Determining the location of an object during environmental monitoring in conditions of limited possibilities for the use of satellite positioning

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Abstract. The article is devoted to the problem of determining the location of an object in space within the framework of various tasks of monitoring the state of the environment, in conditions of inaccessibility of traditional satellite positioning. As part of the task of monitoring the state of the environment, monitoring agricultural territories and observing the atmosphere, the use of traditional satellite navigation systems in many cases is not available. To solve it, it is proposed to use passive methods for determining the location of the object. To increase their reliability in solving environmental monitoring problems, a new algorithm was developed for the difference-ranging method by increasing the number of used differences of arrival times. The difference between the signal arrival times may be less than 0.02 μs. Using the algorithm allowed to abandon the use of the reference station and move on to differences in arrival times between all pairs of stations. In this case, the accuracy of determining the position of the object increases by 20 - 45%. The error in determining the position of the object does not exceed 1 m. This value allows the operational search of weather balloons and other equipment for environmental monitoring.

1 Introduction

Recently, various methods have been used to control the state of the environment [1-8]. One of the most common is environmental monitoring [5, 7-13]. To determine the state of water, soil on agricultural land, the state of forest cover, and others, it is divided into several types (space, air, sea (water), land, etc.) [14-23]. In all types of this monitoring, an important element is the determination of the coordinates of the position of the point (in airspace, sea or earth surface), in which measurements are made [24-28]. Even in the case of using radar stations for monitoring the atmosphere and underlying surface, it is necessary to additionally use a position determination system [27-30].

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Currently, the most accurate and efficient method for determining the coordinates of any object is a satellite navigation system [31-35]. The accuracy of determining the position of the object, depending on the conditions, reaches up to 40 cm. In some cases, environmental monitoring must be carried out in places where satellite signals are poorly received due to their low power. Determining coordinates using them is extremely difficult. Therefore, it becomes necessary to use other methods for determining coordinates [27, 36].

In addition, to monitor the state of the frequency environment, autonomous stations located in hard-to-reach areas or air meteorological balloons are used. With the latter, the greatest difficulties arise. Weather balloons send signals for a specific time. According to these signals, they must be quickly found after landing, often in a hard-to-reach area. It is impractical to tie meteorological balloons to satellite systems, since in some areas satellite signals are poorly received, etc.

Therefore, the task of determining the location of an object with high accuracy in these cases is extremely relevant. In addition, for the demand for such methods and devices based on them, other tasks for determining the location of the object must be solved with their use. This paper presents one of the options for solving the problem under consideration by increasing the efficiency of the existing method through the use of new algorithmic solutions.

2 Methods

When determining the location of an object in environmental monitoring, the positioning system is passive. The signal emitted by the object is not directly associated with the receiving stations of this system. Difficulties arise in determining the time of arrival of the signal from the source of radio emission to the receiving station. In fig. 1 shows the classic situation with the placement of an object on the territory, the coordinates of which must be established. This is necessary both for picking up an object from the territory (for example, a radiosonde) or for determining its coordinates when receiving other information related to the determination of the ecological situation.

![Fig. 1. Mutual arrangement of source and receiving stations on the plane.](image)

The position of the radiation source must be determined using a reference station. For this, in the method developed by us, it is proposed to use several receiving stations. In this case, it is necessary to estimate the difference in the arrival times of the signal between the receiving stations. The time differences of arrival are determined relative to one receiving station, which is called the reference station. In practice, the remaining receiving stations, receiving the signal from the source, transfer it to a frequency belonging to a specific receiving station and relay it to the reference station. The coordinates of the receiving stations are known in advance. In some cases, you can use a backup ground-based radio navigation
system. The reference station, which is used by users in environmental monitoring, by receiving signals, can uniquely determine from which station the signal came.

The difference is determined by cross-correlation analysis of the signal at the reference station with signals from other stations. The argument of the maximum of the resulting function will be the estimate of the difference in arrival times. In this case, the system takes into account that from the obtained estimate it is necessary to subtract the time for transmission from the receiving station to the reference station and the time for transferring the signal from the source frequency to the receiving station frequency. In addition, the set of time difference of arrival between the reference station and the rest is determined \[-[\tau_{12}, \tau_{13}, \ldots, \tau_{1n}]\], it is also possible to determine the time difference of arrival between any two stations by performing a similar cross-correlation analysis, or using the formula:

$$\tau_{ij} = \tau_{1i} - \tau_{1j}$$  \hspace{1cm} (1)

The output of the system is the vector \(T\) containing the time differences of arrival of all possible combinations of pairs of receiving stations, total \(\frac{n(n-1)}{2}\) elements, where \(n\) is the number of receiving stations. Further, this vector, by multiplying by the speed of light, is recalculated into the vector of the distance difference \(R\).

