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Dynamic concepts to handle geodetic networks with continuous monitoring data in areas with ground movements

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ABSTRACT

Since decades the discrepancy exists that geodesists monitor changes of the earth surface resp. large engineering structures with most-modern equipment, but the results are computed and presented in a suboptimal manner: In many cases, the displacements are computed in relation to reference (datum) stations, which are not stable over a long time. Aside, the variations of an object are presented as coordinates for representative points with time stamps or with displacements rates (absolute values or velocities). Finally, nowadays often we have continuous measuring sensors and data, but there is no complete concept to treat variations continuously within the coordinate approach. In this paper at first the problems are outlined and open questions are formulated. Then some ideas are presented, how to analyse and describe coordinates in a continuous manner, taking into account the classical concepts and thinking of the surveying profession. The new ideas start with the definition of a stable reference frame over time, followed by the introduction of time dependent coordinates. A specific objective is to deliver day-by-day precise reference coordinate values for different groups, working on monitoring with their own sensors and computational concepts in the same area. These concepts are applied to an extended monitoring network of the mining authority Ruhrkohle AG (RAG), responsible for the eternal obligations that the German hard coal mining industry has left behind. This RUHR-network is located in the federal state North-Rhine-Westphalia within German, where after 300 years of coal mining larger and irregular ground movements can be expected.

I. INTRODUCTION

Starting in the middle of the last century, the monitoring of large engineering structures, of local, regional or larger areas of the earth surface and even of small industrial objects has found more and more attention within partial disciplines of our profession.

In general the most-modern sensors are used and sophisticated methods for the evaluation and analysis of data are applied. Aside, after a long period with discontinuous monitoring, *i.e*. capturing the geometry of an object in specific campaigns or epochs, nowadays more and more continuous sensors and by this continuous data are available.

For any time-related project an adequate description of the object geometry over time is of primary importance. In section III some concepts are presented and applied, which seem to be suitable to serve for this task, *i.e*. to describe time-dependent coordinates in a dynamic environment.

But first, in section II, a fundamental problem of any long-term monitoring project is discussed, *i.e*. the setting-up and maintenance of a stable reference frame or a stable datum system. For use of a network with permanently installed and continuously active GNSS-receivers, here innovative solutions are applied, based on developments given in Tengen *et al*. (2019), which are outlined and described in detail in Niemeier (2022).

In this paper the focus is laid on regional studies of vertical ground movements in the Ruhr Area in Germany, which has an original extension of about 7000 km^2, effected by underground hardcoal mining. Now, being in the post-mining era, an area of about 140 km^2 is undergoing flooding of the old mines within the next years. By this an extended rising of the groundwater level have to be considered, see Spreckels (2022).

For a 3-year-period of continuous GNSS-monitoring between 2019 - 2021 for this region the developed concepts are presented and first results are depicted in this paper.

All processing and analysis steps were performed with an extended version of the established software package PANDA of GEOTEC GmbH. The data-storage concepts and the visualization are explained in the paper Schulz and Schäfer (2022).

II. STABLE REFERENCE FRAME

As each information on displacements or deformations at time t_i has to be related to the geometry of the monitoring object at time t_{i-1}, both sets of information - and by this all data since time t_0 - have to be defined within an identical reference frame. For long-term monitoring project the realization and maintenance of such a stable reference frame over time is a serious problem: Many practical monitoring projects suffer from the non-existence of a stable geodetic datum!!

A. *Cascading sensor systems for monitoring*

In Figure 1 a typical example is given for the interaction of various sensors used for monitoring of a larger area.

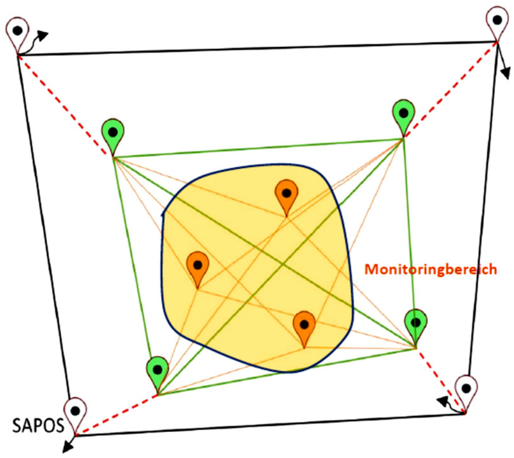

Figure 1. Cascading groups of sensors resp. networks for monitoring of larger areas (Spreckels *et al*., 2020).

