Estimation of the Medium Earth Orbit Local User Terminal Service Area

D.V. Antonov, *antonov_dv@spacecorp.ru*
Joint Stock Company "Russian Space Systems", Moscow, Russian Federation

Abstract. This article for the first time presents an algorithm for satellite selection that iterationally optimizes the service area of the Medium Earth Orbit Local User Terminal (MEOLUT). The mathematical simulation performance results of the existing MEOLUTs with four and six antennas when they detect a fixed and slow moving beacon are presented. It is shown that the MEOLUT with four antennas cannot locate slow moving beacons with the required accuracy, while the MEOLUT with six antennas is capable of meeting requirements working with fixed and slow moving beacons. A mathematical simulation of the MEOLUT service area depending on the number of antennas at the MEOLUT and an algorithm for satellite selection are presented. These results are to determine the minimum number of antennas that allow one to reach the desirable service area. It is noticed that this number of antennas can be obtained either by installing antennas or by the process of the measurements exchange with the nearest MEOLUTs.

Keywords: COSPAS-SARSAT, MEOSAR, MEOLUT, service area, algorithm for satellite selection

Introduction

The most important characteristic of the Medium Earth Orbit Local User Terminal (MEOLUT) of COSPAS-SARSAT is a service area – an area of the Earth's surface in which a MEOLUT is capable to meet the requirements described in [1].

At the fixed precise measurements of times of a signal arrival of the emergency beacon (EPIRB) to relay satellites (TOA – Time Of Arrival) and its frequencies (FOA – Frequency Of Arrival), the size of a service area depends on the algorithm of the choice of relay satellites for pointing the MEOLUT antennas on them, a number of antennas on a MEOLUT, and an algorithm of determination of EPIRB coordinates.

In case of a normal distribution of TOA and FOA measurements, the algorithm of determination of coordinates described in [5] is optimum. Thus, the size of a service area can be increased due to increase in quantity of information and measuring complexes and optimization of a planning algorithm of the choice of relay satellites.

Since a considerable part of the MEOLUT cost makes a cost of information and measurement systems, thus, one of the questions of priority is a question on a minimum quantity of antennas necessary to achieve a desirable MEOLUT coverage area. Today in literature, there are no studies directed to the solution of the specified task. Moreover, there are no assessments of a service area for already in existence MEOLUTs with four and six antennas considering slow moving EPIRBs.

Thus, in terms of the present paper, the analysis of the size of the service area of already existing MEOLUTs will be carried out and also the size of the service area of a MEOLUT depending on the number of antennas and planning algorithm of pointing of MEOLUT antennas on relay satellites will be investigated.

Review of planning algorithms

In [2], the reference to two algorithms of the choice of satellites for pointing MEOLUT antennas on them is given.

The first of these algorithms is heuristic and suggests selecting relay satellites with the greatest elevation relative to the MEOLUT. The advantage of this method is its simplicity and less time for calculation. The lack of optimization when choosing relay satellites is a disadvantage.

The second algorithm offers a complete selection of all possible sets of relay satellites. For each set in the circle with the center in the place of the MEOLUT location and a radius of 2000 km, a geometric mean is calculated in the assumption that an EPIRB is motionless (a geometric mean calculation is given in [1]). For pointing of MEOLUT antennas, a set of relay satellites, which has the best geometric mean, is chosen. The advantages of this algorithm are the optimization when choosing a set of relay satellites. A potentially big labor input of a complete selection, the lack of a record of slowly mobile EPIRBs, and also the fact that in the course of the choice a combination of satellites the part of a responsibility area of a MEOLUT fulfills the set requirements is not checked. Fig. 1 gives an example when the best mean accuracy is not a correct criterion of the selection of relay satellites. In this example, the mean accuracy in the service area in the first case is 2.1 km, however not the whole area of responsibility meets the requirement for the accuracy of the independent solution. In the second case, the mean accuracy is 3 km, but at the same time the requirements for the accuracy of the independent solution are fulfilled in the whole area of responsibility. In addition, fixing of a radius of a circle for optimization (2000 km) is not considered rational, especially at a large number of antennas on a MEOLUT.

Taking into account the listed disadvantages, the author has developed a special algorithm allowing one to optimize a MEOLUT service area.

