Emitter Position Finding Methods and Their Advantages

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To locate emitters by means of a mobile radio monitoring/direction finding station is a difficult task because here we have to cope with multipath wave propagation and a lack of direct visibility. When a mobile station is used together with a fixed point network, emitters can be located faster and more effective [1]. However, stationary radio monitoring systems cannot fully cover the area where emitters are searched and therefore single mobile stations will be still required.

When we need to find emitters and use a single mobile station for that, the following methods can be applied: homing method, quasi-stationary method and calculation of coordinates on the move [3].

The homing method is based on moving the mobile station to the emitter's location conformably to bearings and signal amplitude increase. As a result, the mobile station will eventually appear in close vicinity to the emitter. The quasi-stationary method requires several direction finding sessions from different fixed points. The emitter's coordinates are determined on a map based on bearing crossings. On the move, the coordinates will be calculated based on continuous direction finding and signal amplitude measurement over the entire route.

If the mobile station is equipped with quick-response radio and navigation equipment as well as appropriate software, then emitters can be easily located on the move. When the station is moving, it will receive signals all the time and this is especially important when you need to detect periodical or intermittent emissions. Also, it will be possible to use multi-channel direction finding options and calculate coordinates of several emitters at the same time. Besides, since the station will work in an urban traffic, it will not call attention. With this, the homing method still will be applicable. Also, when there is a good place (e.g. a top height), you can stop there, perform a search and then resume moving.

To calculate emitter's coordinates on the move is possible when you have special software that can treat a single mobile station as a distributed multi-positional system. SMO-KN, the special cartography and navigation software system developed for ARGUMENT mobile station, supports several methods of emitters' coordinates calculation [3, 5, 5]:

- Matrix Method
- Cluster Method
- Maximum Likelihood Method
- Amplitude Method
- Amplitude & Goniometrical Method

The purpose of this article is to classify the above methods, review results of their test application in urban and country conditions as well as to find the most suitable methods for emitters position finding by means of a single mobile station.

But first let's review the basis of all those methods.

Emitters Coordinates Evaluation Methods

In all methods, any moving radio monitoring station is considered as a multi-positional system covering several points on the station route and ensuring sequential processing of received signals. The emitters' coordinates are calculated by means of space/time processing of bearing measurement results or amplitudes of the received signals.

The Matrix method of emitters position finding is based on a matrix grid covering the required area in the electronic map. The grid cell sizes depend on the area dimensions and accuracy requirements.

The grid is treated as a bitmap, the bearings are routed there using a bitmap algorithm and then their amplitudes are summed up in the cells of the grid. The result will be a 3D surface with maximums in those cells where the bearings were superimposed and had larger amplitudes. Thus, the emitter location will be the cell with the maximum obtained value.

The bearings surface will be shown in the map as a figure with colored amplitude ranges (similar to height color scale). The scope of displayed data can be adjusted by setting the display threshold as a percentage from the absolute maximum.

For automatic calculation of maximums, a special algorithm is applied. As a result, there appear separated areas where the amplitude exceeds the threshold value. Then in each insulated area, the center is calculated i.e. the absolute maximum coordinates (if it is clearly seen) or mathematically expected value (if it is smeared out). The coordinates of the insulated area center exceeding the threshold are deemed as the emitter calculated point [2, 5].

On Fig. 1 you can see the surface formed by bearings in the matrix algorithm. The white circle with an arrow means a mobile direction finder, the light-colored circle means the calculated point.

When there are several radio stations functioning at the same frequency there can be two or more maximums with similar values. Consequently, in such a situation, you can find several emitters working at the same frequency.

The advantage of the matrix method is its calculation simplicity. Therefore this method does not require high-performance PCs.

However, the main drawback of that method is that emitters coordinates can be found only when the station moves towards the emitter. Indeed, in this case the bearings will pass through the same matrix cell thus forming a long "range" with large amplitudes, not a localized area with the clearly seen maximum and emitter's location. In other words, it is difficult to use this method when operating a mobile station in the homing mode. Besides, when there is a network formed by stationary direction finders and a non-moving emitter, the bearings will pass through the same matrix cells and form "ranges".

