Comparison of SpatialAnalyzer and different adjustment programs

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Abstract. Net adjustment is one of the basic tools for various surveying tasks. Among the transformation of coordinates or the analysis and comparison of geometries, the adjustment of geodetic networks is an important part of the surveyor's work. The market offers a number of software solutions, both commercial and freeware.

Seeing the range of software solutions, the question arises, whether the programs give equivalent results. Earlier evaluations of net adjustment programs, partly including New River Kinematics' SpatialAnalyzer (SA), revealed on the one hand almost identical adjustment results for the classic programs. On the other hand, the evaluations showed that SA, using a different mathematical model (bundle adjustment), yields clearly distinguishable deviations. Hence, in this paper the authors focused on SA with the classic programs as reference. The first part of the comparison deals with the results of evaluating a terrestrial network. As programs do not account for the earth's curvature in a standardized way, the chosen network is of small size to minimize the influence of the curvature to an insignificant level.

The second part of the paper compares the results of the evaluation of basic geometries (plane, circle, cylinder, sphere) using SA and other software packages with the least squares solution obtained in a rigorous Gauss-Helmert model.

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1 Introduction

A study from Schwieger et al. (2010) took a brief look on commercially available software products for net adjustment. The authors discussed the user requirements for such software and the various quality parameters dedicated to assess reliability, efficiency and accuracy. The comparison of the numerical results focused on the estimated coordinates of the network points and a couple of quality parameters. Deviations up to several millimetres in the coordinates between the results of the different programs were observed.

Lösler and Bähr (2010) extended the list of compared programs a little, including open source software and freeware as well. They focused on the estimated coordinates as a result solely. SpatialAnalyzer, taking part in their comparison, revealed deviating results with respect to the other programs and some characteristics concerning the data processing. Consequently the present paper focuses on SpatialAnalyzer with some other programs as reference. The authors extended the study by a comparison of different form fitting algorithms to discuss the availability of quality parameters of the estimated geometries.

2 Net Adjustment

2.1 SpatialAnalyzer

This commercial software is developed and distributed by New River Kinematics. It is designed for an industrial environment and mainly used for quality control purposes. The software architecture of SA allows the user to connect and directly operate a large variety of measuring equipment (total stations, laser trackers, scanners etc.). SA presents the measurements on-line in a CAD environment.

Compared to the classic adjustment programs, SA uses a different mathematical model. Instead of the common approach of directly adjusting observations in one step, the software uses concatenated similarity transformations. In SA the tachymetric observations (distances, horizontal directions and vertical angles) cannot be used for the adjustment directly. Instead, SA calculates local coordinates of all target points per station. Thus, each station and the measurements taken there, form an independent (sub-) system with individual orientation. The adjustment is then performed by simultaneously concatenating the station subsystems of the network via similarity transformations (Calkins 2002). Up to seven transformation parameters (translations in x, y and z, rotations about the three axes and one scale factor) can be estimated individually for each station. The adjustment process is initially carried out in an arbitrary coordinate system. To finally acquire the coordinates in the target system, the adjusted network is transformed to the point group of the initial values of the network points, again via similarity transformation.

The other programs included in this study are GNU Gama, Java Graticule 3D (JAG3D), Leica Geo Office (LGO), Netz3D and NetzCG.

GNU Gama is developed by Aleš Čepek. The software is open source and capable of adjusting geodetic networks consisting, for instance, of observed distances, angles, height differences and/or observed coordinates. (see URL 2)

JAG3D is developed by Michael Lösler and is open source. The program offers adjustment of geodetic networks in 1D, 2D or 3D. Furthermore routines for coordinate transformation, form fitting and coordinate conversion are included. (see URL 1)

LGO is distributed by Leica Geosystems. It is commercial software to evaluate geodetic measurements. The mathematical model of LGO's computation module MOVE3 is rigorously ellipsoidal (Grontmij).

Netz3D is developed by the Geodetic Institute Karlsruhe. It is a program for the adjustment of three dimensional networks.