Planning algorithm allowing one to estimate a MEOLUT service area

A service area of the MEOLUT with an M-antenna is approximated by a circle with *R* radius. It is required to make the schedule of tracking of relay satellites with the MEOLUT antennas, providing the radius of the R_{max} service area as big as possible.

Such a circle of the largest radius can be found iteratively. On the *i*-th iteration, a circle with the R_i radius is considered. In this circle, a work of the equispaced EPIRBs is simulated.

Then a complete selection of all possible combinations of *M* out of N_j of the relay satellites being visible at the moment is made to each *j*-th analyzed time point. For each EPIRB under analysis in the circle with the R_i radius at each combination of *M* satellites being considered, a possibility

Fig. 1. Example of a wrong selection of satellite combinations according to the criterion of the best mean accuracy

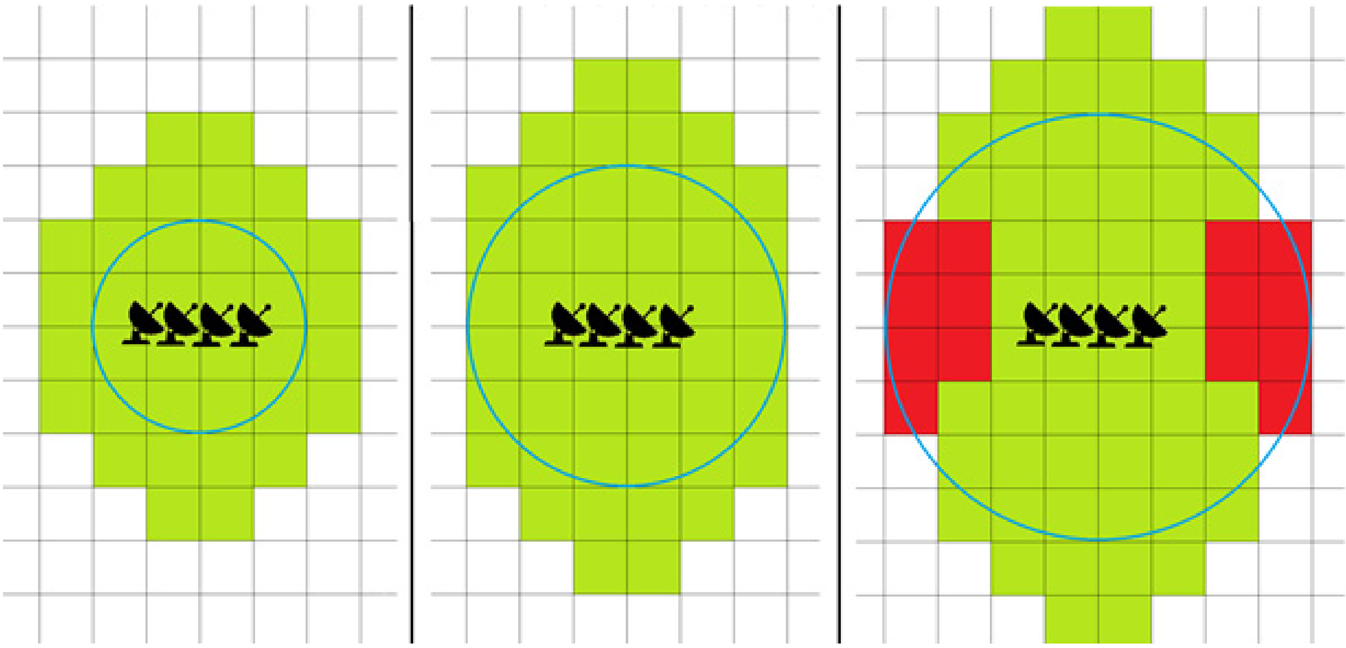

Fig. 2. Illustrations of the algorithm's operation on different iterations for the MEOLUT with four antennas

of determination of the coordinates of each EPIRB with an error not less than 5 km (formulae for calculation are given in [1]) is calculated and a constellation providing the largest number of conceptional EPIRBs in the circle with the radius R_i, which probability is not less than 0.95, is calculated.