To get detailed information on the behaviour of the most critical, central section of the area, specific sensors are used like UAV, RTK-GNSS, total stations and levelling. These measurements refer to reference stations, which are close by, often in instable areas (yellow area in Figure 1).

These observations have to be related to reference stations, which are less effected by possible ground movements, *i.e*. are in a more stable zone (in green in Figure 1).

All these data have to be related to really invariant stations in geologically stable zones, here called *external reference stations.* As possible external reference stations in our area existing permanent GNSS-stations could be used, the SAPOS-stations of the state survey authorities of Germany. The RINEX-files of these stations area available free of charge and these data were processed by adequate GNSS-software, see Schäfer and Schulz (2022).

As we doubt the long-term stability of these SAPOS-stations, our statistical analysis does include the data-sets of these stations and it was found out, see section II/D, that significant movements were detects for these external stations, as well.

B. *Basic strategy to derive movement pattern*

We start by applying the classical congruency test (*e.g*. Niemeier, 2008;2022), using the weekly mean GNSS-coordinate sets incl. covariance matrix as input data. By comparing the epochs one-by-one, *i.e*. the data sets of each subsequent week with the first week, we found out that after several weeks for a lot of stations, even out of the expected “stable” external reference stations, significant movements were identified.

A first possibility to account for irregular point movements is to allow for “individual points movements”, realized by enlarging the covariance information. But this tool does not help in a sufficient way.

The here selected basic strategy is depicted in Figure 2, it is the search for movement pattern within the displacement quantities after several epochs, in Figure 2 shown with epochs on an annual basis.

In theory, this strategy can be classified as *data-driven and/or behaviour-oriented*, and by this as being suboptimal, see Niemeier and Velsinck (2019). But for the surrounding we have in the RUHR area, due to 300 years of intensive coal mining, water management and city developments, no physical or mechanical model for the behaviour of the surface is known; the situation is too complicated.

In detail, the following steps are performed: If after the analysis of several epochs the group of stable reference stations is reduced, but still valid, an analysis of the movements of the unstable stations up to this time is encountered: We try to find out, whether there are linear movements (see station 1), just one outlier or jump (see station 8) or just irregular movements (see station 3).

All stations with “known” movement pattern now can remain within the group of reference stations, what has the most relevant effect that even after several epochs and detected movement pattern the number of reference stations does not reduce dramatically. The reference frame or geodetic datum is still valid for the subsequent congruency tests.

C. *Advanced strategy to analyse time series of data*

For the analysis of the full data-sets of all 3 years of GNSS observations in the RUHR area we extended this concept by a detailed time series analysis of the coordinate components x, y and z of each station.

For each component we allow:

- **Linear movements** (kinematic concept).
- **Seasonal movements** with period length of one year, to account for temperature effects or groundwater level variations.
- **Offsets**, *e.g*. known antenna changes or not yet detected offsets.

