HOMOGENEOUS COORDINATE FRAMES VS. EXISTING INHOMOGENEOUS DATA

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ABSTRACT

Nowadays, the vast majority of data are captured with Global Navigation Satellite Systems (GNSS) or remote sensing. Both methods use homogeneous reference frames, i.e., there are no local distortions in the geometry of the reference frame implementation. This is different from data collected previously. Traditional data capture for mapping (including cadastral mapping) is based on terrestrial reference frames based on local observations. Although these observations were linked to each other in networks and contradictions eliminated with suitable mathematical methods, local deviations were inevitable. As a result these data are based on inhomogeneous reference frames.

Combining data in a homogeneous reference frame with data in an inhomogeneous one shows the deviations between the reference frames. These deviations need to be eliminated in order to provide a consistent reference frame. In this paper we first show the historic reasons for the inhomogeneities using the Austrian case as an example. Then we present some approaches to deal with the deviations.

Key word: GNSS, Coordinate Frame, Cadastre, Inhomogeneity

1. INTRODUCTION

The problem of databases containing data captured during a long time is keeping a unique coordinate frame. Coordinate frames in the 19th and 20th century were typically defined by reference points. Their coordinates were determined by ground surveys (typically triangulation or trilateration) and astronomical observations. Approximate homogeneity was achieved by least squares adjustment. This, however, was not always possible, e.g., in Austria. Today coordinate frames are realized by Global Navigation Satellite Systems (GNSS) like the American GPS or in future the European GALILEO. This difference creates problems when converting data from one system to the other. Local inhomogeneities have to be addressed and compensated. Typical

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approaches to deal with this problem include triangulation with affine transformation in each triangle and residual grids. Each of these approaches has its own strengths and weaknesses, which we discuss in the paper.

In this paper we present examples from Austria showing the effect of the difference for engineering tasks like building tunnels. These situations have been deal with and we show how it was done. We then discuss other possible solutions and show their advantages and problems. We then extend the discussion to whole datasets like cadastral maps, which are basic building blocks for Spatial Data Infrastructures. Surveys for these data sets are also typically conducted using satellite technology, i.e., using GPS. This again leads to the problem of inhomogeneous data sets. The problem of inhomogeneous reference frames should therefore be addressed as early as possible to achieve consistent base data for both, data updates and external use of data for engineering projects.

The remainder of the paper is structured as follows. In section 2 we present a brief history of the Austrian reference frame since its beginning in the 19th century. We then show practical examples for problems occurring when combining data based on this reference frame with measurements taken with modern equipment. Finally, we show some mathematical concepts that can deal with these problems and discuss their properties and the suitability for international endeavours like INSPIRE.

2. A BRIEF HISTORY OF THE AUSTRIAN REFERENCE FRAME AND DERIVED DATA

The current reference point network in Austria is based on measurement campaigns started in 1862 (Sommer 1967; Zeger 1993). Some of the stabilized points have already been used in earlier campaigns, e.g., for the 1st Austrian military triangulation network started in 1806, however the old observations were not used. The scale for the triangulation network was derived from a distance observation near Josefov in the Czech Republic. Originally it was planned to adjust all observations using the least squares method (Ghilani and Wolf 2006). However, this was not possible due to a lack of computational resources. The network was divided into several parts and these were adjusted separately. Small deformations in the overlapping parts of the sub-networks were inescapable. Another problem was that conditional adjustment was used. The network itself had holes and with conditional adjustment it was not possible to model this geometry. Figure 1 shows such a hole (marked with 'I') and its effect on the result of the adjustment. The triangles south east of the hole are not connected as they should be. This was later corrected locally. The resulting network was called the Austrian military triangulation.

