intersection, related to the applied methods, in the 3D space, is shown in Figure 7 in chapter 3.5.

The COMINT vulnerability and the immunity enhancement methods against the enemy Electronic Attack (EA) are described in chapter 4. The COMINT capability of the PCL jamming detection and its protection from wrong indications is pointed out as useful side-effect feature.

Table 1: PET vs PCL system features comparison.

System	Advantages	Limitations
PET COMINT	• long range of the airborne emitter detection and location; • possibility of the stationary objects location, hovering (suspended) at a low altitude or placed on the ground; • location possibility of jamming devices; • allow to classify and identify the transmitter based on signal analysis; • possibility of demodulation (e.g. airplane pilot correspondence) and decoding (e.g. ADS-B, IFF transmission) of the transmitted signal; • location possibility of small, e.g. UAV drone class, and 'Stealth' objects (detection and location don't depend on the reflection surface (RCS));	• requires the activity of on-board RF/MW transmitters on the recognized object; • the location range depends on the parameters of the transmitter (power, band, emission duration); • requires min. 2, 3, 4 deployed stations/sensors, depending on the method (AOA, TDOA, FDOA, SSD) and the number of space dimensions (2D/3D) of the geolocation.

System	Advantages	Limitations
PCL	• does not require the presence/activity of on-board RF/MW transmitters placed on the recognized object; • a single measuring station is sufficient to locate a single object (in case of several occasional transmitters availability); • continuity of measurement data for individual route points of the located object; • potential capability of location objects made in the 'Stealth' technology.	• requires min. 3 occasional transmitters (3D localization) if only single PCL station is operating; • the location range depends on the presence and parameters (incl. power) of occasional transmitters and the reflection surface (RCS) of the localised object; • a limited number of occasional transmitters types can be used; • requires the located object movement; • limited ability of automatic classification of the localized object type; • vulnerable (sensitive) for interferences coming from the moving objects (e.g. terrestrial wind turbine blades); • ambiguity of indications if the SFN (Single Frequency Network) transmitters operate; • the compensation of the NLOS radio channel impact, based on the estimation of the impulse response characteristics on the basis of the training sequences, is not always possible

2.0 COMINT SYSTEMS GENERAL DESCRIPTION

2.1 Signals of Interest

Among the signals of the COMINT systems interest there is a wide range of analog and digital communication systems transmissions, open access or ciphered, Fixed Frequency or Spread Spectrum (Frequency Hopping and Direct Sequence), continuous or packet transmissions covering the HF/VHF/UHF/SHF frequency ranges:

- HF (1 – 30 MHz) radiocommunication systems, analog (e.g. AM, FM, SSB voice) and digital transmissions (e.g. Link-11, MIL-STD-188-141B App C, CIS-12);
- VHF (30 – 88 MHz) land band radiocommunication systems;
- **VHF (108/116 – 138 MHz) air band radiocommunication systems;**
- VHF (156 – 163 MHz) marine band radiocommunication systems;
- **UHF (225 – 400 MHz, 960 – 1215 MHz) air bands radiocommunication systems and data links (e.g. Link 16, C-107-1, C-111/AT-21);**
- **ISM bands (433 MHz, 868 MHz, 2.4 GHz, 5.8 GHz) not licenced devices;**
- L/S (1.250 – 2.6 GHz), C (5.85 – 8.20 GHz), X (8.2 – 12.4 GHz), Ku (12.4 – 18.0 GHz), K (18 – 26.5 GHz), Ka (26.5 – 40.0 GHz) satellite communication systems, including the Personal Communication Systems (PCS): Inmarsat, Thuraya, Iridium (1626.5 – 1660.5 / 1525 – 1559 MHz,

6 / 3.5 GHz);

- other VHF/UHF/SHF radio relays, data links and **telemetric data transmitters (UAV, rocket missiles).**

Apart from the strictly communication signals, other sources of RF emission can be used for the transmitter and object location by the COMINT system, provided that they occupy the frequency range of the COMINT system. Among them there are:

- identification transponders (e.g. IFF, ADS-B, PAROL, SOPKA-2);
- radionavigation devices (e.g. TACAN, radio altimeters);
- radiolocation radars;
- other (e.g. radiocommunication and radar jammers).

2.2 COMINT System Functionalities

Typical, contemporary, modern COMINT system performs the following operations:

- wideband signal acquisition, buffering and signal recording (for the off-line processing);
- wideband spectrum estimation;
- automatic search and active signals detection;
- narrowband (NB) signals digital extraction (channelizing);
- signal analysis and parameters estimation, modulation and coding types recognition of extracted signals;
- information interception (demodulation, decoding, recording);
- Direction Finding (depending on configuration);
- signal source (transmitter) geolocation;
- transmitter position tracking;
- data and information (coming from the detection, parameters estimation and automatic recognition, direction finding, geolocation, interception) fusion.

For the PET/COMINT system, the most important functionality is the ability to estimate the location of the adversary target transmitter.

2.3 COMINT System Network

Typical COMINT ground system network, intended for the airborne radiocommunication transmitters recognition, consists of a set of ground RF/DF sensors deployed in the area of operations (opposite to the PCL, where a single station/sensor, cooperating with several occasional transmitters, can locate the air target object). The number of sensors depends on the location method and the area of system coverage.

COMINT system sensor deployment, presenting its RF signal measurement capabilities, such as Direction Finding (azimuth and elevation estimation), time differences and frequency differences evaluations of signals coming from the airborne transmitter, is shown in Figure 1.