If there are several constellations, for which all analyzed EPIRBs in the circle with the radius R_i meet this requirement, so any of these constellations is chosen. For example, it can be done by the criterion of the best mean accuracy (formulae of calculation of a theoretical accuracy are given in [4]) or the smallest number of

Table 1. Simulation parameters of the MEOLUT service area

Parameter	Criterion/value
Minimum MEOLUT angle of tracking of a satellite,°	5
Number of the radiated EPIRB messages	13
Time after receiving the first message, after which a solution is taken, min	10
Simulation duration, days	10
Time increment, min	15
Number of satellites to solve a navigation task	Not less than 3
σTOA	25 ms (the value taken from [1])
σFOA	0.2 Hz (the value taken from [1])
Dependence of the percent of the received messages on the elevation on the EPIRB – spacecraft line	70% for elevations 5-75° for S-band 70% for elevations 5-83° for L-band Only 9 first messages out of 13 (1-9) are considered received
Space segment	Suggested composition of the constellation for 2020 – 56 satellites

transfer of antennas from the satellite on the satellite. In such a way constellations are chosen for the whole time interval being analyzed.

Then for each imitated EPIRB and for each set of satellites on the *j*-th time point, probability of determination of the coordinates and the probability of determination of the coordinates with an accuracy not less than 5 km is calculated. Mean values of these probabilities for the whole considered interval of time will be P_1 and P_2 respectively. If for these probabilities the following conditions are satisfied

$$\begin{cases} P_1 \geq 0.98 \\ P_2 \geq 0.95 \times P_1, \end{cases} \quad (1)$$

so this point is included in the MEOLUT service area.

If the conditions (1) are met for all imitated beacons in the R_i circle, then the following iteration of the algorithm with the radius of a service area of $R_{i+1} = R_i + \Delta R$ is made. If for any EPIRB from a circle with the R_i radius the conditions (1) are not met, then R_{i-1} will be the circle with the largest R_{max} radius.

In the offered algorithm, the combination of satellites for each time point is chosen according to the criterion of the greatest one-time coverage area in the circle with R_i radius. However, other criteria can be considered. Further in article, the results of the operation of this algorithm, where the combination of satellites according to the criterion of the best geometric mean taking into account the presence of slowly moving beacons will be selected, will be considered.

Thus, as a result of fulfillment of this algorithm, the schedule of spacecraft for pointing on them the antennas and the evaluation of the service area will be obtained. Fig. 2 gives the example of the operation of an algorithm on different iterations of the selection of a service area to optimize the MEOLUT operation in this service area. A blue circle on each iteration is an area for optimization. A green color is the MEOLUT service area on each iteration, a red color is an area, which should join a service area, however the MEOSAR requirements are not fulfilled here. In this example on the left drawing, the area for optimization is too small, and on the right, this area is too big. Thus, the area shown in the middle drawing will be a service area.

Estimation of the service area of the present MEOLUTs

To check a possibility of a MEOLUT to implement the MEOSAR, to evaluate the accuracy of independent solution and size of a service area as well as to evaluate the influence of slowly moving EPIRBs (the velocity does not exceed 5 m/s; the peculiarities of the solution of a

