The Use of Software-Defined Radio Systems in Multilateral Navigation Radio Systems

G. M. Mashkov, E. G. Borisov, A. G. Vladyko, and A. I. Gomonova

Abstract — The paper describes an optional application of software-defined radio systems technology in multilateral range finding systems for solving tasks of determining the flying objects coordinates. The design feature of the described system is the use of cooperative processing of range measurements aggregate to improve accuracy of object positioning.

***Keywords* — multilateral, range measurements, cooperative processing, mean square error (MSE), and software-defined radio systems (SDR).**

I. INTRODUCTION AND PROBLEM DEFINITION

The last decade has shown a significant growth in passenger and cargo air traffic, as well as a considerable increase of flights of privately owned aircraft. This leads to growing of air traffic density, overloading of airfield areas and flight routes. Besides, constantly tightened security requirements place higher demand on the accuracy of flying objects positioning in the shortest possible period. That is the reason why the developing of multi-position navigation radio stations is being carried out worldwide nowadays (for range finding only as well as for range finding and multilateration – MLAT - together).

Multilateral radio systems represent an independent cooperative navigation system of a new type, combining in single unit measurement subsystems, means of communication, data transfer, and computing devices. An example of such system is the MLAT system developed by Czech company Era [1]. Successful achievements in this field have been achieved by the French multinational group “Thales” [2]. The multilateral surveillance system “Mera”, developed by NIIRA JSC [3], is actively used in this country. Multilateral navigation system, developed by Australian company “Locata”, incorporates pinpoint accuracy characteristic, working in the 2.4 GHz frequency range [4]. General requirements for multilateral systems are given in [5].

The need for the emergence of such systems arrived due to the fact that the existing satellite navigation systems (GPS, GLONASS, and prospective European GALILEO system), have the following main disadvantages: low resistance when exposed to electronic interference, low signal value, complexity of working indoors, as well as in areas of dense urban development, in the mountain gorges, etc. Furthermore, the aforementioned systems lack positioning accuracy in urban areas and to the North of the 60^{o} parallel. The positioning error of GPS/GLONASS can reach over 30 m and more. The main advantages of MLAT systems in comparison with single position systems are the following: the possibility to form spatial view areas of complex configuration with a given overlap ratio, the ability to control and redistribute energy within the system, precise accuracy of flying objects positioning, the ability to measure objects complete velocity vector, etc [6, 7].

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II. BASIC PRINCIPLES OF MLAT SYSTEM DESIGN. NI USRP SOFTWARE-DEFINED RADIO SYSTEMS TECHNOLOGY

For mass adoption, MLAT systems need to have a low cost of installation with minimum operating costs, small size combined with low power consumption by using different power supply, easy to build up, update and reconfigurable hardware platform.

It is necessary to allow the operation of navigation equipment developed in conjunction with the systems used in the management of air traffic, such as ADS-B (Automatic dependent surveillance-broadcast) and their modifications, enabling the pilots in the cockpit and air traffic controllers on the ground point to observe the traffic of aircraft movements with greater accuracy and receive aeronautical information.

The instruments of software-defined radio systems could be used as prospective MLAT system transceiver modules. It would allow carrying on the tasks of generating signals of any modulation type, range finding, communication with an object being located, an exchange of information between modules, synchronization of functioning modes of the modules, and optimization of frequencies allocation inside the system etc. Software-defined radio system is a radio communication system in which the functions of the main instruments are implemented by software solutions. These instruments can include filters, amplifiers, modulators or/and demodulators. As soon as these instruments are configurable by software only, there is a possibility of modifying such a system without any significant changes in the hardware configuration. When using SDR, almost the entire volume of work on signal processing is shifted to the software that can run on digital signal processors or special DSP-purpose high-speed PLD. The main reason for such an approach is to create a system that can receive and transmit radio signals in a given frequency range and easily select the desired modulation law [10].

National Instruments Corporation proposes its own solution - NI USRP (NI Universal Software Radio Peripheral). It is a

HF transceiver controlled by a computer. The company offers the functional abilities of a graphical development environment NI LabVIEW for configuring SDR platform. Due to the programmability of the measuring equipment, this is a unique possibility to generate periodic test signals, depending on navigation receiver trajectory, i.e. there is no need for costly tests with participation of air traffic control. The NI USRP software contains a set of functions implemented in the form of virtual instruments (VIs for LabVIEW) to control one or more platforms for USRP. At the higher level, NI USRP driver proposes to use Vis for session opening, configuring of hardware, performance of read/write operations, and session closing. The basic principle of programming is the creation of virtual objects: a satellite, positions of a receiver and an HF generator. Each object is being operated by a link specially designated for it in the software. All of the properties, status and control are exercised by using functional tools incorporated into the set of built-in libraries for visualization [11].