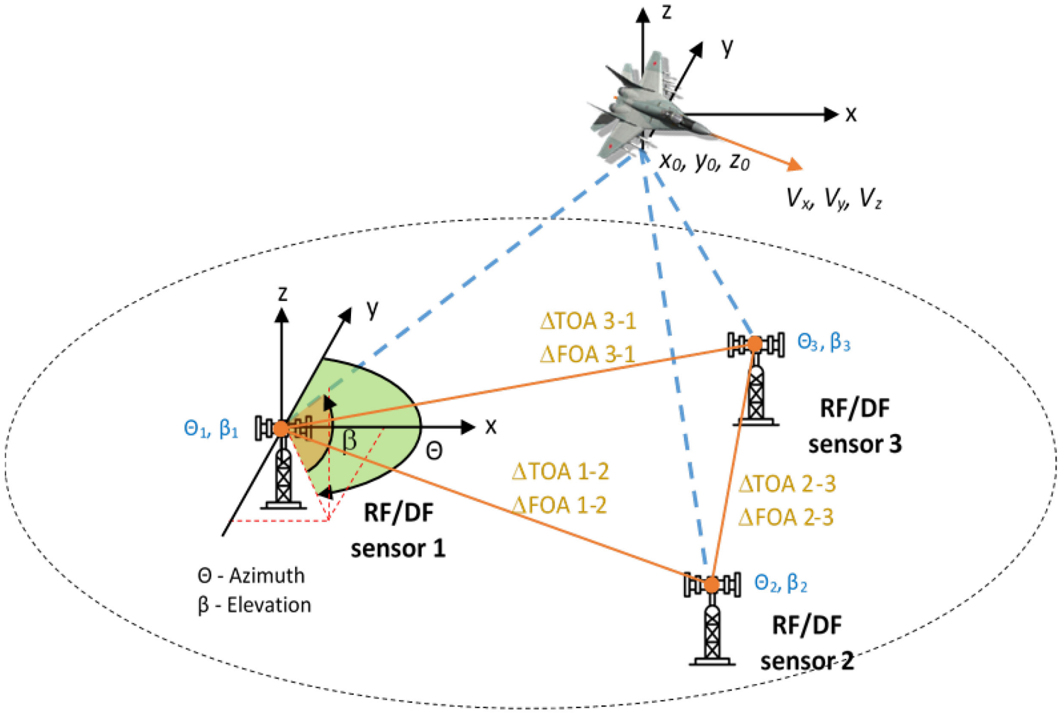

Figure 1: Ground COMINT system network for the Air Defence - representative deployment of RF/DF sensors.

2.4 Examples of Developed Systems

Several countries in the world have developed their own PET systems, some of them having the COMINT capabilities. Examples are listed below.

- Poland (PIT/PW/AMT): PLS;
- Czech Republic (Era): VERA S/M, VERA-E, VERA-NG;
- Finland (Patria): ARIS, ARIS-E;
- Sweden (Saab): SIRIUS GBAD (Ground Based Air Defence);
- Israel (Elta): EL/L-8388;
- Ukraine: KOLCHUGA;
- Russian Federation: AVTOBAZA-M, ORION/VEGA 85V6A, KRASUHA-S4, MKTK-1A JUDOIST, POLE-21;
- China: YLC-20, YLC-29, DWL-002.

3.0 GEOLOCATION METHODS

All of the RF signal source geolocation methods depend on the fact that the radio signal EM waves propagate straight-line, with all directions in the surrounding vicinity of the transmitter, with limited, well known velocity. Obstacles causing reflections and refractions can disturb the propagation direction. Moreover, the signal strength decreases with the distance from its source.

Geolocation systems employ a set of fixed (or being on the move) sensors, deployed in the analysed space or in the vicinity of the area of interest, placed on ground, sea or put on the air platform, allowing to receive and analyze the signal. Measured features / signal properties that are used for the geolocation:

- propagation direction;
- propagation time delays or time differences of signal arrival;
- received frequency or frequency changes, caused by the Doppler effect, if the source and/or the sensors are on the move;
- received signal power strength or signal strength differences.

In general, there are following geolocation methods of RF signals:

- Angle based:
  - Angle of Arrival (AOA);
- Distance based:
  - Time of Arrival (TOA);
  - Time Difference of Arrival (TDOA);
  - Time Sum of Arrival (TSOA) – applied to the PCL for reflected signals location;
- Velocity based:
  - Frequency Difference of Arrival (FDOA);
  - Signal Doppler Frequency (SDF);
- Signal property based:
  - Signal Strength Difference (SSD) / Receive Signal Strength (RSS) / Receive Signal Strength Indicator (RSSI) / Power of Arrival (POA) / Power Difference of Arrival (PDOA);
- Hybrid (combination of the above methods).

For the airborne transmitters localisation, by the ground COMINT system, only some of the mentioned above methods are practically implemented (AOA, TDOA, FDOA, hybrid).

Synthetic comparison of the geolocation methods of primary signal sources (transmitters placed on the recognised objects) or signals reflected from the recognized objects (originally coming from the occasional ground transmitter) is given in Table 2.

More detail description of selected methods and the graphical illustration of principles of work are presented in the following subchapters.

Table 2: Geolocation methods of RF signal sources or signals reflected from the recognized objects.

Method	Advantages	Limitations
AOA	• ability to estimate azimuth and elevation by a single direction finder; • possibility of narrowband, wideband and short emissions location; • possibility of the 2D/3D location of the emitter based on 2 direction finders; • small amount of data transferred within the system	• multi-element antenna arrays (systems); • multichannel, coherent hardware; • advanced signal processing
SSD	• single-channel RF sensors; • small amount of data transferred in the system	• low location accuracy; • requires sensors with known directional characteristics (in elevation and azimuth) and assumption that transmitter has omnidirectional radiation characteristic
FDOA	• single-channel RF sensors; • good location accuracy for narrowband and the long lasting signals.	• low accuracy for the short signals and/or the low velocity of the object/sensor and/or the low nominal frequency of the source; • location of a mobile emitter wit not known velocity vector by a set of fixed sensors requires large number of sensors; • the transmission system requires relatively high throughput (bandwidth) if the I/Q data are transmitted
TDOA	• single-channel RF sensors; • good location accuracy for broadband signals.	• low location accuracy for narrowband signals; • 2D positioning requires signal reception by 3 sensors at least, 3D positioning requires 4 sensors; • low 2D location accuracy for the high altitude objects; • the transmission system requires large bandwidth (throughput)
TSOA	PCL (see Table 1)	PCL (see Table 1)

3.1 Angle of Arrival

Angle of Arrival (AOA) geolocation method is the most popular method for radiocommunication transmitters location. AOA is based on directions (angles) of incoming RF signals estimation, by a set of sensors - Direction Finders (DF), deployed in the area at known positions. Depending on the applied technology, Direction Finders are able to estimate only azimuths or both azimuths and elevations for received RF signals. Azimuth is represented in the 2D space as Line of Bearing (LOB) what corresponds the semiplane in the 3D space. The direction described by the azimuth and elevation is represented by a straight semi-line (radius) in the 3D space. Example for the 3D space is shown in Figure 2.

Some most advanced Direction Finders, with super resolution algorithms implemented, e.g. Multiple Signal Classification (MUSIC), in case of co-channel signals simultaneously coming to the DF antenna from various directions, are able to estimate, instead of a single resultant bearing on an analysed frequency, the whole space spectrum, i.e. angle distribution of all incoming signals (an example shown in Figure 3).

The DF accuracy depends on the Signal to Noise Ratio (SNR), time-bandwidth product (number of independent samples), number of antenna elements and the relative, with respect to the wavelength, distance between the antenna elements.

