MONITORING CONSTRUCTIONS BEHAVIOR USING SPATIAL GEODETIC TECHNOLOGIES

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***Abstract**: The present article addresses the monitoring of the behavior of three object points located on the Râuşor dam crest, considering two different measurement epochs. The measurements were obtained using spatial geodetic technologies, carried out over 24 hours on two different dates and during two different measurement epochs, namely in the years 2023-2024.*

The processing of the measurements obtained from satellite observations conducted during the two measurement epochs was performed using a mathematical model. The goal was to determine the positions of the three object points in each epoch, and subsequently to determine their displacements.

To conduct the necessary measurements for the case study, a network was used where the three points, named G501, G502, and G601, were considered new points, while point GPS4, where a permanent station is installed, was considered a fixed point.

Observations were made at all four points in the network mentioned above. These observations were represented in the processing stage by observation files and navigation files. After the observation sessions, these files were input into the Emlid Studio application. Using this application, the coordinate increments and the necessary precisions for processing were extracted, taking into account the use of a local geodetic coordinate system.

To determine the positions of the object points, the coordinates of the permanent station GPS4 were known, thus enabling a relative determination of the positions of the three points using these coordinates. With the coordinates of the fixed point GPS4 and the coordinate increments extracted from the Emlid Studio program, the provisional coordinates of the three new points were calculated.

An important step in the processing was the development of the stochastic functional model, from which the coefficient matrix was extracted. Since the measurements were correlated, the variance-covariance matrix could also be compiled, from which the weight matrix was calculated. With all these components, the normal equation system of corrections and its inverse were developed.

To determine the adjusted coordinates of the new points, the solutions to the normal system were calculated and applied to the provisional coordinates of the points. Additionally, the values of the corrections applied to the coordinate increments extracted using the Emlid Studio program were determined.

For all three points located on the dam's crest, considered new points, the steps described above were followed, with processing performed for both years 2023 and 2024. The precision estimates and the calculation of the error ellipses for each point were also completed.

To draw a conclusion, the coordinates of the three points obtained in the two measurement stages were compared, allowing the observation of their displacements on the

North and East components, as well as altitude displacements. It was concluded that the equipment used, the chosen measurement method, the method of determining the points positions, and the coordinate system used together resulted in high precision in determining the positions of these points. This indicates that these combined methods are suitable for monitoring constructions over time.

Keywords: *satellite positioning system; monitoring; correlated measurements; displacement; correction; static measurement method*

1. Introduction

By definition, Satellite Geodesy is the branch of geodesy that deals with the study of the shape, dimensions, and physical field of the Earth using artificial satellites. It is also referred to as Spatial Geodesy, considering that spatial measurements (station-satellite) are frequently used, in contrast to terrestrial distances (station-station) measured in classical trilateration.

An artificial satellite is a body created by human science and technology, which is launched into an orbit around a celestial body and moves along this orbit according to the laws of celestial mechanics.

GNSS - Global Navigation Satellite System - These systems are used to determine the position of a point with a high degree of accuracy, regardless of whether the point is on, near, or outside the Earth's surface.

Measurements, known in Spatial Geodesy as observations, are made between a receiver located at ground level and one or more satellites orbiting the Earth. The principle of determining the position is based on the signals transmitted by artificial satellites, which are subsequently received by ground-based receivers. These receivers have the ability to decode the received messages and determine the position of the receiver. The extraction of the necessary information for positioning is typically achieved by correlating the two signals: the one received from the satellites and the one generated by the receiver, also referred to as the replica signal.

2. Materials and Methods

To monitor the behavior of the dam, we selected three points located on its crest, namely G501, G502, and G601. These points were considered new points where GNSS measurements were carried out for 24 hours, along with the permanent GNSS station PS4, which was considered a fixed point. Measurements were taken from these points in two different stages: one in 2023 and the second in 2024, aiming to determine the displacements of the studied points during this interval.

Fig. 1 - Permanent station PS4

Fig. 2 - Point G501

Fig. 3 - Point G502

Fig.4 - Point G601

Fig. 5 - Location of monitored points

At the same time, the three points whose displacements are monitored within the project are part of the Rockfill Dam Monitoring System, which is currently used for monitoring the Râuşor dam. This system includes the following modules: *a software module for data recording, a software module for converting and organizing files in RINEX format, and a software module for data transmission*.

