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The Evolution of Space Geodesy

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Abstract

The article considers the state and development of space geodesy. Geodesy is the science of space, and space geodesy is the science of outer space. The connection between space geodesy and space geoinformatics is shown. The directions of development of space geodesy are described. Space geodesy is developing in two different directions. The first direction is connected with the study of the Earth from space. The second direction is directed from the Earth to the exploration of outer space. Space geodesy can be applied independently or to support other sciences and technologies. It is shown that fuzzy sets and fuzzy situations can be used in ground and space geodesy. With fuzzy or incomplete information, it is necessary to replace the concept of the optimal solution with the concept of an expedient solution. Fuzzy sets are used when classical geodetic computational methods fail. Studies have shown the expediency of introducing the concepts and models of "spatial information situation", "fuzzy spatial information situation". These models allow solving new problems and expand the possibilities of spatial analysis. The methods of space geodesy provide opportunities for establishing cause-and-effect relationships of past events. This is possible due to the fact that space observations are recorded and accumulated in databases. Space geodesy applied to support other technologies is called space geodesy. There are strategic and tactical tasks of space geodesy. The article confirms the conclusion that space geodesy and space geoinformatics are applicable to the study and measurement of space bodies.

Keywords: space research, geodesy, space geodesy, space geoinformatics, space geodetic measurements.

1. Introduction

Space geodesy (Bertiger et al., 2020) and space geoinformatics (Bondur, Tsvetkov, 2015) are constantly increasing. Space geodesy is developing in five directions. Creation of new methodological solutions for information processing. Development of space geodesy tools. Solution of new applied problems. Integration of ground-based methods technologies with methods of space geodesy. Accumulation of experience and improvement of methods of application of space geodesy in the exploration of outer space. The study of near-Earth space continues (Barmin et al., 2014). The GLONASS/GPS system is developing (Ryabov et al., 2019). Space geodesy has created new opportunities for the development of ground geodesy, photogrammetry and geoinformatics. Space technologies make it possible to solve the problems of cadastre and real estate management. The information content of space images is great and creates the problem of big data. The satellite image replaces containing information from hundreds of aerial photographs. Toosmic research showed (Savinykh, 2019) that time geodesy has gone beyond the science of the Earth and has

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become a science of terrestrial and extraterrestrial space. Geodesy is used to support space research (Oznamets, 2020). Space geodetic support integrates: space geodesy, geodetic astronomy, space geoinformatics, geodynamics and satellite geodesy. Space geodetics. Securing is one of the stages of development toosmic geodesy. Space geodesy requires periodic systematics and generalization.

2. Discussion and results

Creation of new methodological solutions for information processing

The creation of new methodological solutions for information processing can be shown on the example of a geodetic survey of the territory to find suitable sites for landing spacecraft (SC) (Tsvetkov, Oznamets, 2018). The problem of choosing a site for landing a returned spacecraft belongs to the class of placement problems. The problem of placement is a typical problem of geodesy and geomarketing. In the work (Kamynina i dr., 2021), the theory of geodesy is developed by applying the theory of fuzzy sets. That is, theory of fuzzy sets is used to process the results of complex geodetic surveys.

Complex geodetic surveys include not only geodetic measurements, but also the collection of various thematic information. This information describes the planting conditions and analyzes the risks (Tsvetkov, 2014). The information situation model was used methodically as a spatial analysis tool.

In addition to the results of comprehensive geodetic surveys, customer information was used, defining fuzzy placement criteria. Complex information was a collection of interval variable information. The method consists in constructing linguistic variables to describe fuzzy situations given by fuzzy criteria. The technique includes fuzzy optimization, which replaces the problem of global discrete optimization with the choice of a rational solution. A clear spatial situation is described using the results of a geodetic survey. Fuzzy spatial is built according to fuzzy customer criteria and compared with the data of each possible landing site. The work was carried out in accordance with the task of Roscosmos. The paper proves that in the presence of fuzziness, the optimal solution should be replaced by a rational solution. Geodetic processing includeswithituational analysis (Tsvetkov, 2014) and is associated with the application of the model of the information situation. Two models of a clear information situation and a fuzzy information situation are used in the work.