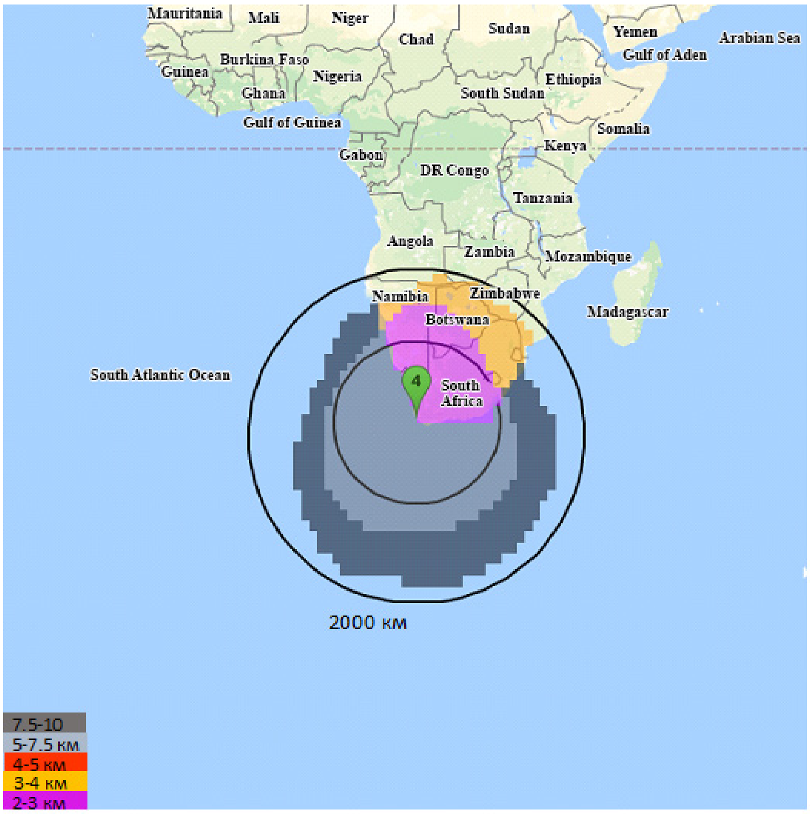

Fig. 3. Service area of the MEOLUT with four antennas in Cape Town (yellow and purple areas)

