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Local positioning of the communication receiver and the problem of multipath in difficult conditions

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Abstract: **In conditions when the signals of satellite navigation systems are unavailable or distorted, the receiver positioning task could be solved by local positioning system with an integrated data transmission channel. However, when such a system operates in various environments, a lot of multipath signals might appear, which strongly distort delay and phase measurements, on the basis of which the receiver coordinates are calculated. The accuracy of measurements can be significantly increased by introducing measurement redundancy by using the signal reflection properties and increasing the tracking channels on the receiver. In this article, a technique is proposed for creating and using the redundancy of phase measurements, as well as the phase derivatives differences of the local positioning system signals. This technique is based on the effects of signal reflection. An algorithm is proposed for estimating the intensity of the relative acceleration of a moving object, which makes it possible, using the threshold method, to switch between receiver channels at the moments when abnormal spikes appears because of the influence of a multipath signal propagation channel. An algorithm for smoothing transitions between antennas is also proposed using cubic spline interpolation. The obtained methods and algorithms, using two receiving antennas with a single phase center, make it possible to exclude about 80% of spikes caused by multipath effects from estimates of the relative velocity of a moving object, and also provide a basis for developing more advanced methods for using redundancy and further research in this area.**

Keywords: **radio receiving circuits, receiver coordinates, phase estimation, multipath mitigation, tracking channel, cubic spline interpolation**

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Contents

1. INTRODUCTION

Currently, an urgent task is to solve the problem of positioning in conditions when the signals of satellite navigation systems are unavailable or distorted. As a rule, in such cases, a local positioning system (LPS) is deployed in a certain area or in a room [1]. However, when such a system operates indoors, at mining, or in other difficult conditions, a lot of multipath signals arise, which greatly distort the measurements, on the basis of which the receiver coordinates are calculated. It was shown in [1] that the introduction of redundancy into the system can significantly improve the location accuracy. This article describes in more detail the method of using redundancy implemented in [1], as well as a new more efficient method is proposed and its characteristics are analyzed based on the records of LPS operation in the hangar.

2. THE PROBLEM OF MULTIPATH DURING OPERATION

As a rule, the receiver operation algorithm in LPS is divided into two stages:

1. First, the object must remain stationary for a while to estimate the current location. Or it is possible to set the object to a point with known coordinates. This point is considered the starting point.
2. Next, the receiver implements tracking of the phase of the signals of the LPS transmitters, by which it is possible to calculate the change in the coordinates of the object. As a rule, for the implementation of this task, the difference-range method of location is used. The features of the construction and operation of the LPS are described in more detail in [1].

The first stage is a separate research task, so for the moment we will focus on the second stage. When implementing this stage, a situation often arises when at the receiver input, in addition to the direct signal of a certain transmitter, a lot of re-reflected signals appear, which strongly distort the estimate of the phase of the direct signal. In this case, as a rule, signal reflections come from objects of various shapes and sizes, which have complex reflection characteristics, which makes it difficult to analytically synthesize algorithms for combating the effects that cause reflected signals in a phase-locked loop (PLL) and a delay-locked loop (DLL).

Therefore, the main research methods in the work are experiments in real conditions and simulation based on the records obtained during the experiments.

Let us further consider two main theses that form the basis of the proposed method for combating multipath in LPS.

First, based on the works [2-5], we can confidently judge that when a signal with a limited band falls on an object of complex shape, the harmonics of the reflected signal have different frequencies, phases, amplitude and polarization than harmonics in a direct signal, and these parameters will depend on the characteristics of the object and the properties of the signal itself.

Secondly, it is known that there are three types of diversity used to improve the quality of communication systems in difficult conditions [6-9]: in frequency, in time and in space (or polarization). Thus, using the properties of signal reflection, as well as several diversity options at the LPS transmitter, it is possible to increase the order of measurement redundancy at the receiver.