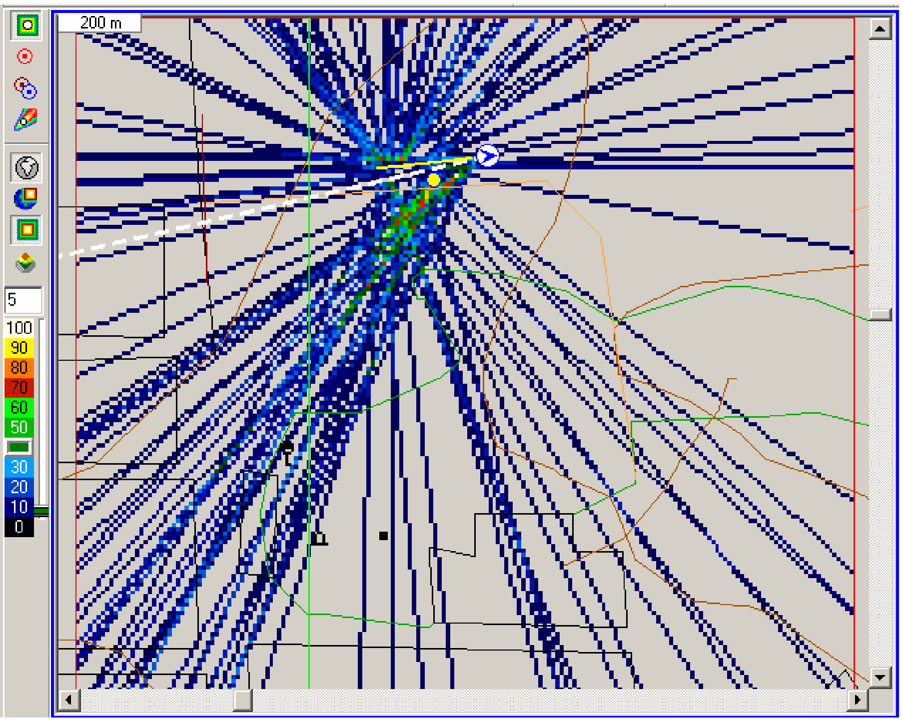

Fig. 1. Bearing-Formed Surface and Calculated Point as per the Matrix Method

The **cluster method** is a new development of the matrix method. It is based on the method of moments [6]. The source data for the calculations are as follows: Bearing sampling $\hat{\theta}_n$, measured subject to the direction finder azimuth, direction finder coordinates at the time of signal acquisition $\dot{Z}_n = X_n + j \cdot Y_n$ ($n = 0,\ldots,N-1$ means the number of the point of acquisition).

The measured bearings are set equal to the true values depending on emitters' unknown coordinates (x, y).

$$\hat{\theta}_n = \theta_n(x, y) = \arg(\dot{z}(x, y) - \dot{Z}_n) \quad , \tag{1}$$

where arg(y) means calculation of the y-function argument. Based on equation (1) we can derive the bearing equation.

$$\hat{y}_{(n)} = Y_n + (\hat{x}_{(n)} - X_n) \cdot tg\hat{\theta}_n \quad . \tag{2}$$

The bearing line equation (2) is a half-line in Cartesian coordinates. Now let's represent this half-line as a two-variable function.

$$\hat{z}_n(x, y) = \begin{cases} 1, \text{если}\, x = \hat{x}_n, y = \hat{y}_n; \\ 0, \text{если}\, x \neq \hat{x}_n, y \neq \hat{y}_n. \end{cases} \tag{3}$$

After a single direction finding operation, the emitter's coordinate are not clearly seen. Therefore they should be averaged based on the total bearing amount obtained from N positions of the mobile station. Evaluation of emitter's coordinates is performed through maximization of function (3).

$$(\hat{x}, \hat{y}) = \arg\left(\max_{(x,y)} \sum_n \hat{z}_n(x, y) \right), \tag{4}$$

where $\arg(y)$ means calculation of the y-function arguments.

Technically, implementation of the cluster method is also based on a matrix covering the required area in the map. However, in this case the grid cells will accumulate not the bearing lines but the bearing crossing points found as a triangulation task solution. The result will be a 3D surface whose amplitude will reach its maximum in the point where the bearings crossed most often.

The first part of the algorithm is aimed at bearing surface development. The triangulation task is solved by calculation of bearing crossing point coordinates for two positions of the mobile station with known coordinated. Compared with the matrix method, calculation of the bearing crossing points will require much more resources. To find the crossing points, all bearing values should be used. Each point should have its weight factor subject to the bearing crossing angle. The maximum factor will be given when the angle is 90 deg.

The second part of the algorithm is intended for calculation of centers or maximums in the matrix. Here we use the same procedures as in the matrix method.

On Fig. 1 you can see the surface formed by bearings in the matrix algorithm.

Like in the matrix method, when several radio stations are operated at the same frequency, there can appear several maximums in the bearing surface. It means that the cluster method enables finding coordinates of several emitters working at the one frequency.

