Experimental Validation of Multipoint Joint Processing of Range Measurements via Software-Defined Radio Testbed

Georgy Mashkov*, Eugene Borisov*, Grigorii Fokin*

* *State University of Telecommunication, 22 Prospekt Bolshevikov, St. Petersburg, Russia*

MashkovGM@sut.ru, kafedra@sut.ru, grihafokin@gmail.com

***Abstract*—In this paper we present an algorithm for multipoint positioning in multilateration (MLAT) radio navigation system and prove that taking into account redundant primary estimates such as sum of range measurements between the object of location and a pair of transceiver stations could improve single range accuracy estimation after joint processing with appropriate weighting coefficients. The approach for experimental evaluation is a testbed including four SDR-based transceiver stations, three of which perform primary measurements collection and one acts as the object of location estimation and measurement processing unit. Transceiver stations are working on National Instruments (NI) Universal Software Radio Peripheral (USRP) hardware with LabVIEW software, performing transmission, reception and processing of signals. Experiment was conducted in mobile scenario with slow pedestrian object of location movement and revealed position Mean Square Error (MSE) of one meter for range measurements with ten trial results accumulation.**

***Keyword*— Analytical model, Distance measurement, Radar signal processing, Radio navigation, Software radio**

I. INTRODUCTION

THE field of application of presented results are navigation, radar and sonar systems which consist of multiple transceiver stations gathering measurements, object of location estimation and measurement processing unit.

Increasing positioning accuracy is an important task for radio navigation systems in civil and military applications to accurately locate an aircraft or vehicle [1-3].

One of the ways for such flight tracking are MLAT systems widely developed in several countries. Its construction, navigation signals processing principles, base transceiver station synchronization approaches, functionality and operating modes are defined by conditions of practical application such as accuracy demands and location area topography [4].

Examples of widely spread Automatic Dependent Surveillance – Broadcast (ADS–B) multilateration radio navigation systems employed in aircraft navigation are presented in [5,6].

Multilateration navigation technique is based on TDOA (Time Difference of Arrival) measurements gathered by a number of ground base transceiver stations, which are placed in known locations and cover surrounding airspace. Time of Arrival (TOA) based algorithms and its comparison with TDOA are presented in [7]. Influence of geometric arrangement of base transceiver stations in conjunction with radio wave propagation conditions on the positioning accuracy by means of computer simulation and experimental validation is evaluated in [8]. Dependence of the base transceiver stations number and its geometric arrangement on the positioning accuracy is developed in [9]. Joint processing of range measurements in multilateration radio navigation system is investigated [10] and [11], however these work lack of experimental evaluation in field conditions. Experimental validation of multipoint joint processing of primary range measurement via software-defined radio (SDR) testbed is performed in [12].

The aim of this paper is to evolve the approach of analytical and experimental evaluation proposed in [12] and validate joint processing of primary range measurement algorithms influence on positioning accuracy in field conditions with slow pedestrian object of location movement.

The material in the paper is organized in the following order. Multipoint radio system under consideration, algorithm for joint processing and its analytical accuracy performance evaluation are presented in the second part. Developed software-defined radio MLAT, including experimental scenario and its accuracy performance evaluation results are presented in the third part. Finally, we draw the conclusions in the fourth part.

Manuscript received on November 15, 2016. This work was supported by Ministry of Science and Education of the Russian Federation within the scope of Federal Target Program «Research and development in priority sectors of scientific and technical complex of Russian Federation in 2014-2020 years» within the project «The development of experimental model of multi-position fast deployment self-contained radar system ground infrastructure for landing aircraft on unprepared ground» (unique project identifier RFMEF160714X0057).

Georgy Mashkov is with the State University of Telecommunication, 22 Prospekt Bolshevikov, St. Petersburg, Russia (e-mail: MashkovGM@sut.ru).

Eugene Borisov is with the State University of Telecommunication, 22 Prospekt Bolshevikov, St. Petersburg, Russia (e-mail: kafedra@sut.ru).

Grigorii Fokin is with the State University of Telecommunication, 22 Prospekt Bolshevikov, St. Petersburg, Russia (corresponding author phone: 8 921 985 80 04; e-mail: grihafokin@gmail.com).

II. Analytical Results on Multipoint Joint Processing of Range Measurements

A. MLAT with Joint Processing of Range Measurements Operating Principle

Multipoint joint processing radio system under consideration operates in the following way. Transceiver stations transmit unique signals based on pseudorandom binary sequence and then receive their retransmitted copies from object of location and thus gather time of arrival (TOA). Object of location estimation is an active reflector which retransmits unique signals. Finally measurement processing unit gathers TOA measurements from transceiver stations and derives range estimates between transceiver stations and object of location and after that performs joint processing of derived ranges to locate the object in a three-dimensional space based on known transceiver stations reference positions.

B. Joint Processing of Range Measurements Problem Statement

In general case MLAT joint processing of range measurements problem statement is formulated as follows. We assume that it includes N transceiver stations for gathering of measurements and so we get N possible range measurements between transceiver stations and object of location denoted by $R_1, R_2, ...R_N$ and $N(N-1)$ sum of range measurements denoted by $R_{\Sigma 12}, R_{\Sigma 21}, ...R_{\Sigma N(N-1)}$.

