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GENERATING EFFECTIVE JAMMING AGAINST GLOBAL NAVIGATION SYSTEMS

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Abstract: *The article treats the possibilities of generating effective jamming against global navigation system users' equipment. It reveals that application of special ways of controlling the system of spatially distributed GNSS jamming transmitters makes it possible to generate jamming defeating the potentially feasible antijamming means.*

Keywords: *global navigation systems, adaptive antennas, auto jamming canceller, pattern.*

1. INTRODUCTION

The global navigation systems (GPS, GLONASS, Galileo, Compass/ BeiDou, eventually, IRNSS and QZSS) are playing an increasingly important role in human activities. Their impact on military science is unprecedented. The quality of control exercised over troops has dramatically improved using GNSS, modern computer and communication assets. GNSS are very effective in controlling air traffic and weapons.

However, in reality the GNSS (Global Navigation Satellite System) user navigation equipment (UNE) still plays a mainly secondary role in navigation and weapon guidance systems, military and special equipment. The principal reason behind it is exceptional vulnerability of GNSS UNE to jamming.

To remediate this situation, major designers and producers of UNE have carried out a wide scope of R&Ds aimed at promoting UNE jamming immunity.

As the designers claim, the newly created satellite navigation system has succeeded in receiving GNSS signals even in the conditions of directed active jammers, which makes UNE practically immune to electronic countermeasure (ECM) assets. Among others, the claim comes from naval-technology.com. According to this source, tests of this new jam-protected satellite navigation systems were conducted at a naval base in Maryland, using UAVs, whereby, due to employment of special antennas, the impact of directed jamming generators was successfully neutralized.

Evidently, the task of developing efficient means of suppressing radio navigation systems and means of their protection enabling the functioning of navigation system UNE under jamming, in their location, remains topical.

2. GNSS VULNABILITY TO JAMMING.

The principles of design of all GNSS are very similar and consist in transmitting mutually synchronized high-frequency broadband signals from a constellation of navigation satellites (24-30 units) from orbits in the order of 20 000 km above the Earth. The totality of such signals from several satellites is simultaneously received and processed by a ground-based (or on-board) navigation receiver, whereby, resultant from processing, information is extracted about the time of arrival of the signal of each satellite in a uniform time system. The spatial coordinates of each of those satellites are known in advance. Usage of the obtained and a priori known information as well of certain additional, so-called ephemeris, information makes it possible to unambiguously determine, with high accuracy, the spatial position of the phase center of the GNSS receiver antenna.

Continuous coded phase shift-keyed (PSK) signals are usually employed as navigation signals, with 1-2 MHz and 10 MHz spectrum width at 1200-1600 MHz carrier frequency. The law of modulation of the navigation signals normally represents variations of the so-called zero sequences of maximum duration (long-duration recurrent sequences with a low sidelobe level following compression), called M-codes.

Vulnerability to active jamming is a fundamental specific trait of GNSS. There are three clear physical factors causing it:

– great signals' transmission distance (~20 000 km);

- limited power of the satellite signal (10…50 W);
- low gain of the satellite transmitter antenna (evidently, usually not more than 10-15 dB).

Therefore, the power stream density of a signal of a single navigation receiver at the Earth surface, even if losses are ignored, is extremely small and does not exceed 10^{-13} W/m^2. Obviously, generating effective jamming by ground-based transmitters over the actual distances of 30-150 km, vs. such a low power of the useful signal, poses no technical problem. The 30-150 km distance is cited as actual due to limitation of the line-of-sight caused by Earth's sphericity and limitation of height to which the jammer antenna can be risen. Even portable GPS jammers can, over such distances and with emitting power of a few to tens of Watt, ensure a power excess over the satellite signal by 40-60 dB, even through the sidelobes.