The cluster method has several advantages, e.g. it requires a lesser number of bearings to find the emitter (compared with the matrix method). Also, it can be used for positioning in a distributed system comprising several direction finders.

However, this method also requires a big number of computations and this is the main drawback of this method. Therefore, if you use the cluster method, you should take a high-performance PC.

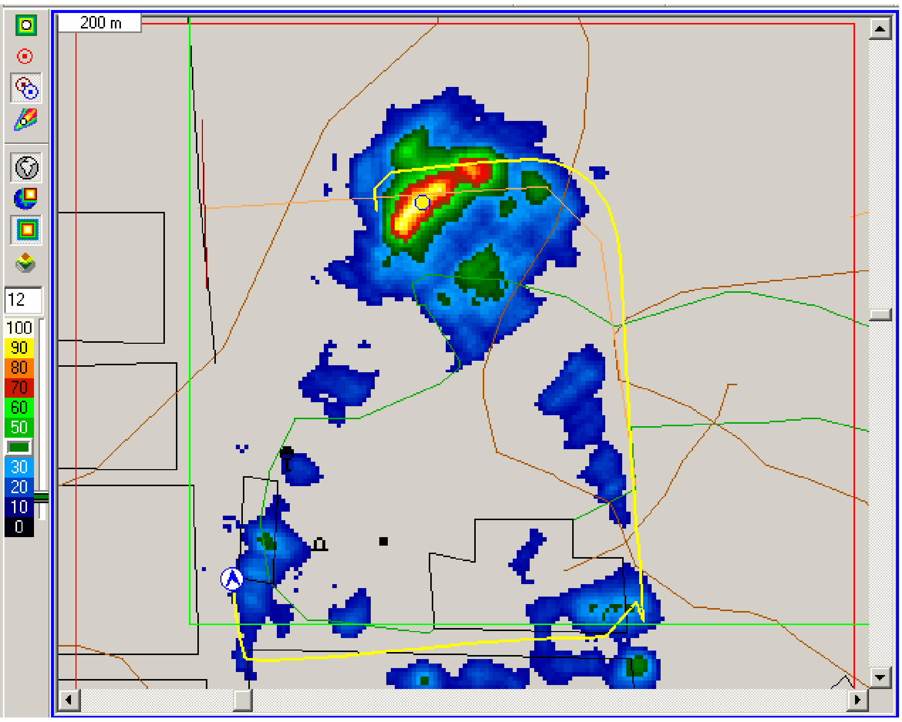

Fig. 2. Bearing-Formed Surface and Calculated Point as per the Cluster Method

The maximum likelihood method is based on application of multi-dimensional normal distribution density to a number of non-correlated bearings.

$$w\left[\hat{\theta}, x, y\right] = \frac{1}{(2\pi\cdot\sigma_\theta^2)^{\frac{N}{2}}}\cdot e^{-\frac{1}{2\sigma_\theta^2}\cdot\sum_{n=0}^{N-1}\left(\hat{\theta}_n-\theta_n(x,y)\right)^2}, \qquad (5)$$

where σ_θ^2 means bearing measurement dispersion depending on radio wave instrumental error, signal-noise ratio and wave propagation conditions; $\hat{\theta}_n$ - , $\theta_n(x, y)$ means unknown true bearing value for the N^th position of the mobile station.

The emitter's coordinates correspond to the coordinates of the likelihood function maximum (5) or evaluation dispersion minimum.

$$(\hat{x}, \hat{y}) = \arg\left(\min_{(x,y)}\left(\frac{1}{N}\sum_{n=0}^{N-1}\left(\hat{\theta}_n - \theta_n(x, y)\right)^2\right)\right), \qquad (6)$$

where $\arg(z)$ means calculation of the z-function arguments.

When emitters' coordinates are calculated as per this method, the calculation goes sequentially in proportion to the bearings increase [3].

The **amplitude method** is based on relationships between emitter field amplitudes and distances to that emitter. Initial Data: amplitude take-off and direction finder coordinates at the time of signal acquisition. When it is assumed that some complex amplitudes of signals $\hat{\dot{S}}_n$ are not interrelated, they can be set using a multi-dimensional normal distribution density.

$$w\left(\hat{\dot{S}}, x, y\right) = \frac{1}{(2\pi\cdot\sigma^2)^{\frac{N}{2}}}\cdot e^{-\frac{1}{2\sigma^2}\cdot\sum_{n=0}^{N-1}\left(\hat{\dot{S}}_n-\frac{\mu}{r_n^p(x,y)}\cdot e^{i\cdot\varphi_n}\right)^2}, \qquad (7)$$

where σ^2 means noise dispersion in the receiving channel, φ_n means signal initial phase, μ means power and $r_n(x, y) = \left|\dot{z}(x, y) - \dot{Z}_n\right|$ means the distance between the emitter and receiver.

