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COMPARISON OF SPECTRUM MONITORING COVERAGE FEATURES OF AOA AND TDOA GEOLOCATION METHODS

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Introduction. In the recent practice, the determination of coordinates of sources of radio emissions (SRE) in the course of the spectrum monitoring they mainly use the triangulation method assuming the determination of a point (and taking into account the instrumental errors which are taking place even in the conditions of absence of noises and interferences, - a certain zone) of crossings of bearings lines from two or more radio direction finders [1 - 3]. The triangulation method, along with a simultaneous estimation of amplitude variation of a received signal [1], is used also by mobile monitoring stations (MMS) for finding of SRE at its site, for example, by homing. This technology became more and more frequent to name as AOA - Angle Of Arrival method [3].

Along with it, last years the increasing attention began to involve "differential range measurement" method of the SRE coordinates determination based on measurement of a time of arrival difference of radio signals from SRE to several separated from each other receivers [4] which recently obtained the name TDOA - Time Difference Of Arrival [3]. A geometric locus of points, separated from two points with the same difference of distances (i.e. the same difference in time of a signal arrival) is a hyperbole. Therefore, in TDOA systems the SRE coordinates determination is carried out on a point (or areas) of crossings of hyperboles that are created by various pairs of interacting receivers (figure 1), instead of on an area of crossing of lines of bearings in AOA systems (figure 2). So, TDOA systems are

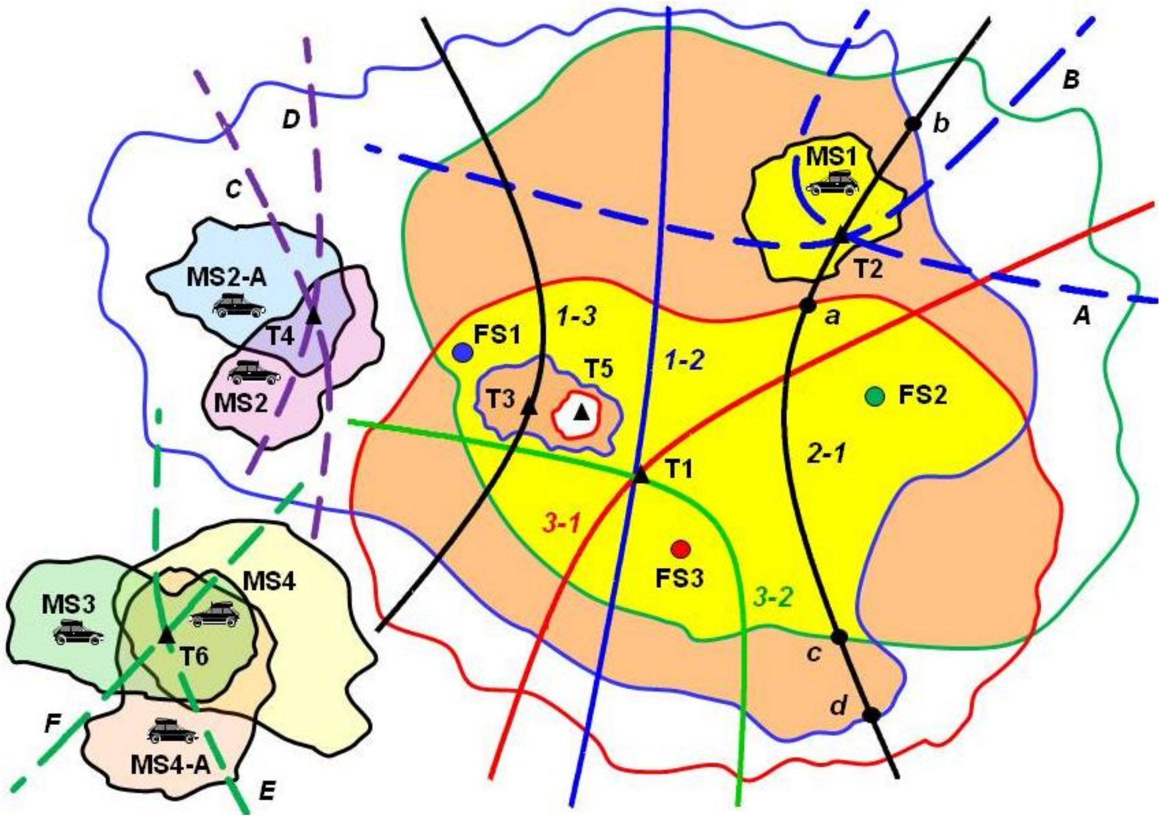

Figure 1. (Geolocation coverage of a TDOA system)