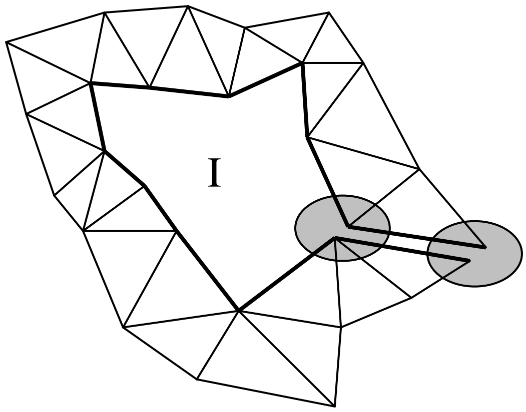

Figure 1. Effects of the holes in the Austrian network in the part of the network between the Buschberg in Austria and Josefov in the Czech Republic (Sommer 1967)

In 1907 a new adjustment was started because

- the holes have been filled and
- too large triangles have been split into smaller ones.

Both activities should have improved the result of the adjustment. It should have also eliminated the problem with the holes. However, World War I stopped the computation and it was never resumed. 40 points of the highest quality level in the current Austrian network are still based on this network. These points form the legal Austrian reference frame together with triangulation points from consolidation networks of 2nd to 5th order and inserted points.

Several activities to assess and improve the quality of the network were initiated. The quality assessment activities include

- the analysis of the residuals of the angular sums in the triangles of the network for the observations before the World War I (Rohrer 1935),
- the analysis of contradictions in the 1st order network (Bretterbauer 1967), and
- a readjustment of the original observations and comparison with the coordinates in use (Litschauer 1974; Litschauer 1979) in connection with the Réseau Européen Trigonométrique (RETrig) campaign.

Activities to improve the quality include campaigns in connection with European or international efforts to create high quality reference frames. These activities include work done for the European Datum 1977 (ED77) and the European Terrestrial Reference Frame 1989 (ETRS89). In parallel starting in the mid 1990ies a GNSS reference framework for Austria was created, consisting of the Austrian Geodynamic Reference Frame (AGREF) and the Austrian Reference Frame (AREF) (Döller, Höggerl et al. 1996; Erker, Stangl et al. 1996). The deviations between the Austrian network and the ETRS89 show a systematic effect. The difference vectors have a length of up to 2 m and rotate around two centres. One is located in the western Tyrol and the other in the eastern part of Austria (Erker 1997; Höggerl and Imrek 2007).

The elimination of these deviations for the reference points is possible. Austria has currently approximately 60,000 triangulation points and 270,000 points determined with other methods. A complete readjustment is possible since the original observations are available in digital form. The amount of data may require careful preparation but these challenges are solvable.

The task is much more complex for data based on these reference points. Data for cadastral and topographic maps, spatial planning, and many large constructions are based on the existing reference points because for decades all measurements were taken with respect to the reference point network. Only after GPS became operational and equipment with sufficient measurement quality became available, measurements could be taken without using the reference points. This clearly shows deviations between the GNSS reference frame and the Austrian reference frame, i.e., it is impossible to determine legally valid data like cadastral boundaries by GNSS without a transformation of the results to the local system.

There is a second reason for deviations between Austrian cadastral data and the Austrian reference frame. The collection of the cadastral data started long before the triangulation network was measured. The cadastral mapping was based on its own triangulation network. However, the cadastral triangulation had several flaws (Rohrer 1934):

- The triangulation was computed in 7 plane coordinate systems with its own scale and orientation.
- The computation was only done in form of an approximation.
- Triangulation and detailed survey were done in parallel. Thus local observations had a strong influence on the quality of the whole triangulation
- The triangulation of the lowest quality was done in graphical form only.
- The reference points used were not adequately stabilized. Sufficient stabilization in parts of Austria was done 30 years after the survey. At that time 12% of the points were already destroyed. In the southern parts of Austria the reference points were never stabilized.

Thus the original cadastral data has a different reference frame than the network of reference points. Still the reference point network is nowadays used to determine cadastral boundaries. In that case there is not only a deviation between the European reference system and the Austrian reference system but also between the Austrian reference system and the reference system used to determine geometry of the data. Since many other data sets in Austria (e.g., for spatial planning) are based on the cadastral data, these differences must be taken into account when using modern measurement technologies like GNSS.