Algorithm for joint processing of range measurements was presented in prior work [12] that's why here we only rewrite main equations and notations.

It is a well-known fact, that system is redundant when $N \geq 3$ [10], that's why approach used for independent measurements acquisition enables us to form system of N^2 linear equations which is substantially redundant:

$$
\begin{cases}
\begin{cases}
R_1 = 1\cdot R_1 + 0\cdot R_2 + 0\cdot R_3 + ... + 0\cdot R_N,\\
R_2 = 0\cdot R_1 + 1\cdot R_2 + 0\cdot R_3 + ... + 0\cdot R_N,\\
\vdots\\
R_1 = 0\cdot R_1 + 0\cdot R_2 + 0\cdot R_3 + ... + 1\cdot R_N,
\end{cases}\\
\begin{cases}
R_{\Sigma 12} = 1\cdot R_1 + 1\cdot R_2 + 0\cdot R_3 + ... + 0\cdot R_N,\\
R_{\Sigma 21} = 1\cdot R_1 + 1\cdot R_2 + 0\cdot R_3 + ... + 0\cdot R_N,\\
R_{\Sigma 13} = 1\cdot R_1 + 0\cdot R_2 + 1\cdot R_3 + ... + 0\cdot R_N,\\
R_{\Sigma 31} = 1\cdot R_1 + 0\cdot R_2 + 1\cdot R_3 + ... + 0\cdot R_N,\\
\vdots\\
R_{\Sigma N} = 1\cdot R_1 + 0\cdot R_2 + 0\cdot R_3 + ... + 1\cdot R_N.
\end{cases}
\end{cases}
\tag{1}
$$

In matrix form system of N^2 linear equations (1) can be represented as

$$\mathbf{H} = \mathbf{AS}, \tag{2}$$

where $\mathbf{H}^T = \left[R_1, R_2, ..., R_N, R_{\Sigma 12}, R_{\Sigma 21}, R_{\Sigma 13}, ..., R_{\Sigma N}\right]$ – row vector of range and sum of range measurements of size $1 \times N^2$; $\mathbf{A}$ – matrix of coefficients of size $N^2 \times N$, with elements equal to one for available in (1) range measurement and zero otherwise; $\mathbf{S}^T = \left[R_1, R_2, ..., R_N\right]$ – row vector of unknown range estimates of size $1 \times N$.

Solving (2) with nonlinear least squares estimation theory methods [11] we get the following solution:

$$\mathbf{S} = \left[\left(\mathbf{A}^T \mathbf{\Lambda} \mathbf{W}^{-1} \mathbf{A}\right)^{-1} \mathbf{A}^T \mathbf{\Lambda} \mathbf{W}^{-1}\right] \mathbf{H}, \tag{3}$$

where $\mathbf{W}$ – square matrix of primary range measurements accuracy of size $N^2 \times N^2$, with range and sum of range primary measurement error variance $\sigma^2_{R1}, \sigma^2_{R2}, ..., \sigma^2_{R\Sigma N}$ as diagonal elements, and possible correlations between them as non-diagonal elements:

$$\mathbf{W} = \begin{bmatrix} \sigma^2_{R1} & \cdots & \cdots & \cdots \\ \vdots & \sigma^2_{R1} & & \vdots \\ \vdots & & & \vdots \\ \cdots & \cdots & \cdots & \sigma^2_{R\Sigma_{N^2}} \end{bmatrix}, \tag{4}$$

$\mathbf{\Lambda}$ – diagonal matrix of coefficients j of size $N^2 \times N^2$ with diagonal elements equal to one for available in (1) range measurement and zero otherwise:

$$\mathbf{\Lambda} = \begin{bmatrix} j & 0 & 0 & 0 \\ 0 & j & 0 & 0 \\ 0 & 0 & & \vdots \\ 0 & 0 & \cdots & j \end{bmatrix}. \tag{5}$$

Geometric arrangement of MLAT under consideration is depicted in Fig. 1.

Multipoint range measurement radio system depicted in Fig. 1 has 3 spatially distributed transceiver stations with known reference positions in a three-dimensional space $(x_1, y_1, h_1), (x_2, y_2, h_2), (x_3, y_3, h_3)$ for gathering of range measurements R_1, R_2, R_3 between them and object of location.

