Structural design of satellite geodetic networks using mobile monitoring stations

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Abstract. The article considers a method for solving the problem of structural design of modernized networks of non-request measuring instruments of a ground-based control complex for navigation stations of a space complex. The object of research is satellite geodetic networks using mobile monitoring stations. The type of such networks is information and control systems distributed over the territory, dispersed in space. Structurally, they are determined by multifunctional sets of stationary and mobile elements with advanced technical means for receiving, transmitting and processing information. It is shown that in the structural design of satellite geodetic networks, special attention is paid to the cost of the network, since this can significantly reduce the cost of field work associated with the use of mobile monitoring stations. An analysis of various approaches to the formation of the structure of such systems was carried out, which showed that the tasks of formation can be divided into two groups: the formation of the topological structure of the system and the formation of the functional structure of the system. The paper presents the stages of the analytical and simulation procedure, which includes optimization and simulation models and allows solving the problem of structural design of satellite geodetic networks.

1 Introduction

Structural design issues are relevant for modern tasks of building modernized networks of non-request measuring instruments of the ground-based control complex for navigation stations (NS) of the space complex (SC), which is used as part of geodetic networks [1-3]. It is noted in [4] that solving the problems of designing geodetic networks intended for observing the movements and deformations of the earth's crust and large engineering

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structures is of great practical interest. As a rule, in the structural design of satellite geodetic networks, special attention is paid to the cost of the network, since this can significantly reduce the cost of field work associated with the use of mobile monitoring stations. The authors in [4] formulate the following network structural parameters (attributes) optimized during design, which affect the cost of work:

– weights of measured values (angles, distances, etc.);
– position of monitoring points (network configuration);
– number of network monitoring points.

Accounting for the parameter that reflects the number of network monitoring points is due to the fact that the largest contribution to the cost of all field work is made precisely by the laying of geodetic points, the construction of signals, the cost of materials, transportation costs, etc. For mobile monitoring stations, these costs are significantly lower, which allows reducing the overall costs for the development of a geodetic network.

It should be noted that despite the importance of solving the problem of determining the minimum required number of network points and their optimal position, especially if the construction of points is possible only in places strictly fixed on the ground or in an engineering structure, it has not yet found proper coverage, much less a complete solution in geodetic literature. A number of works [5-7] are devoted to solving this problem.

Thus, the structural design of satellite geodetic networks using mobile monitoring stations at the moment, for the indicated reasons, is an unresolved and rather difficult task. This problem is formulated as the problem of finding the minimum number of optimally located points necessary for the correct functioning of satellite geodetic networks using mobile monitoring points. In this case, it is assumed that strictly fixed places (coordinates) are known in advance, where both the construction of stationary and the placement of mobile monitoring points is possible.

2 Materials and methods

Modern materials and methods that exist today allow, in general, to successfully solve the mathematical problems of fixing the general earth kinematic coordinate system only according to measurement data in space geodetic networks. It is noted in [4] that until now, in world practice, such fixation was carried out by reference to any geological and geophysical model of lithospheric plate movements. The authors state that the refusal to use any hypotheses and models of the Earth's evolution will make it possible to more reliably fix the coordinate system in the Earth's body to provide satellite navigation systems such as GPS/GLONASS. This will also make it possible to more reliably solve such problems of geology and geophysics as independent testing of various hypotheses and models of the Earth's evolution, possible changes in its radius, post-glacial uplift of the earth's crust, etc.

At present, computer algorithms have been developed and implemented for optimal design of the most informative measurements in geodynamic GPS networks for monitoring active volcanoes and faults in the earth's crust [8–13]. The algorithms can significantly reduce the cost and time spent on field work and are ready for practical use.

An algorithm has been developed for estimating the average annual displacement rates of geodetic points from short series of average daily coordinates of GPS stations, taking into account a priori information about the amplitudes and initial phases of seasonal variations, which can significantly improve the accuracy and reliability of determining modern movements of the earth's crust.

Experimental work has been carried out to combine various global space geodetic networks and determine the current movements of the earth's crust on a global and regional scale. The point displacement rates in global networks are in good agreement with the NNR NUVEL-1A tectonic model and the ITRF2000 international coordinate system. The materials and methods used in these studies have been repeatedly reported at various international symposia, published in [8-13] and other publications.

Thus, today the main theoretical methods related to mathematical processing and optimal design of geodetic measurements are well developed. Developing an approach based on the structural design of satellite geodetic networks using mobile monitoring stations, attention should be paid to the method of fixing the coordinate system.

The physical essence of the method for determining the movements and deformations of the earth's crust and large engineering structures consists, as a rule, in calculating the displacements of fixed points in any coordinate system from geodetic measurements. If these displacements are determined relative to the initial geodetic points fixed in the non-deformable zone, the problem is known to be solved without any problems in the coordinate system fixed by these initial points. Otherwise, which is also typical when using mobile monitoring points, all points of the geodetic network experience shifts and the problem is solved ambiguously, since fixing the coordinate system requires, firstly, to select quasi-stable points according to some criteria and, secondly, set in some way the preliminary coordinates of the points of the geodetic network, which, in fact, will fix the coordinate system by applying the theory of mathematical processing of free geodetic networks using the apparatus of generalized inverse matrices. At the same time, in [4], it is proposed to solve the following system of correction equations

$$K\sigma Y + B = C \tag{1}$$

with restrictions

$$E\sigma Y = 0, \tag{2}$$

where B is the vector of free members; K - matrix of correction equation coefficients; $\sigma Y = (\sigma y_1, \sigma x_1, \sigma z_1, ..., \sigma y_q, \sigma x_q, \sigma z_q)^{\mathrm{T}}$ is the vector of unknown station velocities in the rectangular coordinate system X, Y, Z; x, y , z - rectangular coordinates of q network points; C is the vector of corrections to the measurement results.