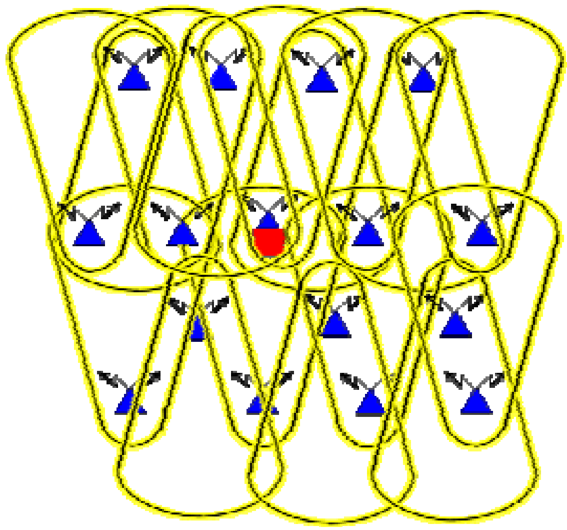
3. NOTES ON REASONABLE ORGANIZATION OF A GNSS JAMMING SYSTEM.

3.1. Feasible spatial configuration of a GNSS jamming system.

The above-stated makes it possible to assert that attaining high values of the jamming-to-signal ratio in jamming generation poses no technical problem. To ensure a steady jamming of GNSS receivers, one has to determine the reasonable level of the jam power within the selected jamming system configuration. In selecting the spatial configuration, one should take into account a number of factors:

- firstly, it has been practically ascertained that, in the frequency range under consideration, jamming is effective within the line-of-sight distance;
- secondly, based on analogy of the principles of coverage within the near cellular communication frequency range, we can easily see that configuration of a territorial anti-jamming system has to be similar to the structure of GSM 900/1800 cellular communication system, i.e. be a multi-position one with the grid step of 10…30 km over open terrain and considerably lesser step in the mountains and inhabited areas (to ensure the required line-of-sight effect);
- thirdly, the problem of selecting the power of the jamming signal of a single transmitter is highly debatable. Evidently, increasing the transmitter power to, say, a few kilowatt (as some experts suggest), boosts the jamming effect, increases the territory overlap factor, makes it possible to reduce the quantity of transmitters and, generally, reduces the system cost. However, it is obvious that a physically stable GNSS jamming system across a certain territory has to be a multi-position one, whereby increasing the number of transmitters complicates counteracting it. Increasing the number of jamming transmitters also corrupts the potential quality of suppressing them through coherent compensation.

A sample advisable spread of jamming transmitters (shown as blue triangles) across a certain territory is presented in Picture 1. The oval bodies represent horizontal cross-sections of the antenna patterns of individual transmitters. The square stands for the system control post. One can see that such distribution of the transmitters and orientation of their antennas form the jamming "patchwork blanket" wherein the moving victim object of jamming always hits the main jamming zone of at least one jamming transmitter (in reality, it is simultaneously impacted by 3-5 and more signals of the neighboring transmitters), whereby information about its own coordinates is lost due to permanent suppression of reception of GNSS signals.



Picture 1. Example of deployment of jamming transmitters in the terrain

Note. In the course of the latest conflict in Iraq (prior to the toppling of the regime) several sufficiently powerful GPS jammers were deployed across the country's territory. As the result of their employment, the aggressor lost a few dozen of cruise missiles during the first three days of the conflict.

Once the causes of deterioration of effectiveness of firing were determined, firings were suspended. Location of the jammers was pinpointed and they were destroyed. Firings were resumed with normal efficiency.

Lesson to be learnt. Preferably, it should be lesser power but more transmitters scattered across the territory. This would obstruct detection and destruction of the system's elements, which becomes less vulnerable.

3.2. Reasonable jamming power and law of modulation.

The years-long experience of using GNSS jammers in different conditions shows that, based on the criteria:

- relatively low per-unit cost of the jammers;
- reasonable rise of the transmitters above the ground (depending on the terrain, commensurable with the height of buildings, GSM towers, etc.);
- employment of mobile transmitter antennas with a low gain, not to exceed 10-15 dB;

– possibility of relatively protracted use of the jammers with autonomous chemical primary power supplies, the optimum value of the jammer output power would be 10-50 W.