For example, in the simplest case, one signal is generated from one transmitter antenna. Then one tracking channel in the receiver is used to receive it. With the use of two antennas on the transmitter, as well as radiating at two frequencies at each of them, it is already possible to obtain 4 independent tracking channels on the receiver for one transmitter. In this case, you can go further and implement diversity reception at the receiver by installing two independent antennas. Thus, the number of channels involved, operating independently on input signals, will increase to 8, which is already a fairly large order of redundancy. Let us further consider in more detail the main theoretical features of signals under such conditions.

3. MAIN THEORETICAL ASPECTS OF LPS WITH MEASUREMENT REDUNDANCY

As a rule, indoors or on a terrain containing many different structures, the number of reflected signals at the input of the receiving antenna is in the tens [10]. For a general understanding of the processes occurring with the resulting signal at the antenna input, we first turn to a simplified model, when in addition to the direct signal there is one reflected signal on the air (**Fig. 1**). The figure shows an LPS implementation containing N transmitters operating with time division.

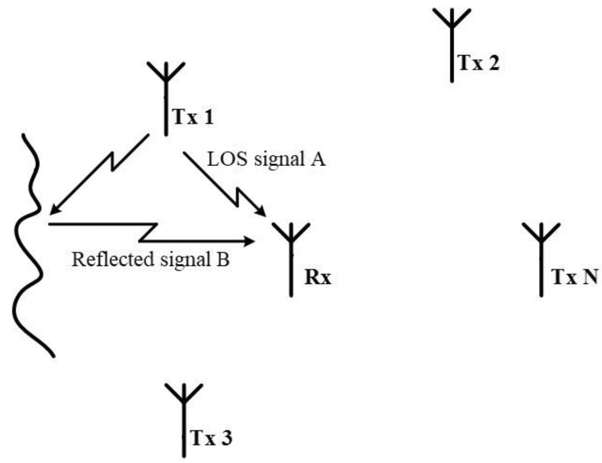

Fig. 1. *Simplified signal reflection diagram.*

At a given time slot, the transmitter signal Tx 1 begins to radiate. The signal arriving at the antenna of the Rx receiver is called the direct signal (LOS – Line-of-Sight) A, which is most subjected to only attenuation during propagation in space and carries useful information about phase to be used for positioning. In addition to signal A, the input of the receiver Rx also receives the reflected signal B, which appeared as a result of the fall of the transmitter signal Tx 1 on a surface of complex shape or otherwise – the target.

When considering the vector diagram of the received signals, it can be seen that the reflected signal B has a different phase and amplitude than the direct signal A, which causes distortion of the resulting signal C. As a result of this effect, the PLL loop discriminator [1] will generate an error signal $\Delta\varphi$ at the output (**Fig. 2**). Thus, a dynamic tracking error will appear in the loop and the measurements will be distorted.

Let us further consider the diversity methods applicable to the LPS operating with the time division of the transmitter signals.