This technique allows you to make rational decisions with information fuzziness for trapezoidal and interval variables that characterize the information situation. However, the results of the assessment are conditional. Conditionality is determined by a finite set of evaluation criteria and the sample size of the objects being compared. If the number of criteria or the totality of research objects changes, the evaluation result may or may not change. The results of the technique cannot be called optimal. They can be called appropriate. This is an important takeaway. With unclear information, you cannot talk about the optimal solution, but you can talk about an appropriate solution. This is natural, since with incomplete information there are no guarantees of obtaining an optimal solution. However, this method is applicable in situations where classical methods are powerless.

The proposed method makes it possible to obtain estimates of spatial situations in case of fuzzy information. It is applicable when classical optimization methods do not give a result. Of interest is the philosophical and mathematical aspect of the relationship between quality and quantity. This relationship begins at the level of the ordinal scale, that is, at the level of ranking the qualities that correspond to fuzzy numbers: interval or trapezoidal. The method requires further research and development. For example, while there is arbitrariness in the choice of the number of thermos. At the same time, the method is new in the field of situational analysis. Studies have shown that it is advisable to introduce the concepts and models of “spatial information situation”, “fuzzy spatial information situation”. New models make it possible to solve new problems in new conditions and expand the possibilities of using space geodesy.

Development of instrumental support for space geodesy

The development of instrumental support for space geodesy is based on the development and application of new devices. One example is the demonstration of a broadband interferometric system with an ultra-long base: a new tool for high-precision space geodesy (Niell et al., 2018). The paper (Niell et al., 2018) describes a broadband geodetic interferometric system with an ultra-long base. Measurements of the length of the baseline are carried out to test the system, develop operational procedures and assess geodetic accuracy for broadband surveillance. The work was carried out for two years. Statistical analysis of data from 19 sessions that were observed during this period yielded a weighted average root square deviation of the residues of the original length of about 1.6 mm. Laser geodetic satellites (Pearlman et al., 2019) are a typical tool of space geodesy.

Integration of ground-based technology methods with space geodesy methods

The integration of ground-based technology methods with space geodesy methods can be shown by the example of space geodetic observations of the critical infrastructure of the Morandi Bridge, Genoa, Italy (Milillo et al., 2019). This work contains a retrospective analysis of the past event. However, it demonstrates the possibilities of space geodesy to establish cause-and-effect relationships of past events. The paper provides a methodology for assessing the past event. possible deformations of the bridge before destruction. The bridge was destroyed on August 14, 2018. Synthetic aperture radar (SAR) observations are used as a basis. A displacement map was created for the structure from space.

Satellite data sets for 2003–2011 allowed for retrospective analysis. The results of the treatment show that the deformations of the bridge grew over time until it collapsed. It was revealed that the decking next to the collapsed pier since 2015 was characterized by an increase in relative movements. It was concluded that the interferometric synthetic aperture radar (InSAR) and constant scattering interferometry (PSI) make it possible to track the deformation of the surface of objects due to the presence and density of coherent radar targets. The results of the study showed that the technique can detect deformations of millimeter scale. The use of the technique reduces the risks associated with the deformation of urban infrastructure objects.

Another example of the application of space geodesy is the study of soil deformation and fault velocity in the Greater San Francisco Bay Area (Xu et al., 2018). The work states that the accumulation of deformation and creep on large faults in the northern part of the San Francisco Bay Area (North Bay) are poorly understood. The study jointly processed synthetic aperture interferometric radar data from satellites with continuous GPS data. SAR data from ascending and descending orbits were used to separate the horizontal and vertical components of the deformation.

Development of spacegeodesy

Space geodesy is evolving in two different directions. The first direction is related to the study of the Earth from space. The second direction is directed from the Earth to the study of outer space.

Space geodesy, used to support other technologies, is called geodetic space support (Oznamets, 2020). Geodetic space support uses space geodesy as a basis (Calonico et al., 2019). Geodetic space support is characterized by a small number of data measurements and a large number of data modeling.