Using a lower power would entail an unreasonable increase of the number of transmitters required for creation of a continuous jamming field. Using a higher power would deteriorate mobility (meaning, the portable and towed jammer versions), the autonomous operation time (at least a few hours), facilitate reconnoitering the jammers' position for their destruction by fire.

The jamming law of modulation is a special subject, that of "know-how". We would note here that even a jammer in the form of a continuous sinusoid within the C/A or P/Y – code bands will be sufficiently effective.

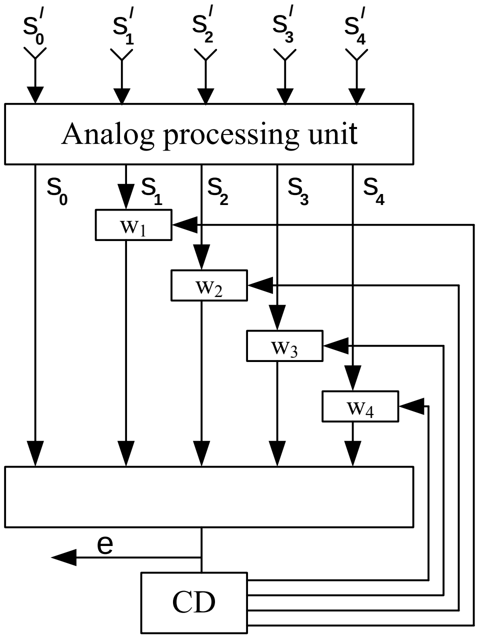
It has been established that jamming by sheer power can cause forcing the receivers into non-linear saturation mode (effectively, "blind" them), whereas lower power will result in the effect of disruption of resolution of the navigation problem without the above-mentioned non-linear effects. It has also been established that employment of a jammer with complex modulation affecting separate sub-systems of the navigation receiver (delay time, frequency, phase tracking) and suppressing reception of ephemeris information, provides a considerable economy of the jam power (or, given all other equal conditions, increased effectiveness of the navigation jamming system).

4. POTENTIAL POSSIBILITIES OF PROTECTING GNSS FROM JAMMING.

The practical possibility of jamming GNSS receivers demonstrated in the early 2000's has stimulated special research and improvement of satellite global navigation equipment. A number of publications have seen the light, mostly American ones, dealing with tangible achievements in perfecting the anti-jamming capacity of GNSS. Yet, it remains evident that no considerable achievements in enhancing anti-jamming capacity of GNSS can be expected by virtue of their principles of operation and the fact that satellite constellations have already been formed.

In the present treatise, we are not aiming at detailed analysis of the ways of improving GNSS anti-jamming, we shall only mention the most effective ones (in this case, we will deal only with GPS):

– introducing the new L5 frequency channel which will be used to transmit both the C/A- and P/Y-code signals. (Indeed, jamming the new frequency channel will, to an extent, complicate the jamming transmitter's design, but this is of no particular importance);
– introducing the new law of modulation of the navigation signal (distinct from the Gold code as variation of the M-codes mentioned earlier) with an expanded spectrum announced as especially jam-protected. It is transmitted on the L1 and L2 frequencies. To us it is obvious that this "dramatic" solution is not decisive. It does influence the effective jammer signal spectrum, but not too much in terms of additional power spent in jamming. A premium of power in using new navigation signals is achieved mainly by narrowing-down the satellite antenna's pattern to the diameter of a "spot" on the ground of a few hundred kilometers. The declared energy premium of 20 dB, even though doubtful, nevertheless does not negate the approach to jamming under discussion as unfeasible or ineffectual;
– quite likely, the most potentially effective way, out of the suggested ones, would be to introduce auto jamming canceller systems into GNSS receiver designs (usually called "adaptive antenna arrays" in the Western literature). A generic structural chart of an auto jamming canceller is presented in Picture 2. It is exactly the potential effectiveness of coherent jamming of GNSS that our Proposal is dedicated to.



Picture 2. Auto jamming canceller block diagram

The Picture 2 shows the GNSS receiver main antenna indexed 0 and four additional antennas indexed 1-4. Following the analog processing, signals of the additional antennas are weighed with subsequent summing resulting on rejection of the jammer from undesirable directions. The weight vector elements are formed in the control device CD.