For efficient system management, a VNC connection is used for remote administration, as well as a cloud connection through which data is transmitted and stored.

The following equipment is used within the monitoring system:

- *GNSS Antennas (Beitian)* – antennas compatible with multiple systems and offering high reliability;
- *GNSS Receivers (u-blox)* – these multi-band receivers provide centimeter-level accuracy in just a few seconds by simultaneously receiving signals from all satellites;
- *Raspberry Pi Mini Computer*;

Fig. 6 - Beitian BT-160 GNSS antenna

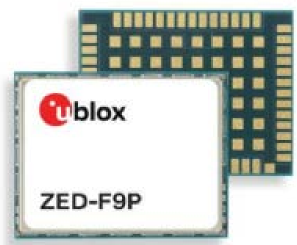

Fig. 7 - u-blox ZED-F9P GNSS module

The initial data for the project consisted of a set of measurements taken using GNSS equipment. These data were recorded by the four devices located at the network tracking points and were extracted as Compact Rinex (.crx) files and navigation (.nav) files.

To process the measurements, we used the Emlid Studio software, which helped extract coordinate increments used later in the network processing.

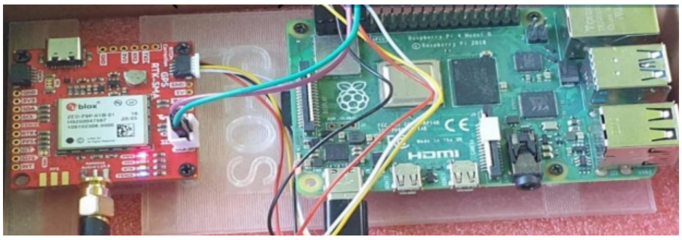

Fig. 8 - ublox GNSS receiver and Raspberry Pi minicomputer interconnected

The first step to enable processing within the application was to convert the Compact Rinex files into Rinex files, as the program only accepts a limited range of file formats. Therefore, to achieve the appropriate format for input into the application, we used the Command Prompt in Windows, where we entered the following commands, applied to the .crx files for conversion:

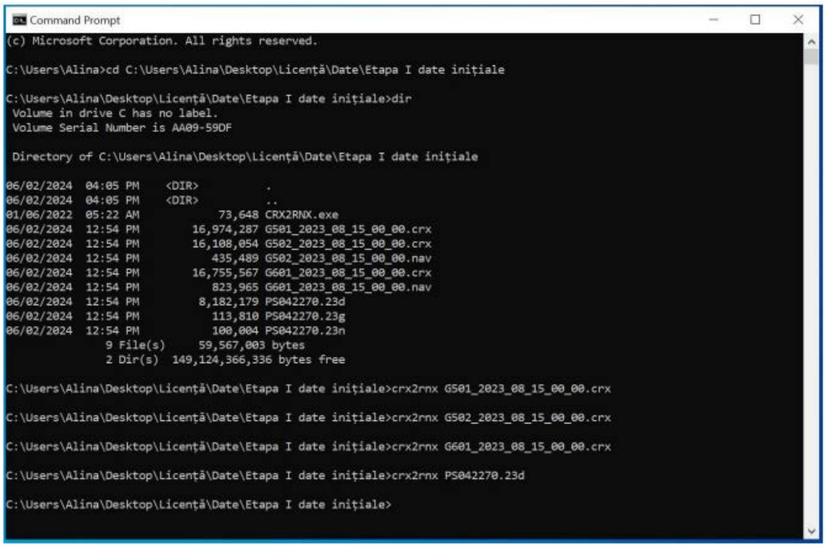

Fig. 9 - Convert .crx file to .rnx file

The next steps involved selecting the type of processing, configuring the appropriate settings for the desired processing type, and then loading the Rinex files and navigation files, after which the processing was carried out.