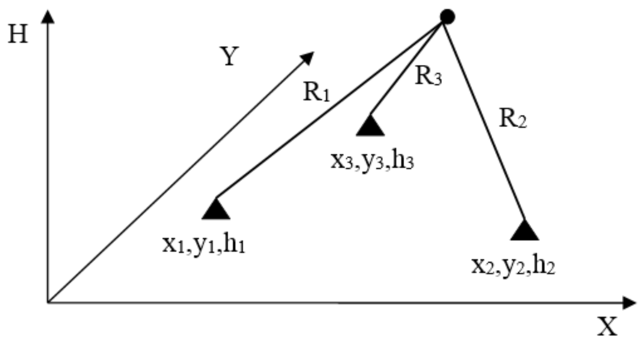

Fig. 1. MLAT radio navigation system with 3 transceiver stations

Developing an approach in [12] and taking into account range and sum of range primary measurement error variance equal to $\sigma_{R1}^2 = \sigma_{R2}^2 = \sigma_R^2$ and $\sigma_{R\Sigma12}^2 = \sigma_{R\Sigma21}^2 = \sigma_{R\Sigma}^2$ respectively, we can get following analytical solutions for unknown range estimates:

$$
\begin{aligned}
\mathrm{R}_1 = {} & \frac{\mathrm{R}_1\left(\sigma_{\mathrm{R}\Sigma}^4 + 6\sigma_{\mathrm{R}}^2\sigma_{\mathrm{R}\Sigma}^2\right)}{\left(2\sigma_{\mathrm{R}}^2+\sigma_{\mathrm{R}\Sigma}^2\right)\left(8\sigma_{\mathrm{R}}^2+\sigma_{\mathrm{R}\Sigma}^2\right)} - \frac{2\mathrm{R}_2\sigma_{\mathrm{R}}^2\sigma_{\mathrm{R}\Sigma}^2}{\left(2\sigma_{\mathrm{R}}^2+\sigma_{\mathrm{R}\Sigma}^2\right)\left(8\sigma_{\mathrm{R}}^2+\sigma_{\mathrm{R}\Sigma}^2\right)} - \\
& - \frac{2\mathrm{R}_3\sigma_{\mathrm{R}}^2\sigma_{\mathrm{R}\Sigma}^2}{\left(2\sigma_{\mathrm{R}}^2+\sigma_{\mathrm{R}\Sigma}^2\right)\left(8\sigma_{\mathrm{R}}^2+\sigma_{\mathrm{R}\Sigma}^2\right)} + \frac{\mathrm{R}_{\Sigma12}\left(4\sigma_{\mathrm{R}}^2+\sigma_{\mathrm{R}}^2\sigma_{\mathrm{R}\Sigma}^2\right)}{\left(2\sigma_{\mathrm{R}}^2+\sigma_{\mathrm{R}\Sigma}^2\right)\left(8\sigma_{\mathrm{R}}^2+\sigma_{\mathrm{R}\Sigma}^2\right)} + \\
& + \frac{\mathrm{R}_{\Sigma21}\left(4\sigma_{\mathrm{R}}^2+\sigma_{\mathrm{R}}^2\sigma_{\mathrm{R}\Sigma}^2\right)}{\left(2\sigma_{\mathrm{R}}^2+\sigma_{\mathrm{R}\Sigma}^2\right)\left(8\sigma_{\mathrm{R}}^2+\sigma_{\mathrm{R}\Sigma}^2\right)} + \frac{\mathrm{R}_{\Sigma13}\left(4\sigma_{\mathrm{R}}^2+\sigma_{\mathrm{R}}^2\sigma_{\mathrm{R}\Sigma}^2\right)}{\left(2\sigma_{\mathrm{R}}^2+\sigma_{\mathrm{R}\Sigma}^2\right)\left(8\sigma_{\mathrm{R}}^2+\sigma_{\mathrm{R}\Sigma}^2\right)} + \\
& + \frac{\widehat{\mathrm{R}_{\Sigma31}}\left(4\sigma_{\mathrm{R}}^2+\sigma_{\mathrm{R}}^2\sigma_{\mathrm{R}\Sigma}^2\right)}{\left(2\sigma_{\mathrm{R}}^2+\sigma_{\mathrm{R}\Sigma}^2\right)\left(8\sigma_{\mathrm{R}}^2+\sigma_{\mathrm{R}\Sigma}^2\right)} - \frac{\widehat{\mathrm{R}_{\Sigma23}}\left(4\sigma_{\mathrm{R}}^2+\sigma_{\mathrm{R}}^2\sigma_{\mathrm{R}\Sigma}^2\right)}{\left(2\sigma_{\mathrm{R}}^2+\sigma_{\mathrm{R}\Sigma}^2\right)\left(8\sigma_{\mathrm{R}}^2+\sigma_{\mathrm{R}\Sigma}^2\right)} - \\
& - \frac{\widehat{\mathrm{R}_{\Sigma32}}\left(4\sigma_{\mathrm{R}}^2+\sigma_{\mathrm{R}}^2\sigma_{\mathrm{R}\Sigma}^2\right)}{\left(2\sigma_{\mathrm{R}}^2+\sigma_{\mathrm{R}\Sigma}^2\right)\left(8\sigma_{\mathrm{R}}^2+\sigma_{\mathrm{R}\Sigma}^2\right)},
\end{aligned}
\tag{6}
$$