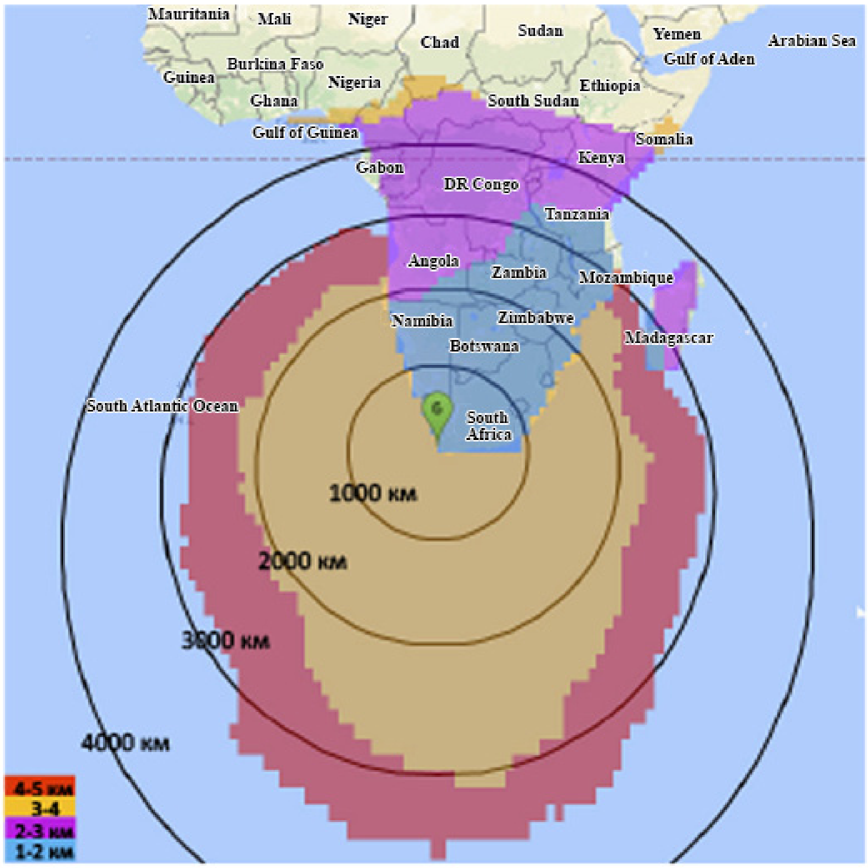

Fig. 4. Service area of the MEOLUT with six antennas in Cape Town

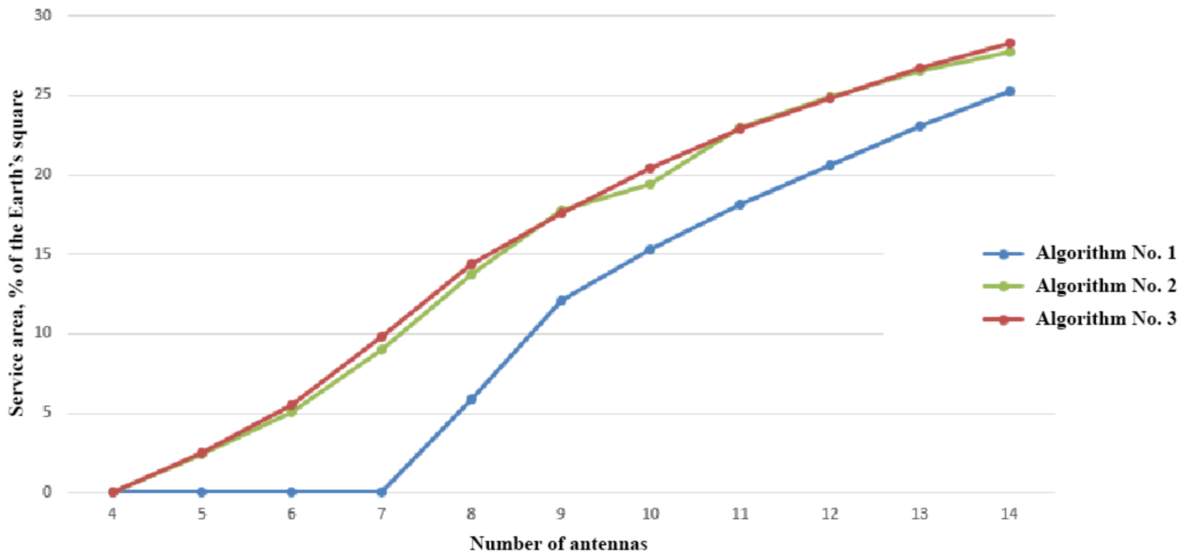

Fig. 5. Dependence of the size of the service area of the MEOLUT on the number of antennas with the assumption that all EPIRBs are movable

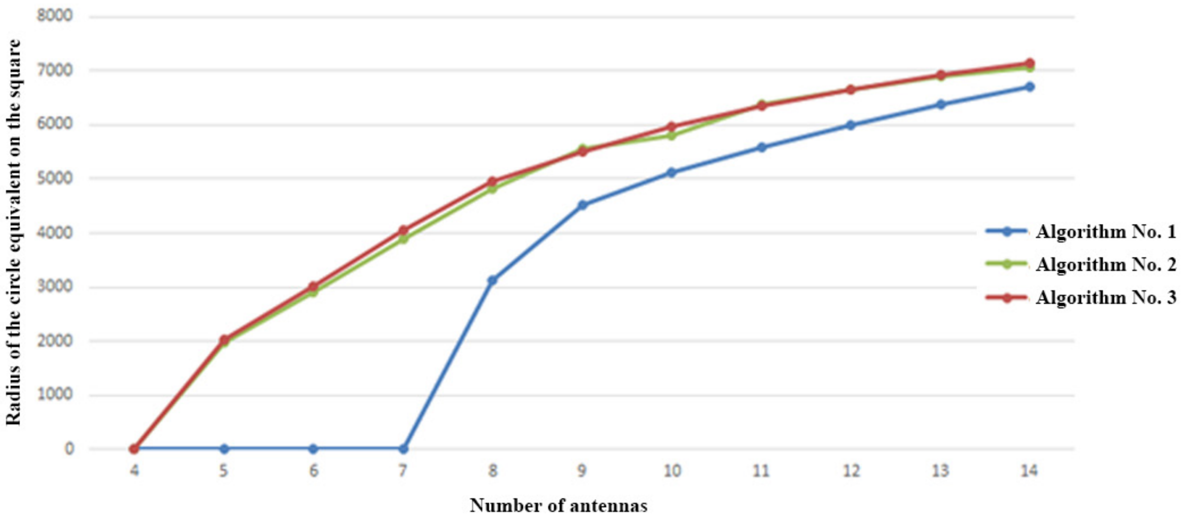

Fig. 6. Dependence of the radius of the circle equivalent as to the square of the service area of the MEOLUT on the number of antennas with the assumption that all EPIRBs are movable

navigation task in case of a slowly moving EPIRB can be found in [5]), a number of simulations was carried out. The general parameters for all simulations are presented in Table 1.

Since today all MEOLUT stations have four or six antennas, so the analysis of a service area of the MEOLUT of such configurations deserves attention first of all. Cape Town, the Republic of South Africa was chosen as the location for the MEOLUT under simulation. Such choice is caused by existence in close proximity both extensive water areas and land that makes it possible to compare the characteristics of the MEOLUT performance during the work on motionless and slowly moving EPIRBs. All EPIRBs being on the land were considered motionless; all EPIRBs being on water were considered slowly moving under the influence of rolling, wind, and currents.

