Survey Review, **39**, 305 pp.203-211 (July 2007)

AUTOMATIC MULTI TOTAL STATION MONITORING OF A TUNNEL

A. Berberan[1], **M. Machado**[2] **and S. Batista**[3]

[1] Laboratorio Nacional de Engenharia Civil, Portugal
[2] Sociedade de Projectos e Gestão de Obras, Lda Portugal, Lisbon.
[3] Engineering Software Solutions.

ABSTRACT

A tunnel has been under construction for the Lisbon Metro network on the muddy bed of river Tagus. An incident during the jet-grouting for the muddy soil treatment led to flooding of a specific sector of the tunnel and to the need for repair works. Consequently, a decision has been made to monitor with a short time resolution the movements of that sector before, during and after reparation works. This includes the period in which the tunnel will be in use for its regular operation, with commuters using the subway. Given these general conditions with severe inter-visibility limitations, as well as the cost restraints, an automatic monitoring system has been designed and put in place, resorting to four LEICA TC2003 motorised total stations and to the available commercial software, LEICA GeoMoS. The computational procedure of the mentioned software implies a network configuration, in which every total station set up needs a cluster of control points associated with that particular setup in order to perform a space resection. However, it is often difficult to find stable points inside a tunnel under monitoring let alone during repair works. Therefore, to overcome this difficulty, adjustment software - EpochSuite – has been integrated into the monitoring system. Since it runs after the collection of data, the adjustment software makes it possible to perform a more robust and accurate computation of displacement vectors of signalised object points, which represent the tunnel under study. EpochSuite uses a database management approach that is particularly useful in handling many monitoring epochs and uses automatic outlier detection tools. This paper reports on the network configuration, the instrumental setup and the software framework in which the automatic monitoring system actually operates.

KEYWORDS: Automatic monitoring. Metro tunnel. Total station. Adjustment software.

INTRODUCTION

According to development plans for the Lisbon Metro network, a sector of the Blue Line tunnel expansion has been under construction on the muddy bed of river Tagus. This sector became partially flooded during the jet-grouting works for the muddy soil treatment and the tunnel, a TBM (Tunnel Boring Machine) solution construction consisting of successive rings, was locally deformed and damaged. Reinforcement and other remedial works are to be carried out to repair the tunnel and a decision has been made to monitor it before, during and after the mentioned works. As part of the whole monitoring system, an automatic geodetic monitoring system has been designed and implemented.

During specific periods of the works, heavy machinery, rolling concrete mould scaffolds, etc., are expected to limit visibility and, therefore, the operation of the automatic monitoring system is to be affected. After repair works, train circulation is also expected to place some limitations to the operation of the monitoring system and, consequently, those limitations had to be considered in the design phase of the mentioned system. Other factors influenced the configuration of the network: epoch resolution (1 epoch of observations starting every hour, if necessary), need for an automatic monitoring system, availability of software and equipment, curved and longitudinal geometry of the structure under study, availability of control points and cost restraints.

Contact: A Berberan. e-mail: berberan@lnec.pt

DOI 10.1179/003962607X165177

The automatic monitoring system, due to the limitations influencing its design, has well known weaknesses namely error propagation. In order to minimise this unwanted propagation, EpochSuite adjustment software has been integrated in the existing software framework. Designed for adjusting monitoring networks, EpochSuite uses a database approach to handle large amounts of both the measurements and the results, in an epoch-by-epoch basis. Several outlier detection and elimination techniques also make it an adequate tool for an automatic monitoring system.

In an expert report [**1**] on this geodetic monitoring system, the National Laboratory for Civil Engineering (LNEC) has advised the Owner, Lisbon Metro, to adopt adjustment procedures to process the data, wherever possible.

The tunnel has been monitored every 6 hours during the last 9 months. Non adjusted results have shown a consistent trend towards the inner part of the tunnel. The adjusted results have confirmed that there were no significant movements during that period, which is in agreement with the fact that no repair works have started so far.

This article aims at describing the instrumental set up, the data transmission and management, the network configuration, as well as the link established between the SQL (Structured Query Language) Server database and the EpochSuite adjustment software.