$$
\begin{aligned}
\mathrm{R}_2 = {} & \frac{2\mathrm{R}_1\sigma_{\mathrm{R}}^2\sigma_{\mathrm{R}\Sigma}^2}{\left(2\sigma_{\mathrm{R}}^2+\sigma_{\mathrm{R}\Sigma}^2\right)\left(8\sigma_{\mathrm{R}}^2+\sigma_{\mathrm{R}\Sigma}^2\right)} - \frac{\mathrm{R}_2\left(\sigma_{\mathrm{R}\Sigma}^4 + 6\sigma_{\mathrm{R}}^2\sigma_{\mathrm{R}\Sigma}^2\right)}{\left(2\sigma_{\mathrm{R}}^2+\sigma_{\mathrm{R}\Sigma}^2\right)\left(8\sigma_{\mathrm{R}}^2+\sigma_{\mathrm{R}\Sigma}^2\right)} - \\
& - \frac{2\mathrm{R}_3\sigma_{\mathrm{R}}^2\sigma_{\mathrm{R}\Sigma}^2}{\left(2\sigma_{\mathrm{R}}^2+\sigma_{\mathrm{R}\Sigma}^2\right)\left(8\sigma_{\mathrm{R}}^2+\sigma_{\mathrm{R}\Sigma}^2\right)} + \frac{\mathrm{R}_{\Sigma12}\left(4\sigma_{\mathrm{R}}^2+\sigma_{\mathrm{R}}^2\sigma_{\mathrm{R}\Sigma}^2\right)}{\left(2\sigma_{\mathrm{R}}^2+\sigma_{\mathrm{R}\Sigma}^2\right)\left(8\sigma_{\mathrm{R}}^2+\sigma_{\mathrm{R}\Sigma}^2\right)} + \\
& + \frac{\mathrm{R}_{\Sigma21}\left(4\sigma_{\mathrm{R}}^2+\sigma_{\mathrm{R}}^2\sigma_{\mathrm{R}\Sigma}^2\right)}{\left(2\sigma_{\mathrm{R}}^2+\sigma_{\mathrm{R}\Sigma}^2\right)\left(8\sigma_{\mathrm{R}}^2+\sigma_{\mathrm{R}\Sigma}^2\right)} - \frac{\mathrm{R}_{\Sigma13}4\sigma_{\mathrm{R}}^4}{\left(2\sigma_{\mathrm{R}}^2+\sigma_{\mathrm{R}\Sigma}^2\right)\left(8\sigma_{\mathrm{R}}^2+\sigma_{\mathrm{R}\Sigma}^2\right)} + \\
& - \frac{4\mathrm{R}_{\Sigma31}\sigma_{\mathrm{R}}^4}{\left(2\sigma_{\mathrm{R}}^2+\sigma_{\mathrm{R}\Sigma}^2\right)\left(8\sigma_{\mathrm{R}}^2+\sigma_{\mathrm{R}\Sigma}^2\right)} + \frac{\widehat{\mathrm{R}_{\Sigma23}}\left(4\sigma_{\mathrm{R}}^2+\sigma_{\mathrm{R}}^2\sigma_{\mathrm{R}\Sigma}^2\right)}{\left(2\sigma_{\mathrm{R}}^2+\sigma_{\mathrm{R}\Sigma}^2\right)\left(8\sigma_{\mathrm{R}}^2+\sigma_{\mathrm{R}\Sigma}^2\right)} - \\
& - \frac{\widehat{\mathrm{R}_{\Sigma32}}\left(4\sigma_{\mathrm{R}}^2+\sigma_{\mathrm{R}}^2\sigma_{\mathrm{R}\Sigma}^2\right)}{\left(2\sigma_{\mathrm{R}}^2+\sigma_{\mathrm{R}\Sigma}^2\right)\left(8\sigma_{\mathrm{R}}^2+\sigma_{\mathrm{R}\Sigma}^2\right)},
\end{aligned}
\tag{7}
$$

