UDK 528.41:656.2+624.19/.21
Izlaganje sa znanstvenog skupa*

Geodetic Networks for Special Purposes

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ABSTRACT. This paper shows additional densification of the NGBNs to improve the geometric characteristics and the accessibility and to assure that all points maintain the intended relativ accuracy for construction sites. Further in the paper, this will be discussed with typical examples: networks for high speed railway lines, for tunnels and for bridges.

Key words: geodetic networks, GPS, Real-time kinematic, bridges

1. Introduction

In the nineteenth century many countries in Europe established National Geodetic Base Networks (NGBN), using triangulation. At that time the networks mainly served as a basis for topographic surveys and land registration. In the early 1970s some countries improved the scale of the networks by applying trilateration methods. Since the late 1980s mainly GPS measurements were applied to get a better quality of the historical networks and to establish an International Terrestrial Reference Frame (ITRF). Today the historical NGBNs and the ITRF serve as a basis for map-production, land registration, GIS and technical projects.

For construction sites, however, normally an additional densification of the NGBNs is necessary, to improve the geometric characteristics and the accessibility and to assure that all points maintain the intended relativ accuracy. In many cases additionally ITRF points are used so that either terrestrial or GPS surveys can be involved in the practical work. In the following this will be discussed with typical examples: networks for high speed railway lines, for tunnels and for bridges.

* The Paper was presented at "Državne geodetske osnove i zemljišni informacijski sustavi" in Opatija
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2. Networks for high speed railway lines

In Europe the densification and improvement of the high speed railway network has been made a priority, as it is generally accepted that railroads are most efficient for transporting people. In the near future high speed trains will connect all major towns with a speed of about 200 km/h. The Dept. of Engineering Geodesy, Technical University in Vienna, was involved in the development of fundamental concepts concerning geodetic networks and rail track alignment methodes.

2.1. Design of the networks

The fundamental concept of the network was applied to the design of a special 45 km long section of the new high speed railway line Cologne – Frankfurt in Germany (Kahmen et al. 1998).

A maximum speed of 300 km/h shall be possible. That means that the networks have to satisfy the highest requirements concerning accuracy and reliability. In summary, the following were the major points of the network design:

- A fundamental network should provide points in the proximity of the railway line, whereby the spacing between them should be about 1 km.
- The relative accuracy should not exceed 1 cm.
- The fundamental network should be densified by traverses implemented on both sides of the railway line, whereby the spacing of the points should be about 200 m and the relative accuracy 1 cm.
- The network of tunnels and bridges should be integrated into the fundamental network.

It was decided to implement the network in four steps. The fundamental network should be established by GPS surveys in two steps, the densification with traverse nets by terrestrial surveys in a third step and finally by integration of the nets for tunnels and bridges in a fourth step. The main reasons for the hierarchical concept were:

- The connection with the national datum should be performed using a homogeneous network.
- The transformation parameters between the GPS network and the NGBN should be derived from a network of the highest accuracy.
- The points along the railway line should be of a high relative accuracy.

The fundamental network (step 1) consists of 12 points (Figure 1).

Six points belong to the NGBN. The other points were established – referred to here as modular points – along the railway line with an average spacing of 7.5 km. These points could then be considered control points for the 2nd order network.

For the GPS surveys 6 receivers were used. The planning of the surveys was based on simulation calculations. Four sessions were required each lasting 5 hours. For the least squares adjustment of the network (step 1) the vectors between the modular points, being measured during step 2, were used in addition. Thus they could be considered linearly independent.