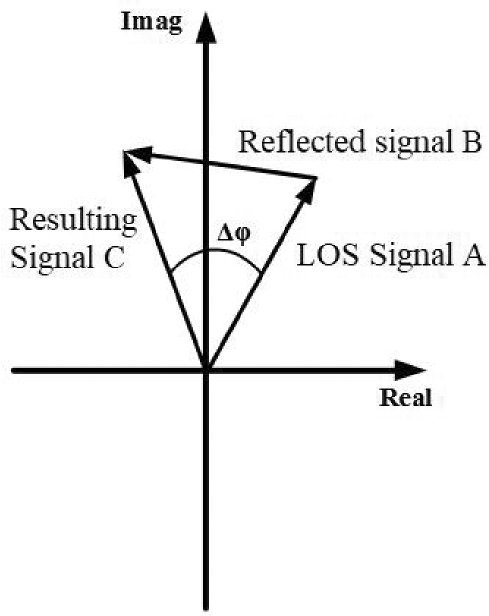

Fig. 2. *Influence of reflection on PLL.*

3.1 Polarization diversity

Let us turn to the mechanism of reflected signal formation. The book [5] introduces the concept of the target's own polarization. When a target is irradiated with a wave whose polarization coincides with one of the target's own polarizations, the shape and orientation in space of the scattered wave polarization ellipse will coincide with the corresponding parameters of the irradiating wave. In this case, the directions of rotation of the field vectors will be opposite when both waves are observed from the side of the target or the antenna, and coinciding when observed along the normal to the front of each wave. If one of the modules of reflection coefficients for eigenpolarizations is greater than the other, then it determines the polarization at which the value of the power flux density of the reflected wave will be maximum. A case is possible when the wave polarization does not coincide with any of the target's own polarizations. Then, in the target's own basis, any wave can be expanded in terms of its own polarizations. The target's own basis has the advantage that it can be used to most simply represent the polarization transformation when the wave is reflected from the target.

Thus, the action of the scattering matrix in its own basis is equivalent to multiplying each of the components of the irradiating wave by some complex factor [5]. We can say that the target scattering operator amplifies or attenuates the components that coincide with the target's own polarizations, and the gain or attenuation coefficients are generally complex and different for different vectors of the target's own basis. After addition, the enhanced or attenuated components parallel to the vectors of their own basis add up to the complex vector of the reflected wave, which differs from the complex vector of the irradiating wave.

From the foregoing, we can draw an important conclusion from a practical point of view: when signals are emitted from two antennas of different polarization, the reflected signals will also have different polarization and will have a different effect on the resulting signal at the receiver input (**Fig. 3**). It can be seen that situations are possible when the reflected signal of antenna 1 has a much greater effect on the operation of the

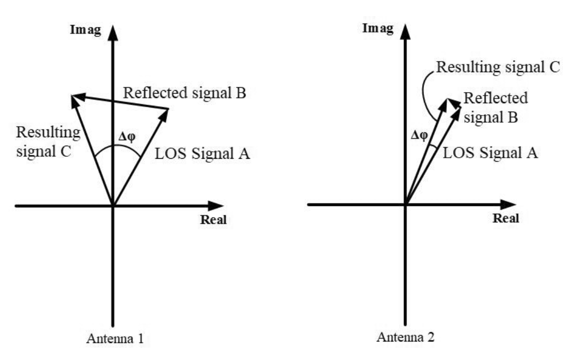

Fig. 3. *Resulting signals using antennas with orthogonal polarization.*

PLL loop discriminator than the reflected signal of antenna 2. However, it should be noted that the behavior of these signals will mainly be determined by the objects from which the LPS signals are reflected, and in different rooms, the behavior of the signals will also be different.

Next, imagine that the receiver is moving at some speed, and the targets are objects of complex shape. In this case, the reflection characteristics will constantly change: new reflected signals will appear, old ones will disappear. In this case, since reflections will occur each time from different simplified targets, then the own bases of these targets will be different, and, as a result, the effect on the resulting signal will also be different each time.

There is an important remark to be made next. It is obvious that if, with such a behavior of the reflected signals, their influence on the resulting signals turns out to be uncorrelated with each other, then using some mechanism for switching between signals coming from different transmitter antennas, it is possible to minimize the effect of multipath. However, in reality, the magnitude of the correlation will be determined by the characteristics of specific targets or objects in the room.

It is obvious that one more practically significant conclusion can be drawn from the above: this mechanism of using polarization is also applicable to the receiver. Let us assume that the signal from the transmitter is emitted from one antenna, and is received independently on two receiving antennas with a single phase center (**Fig. 4**).