$$
\begin{aligned}
\mathrm{R}_3 = {} & \frac{2\mathrm{R}_1\sigma_{\mathrm{R}}^2\sigma_{\mathrm{R}\Sigma}^2}{\left(2\sigma_{\mathrm{R}}^2+\sigma_{\mathrm{R}\Sigma}^2\right)\left(8\sigma_{\mathrm{R}}^2+\sigma_{\mathrm{R}\Sigma}^2\right)} - \frac{2\mathrm{R}_2\sigma_{\mathrm{R}}^2\sigma_{\mathrm{R}\Sigma}^2}{\left(2\sigma_{\mathrm{R}}^2+\sigma_{\mathrm{R}\Sigma}^2\right)\left(8\sigma_{\mathrm{R}}^2+\sigma_{\mathrm{R}\Sigma}^2\right)} + \\
& + \frac{\mathrm{R}_3\left(\sigma_{\mathrm{R}\Sigma}^4 + 6\sigma_{\mathrm{R}}^2\sigma_{\mathrm{R}\Sigma}^2\right)}{\left(2\sigma_{\mathrm{R}}^2+\sigma_{\mathrm{R}\Sigma}^2\right)\left(8\sigma_{\mathrm{R}}^2+\sigma_{\mathrm{R}\Sigma}^2\right)} - \frac{4\mathrm{R}_{\Sigma12}\sigma_{\mathrm{R}}^4}{\left(2\sigma_{\mathrm{R}}^2+\sigma_{\mathrm{R}\Sigma}^2\right)\left(8\sigma_{\mathrm{R}}^2+\sigma_{\mathrm{R}\Sigma}^2\right)} - \\
& - \frac{4\mathrm{R}_{\Sigma21}\sigma_{\mathrm{R}}^4}{\left(2\sigma_{\mathrm{R}}^2+\sigma_{\mathrm{R}\Sigma}^2\right)\left(8\sigma_{\mathrm{R}}^2+\sigma_{\mathrm{R}\Sigma}^2\right)} - \frac{\mathrm{R}_{\Sigma13}\left(4\sigma_{\mathrm{R}}^2+\sigma_{\mathrm{R}}^2\sigma_{\mathrm{R}\Sigma}^2\right)}{\left(2\sigma_{\mathrm{R}}^2+\sigma_{\mathrm{R}\Sigma}^2\right)\left(8\sigma_{\mathrm{R}}^2+\sigma_{\mathrm{R}\Sigma}^2\right)} - \\
& - \frac{\mathrm{R}_{\Sigma31}\left(4\sigma_{\mathrm{R}}^2+\sigma_{\mathrm{R}}^2\sigma_{\mathrm{R}\Sigma}^2\right)}{\left(2\sigma_{\mathrm{R}}^2+\sigma_{\mathrm{R}\Sigma}^2\right)\left(8\sigma_{\mathrm{R}}^2+\sigma_{\mathrm{R}\Sigma}^2\right)} + \frac{\widehat{\mathrm{R}_{\Sigma23}}\left(4\sigma_{\mathrm{R}}^2+\sigma_{\mathrm{R}}^2\sigma_{\mathrm{R}\Sigma}^2\right)}{\left(2\sigma_{\mathrm{R}}^2+\sigma_{\mathrm{R}\Sigma}^2\right)\left(8\sigma_{\mathrm{R}}^2+\sigma_{\mathrm{R}\Sigma}^2\right)} - \\
& - \frac{\widehat{\mathrm{R}_{\Sigma32}}\left(4\sigma_{\mathrm{R}}^2+\sigma_{\mathrm{R}}^2\sigma_{\mathrm{R}\Sigma}^2\right)}{\left(2\sigma_{\mathrm{R}}^2+\sigma_{\mathrm{R}\Sigma}^2\right)\left(8\sigma_{\mathrm{R}}^2+\sigma_{\mathrm{R}\Sigma}^2\right)}.
\end{aligned}
\tag{8}
$$

C. Joint Processing Range Estimates Accuracy Analysis

Equations (6) – (8) are range estimates between transceiver stations and object of location derived by measurement processing unit from primary range measurements received from all transceiver stations. Let's define range estimates variance as $\sigma_{\mathrm{RK}}^2 = \mathrm{diag}\left(\mathbf{A}^{\mathrm{T}}\mathbf{W}^{-1}\mathbf{A}\right)^{-1}$, then computed range estimates variance for (6) – (8) can be expressed by

$$
\sigma_{\mathrm{RK}}^2 = \frac{\sigma_{\mathrm{R}}^2}{16\sigma_{\mathrm{R}}^4 + 10\sigma_{\mathrm{R}}^2\sigma_{\mathrm{R}\Sigma}^2 + \sigma_{\mathrm{R}\Sigma}^4} \cdot \begin{bmatrix} 6\sigma_{\mathrm{R}}^4\sigma_{\mathrm{R}\Sigma}^2 + \sigma_{\mathrm{R}}^2\sigma_{\mathrm{R}\Sigma}^4 & -2\sigma_{\mathrm{R}}^4\sigma_{\mathrm{R}\Sigma}^2 & -2\sigma_{\mathrm{R}}^4\sigma_{\mathrm{R}\Sigma}^2 \\ -2\sigma_{\mathrm{R}}^4\sigma_{\mathrm{R}\Sigma}^2 & 6\sigma_{\mathrm{R}}^4\sigma_{\mathrm{R}\Sigma}^2 + \sigma_{\mathrm{R}}^2\sigma_{\mathrm{R}\Sigma}^4 & -2\sigma_{\mathrm{R}}^4\sigma_{\mathrm{R}\Sigma}^2 \\ -2\sigma_{\mathrm{R}}^4\sigma_{\mathrm{R}\Sigma}^2 & -2\sigma_{\mathrm{R}}^4\sigma_{\mathrm{R}\Sigma}^2 & 6\sigma_{\mathrm{R}}^4\sigma_{\mathrm{R}\Sigma}^2 + \sigma_{\mathrm{R}}^2\sigma_{\mathrm{R}\Sigma}^4 \end{bmatrix}. \tag{9}
$$

Replacing range and sum of range primary measurement error variance in (6) – (8) by range estimate variances computed beforehand, we can get optimal estimation algorithm for range estimation in the case of unknown error variances.