After the bearings are collected, the transmitter position is estimated. There are several methods and algorithms of the transmitter geolocation, in the 2D and 3D space. Among them there are closed form solutions, e.g. based on least squares, or iterative algorithms.

The main advantage of Direction Finding is the capability of the target direction information estimation, by a single sensor. The main disadvantage is quite complex hardware and software architecture, coming from the advanced antenna systems (arrays) and multichannel, coherent signal processing requirements.

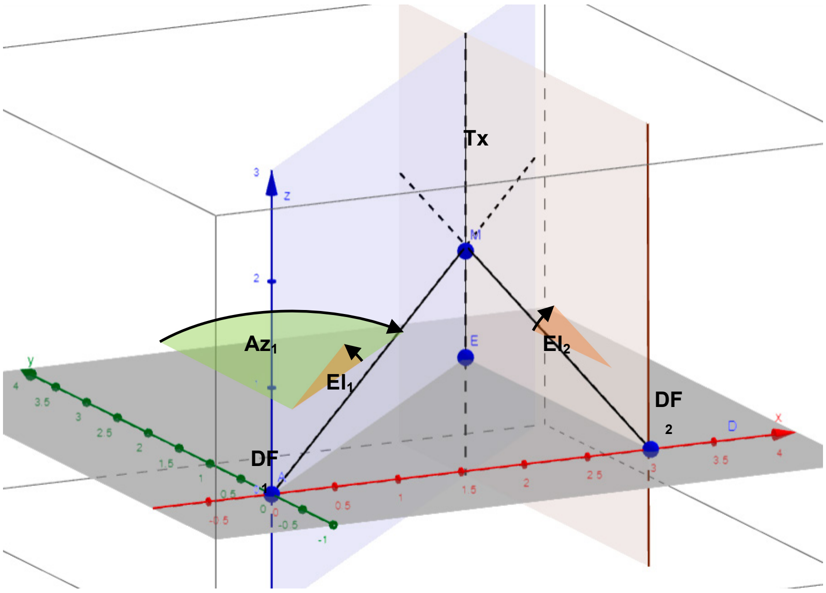

Figure 2: Illustration of the Direction Finding and the AOA principle transmitter geolocation in the 3D space by two Direction Finders.

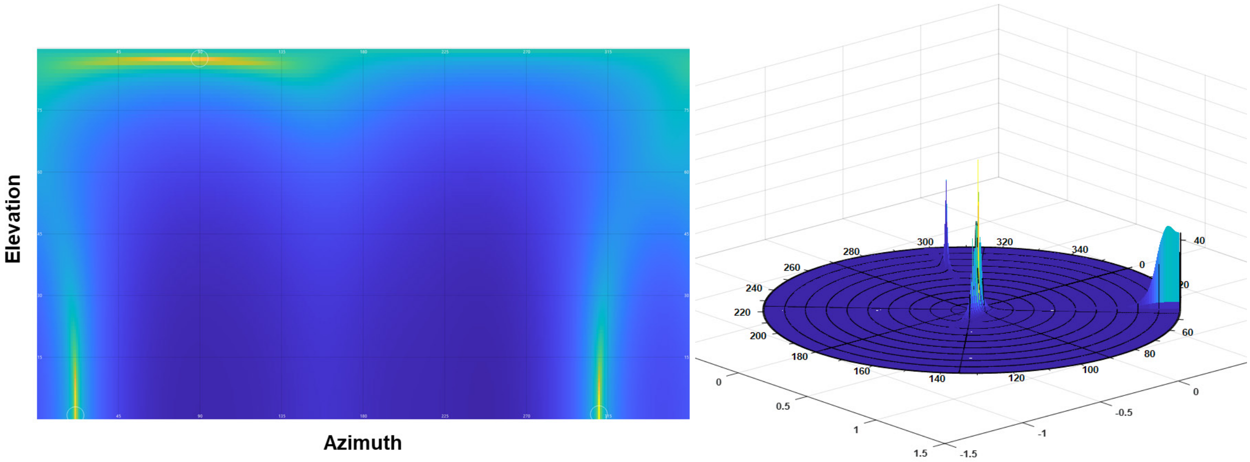

Figure 3: Super-resolution Direction Finding MUSIC algorithm (azimuth and elevation), rectangular and polar results representation for 3 emitters.

3.2 Time Difference of Arrival

Time Difference of Arrival (TDOA) is a second most popular method for the RF signal geolocation.

TDOA determines the relative position of a transmitter based on estimated differences in the propagation time between transmitter and multiple reference sensors. Time delays between RF sensors in pairs are estimated on the time correlation principle and its maximum search.

For moving signal sources, two-dimensional Cross Ambiguity Function (CAF) estimation is required, that allows to determine both the time and the frequency (caused by the Doppler effect) differences. An example is shown in Figure 4.

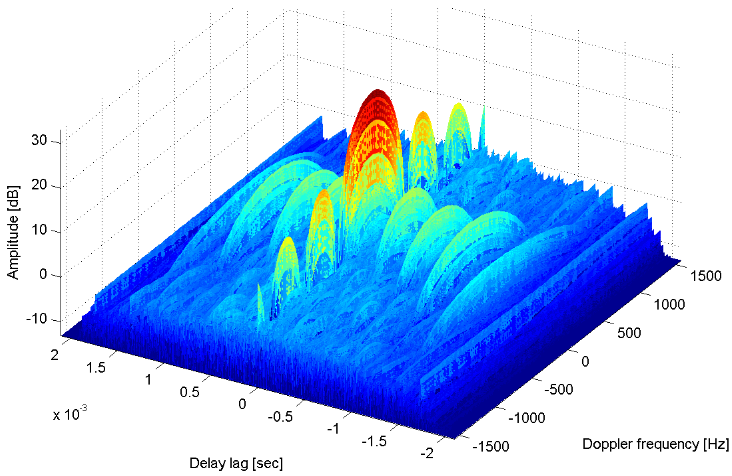

Figure 4: CAF function example.

The time domain accuracy of the CAF function depends on the signal bandwidth (higher bandwidth better accuracy). The accuracy in the frequency domain depends on the signal duration (longer signal better accuracy). Both of them depend on the SNR and the number of independent samples (Time-bandwidth product) taken into account for the calculations.

On the basis of the signal time difference value, estimated for a pair of Rx sensors with known positions, the respective hyperboloid (3D surface) can be calculated. The position of the transmitter, can be estimated on the basis of several hyperboloids intersection point. In the 3D space 3 independent hyperboloids are required (calculated on the basis of signals received by four RF sensors). An Example is shown in Figure 5.

