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Analysis of existing methods for processing GNSS survey data for deformation monitoring

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ABSTRACT: The issues of processing GNSS survey data, the results of observations at the points of the state geodetic network, the concepts of the quality of the result of deformation monitoring are considered.

GNSS survey data processing occupies one of the most important places in the methodology. The results of observations at GNSS points carry information both about displacements of the foundations of structures (for example, pit wall landslides) and about periodic (seasonal, annual) deformations of components caused by external factors (uneven solar heating, temperature fluctuations, wind load, snow load, icing, seismic activity, etc.). Periodic observations help to identify negative geological processes in the area where the engineering facility is located.

Changes in the position of Permanent Operating Base Stations (PBSs) installed at dynamic sites can have different values, speeds and nature. In order to determine the most accurate antenna phase centre displacement under certain conditions, different, sometimes non-standard methods of spatial information processing need to be applied. At the same time it is necessary to know exactly the expected accuracy of geodetic observations. The notion of quality of result of deformation monitoring implies high accuracy of coordinates measurement, detailed description of antenna motion, absence of influence of big errors and so on. [1].

It should also be remembered that each object of study has its own unique nature. Data processing methods may be acceptable for one type of object, but for another, seemingly identical object, such methods will not be correct. In order to accurately assess the suitability of a methodology, control or test measurements are usually carried out. This activity is experimental in nature, needed to confirm suitability by testing the same survey results, but carried out using different techniques. The method that gives the most accurate result, corresponding to the actual movement of the object, is deemed optimal and is used for further work on an ongoing basis. Such measures also help identify the influence of various mistakes that occur during surveying. One of the most widespread mistakes is signal over-reflection that occurs as a rule in urban areas with high-rise buildings. Multipathing is the cause of an error ranging from a few centimetres to a metre. Such measurements are to be rejected [2].

Geodetic monitoring of dynamic objects involves measuring the coordinates of the points in the deformation network in order to detect coordinate deviations of the points. In order to describe the coordinate deviation in detail, mathematical processing of the data obtained is necessary. This step is one of the most important, as the choice of mathematical function determines the details of the display of dynamic processes in the terrain. In practice, the most commonly used methods for mathematical processing are the moving average method, the median filter, the window function and the interval composite method. To further select the best method it is necessary to disambiguate them, in particular [3].

The moving average method is often used when it is necessary to smooth time series and remove high frequency components from the radio signal. According to the algorithm, an

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interval of a certain length is first taken from the original data set. This is followed by finding the arithmetic mean of all signal values in this interval.

For the example, assume that signal f has N points. For each N-point there is a signal value K. The value of the moving average gi in the interval of point i will be equal to the arithmetic mean of the K previous and subsequent points, including point i. Each new value of gi will be defined as the smoothing factor in the 2K+1 interval (1).

$$g_i = \frac{1}{2K+1}\left(f_{i-k} + f_{i-K+1} + \cdots + f_i + f_{i+k}\right) \tag{1}$$

The calculation results in a new series of smoothed data consisting of arithmetic mean values (Figure 1). This method is good in that it allows fast data processing, but has a disadvantage in the accuracy of the result obtained. This is due to the fact that the averaging takes place where there may be incorrect signal values (noise, radio wave reflections, etc.). Therefore, values from the start and end points of the signal are not taken into account in the smoothing calculation. If a result with an accuracy of 1 cm is required (example: determination of the deformation of a job during operation), this method is not optimal [4].

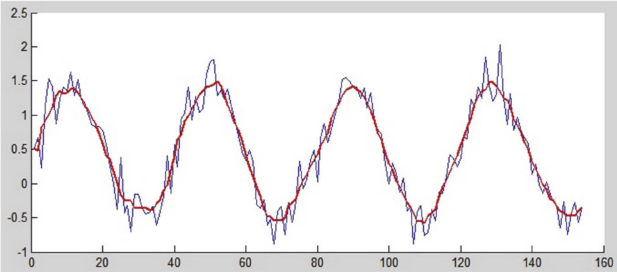

Figure 1. Result of smoothing the signal using the moving average method.