It can be shown that

$$
\lim_{\sigma_{\mathrm{R}}\to\infty}\left(\mathbf{A}^{\mathrm{T}}\mathbf{W}^{-1}\mathbf{A}\right)^{-1} = \frac{1}{8}\begin{bmatrix} 3 & -1 & -1 \\ -1 & 3 & -1 \\ -1 & -1 & 3 \end{bmatrix}\sigma_{\mathrm{R}\Sigma}^2, \tag{10}
$$

$$
\lim_{\sigma_{\mathrm{R}\Sigma}\to\infty}\left(\mathbf{A}^{\mathrm{T}}\mathbf{W}^{-1}\mathbf{A}\right)^{-1} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}\sigma_{\mathrm{R}}^2, \tag{11}
$$

$$
\lim_{\sigma_{\mathrm{R}}\to\sigma_{\mathrm{R}\Sigma}}\left(\mathbf{A}^{\mathrm{T}}\mathbf{W}^{-1}\mathbf{A}\right)^{-1} = \frac{1}{27}\begin{bmatrix} 7 & -2 & -2 \\ -2 & 7 & -2 \\ -2 & -2 & 7 \end{bmatrix}\sigma_{\mathrm{R}\Sigma}^2, \tag{12}
$$

$$
\lim_{\sigma_{\mathrm{R}\Sigma}\to\sigma_{\mathrm{R}}}\left(\mathbf{A}^{\mathrm{T}}\mathbf{W}^{-1}\mathbf{A}\right)^{-1} = \frac{1}{27}\begin{bmatrix} 7 & -2 & -2 \\ -2 & 7 & -2 \\ -2 & -2 & 7 \end{bmatrix}\sigma_{\mathrm{R}}^2, \tag{13}
$$

$$
\lim_{\sigma_{\mathrm{R}}\to0}\left(\mathbf{A}^{\mathrm{T}}\mathbf{W}^{-1}\mathbf{A}\right)^{-1} = 0,\ \lim_{\sigma_{\mathrm{R}\Sigma}\to0}\left(\mathbf{A}^{\mathrm{T}}\mathbf{W}^{-1}\mathbf{A}\right)^{-1} = 0\,. \tag{14}
$$

From the analysis of (10) – (14) we can conclude that increasing range and sum of range primary measurement error variance to maximum does not affect correct joint processing algorithm operation hence it is possible to increase range estimation accuracy by primary redundant measurement trials accumulation [12].

III. EXPERIMENTAL RESULTS ON MLAT WITH JOINT PROCESSING OF RANGE MEASUREMENTS

A. Developed Software-Defined Radio MLAT Testbed

To realize experimental validation of proposed algorithm for multipoint joint processing of range measurements with trial results accumulation we developed a software-defined radio MLAT testbed by means of model based design via software defined radio [14] on National Instruments hardware NI USRP-2932 [15] and LabVIEW software [16]. It consists of three transceiver stations gathering measurements, one transceiver station realizing functions of an object of location (active reflector), and one processing unit. Layout of the developed multipoint software-defined radio testbed for joint processing of range measurements experimental evaluation is depicted in Fig. 2.

NI USRP-2932 worked in 433 MHz Low Power Devices (LPD) band with power constraint of 20 dBm for communication with binary phase shift keying signals of 2 MHz bandwidth modulated by unique pseudorandom Gold sequence with 500 ns pulse duration and 3 ms pulse-repetition cycle.

It is worth noting, that previous experimental validation [12] was carried out for indoor laboratory conditions in the static scenario when transceiver stations and object of location were placed in the room with spatial separation of several decades of meters and worked stationary. To ensure autonomous mobile deployment for outdoor field conditions of presented MLAT testbed we manufactured 4 prototype models of transceiver stations with self-contained power supply and cooling depicted in Fig. 3.