One can confidently assert that, provided correct ways of controlling the system of spatially distributed GNSS jamming transmitters are properly selected, it is possible to generate jamming defeating the potentially feasible antijamming means.

5. TECHNIQUES OF DEFEATING ANTIJAMMING MEANS.

The jamming canceller's input signals $S_0^{`}$ and $\mathbf{S}^{`}=\{S_1^{`}\ldots,S_4^{`}\}^T$ represent signals of the GNSS receiver's main antenna $S_0^{`}$ and four additional antennas $S_1^{`}$, $S_2^{`}$, $S_3^{`}$, $S_4^{`}$. Here and below, the bold type stands for vectors and matrices, and the symbol T stands for transposing. The practical number of additional antennas is usually 2…5. Following the analog processing, vector $\mathbf{S}^{`}$ is transformed into vector $\mathbf{S}=\{S_1…,S_4\}^T$ and, for coherent jamming cancellation, is multiplied by the weight vector $\mathbf{W}=\{W_1, W_2,…,W_4\}$. Vector **W**, in a case following the complete adaptation procedure, assumes the value

$\mathbf{W}=\mathbf{R}^{-1}\mathbf{R_0}$, where $\mathbf{R}=\overline{\mathbf{S}\cdot\mathbf{S}^{+}}$, $\mathbf{R_0}=\overline{\mathbf{S}\cdot\mathbf{S}_0^{*}}$ - are the jammer correlation matrix and vector of cross correlation of signals of the additional and main antennas correspondingly, + and * - are the Hermitian conjugate and complex conjugate signs, the overhead line means temporal (or statistical) averaging.

The description of the cancellation procedure is widely known from the theory of adaptive antennas. The procedure of determining the weight vector **W** cancelling the jammer in an optimal manner can be realized in a number of ways – as the result of carrying out different self-tuning procedures or through direct calculations of different types. The most important reason why we have initiated this discussion with formulas, and being the foundation of our proposal, is that efficiency and convergence of any of the self-tuning procedures (adaptive one or based on direct calculations), depend on conditionality of the jammer correlation matrix **R,** whereby the worse the conditionality is, the worse is convergence. In practical terms, it means that when matrix **R** is poorly conditioned, the jamming canceller's tuning will proceed inadmissibly slow, i.e. slower than required to attain the effect of reliable cancellation of the jam in real time.

We shall remind here that correlation auto jamming cancellers are manifestly parametric devices. This means that their properties, including speed and efficiency, greatly depend on properties of the received signal. These properties practically cannot be effectively ridden of this dependence. In particular, conditionality of the correlation matrix **R** has direct influence on duration of the self-tuning process [1,6].

By shaping the jammer simultaneously using several transmitters, we can easily control conditionality of the matrix **R** through synchronous control of power of individual transmitters and interconnection of the laws of modulation of the jammers they radiate.

Formulating the essence of the idea.

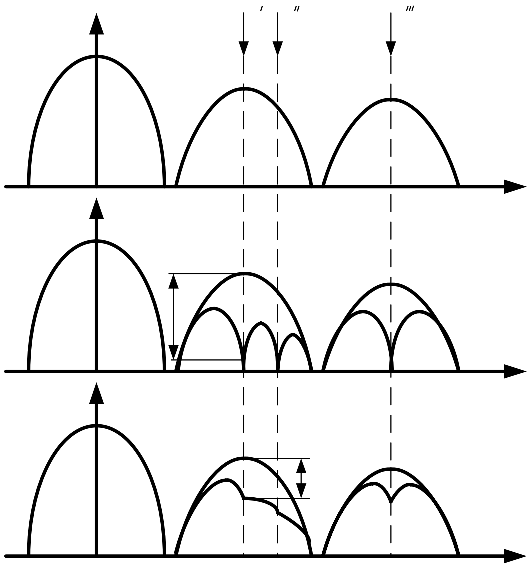
1. The subject of the discussion is a controllable multi-position system of jamming jam-protected GPS receivers by sheer power.