The second method is median signal filtering. This method is widely used in digital processing and can reduce impulse noise. Impulse noise is caused by electromagnetic waves or a technical failure in the signal reception system. The median filter differs from the arithmetic average filter in that it is selective in the signal window (aperture). If the values in the signal window are a monotonous sequence of numbers, the filter will leave them unchanged. With values standing out from neighbouring points, the filter performs averaging, depending on the chosen aperture. As can be seen in Figure 2, median filtering with the correct aperture is able to preserve the sharp variations in the signal while suppressing the interference in the array [5].

The median method has found its application in inertial navigation systems where fast orientation in space with an accuracy of approximately 1 meter is required. However, it is not widely used in engineering geodesy, as two-step processing first of statistical, then of impulse noises is not rational for high-precision measurements [6].

The processing methods discussed above are based on calculating the average value of a section of the signal and then averaging it further. We will now look at a new technique. This method is called the interval superposition method. The main difference from previous methods is that it applies a statistical calculation algorithm inside the signal segment. This method is basic in deformation monitoring for a structure along with the kinematics mode. The great advantage of this method is the millimetre accuracy of coordinate determination, but such a result requires strict consistency in methodology and favourable surveying conditions [7]. In static mode, the resulting data array is divided into time intervals of a certain length. Depending on the company of the equipment used (Leica, Trimble etc.) these intervals are processed in special software. The result of the processing is presented as a diagram,

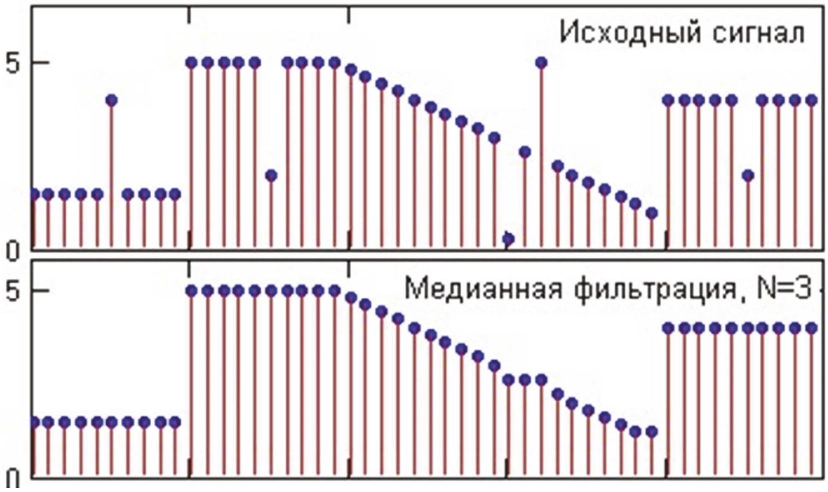

Figure 2. Comparison of signal after median filtering.

where the abscissa axis shows the offset, and the ordinate axis the time interval. Figure 3 shows an example of processing, where 1 hour was taken as the time interval.

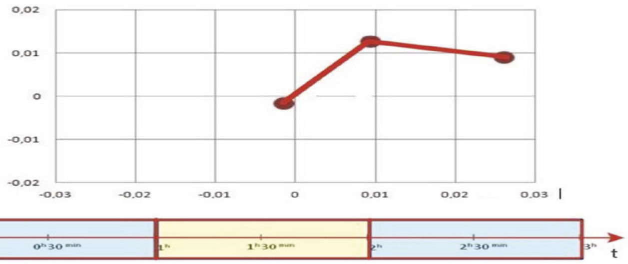

Figure 3. Processing of satellite measurements in static mode at 1-hour intervals.

Static mode requires presetting, as the quality of the result may vary depending on the shooting conditions and the task at hand. The detail can be improved by reducing the time interval, but this may lead to a decrease in the accuracy of the displacement detection. Repeated measurement of coordinates in a short period of time contributes to error accumulation. Studies have shown that 15 to 20 minute intervals are possible if there is no chance of signal re-reflection; the required number of satellites is available; and the geometric arrangement of the receiver stations is correct. But such conditions are rare. For this reason, other survey parameters must be used. The optimum is to have overlapping time slots so that observations are frequent, but not excessive. We now have four time slots of 1 hour and an overlap of 45 minutes. The observation time is three hours. As shown in Figure 4, the overlapping of intervals allows detailed tracking of the GNSS receiver antenna movements on a dynamic object. The appearance of intermediate points helps to study the trend of the object. When monitoring deformation of structures it is possible to track how stable a structure is. For geological monitoring of crustal movement, the data obtained is of great importance if the area is seismically active and suffers from destructive natural phenomena [8].