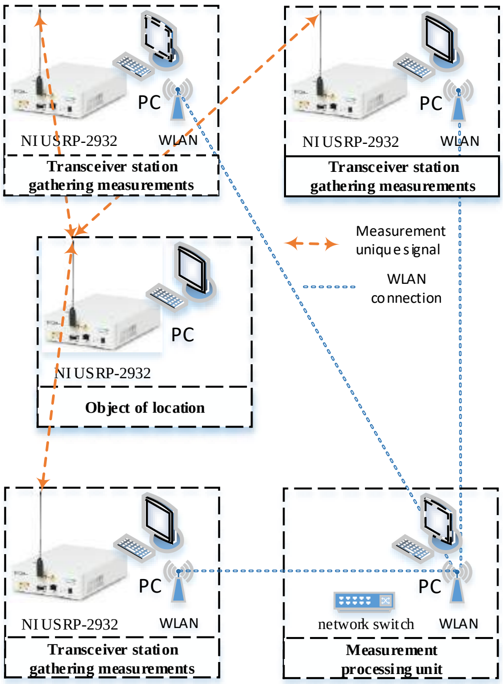

Fig. 2. MLAT radio navigation system with 3 transceiver stations

Fig. 3. Prototype of mobile autonomous manufactured MLAT transceiver station

Transceiver stations are realized on National Instruments hardware NI USRP-2932 and work under specially developed LabVIEW software applications. Developed software-defined radio testbed operates in the following way [12]. Transceiver stations based on NI USRP-2932 and working on Core I7 microPC under Windows 7 with LabVIEW application "Server" transmit unique signals based on pseudorandom binary sequence and then receive their retransmitted copies from object of location and thus gather TOA. Object of location estimation is an active reflector based on NI USRP-2932 and working on Core I7 microPC under Windows 7 with LabVIEW application "Repeater" which retransmits unique signals, received from "Server". Finally, measurement processing unit working on Core I7 microPC under Windows 7 with LabVIEW application "Active Positioning" gathers multiple TOA primary measurements from transceiver stations, process them and visualize result.

To provide investigation of positioning accuracy for outdoor mobile conditions we mounted manufactured transceiver stations and antennas on carts with slow pedestrian object of location movement capability as depicted in Fig. 4.

We used 2 omnidirectional antennas AH-433: one for transmit and one for receive channel as depicted in Fig. 5.

Fig. 4. Mobile organization of experiment layout

Fig. 5. Antenna AH-433

B. Experimental Scenario and its Accuracy Performance Evaluation Results

Experiment was carried out in the court of the Bonch-Bruevich St. Petersburg State University of

Telecommunications with object of location track movement according to layout, depicted in Fig. 6.

During experiment 3 manufactured MLAT transceiver stations operated in the mode of gathering primary measurements and one transceiver station operated as the object of location and measurement processing unit with spatial separation of several decades of meters under line of sight (LOS) conditions.

Network connection between transceiver stations gathering primary measurements and processing unit is based on IEEE 802.11n WLAN. Estimated positioning accuracy was visualized in the LabVIEW application "Active Positioning" running on measurement processing unit and true ranges were estimated by laser ranger.

We performed positioning accuracy performance evaluation in terms of range measurements MSE for two cases of joint processing: with and without primary redundant measurement trials accumulation. During experimental evaluation we got following results in terms of MSE depicted in Fig. 7 and Fig. 8.

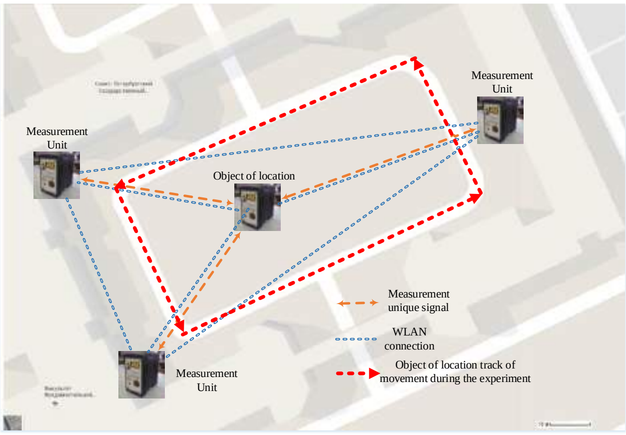

Fig. 6. Experiment layout in the court of The Bonch-Bruevich St. Petersburg State University of Telecommunications

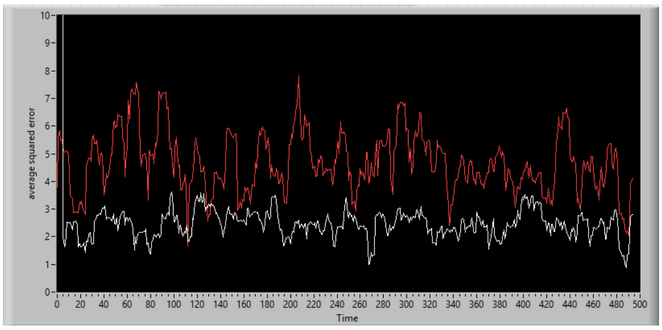

Fig. 7. MSE for range measurements without trial results accumulation

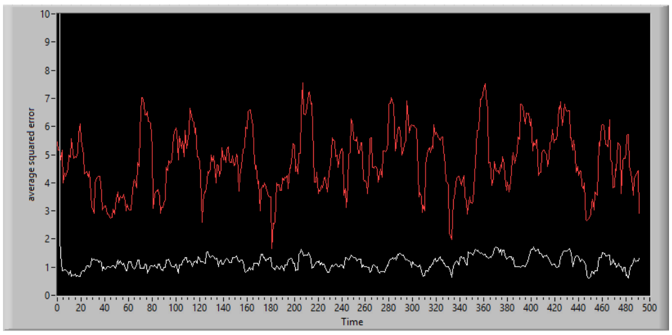

Fig. 8. MSE for range measurements with ten trial results accumulation

We have the following notations in Fig. 7 and Fig. 8 considering experimental evaluation in terms of MSE: upper (red) line indicates range and sum of range primary measurement error variance and lower (white) line indicates range estimation error variance after joint processing over time in the steady-state condition; Fig. 7 demonstrates the range MSE in meters for the case without trial results accumulation while Fig. 8 demonstrates range MSE in meters for the case of joint processing and ten trial results accumulation. It can be seen, that increasing the number of trial results accumulation during joint processing can double positioning accuracy estimation in terms of MSE up to one meter and these field results confirm the result reported in [12] for laboratory testbed evaluation.