The accuracy of the classical difference-ranging method depends both on the relative position of the receiving stations and the object of observation, and on the number of used time differences of arrival. Additional differences in arrival times can be obtained by increasing the number of receiving stations, that is, when considering the differences in arrival times between all pairs of stations.

The influence of the relative position of receiving stations and the object of observation on the accuracy of the method is described by the concept of a geometric factor (GF). GF is the coefficient of proportionality between the root-mean-square error (RMS) of determining the position of the source and RMS of the assessment of radar parameters [8]. In the absence of noise, the vector \(R\) is represented as follows:

$$R = [R_{12}(x, y), R_{13}(x, y), \ldots, R_{(n-1)n}(x, y)]^T$$  \hspace{1cm} (2)

where \(R_{ij}(x, y) = \sqrt{(x_i - x)^2 + (y_i - y)^2} - \sqrt{(x_j - x)^2 + (y_j - y)^2}\) - the difference between the distances from the source to the \(i\) and \(j\) receiving stations.

In fact, the signal from the source is subject to additive white Gaussian noise \(n\). Then the vector of distance differences is represented as follows:

$$\hat{R} = R + n$$  \hspace{1cm} (3)

where \(n = [n_{12}, n_{13}, \ldots, n_{(n-1)n}]\).

Let us introduce the objective function

$$F(x, y) = (R(x, y) - \hat{R})^T(R(x, y) - \hat{R})$$  \hspace{1cm} (4)

The position of source will be estimated by the coordinates \((\hat{x}, \hat{y})\) such that

$$\hat{x}, \hat{y} = \arg \min_{(x,y)} (F(x,y))$$  \hspace{1cm} (5)
3 Results and Discussion

To demonstrate the effectiveness of the method of working with all pairs of stations, two cases were considered: the use of delays relative to one reference station, the use of all available delays. The simulation was carried out with a different number of receiving stations.

Table 1. Comparison of a method that deals with time differences of arrival relative to a reference station and a method that deals with all available time differences of arrival.

| Number of receiving stations | The number of time differences during operation relative to the reference station | The number of all available arrival time differences | Difference in used time delays | GF when working relative to the reference station | GF using all available arrival time differences | Difference between GF for the two methods considered |
|-----------------------------|-------------------------------------------------|--------------------------------------------------|-------------------------------|-----------------------------------------------|-----------------------------------------------|--------------------------------------------------|
| 3                           | 2                                               | 3 (33%)                                          | 0.98                          | 0.72                                          | 0.26 (26%)                                     |
| 4                           | 3                                               | 6 (50%)                                          | 0.8                           | 0.51                                          | 0.29 (36%)                                     |
| 5                           | 4                                               | 10 (60%)                                         | 0.74                          | 0.43                                          | 0.31 (41%)                                     |
| 6                           | 5                                               | 15 (66%)                                         | 0.7                           | 0.37                                          | 0.33 (47%)                                     |
| 8                           | 7                                               | 28 (75%)                                         | 0.61                          | 0.26                                          | 0.35 (57%)                                     |

From table 1 it follows that using the maximum possible number of receiving stations leads to a significant decrease in the GF values. It should be noted that for modelling all the distance differences were taken as independent normally distributed random variables with a mathematical expectation equal to the true value of the distance difference. In reality, there may be dependencies between the errors in the values of the time differences of arrival, which will worsen the result and increase the GF. Therefore, the results obtained should be referred to as the lower boundary of the GF.

But for a more objective assessment, it is advisable to introduce such an indicator as a decrease in GF (in percent) by 1% increase in the number of used time differences of arrival.