INSTRUMENTAL SETUP

The monitoring system has been designed, set up and observed by the company *SPGO - Sociedade de Projectos e Gestão de Obras*. A decision has been made to use a reliable, integrated system that is available on the market. The choice for LEICA GeoSystems is related with previous experiences in automatic monitoring systems implemented by SPGO using the discontinued LEICA APSWIN software and previous versions of LEICA GeoMoS. This software needs a cluster of control points sighted from every station, which, usually, is not suitable for a tunnel. Then, to overcome this problem, an external routine was requested to LEICA. This external routine changes, within GeoMoS database, the classification of (unstable) points, which will have their coordinates determined, into momentary control points, being then used for space resection of an inner total station.

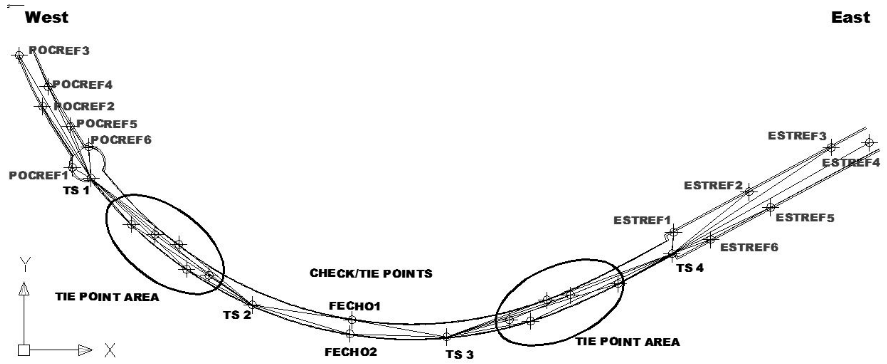


Fig. 1. East and West monitoring sub-networks: control points, check points, tie point areas and station points.

Four types of points are present in the monitoring system: control points (which are expected to be stable and to materialise the reference system), station points (where a motorised total station is permanently set up), tie points (materialised by 360º prisms) and object points (which are materialised by regular prisms placed on representative points of the object under study). Only the control points are located outside the monitored part of the tunnel. In specific rings of the tunnel, there are groups of three object points (at the inner, upper and outer part of the ring), of which the coordinates are computed by four permanent motorised total stations with no redundancy.

Four LEICA TC2003 motorised total stations are assisted by GeoMoS software version 1.55 targeting a total number of more than 60 points. Twelve of those points (the tie points) are materialised by 360º prisms. The remaining targeted points are materialised by regular total reflective prisms. The number of object points will increase and, after trains start running, more than 250 prisms will be under automatic observation.

Data transmission is accomplished via full duplex modems. Raw data, operational parameters for the total stations, computational parameters, computed and corrected coordinates, as well as measurements are stored in a SQL Server database. GeoMoS has two main modules, Monitor and Analyzer. Monitor controls the automatic operation of motorised total stations, as well as pressure and temperature sensors after their parameterisation. This module also handles the transmission, correction, storage and processing of data, as well as spatial resection and staking out computations to determine the XYZ coordinates of both the station and the targeted points, respectively. Analyzer is conceived to visualise results, both graphically and numerically, in order to assist in the chronological interpretation of movements in a point by point basis.

NETWORK CONFIGURATION AND COMPUTATIONAL PROCEDURES

The same configuration, datum definition and operational set up described above can be seen in two different approaches, as far as the computational procedure is concerned. Firstly, the independent monitoring sub-networks approach, to which a sequential type of computational procedure is applied, will be explained based on the GeoMoS version 1.55 software capabilities, which has been upgraded with the previously mentioned external routine. A second approach uses adjustment software, integrating the two sub-networks into a single network, to process exactly the same data.

The independent monitoring sub-network approach

During certain periods and due to persistent obstruction, it will not be possible to carry out the observation of the entire network. However, monitoring is to be performed and an alert criterion is to be in place. Therefore, the monitoring network is subdivided into two independent monitoring sub-networks (West Monitoring Network and East Monitoring Network).

A permanent and motorised total station located at TS1, automatically performs a space resection using GeoMoS software and based on a cluster of control points named POCREF*, on the West side of the tunnel, figure 1. After space resection, TS1 total station measures and computes the coordinates of a set of points materialised by 360º prisms, on the TS1 tie point area. These measured points are then reclassified, with the help of the external routine, to become (momentary) control points. The latter are used by the TS2 permanent and motorised total station to perform its own space resection and to monitor two points materialised by 360º prisms, which are named FECHO1 and FECHO2, respectively.