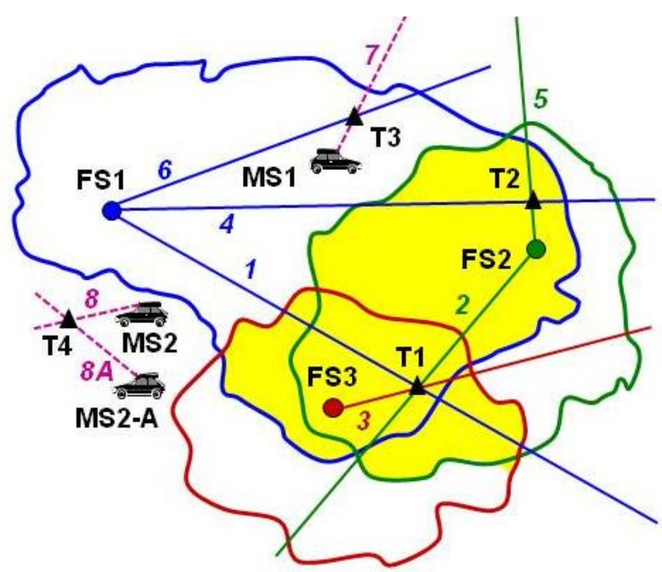

Figure 2. (Geolocation coverage of an AOA system)

also named as "hyperbolic" ones [5], and corresponding receivers, due to their relative simplicity and small size - by "sensors" [6] (lower, for ease and versatility, sensors are also named as stations).

New Recommendation ITU-R «Spectrum Monitoring Evolution» [7] mentions promising features of TDOA systems in application to objectives of the terrestrial spectrum monitoring. There is an information that some administrations are already planning their spectrum monitoring networks based on TDOA or hybrid AOA/TDOA equipment [8 - 10], including those within large territories.

As a spectrum monitoring system usually makes the fundamental share of expenses for an overall national spectrum management system, implementation of TDOA systems in addition to existing AOA networks or replacement by TDOA (or by hybrid AOA/TDOA systems) existing AOA networks in the process of the expiry of the life cycle of the corresponding equipment, is rather serious step for any administration, having essential financial and organizational consequences. The administration should carefully and comprehensively weight all pro's and con's, taking into account existing conditions and development prospects.

For the aid to administrations, in ITU-R Report SM.2211 [11] a rather detailed comparison of TDOA and AOA systems is performed by criteria of the equipment complexity, possibility of SRE geolocation in relation to various kinds of modulation, protection against reflections, noises and interferences, by requirements to data exchange and processing systems etc. At the same time, in the Report [11] the insufficient attention is given to comparison of these systems by criterion of geolocation coverage of a territory in monitoring networks consisting of different numbers of fixed monitoring stations (FMS) in their interaction with MMS.

It seems that exactly this lack of the Report [11] has not allowed to formulate in it particular conclusions concerning efficiency of various configurations of local TDOA and AOA networks consisting of various numbers of FMS in their interaction with MMS, but namely this criterion, along with the cost, can have a crucial importance for administrations in their choice in favor of this or that system.

In the present article on the basis of the experience obtained in the course of development of procedures for AOA network planning [12], an attempt is undertaken to clear up the given issue.

Geolocation features of various groups of AOA and TDOA stations may be analyzed by considering AOA and TDOA monitoring networks comprising up to three interacting FMS (being sensors or DF stations), since these give rise to zones in which the coverage areas of three and two FMS overlap as well as areas covered by only one FMS. From the point of view of geolocation conditions, the case of four or more interacting FMS (i.e. with multiple overlapping coverage areas) is not fundamentally different from the case of three FMS in zones where their individual coverage areas overlap.

Thus, it is necessary to take into account that the analysis of geolocation coverage cannot be limited by the distant estimation of SRE sites only by means of FMS as it usually becomes with reference to TDOA [3, 10, 11]. In many cases a final goal is the detection of a particular SRE at its site, and it can be fulfilled only by means of MMS. Therefore, the analysis should also include an estimation of efficiency of interactive use of FMS and MMS in the course of the determination of SRE coordinates and its homing, or using only MMS in those areas which are not covered by any FMS. The last is rather actual for countries having large territories and essentially non-uniform distribution of settlements and industrial centers (and, therefore, SRE to be monitored) throughout the territory.