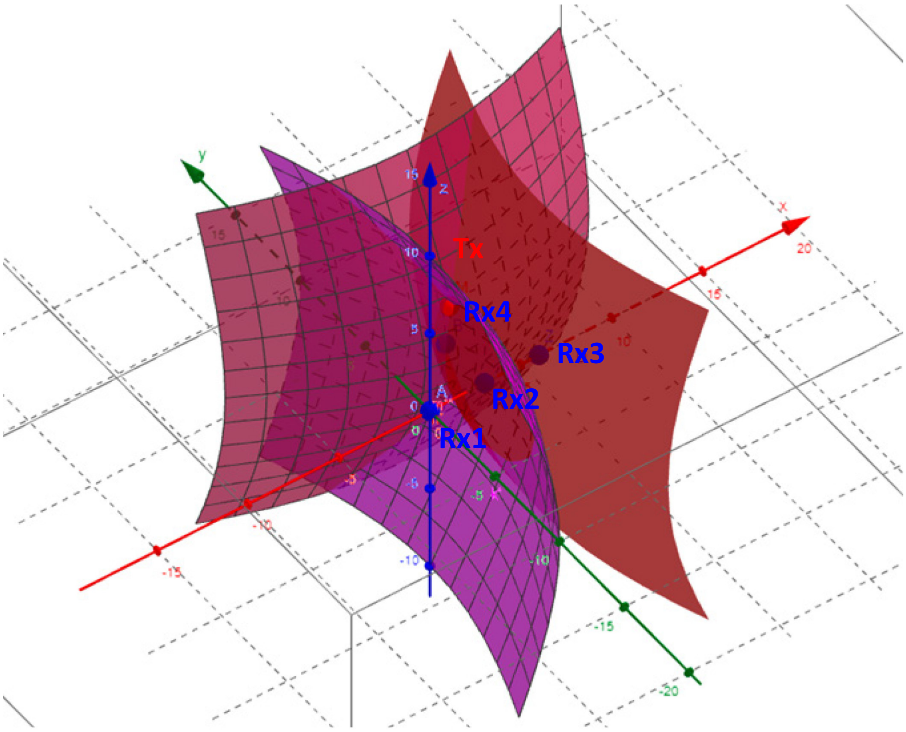

Figure 5: Illustration of the TDOA principle transmitter geolocation in the 3D space by a set of Rx sensors.

3.3 Time Sum of Arrival

The Time Sum of Arrival (TSOA) method is used for the air moving objects location on the basis of signals reflected from them, that were originally transmitted by occasional ground transmitters with known positions (usually radiocommunication TV and radio broadcast or cellular) available at the area of operation. TSOA method is used in the PCL passive radars and cannot be applied to the PET/COMINT system. Because of the strong analogy between the TSOA (applied to PCL) and the TDOA (applied to PET/COMINT) the TSOA description is put in this paper. Another reason is the need of the intelligence data fusion coming from the PET and the PCL systems. Additional reason is the ability of the COMINT system to detect and locate potential jammers working in the frequency bands of the PCL radars.

The basic idea of the TSOA method is to use the RF sensor (receiver Rx) deployed at known position and employ the occasional ground transmitter Tx, also with known position, in order to measure (e.g. on the basis of CAF function) the time delay difference between the signal received directly from the ground transmitter and the signal reflected from the located object. Measured time difference is related to the distance difference (assuming known velocity of propagating radio waves). The calculated sum of two distances:

- distance between ground occasional transmitter Tx - RF sensor (receiver Rx), and
- distance related to the measured time delay,

can be used to describe ellipsoid equation, whose focuses are located at the transmitter and receiver positions. This ellipsoid is treated as a set of points that are distanced from two focuses in that way that the sum of ranges to focuses is equal for every point of ellipsoid and is equal to calculated above sum of distances.

Single ellipsoid contains the set of all potential positions of the target object. In order to define the target position in the TSOA method at least 3 ellipsoid surfaces must cross. It can be achieved either by using several occasional transmitters (with limited number of sensors) example shown in Figure 6, or using several deployed RF sensors (with limited number of transmitters).

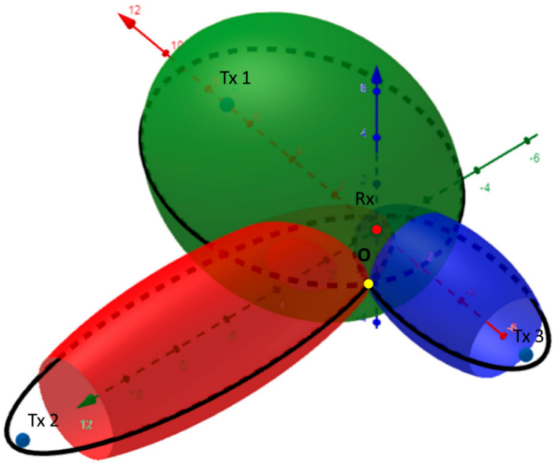

Figure 6: Illustration of the TSOA (PCL) object geolocation principle in the 3D space.

Rx	Receiver
Tx 1..3	Occasional Transmitters
O	Recognized Object

3.4 Frequency Difference of Arrival

Frequency Difference of Arrival (FDOA) geolocation method employs the received RF signal frequency changes caused by the Doppler phenomenon, appearing when the target transmitter or the RF sensor are in relative move. Frequency changes are measured by comparison i.e. estimation of their differences. FDOA is usually described as a method used for geolocation of stationary transmitter (ground placed) with RF sensors placed on moving (e.g. airborne) platforms with known positions and velocity vectors. In this case, depending on the number of sensors, the ground target location can be determined either almost immediately or after some time, when sufficient amount of information, taken from various points of the sensor route, is gathered.

In the PET/COMINT system the situation is quite opposite i.e. sensors are stationary, placed on the ground, with known position and the target is moving, usually with not known velocity vector.

It is possible to locate a moving target transmitter, which is non-maneuvering and radiates a constant frequency signal, from measurements of the Doppler-shifted frequencies by several RF sensors, but there is no closed form solution [4], [6]. Due to the nonlinear nature of the problem, it is necessary to find the solution by 'brute force' grid searches. The minimum number of Doppler-shift measurements at distinct generic sensor positions in order to have a finite number of solutions, and later, a unique solution for the unknown target position and velocity are stated analytically [9].