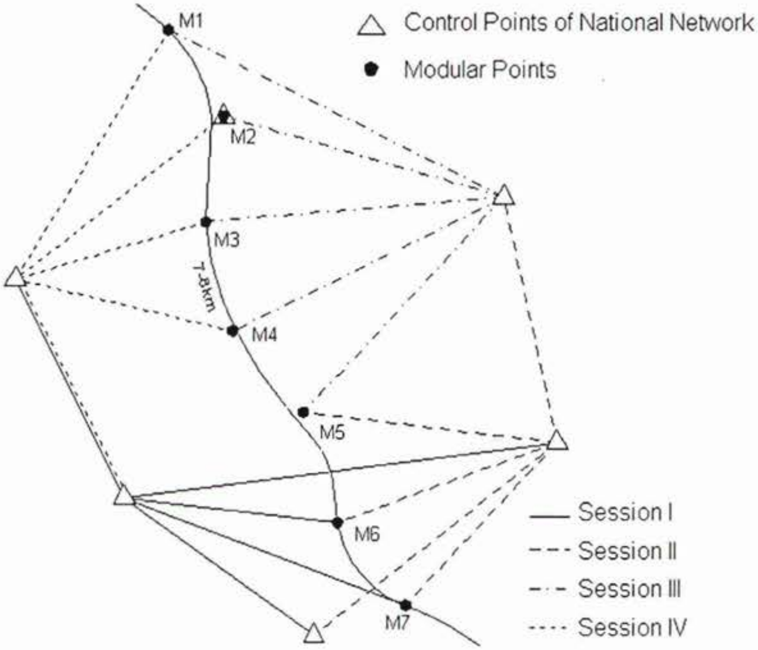

Figure 1. *Fundamental network (1st order)*

The linear networks of step 2 were tied to the modular points of step 1. Every of those networks consists of 8 additional points with a spacing of 1 km (Figure 2). For economical reasons the planning of the surveys was also based on simulation calculations.

Six receivers were used, two of them occupied modular points (temporary reference stations) and the rest of them visited the unknown points. Four sessions were required each lasting 30 minutes.

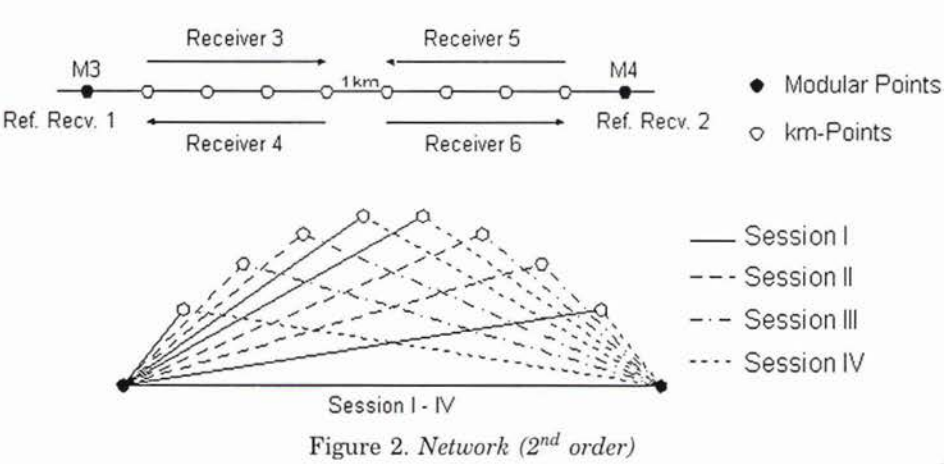

Figure 2. *Network (2nd order)*

The design of the densification network (Figure 3) was also based on simulation calculations. Two traverses connect the 1-km-points of the fundamental network. Simulation calculations showed that it is necessary to add diagonal connections to increase the reliability of the network and it is more economicly to use electronic tacheometers for the measurements.