Figure 1 shows a scheme of the MLAT navigation system, consisting of N ground-based transceiver points (GTP); each point emitting a broadband signal on a lettered frequency. Onboard equipment contains a multi-channel transceiver, receiving signals from GTP, and then relaying them. Each of the spatially separated GTPs receives relayed signals due to the request from each position, thus forming range-finding and summarized range-finding measurements. One of the GTPs is nominated as a primary point and takes all the measurements from the others (thus implementing cooperative processing), calculates estimates of rectangular coordinates and speed of their change.

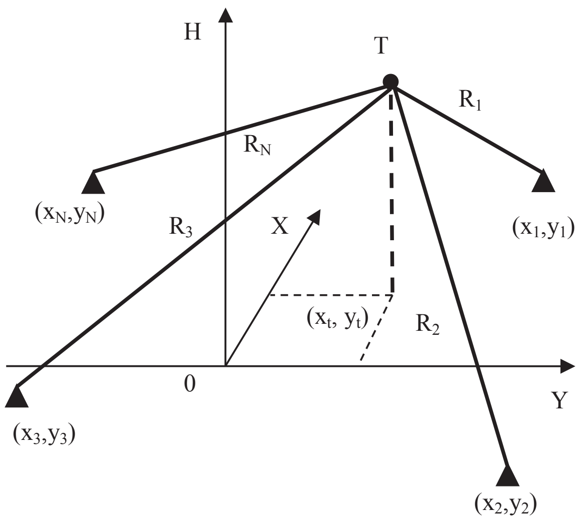

Fig.1 Layout of flying object positioning

For this case let us write a system of linear algebraic equations (SLAE), which takes into account the number of direct x - N and summarized N(N-1) measurements - , forming N^2 measurements, i.e.:

$$\begin{cases} \begin{cases} \hat{R}_1 = 1\cdot R_1 + 0\cdot R_2 + 0\cdot R_3 + \ldots + 0\cdot R_N \\ \hat{R}_2 = 0\cdot R_1 + 1\cdot R_2 + 0\cdot R_3 + \ldots + 0\cdot R_N \\ \vdots \\ \hat{R}_N = 0\cdot R_1 + 0\cdot R_2 + 0\cdot R_3 + \ldots + 1\cdot R_N \end{cases} & N\ meas. \\ \begin{cases} \hat{R}_{\Sigma 12} = 1\cdot R_1 + 1\cdot R_2 + 0\cdot R_3 + \ldots + 0\cdot R_N \\ \hat{R}_{\Sigma 21} = 1\cdot R_1 + 1\cdot R_2 + 0\cdot R_3 + \ldots + 0\cdot R_N \\ \hat{R}_{\Sigma 13} = 1\cdot R_1 + 0\cdot R_2 + 1\cdot R_3 + \ldots + 0\cdot R_N \\ \hat{R}_{\Sigma 31} = 1\cdot R_1 + 0\cdot R_2 + 1\cdot R_3 + \ldots + 0\cdot R_N \\ \vdots \\ \hat{R}_{\Sigma N(N-1)} = 0\cdot R_1 + 0\cdot R_2 + 0\cdot R_3 + \ldots + 1\cdot R_{N(N-1)} \end{cases} & N(N-1)\ meas. \end{cases} \tag{1}$$

$\hat{R}_1, \hat{R}_2 \ldots \hat{R}_N$ - primary measuring the slant range;

$\hat{R}_{12}, \hat{R}_{21} \ldots \hat{R}_{N(N-1)}$ - the primary measure summary ranges.

Equations (1) contain measurements relative to N^2 estimated parameters that allow us to implement their solution using the least-squares method [8,9]:

$$\widetilde{X} = \left[\left(A^T \Lambda W^{-1} A\right)^{-1} A^T \Lambda W^{-1}\right] H, \tag{2}$$

where A is the matrix of dimension NxN^2, consisting of zeros and ones, where "1" indicates the presence of corresponding dimension, and "0" its absence.