3.5 Hybrid Geolocation Methods and Homogenous/Heterogeneous Elementary Data Fusion

When the hybrid target geolocation methods are considered, in this paper, it concerns elementary measurements data fusion, (i.e. measured: azimuths, azimuth+elevations, time differences, frequency differences, bistatic distances) and corresponding to them iso-surfaces (semi-planes, semi straight lines, hyperboloids, isofreq surfaces, ellipsoids) in the 3D space. As a result of this fusion, the target position should be estimated, according to the maximum likelihood algorithm assuming the common probability density function. Illustration of various, heterogeneous, elementary data (PET/COMINT& PCL), put in the common 3D space, is shown in the Figure 7.

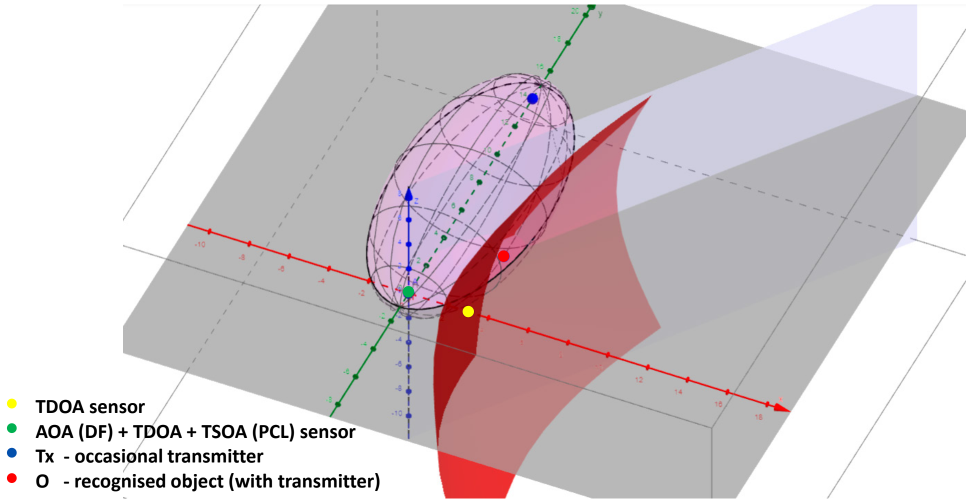

Figure 7: Hybrid PET (AOA+TDOA) + PCL (TSOA) target geolocation graphical illustration.

The minimum number of the DF (PET) and RF (PET and PCL) sensors and occasional transmitters (PCL), necessary to reduce the set of potential target locations to a finite number, using homogeneous or hybrid geolocation methods, evaluated on the basis of [3], [9], [10] and on the geometrical interpretation of the AOA, TDOA, FDOA, TSOA (PCL) measured parameters iso-surfaces is presented in the Table 3.

Table 3: Minimum number of the PET (AOA, TDOA, FDOA) and PCL (TSOA) sensors and occasional transmitters (PCL) necessary to reduce the set of potential target locations to a finite number, for 2D or 3D hybrid geolocation.

System	Item	Geolocation method		No. of Receivers (sensors)																		
				2D geolocation								3D geolocation										
PET	1.1	AOA (Azimuth only)		2				1	1		1						1			1		
	1.2	AOA (Azimuth + Elevation)										2				1	1				1	
	1.3	TDOA only			3			2					4			2						3
	1.4	FDOA only				5			4					7								
PCL	2.1	TSOA	Receiver							1	1							1	3	1	1	1
	2.2		Occasional transmitter							2	1							3	1	2	1	1

4.0 JAMMING IMPACT

The PET/COMINT system principle of operation is based on the target signal reception by a ground network of RF/DF sensors. As every receiving device, the RF/DF sensors are also vulnerable for the environmental RF interferences and the intentional jamming signals.

Adversary EA mission, against the ground COMINT RF/DF sensors, is performed using jammers (specialised RF transmitters intentionally emitting interfering signals). The aim of jamming is to superimpose false targets (causing false alarms) or decrease the true target SNR ratio (increasing additive + intermodulation Noise level) and, as effect, either decrease the measurement accuracy and the range of the RF/DF sensor operation or completely exclude the RF/DF sensor from its operation.

The overall PET/COMINT system (or the integrated PET/PCL system) jamming immunity analysis should take into account not only the single RF/DF sensor but all sensors being integrated in the network, that are under the influence of an adversary jamming (what exceeds the scope of work of this article).

4.1 Jamming Scenarios and Signal Types

There are following adversary jamming scenarios:

- **Escort Jamming –** performed by jammers installed on airborne platforms (manned or unmanned) that fly together with the defended intruder or are installed in an external pod of the intruder;
- **Stand-in Jamming –** performed by jammers placed in the close vicinity of attacked objects (mobile UAV drone platforms or 'single use' artillery shell jamming transmitters, with relatively low RF transmitted power);
- **Stand-off Jamming –** performed by jammers installed on airborne platforms or by the ground jammers, from a safe distance from the enemy assets, both with high RF transmitted power.

Listed above jamming scenarios are graphically presented in Figure 8.

Among the modulation techniques and the RF signal types, that are commonly used for the radiocommunication jamming purposes, there are:

- Narrowband, frequency selective (analogue or discreet modulations);
- Wideband barrage (RF noise or Linear Frequency Modulation 'CHIRP' or a group of regularly distanced spectrum lines 'COMB');
- Continuous or responsive;
- Intelligent (incl. 'deceiving', imitating signals).

From the technical, economical and the military personnel safety point of view (ground, stationary jamming station can be an easy target for the EM energy guided missiles), it seems that unmanned (using the UAV platform or 'single use' artillery shell jammers) stand-in jamming, operating in a limited area, in a close vicinity of only selected PET/COMINT RF/DF sensors, is the most probable scenario of the contemporary jamming. Scenario that all of the RF/DF sensors, incorporated in the COMINT system, are effectively jammed by the UAV swarm or using stand-off jammers should be considered as less probable.

Applying both of the following signal types seems to be likely to the same extent:

- wideband noise barrage jamming, increasing the additive background 'noise floor', lowering the sensitivity of the COMINT sensor and reducing its operational range;

- narrowband jamming or COMB jamming.

If the jammer is sufficiently close to the COMINT RF/DF sensor antenna, its signal can exceed the receiver dynamic range and cause intermodulations ('false' signals generation) and, in some cases, cause the total 'blackout' of the sensor and make it 'blind', not having a significant impact on the enemy's own communication system, at the same time.