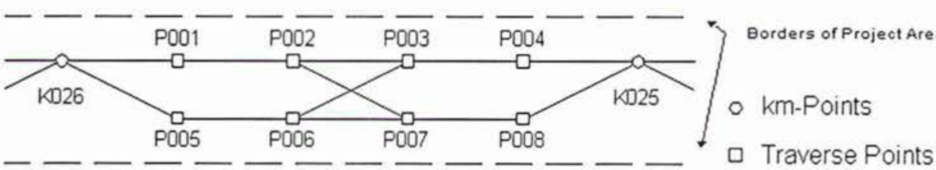

Figure 3. *Densification network (3rd order)*

2.2. Simulation calculations

The accuracy and reliability analysis of the network, which had to be performed in advance, to organize the sessions in a most economical way, was based on a simulated least squares adjustment. For these calculations the geometry of the network and the stochastic parameters were needed. One part of the geometry was given by coordinates of fixed points of the national network. The rest of the information was taken from topographical maps showing the new points. While the a-priori standard deviations of the measurements were known from the operating characteristics of the GPS receivers the covariances had to be derived from simulated observations.

At first the coordinates of the network (step 1) available from the NGBN and from a 1 : 200,000 map were transformed into the "ITRF-System". Then, for the simulation of the observations, the GPS-Software Bernese 4.0 was used. Ephemeries and earth rotation parameters were provided from the CODE-Centre Bern. The reference time was chosen in such a way that the configuration of the satellites was comparable with the configuration during the measurements.

The simulations showed, that after an observation time of 5 hours, baselines up to 23 km in length would have an accuracy of ± 3.7 mm (1 s). Within an observation time of only 3 hours the accuracy decreased towards 6 mm. This accuracy was considered too small, as for the calculations based on real measurements, unresolved ambiguities and cycle slips had to be taken into account. Observation times longer than 5 hours did not really improve the results. Consequently an observation time of 5 hours was prescribed for the sessions.

The relative accuracy of the modular points is described by relative coinfidence ellipsoids; their horizontal components did not exceeding 3 mm. Consequently we could see hat enough clearance was available for unforeseen difficulties during the measurement procedures.

The simulated least squares adjustment of the network (step 2) was performed in a similar way. In that case, however, the observation time of one session was estimated a-priori with 30 minutes, based on past GPS experience in the Department.

The results obtained after the practical measurements confirmed, that GPS surveys can be performed more economicly if they are planned with simulated least squares adjustments a priory.

2.3. Setting out and maintenance of the high speed railway tracks

For track-surveying special railway vehicles will be used in the near future, carrying a multi sensor system for data acquisition. A research project of the Department of Engineering Surveys of the University of Technology in Vienna showed, that GPS surveys can be used for the positioning of the measurement vehicle if Wiener filters are applied for the data evaluation procedures.

The measured data and the railway track can be described by signals, whereby three signal components have to be distinguished (Figure 4). Mathematically the signals can be described by the fundamental equation of the Wiener filter (Kahmen, Retscher 1997):

$$\underline{l} = \underline{Ax} + \underline{s} + \underline{n} \tag{1}$$

where $\underline{l}$ is the observation vector, $\underline{Ax}$ is the function of the best fitting alignment, $\underline{s}$ describes the differences between the actual alignement and the best fitting alignment and $\underline{n}$ is a noise vector.

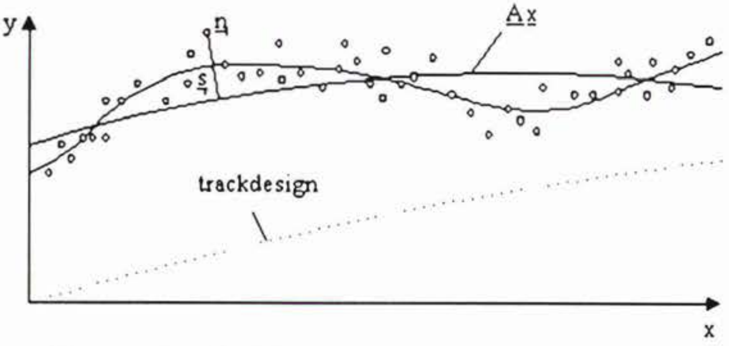

Figure 4. *Model of the Wiener filter evaluation procedure*

The function comprises elements, normally used for the alignment, such as straight lines, circles or clothoids. It must not conform to the trackdesign, however maximum or minimum alignment parameters and certain shifts of the rails per pendicular to the railway axis are not allowed to exceed specified limits. There should not be any shifts at the beginning and end of the surveyed track. This is met by increasing the weighting of the measurements at the beginning and the end of the track section in the Wiener filter evaluation procedure.