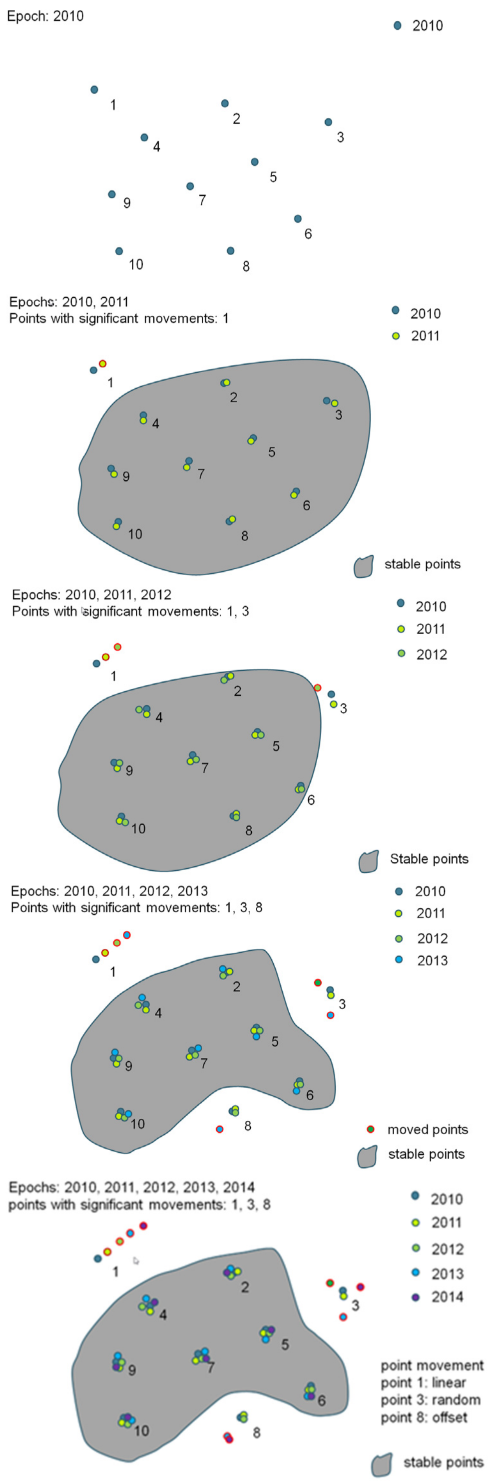

Figure 2. Strategy to derive movement pattern out of repeated coordinate sets. (Tengen *et al.*, 2019).

The formula to describe these movements is (Eq. 1):

$$f(t) = a_0 + a_1 * (t - t_0) + A * \sin\left(\frac{2\pi}{365}(t - t_0) + P\right) + o \qquad (1)$$

In this formula a parameter P is included to account for seasonal shifts of the seasonal effects.

Two examples for such movement pattern, detected for reference stations oft the RUHR network, are depicted in Figure 3. Station 2594 has just an offset, but does not show seasonal or linear effects. For station 2579 all three effects are encountered.

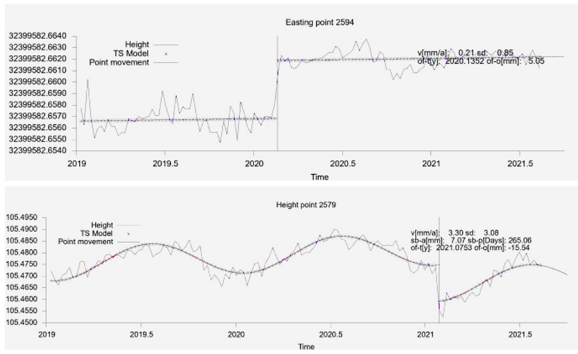

Figure 3. Movement pattern for the reference stations 2579 and 2594 with velocity, seasonal effect and offset.

It has to be mentioned that seasonal effects cannot be determined with just a few epochs of data. We need about two years of data to have valid estimates for seasonal effects. Aside the detection of offsets needs a detailed analysis of data directly before and after the variation, to be able to compute the offsets and to differentiate them from pure outliers.

D. *Results for the RUHR network 2019 - 2021*

As depicted in Figure 4, the GNSS monitoring network of the RUHR area consists of 10 SAPOS permanent stations of Geobasis NRW, the state survey authority in this region, which raw data can be downloaded online and are free of charge. These stations have 4-digit identifiers.