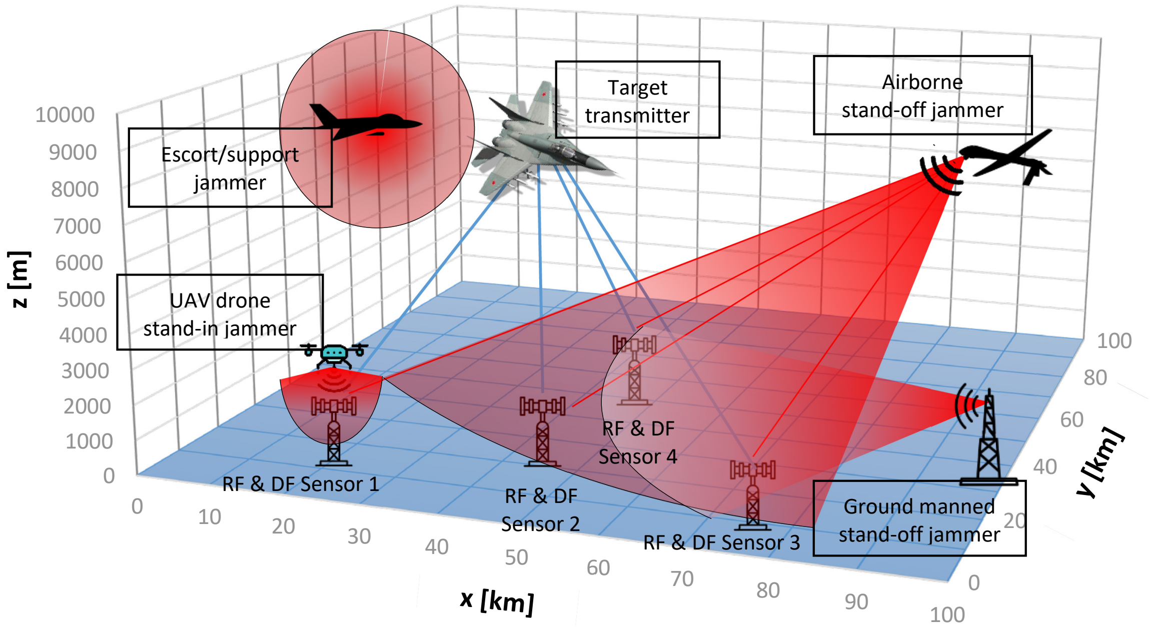

Figure 8: Jamming scenarios of the PET/COMINT system.

4.2 RF Front-End Limitations

The receiver analogue RF front-end and its parameters (NF, IP3, BW, SFDR) have the decisive influence on the COMINT capability of low and high power level signals detection, the operational range and the co-channel jamming immunity.

Quantitative relationship between the IP3 (parameter describing nonlinearity and the 3rd order intermodulation), processing bandwidth BW, Noise Figure NF and the resultant dynamic range SFDR is defined by

$$SFDR\,[dB] = \frac{2}{3}\left(IIP3 - \left(-174 + 10log(BW) + NF_{cas}\right)\right) \quad (1)$$

$$IP3\,[\mathrm{dBm}] = OIP3 - Gain_{cas} \quad (2)$$

where:

SFDR – spurious free Dynamic Range, in dB
BW – Bandwidth, in Hz
NFcas – Noise Figure of the system, in dB
IIP3 – Input Third Order Intercept Point, in dBm
OIP3 – Output Third Order Intercept Point, in dBm
Gaincas – Gain of the system, in dB

Linearly, with the increase of the BW, dynamic range decreases (even if the NF is still at the same, low level). As a result, 'unwanted' intermodulation products arise in the receiving device, even for lower levels of input signals (of the COMINT system interest, interfering or transmitted by jammer).

The problem is particularly important in the case of 'dense' frequency ranges with high activity and the need of 'weak' signals detection in the vicinity of 'strong' ones (e.g. transmitted by jammer).

In case of common wideband processing in modern receivers, the influence of co-channel interfering signals (narrowband and broadband), potentially causing intermodulations, is much more important than when the narrowband receivers were used.

4.3 Propagation Models

For the jamming efficiency assessment, the propagation impact on the distances between the transmitters (communication transmitter placed on the recognized object and the jammer transmitter) and the COMINT RF/DF sensor, should be taken into account. Appropriate model should consider the true propagation phenomena that actually take place (e.g. attenuations, refractions and reflections from all obstacles, incl. moving objects). Most accurate models, especially when the 3D terrain and mobile communication is considered, depict the propagation using the channel (or environment) impulse response containing all components (Time, Doppler, Direction of Arrival). For the purpose of this article, for the path loss and the received signal level (or received signal ratio) estimation, only the 'Free Space' and 'Two-Ray' simplified models are considered as good enough for most VUHF, high altitude, airborne communication and the UAV platform jammer transmitters.

For the 'Free Space' propagation model, the path loss $L_{F\text{-}S}$ can be calculated by the following equation

$$L_{F\text{-}S}\ [\text{dB}] = 32.45 + 20 \log f\ [\text{MHz}] + 20 \log d\ [\text{km}] \quad (3)$$

For the 'Two-ray' propagation model, more appropriate for the propagation close to the Earth surface, the path loss $L_{T\text{-}R}$, can be calculated by the following equation

$$L_{T\text{-}R}\ [\text{dB}] = 120 + 40 \log d\ [\text{m}] - 20 \log h_T\ [\text{m}] - 20 \log h_R\ [\text{m}] \quad (4)$$

Model selection criterion should be as follows: if the distance d between the transmitter and receiver is less than FZ (Fresnel Zone) the 'Free Space' propagation model should be used, otherwise, if the distance d is grater then FZ use the Two-ray propagation model ought to be used.

FZ can be calculated from

$$FZ\ [m] = \frac{4\pi h_T[m] h_R[m]}{\lambda[m]} \quad (5)$$

Alternatively FZ can be determined by

$$FZ\ [km] \simeq \frac{h_T[m] h_R[m] f[MHz]}{24000} \quad (6)$$

4.4 Jamming Influence Assessment

4.4.1 J/S Power Ratio

Jammer to target transmitter signal power ratio J/S is a good metrics of a jamming efficiency when the jammer and the target transmitter operate on the same frequency and the resulting S/(N+J) sensitivity reduction of the COMINT RF/DF sensor is considered. Assuming the Free Space propagation model, omnidirectional characteristic of the RF/DF sensor receiving antenna, and the uniform distribution of the power spectral density of the wideband barrage jammer, the J/S ratio, within the target transmitter signal bandwidth BW_S, at the reception point distanced from the jammer and the target transmitter, can be calculated on the basis of:

$$J/S = EIRP_J - EIRP_S - 20\log(d_J/d_S) - 10\log(BW_J/BW_S) \quad (7)$$

where:

- *J/S* – jammer signal to target transmitter signal power ratio, in dB
- $EIRP_J$ – jammer EIRP (Effectively Isotropic Radiated Power incl. jammer antenna radiation characteristics for its signal direction of arrival at the reception point), in dBm
- $EIRP_S$ – target transmitter EIRP, in dBm
- d_J – distance from the COMINT sensor to the jammer, in km
- d_S – distance from the COMINT sensor to the target transmitter, in km
- BW_J – jammer signal bandwidth, in Hz
- BW_S – target transmitter signal bandwidth, in Hz

Example calculations of the J/S ratios for the 2D space are presented in Figure 9.