During the work on moving EPIRBs (at the sea), it is required to determine five parameters by the measurements of the FOA differences – the longitude, latitude, and three components of velocity (an EPIRB can have both horizontal velocity due to current and wind and vertical component because of rolling). Therefore, MEOLUTs with four antennas during the work on slowly moving EPIRBs cannot use the FOA measurements.

For such EPIRBs, the location is calculated only according to the TOA measurements. While operating a motionless EPIRB (on the land) in the presence of the measurements from three and more spacecraft, the TOA and FOA measurements were used. Fig. 3 presents the results of simulating of the MEOLUT with four antennas.

The schedule was formed on the algorithm described in the previous section. The carried-out simulation has shown that the required accuracy of 5 km in 95% of cases was not reached at the sea in any area; the accuracy of 5.5–10 km has been reached in the area of 1500–2000 km. On the land, the accuracy was 2–4 km in the area about 2000 km.

Moreover, the simulation was carried out for the MEOLUT with six antennas. When determining the coordinates of EPIRBs, the TOA and FOA measurements of on both motionless and slowly moving beacons were used. The results of the simulation of the service area for the MEOLUT with six are given in Fig. 4. At the sea, the accuracy of 3–5 km was reached in the radius of 3000 km. On the land, the accuracy was 2–4 km, and the radius of the service area exceeded 4000 km.

Thus, the MEOLUT with six antennas unlike the MEOLUT with four antennas is capable to fulfill the MEOSAR requirements both during the work on a motionless EPIRB and during the work on a slowly moving EPIRB. When operating motionless EPIRBs, the radius of the service area of the MEOLUT with six antennas exceeds by more than 2 times the radius of the service area of the MEOLUT with four antennas (more than four times as to the square of the service area). It leads to an important conclusion about a low efficiency of the MEOLUT with four antennas and impossibility of their work with the required quality on maritime EPIRBs.

Simulation of the service area depending on the planning algorithm and the number of antennas on the MEOLUT

As it was mentioned above, the size of the MEOLUT service area can be increased due to optimization of the algorithm of the choice of satellites for pointing of the MEOLUT antennas on them and due to increase in number of antennas on the MEOLUT. To make an assessment of the size of the MEOLUT service area depending on these parameters, a mathematical simulation was carried out. At the same time the following algorithms of the choice of spacecraft for pointing of the MEOLUT antennas on them was used:

- An algorithm No. 1 is the algorithm with the choice of relay satellites with the biggest elevation relative to the MEOLUT.
- An algorithm No. 2 is the algorithm with a complete selection of sets of satellites and the choice of the set, which provides the best one-time mean accuracy in the service area. The service area is approximated by a circle of the largest radius of service; its radius is found iteratively.
- An algorithm No. 3 is the algorithm with a complete selection of sets of satellites and the choice of the set, which provides the largest one-time square in the service area. The service area is approximated by a circle with the largest radius of service; its radius is found iteratively.

Figs. 5–8 show the results of the carried-out simulation. Depending on the number of antennas for each algorithm, Fig. 5 depicts the service area (in % of the Earth's surface), and Fig. 6 illustrates the size of the radius of a circle equivalent on the square to the MEOLUT service area.

As it can be seen form Figs. 5 and 6, at the number of antennas less or equal seven, using the algorithm No. 1 leads to a zero service area. At eight antennas, the service area by more than 2 times is at disadvantage in relation to the service area obtained according to the algorithms No. 2 and 3. At further increase in the number of antennas, the difference in the results of operation of these algorithms decreases, but, nevertheless, the algorithms No. 2 and No. 3 always provide a big service area than the algorithm No. 1.The algorithm No. 3 gives advantage in the service area (up to 10% of the service area) relative to the algorithm No. 2 at the number of antennas less or equal ten, however at further increase in the number of antennas both algorithms provide a service area identical in the size.

Fig. 7 gives a diagram of the dependence of the mean accuracy in the service area depending on the number of antennas for each planning algorithm. It is seen that the algorithm No. 2 has a kind of better mean accuracy (up to 15% of the required accuracy) comparing to the algorithm No. 3.

Fig. 8 illustrates the dependence diagram of the effectiveness (the square per one antenna) of using the MEOLUT antennas for each algorithm depending on the number of antennas.