In this case, dependence emitter remoteness and field strength amplitude at the point of acquisition is determined by distribution parameter p. This dependence may be more complicated subject to the available terrain and housing density. Power parameter μ depends on emissive power, transmitter and direction finder antenna heights and wave length. After averaging of the likelihood function (7) over unknown parameters μ and φ_n, we can derive the following equation:

$$(\hat{x}, \hat{y}) = \arg\left(\min_{(x,y)}\left(\sum_{n=0}^{N-1}\left|\dot{S}_n\right|^2 - \frac{\left(\sum_{n=0}^{N-1}\left|\dot{S}_n\right|\cdot r_n^{-p}(x, y)\right)^2}{\sum_{n=0}^{N-1} r_n^{-2\cdot p}(x, y)}\right)\right). \qquad (8)$$

In SMO-KN software environment, the amplitude method can take account of the terrain, urban structures, wooden areas and reflections of the signal from the living blocks.

As an example, you can see the signal level surface obtained when finding emitter's position. The white circle corresponds to the calculated point. The flags mean the points of measurement and signal levels used for emitter's coordinates calculations.

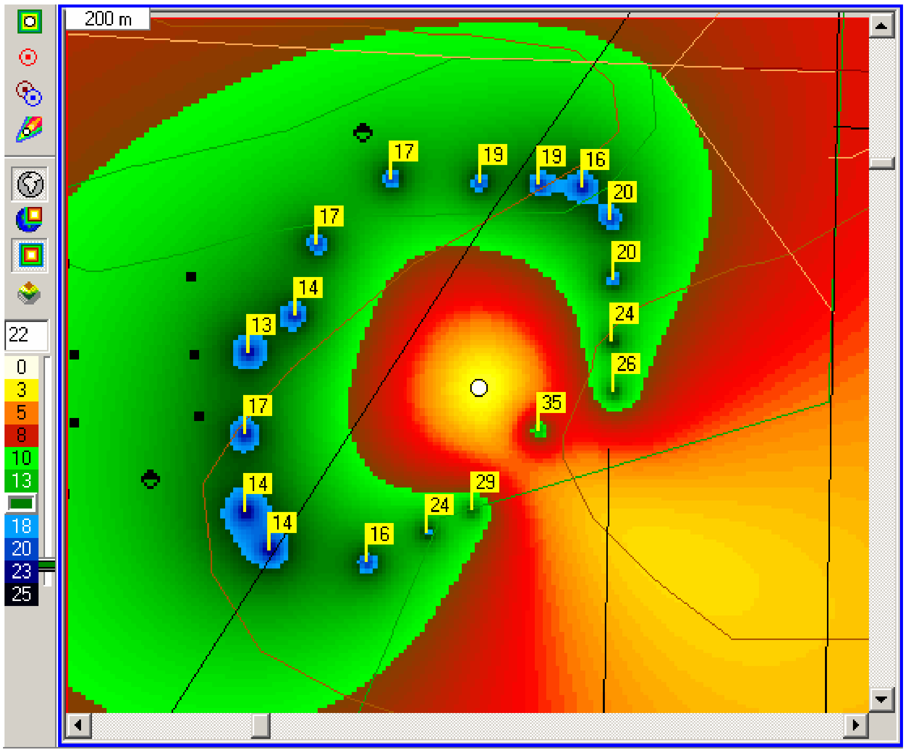

Fig. 3. Signal Levels Surface and Calculated Point as per the Amplitude Method

Evidently, when using the amplitude-based method, the route should be such that the signal amplitude changes expressly. The amplitude method requires just a measuring receiver and navigation equipment. The direction finder as such is not required and this can help save equipment costs.