In the course of considerations below we will take into account only main effects, i.e. disregard influence of reflections, noises and interferences on accuracy of the SRE coordinates determination and on the homing efficiency. Following [11], with reference to FMS networks we will consider the comparison of only "pure" TDOA and AOA systems, having left outside consideration of hybrid ones. Thus, under "efficiency" we will everywhere understand the productivity of the spectrum monitoring equipment regarding sizes of SRE geolocation areas and workload of its homing by MMS without taking into account the complexity and cost of the corresponding equipment.

Let us consider geolocation coverage by three FMS identified in figures 1 and 2 as FS1 to FS3 which have the exact same geometry but operating in TDOA (figure 1) and AOA (figure 2) networks. The networks are also assumed to be equipped by MMS, identified in figures as MS, using equipment with the exact same technology as FMS. Notional individual coverage areas of each FMS are depicted by contours of different colors. Zones shown in yellow indicate the overlapping coverage areas of FMS within which the SRE coordinates can be distantly determined using only FMS, without the need to involve MMS. Since FMS of the TDOA systems are considered as to be more sensitive than those belonging to AOA, the corresponding coverage areas of the individual stations S1 to S3 in figure 1 are shown as exceeding those in figure 2.

It should be pointed out that the coverage areas in both figures are drawn purely notionally in relation to a certain test SRE with some power and antenna height. If these parameters are modified, this will inevitably alter the contours of the coverage areas to some extent.

For a TDOA network, the SRE coordinate determination only by FMS can be performed exclusively within the zone served by all three FMS i.e. where their individual coverage areas overlap [3, 10, 11]. Within this zone, the SRE coordinates are determined on the basis of the place of intersection of three hyperboles, as shown in figure 1 in relation to SRE T1, where hyperboles 1-2, 3-1 and 3-2 intersect. For an AOA network, a SRE coordinate determination using only FMS is performed with approximately the same level of effectiveness on the basis of the intersection of the lines of bearing within areas covered by all three FMS, as shown in figure 2 in relation to SRE T1 (bearing lines 1 to 3), as well as in areas covered by only two FMS, as shown in the same figure in relation to SRE T2 (bearing lines 4 and 5). Depending on the geometry of the FMS in the network, the overlapping coverage areas of two FMS may be significantly larger than the overlapping coverage areas of three ones.

If, in a TDOA network, the sought SRE is situated in areas covered by only two FMS (brown color in figure 1), the system can produce only one hyperbole, as depicted by line 2-1 in relation to SRE T2. In this case, therefore, the SRE coordinates can only be determined with the help of a MMS (MS1 in figure 1), interacting with the two FMS, on the basis of the place where the hyperbole 2-1 intersects with two others established by this MMS (hyperboles A and B in figure 1 depicted by broken lines in order to highlight their variability as the MMS moves around). Here, the sought SRE has to be in the coverage area of the MMS, which is usually small due to its low antenna height. Thus, in an area covered by only two FMS, a MMS generally has to fulfill not only the homing function in respect to the SRE, but also the distance determination of its coordinates, which increases the burden and hence reduces the effectiveness of the MMS operation.

In particular, if the MMS coverage area is inadequate to capture the SRE signal (SRE T2 in the case under consideration), the operator, having only the hyperbole 2-1, may conclude that the sought SRE is most probably situated somewhere towards the outer parts of that line, i.e. within its segments a-b or c-d, rather than in its central segment, which has a greater probability of being covered by all three FMS, if there are no significant irregularities in the local terrain relief there. Here, the operator must take into account that the end points of these segments (a-b or c-d) are not known, insofar as the borders of the coverage areas of individual FMS, including overlapping coverage areas, depend on the power and antenna height of the sought SRE, which are usually not known until the time when it is effectively detected at its site. Thus, the segments a-b and c-d move towards the centre of the line for low-power SRE with low antennas and towards the outer parts of the line in the opposite case, with the distances between the points a-b and c-d also change.