On the East side of the tunnel, there is a mirror-reversed situation. Starting from a cluster of control points named ESTREF*, the TS4 permanent and motorised total station automatically performs a space resection and measures a cluster of points materialised by 360 º prisms, in the TS4 tie point area. The external routine reclassifies these points into (momentary) control points and, from these, the TS3 permanent and motorised total station automatically performs a space resection. From TS3, points FECHO1 and FECHO2 are monitored again. These points may be considered in this approach as checkpoints.

Figure 2 shows the comparison between the Y component of the movements of both checkpoints. From this figure, it is possible to conclude, with relevance for this article, that: first, maximum discrepancies between results from the independent sub-networks amount to 6 millimetres and, second, the results suggest that the tunnel has a tendency towards the inner part of the curve, which is not likely to occur. With their coordinates independently calculated by both the West and the East monitoring sub-networks, the duplicated coordinates of FECHO1 and FECHO2 may be used as a good empirical measure of the accuracy that is reachable by the automatic geodetic monitoring system, when, due to lack of visibility, the entire network cannot be observed and computed under the approach described below.

The monitoring network/adjustment approach

The effects of error propagation on the previous sequential procedure are well known and a decision has been made to integrate adjustment software into the computational functionalities of the monitoring system. The adjustment approach treats both sub-networks as a single network and will provide more robustness, reliability and accuracy to the positioning of object points, as long as inter-visibility makes it possible to carry out an integral observation of the network. The adjustment approach will be used either to confirm, or not, the results provided by the sequential procedure described above.

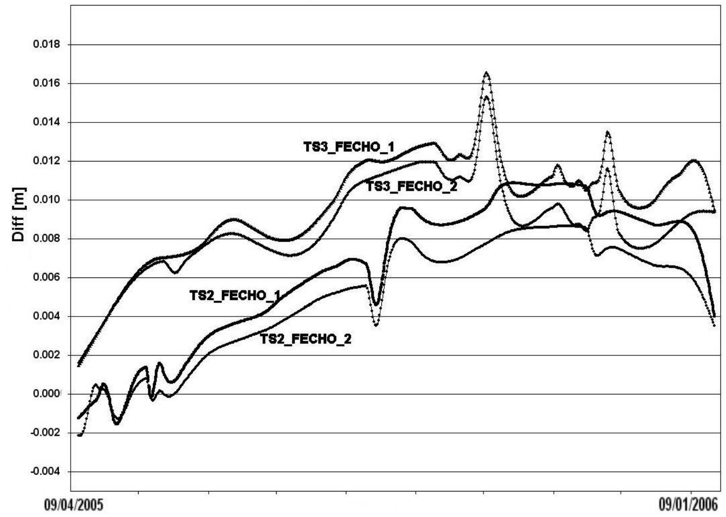


Fig. 2. Evolution and comparison between Y component movements of points FECHO1 and FECHO2, as monitored from the West monitoring network (TS2) and from the East monitoring network (TS3)

Figure 3 shows, for the 2005-08-23 epoch, the discrepancies between results provided by the sequential procedure and results provided by the adjustment approach. For the sake of clarity, only the results of the East central part of the tunnel are shown. However, the results for the remaining part are similar to those presented in figure 3.

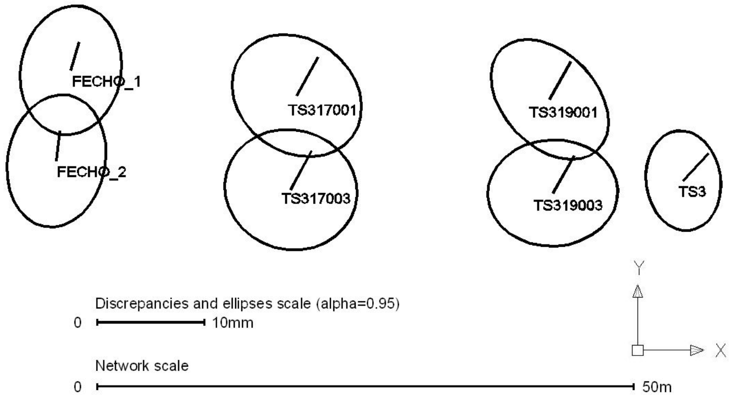


Fig. 3 Lines show discrepancies between the results computed according to the sequential approach and results with the same data, but computed by EpochSuite adjustment software. Inner part of the tunnel, East side only.