In the course of the work, the optimum mathematical variant of satellite signal processing for monitoring dynamic objects was established. The static mode proved to be one of the most

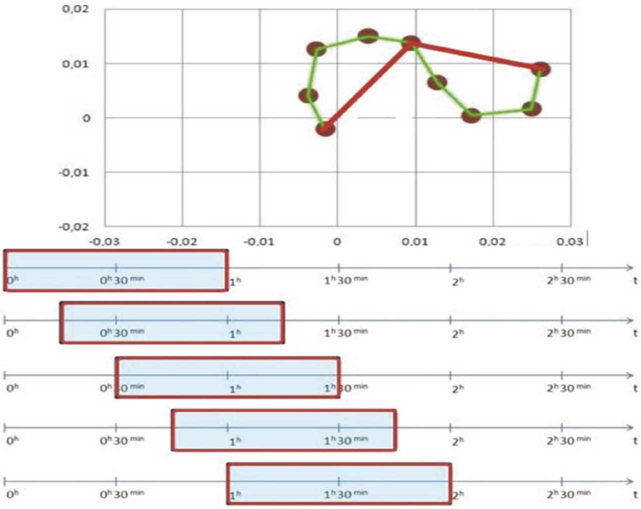

Figure 4. Processing in static mode with overlapping time slots.

feasible, as it meets most of the monitoring requirements. The resulting detail of the displacement trajectory has been realised through repeated measurements under different conditions.

Satellite observation methods have opened up new possibilities for geodetic monitoring of buildings, structures and geological processes. GNSS geodetic monitoring is actively used to study areas of high seismic hazard; for landslide monitoring of quarry sides; for geodetic monitoring of dynamic structures such as towers, bridges, etc. However, it should be noted that the development of the latest technical solutions in the field of geodesy implies the development of modern approaches to geodetic solutions [9]. In other words, when using modern geodetic equipment, it is also necessary to use modern methods of fieldwork and cameral work to replace traditional methods. Therefore, a GNSS overlay survey interval method was developed to address the processing of displacement monitoring data [10].

As is already clear from the name of the interval method, the main role here is played by the duration of those very intervals. The use of one-hour intervals is an acceptable survey parameter, but results in an averaging of the resulting structural displacement. One hour intervals may be used when monitoring targets that are not highly deformable, or when creating an overview model to show the total displacement pattern [11]. If there is a requirement to show more detailed displacement of structures, intervals of 15-20 minutes are used. And following this logic, the shorter the time interval, the more detailed changes to the object will be shown. The reason for this is that more intermediate measurements are taken in a shorter time interval. However, there is always the danger in processing satellite measurements - using short intervals may lead to a poor quality solution. As foreign experience of GNSS application shows, in absence of objects reflecting the signal, sufficient number of satellites and optimum geometric position the use of intervals of 10-15 minutes for processing of observations in static mode allows to receive the solution corresponding to the required level of accuracy of equipment. However, if conditions are different from ideal, the use of 10-minute intervals becomes risky and may affect the accuracy of the final result, so the length of the interval should be chosen, starting from external survey conditions [12]. As can be seen in Figure 5, the interval stacking method is good in that it allows the coordinates of intermediate points to be obtained.

From the above, intermediate points increase the detail of the detected antenna displacements of the receiver and allow for a more accurate representation of the dynamics of the instrument's point of origin. Increasing the detail of the detection of displacements is in fact an increase in the accuracy of the coordinates of the antenna attached to a dynamic object, as a more detailed trajectory at any given time shows a closer approximation to the real position of the antenna [13].

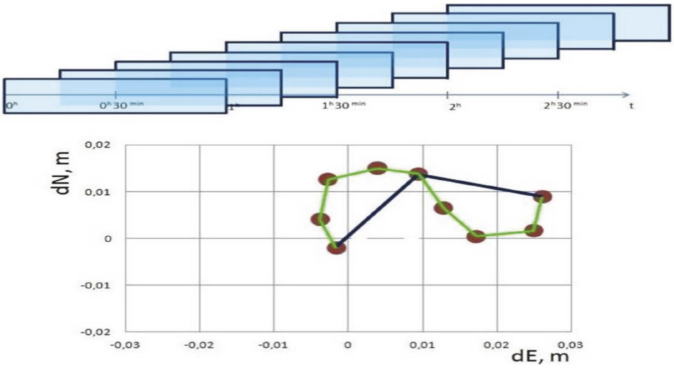

Figure 5. Diagram of displacements using the 1-hour interval treatment.