Modern space geodesy is associated with the need to process large amounts of information, which is due to the improvement of measuring instruments and the variety of sensors that receive spatial information. It comes into contact with the problem of “big data” (Buravtsev, Tsvetkov, 2019).

Osmic geodesy in relation to Earth exploration is supported by the following scientific areas:

- Study of the Earth Figure;
- study of the Earth's gravitational field;
- creation of a coordinate system for different ones;
- conducting geodetic measurements on the surface, subsurface and above the surface of the Earth;
- representation of spatial information on topographic maps and plans;
- formation of digital models and digital maps (Tsvetkov, 2016);
- study of dynamic displacements of the earth's crust.

The creation of a single coordinate system on the territory of different scales of a single state, a continent and the entire Earth as a whole is included in the tasks of space geodesy (Merkowitz et al., 2019). In relation to geodetic support for space research, special geodetic networks for space research have been developed (Merkowitz, 2019). Some of theadacsand geodetic space support are not directly related to comic research.

There is a state program for the transition from ground-based geodetic measurements to satellite measurement methods. Satellite-based positioning, as well as the creation of a spatial data infrastructure, currently rely on space geodesy.

The tasks of geodetic support for space research are of wide importance (Savinykh, 2012). New measurement methods have appeared, and the accuracy of geodetic space measurements has increased.

The use of artificial Earth satellites (SATELLITES) for solving geodetic problems contributed to the development of space geodesy. Initially, osmic geodesy was engaged in determining the size and figure of the Earth, the parameters of its gravitational field. The basis of these works was the results of observations obtained from satellites of various types and purposes, as well as from the board of spacecraft. This defined the first group of space geodesy technologies as providing ground research from space and near-Earth space exploration (Barmin et al., 2014). Then space geodesy research was directed away from Earth into comic space. Asteroid-comet hazard played a big role in this. This determined the second group of space geodesy technologies to support space extraterrestrial research.

Satellite geodesy uses methods of finding a connection between the points of location of satellites based on the laws of motion dynamics. Satellite geodesy technologies do not require simultaneous measurement at all points. Satellite geodesy technologies have led to the creation of a new geodetic network. This is a space geodetic network. This is a network on the earth's surface, which is created and developed on the basis of geodetic points, the position of which is determined from the observations of satellites. Measurements on the earth's surface are carried out on the basis of the theory of spatial serif. According to this theory, it is necessary to use at least 4 spatial points (satellites) visible from this surface.

The dynamic tasks of space geodesy include the determination of the parameters of the Earth's gravitational field. For this purpose, measurements of satellite orbit parameters calculated from the results of positional and rangefinder observations are used. Space geodesy makes it possible to solve a number of existing problems in a new way. These are satellite triangulation, measurement of large-scale objects, measurement of geopotential, application of satellite altimetry.

Satellite triangulation is the one of the methods of space geodesy. It involves the synchronous observation of satellites from several points on the earth's surface. If the positions of two (or more) of these points are known in the earth's coordinate system, then by solving spatial triangles with one of the vertices at the point of location of the space object, it is possible to calculate the positions of other points from which observations were made.

Conducting coordinate and rangefinder observations from satellites make it possible to develop the geodetic vector course in a new way. With this method, the location point of the satellite is analogous to the ground observation point transferred beyond the earth's surface.

Measuring large objects on the earth's surface has always been a problem due to the peculiarity of displaying the earth's surface by zones. From a great height, a person was able to measure extended linear objects on the surface of the Earth (hundreds and thousands of kilometers).

The measurement of the geopotential is carried out using dynamic methods. Using comparative analysis, experimental and theoretically calculated positions of the satellites in space are compared. On the basis of comparison, differences are found that allow you to build a dynamic model. The differences between theory and experiment are attributed to the information uncertainty of determining the harmonic coefficients of the geopotential. According to statistical data and corresponding equations, it is possible to clarify the primary parameters of the harmonic coefficients of the geopotential. In turn, the refined values of the geopotential coefficients make it possible to determine with greater accuracy the location or localization of the satellite, as well as to obtain a refined position of its orbit. This process can be repeated iteratively and the methods of successive approximations increase the accuracy of determining the geopotential coefficients. Thus, an incremental research model is obtained, increasing the accuracy of determining orbital coordinates and geopotential parameters.