It should be pointed out that the region in which a sought SRE is situated is usually associated with the site of a receiver suffering interference or (especially in the case of illegal SRE) is presumed to be known on the basis of other data. Where there is a high density of TDOA FMS (e.g. in large cities), the interference to a receiver located in the lower part of figure 1 may well be caused by a SRE located in the upper part of this figure, such as SRE T2. Therefore, in many cases, the MMS has to move along the whole hyperbole (or a significant portion of it) in order to detect the sought SRE at its site. This may be quite onerous, which reduces the homing effectiveness of a TDOA system in areas with overlapping coverage of only two FMS.

The features considered above also hold in cases where, due to the local terrain relief irregularities or built-up urban zones, an area with overlapping coverage of only two FMS lies inside the broader area covered by all three FMS. As shown in figure 1 in relation to SRE T3, here again only one hyperbole 1-3 is produced and, in order to determine the SRE coordinates on this line, it is necessary to use a MMS similarly as it was described above for SRE T2.

On the contrary, as mentioned above, an AOA system enables coordinates of a SRE to be determined in areas covered by only two FMS almost as effectively as in an area covered by three or more FMS. As can be seen from a comparison of the hyperboles 2-1 and 1-3 in figure 1 and the line of bearing 4 from a single AOA station FS1 in figure 2, the search area of a MMS with TDOA is generally twice as large as for a MMS with AOA. This once again points to the lesser effectiveness of operation of a MMS in a TDOA system as compared with an AOA system.

In the area of coverage by only one FMS of the TDOA system, the determination of the coordinates and homing of a SRE become even more complex and it places an even greater burden on the MMS. The MMS, not having any point of reference other than such as the position of the receiver suffering an interference or the presumed region in which the illegal SRE is situated, has to approach the sought SRE closely enough for the latter to fall within its coverage area, as shown in figure 1 by the example of MMS MS2 in relation to SRE T4. Even in that case, however, only one hyperbole C will be produced. In order to determine the coordinates of the sought SRE on that line, the MMS, respecting the same conditions, has to move to another point, such as point MS2-A in figure 1, so as to establish the second hyperbole D that intersects with the first one. Obviously, these operations may be even more onerous than in the case considered above, with a hyperbole in the area covered by two FMS, and hence even less effective, especially in regions where a road network is poorly developed.

The same effect occurs in the case where, on account of the terrain relief features or built-up urban zones, an area served by only one FMS lies within the broader area covered by all three FMS. As shown in figure 1 in relation to SRE T5, situated in an area served only by FMS FS3, depicted notionally by a red contour, the network of FMS simply does not “see” that SRE at all, and its location may only be determined with the help of a MMS in the same way as described above for SRE T4.

In an AOA system, location of a SRE using a MMS on the basis of a bearing provided by only one FMS is a very common operation, carried out relatively effectively, at least under conditions with no reflections present. In accordance with figure 2, in order to detect the sought SRE T3, the MMS MS1 only has to follow along the line of bearing 6, until it acquires the signal from that SRE. Homing of the sought SRE is then carried out on the basis of the bearing of the MMS itself. If the operator wishes to determine upfront the probable position of the sought SRE (for instance, so as to select the best approach path), it may take a bearing from any other point, as shown notionally by line of bearing 7 in figure 2. The intersection of bearing lines 6 and 7 indicates the coordinates of the sought SRE (in this case T3), which facilitates its subsequent homing. Under real conditions with reflections present, reliable geolocation of the sought SRE may require several bearings of the MMS from a number of different points.

Any effective geolocation of an interfering or illegal SRE outside the coverage areas of TDOA FMS is generally unrealistic. When one nevertheless to try, for such an operation a minimum of two interacting MMS would be required, as shown by MMS MS3 and MS4 in figure 1. As a first step, starting from the position of the receiver suffering the interference or the presumed region in which the illegal SRE is situated, two TDOA MMS have to capture the sought SRE in their overlapping coverage areas for it to be possible to establish the corresponding hyperbole, but this is highly problematical. That having been said, reception of the signal from the sought SRE by just one MMS does show the operators that the sought SRE is situated somewhere relatively close by, and one of the MMS may continue searching in that region until such time as the hyperbole is established (for example, hyperbole E between MMS MS3 and MS4 in figure 1). As a second step, one of the MMS, respecting the same conditions, must move to another point, such as for example MMS MS4 to point MS4-A in figure 1, in order to establish a second hyperbole F and determine the SRE place (T6 in figure 1) on the basis of the intersection of these hyperboles. Only then it is possible proceed with homing.