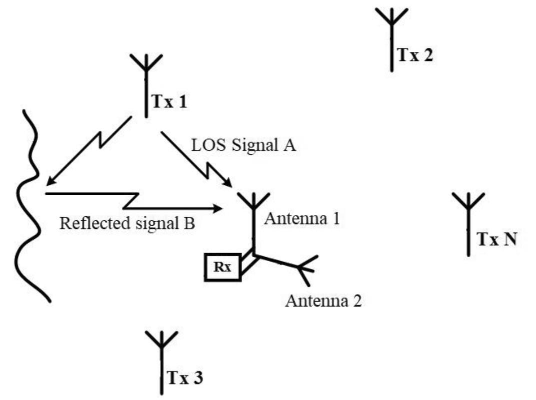

Fig. 4. *Signal reception on two independent antennas with same phase center.*

Since the transmitter and receiver antennas, when considered in a single basis, do not always have the same polarization, since. the receiver can move along any trajectories, including inclined ones. In this case, one reflected signal with some polarization distorted relative to the transmitter will arrive at the receiving antennas. In this case, it is also not difficult to see that its effect on receivers connected to antennas of different polarization will also be different and will obey the same laws as described above for purposes.

3.2 Frequency diversity

Above, the mechanisms of signal reflection were considered on the basis of the radar approach. The frequency diversity method can be conveniently described using an analysis of the characteristics of the propagation channel characteristic of wireless information transmission systems. It is known [6] that the signal propagation channel has a certain frequency correlation interval, which is determined by the nature of the movement of the object, as well as by the set of reflecting objects that generate reflected signals. Obviously, the separation of the transmitter signals in frequency by

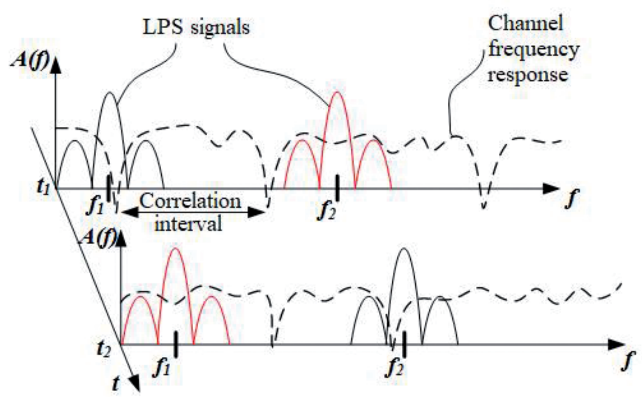

Fig. 5. *Frequency division multiplexing.*

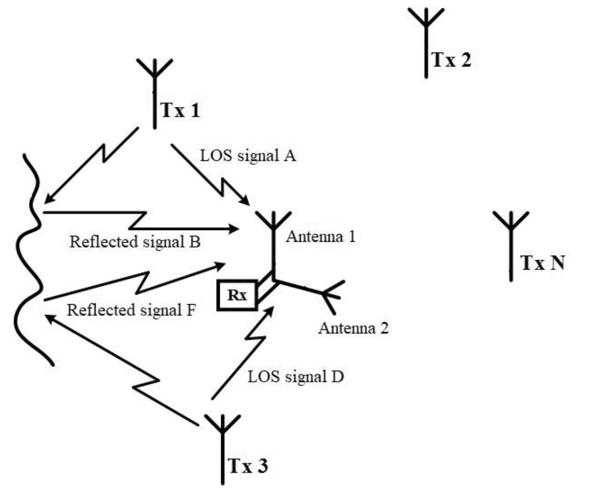

Fig. 6. *LPS functioning.*

values larger than the correlation interval will allow, using some mechanism for switching between signals, to minimize the effect of multipath. To explain this mechanism for two moments of time t_1 and t_2, such that ($t_2 - t_1$) > dt, where dt is the correlation interval of the channel frequency response over time, below are estimates of the channel frequency response, and the spectra of emitted signals are shown relative to it (**Fig. 5**). Red in the figure indicates a signal whose carrier phase estimate is used for positioning. It can be seen that at time t_1, the dip in the channel's frequency response falls on the signal at frequency f_1, while the signal at f_2 is practically undistorted. At time t_2, the situation is reversed.