Table 2. Decrease in GF (in percent) by 1% increase in the number of used time differences of arrival when switching from a method that works with time differences of arrival relative to the reference station to a method that works with all available time differences of arrival.

| Number of receiving stations | Decrease in GF (in percent) by 1% increase in the number of used arrival time differences |
|-----------------------------|------------------------------------------------------------------------------------------|
| 3                           | 0.78                                                                                     |
| 4                           | 0.72                                                                                     |
| 5                           | 0.68                                                                                     |
| 6                           | 0.71                                                                                     |
| 8                           | 0.76                                                                                     |

The table 2 indicates that the transition from working with one reference station to working with all available time delays allows you to get approximately the same gain in terms of the accuracy increase (in percent) by 1% increase in the number of used arrival time differences. It should be noted that the results are seriously influenced by the relative position of the receiving stations. It can be observed that with 5 receiving stations, 4 of which are located at the tops of the square, and the fifth at the intersection of the diagonals of this square, there is a slight loss relative to the positions when the stations are on the same circle. The greatest gain is achieved when the stations are evenly located around the perimeter of the working area. This circumstance must be used when carrying out environmental monitoring in urban areas.
4 Conclusions

The obtained results of determining the coordinates of various objects have shown that they can be successfully used to solve the problems of determining the coordinates of systems of air, sea and ground environmental monitoring. The methods proposed in the work can significantly increase the accuracy of determining the location due to the algorithmic solutions developed for the equipment that is in operation. This is the main advantage of our work, since the development of new methods for determining coordinates during environmental monitoring requires the commissioning of new equipment.

An analysis of the results of measurements of the coordinates of various objects showed that the use of new algorithmic solutions makes it possible to determine the coordinates of an object with an error of up to 1 m both in the atmosphere and in the hydrosphere. On the surface of the Earth, the accuracy of determining the coordinates depends on the terrain in which environmental monitoring is carried out (urban area, suburban area or remote areas of the Far North). At the same time, an important advantage of the system is its passivity, that is, the ability to work without establishing direct contact with the object of observation. This is especially important in urban areas \[22, 23, 37-38\], in the presence of a large number of interferences \[39-42\].