The amplitude-goniometrical method is based on a comprehensive using of the amplitude and direction finding information. It combines the amplitude method and the maximum likelihood method. When based on independent measurements, coordinates will be evaluated by multiplication minimization.

$$(\hat{x},\hat{y}) = \arg\left\{\min_{(x,y)}\left\{\left(\sum_{n=0}^{N-1}\left(\hat{\theta}_n - \theta_n(x,y)\right)^2\right)\cdot\left(\sum_{n=0}^{N-1}\left|\hat{\dot{S}}_n\right|^2 - \frac{\left(\sum_{n=0}^{N-1}\left|\hat{\dot{S}}_n\right|\cdot r_n^{-p}(x,y)\right)^2}{\sum_{n=0}^{N-1} r_n^{-2\cdot p}(x,y)}\right)\right\}\right\}. \tag{9}$$

When values of bearings and amplitudes related with the emitter coordinates are taken in total in (9), it can save time for emitters position finding. Besides, it can help finding emitter coordinates when moving the mobile station towards the emitter what cannot be achieved when using matrix, cluster or maximum likelihood method.

In this method, SMO-KN software can display the likelihood function showing the most probable emitter's location. On Fig. 7 you can see the emitter area right after the mobile station has started moving. The station route is shown as a line. The more data is obtained, the more narrow is the area around the emitter and its coordinates will be more exact.

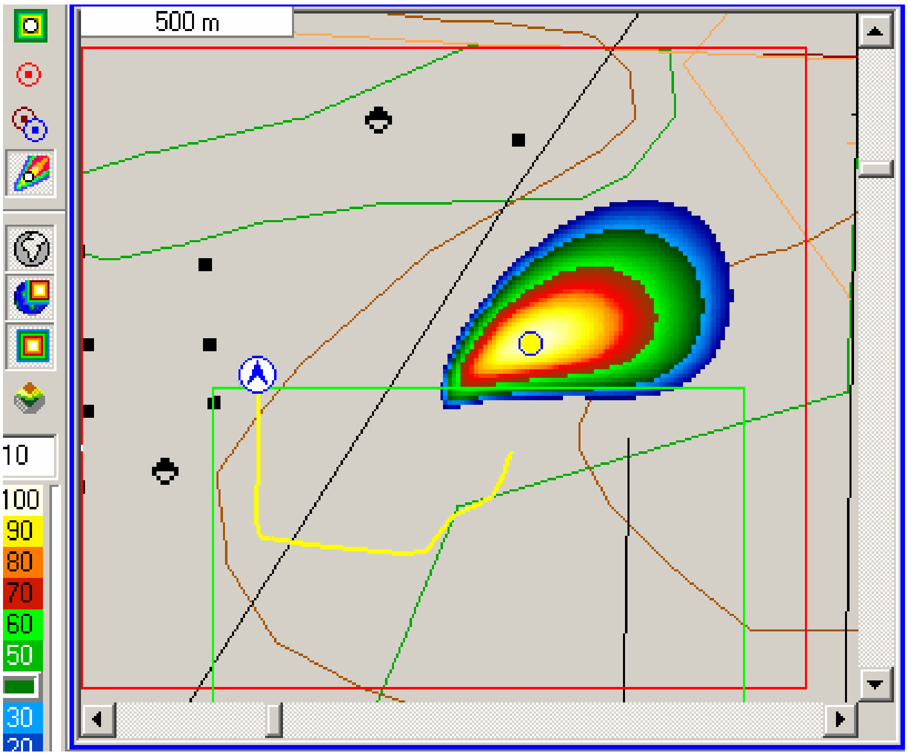

Fig. 4. Amplitude and Goniometrical Method

When the amplitude and goniometrical method is used for emitter's coordinates calculation, the station can move both towards the emitter and from the emitter. Therefore this method can be very helpful for a vehicle-based search. One more advantage is that it can show the vehicle direction on the electronic map.

Test Conditions

For the testing, we have used ARGUMENT mobile radio monitoring station with ARTIKUL-M direction finder, easily mounted antenna system, ARK-KN1 navigation pack, ARGAMAK-IM panoramic measuring receiver with ARK-A7A active antenna and three PCs connected into a LAN [6]. The first PC used SMO-PPK software ver. 4.5.22. The direction finder and navigation equipment were connected to that very PC. The second PC used cartography and navigation software SMO-KN, ver. 1.18.8. The third PC used SMO-PAI software ver. 4.5.18; the panoramic receiver was connected to the third PC.

For the testing we have used two routes – in the country area and in urban area, about 4 km each. The routes are shown in Fig. 9 and 10 as dotted lines. The black rectangles in the figures mean urban blocks. The green areas mean wooded areas. The white cross in the figure means the emitter's position. The route starts in point A. This is the nearest point to the emitter. The mobile station moved in a circle, clockwise from point A to point K.