Values 0.5mgon, 0.5mgon and 2mm+2ppm were used as *a priori* standard deviations for horizontal direction, vertical angle and horizontal distance measurements, respectively. These values were confirmed by a χ^2 statistical test on the reference variance factor σo (Ho: $\sigma o=1$; Ha: $\sigma o>1$) and corroborate the expected atmospheric stability inside the tunnel and the good quality of the LEICA ATR (Automatic Target Recognition) system.

Figure 4 shows the discrepancies between the Z components, as computed according to the sequential or adjustment approaches.

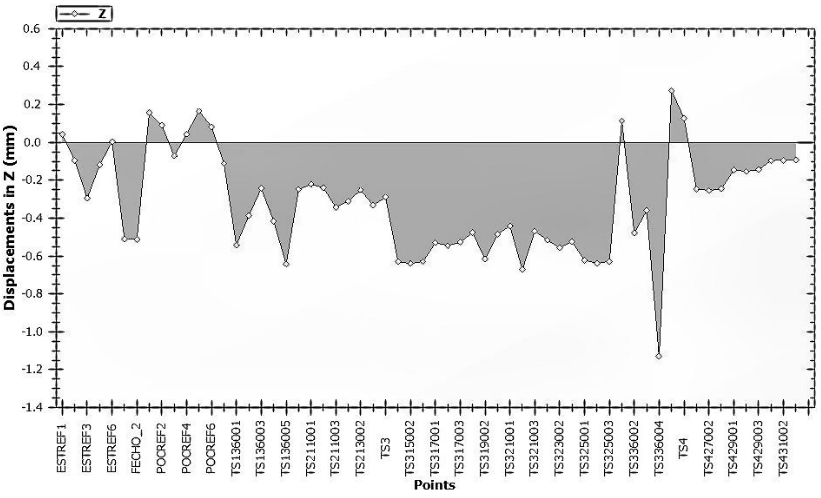


Fig. 4 Discrepancies between Z values computed according to the sequential and adjustment approaches

Concerning quality, the differences between both computational approaches can be quantified objectively. For the sake of space economy, this article only shows some point confidence ellipses (α=0.95) in Figure 5. This figure confirms the expected improvement in precision when using the adjustment approach rather than the sequential one.

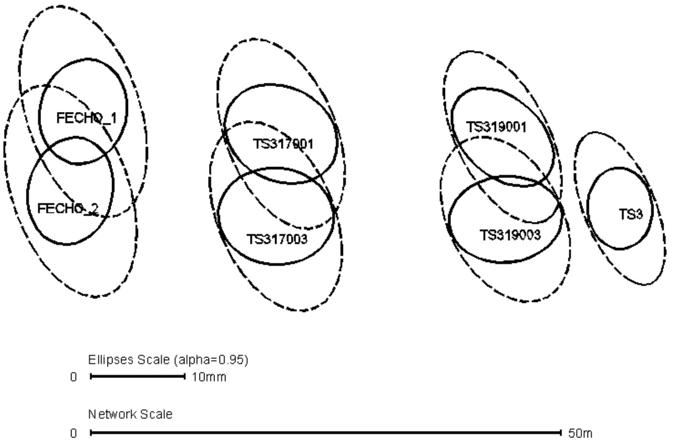


Fig. 5 Point confidence ellipses (α=0.95) computed for the East monitoring sub-network, when compared to those corresponding to the East portion of the entire network adjustment approach (continuous dark line). Remaining points and respective ellipses have been discarded for the sake of clarity

As for numerical values, table 1 shows average values for standard deviations, average values for ellipses semi-axis of groups of points both taken from the covariance matrix of unknowns. From the network to the East side sub-network, from the outer total station setups to the inner total station setups, the expected degradation of precision is quantified in the same table.

Table 1. Average parameters for point positioning quality

Average values Points	Network						East side sub-network					
	standard deviations			ellipses semi-axis			standard deviations			ellipses semi-axis		
	σx	σy	σz	a	b	a/b	σx	σy	σz	a	b	a/b
outer stations (TS1, TS4)	0.7	0.8	0.4	2.0	1.7	1.2	0.8	1.0	0.5	2.6	2.0	1.3
inner stations (TS2, TS3)	1.5	1.7	0.5	4.6	3.5	1.3	2.0	3.3	0.6	8.7	3.8	2.3
stations (TS1-TS4)	1.1	1.2	0.5	3.3	2.6	1.3	1.4	2.2	0.6	5.7	2.9	1.8
checkpoints	1.9	2.3	0.5	6.2	4.7	1.4	2.9	4.6	0.8	11.7	6.2	1.9
tie points	1.6	1.5	0.5	4.3	3.4	1.3	1.9	2.2	0.7	5.7	4.4	1.3
object points	2.3	1.7	0.6	6.1	4.2	1.6	2.5	2.9	0.7	7.8	5.3	1.5

