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HIGH PRECISION PASSIVE RADAR ALGORITHM

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The work is devoted to the study of the location determination algorithm for an arbitrary number of receiving stations using the differential-rangefinder method. The algorithm uses all possible Time Differences of Arrival (TDOAs) of the signal from the radio emission source to the receiving stations. In this case, the concept of a “reference” receiving station is excluded, relative to which the range differences are estimated in the classical method, and the signal TDOAs from the source between all possible pairs of receiving stations are used. It is shown that for a given number of receiving stations, the transition from the algorithm with one “reference” station to the proposed algorithm can significantly increase the accuracy of determining the location. Moreover, with an increase in the number of receiving stations, the efficiency of such a transition increases. In addition, for both methods, it has been demonstrated that adding a new receiving station improves positioning accuracy, but the gain decreases with the increasing number of stations. The work can find application in various monitoring systems, since it can significantly increase the accuracy of location determination only through algorithmic solutions, without costly replacement of equipment.

Keywords: determination of object location, receiving station, time difference of arrival, radio emission source, positioning accuracy.

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АЛГОРИТМ ПАССИВНОЙ РАДИОЛОКАЦИИ ПОВЫШЕННОЙ ТОЧНОСТИ

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Работа посвящена исследованию алгоритма определения местоположения (ОМП) для произвольного числа приемных станций (ПС) разностно-дальномерным методом (РДМ). Алгоритм использует все возможные разности времени прихода сигнала от источника радиоизлучения (ИРИ) до ПС. При этом исключается понятие «опорная» ПС, относительно которой в классическом РДМ оцениваются разности дальностей, и используются разности времен прихода сигнала от ИРИ между всеми возможными парами ПС. Продемонстрировано, что при заданном числе ПС переход от алгоритма с одной «опорной» ПС к предлагаемому алгоритму позволяет существенно повысить точность ОМП. При этом с ростом числа ПС эффективность такого перехода возрастает. Кроме того, для обоих методов продемонстрировано, что добавление новой ПС повышает точность ОПМ, однако с ростом числа ПС выигрыш уменьшается. Работа может найти применение в различных системах мониторинга, поскольку позволяет существенно повысить точность ОМП лишь за счет алгоритмических решений, без дорогостоящей замены оборудования.

Ключевые слова: определение местоположения объекта, приемная станция, разность времен прихода, источник радиоизлучения, точность позиционирования.

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Introduction

Classical methods of location determination (LD) of a radio emission source (RES) are based on the use of minimal necessary number of time differences of the signal arrival (TDoA) from the RES to various receiving stations (RSs). At the same time, it is possible to improve the LD by means of using a redundant number of TDOAs.

Let us consider a passive system that employs the differential-rangefinder method (RDM) for the LD. With a classical approach, there are 3 RSs and one signal processing point used a in such a system for the LD in a plane [1]. One RS is a reference one relative to which the TDOAs are computed. Using the TDOAs obtained, we can construct lines of position with their junction point applied to estimate the location determination. Increasing the number of the RS facilitates formation of new TDOAs, and as a consequence induces the appearance of new information on the positioning. The use of such information can essentially lead to an improvement of the RES LD. However, either a possibility of increasing the number of RSs, as a rule, is not considered at all [1, 2], or a method of an arbitrary number of RSs is considered which is based on calculating TDOAs relative to one reference RS [3, 6, 8–10, 12–14]. Publications [4, 5] consider a method with a greater number of RS based on splitting a set of RS into 3 RSs for each of which, however, there is a reference RS assigned.

Paper [11] is devoted to the application of RDM in maritime navigation and considers a possibility of using 3–4 mobile RSs. I presents a method which evaluates the influence of the mutual positioning of the RSs on the precision of the LD.

Articles [15, 16] consider a possibility of combining RDM with the angle-of-arrival (AOA) method to obtain more accurate results. The proposed method uses 3 RSs.

Works [17–21] generalized an RDM algorithm for the three-dimensional space. For this purpose, the 4th RS was added to the system. One of the RSs is chosen as the reference receiving station.

The above listed methods do not take into account all available TDOAs which makes the algorithm insufficiently complete. These papers present no study of the possibility of increasing the number of the RSs.

The purpose of the paper consists in the development and research of the LD method for an arbitrary number of RSs which employs all possible TDoAs from RES to RS.

Algorithm

The proposed method is a generalization of the method considered in publications [3, 6]. According to this method, in addition to the use of a set $[\tau_{12}, \tau_{13}, \ldots, \tau_{1k}]$ (where k is the number of RSs) from $n = k - 1$ (method 1) TDOAs between the reference station (which is denoted by number 1) and the rest of the stations, we also account for the TDOAs between any two stations, i.e. the τ_{ij} TDOAs. The additional TDOAs are obtained as a result of a cross-correlation analysis of the realizations of input signals of the respective RSs. However, “mirror” τ_{ij} TDOAs are not taken into account. As a result, we obtain a vector of the TDOA measurements the elements of which include the measurements between all possible combinations of the RS pairs, excluding the “mirror” pairs. The number of the elements not excluding the “mirror” pairs is obviously equal to the number of the combinations from k by 2. Therefore, the measurements vector has $n = k\ (k - 1)\ /\ 2$ elements (method 2). By multiplying this vector by the radiation (light) speed, we obtain a measurement vector of the range difference R.