Fig. 5. Urban Route

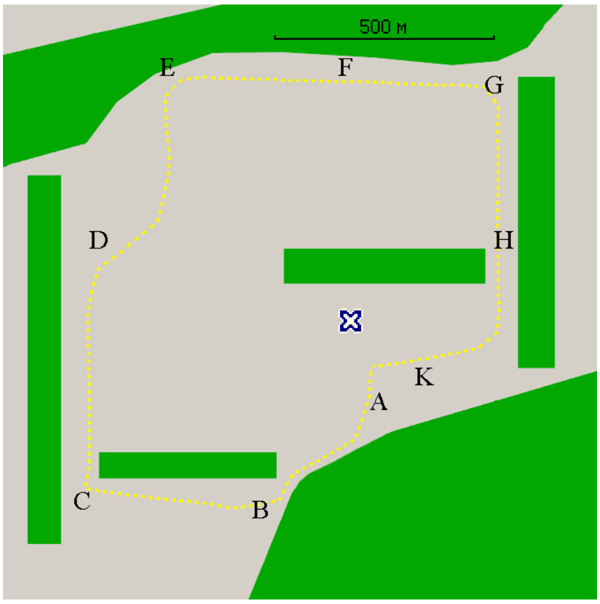

Fig. 6. Country Route

As an emitter we have used ARK-TG1 low-strength reference generator with a rod antenna, rated for max. 30 mW output power. The generator was programmed for two amateur frequencies: $f_1 = 145$ MHz and $f_2 = 434$ MHz. Type of emission: continuous harmonic signal. In the urban area, the emitter was placed on the ground floor of a multi-storied building. In the country area it was placed directly on the ground.

In the urban area there are multi-storied buildings. Direct visibility (unobstructed signal path from the emitter to the mobile station) was not available almost everywhere. The country route passed through an open place, though there were several forest belts (green areas in Fig. 6).

For the both routes, the vehicle speed did not exceed 40 km/h. On the move, the station was used for direction finding and emitter's signal amplitude measurement. The measured bearings and amplitudes as well as station coordinates and azimuth were saved in the database.

Test Results

Resultant dependences between receiver input signal amplitudes (dB vs. mV) and positions on the route are shown on Fig. 7. Dependence No. 1 and 2 are shown for the country area and No. 2 and 3 are shown for the urban conditions. With this, dependence No. 1 and 3 correspond to 434 MHz frequency, and dependence No. 2 and 4 correspond to 145 MHz.

As you can see in the figure, the dependence of the received signal amplitude vs. station position on the route shows some fluctuations from the average value. In some points the amplitude exceeds 10 dB. In point A (the route starting point) i.e. in the point where the distance between the station and the emitter is minimal, the signal amplitudes in both urban and country conditions are quite comparable in their values. However when the station approaches the urban area the signal strength falls abruptly (as compared with the country area). The above amplitude/station position dependencies as well as position coordinates are the source material for the amplitude-based emitter location method.