So, for three-position system, this matrix has the following form:

$$A^T = \begin{Vmatrix} 1 & 0 & 0 & 1 & 1 & 1 & 1 & 0 & 0 \\ 0 & 1 & 0 & 1 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 1 & 1 & 1 & 1 \end{Vmatrix}, \tag{3}$$

- matrix system condition, taking into account the totality of the processed measurements;

$H^T = \left\| \hat{R}_1, \hat{R}_2 \ldots \hat{R}_N, \hat{R}_{\Sigma 12}, \hat{R}_{\Sigma 21}, \hat{R}_{\Sigma 13}, \hat{R}_{\Sigma 31} \ldots \hat{R}_{\Sigma N(N-1)} \right\|$ - line vector of the estimated parameters (vector row of primary measurements);

$$W = \begin{Vmatrix} \sigma_R^2 & 0 & 0 & 0 \\ 0 & \sigma_R^2 & 0 & 0 \\ 0 & 0 & \ddots & \vdots \\ 0 & 0 & \ldots & \sigma_{R\Sigma}^2 \end{Vmatrix} \tag{4}$$

W is a precision matrix of dimension N^2 x N^2 containing the variance of range-finding errors and the sums of the ranges:

$$\Lambda = \begin{Vmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & \ddots & 0 \\ 0 & 0 & 0 & 0 & 1 \end{Vmatrix} \tag{5}$$

Λ is a diagonal matrix of coefficients, the diagonal element of which is equal to one if the measurement is present (or is used for measurements) and equal to zero if the measurement is not used.

Error covariance matrix for the system (2) is defined as [8]

$$K_{\hat{X}} = \left(A^T W^{-1} A\right)^{-1} \sigma_0^2 = diag\left(A^T A\right)^{-1} \sigma_0^2 , \quad (6)$$

where $\sigma_0^2 = \sigma_R^2 = \sigma_\Sigma^2$ - is the variance of measurement error of the range-finding parameter.

Therefore, for range-finding and summarized range-finding systems the expression of angle ranges and variances of the measurement errors obtained with (2) and (6) will take the following form:

- for three positions systems

$$\widetilde{R}_1 = \frac{7}{27}\hat{R}_1 - \frac{2}{27}\hat{R}_2 - \frac{2}{27}\hat{R}_3 + \frac{5}{27}\hat{R}_{\Sigma 12} + \frac{5}{27}\hat{R}_{\Sigma 21} + \frac{5}{27}\hat{R}_{\Sigma 13} + \frac{5}{27}\hat{R}_{\Sigma 31} - \frac{4}{27}\hat{R}_{\Sigma 23} - \frac{4}{27}\hat{R}_{\Sigma 32}$$

$$\widetilde{R}_2 = -\frac{2}{27}\hat{R}_1 + \frac{7}{27}\hat{R}_2 - \frac{2}{27}\hat{R}_3 + \frac{5}{27}\hat{R}_{\Sigma 12} + \frac{5}{27}\hat{R}_{\Sigma 21} - \frac{4}{27}\hat{R}_{\Sigma 13} - \frac{4}{27}\hat{R}_{\Sigma 31} + \frac{5}{27}\hat{R}_{\Sigma 23} + \frac{5}{27}\hat{R}_{\Sigma 32} \quad (7)$$

$$\widetilde{R}_3 = -\frac{2}{27}\hat{R}_1 - \frac{2}{27}\hat{R}_2 + \frac{7}{27}\hat{R}_3 - \frac{4}{27}\hat{R}_{\Sigma 12} - \frac{4}{27}\hat{R}_{\Sigma 21} + \frac{5}{27}\hat{R}_{\Sigma 13} + \frac{5}{27}\hat{R}_{\Sigma 31} + \frac{5}{27}\hat{R}_{\Sigma 23} + \frac{5}{27}\hat{R}_{\Sigma 32}$$

$$\sigma_{RC}^2 = diag\left(A^T A\right)\sigma_R^2 = diag\begin{Vmatrix} \frac{7}{27} & -\frac{2}{27} & -\frac{2}{27} \\ -\frac{2}{27} & \frac{7}{27} & -\frac{2}{27} \\ -\frac{2}{27} & -\frac{2}{27} & \frac{7}{27} \end{Vmatrix}\sigma_R^2 , \quad (8)$$