In 1950, only one parameter was known for sure - the compression of the earth's ellipsoid. Another parameter, the compression of the equator, was determined with less accuracy. After the start of satellite launches, it became possible to obtain the values of harmonic coefficients of high degrees. In particular, fairly accurate values of harmonic coefficients for the order *of* $n = 8$ and the degree $m = 8$ were calculated. Modern methods of studying the geopotential make it possible to calculate the values of harmonic coefficients for order $n = 24$ and the degree $m = 24$. This order and degree make it possible to determine not two as in 1950, but about 500 coefficients characterizing the model of the Earth's gravitational field. Thus, methods of space geodesy make it possible to increase the accuracy of spatial models of the Earth and, in principle, of any planet when using satellite observations of this planet

Satellite altimetry has been developing since 1974. Laser, as well as radio altimeters (altimeters) on satellites, provided data that made it possible to determine the parameters of the orbit of the satellite. Here the same situation developed as with the geopotential. With the increase in the accuracy of determining the height of the Earth's surface, methods for introducing corrections to the orbital parameters appeared. The introduction of corrections to the orbital parameters made it possible to determine the orbital height with greater accuracy. More accurate determination of orbital parameters led to a more accurate determination of orbital parameters. In particular, the Geos satellite uses an altimeter to measure the distance to the ocean surface with an accuracy of 1 to 3 m. This accuracy makes it possible to refine the shape of the geoid in the World Ocean and to identify spatial anomalies. Comparative analysis of measurements using an altimeter and measurements by other methods showed a high information correspondence when measuring the profile of the geoid by these methods. It is possible to increase the accuracy of satellite altimetry to 10 cm. Laser altimetry provides an accuracy of the order of altitude determination up to 1 cm.

The geocentric coordinate system is harmonized with other networks. First of all, this is a high-precision geodetic network (GHS), as well as a satellite geodetic network of the 1st class (GHS-1). GHS-1. The coordination of these networks provides optimal conditions for the implementation of accurate and operational measurements using satellite equipment. Networks as a whole ensure the creation of a High-Precision National Geocentric Coordinate System.

Global navigation satellite systems work with the help of equipment for SATELLITES of GPS systems and for satellites of the GLONASS system. There is equipment for GPS systems and for the GLONASS system. There is hybrid equipment for both systems. Dynamic measurements in real time allow you to create a single navigation field for determining the coordinates of points on the earth's surface and mobile objects. Application efficiency. Geodetic support for space extraterrestrial research is manifested on the example of research in the field of cometary-astroid danger. It is associated with the calculation of the trajectories of dangerous cosmic bodies and measurements on the surface of other planets or other celestial bodies.

3. Conclusion

Studies show that the methods of space geodesy are constantly evolving and allow solving an increasingly wide range of tasks. It is shown that fuzzy sets and fuzzy situations can be used in terrestrial and space geodesy. In case of unclear or incomplete information, it is necessary to replace the concept of the optimal solution with the concept of an expedient solution. Fuzzy sets are used when classical geodetic methods of calculations do not give a result. Studies have shown the expediency of introducing the concepts and models of “spatial information situation”, “fuzzy spatial information situation”. These models allow you to solve new problems and expand the possibilities of spatial analysis. Methods of space geodesy provide opportunities for establishing cause-and-effect relationships of past events. This is possible due to the fact that space observations are recorded and accumulated in databases. Unlike ground geodesy, space geodesy stores a large number of images that allow for the reconstruction of events. The development of terrestrial sciences increases the potential of space geodesy. Methods of space geodesy are applicable to the study of other planets Space geodesy is a criterion for the potential for scientific development of mankind.

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