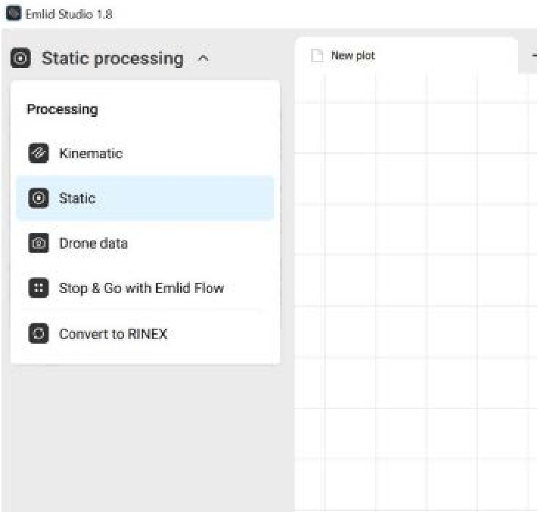

Fig. 10 - Selection of the desired processing type - Static

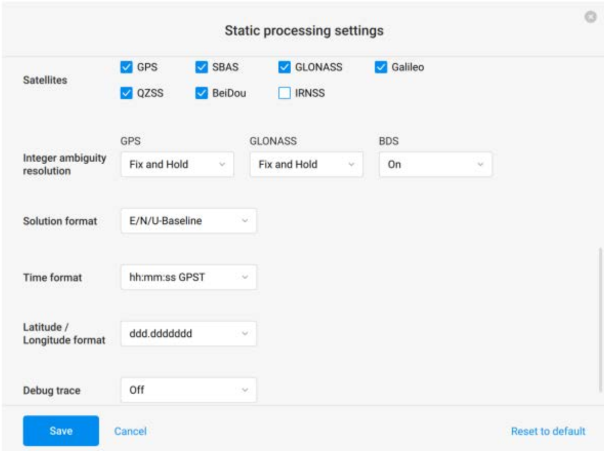

Fig. 11 - Setting of satellites and the E/N/U solution format

After completing all the necessary settings, the Rinex files containing the measurements and the navigation file for each of the measured GNSS vectors were loaded. At the end of the processing stage, six files were extracted for each measurement phase. After processing all the measurements, the results were saved in .pos format, with the resulting file having the following structure:

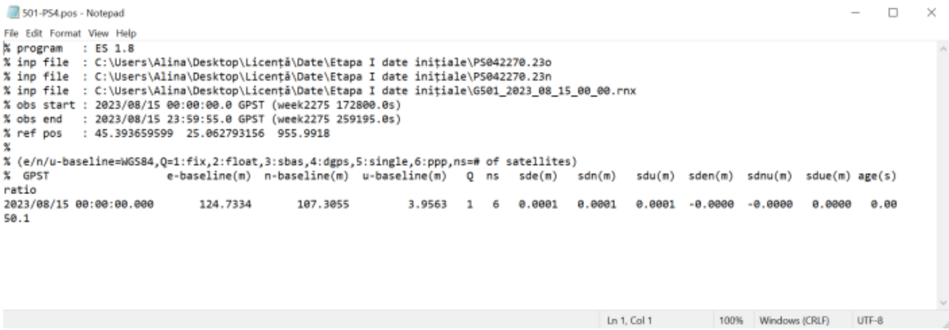

Fig. 12 - Result file after processing

Within the file shown in the figure above, one can observe the coordinate increments, their precision, the number of satellites received, and the Q value, which can be: 1 – fixed; 2 – float; 3 – SBAS; 4 – DGPS; 5 – single; 6 – PPP.

Additionally, using Emlid Studio, we were able to extract the geographic coordinates (latitude and longitude) of the points used in the measurement process.

Table 1 - The geographic coordinates of the points

Point	Latitude (B)	Longitude (L)
PS4	45°23'40.65"N	25° 3'51.78"E
501	45°23'37.18"N	25° 3'46.04"E
502	45°23'36.85"N	25° 3'46.06"E
601	45°23'37.09"N	25° 3'45.24"E

The initial data includes the definitive coordinates of point PS4, which is considered a fixed point.

Table 2 - The coordinates of the PS4 point

	N (m)	E (m)	H (m)
PS4	1847.009	891.849	919.657

Table 3 - Coordinate increments extracted from processing – example for Stage I

	dE (m)	dN (m)	du (m)	sde (m)	sdn (m)	sdu (m)	sden (m)	sdnu (m)	sdue (m)
502-501	-0.0980	10.0504	0.0061	0.00003	0.00010	0.00010	-0.00002	-0.00003	0.00002
601-501	17.3939	2.5995	0.0236	0.00003	0.00002	0.00010	-0.00003	0.00002	0.00002
601-502	17.4927	-7.4519	0.0180	0.00004	0.00010	0.00010	-0.00002	-0.00003	0.00002
501-PS4	124.7334	107.3055	3.9563	0.00010	0.00010	0.00010	-0.00002	-0.00003	0.00002
502-PS4	124.6363	117.3515	3.9679	0.00003	0.00010	0.00010	-0.00004	-0.00010	0.00002
601-PS4	142.1273	109.9037	3.9814	0.00002	0.00010	0.00010	-0.00001	-0.00004	0.00003

Using the extracted coordinate increments in the table above, we calculated the closure errors in the polygon, as well as the provisional coordinates of the new points.