2. The system principle of operation consists in synchronous employment of several spatially misaligned GPS signal jamming transmitters, while simultaneously controlling the jamming signals' power values and (or) jamming signal modulation parameters.

3. The objective of simultaneous jams control is to make the auto jamming cancellers in the GNSS receivers function constantly in a transitional mode, by changing the jamming environment.

Essence of the changes – controllable variation of conditionality of the jam correlation matrix, or employment of blinking (periodically disappearing and appearing) jammers. The rate of changes is directly related to the close-loop auto jamming canceller's bandpass as an automatic control system.

The result of implementation of the proposed principle in terms of quality is shown in Picture 3. Picture 3a shows an antenna pattern of a GNSS receiver's main channel while the auto jamming canceller is deactivated, and directions at three simultaneously functioning jamming sources.



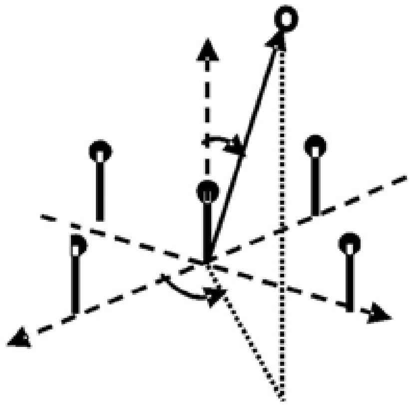
Picture 3. Receiver's main channel antenna pattern: a) auto jamming canceller is deactivated, b) auto jamming canceller is activated and jam is typical, c) special algorithm of synchronous jam control is used.

Picture 3b shows the result of normal cancellation of jamming by a correlation auto jamming canceller, demonstrating the effectiveness of normal suppression of jamming by a correlation jammer canceller declared by the authors of the project (minimum 60 dB – a propos, an obviously exaggerated picture). Upon activation of the special algorithm of synchronous jam control, the depth of nulls in the pattern will drop sharply. We are predicting that feasible cancellation efficiency will not exceed 5-7dB. i.e. the auto jamming canceller will stop resolving its task normally.

6. CONTENT OF THE WORK.

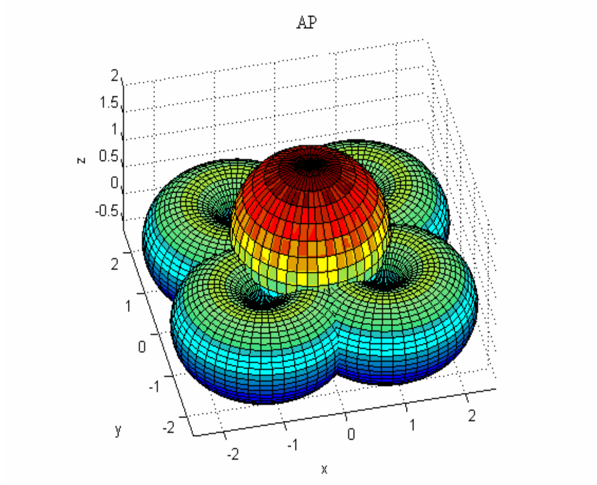
In order to verify the assumptions put forth, a simulation model of an automatic jamming canceller was realized, whose receiver elements' configuration is shown in Picture 4 (0 – position of the main antenna, 1…4 – position of the canceling antennas). Data from open literary sources were used in selecting the configuration [4,5].

The main channel antenna pattern (AP) is shaped as a rotation cardioid. The choice of the shape is not incidental, as similar antenna patterns are typical for GPS equipment of several producers, e.g. Sarantel Group PLC, Great Britain. Antennas generating AP of this shape ensure phase stability of the received signal in any direction as well as satisfactory gain and ellipticity, in addition they have small dimensions.



Picture 4. Configuration of the receive elements

The shape of the canceling channels' AP is toroid, selected as such to ensure suppression of the useful signal at channel inputs on its arrival from direction corresponding to θ = 0°. Thus, influence is eliminated (weakened) on the useful signal adaptation circuits on its arrival from the zenith direction. The shapes of the antenna patterns of the main and canceling antennas of the simulation model are shown in Picture 5.