- for four positions system:

$$\widetilde{R}_1 = \frac{11}{65}\hat{R}_1 + \frac{9}{65}\hat{R}_{\Sigma 12} + \frac{9}{65}\hat{R}_{\Sigma 13} + \frac{9}{65}\hat{R}_{\Sigma 14} - \frac{2}{65}\hat{R}_2 + \frac{9}{65}\hat{R}_{\Sigma 21} - \frac{4}{65}\hat{R}_{\Sigma 23} - \frac{4}{65}\hat{R}_{\Sigma 24} - \frac{2}{65}\hat{R}_3 + \frac{9}{65}\hat{R}_{\Sigma 31} - \frac{4}{65}\hat{R}_{\Sigma 32} - \frac{4}{65}\hat{R}_{\Sigma 34} - \frac{2}{65}\hat{R}_4 - \frac{4}{65}\hat{R}_{\Sigma 43} - \frac{4}{65}\hat{R}_{\Sigma 42} + \frac{9}{65}\hat{R}_{\Sigma 41}$$

$$\widetilde{R}_2 = -\frac{2}{65}\hat{R}_1 + \frac{9}{65}\hat{R}_{\Sigma 12} - \frac{4}{65}\hat{R}_{\Sigma 13} - \frac{4}{65}\hat{R}_{\Sigma 14} + \frac{11}{65}\hat{R}_2 + \frac{9}{65}\hat{R}_{\Sigma 21} + \frac{9}{65}\hat{R}_{\Sigma 23} + \frac{9}{65}\hat{R}_{\Sigma 24} - \frac{2}{65}\hat{R}_3 - \frac{4}{65}\hat{R}_{\Sigma 31} + \frac{9}{65}\hat{R}_{\Sigma 32} - \frac{9}{65}\hat{R}_{\Sigma 34} - \frac{2}{65}\hat{R}_4 - \frac{4}{65}\hat{R}_{\Sigma 43} + \frac{9}{65}\hat{R}_{\Sigma 42} - \frac{4}{65}\hat{R}_{\Sigma 41} \quad (9)$$

$$\widetilde{R}_3 = -\frac{2}{65}\hat{R}_1 - \frac{4}{65}\hat{R}_{\Sigma 12} + \frac{9}{65}\hat{R}_{\Sigma 13} - \frac{4}{65}\hat{R}_{\Sigma 14} - \frac{2}{65}\hat{R}_2 - \frac{4}{65}\hat{R}_{\Sigma 21} + \frac{9}{65}\hat{R}_{\Sigma 23} - \frac{4}{65}\hat{R}_{\Sigma 24} + \frac{11}{65}\hat{R}_3 + \frac{9}{65}\hat{R}_{\Sigma 31} + \frac{9}{65}\hat{R}_{\Sigma 32} + \frac{9}{65}\hat{R}_{\Sigma 34} - \frac{2}{65}\hat{R}_4 + \frac{9}{65}\hat{R}_{\Sigma 43} - \frac{4}{65}\hat{R}_{\Sigma 42} - \frac{4}{65}\hat{R}_{\Sigma 41}$$

$$\widetilde{R}_4 = -\frac{2}{65}\hat{R}_1 - \frac{4}{65}\hat{R}_{\Sigma 12} - \frac{4}{65}\hat{R}_{\Sigma 13} + \frac{9}{65}\hat{R}_{\Sigma 14} - \frac{2}{65}\hat{R}_2 - \frac{4}{65}\hat{R}_{\Sigma 21} - \frac{4}{65}\hat{R}_{\Sigma 23} + \frac{9}{65}\hat{R}_{\Sigma 24} - \frac{2}{65}\hat{R}_3 - \frac{4}{65}\hat{R}_{\Sigma 31} - \frac{4}{65}\hat{R}_{\Sigma 32} + \frac{9}{65}\hat{R}_{\Sigma 34} + \frac{11}{65}\hat{R}_4 + \frac{9}{65}\hat{R}_{\Sigma 43} + \frac{9}{65}\hat{R}_{\Sigma 42} + \frac{9}{65}\hat{R}_{\Sigma 41}$$

$$\sigma_{RC}^2 = diag\left(A^T A\right)\sigma_R^2 = diag\begin{Vmatrix} \frac{11}{65} & -\frac{2}{65} & -\frac{2}{65} & -\frac{2}{65} \\ -\frac{2}{65} & \frac{11}{65} & -\frac{2}{65} & -\frac{2}{65} \\ -\frac{2}{65} & -\frac{2}{65} & \frac{11}{65} & -\frac{2}{65} \\ -\frac{2}{65} & -\frac{2}{65} & -\frac{2}{65} & \frac{11}{65} \end{Vmatrix}\sigma_R^2 \quad (10)$$

The rectangular coordinates of an object are determined by solving the system of equations

$$R = \sqrt{\left(x_t - x_i\right)^2 + \left(y_t - x_i\right)^2 + \left(h_t - h_i\right)^2} , \ i = 1 \div N , \quad (11)$$

x_t, y_t, h_t - desired object coordinates;

x_i, y_i, h_i - known coordinates of GTPs.