NetzCG is developed by the Geodetic Institute Karlsruhe and COS Systemhaus OHG. It is an integrated net adjustment tool for AutoCAD. NetzCG automatically separates horizontal position and height and adjusts them separately.

2.2 Network

The network for this comparison was kindly provided by COS Geoinformatik GbR. It consists of 72 sets of measurements (slope distances, horizontal directions and vertical angles) taken on six stations with 23 network points in total. The maximum distance between two points is approx. 31 m.

As mentioned above, the programs account differently for the earth's curvature. The influence of the deflection of the vertical increases with the network's size. Witte & Schmitt (2000) give a rule of thumb to assess the effect on the height between two network points with

$$k = \frac{s^2}{2R} \quad (1)$$

where s is the horizontal distance and R is the earth's mean radius. The effect is smaller than 0.1 mm for distances below 36 m. This motivates the choice of a small network, minimizing the influence of the curvature to an insignificant level.

All the programs offer to calculate the adjustment with a priori uncertainty values. Unfortunately the handling differs with each program. To produce comparable results, the authors chose a distance uncertainty of 0.3 mm and an angle uncertainty of 5.5 arc seconds (1.7 mgon) for all the software packages.

The reader might wonder why the value for the angles is that large and why the authors chose absolute values rather than using a distance-depending stochastic model. The fact, that the programs cope differently with the a priori uncertainties, made it necessary to choose this approach. Especially the stochastic model of SA lacks the option to take centering or aiming uncertainties into account. The user is only able to define an absolute value (1 sigma level) for the angle uncertainty of the horizontal and vertical angles separately.

The stochastic model of the direction uncertainty with a distance-dependent approach is as follows:

$$\sigma_{direction} = \sqrt{{b_1}^2 + \left(\frac{b_2}{s} \cdot \rho\right)^2} \quad (2)$$

where b_1 is the direction uncertainty of the instrument, b_2 is the distance-dependent part representing an aiming or centering uncertainty and s is the distance to the target point. ρ is for converting $b_2/\ s$ into an angle value, e. g. 180/π. It is obvious that the influence of the aiming is largest at short distances. Hence, especially in a network of small size, the aiming uncertainty contributes significantly to the overall uncertainty budget of a point and cannot be neglected. Due to the rather small size of the network the authors chose the relatively high absolute value of 5.5 arc seconds (1.7 mgon).

The programs differ in the stochastic model of the distance uncertainty as well. (3) is implemented in LGO, NetzCG and Netz3D. JAG3D calculates the distance uncertainty according to the law of propagation of variances with (4). The model (5) is implemented in Gama. Similar to the model of the directions, a_1 is the absolute uncertainty of the distance measurement and a_2 is the distance-dependent part. With $a_3 = 1$, (5) is the same as (3). Because of the different models, the authors chose an absolute value for the distance uncertainty. Compared to the horizontal directions, this has a rather small effect, especially when measuring short distances.

$$\sigma_{distance} = a_1 + a_2 \cdot s \quad (3)$$

$$\sigma_{distance} = \sqrt{{a_1}^2 + (a_2 \cdot s)^2} \quad (4)$$

$$\sigma_{distance} = a_1 + a_2 \cdot s^{a_3} \quad (5)$$

2.3 Results

The adjustment was carried out with four constraints for the datum defect (three translations and one rotation parameter) as it is appropriate for tachymetric 3D networks (Illner 1983). Table 1 provides an overview of the differences in coordinates and standard deviations between the results of the compared programs. Gama represents the results of JAG3D and Netz3D, too, because the three of them provided identical values, in coordinates as well as standard deviations.

Using an alternative mathematical model, the results of SA are similar to the other programs with a maximum deviation of 0.5 mm. Taking into account the introduced distance uncertainty of 0.3 mm and the tachymetric application, this result is satisfying. On the other hand, the standard deviations of SA's solution are up to four times larger than the ones of Gama (representing JAG3D and Netz3D, too, as stated above) (table 1) and are only calculated for actually measured points. Point 3333, which was determined by setting up a station there, is not included in the covariance matrix of SA's net adjustment routine. The available covariance matrix is only of a 3x3 block diagonal structure. The reason for the differences of the standard deviations could not be distinguished clearly. The developers have been notified on this discrepancy.