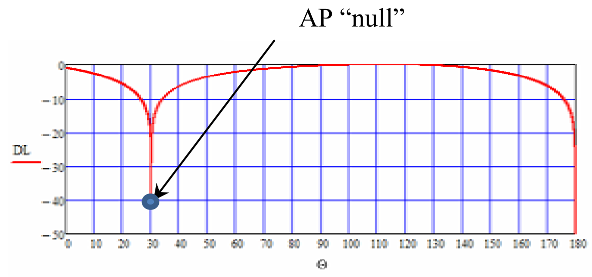
Picture 5. Main and canceling channels' AP shape

Below, we present a description of the numerical experiments done using the auto jamming canceller model developed, as well as conditions of their performance.

In the course of the experiments, we researched the influence of modulation of the jammer signals' power and cross-correlation of jamming signals on formation of the auto jamming canceller's jamming zones.

Each experimental test used a definite set of source data.

Based on sectioning of the spatial AP at the jamming canceller output by a plane passing along axis Z from the jamming source direction, we determined the intensity of the AP compression in the direction at the jamming source. The cross section of the altered spatial AP on formation of a "null" in the direction of the jamming source located at an angle of θ = 30 on logarithmic scale, is shown in Picture 6.° The value at AP «null» – jamming suppression intensity", was used as the auto jamming canceller efficiency criterion.



Picture 6. Spatial AP cross section

The power of the jamming sources in the simulation model exceeds 1000 times the power of the jamming canceller's internal noise, which corresponds to power received by the jamming canceller's antennas from a 10W jamming source located at a distance of about 100 km (we assumed the jammer's antenna gain to be equal to 10 dB). The jamming source power modulation followed the law

$$P_i(\mathrm{t}) = P_0 \cdot (1 + \cos(2 \cdot \pi \cdot f_m \cdot t + \varphi_0) \qquad (1),$$

where P_o - is the assigned power value;

f_m - is the jammer modulation frequency;

φ_0 - is the jammer initial phase.

The results obtained by six experiments with different source data are presented in Table 1.

Table 1. Modeling results

Number of jamming sources	1	1	2	2	2	2
1st jammer angular position						
θ°	30°	30°	30°	30°	30°	30°
φ°	0°	0°	0°	0°	0°	0°
2nd jammer angular position						
θ°	-	-	60°	60°	60°	60°
φ°	-	-	90°	90°	90°	90°
Modulation presence	No	Yes	No	Yes	No	No
Jamming signals cross-correlation factor	-	-			0.41	0.81
1st jammer cancellation factor (dB)	41.6	13.0	10.7	7.3	9.9	7.4
2nd jammer cancellation factor (dB)	-	-	19.7	15.9	11.5	7.1

7. CONCLUSION

Analysis of the results obtained in simulation modeling puts to doubt the assertion that employment of the new jam-protected satellite navigation system renders the user navigation equipment practically invulnerable to electronic countermeasures (ECM).

Using modulation of jammer signals with a cleverly selected modulation frequency tangibly corrupts operational efficiency of auto jamming cancellers.

Simultaneous employment of several jammers from different directions, even in a quantity lesser than that of the jamming canceller's degrees of freedom, will result in the jamming canceller’s suppression factor drop by 20-30 dB, whereas employment of cross-correlated jamming will decrease the jamming canceller’s efficiency down to 7dB. The five-fold (7dB) premium in the “signal/jammer+noise” ratio will shorten the UNE suppression range 2.24 times, e.g., from 145km (as pointed out in [3]) down to 64.78km for a 4W jamming transmitter.

Quite evidently, even in the face of deterioration of efficiency of a controllable multi-position jam-protected GPS receivers’ jamming-by-sheer-power system, a rational placement of the jamming transmitters and control over power and parameters of modulation of the jamming signals will make it possible to generate a continuous-solid UNE jamming zone.

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