4. MATHEMATICAL DESCRIPTION OF THE SWITCHING MECHANISM BETWEEN CHANNELS

When implementing the switching mechanism between channels, from a practical point of view, it does not matter which method the redundancy is implemented. Let us consider the algorithm for switching between channels for the case when the receiver in the LPS operates at the second stage of operation, namely, it determines the increment of local coordinates. In this case, to implement the difference-range method, it is necessary to calculate the estimates of the difference in increments of the total phases of coordinates for three pairs of LPS transmitters. Assume that redundancy is implemented using polarization diversity at the receiver.

In **Fig. 6**, you can see how the signals emitted by the transmitters Tx 1 and Tx 3 were reflected from the surface of a complex shape and arrived at the antennas of the Rx receiver.

Fig. 7 shows vector diagrams of the resulting signals at various receiving antennas. It can be seen that the effect on the PLL loop is different, while on antenna 2 it is noticeably less than on antenna 1.

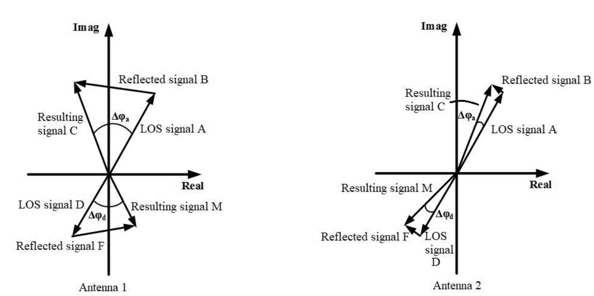

Fig. 7. *Vector diagrams.*

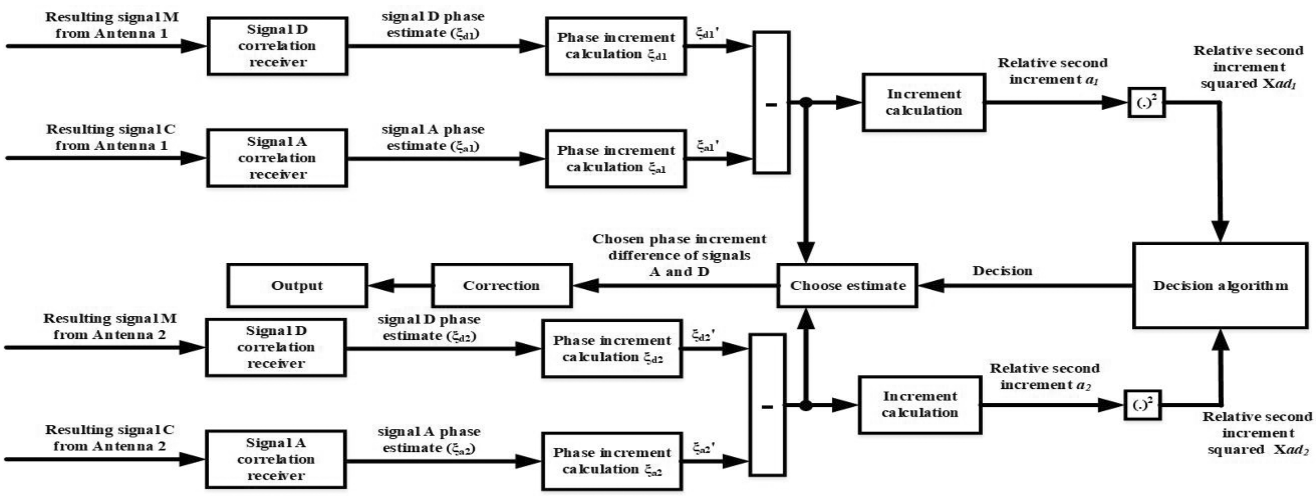

Fig. 8. *Antenna switching algorithm for local coordinates calculation.*

Fig. 8 shows a diagram of the operation algorithm for one difference in phase increments of the carrier frequency of the signals of a pair of transmitters. The resulting signals M and C are fed to the inputs of the correlation receivers of these signals. Based on the results of the work, these receivers give estimates of the total phase of signals A and D. Further, in blocks and, the increment of these estimates and the difference between them are calculated. Thus, the difference in increments of estimates of the total phases of the signals of transmitters A and D for antenna 1 is obtained. Similarly, the difference in increments of estimates of the total phases of the signals of transmitters A and D for antenna 2 is calculated. These differences are then recalculated into estimates of relative velocities ν_1 and ν_2 in blocks and, respectively.