The evaluation process consists of 3 steps (Retscher 1996).

In step 1 single track elements are computed. We get parameter vector $\underline{x}$ from:

$$\underline{x} = (\underline{A}^T \underline{Q}u^{-1} \underline{A})^{-1} \underline{A}^T \underline{Q}u^{-1} \underline{l} \tag{2}$$

where $\underline{Q}u = \underline{Q}u + \underline{Q}s$ is the cofactor matrix. The cofactor matrix $\underline{Q}u$ of the measurements and $\underline{Q}s$ of the signal can be estimated using the correlation function:

$$C(\Delta l) = Coe^{-\left(\frac{\Delta l}{a}\right)^2} \tag{3}$$

a can be estimated from $a \approx (2/5)\,\lambda$ where is a mean value of the wavelength of $\underline{s}$ and $\underline{l}$ the length of the elements.

The elements are connected in a 2 step procedure. Then certain conditions must be met

$$\begin{aligned} x_i\,(l) &= x_{\underline{i+1}}\,(l) = x \\ y_i\,(l) &= y_{i+1}\,(l) = y \\ z_i\,(l) &= z_{i+1}\,(l) = z \\ T_i(l) &= T_{i+1}(l) = T \\ \kappa\,(l) &= \kappa_{i+1}(l) = \kappa \end{aligned} \tag{4}$$

where T is the azimuth of the tangents, κ the curvature.

In step 3 finally the signal $\underline{s}$ is computed:

$$\underline{s} = \underline{Q}_s\,\underline{Q}u^{-1}\,(\underline{l} - \underline{Ax}) \tag{5}$$

It contains the corrections (shifts) for the rail straightening machine. Practical results confirm that the high relative accuracy of 1...2 mm/10 m for the construction and maintenance of high speed railway tracks can be met (Retscher 1996).

3. Nets for tunnels and bridges

For high speed railway lines a large number of tunnels and bridges have to be built in mountainous areas.

A tunnel net normally consists of at least 10 control points (Figure 5a):

- one control point at each portal end section
- three control points about 1 km away from the portal points, to define the orientation of the tunnel traverse
- four control points of the NGBN in the neighbourhood of the tunnel.

The only condition for the design of the network was that the standard deviation of the cut through error should not exceed 1 cm.

The control points at each portal end section and on both sides of the tunnel are needed to transform ITRF coordinates of the local tunnel net into the coordinate system of the NBGN.

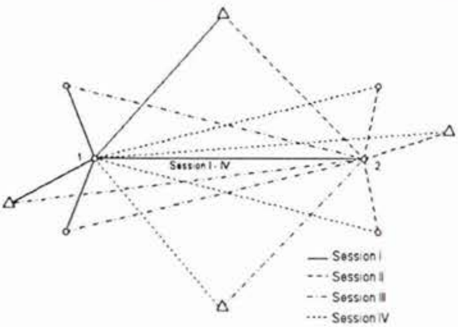

Figure 5a. *Design of a tunnel net and the planning of the measurement*

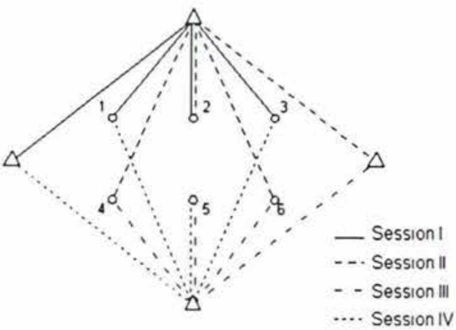

Figure 5b. *Design of a bridge net and the planning of the measurement*

If the tunnels are being built with a new railway line, for the points at the portal modular points or 1-km-points can be chosen and the two points on both sides of the tunnel can then be measured together with the GPS surveys of the fundamental network (step 2).