As it is seen from these drawings, existing MEOLUTs with six antennas are capable to fulfill the MEOSAR requirements both for mobile and for slowly moving

Table 2. Increase in the service area when adding antennas to the MEOLUT with six antennas

Number of antennas added to the MEOLUT with six antennas	Resulting number of antennas on the MEOLUT	Increase in service areas in % relative to the service square of the MEOLUT with six antennas
+1	7	+78%
+2	8	+162%
+3	9	+220%
+4	10	+271%
+5	11	+316%
+6	12	+351%
+7	13	+385%
+8	14	+415%

beacons (in the circle with the radius about 3000 km), however installation of six antennas on the MEOLUT is not effective. If the size of the service area of the MEOLUT with six antennas is taken as a unit of measure, then addition of only one antenna increases a service area by 78%, two antennas – by 162%, three antennas – by 220%. Other values are given in Table 2. At further increase in antennas, the efficiency of their use will decrease.

The number of antennas installed on a MEOLUT directly depends on a desirable service area. The diagrams given above are designed to estimate the necessary number of antennas and to give an assessment of the received service area. At the same time, the required number of antennas can be reached both due to installation of antennas on MEOLUTs and due to exchange of measurements with next MEOLUTs on condition of their coordinated work.

However, the desirable service area can differ from a circle, the accuracy of measurement of times and frequencies can also not coincide with the brought values in [1], geographical coordinates of a MEOLUT and a space segment will also differ. In practice, for each specific MEOLUT, knowing its parameters and a desirable service area, it is necessary to carry out separate simulations.

Conclusions

This paper presents the analysis of the size of the service area of the MEOLUT with various number of antennas when using different algorithms of the choice of satellites for pointing of MEOLUT antennas on them taking into account the presence of slowly moving beacons.

The analysis of two available algorithms of the choice of relay satellites for pointing MEOLUT antennas on them is carried out, their advantages and disadvantages are given. It is necessary to point out a lack of the record of the presence of slowly moving beacons and a lack of optimization of the MEOLUT service area among the disadvantages.

The new planning algorithm providing iterative optimization of the MEOLUT service area considering the presence of slowly moving EPIRB is offered.

A mathematical simulation of the service area for the configurations of the MEOLUTs that are present today (four or six antennas) is performed. This simulation has shown a low efficiency of the MEOLUT with four antennas and impossibility of operation of a slowly moving EPIRBs, while the MEOLUT with six antennas has shown a possibility of implementation of requirements as on motionless (in the radius about 4500 km) and on mobile EPIRBs (in the radius about 3000 km).

The analysis of the MEOLUT service area depending on the number of antennas and three algorithms of planning is carried out:

- An algorithm No. 1 is the algorithm with the choice of spacecraft with the greatest elevation relative to the MEOLUT.
- An algorithm No. 2 is the algorithm with the choice of the set of satellites providing a one-time best geometrical factor in a circle with the maximum radius. The circle with the maximum radius is found iteratively.
- An algorithm No. 3 is the algorithm with the choice of set of satellites providing a one-time biggest service area in a circle with the maximum radius. The circle with the maximum radius is found iteratively.

By the results of the simulation, the algorithm No. 1 provides a less service area than the algorithms No. 2 and No. 3 that is most expressed at the small number of antennas. At twelve and more antennas, disadvantage of the algorithm No. 1 makes less than 20% of the service area.

The algorithms No. 2 and No. 3 lead in many respects to similar results. At the number of antennas less than 10, the algorithm No. 3 gives advantage in a service area (up to 10% of the size of the service area), while the algorithm No. 2 has advantage on mean accuracy in the service area (up to 15% of the required accuracy).

It is shown that in the autonomous mode a MEOLUT reaches the biggest specific efficiency (per one antenna) with 9–11 antennas installed on it. If the value of the service area of the MEOLUT with six antennas is taken as a unit of measurement, so addition of only one antenna increases a service area by 78%, two antennas – by 162%, three antennas – by 220%.

The given simulations should give an assessment of the minimum number of antennas required for providing the service with the set characteristics in the desirable service area. It is noted that the necessary number of antennas can be reached due to their installation on a MEOLUT or due to the exchange of measurements with the nearest MEOLUTs on condition of the coordination of their work.

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