The accuracy of estimating the location of an object we define by the dependence:

$$\sigma = \sqrt{tr\left(D^T W^{-1} D\right)^{-1}} \quad (12)$$

Where : tr - trace - the sum of diagonal elements of a matrix;

$$D = \begin{Vmatrix} \frac{\partial R_1}{\partial x_t} & \frac{\partial R_1}{\partial y_t} & \frac{\partial R_1}{\partial h_t} \\ \frac{\partial R_2}{\partial x_t} & \frac{\partial R_2}{\partial y_t} & \frac{\partial R_2}{\partial h_t} \\ \vdots & & \\ \frac{\partial R_N}{\partial x_t} & \frac{\partial R_N}{\partial y_t} & \frac{\partial R_N}{\partial h_t} \end{Vmatrix}$$ - conversion matrix.

III. RESULTS OF CALCULATIONS. SCHEME OF THE EXPERIMENTS

Figures 2 and 3 show, as an example, the values of MSE for the range-finding of the objects driven in a circle with a radius of 200 km around the origin of coordinates. Figure 2 shows the MSE for range-finding for the normal law of error distribution with σ=20 m at zero expectation value, and Figure 3 - for a uniform law of error distribution with a maximum error ΔR=± 60 m.

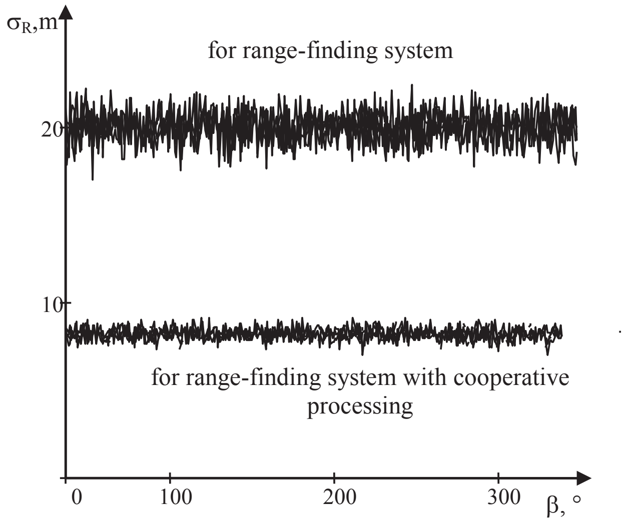

Figure 2 – MSE for range-finding of the object for different methods of measurements processing (for normal distribution)

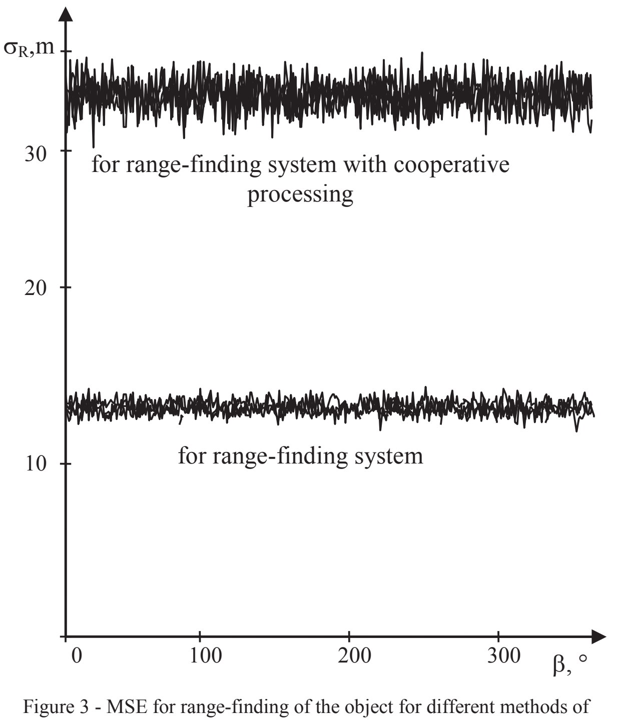

Figure 3 - MSE for range-finding of the object for different methods of measurements processing (for uniform distribution)

Figure 4 shows MSE for positioning of object driven in a circle with a radius of 200 km around the origin of coordinates with ground transceivers stationed as a distance of 20 km from the origin.