One of the parameters that characterise the accuracy of a measurement is the RMS value. According to theory, the RMS characterises the internal convergence of measurement results. If a systematic error is taken as a constant value, such as an error for signal over-reflection, this error will have a negligible effect on the RMS value. The RMS value may not be affected by a systematic error which is constant in magnitude, e.g. due to the effect of an over-reflected signal [14]. However, there is the potential for error in short acquisition sessions if the interreflected signal is active for the whole processing interval. One advantage of using the interval overlapping method is that the influence of the signal over-reflections on the measurement result is eliminated. This advantage is due to the fact that there will always be several intervals that include the start or end of an overreflected signal [15].

When selecting the interval length, it is worth paying attention to the drift rate of the permanently installed base station antenna. This value can vary depending on the type of object: for dams and low-rise buildings it can be millimetres, while for radio towers and TV towers the displacement is up to a metre. Accordingly, displacement rates are measured in mm/h to dm/h and, in exceptional cases, in m/h. Logically, when station displacement rates are high, processing using long intervals will produce poor quality results. In theory, the rate of change of position of some structural elements can be calculated from the original data on the parameters of the structure. However, as practice shows, these calculations do not always coincide with reality: this is due to many factors, for example, external conditions, period of operation, etc. [16].

In order to study the dependence of the interval value on the displacement velocity in more detail, test observations using GNSS receivers were carried out. In order to study the dependence of the interval limit value on the displacement rate of the receiver antenna attached to a dynamic object, we carried out observations using GNSS receivers capable of working simultaneously with the signals of most satellite geo-positioning systems.

From the results of the test field surveys, a graph was plotted showing the dependence of the interval value on the receiver antenna displacement rate (Figure 6). It allows determining the limit value of the processing interval depending on the displacement velocity of the structure. If, for a particular velocity, the interval length is greater than the limit values shown in the graph, an incorrect solution is likely [17].

For length intervals between 1 and 5 minutes, it is possible to process measurements even at high displacement rates, up to metres per hour. However, such results require input data with high accuracy and a clear signal. To summarise, the interval stacking method has a number of advantages but, like other methods, requires certain survey conditions. Sufficient number of satellites throughout the measurement period, monitoring network geometry, over-reflection of signals from extraneous objects - all this leads to a decrease in the accuracy of coordinate determination [18].

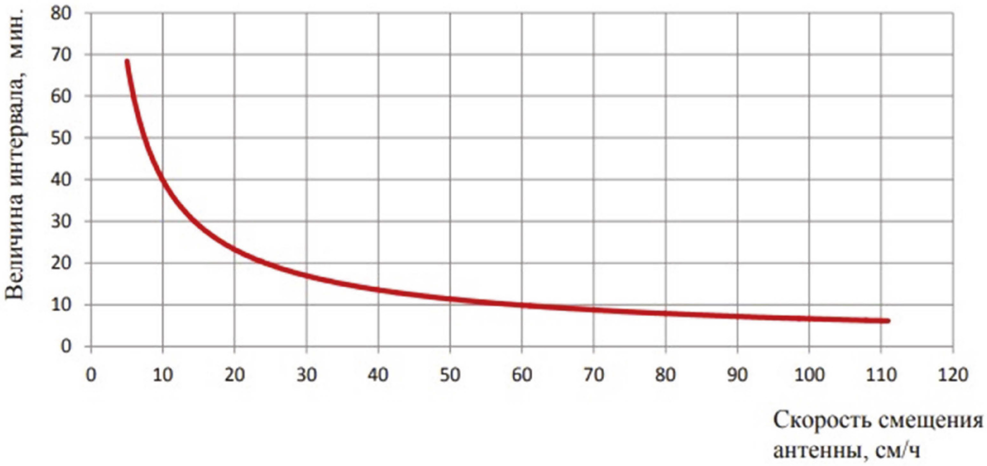

Figure 6. Plot of the interval value versus receiver antenna shift speed.

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