MATHEMATICAL MODEL AND OUTLIER DETECTION

The adjustment software uses a consensual and well proven mathematical model in terms of both functional and stochastic components. As far as the functional model is concerned, the "method of variation of coordinates" is used [**2**].

As for the stochastic model, we assume that no correlation exists between measurements, because these co-relations are not known. Besides, this simplification has no significant effect on the results when using real data and the covariance matrix of the measurements becomes a diagonal one with computational advantages.

The reference system is defined stochastically [**2**], treating the known coordinate components as observations**.** The formulation of what has been written above formally results in

$$\mathrm{Ax} = \mathrm{l} + \mathrm{v}\ ;\ \mathrm{D} \qquad (1)$$

where **A** is the first order design matrix, **l** is a vector with the observations, **v** is a vector that makes the linear system **Ax = l** consistent and **D** is the dispersion matrix of the observations.

Outlier detection

The adjustment software has three techniques for automatic outlier detection, namely: data snooping [**3**], the hybrid method and a modification of the Danish method **[4]**. The last two belong to the iteratively robustified least square group of techniques.

The modified Danish Method [**5**] takes into account the heterogeneity of the data reweighting the diagonal elements of weight matrix **P**, the inverse of **D,** according to:

$$\begin{cases} p_{ii} = \dfrac{1}{\sigma_{li}^2}\exp\left(-\dfrac{v_i^2}{a^2}\right) & \text{if } |v_i| > \mathrm{a} \\ \quad \text{or} & \\ p_{ii} = \dfrac{1}{\sigma_{li}^2} & \text{if } |v_i| \le \mathrm{a} \end{cases} \qquad (2)$$

where p_{ii} is the ith diagonal element of matrix **P**, σ_{li} is the standard deviation of the ith observation, v_i is the ith element of vector **v** and **a** is a constant usually taken equal to 2.

The hybrid method [**6**] intends to use the benefits of robust estimation, together with the objective and theoretically based rejection criteria of statistical testing. Thus, the selection criteria to reweight some observations will be based on standardized residuals (w_i), rather than on residuals themselves.

The critical value, **k,** will be used and progressively increased (i. e., α will decrease). During 3 reweighting iterations, α will be taken equal to 0.05, 0.01 and 0.001 leading respectively to values of **k** equal to 1.65, 2.58 and 3.29 (two tailed test on w_i , which is supposed to follow a standard normal distribution curve). Diagonal matrix **P** will be built iteratively according to

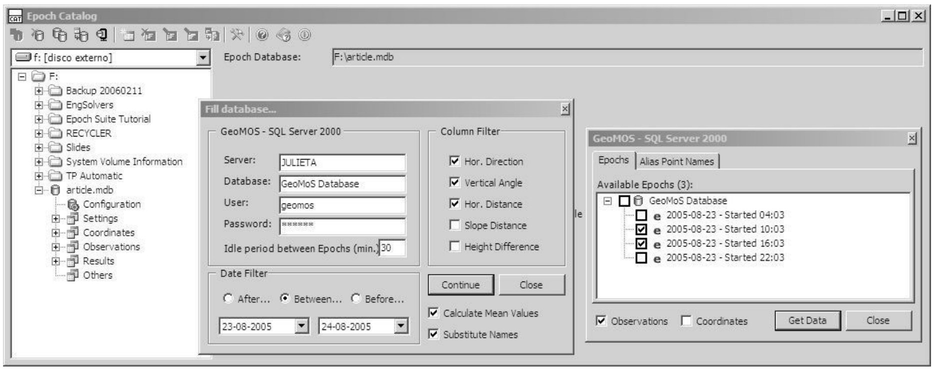
$$\begin{cases} \mathrm{p}_{\mathrm{ii}} = \dfrac{1}{\sigma_{li}^2 w_i^2} & \text{if } |v_i| > \mathrm{k} \\ \quad \text{or} & \\ \mathrm{p}_{\mathrm{ii}} = \dfrac{1}{\sigma_{li}^2} & \text{if } |v_i| \le \mathrm{k} \end{cases} \qquad (3)$$

The ATR system has provided reliable measurements. However, an automatic measuring system must have outlier detection tools, as this will be the only way to replace human judgment on whether to accept or to reject a given measurement.