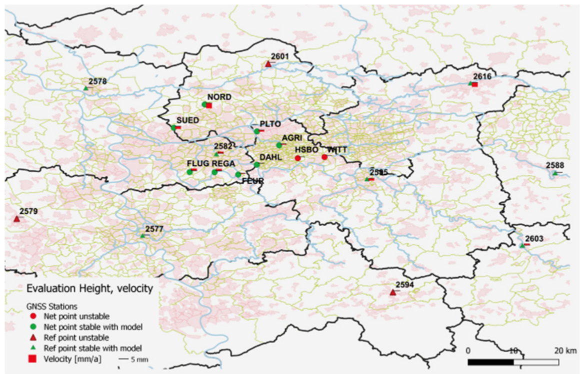

Figure 4. Linear velocities for the height component for all stations of the RUHR GNSS network.

In the central section 11 permanent GNSS-stations were installed and maintained by the mining authority Ruhrkohle AG (RAG), responsible for the eternal implications of 300 years of coal mining to this area.

In Figure 4 and 5 the achieved results after almost three years of observation are presented. It turns out that for several of the external reference stations (SAPOS) significant movements are detected. But due to our approach, most of them could maintain within the group that define the datum of the system.

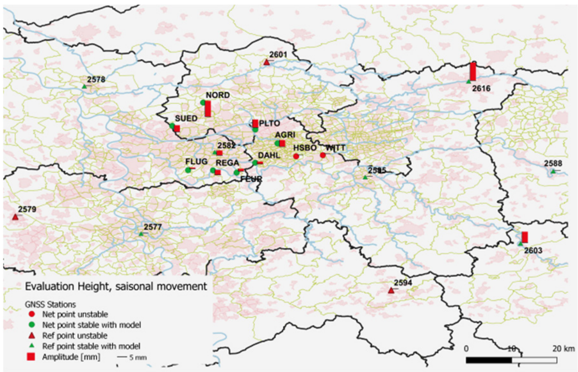

Figure 5. Amplitudes for seasonal variations in the height component for all stations of the RUHR GNSS network.

III. Time-variant coordinates

A. *Outline of the problem*

Since decades within Geodesy, Geoinformatics, Surveying and Photogrammetry the concept of stable coordinates is valid, *i.e.* the geometry of an object is represented by a set of fixed coordinates. Maybe, better observations lead to more precise coordinates, but in principle is geometry of an object is considered as being invariant over time.

Coming to height systems, variations with time are more common in our disciplines. Due to new height definitions, new measuring campaigns and more sophisticated processing, there are different height systems, in Germany called “height status”, which are established from time to time and then set to be valid (official) for the next years or decades.

As outlined in Figure 6., this sequence of height fixations does not represent the real or complete behaviour of a stations resp. the surface of the earth. No one knows what happens in-between the fixations at time t_1, t_2, t_3, or how long a defined height status is really valid. Figure 6 makes it very clear that the challenge is to define a continuous “movement-model”, *i.e.* we need a new concept for a time-variant representation of heights.

Figure 6. Height variation of a station, described by a sequence of different height values or a movement-model.

A very similar situation is given for the 3D-presentation of monitoring results of the earth surface and of large engineering structures: Either the coordinates get a time stamp or the displacement rates are added just as attributes to given (a priori) coordinates. No movement or displacement model is included in our data sets.

Modern concepts for data management, following these concepts of time-variant coordinates, can be found in Schulz and Schäfer (2022).

B. *Coordinates on a day-by-day basis*

As mentioned before, different sensors are used for monitoring and most of them give relative information, *i.e.* they have to be related to reference station near by. If we accept a variable surrounding, the coordinates of these near-by reference stations may change with time, as well, see section II/A. This makes it necessary, to keep ready coordinates on a daily basis. If we determine coordinate sets for the reference stations once a week, the daily values will be – in many cases - a prognosis, *i.e.* their quality may be reduced a bit.

In Figure 7 this situation is depicted: For image flights (airplane or UAV) and the determination of passpoints the coordinates of any reference station have to have values that are valid for the time of observation.