Another problem with cadastral data emerges from the necessary processing steps since the original creation of the Austrian cadastre. Because the original mapping was done using plane coordinate systems, the change to the Gauß-Krüger-projection required a reprojection and thus redrawing of the maps. The same was necessary when the original scales of 1:1440 and 1:2880 were changed to 1:1000 and 1:2000. Finally, in the 1990ies the cadastral map was digitized. Each of these steps allow the occurrence of drawing errors. Thus today's digital cadastral map in Austria itself has limited accuracy (compare Navratil, Hafner et al. 2010).

3. EFFECTS OF THE INCONSISTENCIES FOR ENGINEERING PROJECTS

Two examples from engineering projects shall illustrate the practical implications of the problem in engineering applications. In both cases the streets were constructed and homogeneous networks were necessary for planning, implementation, and documentation. Cadastral registration of the streets requires a connection to the reference frame used for the cadastre. Modern construction machines, however, use GNSS-receiver for automatic or semi-automatic control. Thus, a connection to a homogeneous network is necessary, too, for planning and implementation.

The first project is a network for a 40 km section of a river in the Tyrol. The network consists of 22 points, which were determined by 104 GPS-vectors (Figure 2). A constraint-free adjustment of the observations provides estimates for the quality of the observations. The maximum standard deviation for the coordinates of the points in the network is 1.3 mm and the maximum standard deviation for the components of the GPS-vectors is 1.7 mm. This shows that networks measured with GPS-equipment have a high internal accuracy. Since the longest observed GPS-vectors were longer than 14 km, the network is homogeneous.

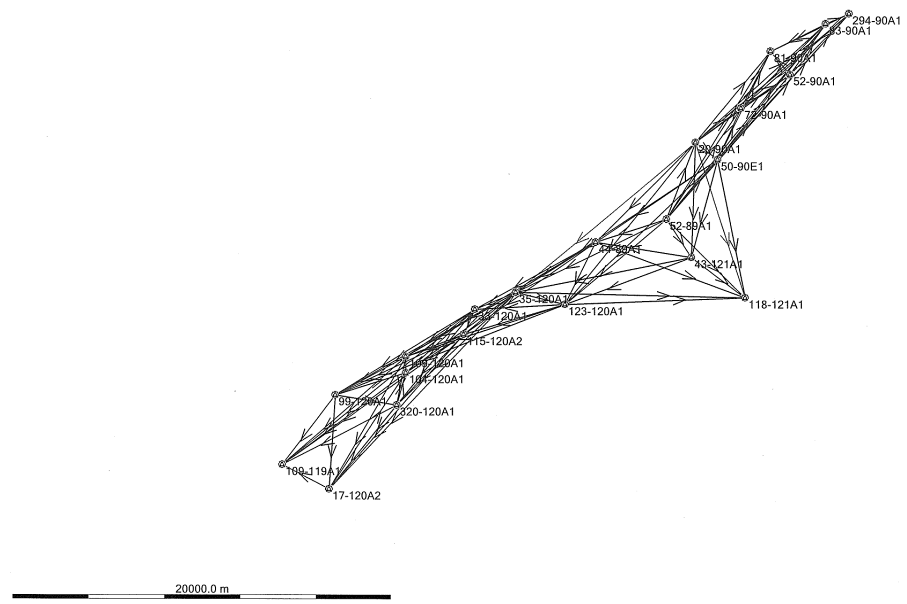

Figure 2. Network layout for a river survey project in the Tyrol, Austria (© Vermessung Angst ZT GmbH)

The alignment of the network with the reference points was performed with a Helmert-transformation. It resulted in residuals of up to 18 cm. This is 10 times the internal accuracy of the network.

The second project is a road section of similar size in Upper Austria. This network also consists of 22 points, which were determined by similar number of GPS-vectors as in the first example (Figure 3). The quality of the network is also comparable to the first example. The alignment of the network with the reference points was performed with a Helmert-transformation. It resulted in the residuals shown in Table 1. It is evident that the internal accuracy of the network is much better than the accuracy of the reference frame. The residuals of the transformation are up to 7 cm. This is too much for many engineering applications where constraints have to be fulfilled at specific points (e.g., there must be a smooth transition at the ends of the street segment and possible on-/off-ramps).