IV. Conclusion

In the conclusion we can state that joint processing of range measurements with trial results accumulation can double positioning accuracy and approach MSE of one meter. An algorithm for such processing was proposed, then it was evaluated analytically and finally it was experimentally validated with software-defined radio testbed specially manufactured for outdoor mobile conditions.

References

[1] V. Averianov, Multiposition radar station and system. *Science and Technics, Minsk*, 1978.
[2] V.S. Chernyak, The multiposition radar. *Radio and Communications, Moscow*, 1993.
[3] V.S. Chernyak, Fundamentals of Multisite Radar System. *Gordon and Breach Science Publishers*, 1998.
[4] ICAO: Multilateration (MLAT) Concept of Use, 2007.
[5] ERA company. (2015, February 27). NEO datasheet. [Online]. Available: http://www.era.cz/downloads/data-sheets/NEO.pdf
[6] ICAO organization. (2011, September 2). ADSB, WAM, MLAT ATM International & Airports ADSB, WAM, MLAT implementations. ADSB/WAM integration Systems. [Online]. Available: http://www.icao.int/NACC/Documents/Meetings/2011/ADSBMLT/Day01-04-INDRA-INDRA.pdf
[7] M. Leonardi, A. Mathias, G. Galati, "Closed form localization algorithms for mode S wide area multilateration", *in Radar Conference*, pp. 73-76, EuRAD, 2009.
[8] J. Honda, Y. Kakubari, T. Koga, "DOP simulation considering LOS/NLOS for aircraft positioning on airport surface", *in: IEEE 5th Asia-Pacific Conference on Synthetic Aperture Radar (APSAR)*, pp. 773-776, 2015.
[9] P. Xinxin, L. Yong, L. Wei, Z. Yanbo, W. Yongchun, "An approach of fast stations selection algorithm for multilateration surveillance system", *in Integrated Communications, Navigation and Surveilance Conference (ICNS)*, pp. P1-1-P1-7. Herndon, VA, 2011.
[10] G.M. Mashkov, E.G. Borisov, A.G. Vladyko, A.I. Gomonova, "The Use of Software-Defined Radio Systems in Multilateral Navigation Radio Systems", *Infocommunications Journal*, vol. VII. n. 2. pp. 26-31, 2015.
[11] E.G. Borisov, G. M. Mashkov, A. G. Vladyko, "Analysis of Object Positioning Accuracy Provided by Range-Finding Systems of Various Types", *Russian Aeronautics*. Vol. 58 № 4. pp. 401-406, 2015.
[12] E. Borisov, G. Mashkov, G. Fokin, "Experimental Validation of Multipoint Joint Pro-cessing of Range Measurements via Software-Defined Radio Testbed*", in: 18th International Conference on Advanced Communication Technology (ICACT)*, pp.268-273, 2016.
[13] E.G. Borisov, S.V. Bachevskiy, G. M. Mashkov, "Increasing Estimation Accuracy of Unknown Parameters by Means of Cooperative Processing of Redundant Measurements in a System of Spatially Distributed Sensors", *Sensors an Systems*. № 12 (198). pp.16-20, 2015.

[14] G.A. Fokin, D.V. Bulanov, D.B. Volgushev, “Radio communication systems model based design via software defined radio”, *Vestnik sviazy*, vol. 6, pp. 26-31, 2015.
[15] National Instruments company. (2015, August 17). NI USRP-292x/293x datasheet. Universal Software Radio Peripherals. [Online]. Available: http://www.ni.com/datasheet/pdf/en/ds-355
[16] LabVIEW home page. [Online]. Available: http://www.labview.ru/

Georgiy Mashkov was born in 1954 in Uzlovaya, a town and the administrative center of Uzlovsky District in Moscow Region. He graduated Kiev Higher engineering school in 1977 as the engineer at speciality air defence systems, then received Ph. D and D. Sc there in 1984 and 1993 respectively.

He is working is working in St.Petersburg University of Telecommunication as first Vice-rector (Vice rector for Academic Affairs). His studies focus on radio navigation.

Dr. Sc. Mashkov is Honorary Worker of Higher Professional Education of Russia.

Evgeny Borisov was born in 1967 in Novosibirsk. He graduated Kiev Higher engineering school in 1990 as the engineer at speciality air defence systems, then received Ph. D in 2000 in Smolensk Higher engineering school.

He is working is working in St.Petersburg University of Telecommunication as leading researcher of St.Petersburg University of Telecommunication.

Grogorii Fokin was born in 1984 in Pskov. He graduated St.Petersburg University of Telecommunication in 2005 as the engineer at speciality radiocommunications, then received Ph. D there in 2009.

He is working is working in St.Petersburg University of Telecommunication as Associate Professor of Department of Radio Communications and Signal Broadcasting..