Table 4 - Non-closures in the polygon – example for Stage I

Non-closures in the polygon			
501-502-601	-0.00080	0.00100	-0.00050
501-601-PS4	0.00000	-0.00130	0.00150
502-601-PS4	-0.00170	0.00410	-0.00450

Table 5 - The provisional coordinates of the new points – example for Stage I

	N (m)	E (m)	H (m)
501	1739.704	767.116	915.701
502	1729.658	767.213	915.690
601	1737.106	749.722	915.676

The next step was to compile the variance-covariance matrix. Using the previously calculated matrix Σ, we determined the weights matrix, and finally, after a series of calculations, we obtained the pseudoinverse, which allowed us to determine the vector of unknown parameters.

To determine the correction values applied to the coordinate increments, the vector $\boldsymbol{v}$ was calculated. The verification was performed by comparing the computed compensated coordinate increments with those obtained from the differences of the compensated coordinates.

In the following steps, I calculated the precision estimates and determined the elements of the error ellipses.

3. Results and Discussion

Table 6 - Presentation of the results – Stage I

Point	501	502	601
N (m)	1739.705	1729.655	1737.106
E (m)	767.116	767.214	749.722
H (m)	915.699	915.692	915.675
S_N (m)	0.0008	0.0008	0.0007
S_E (m)	0.0006	0.0005	0.0004
S_H (m)	0.0009	0.0008	0.0009
S_{pi}(m)	0.0013	0.0013	0.0012
S_t (m)	0.0013		
a (m)	0.00089	0.00091	0.00078
b (m)	0.00040	0.00027	0.00038
φ(gon)	133.1183	131.2286	122.8827

Table 7 - Presentation of the results – Stage II

Point	501	502	601
N (m)	1739.713	1729.659	1737.112
E (m)	767.117	767.207	749.718
H (m)	915.679	915.676	915.659
S_N (m)	0.0008	0.0008	0.0008
S_E (m)	0.0005	0.0006	0.0005
S_H (m)	0.0012	0.0008	0.0010
S_{pi}(m)	0.0015	0.0013	0.0014
S_t (m)	0.0014		
a (m)	0.00086	0.00092	0.00087
b (m)	0.00037	0.00040	0.00041
φ(gon)	123.00063	132.60444	128.52831

The two tables presented above represent the results obtained in the two stages following the compensation. Using the elements obtained for each stage, I was able to make a comparison to draw a conclusion regarding the displacement of the object points over the studied time interval. At first glance, we can observe that the achieved precisions are remarkable.

4. Conclusions

As we know, there is no measurement session or processing stage without errors, which led me to determine the error ellipse elements for each point in the network. Additionally, I was able to conclude that the error ellipses obtained for the three object points are homogeneous. The homogeneity is indicated by the generally uniform precision of determination for all the points in the network. These error ellipses, along with the calculated closure errors, indicate that the measurement method using space geodetic technologies provides us with high accuracy.

To determine the displacements, I calculated the difference between the compensated coordinates of the new points from the two stages by subtracting the coordinates obtained in the previous stage from those obtained in the most recent stage. At first glance, we can observe that all three points are shifting downward in elevation, resulting in a settling effect in the studied area. Additionally, we can affirm that all three points are moving in the North and East directions.

Table 8 - Object point displacements

	501	**502**	**601**
ΔN (m)	0.008	0.004	0.006
ΔE (m)	0.001	-0.007	-0.004
ΔH (m)	-0.020	-0.016	-0.016

We can conclude that the method of space geodetic measurements is suitable for such monitoring work, with the precision obtained being quite satisfactory. The case study addressed in this paper aimed to monitor the area during the two measurement epochs; however, for a more detailed study of the displacements of the object points (G501, G502, G601), daily measurements can be conducted. This is feasible because special devices are installed at the aforementioned points, capable of transmitting the measurements in real-time to any device.

5. Acknowledgments

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