Table 1. Residuals dX, dY, and dZ of the network points after the Helmert-transformation in [mm] (data: Vermessung Angst ZT GmbH)

Pt.	dX	dY	dZ	Pt.	dX	dY	dZ
1	13.4	2.5	44.7	9	11.3	-7.6	68.3
2	8.0	-8.4	32.0	10	3.6	42.1	59.2
3	-5.1	-38.7	-33.7	11	-11.8	-12.3	-31.9
4	28.5	5.3	27.0	12	52.8	0.1	30.9
5	-22.2	3.7	-31.7	13	-23.8	-10.5	-2.8
6	-17.0	5.2	-16.5	14	35.5	15.4	-23.6
7	-16.6	-28.5	-20.9	15	-55.0	16.3	-49.9
8	31.5	21.2	-16.3	16	-33.0	-5.8	-67.5

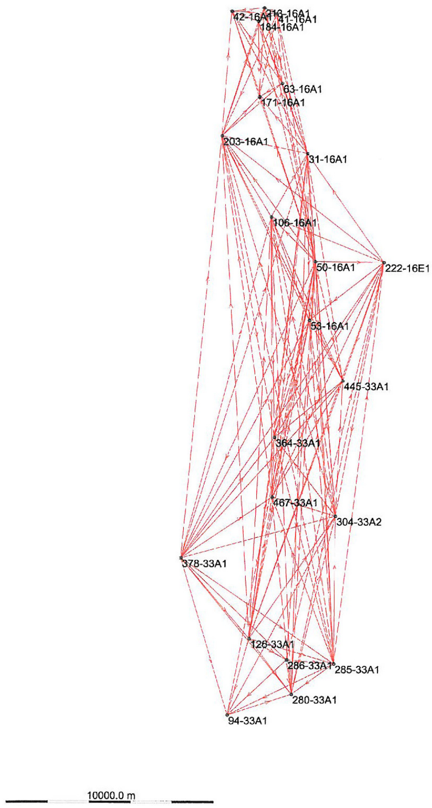

Figure 3. Network layout for a street construction project in Upper Austria (© Vermessung Angst ZT GmbH)

The examples presented here do not show the worst case. Although a road of 40 km length is not a small project, the distortion of the reference frame will not vary too much. This changes when larger areas are affected, e.g., the whole area of Austria. Then the residuals exceed 1 m, which is problematic even for application with lower accuracy requirements. It may even happen in smaller areas, for example in the south-western part of Salzburg, where the direction of the residual vectors changes rapidly and thus the elimination of a trend does not eliminate the difference. The examples also concentrate on reference networks. If detailed data like cadastral data are used then not only the systematic influences become evident but also random deviations of 20 cm and more.

4. MATHEMATICAL SOLUTIONS TO ELIMINATE THE INCONSISTENCIES

There are several approaches how inconsistencies can be dealt with. There are two ways to classify the approaches. Firstly, there is a separation between geometric and stochastic approaches and secondly, there are exact methods and approximations. We will first give examples for geometric and stochastic approaches and then discuss the difference between exact and approximate implementations.

4.1. Simple Approaches vs. Residual-free Fitting

The simplest way to map data from one reference frame to another reference frame is the similarity transformation. Assuming we have points in a coordinate system (x,y) and need it in another system (X,Y) there formula is

$$\begin{pmatrix} X \\ Y \end{pmatrix} = \begin{pmatrix} a \\ b \end{pmatrix} + m \begin{pmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix}.$$

The transformation parameters *a*, *b*, *m*, and α can be computed if the coordinates of two points are known in both reference frames. Such points are called control points. If there are more than two pairs of coordinates in both reference frames then a parameter estimation is necessary and the model is called Helmert-transformation.

The advantage of this type of mapping is that it is simple, bijective, and exact. The idea behind the mapping is simple. There are just two shifts (*a* and *b*), a rotation (α), and a scale factor (*m*). This leaves geometries unchanged, i.e., parallel lines remain parallel and circles remain circles. Since the mapping is bijective reversing the mapping is no problem and because it is an exact solution the mapping can be done back and forth multiple times without changing the result. However, in practice small deviations may happen due to implementation issues.