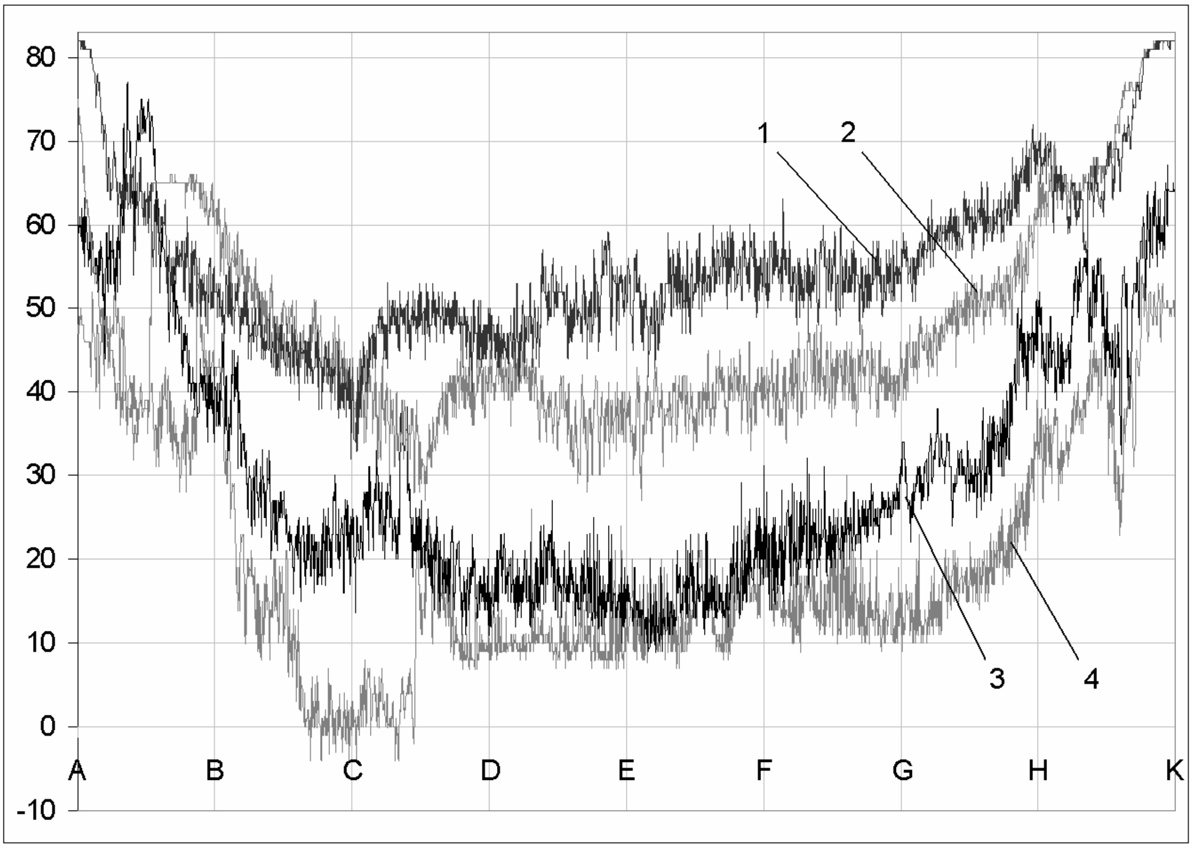

Fig. 7. Radio Signal Amplitude vs. Station Position on the Route

According to direction finding results, the probability of direction finding error $P(\delta < \Delta)$ was estimated – i.e. probability of the event when direction finding error δ is less then target value Δ. The direction finding error is calculated as follows: $\delta = |\alpha_{ИСТ} - \alpha|$; $\alpha_{ИСТ}$ means the true bearing value calculated based on known emitter's coordinates and mobile station, α means the obtained bearing. The results are shown in Fig. 15. Dependence No. 1 and 2 are shown for the country area and No. 2 and 3 are shown for the urban conditions. With this, dependence No. 1 and 3 correspond to 434 MHz frequency, and dependence No. 2 and 4 correspond to 145 MHz.