For the construction sites of bridges networks of high accuracy are also needed. The relative accuracy of the network (Figure 5b) should not exceed 0.5 mm. The number of points depends on the length of the bridges and the topography. The network normally consists of squares. Four control points are needed to transform the local network into the NBGN. In connection with a new railway line two of them can be modular points or 1-km-points, the other two are positioned on the left and right hand side of the bridge. A six parameter transformation is chosen, the scale factor is normally kept fixed.

For the GPS-surveys of the tunnel and bridge-network GPS is most suitable. Examples of the observation plans are depicted in Figure 5a and b.

4. A construction site network of real-time GPS reference stations

For large construction sites a network of real-time GPS reference stations may be more suitable. This was the case, when the Oeresund project was undertaken to construct a road and rail link to cross the narrow sea passage between Denmark and Sweden (Figure 6). The link between Copenhagen and Malmö is 18 km in length and consits of a tunnel, an artificial island, and a bridge. The fundamental network of the construction site is a high precision geodetic network with five permanent GPS reference stations. Additional requirements of the tender are the provision of a mobile station that can be set operational within 24 hours. All stations cover a project area of approximately 6 km × 20 km and should support as well real-time as post-processing GPS surveying for civil engineering, construction and precise navigation. In the following the Leica-concept for multi-purpose real-time GPS reference stations shall be described (Pache, Jackson 1997).

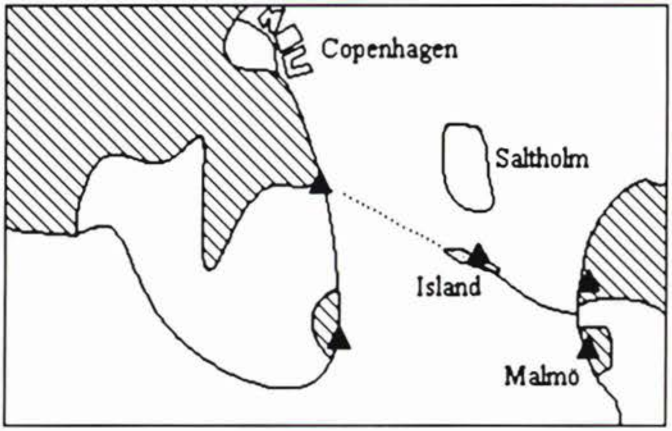

Figure 6. *Reference stations of the Oeresund project*

The hardware at each station comprises (Figure 7):

- 2 dual-frequency receivers
- 1 geodetic antenna
- 2 industrial PC s
- 2 radio modems
- 2 radio antennas
- 1 uninterruptible power supply
- 2 telephone modems.

At the four mainland stations directional antennas pointed at the project area are used. An omni-directional antenna is transmitting at the island station.

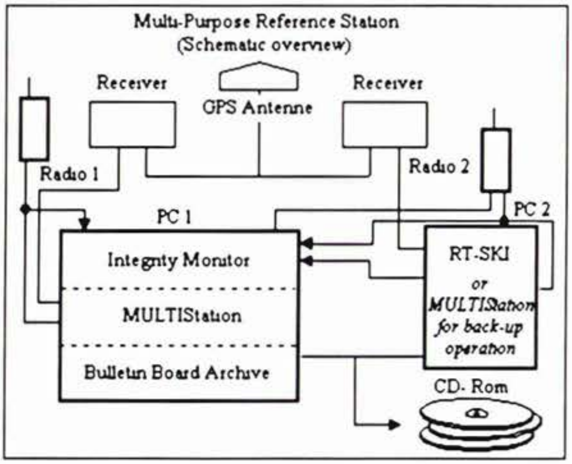

Figure 7. *Multi-purpose reference station (Leica)*

The reference-system part of each multi-purpose reference station performs two parts: the transmission of RTCM V 2.1 messages and the logging RINEX 2.0 data.