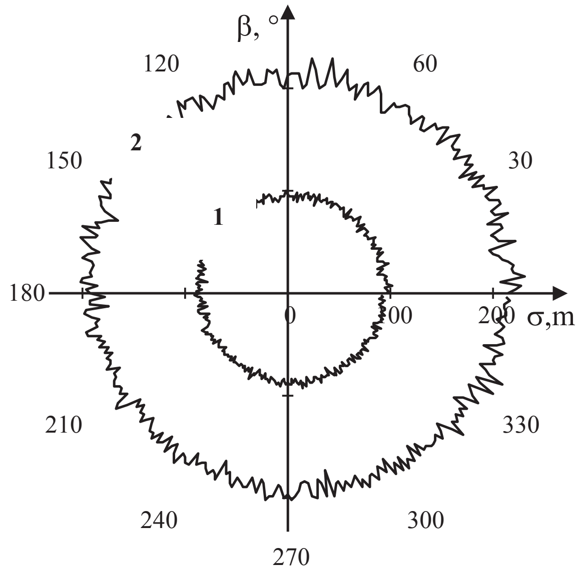

Figure 4 – MSE for positioning of the object for different methods of measurements processing (1 – for range-finding system, 2 – for range-finding system with cooperative processing

Fig. 5 shows MSE for positioning of object driven in a circle at a distance of 20 km around the origin of coordinates with GTPs stationed at a distance of 200 km from the origin.

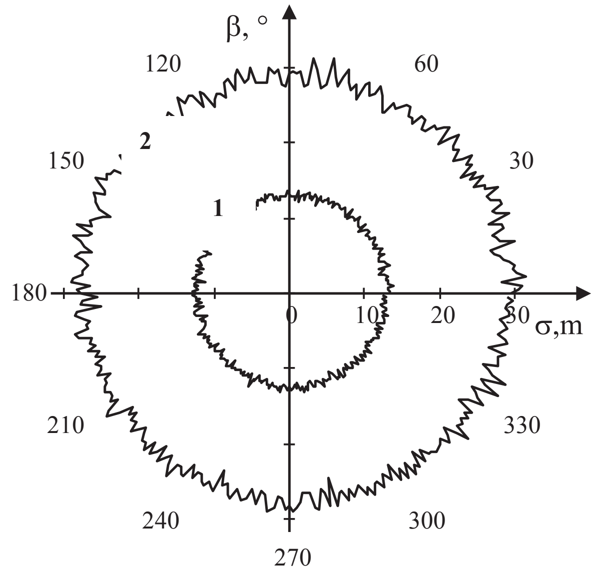

Fig. 5 - MSE for positioning of the object for different methods of measurements processing (1 – for range-finding system, 2 – for range-finding system with cooperative processing)

Fig. 6 shows, as an example, the object positioning MSE for normal distribution of range-finding and sums of ranges when the distance to the object relative to the origin is 200 km and the GTSs are located 20 km from the origin.

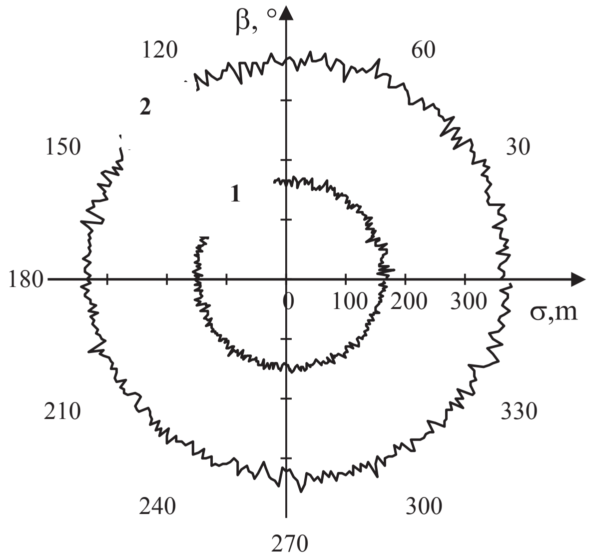

Fig. 6 - MSE for positioning of the object for different methods of measurements processing (1 – for range-finding system, 2 – for range-finding system with cooperative processing)

Fig. 7 shows, as an example, MSE for positioning of the object at uniform distribution of positioning, range-finding and sums of distances errors when the object is 20 km from the coordinates origin, and GTSs are 200 km from the origin.