Concerning classic geodetic measurements, SA lacks some basic features. There are no options for instrument and reflector heights. Consequently they have to be zero or the offset has to be adjusted manually. In contrast to the classic programs, single observations cannot be excluded from the adjustment process (e. g. because of a gross error). If one of the polar elements of a measured point is missing, the other two will be excluded as well, because SA does not use the observations directly, as described in 2.1.

The comparison also revealed minor deviations between LGO and NetzCG on the one hand, to the group of Gama, JAG3D and Netz3D on the other hand. The maximum value of the differences is 0.2 mm. These deviations are easily explained, again through the mathematical models of LGO and NetzCG. LGO works with a rigorously ellipsoidal coordinate system. All observations and coordinates

Point	SA – Gama [mm]			SA – LGO [mm]			SA – NetzCG [mm]			Std.-dev. SA [mm]			Std.-dev. Gama [mm]		
	X	Y	Z	X	Y	Z	X	Y	Z	X	Y	Z	X	Y	Z
1007	-0.1	0.0	0.2	-0.1	0.0	0.1	-0.1	0.0	0.2	0.42	0.27	0.29	0.09	0.06	0.07
1008	0.1	0.0	0.3	0.0	0.0	0.1	0.1	0.0	0.2	0.43	0.24	0.25	0.10	0.06	0.07
1009	-0.1	0.0	0.2	-0.1	0.0	0.1	-0.1	0.0	0.2	0.44	0.32	0.34	0.12	0.10	0.09
1098	0.1	0.1	0.0	0.1	0.2	0.1	0.1	0.1	0.0	0.46	0.36	0.41	0.07	0.06	0.07
3333	0.2	0.1	-0.1	0.2	0.2	0.0	0.2	0.1	-0.1				0.14	0.12	0.12
101	0.0	0.0	-0.1	0.0	0.0	-0.2	0.0	0.0	-0.2	0.46	0.42	0.44	0.18	0.16	0.17
102	-0.3	0.1	0.1	-0.3	0.1	0.1	-0.3	0.1	0.1	0.53	0.53	0.54	0.22	0.21	0.23
103	0.2	-0.2	0.0	0.2	-0.2	0.0	0.2	-0.2	0.0	0.53	0.52	0.53	0.21	0.21	0.22
104	0.0	-0.1	0.1	0.0	-0.2	0.1	0.0	-0.1	0.2	0.37	0.38	0.40	0.12	0.14	0.15
105	0.0	0.0	0.0	-0.1	0.0	0.0	0.0	-0.1	0.2	0.37	0.46	0.45	0.15	0.19	0.20
106	-0.1	0.0	0.0	-0.1	0.0	0.0	-0.1	0.0	0.0	0.29	0.35	0.28	0.11	0.13	0.11
206	-0.1	-0.4	-0.2	-0.1	-0.3	0.1	0.0	-0.4	-0.2	0.67	0.45	0.67	0.13	0.08	0.11
401	0.0	0.0	0.0	0.0	0.0	-0.1	0.0	0.0	0.0	0.53	0.36	0.38	0.21	0.14	0.15
402	-0.3	0.2	0.0	-0.3	0.1	-0.1	-0.3	0.1	-0.1	0.72	0.53	0.71	0.34	0.22	0.35
501	0.1	0.1	0.0	0.2	0.1	-0.1	0.1	0.1	0.0	0.41	0.35	0.31	0.16	0.14	0.13
504	0.3	0.0	-0.4	0.3	-0.1	-0.5	0.2	-0.1	-0.4	0.67	0.53	0.66	0.28	0.22	0.30
505	0.2	0.1	0.0	0.2	0.1	-0.1	0.2	0.1	0.0	0.58	0.54	0.58	0.24	0.22	0.25
506	0.0	0.0	0.0	0.0	0.0	-0.1	0.0	0.0	0.0	0.21	0.26	0.19	0.10	0.10	0.09
602	-0.1	0.0	0.1	0.0	0.0	0.2	-0.1	0.0	0.1	0.50	0.50	0.48	0.19	0.20	0.20
603	-0.1	-0.1	-0.1	-0.1	0.0	0.1	-0.1	0.0	0.1	0.44	0.38	0.44	0.15	0.14	0.17
604	-0.1	0.0	-0.2	-0.1	0.0	0.0	-0.1	0.0	-0.2	0.42	0.38	0.44	0.13	0.14	0.17
605	0.2	0.1	-0.1	0.2	0.2	0.1	0.2	0.2	0.0	0.44	0.50	0.46	0.20	0.20	0.19
606	-0.1	0.0	-0.1	-0.1	0.1	0.1	-0.1	0.0	-0.1	0.35	0.39	0.35	0.13	0.15	0.14