The choice of the system of coordinates depends on the choice of the constraint system (2), in which the velocities of the geodetic points will be obtained. In equations (2), one usually chooses the matrix

$$E = G^T I_e. \tag{3}$$

In expression (3), the following designation is additionally introduced: Ie is a diagonal matrix containing ones on the diagonal for quasi-stable and zeros for mobile points. It is noted in [14] that despite the simplicity of expressions (1)–(3), a number of incorrect statements and conclusions are allowed when using them. For example, matrices K and G do not have to be orthogonal and should only complement each other. It is also noted there that the scale of the network is usually always set by the results of direct measurements.

Taking into account that for a planned network it is expedient to fix the origin of point shifts relative to the center of gravity of a stable territory or a block of the earth's crust, the origin of coordinates should be placed at the center of gravity of quasi-stable points located there, but not always at the center of the network. It makes sense to center the coordinates over all points only if all points are considered to be quasi-stable. For global space networks covering the entire globe, the reference point should be combined with the center of gravity, but not the center of gravity of quasi-stable points. Then, during the rotation of the network, the vertical displacements of points should remain unchanged, for example, during linear transformations by the iterative weighted method of S-transformations performed according to known formulas [15].

3 Results and discussion

The problems of choosing the structural composition of the ground segment of the space complex of the system and the locations of its objects are relevant for the medium term. It is during this period that they will be finally determined. In this regard, the proposed formal model is of a particular nature and, accordingly, will require clarification based on the result of a detailed analysis when conducting model experiments, taking into account the results of ongoing development work. It is obvious that from the network control center in real time and in an automated mode, almost all the main navigation tasks of controlling the NS and controlling the navigation field are solved.

Taking into account the analysis of various approaches to the formation of the structure of such systems [16-18], it is shown that the problems of formation can be divided into two groups. The first includes tasks related to the formation of the topological structure of the system, which consists in determining the composition, territorial location and type of control nodes at all levels of the system hierarchy and communication channels between them. The second group includes the problems of forming the functional structure of the system, that is, the distribution of control functions between the nodes of the system, including the control object and the distribution of technical means among the nodes of the system.

From a mathematical point of view, the considered problems of structural design of satellite geodetic networks using mobile monitoring stations belong to the class of mathematical programming problems in which a number of constraints are specified not explicitly, but algorithmically [19].

The following algorithm is proposed for solving the problem of structural design of satellite geodetic networks using mobile monitoring stations. Denote by the set of variants of structures that are admissible under restrictions on attributes specified in the analytical form, and by β'' – a set of variants of structures that are admissible according to restrictions on attributes specified algorithmically, i.e., the fulfillment of these restrictions can only be verified during simulation. Then the space of admissible variants of structures $\beta = \beta' \cap \beta''$.

Models of formation problems, depending on the method of specifying the objective function and the space of admissible variants of the structure β , can be divided into classes, where the objective function can be specified either analytically or algorithmically. In this case, the space β can be set:

- analytically;
- algorithmically;
- analytically and algorithmically.

Depending on the class of the structural model, various procedures for searching for the optimal structure variant can be used, differing from each other in the way of generating structure variants, the rules for checking analytically and algorithmically specified attributes, and the way to proceed to the next step.

In such a situation, it would be reasonable to use the optimization-simulation approach [3, 16], based on the joint use of optimization and simulation models in the process of searching for optimal structure options.

Below are the main stages of the analytical-simulation procedure for the formation of a basic set of structures with a given set of attributes for multi-attribute selection of the best structure variant:

Stage 1. Generation of a variant of the system structure X_i , $i = 1, \ldots, m$ with a given set of attributes A_j, $j = 1, \ldots, I$.

Stage 2. Checking the admissibility of the structure variant according to analytically specified attributes. If $X_i \in \beta$, then go to step 3, otherwise go to step 1.

Stage 3. Conducting a computer experiment with a simulation model of the system η_{X_i} for a variant of the structure that is admissible in terms of analytically given attributes X_i. Model η displays the functioning of the simulated system for various variants of the structure. Between stages 1 and 3, an information interface is organized to transfer data about the studied variant of the structure X_i.

Stage 4. Checking the validity of the structure option X_i algorithmically defined attributes. If $X_i \in \beta$, then go to step 5, otherwise go to step 1.

Stage 5. Memorizing a variant of the structure that is admissible according to the attributes specified analytically and algorithmically.

Stage 6. Checking the completeness of the analysis of all variants of the structure. If, as a result of the check, it turns out that not all variants of the structure have been analyzed, then go to stage 1. Otherwise, the output of the results obtained and the end of the algorithm.

This analytical and simulation procedure includes optimization and simulation models (stage 3) and allows in iterative mode to solve the problem of structural design of satellite geodetic networks using mobile monitoring stations.

4 Conclusion

Thus, based on the analysis of the problems of structural design of satellite geodetic networks using mobile monitoring stations, the need to search for rational options for the network structure using optimization and simulation models was revealed. This allows in the process of forming the structure to design, evaluate and select rational network options, including mobile monitoring points. Moreover, the proposed optimization and simulation procedure, including optimization and simulation models, allows solving the problem of structural design of satellite geodetic networks using mobile monitoring stations in an iterative mode.

In [20-22], applied aspects of the application of simulation modeling and optimization-simulation approach to solving problems of structural design of space navigation systems, which include satellite geodetic networks using mobile monitoring stations, are presented. Such networks are distributed information and control systems and are multifunctional sets of stationary and mobile elements dispersed in space with advanced technical means for receiving, transmitting and processing information.

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