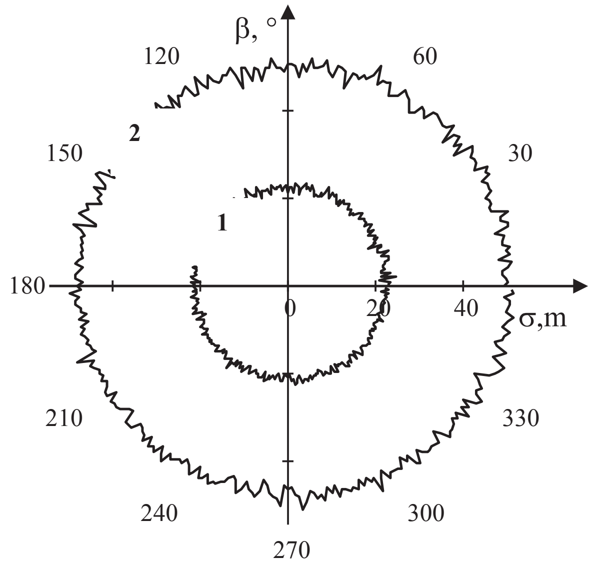

Fig. 7 – MSE for object positioning for different methods of measurements processing (1 – for range-finding system, 2 – for range-finding system with cooperative processing)

Fig. 8 shows MSE for the case of $\sigma_{R\Sigma} = 2\sqrt{2}\sigma_R$. And in case of such MSE values, the errors of positioning grow insignificantly (curves 1 and 2 respectively). Let us assume that from one round of measurements to the other round for some reason or another there is a lack of range measurements and sums of ranges do not exist, i.e. in matrix Λ (formula 5) in 50% of positions we see zeros. Meanwhile, using a conventional range-finding system, indirect measurement of rectangular coordinates in not possible to produce. But in the case of cooperative processing it is still possible to measure rectangular coordinates, but with reduced accuracy and, therefore, to provide algorithmic and informational stability of the system.

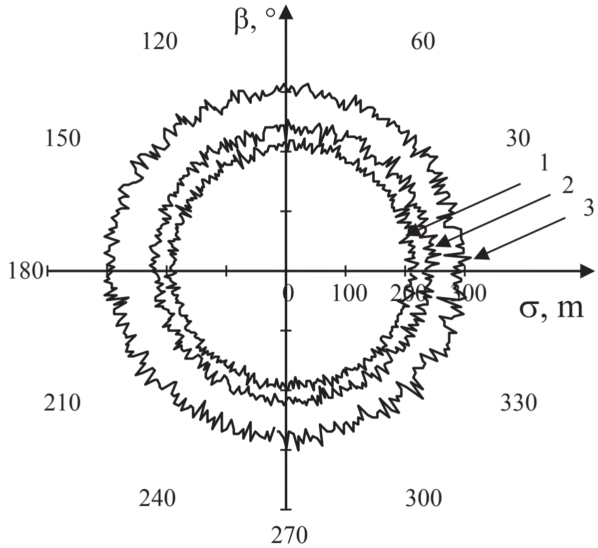

Fig. 8 - MSE for object positioning for different methods of measurements processing (1 – for range-finding system, 2 – for range-finding system with cooperative processing, 3 - for range-finding system with cooperative processing at incomplete set of measurements)

The experiment was made on the NI USRP platform base, which contained four instruments, three of which worked as ground base stations, and the fourth imitated an airborne transponder.

IV. CONCLUSIONS

The aforementioned values of the errors of flying object positioning determination show that cooperative processing of positioning information with respect to the four positional system improves the accuracy of determining the flying object location more than two times in comparison with the conventional range-finding method. In so doing, the high positioning accuracy is achieved by one cycle of data processing within the system. The use of algorithms for filtering trajectory messages will further improve the accuracy of determining the coordinates, without restrictions on the flying object movement hypothesis. This extends the applicability of the proposed options for positioning of maneuvering objects.

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