Let us construct an LD algorithm. For this, consider a hypothesis that a RES has coordinates x, y. Introduce a conditional range vector (column) $R_{hip}(x, y)$, provided that the hypothesis that the RES has coordinates x, y is true, in the plane:

$$R_{hip}(x,y)=\left[R_{12}(x,y),R_{13}(x,y),...,R_{ij}(x,y),...\,R_{(k-1)k}(x,y)\right]^T, \tag{1}$$

where $R_{ij}(x,y)=\sqrt{(x_i-x)^2+(y_i-y)^2}-\sqrt{(x_j-x)^2+(y_j-y)^2}$ is the range difference from a point with the x, y to the RSs with the numbers i and j. Then, in compliance with the criterion of the minimum sum of disparity squares [5, 6] between the vectors R_{hip} and R, we clearly need to minimize the following function:

$$F(x,y)=\left(R_{hip}(x,y)-R\right)^T\left(R_{hip}(x,y)-R\right). \tag{2}$$

With this, the estimation of the RES LD lies in the coordinates $(\hat{x},\hat{y})$ which satisfy an equation

$$F(\hat{x},\hat{y})=\min_{(x,y)}\left(F(x,y)\right). \tag{3}$$

We need to highlight that both for the proposed algorithm and the algorithm with one reference RS [3, 6], one and the same function (2) and Eq. (3) are applied. The difference consists in the n number of vectors R_{hip} and R.

We can find a solution to nonlinear Eq. (3) via various approaches. One of them would obviously be a brute-force search of all possible values within the projected area of the RES location which however is very complex computationally. We could employ the simplex Nelder – Mead method of finding the minimum as a more efficient approach [7].

Modeling

Let us note that the measurement results of the TDOAs (range differences) are not independent random variables, which with other conditions being equal impairs the LD effectiveness. Thus, to verify the initial assumptions of the effectiveness of the proposed algorithm we constructed a model, the purpose of which essentially consists in a demonstration of weak influence of the correlation and, consequently, a significant increase in the LD effectiveness when using additional $k(k-1)/2-(k-1)$ TDOAs in the algorithm at a fixed k number of RSs.

Assuming that the signal-to-noise ratio (SNR) at the RS output does not depend on the serial number of the RS (although, in practice individual RSs can have a SNR that differs from all others), we evaluate a relation $\frac{\sigma_{LD}}{\sigma_r}$ between the LD root-mean-square error (RMSE) σ_{LD} and the range difference RMSE σ_r. Since the range difference RMSE σ_r is defined by the SNR, it does not depend on the serial number of the RS as well.

At the fixed number of the RS, we employed the modeling method to study the $\frac{\sigma_{LD}}{\sigma_r}$ in the center of a circle of a unit radius. The RSs were located on the circle with their polar coordinates described in the following way:

$$\begin{cases} R_i=1 \\ \varphi_i=\dfrac{2\pi}{k}, \qquad i=0,1,...,k-1. \end{cases}$$

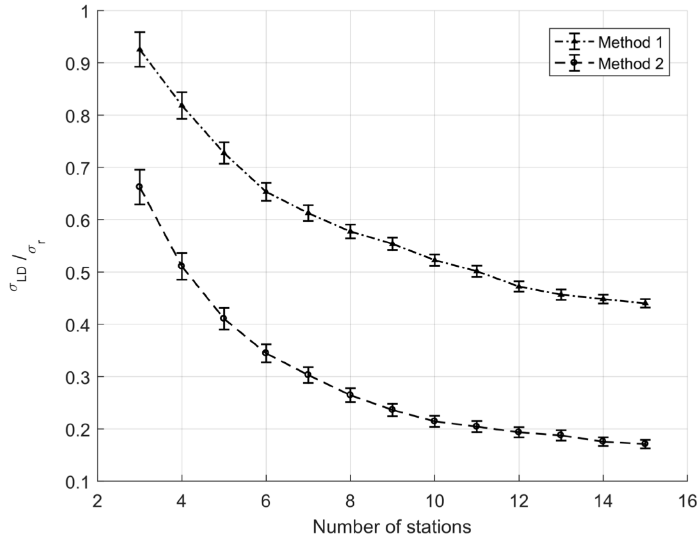

Fig. 1. Dependence of $\frac{\sigma_{LD}}{\sigma_r}$ on the number of RSs for Method 1 and Method 2

The RS input signals were modeled in several steps. First, in the observation interval, we generated a RES signal of a given duration and form. Then, for each RS, we formed a signal delayed for the time equal to the time of propagation of the signal from the RES to the respective RS. Then we added noise to the delayed signals. The obtained signals present the result of modeling the realizations of the RS input signals.

After that, we calculated the cross-correlations between the input signals of each pair of the RSs (excluding the "mirror" pairs). Maximum arguments of the obtained cross-correlations are the estimates of the TDOAs to the RSs. We multiplied them by the speed of light and obtained vector R. This vector is further used in the RES LD algorithm and estimation of σ_{LD}.

After multiple statistical tests we obtained an estimate of the $\frac{\sigma_{LD}}{\sigma_r}$ relation for the RES located in the center of the circle. The modeling results are presented in Fig. 1.

It follows from the Figure, that Method 2 using $k\,(k-1)\,/\,2$ TDOAs leads to a considerable reduction of the $\frac{\sigma_{LD}}{\sigma_r}$ value in comparison with the use of $k-1$ TDOAs relative to one reference RS. For example, with 8 RS $\frac{\sigma_{LD}}{\sigma_r}$ decreases by more than 50%. We can also see that with the growth of the number of RS, a transition from Method 1 to Method 2 becomes more and more feasible.

Let us additionally note that for both methods, adding a new RS reduces the $\frac{\sigma_{LD}}{\sigma_r}$ value. However, with the increase in the number of RS, the gain decreases.

Conclusion

An algorithm using $n = k-1$ TDOAs relative to one reference station is much less efficient than the one that uses all available $n = k\,(k-1)\,/\,2$ TDOAs. In this respect, we can consider the algorithm with $n = k\,(k-1)\,/\,2$ TDOAs to be a high precision passive radar algorithm.

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