Table 1: Coordinate differences and standard deviations of SA and the other programs; Gama represents JAG3D & Netz3D

respectively, are converted into an ellipsoidal reference system. NetzCG separates horizontal position and height automatically and adjusts the two "systems" separately.

3 Form Fitting

A common way for the evaluation of point clouds is the form fitting. Regular geometries, like planes, circles and cylinders, are fitted to the measured points. Through estimating the form parameters, it is possible to derivate the characteristics of the object. Those parameters can be the radius of a sphere or the normal vector of a plane, and by that its orientation, just to name a few. The parameters can later be used to assess the form in terms of quality control (e. g. dimensional accuracy).

As the reference for the comparison, the authors realized the approximate and the rigorous Gauss-Helmert model with MATLAB. They compared this implementation to the form fitting tools of SA and the software packages mentioned below. By using this implementation, the authors could distinguish whether the software packages obtain the least-squares solution via the rigorous or the approximate Gauss-Helmert model. In contrast to the rigorous model, the approximate model does not update the initial values of the adjusted observations with every iteration. For further information on the rigorous evaluation of the Gauss-Helmert model see (Lenzmann and Lenzmann 2004) or (Neitzel 2010).

The Least Squares Geometric Elements (LSGE) is a MATLAB toolbox freely offered on eurometros.org. The toolbox provides estimation of parameters for standard geometries like lines, planes, spheres and cylinders etc.

The Form Fitting Toolbox is part of the program JAG3D by Michael Lösler. It offers the estimation of form parameters through a Gauss-Helmert model for two- and three-dimensional functions (e. g. lines, n-degree polynomials, ellipsoids, see URL 1).

For the comparison of the software packages four basic geometries were chosen. The sample data was taken from the following studies: plane, Drixler 1994; sphere, Jäger et al. 2005; cylinder, Späth 2000a and circle, Späth 2000b. The following equations depict the functional model for each geometry.

The hessian normal form (6) is one way to describe a plane. $n_0 = [n_x \;\; n_y \;\; n_z]^T$ represents the normalized normal vector. d is the shortest distance of the plane to the point of origin. $P_i = [x_i \;\; y_i \;\; z_i]^T$ is a point on the plane.

$$ {n_0}^T P_i = d \qquad (6) $$

The only form parameter of the sphere is its radius r. The radius is defined as the distance between the center point $P_0 = [x_0 \;\; y_0 \;\; z_0]^T$ and the sphere's surface. The center point defines the sphere's position. All points $P_i = [x_i \;\; y_i \;\; z_i]^T$ with the distance r to P_0 lie on the sphere. The functional model can be written as:

$$ \|P_i - P_0\| = r \qquad (7) $$

Reducing the dimension from 3D to 2D enables to describe a circle with (7). However, the conversion of the 2D geometry into the three dimensional space succeeds only with the use of auxiliary quantities (Späth 2000b). Usually, a circle is derived from intersecting two geometries, for instance a plane and a sphere or two spheres. The combination of two rather simple functional models like (6) and (7) leads easily to the estimation of the form (Eschelbach & Haas 2003). Hereby the normal vector of the plane determines the orientation of the circle. The position and radius are obtained with the functional model of the sphere.