It should be emphasized that some Direction Finding technics, especially superresolution (e.g. MUSIC), are able to distinguish and estimate both directions: the jammer noise source and the target transmitter, even if they are co-channel (because the noise emitted by the jammer is 'directional' for the Direction Finder).

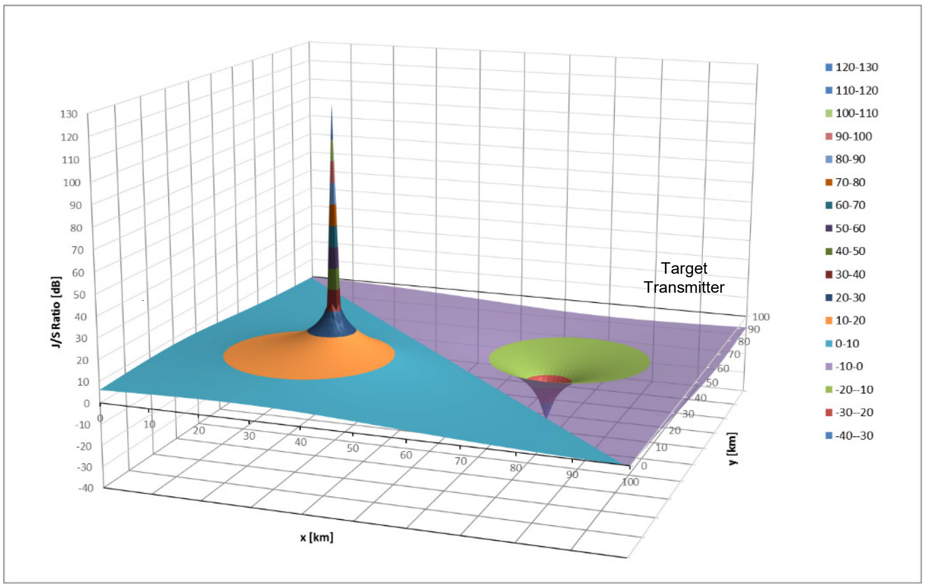

Figure 9: Estimated J/S power ratio, according to the Free Space propagation model, in the 2D space, for the jammer (33, 33) and the target transmitter (66, 66), operating with the same EIRP powers, bandwidths and frequencies (1000 MHz).

4.4.2 Effect of the Wideband Receiver AGC

Impact of a strong jamming signal (wideband or narrowband), exceeding the instantaneous dynamic range, put at the input of the wideband RF/DF sensor receiver, equipped with the AGC (Automatic Gain Control), if the jammer frequency is within the receiver bandwidth, even if not consistent with the target transmitter frequency, can cause:

- if the AGC is ‘on’: automatic reduction of the receiver gain what makes the receiver sensitivity worse and reduce the effective detection range;
- if the AGC is ‘off’ and if the immediate dynamic range is exceeded (or with the AGC ‘on’ and its control range is exceeded): the narrowband and/or wideband intermodulation products creation (described in the next chapter).

4.4.3 Intermodulations

High enough jammer signal power level, exceeding the receiver dynamic range, can cause not only the new detection of, really present in the air, signal (which direction can be found) or cause the target S/(N+J) ratio deterioration but it can also cause the appearance of, internally produced in the receiver, intermodulation products that are not present in the air. Such situation is more dangerous for the sensor and system then described previously.

The distance from the jammer for which the noticeable intermodulations appear in the RF/DF sensor can be treated as a next measure of jamming efficiency.

For illustration (results presented in Figure 10), practical operation ranges (reception distances) for two exemplary receivers (Rec.1 - miniaturised commercial and Rec.2 - professional class) were estimated on the basis of calculated (Free Space propagation was assumed) signal level vs distance from transmitter with fixed output power (1W). Dynamic ranges limited by the noise floors and intermodulations were taken into account. Signal exceeding the dynamic range are treated as effectively jamming.

The technical performance depends on the class of receiver. For the transmitter (e.g. ‘stand-in’ jammer) with the output power of 1 W, the low class miniaturised, commercial receiver (Rec.1), placed in the distance of 100 m, will produce intermodulation products, whereas the higher class receiver (Rec.2) is immune for such power jamming signal for distances above 12 m.

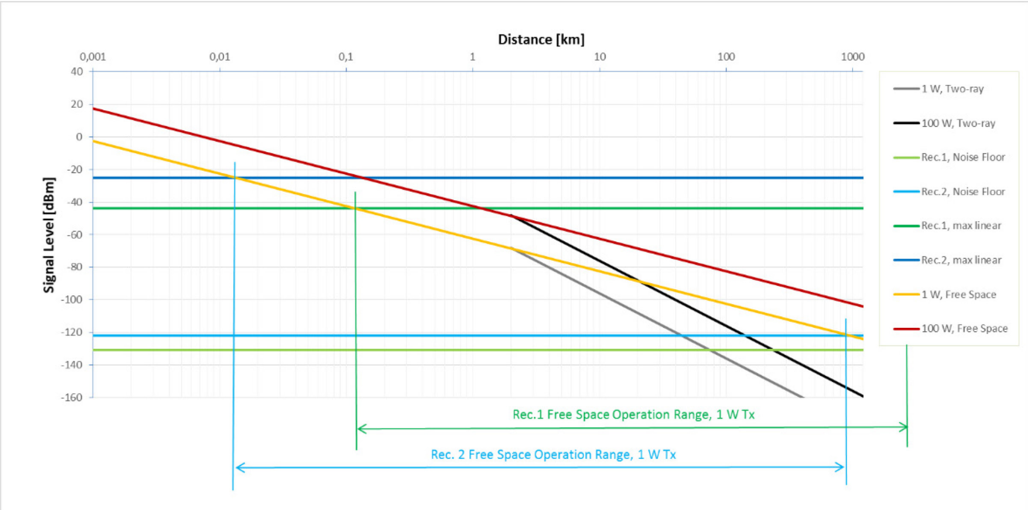

Figure 10: Received signal power level, for various distances from transmitters (1W and 100W, 1000MHz frequency), acc. to the: ‘Free Space’ propagation model (h_T, h_R not defined), and ‘Two-ray’ propagation model (h_T=10m, h_R=5m, FZ=2km).