References

1. M. Kozar, L. Sabliy, M. Korenchuk, S. Makeev, A. Korshunov, and V. Kosolapov, IOP Conference Series: Earth and Environmental Science \textbf{390}(1), 012002 (2019)
2. N. Rumyantsev, O. Bondareva, S. Makeev, and V. Krasnoshekov, IOP Conference Series: Earth and Environmental Science \textbf{390}(1), 012037 (2019)
3. V. Yushkova, G. Kostin, V. Dudkin, and L. Valiullin, IOP Conference Series: Earth and Environmental Science \textbf{390}(1), 012016 (2019)
4. A. Korshunov, N. Gaitova, M. Gaitov, A. Cheremisin, and A. Gerner, IOP Conference Series: Earth and Environmental Science \textbf{390}(1), 012009 (2019)
5. E. Gryznova, N. Grebenikova, D. Ivanov, and V. Bykov, IOP Conference Series: Earth and Environmental Science \textbf{390}(1), 012044 (2019)
6. M. Nikitina, N. Grebenikova, V. Dudkin, and Y. Batov, IOP Conference Series: Earth and Environmental Science \textbf{390}(1), 012024 (2019)
7. E. Gryznova, Y. Batov, and N. Myazin, E3S Web of Conferences \textbf{140}, 09001 (2019)
8. R. Davydov, V. Antonov, S. Makeev, V. Dudkin, and N. Myazin, E3S Web of Conferences \textbf{140}, 02001 (2019)
9. V. V. Elistratov, M. V. Diuldin, and R. S. Denisov, IOP Conference Series: Earth and Environmental Science \textbf{180}(1), 10 (2018)
10. N. M. Grebenikova, A. V. Moroz, M. S. Byлина, and M. S. Kuzmin, IOP Conference Series: Materials Science and Engineering \textbf{497}, 012109 (2019).
11. V. V. Davydov, V. I. Dudkin, N. S. Myazin, and V. Yu. Rud’, Instruments and Experimental Techniques \textbf{61}(1), 140–147 (2018)
12. V. V. Davydov, E. N. Velichko, N. S. Myazin, and V. Yu. Rud’, Instruments and Experimental Techniques \textbf{61}(1), 116–122 (2018)
13. V. S. Reznik, V. A. Kruglov, and A. I. Petrov, Journal of Physics: Conference Series \textbf{1410}(1), 012078 (2019)
14. A. Yu. Karseev, and V. A. Vologdin, Journal of Physics: Conference Series \textbf{643}(1), 012108 (2015)
15. N. S. Myazin, V. V. Yushkova, and T. I. Davydova, Journal of Physics: Conference Series \textbf{917}(4), 042017 (2017)
16. N. S. Myazin, V. V. Davydov, V. V. Yuskhova, and V. Yu. Rud, Environmental, Research, Engineering and Management 75(2), 28-35 (2019)
17. N. Myazin, Y. Neronov, V. Dudkin, and V. Yuskhova, MATEC Web of Conference 245, 11013 (2018)
18. K. J. Smirnov, Journal of Physics: Conference Series 1368(2), 022073 (2019).
19. K. J. Smirnov, S. F. Glagolev, and G. V. Tushavin, Journal Physics: Conference Series 1124(1), 022014 (2018)
20. K. J. Smirnov, S. F. Glagolev, N. S. Rodygina, and N. V. Ivanova, Journal of Physics: Conference Series 1038(1), 012102 (2018)
21. M. Ananin, N. Perfilyeva, I. Vedishcheva, and N. Vatin, IOP Conference Series: Materials Science and Engineering 365(2), 022014 (2018)
22. S. Van, A. Cheremisin, and V. Yuskhova, E3S Web of Conferences 140, 09008 (2019)
23. S. Van, A. Cheremisin, A., Chusov, and F. Switala, IOP Conference Series: Earth and Environmental Science 390(1), 012011 (2019)
24. N. A. Lukashev, and V. S. Lukyanetsv, Journal of Physics: Conference Series 1410(1), 012211 (2019)
25. V. I. Dudkin, and A. Y. Karseev, Measurement Techniques 57(8), 912-918 (2014)
26. A. H. A. Al-odhari, G. Fokin, and A. Kireev, In.: 2018 Systems of Signals Generating and Processing in the Field of on Board Communications (Moscow, 2018) pp. 1-5
27. A. S. Podstrigaev, and A. V. Smolyakov, Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics) 11660 LNCS, 525-533 (2019)
28. A. S. Podstrigaev, A. S. Lukiyanov, and A. V. Smolyakov, Journal of Physics: Conference Series 1410(1), 012155 (2019)
29. V. Fadeenko, I. Fadeenko, V. Dudkin, and D. Nikolaev, IOP Conference Series: Earth and Environmental Science 390(1), 012022 (2019)
30. V. B. Fadeenko, G. A. Pchelkin, and O. O. Beloshapkina, Journal of Physics: Conference Series 1410(1), 012238 (2019)
31. A. A. Petrov, Journal of Communications Technology and Electronics 63(11), 1281-1285 (2018)
32. A. A. Petrov, and D. V. Shapovalov, Journal of Physics: Conference Series 1400(4), 044008 (2019)
33. A. A. Petrov, D. V. Zalyotov, V. E. Shabanov, and D. V. Shapovalov, Journal Physics: Conference Series 1124(1), 041004 (2018)
34. N. A. Lukashev, Journal of Physics: Conference Series 1236(1), 012068 (2019)
35. A. P. Valov, Journal of Physics: Conference Series 1410(1), 012246 (2019)
36. S. A. Zakavat, and R. M. Buehrer, in IEEE Handbook of position location (Wiley-Interscience, New York, NY, 2011), pp. 1281
37. N. Vatin, N. Lavrov, and G. Loginov, MATEC Web of Conferences 73, 01006 (2016)
38. A. V. Chechevichkin, N. I. Vatin, V. V. Samonin, and M. A. Grekov, Magazine of Civil Engineering 76(8), 201-213 (2017)
39. S. Chirikov, A. Shkirin, I. Savchenko, N. Bunkin, and M. Diuldin, IOP Conference Series: Earth and Environmental Science 390(1), 012030 (2019)
40. K. Artem'ev, L. Kolik, I. Podkovyrov, V. Meshalkin, and M. Diuldin, IOP Conference Series: Earth and Environmental Science 390(1), 012030 (2019)
41. E. Stepanov, S. Kotelnikov, G. Ratushnyk, E. Nikulina, and M. Diuldin, IOP Conference Series: Earth and Environmental Science 390(1), 012030 (2019)
42. T. Akimov, O. Beloshapkina, M. Diuldin, and J. Molnár, IOP Conference Series: Earth and Environmental Science 390(1), 012015 (2019)