Based on these values, an increment is calculated, which is an estimate of the relative acceleration, and then, squaring the obtained values, one can obtain estimates of the relative acceleration intensity for antennas 1 and 2, respectively. Based on the admissible motion dynamics of the object, it is further possible to set a threshold for the decision device, which, when the relative acceleration intensity estimate is exceeded, switches between the antennas, forming a solution for the evaluation selection block. Phase increments between antennas can behave in different ways, causing jumps at the moments of switching between antennas.

To combat this, a corrective algorithm, such as 3rd order cubic interpolation, can be used for antenna transitions. The polynomial for such an interpolation can be represented as follows:

$$f(x) = a(x - x_1)^3 + b(x - x_1)^2 + c(x - x_1) + d,$$

where $[x, x_1]$ is the interpolation interval, a, b, c, d are the polynomial coefficients.

The final corrected values of increment differences are fed to the output of the algorithm for the subsequent calculation of coordinate increments.

5. EXPERIMENTS AND SIMULATION

To test the stated hypotheses about the behavior of signals in the hangar, as well as to study the characteristics of the proposed algorithms for switching between channels, a part of the LPS was deployed. Two transmitters Tx 1 and Tx 2 were installed on the wall at different angles, emitting LPS signals. The PC computer is connected by wires to the transmitters: implements control and synchronization. The Rx receiver is located on a movable object and moves in a circle of constant radius in the middle of the hangar.

The scheme of the experimental setup is shown in **Fig. 9**. Such a setup made it possible to evaluate the characteristics of the estimates of the total phase of the signals of the transmitters, as well as the differences in the estimates of the total phase of the signals of two transmitters. An increase in the redundancy of measurements was achieved by installing two independent antennas on the receiver, from each of which the signal was recorded synchronously and independently.

Further, the recorded data were fed to the tracking algorithms described in [1] using simulation modeling. The result of the tracking algorithms was the estimation of the total phase of the signals during the experiment. The estimate data was then processed by an algorithm using the presence of redundant measurements, which produced corrected values. The results of the proposed switching algorithms are shown in