The disadvantage of the Helmert-transformation is that it cannot deal with inhomogeneous reference frames. If the reference frame is distorted then the transformation parameters will vary with the geographic position. This cannot be modelled with one Helmert-transformation. Thus, after mapping the control points the resulting coordinates will deviate from the given ones. These deviations are called residuals. They show the 'goodness of fit' for the control points.

An expanded version of the similarity transformation is the affine transformation. Here it is assumed that there are different scales m_x and m_y for the two coordinate axis and the angle between the axis is not the same in both reference frame, resulting in two rotations α and β.

$$X = a + m_x \cos\alpha\, x - m_y \sin\beta\, y,$$
$$Y = b + m_x \sin\alpha\, x + m_y \cos\beta\, y.$$

The affine transformation requires three control points because there are six parameters. Again more control points can be used and lead to a standard problem of parameter estimation. The affine transformation can deal with some distortions between the reference frames. It can handle systematic distortions like scale differences. It cannot handle, however, local deviations. Thus when using more than three control points the affine transformation leads to the same problems as the Helmert-transformation.

However, there is a method to map a set of points in one reference frame to another reference frame using the affine transformation without residuals (Figure 4). The idea is to split the area into triangles with control points forming the corners of the triangles. The control points *a* to *e* are used to create a triangular tessellation of the space. For each of the triangles a separate set of parameters for an affine transformation are specified. This requires three control points and has an unambiguous solution. The point 1 is then mapped using the parameters determined by *b*, *d*, and *e*. The point 2 lies on the boundary between two triangles. It can thus be mapped using the affine transformation defined for both triangles. Both transformations lead to the same result. Point 3, however, constitutes a problem. It requires an extending of the area covered by the control points. Using the transformation parameters determined by the points *b*, *d*, and *e* may provide a reasonable result but this it neither checked not guaranteed. Another problem of this solution is that it is not possible to check the correctness of the control points. Erroneous control points (e.g., the point was relocated and the coordinates in one reference frame describe the point before the relocation whereas the coordinate in the other reference frame describe the point after the relocation) can then introduce previously non-existing inconsistencies.

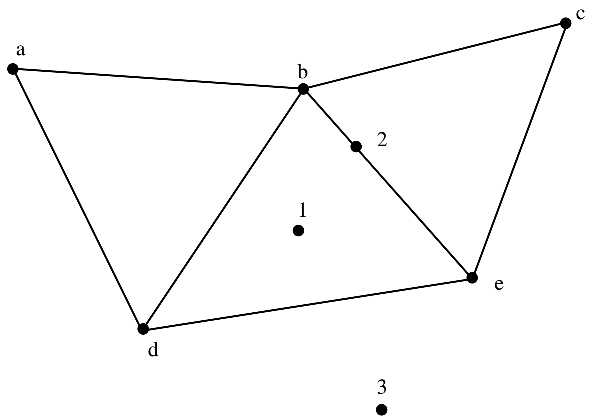

Figure 4. Example for a residual-free affine transformation

Another method to eliminate the residuals is the multi-quadratic interpolation proposed for geodetic applications by Wolf (1968) and Hardy (1971; 1972). Based on the residual vector **r** corrections u_j for each point *j* are computed by

$$u_j=\mathbf{s}_j^T\mathbf{S}^{-1}\mathbf{r}$$

with the quadratic and symmetric matrix **S** containing the distances between the control points and the vector $\mathbf{s}_j$ containing the distances between the point *j* and the control points. This approach can also be expanded to a stochastic method. The methods described so far are purely geometrical. Geometric properties are used to define the parameters of the mapping. This approach ignores that the coordinates of the control points are not error-free. These coordinates emerge from observation processes and such processes are described as stochastic processes. The result of a stochastic process varies for each repetition because random deviations influence the result. The random deviations are typically modelled by normal distribution with estimate zero and a specified variance. This information can be used to eliminate the residuals. The elements describing the interrelation between the control points are then based on the correlation and not the geometric distance. Such approaches typically utilize covariance functions, which map a specific distance to a covariance value.