The cylinder, as well as the circle or the sphere, has only one form parameter, the radius r. An implicit model of a cylinder with infinite length is given by

$$ \|(P_i - P_0) \times n_0\| = r \qquad (8) $$

A point $P_0 = [x_0 \;\; y_0 \;\; z_0]^T$ and the normalized direction vector $n_0 = [n_x \;\; n_y \;\; n_z]^T$ describe the cylinder axis' position and orientation. The radius is the distance of this axis to the cylinder's surface.

The results of the form fitting with the different implementations are identical (table 2 shows the number of identical decimal places of the estimated values). Only the approximate Gauss-Helmert model of the authors' implementation reveals significant differences. This proves that none of the tested programs estimates the form parameters with the approximate Gauss-Helmert model. All the points representing the forms were introduced as uncorrelated with the same weights. An uneven weight distribution would probably have led to a different result.

	Sphere /m	Plane /m	Circle /m	Cylinder /m
x_0	9.99972450		21303.5851708	0.23012344
y_0	7.99980653		22913.70679085	-0.29012746
z_0	6.99930612		25.3418438	0.23419521
r	5.00054199		2.80954434	11.99127993
n_x		0.1947970	0.88546719	-0.74569520
n_y		0.5449293	-0.4647002	-0.66073840
n_z		-0.81554037	-0.0012322	-0.08581051
d		31.748989	8215.588	

Table 2: Estimated parameters of the forms. The compared programs provided identical results.

However, the above mentioned software packages differ in terms of available quality information on the estimates. The geometry fit report of SA presents the estimated parameters of the form (e. g. center point and radius of a sphere). Furthermore the report includes a list of the deviations of each point to the estimated form and a graphical presentation of the point distribution. Apart from that, no other parameters (i. e. standard deviations etc.) are available to assess the estimated form parameters in terms of quality or accuracy.

A simple stochastic model for some forms is implemented in LSGE. The points representing circles, spheres and cylinders can be weighted individually. A weighting of single coordinate values or of points representing lines or planes is not possible. Furthermore the user can retrieve a three by three covariance matrix for the center point. The variance of the radius of circles, spheres and cylinders is also available. For the normal vector of the circle and the direction vector of the cylinder, respectively, another three by three covariance matrix is available. LSGE calculates the deviations of all points to the estimated form as well.

In the Form Fitting Toolbox of JAG3D the coordinates of the points can be weighted separately by introducing a fully populated covariance matrix. The information on the accuracy of the estimated form parameters is available through a fully populated covariance matrix as well. The size of this matrix corresponds to the number of estimated parameters. For instance, center point, radius, normal vector and distance to the point of origin of a circle are characterized by an eight by eight covariance matrix. Besides, the following information is presented for each point: standard deviation, redundancy number, estimation of gross error and whether or not the point is an outlier. This is inferred from two statistic tests with user defined levels of significance.

4 Conclusion

Based on the studies from Schwieger et al. (2010) and Lösler and Bähr (2010) this paper focuses on SpatiaAnalyzer as a tool for net adjsutment and form fitting. In contras to Lösler and Bähr (2010) a special network of small size was chosen, to minimize the influence of earth's curvature. The group of JAG3D, Gama and Netz3D provided identical results in the estimated coordinates as well as in the standard deviations. The differences of up to 0.4 mm of SA to the solution of the above mentioned group of programs are probably due to the different mathematical model of SA using concatenated similarity transformations. The differences of the standard deviations in SA to the above mentioned group could not be explained. By introducing the same (gross error free) data to all the tested programs, the authors ensured no observations being excluded. Therefore the different standard deviations cannot be explained, e. g., by reduced redundancy. Whether the differences in coordinates are significant with respect to the standard deviations has to be verified in further tests. However, a Monte-Carlo simulation in SA of the uncertainties of the adjusted network points provided values similar to the standard deviations of Gama, JAG3D and Netz3D. This leads to the cautiously optimistic assumption, that the differences in coordinates are not significant.

In terms of form fitting all the programs included in the present comparison provided identical results. It could be verified that all the programs obtain their least squares solution in a rigorous Gauss-Helmert model. However, the programs differ in the available quality information on the estimated form parameters. JAG3D offers the widest range of information.

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