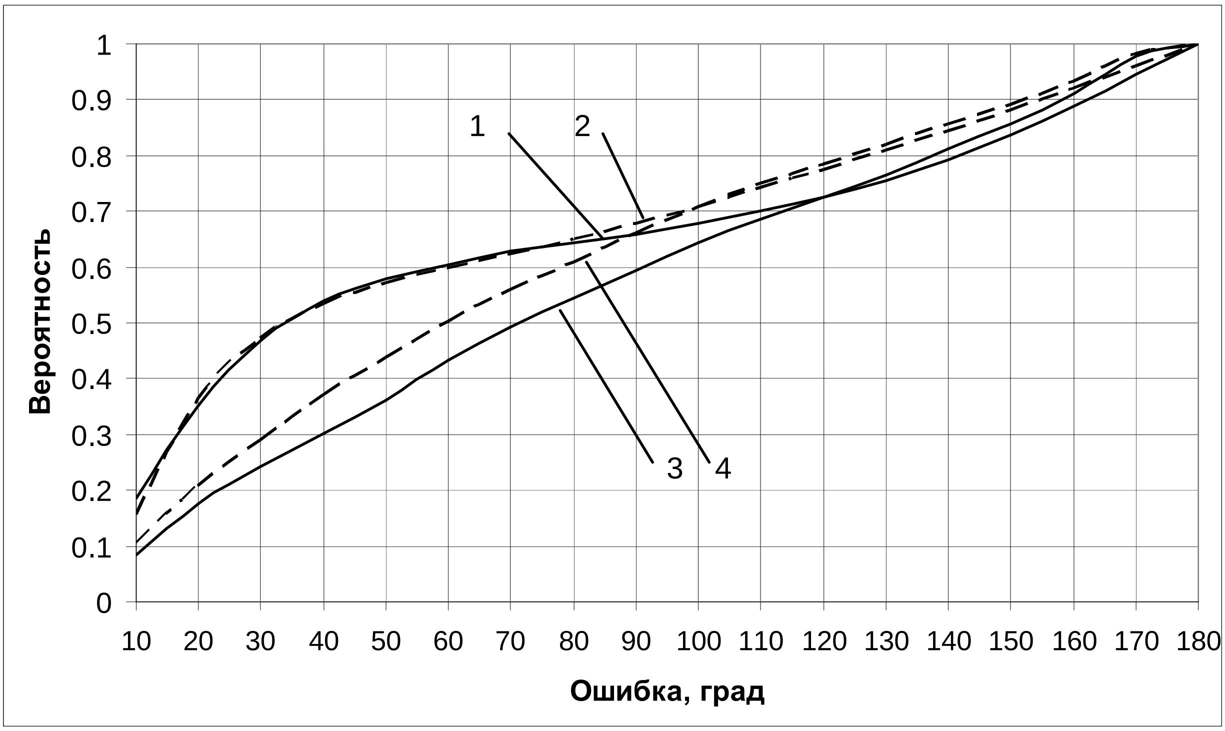

Fig. 8. Direction Finding Error Probability

As you can see from the above dependencies, the probability of 10 deg. bearing error in the country and urban conditions is about 0.2 and 0.1 respectively. Also, the probability of 20 deg. bearing error in the country and urban conditions is about 0.4 and 0.2 respectively. In urban conditions, the direction finding accuracy drop will occur at higher frequencies. Here we can suppose that the main factor impacting the direction finding accuracy is radio wave interference caused by multipath wave propagation. This interference will be more intensive in urban conditions where heterogeneities, which cause reflection, are more numerous. Therefore, compared with the urban conditions, the probability of error in the country area will be lower.

The dependencies shown in Fig. 6 and 7 confirm that finding emitter’s location using a single radio monitoring mobile station is a difficult task that requires statistical processing methods.

Now let’s compare emitters location errors of the methods in question. The errors will be considered as a solution of an inverse position computation i.e. a task when we have two points with known geographic coordinates and need to find the distance between them. Suppose, that the first point is the point of the emitter whose coordinates we already know. The second point will be the point of the emitter which coordinates were calculated using the method in question. Here we should note that such a check can hardly be strict because it concerns only two specific frequencies and two specific routes of the station. Also, here we omit navigation equipment errors when finding the emitters “true” coordinates as well as mobile station coordinates and azimuth. Nevertheless, such a check could be really helpful to evaluate efficiency of the methods in question.

In Table 1 you can see the results of emitter’s location errors (m) for the complete routes ABCDEFGHK in the urban and country conditions.

In the left column there are methods used for coordinate calculations. Also, the table lists location errors for 146 MHz and 434 MHz frequencies. Letters U and C mean Urban and Country conditions. The rightmost column of the table lists average error values for each method. The error values are rounded to 10 m.

Table 1. Location Errors

Coordinate Calculation Method	Emitters Frequency				Average Error
	146 MHz		434 MHz		
	U	C	U	C	
Matrix Method	82	22	130	30	66
Cluster Method	40	30	50	60	45
Maximum Likelihood	90	60	50	40	60
Amplitude Measurement (without considering terrain)	140	50	90	120	100
Amplitude Measurement (considering terrain)	100	40	50	120	77.5
Amplitude-Goniometrical Method	20	40	70	60	47.5

The average errors of the cluster and amplitude-goniometriocal methods were lower than 50 meters. The amplitude method (without terrain data) has showed the greatest average error – 100 meters. After introduction of the terrain data in the amplitude method, the average error was reduced by approx. 33%. According to Table 1, the average emitter's location error is 76 m in urban conditions and 56 meters in the country area.

The results of Table 1 confirm that all the methods – both heuristic (matrix and cluster) and strict mathematical ones (maximum likelihood, amplitude and amplitude-goniometrical) ensure acceptable accuracy in emitters position finding. Therefore to select the most suitable method, additional considerations should be studied.

E.g. when a mobile station has just one measuring radio receiver, then emitter position finding would require the amplitude method, which ensures a sufficient accuracy. With this, it is also advisable to use a digital map showing terrain, houses and structures, wooded areas and water bodies because it will increase the amplitude method accuracy.

If a mobile station has a direction finder, it is advisable to use bearing-based methods because such methods work fast and can be applied when the station stands or is on the move. As it was demonstrated above, the matrix and cluster methods as well as the maximum likelihood methods are not suitable for emitter's position finding when the mobile station is moving to/from the emitter. However, the amplitude-goniometrical method can be applied in this situation because it can measure the signal level. One more thing in favor of this method is that it allows showing the area where the emitter is most likely to be in the electronic map starting from the beginning of the search. Thus, for a search of emitters using a single station with a direction finder, the amplitude-goniometrical method is the most preferred option.

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