4.5 System Jamming Immunity Enhancement

Enhancement of the COMINT system immunity against the intentional jamming, and making it operating, can be achieved by:

- careful selection of hardware components (professional class receivers with high IP2/IP3 and low NF values, assuring the high dynamic range);
- preselector filters implementation;
- incrementation of the PET sensors number;
- replacement of the single channel RF TDOA sensors by the DF sensors;
- state of the art, superresolution DF methods application, enabling the detection and separation of co-channel jamming emissions within the azimuth and elevation domain;
- PET and PCL systems integration.

5.0 SUMMARY & CONCLUSIONS

In this article the basic features of modern PET/COMINT systems, developed for the ground integrated PET/PCL passive netted radars, for the Air Defence purposes, are presented. The need to locate the airborne fast moving target transmitters, as a main task of the PET system, is emphasized. Various homogeneous transmitter location methods are compared, with respect to their technical performance and the number of required sensors.

The AOA method is shown as the most universal, in terms of signal bandwidth and its pulse duration, and is the least demanding as far as the number of sensors is considered. Using only two Direction Finders with the azimuth and elevation estimation feasibility, it is possible to locate the airborne emitter in the 3D space. The super resolution direction finding, allowing for the azimuth and elevation 2D space spectrum estimation and the separation of the directions of arrival, even if various signals appear simultaneously, within the same bandwidth, seems to be the most advanced solution and excellent response for the co-channel transmitters location (including the target operating in the presence of the PET jammer).

Moreover, the COMINT system equipped with the super resolution direction finder, as the only one subsystem of the PET/PCL passive radar, is able to detect the jamming signals of the PCL sensors (by monitoring, Direction Finding and locating RF sources active on civilian frequencies of occasional transmitters - if new directions appear it means the jammer or other interferer activity).

Alternatively, the TDOA or hybrid AOA+TDOA methods are indicated as good enough for the wideband signals 3D geolocation.

Quite a new approach is the interpretation of a hybrid PET/PCL geolocation, based on the combination of heterogeneous elementary measurement results, coming from the PET sensors and the PCL system, responsible for the determination of appropriate iso-surfaces:

- PCL: time sum of arrival – ellipsoids;
- PET/COMINT:
  - time differences of arrival – hyperboloids;
  - frequency differences of arrival – isofreq/isodop surfaces;
  - DF-ing results: azimuths – semiplanes or azimuths & elevations – semilines (rays);

and the common cross-section estimation, in the 3D space, as a location of the target (emitter and platform). Such approach, of elementary results fusion, allows for the target location accuracy improvement and provides redundancy. This redundancy, in some cases, can allow for the target location even if selected sensors of the PET/PCL passive radar are excluded from its operation and individual subsystems don't work properly (i.e. any of homogenous location method alone is not able to provide the location results).

This is extremely important when the most probable adversary stand-in jamming scenario takes place and some selected sensors are effectively jammed.

Calculations, presented in the paper, has proven that the COMINT RF/DF sensor RF frontend can be easily jammed and even overdriven (dynamic range being exceeded by the jammer signal), by the relatively low output power level stand-in jammers and that such kind of jamming is especially dangerous for modern, wideband sensors (dynamic range decreases with the bandwidth), in particular.

If the technical parameters concerning: the RF/DF sensors (frequency, IP3, NF, BW, number of antennas in the array, acquisition time), target transmitter (EIRP, bandwidth) and the jammer (EIRP, bandwidth) and their deployment points are known, quite precise results can be achieved with respect to the possibility and accuracy of the target transmitter geolocation.

The best way to assess the jamming influence would be the software simulator development.

In conclusion: the COMINT systems, in many aspects, play extremely important role as an fundamental part of the PET/PCL passive radars.

ACKNOWLEDGEMENTS

The author of this article would like to express his great appreciation to the whole AM Technologies company Management Board and the R&D Department engineering team, thanks to whom, many of the mentioned in this article digital signal processing algorithms have been practically implemented, tested and verified in the newly developed commercial products:

- wideband VUHF receiver 'CORVUS';
- wideband radiomonitoring system 'CYGNUS';
- wideband radiomonitoring and Direction Finding system 'CRUX';

description of which is available in the company web page: https://amt-sigint.pl/ where the appropriate technical information can be found.

The wideband VUHF receivers 'CORVUS' are installed in the Polish PET/PCL Passive Location System (PLS) stations where they serve as the RF sensors providing RF signal samples for the TDOA location.

The wideband radiomonitoring system 'CRUX', with the DF capability, is designed to be integrated with the Polish PET/PCL Passive Location System at its production stage. Its research and development phase was partially supported by the European Union founds, through the Polish National Centre for Research and Development (NCBiR), under the Intelligent Growth Operational Program 2014-2020, Project No. POIR.01.01.01-00-0022/16.

6.0 REFERENCES

[1] WAN Xianrong, LYU Min, XIE Deqiang, HU Shibo, *Jamming method of passive radar systems based on characteristics of signal structure,* Journal of Radars, 2020, 9(6): 987–997

[2] PAINE Stephen Thomas, Electronic countermeasures applied to passive radar, University of Cape Town, South Africa, 2019

[3] NGUYEN Ngoc Hung, DOGANCAY Kutluyıl, Optimal Sensor-Target Geometries For Doppler-Shift Target Localization, 2015

[4] ELGAMOUDI Abulasad, BENZERROUK Hamza, ELANGO G. Arul and LANDRY René, Jr., A Survey for Recent Techniques and Algorithms of Geolocation and Target Tracking in Wireless and Satellite Systems, 2021

[5] CHAN Yiu Tong, JARDINE F.L., Target localization and tracking from Doppler-shift measurements, 1990

[6] CHAN Yiu Tong, Passive Localization and Tracking of a Narrowband Source, Department of Electrical and Computer Engineering Royal Military College of Canada, 1992

[7] CHENEY Margaret, Passive Source Localization, Colorado State University

[8] PINE Karleigh, Cameron, PINE Samuel, CHENEY Margaret, The Geometry of Far-Field Passive Source Localization with TDOA and FDOA, IEEE Transactions on Aerospace and Electronic Systems (Volume: 57, Issue: 6, December 2021)

[9] SHAMES Iman, BISHOP Adrian N., ANDERSON Brian D. O., Doppler Shift Target Localization, IEEE, Transactions on Aerospace and Electronic Systems VOL. 49, NO. 1, JAN 2013

[10] CAMERON Karleigh J., BATES Daniel J., Geolocation with FDOA Measurements via Polynomial Systems and RANSAC, 2018 IEEE Radar Conference (RadarConf18), 2018