One MMS is enough to detect a SRE within a territory that does not encompass a network of AOA FMS. For example, MMS MS2 in figure 2, in conditions with no reflections present, immediately establishes the bearing to the sought SRE (bearing line 8 in figure 2) as soon as that SRE comes into its coverage area. If an operator wishes to determine upfront the probable position of the sought SRE (for example, so as to select the best approach path), he may take a bearing from any other point, as shown notionally by line of bearing 8A from point MS2-A in figure 2. The intersection of bearing lines 8 and 8A indicates the position of the sought SRE T4, which facilitates its subsequent homing. Under real conditions, with reflections present, the determination of the most probable site of the sought SRE may require several bearings by MMS from a number of different points. This procedure is very widely used by many administrations, especially in countries with large territories much of which cannot be monitored using FMS for quite understandable economic reasons. This function is virtually impossible to perform with a TDOA system.

From the analysis above a number of conclusions can be made. In TDOA networks, a sharp drop in geolocation effectiveness occurs at the periphery of a group of FMS, i.e. where the coverage areas of only two FMS overlap and, *a fortiori*, where there is only one FMS coverage area. Insofar as the ratio of the service area covered by a group of FMS to their peripheral zone increases with the number of FMS in the group, the effectiveness of a TDOA network improves as the number of interacting FMS increases. This means that TDOA networks are more effective for serving large cities and industrial centers, where a large number of FMS may be installed at short distances from each other, resulting in multiple overlapping of their individual coverage areas (minimum of three FMS) allowing genuine automation of the monitoring process, including the SRE geolocation function.

Conversely, relatively small towns and their neighboring suburbs as well as isolated industrial centers are more effectively served by a small number of FMS in an AOA system, separated by relatively large distances. The use of only two AOA FMS is already highly effective for performing geolocation of SRE in overlapping areas and direction finding in individual coverage areas.

Even a single AOA FMS is relatively effective, since within its direction finding coverage area it establishes (as well as measuring emission parameters) bearings to sought SRE, which significantly facilitates their subsequent homing using MMS. A single TDOA FMS is not effective here at all.

MMSs in a TDOA system can perform successfully only within the aforementioned group of TDOA FMS. At the periphery of the TDOA network, the effectiveness of MMS in such a system falls off sharply, whereas in an AOA network it remains relatively high. Therefore, generally speaking, MMS equipped only for TDOA operation cannot be deemed sufficiently effective. Only hybrid TDOA/AOA MMS are of interest.

The trend towards use hybrid TDOA/AOA systems for MMS leads to another extremely important conclusion: for the monitoring of new radio systems with future broadband modulation types one cannot look exclusively to the use of TDOA technology. AOA monitoring systems need accordingly to be developed, too, in order to be able to compensate for the inadequacies of using TDOA technology for mobile monitoring. Otherwise, a key component for monitoring – mobile one – may not be realized. In order to be effective in a hybrid TDOA/AOA network of FMS, AOA FMS must provide coverage areas at least similar to the coverage areas of TDOA FMS.

A network of TDOA FMS, even in the case where MMS are available, is more sensitive than an AOA network to the presence of areas served by only two stations and, *a fortiori*, only by one station, within the broader coverage area of three or more stations. As the relative surface area of such poorly served areas increases, the effectiveness of a TDOA network and the possibility of automated geolocation therein declines sharply; yet, such automation is acknowledged to be a fundamental compelling motive for changing over to TDOA. This calls for more careful planning of TDOA FMS networks in comparison with networks of AOA FMS, with the aim of minimizing such poorly served areas.

The conclusion. The above analysis shows, that both technologies – AOA and TDOA - have their spheres of the effective application in networks of the terrestrial spectrum monitoring, therefore both of them demand the further perfection and development. For development of procedures of optimum planning of TDOA and hybrid AOA/TDOA networks, for that an experience of practical application in the World is still not available, serious additional studies are required. A special attention should be give to features of TDOA system performance at borders of FMS network coverage areas where even at presence MMs in the system the efficiency of the geolocation essentially decreases.

Carried out qualitative comparative analysis of TDOA and AOA geolocation systems can provide a basis for amending Report ITU-R SM.2211 [11], which goal is to provide the aid to communication administrations of various countries in planning ways of their monitoring network future development.

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