The reference system comprises

- A geodetic antenna
- A dual frequency receiver
- A radio modem
- A PC (PC 1) and a "Multi station" software.

Multisation is a standard software developed by Leica. It controls the receiver, logs hourly RINEX data and transmits RTCM V 2.1 messages. Compressed 1-hour RINEX files are available immediately in the bulletin-board archive. Users are given passwords and can dial in and download files for post-processing. After four weeks the RINEX files are copied to a CD Rom for permanent archieving.

The integrity monitoring systems has to ensure the correct functioning of the stations and the validity of the transmitted RTCM V 2.1 messages. The integrity monitoring system consists of the following components:

- A dual-frequency receiver
- A second radio modem (frequency can be switched)
- Integrity-monitoring software (running on PC 1).

The two receivers are connected to the GPS antenna and from a zero baseline. As radio 1 transmits RTCM V 2.1 messages to radio 2 continuously on-the-fly ambiguity-resolution fixes are computed for the zero baseline. This enables an internal check of the operation of the station and the correctness of the transmitted RTCM V 2.1 data. By switching the frequency of radio 2 to that of the neighbouring stations, the baselines to these stations can be computed for additional control of the network.

The hardware of the integrity monitoring system has still a second function, the provision of a full back-up system in case of any malfunction. If receiver 1 or radio 1 of PC 1 or the software on PC 1 should fail the system switches automatically to reciever 2, radio 2 and PC 2.

The real-time reference stations have to be tied into the NGBN. Therefore the coordinates of the GPS antennas of the multi-purpose reference stations have to be determined in both ITRF and NGBN coordinates.

5. Conclusion

In the future it will not be easy to decide whether permanent or non permanent GPS reference stations should be used for the densification of the national networks for construction sites. One point of view is economy. In the case of large construction sites and that most of the surveying and navigation tasks can be performed by the manufacturers with real-time GPS rover units, the establishment and operation of real time GPS reference stations will be more economicly. For many tasks then only one RTK GPS receiver will be needed. Another aspect is that it is normally impossible to allocate a seperate radio frequency to each of the many contractors and survey companies that use GPS as a survey tool. Local Telecom authorities, however, normally agree to provide radio frequencies for up to 5 or 6 GPS reference station. A third aspect is that quality control is provided by integrity monitoring at the reference stations and by the fact that rover units can switch instantly from one reference to another to check position-fixes.

References

Kahmen, H. and Retscher, G. (1997): Gleisvermessung mit einem Multi-Sensorsystem und linearen Filterverfahren. Zeitschrift für Vermessungswesen 12.

Kahmen, H. and Wunderlich Th., Retscher, G., Kuhn, M., Plach, H., Teferle, F. N., Wieser, A. (1998): Ein modernes Konzept zur Absteckung von Hochgeschwindigkeitstrassen. Allgemeine Vermessungs-Nachrichten.

Pache, F. and Jackson, P. (1977): A Network of Real-Time GPS Reference Stations for a Major Civil-Engineering Project. Leica AG, Heerbrugg, April.

Retscher, G. (1996); 3D-Gleiserfassung mit einem Multisensorsystem und linearen Filterverfahren. Geowissenschaftliche Mitteilungen. Heft 44. Institut für Landesvermessung und Ingenieurgeodäsie, TU Wien.

Geodetske mreže posebnih namjena

SAŽETAK. U radu se daju mogućnosti progušćivanja nacionalnih mreža kako bi se popravile geometrijske osobine i pristup te kako bi se osiguralo da sve točke zadrže relativnu točnost potebnu pri graditeljskim radovima i iskolčenjima. Dalje u radu se o tome raspravlja na tipičnim primjerima: mreže za željezničke pruge predviđene za velike brzine te mreže za tunele i mostove.

Ključne riječi: geodetske mreže, GPS, Real-time kinematic, mostovi

Primljeno: 1999-04-14