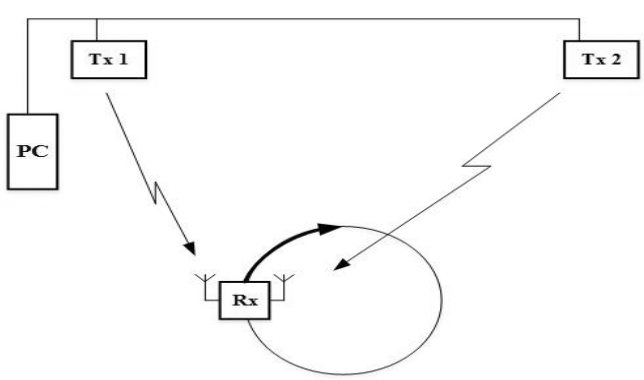

Fig. 9. *Experiment scheme.*

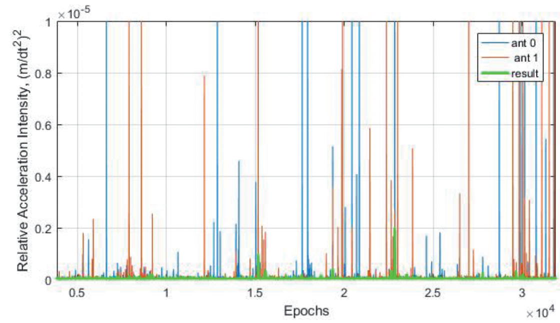

Fig. 10. *Acceleration intensity estimate.*

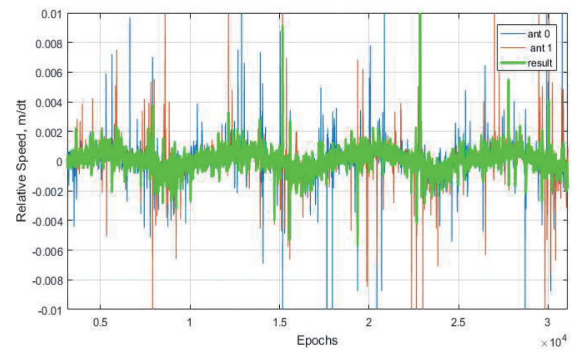

Fig. 11. *Relative speed estimates.*

Figs. 10, 11 for the case when the antennas are installed vertically, as well as in **Figs. 12, 13** for the case when the antennas are installed

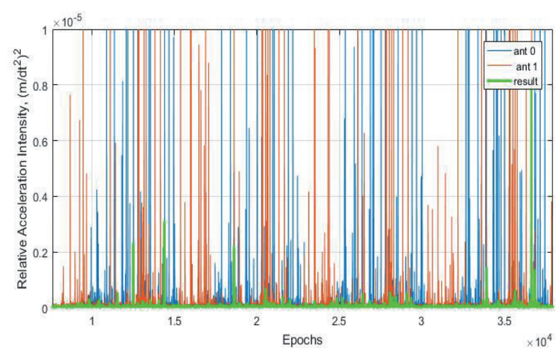

Fig. 12. *Estimate of relative acceleration intensity.*

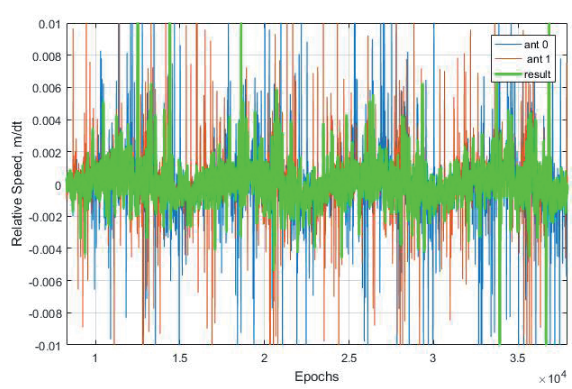

Fig. 13. *Relative speed estimates.*

horizontally. In both cases, the antennas are two vibrators with a single phase center and 90 degree angles between them.

The number of excluded jumps in the intensity of relative acceleration can be considered the main indicator of the efficiency of the algorithm: For vertically mounted antennas, the number of excluded peaks was ~78%, for the case of horizontally mounted antennas, ~83%. Also in fig. 11 and 13, one can see a significant reduction in the amount of emissions in the relative velocity estimate.

6. CONCLUSION

In this article, based on well-known theoretical effects, a method is proposed for creating and using redundancy in measurements of the estimation of the total phases, as well as the difference in the increments of the total phases of signals from transmitters of local positioning systems. An algorithm for estimating the intensity of the relative acceleration of a moving object is proposed, which makes it possible, using the threshold method, to switch between the receiver channels at the moments when anomalous jumps characteristic of the influence of a multipath signal propagation channel are recorded. An algorithm for smoothing transitions between antennas is also proposed, using cubic spline interpolation.

In general, using the described methods and algorithms, using two receiving antennas with a same phase center, it was possible to exclude about 80% of jumps caused by multipath effects from estimates of the relative velocity of a moving object.

These algorithms provide a basis for the development of more advanced methods for using redundancy, as well as further research in this area.

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