4.2. Exact vs. Approximate Implementation

The implementation of the methods discussed so far can be done by programming the necessary formulae. This is no problem if the amount of computations work only depends on the number of points that need to be mapped. This is not the case for all methods presented here. The multi-quadratic interpolation, for example requires a matrix computation and the dimensions of the matrix and vectors depend on the number of control points. Although the term $\mathbf{S}^{-1}\mathbf{r}$ has to be determined one only and can be reused for each point that shall be corrected, the costs of the necessary scalar product depends on the number of control points. Thus for large control point networks the correction is computationally expensive. The same is true for the triangular tessellation.

A way out of this dilemma is the use of approximation methods. The idea is that the corrections are not computed precisely. The approximations can be based on pre-computed values. An example for such a method is the residual grid. Precise corrections for points in a regular grid are pre-computed. When corrections for a specific point are needed, these pre-computed corrections are used to estimate approximate them. Figure 5 shows the basic principle. Corrections for point 1 are needed but only corrections for the points *a* to *d* have been pre-computed since they are part of the grid. In a first step the grid cell containing point 1 is determined. The grid points *a* to *d* with known residuals are then used to approximate the residuals of point 1.

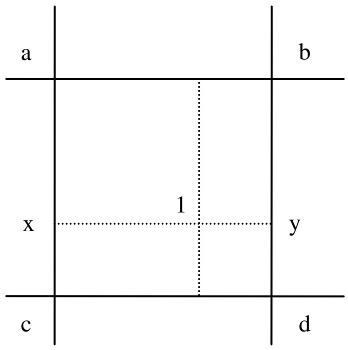

Figure 5. Principle of the residual grid

The interpolation is not without problems. Four points do not necessarily lie on a plane. Thus linear interpolation is not possible. Still, some instruments use it in the following way: First the values for the points *x* and *y* are determined by linear interpolation between (*a*,*c*) and (*b*,*d*) respectively. Then the values for the point 1 are interpolation between (*x*,*y*). In addition the surface approximated by the grid needs not to be a plane. In this case any linear interpolation method causes a linearization error. This error may lead to problems when data are frequently mapped back and forth between two systems. Each mapping process introduces a small error. If this error is not fully compensated by the reverse mapping (which it will not be completely) then the errors may add up to significant amounts.

5. DISCUSSION AND CONCLUSIONS

A practical application for these ideas has been presented by Grillmayer (2010). The problem was controlling construction vehicles using GPS for a road construction. The quality requirements and the residuals did not allow a single transformation, e.g., a Helmert-transformation. In order to fulfil the quality requirements 7 different sets of transformation parameters would have been necessary. This solution presented two practical problems: Firstly, the machine operator would have to select the correct parameter set and would have to change the parameter set when crossing the border where the current parameter set becomes invalid. Secondly, the parameter sets did not match exactly at the boundaries. These deviations would have to be evened during the construction work leading to slight unsteadiness in the path of the street. He used the solution of the residual grid, which was loaded into the GPS-receivers. This solution worked well.

The INSPIRE initiative aims at improving the interoperability of data throughout the European Union. This inevitably leads to situations where data from homogeneous sources (GNSS, satellite imagery, etc.) need to be combined with data from inhomogeneous sources (base on traditionally surveyed networks of reference points). The necessity of adaption arises if the quality requirements of the application exceed the errors introduced by the inhomogeneities. In Austria the inhomogeneities add up to a maximum of approximately 2 m. Thus applications like a general statistics on land cover of public lands or mapping of traffic density on transit routes will not be significantly influenced. Other applications like applying for agricultural subsidies, however, might not be able to tolerate this deviation.

The direction of correction also depends on the application. It may, for example, be required by law that data are mapped on cadastral data even if these data are based on an inhomogeneous reference frame. This may be the case if data have to be correlated with land owners or other data that is related to the cadastre like data on spatial planning. This will reduce the quality of the mapped data which may be inappropriate for other applications. Thus official services should provide a method to map the data to a different reference frame. This shall guarantee that the data are mapped only once and possible problems with approximation methods are avoided. For the Austrian case two different target systems seem feasible: The Austrian cadastral system and the European Terrestrial Reference Frame (ETRF).

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