ADJUSTMENT SOFTWARE

EpochSuite adjustment software package is .NET native. Since it was developed having in mind monitoring tasks, it makes use of Access database to store and manage both the measurements and the results in an epoch-by-epoch basis, within a project. EpochCatalog is the part of EpochSuite that deals with importing, editing, creating and deleting databases, tables or data. EpochAdjustment is the component of EpochSuite that deals with computations. While developing the software, significant effort was put on making a powerful adjustment tool, yet maintaining a “keep it simple” approach. Powerful in the sense that it can interact with a fast and complex acquiring data system like the one installed in the tunnel, processing thousands of equations in seconds, providing quality control parameters, running automatically the adjustment and being able to detect multiple outliers, should they occur. Simple in the sense that a user friendly interface and a Windows-like application make it possible, for instance, to easily control every aspect of the adjustment run in a single window. In a dialog setting window, the user can specify the degree of human intervention he wants for the program in order to allow for a fully automatic run.

Since GeoMoS uses a specific SQL Server 2000 database, a functionality was built to migrate selected data stored (full data or only some epochs with specific time intervals) in the mentioned database into the EpochSuite database format. Figure 6 illustrates the interactivity to achieve the migration.



Epoch Database: F:\article.mdb

Server: JULIETA
Database: GeoMoS Database
User: geomos
Password: ******
Idle period between Epochs (min.) 30

☑ Hor. Direction
☑ Vertical Angle
☑ Hor. Distance
☐ Slope Distance
☐ Height Difference

○ After... ● Between... ○ Before...
23-08-2005 24-08-2005

☑ Calculate Mean Values
☑ Substitute Names

Available Epochs (3):
☐ GeoMoS Database
☐ 2005-08-23 - Started 04:03
☑ 2005-08-23 - Started 10:03
☑ 2005-08-23 - Started 16:03
☐ 2005-08-23 - Started 22:03

☑ Observations ☐ Coordinates

Fig. 6 Selection of specific epochs of the SQL Server database to load the EpochSuite database for adjustment.

CONCLUSIONS

A tunnel has usually a narrow area of observation and a limited availability of stable points. While under construction or repair, machinery operation also occurs in narrow space and interferes with visibility to say the least. On the other hand, and once the tunnel is in use, the operation of trains requires the monitoring system to be fully automatic. The combined effect of the restrictions referred to above demands a certain degree of ingenuity from the surveyor in order to design a suitable monitoring network.

The effective reliability of the data acquisition component (total stations, targets, automatic target recognition, data transmission, etc.) of this specific monitoring system has been shown during the automatic observation of more than one thousand epochs with no significant number of outliers entering the adjustment. Whenever the visibility is disrupted, the tangible accuracy of the sub-networks will be considered satisfactory in terms of structural safety control. However, as long as the entire network is observed, the link between the SQL Server and the EpochSuite databases should be established and the adjustment program should be automatically run. The adjusted coordinates should supersede those provided by the sequential approach.

References

1. LNEC, 2005. Terreiro do Paço Tunnel: Expert Report on the Continuous Displacement Monitoring System by Tacheometric Methods. (in Portuguese)
2. Cooper, M. A. R., 1987. *Control Surveys in Civil Engineering*. Collins Professional and Technical Books, 381 pages, London.
3. Baarda, W., 1968. *A Testing Procedure for Use in Geodetic Networks*. Netherlands Geodetic Commission Publications on Geodesy. New series vol. 2, Delft.
4. Berberan, A., 1995. Multiple Outlier Detection. A Real Case Study. *Survey Review*, 33 (255): 41-49.
5. Krarup, T., Juhl, J., Kubik, K., 1980. Gotterdammerung over least squares adjustment. In: Proceedings of 14th Congress of the ISPRS, B3: 369-378. Hamburg.
6. Berberan, A., 1992. Outlier Detection and Heterogeneous Observables - a Simulation Case Study. *Australian Journal of Geodesy, Photogrammetry and Surveying*, 56: 259-267.
7. www.epoch-suite.com – Epoch Suite Tutorial and Manual, 2006