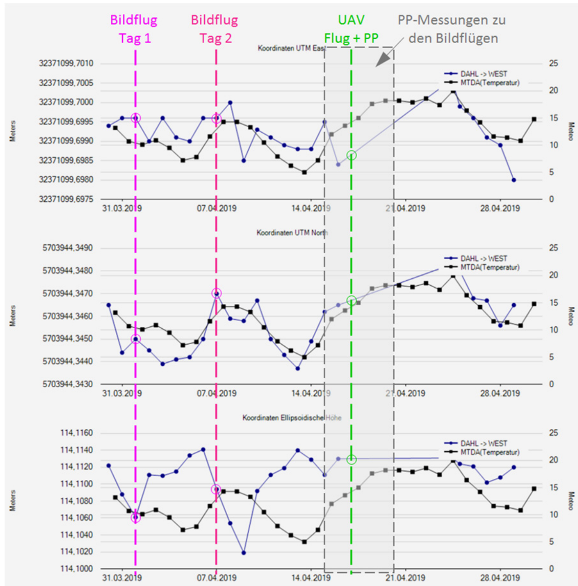

Figure 7. Different sensors, applied for monitoring, need valid coordinates for reference points on a day-by day basis (Spreckels *et al*., 2020).

C. *Derivation of a movement model*

For the description of movements in dynamic environment at first the KALMAN- filtering seems to be the adequate choice, see the principle in Figure 8. In the ideal case we have a physically defined movement model, which is used for the prediction of the behaviour of an object, here the coordinate component of a station.

Actual measurements allow a comparison between predicted and observed values and by this on the validity of the physical model.

Due to the complexity of the surrounding in the RUHR area, no physically justified model for the variation of geodetic stations is available. Therefor again a data driven approach is applied, which does not follow directly the above outlined principle of KALMAN-filtering.

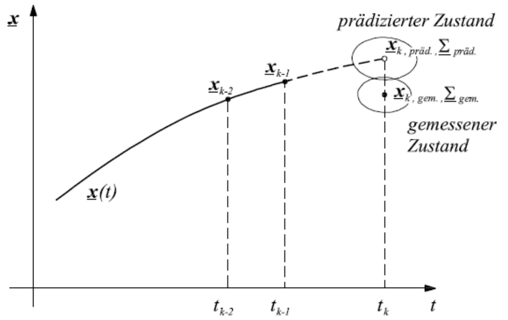

Figure 8. Principle of KALMAN-filtering for the prediction of the status of a system (*e.g*. Niemeier, 2008).

In Figure 9 the numerical strategy for an extrapolation of coordinates for one week is depicted. At the end of GPS-week 2020 the movements of the considered coordinate component is computed, following the approach, given in section II/C. This model - given as full red line – is used for an extrapolation up to the end of GPS-week 2021, the dashed red line.

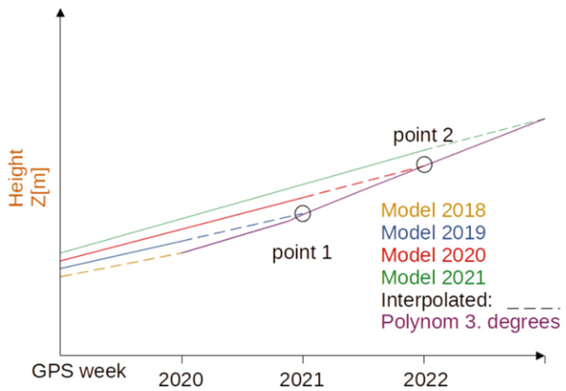

Figure 9. Extrapolation of the movements of stations, based on complete computations for each GPS-week.

For the preceeding GPS-week 2019 the prediction ends at the end point of the blue line. Between the end points of each extrapolation a polynom of grade 3 is applied to smooth the behaviour.

For coordinate of a daily basis these smoothed coordinates are used. Due to our numerical experiences, the deviations between the afterwards computed "real" coordinates and the extrapolation ones are sufficiently small, they lie in the range of about 2 mm, what can be accepted for our task.

D. *Results for stations in RUHR area*

The preceding approach is applied to all stations of the RUHR area; here just the height component is discussed. For two typical stations within the RUHR network the results are given in Figure 10. for a time span of several month in 2021.

The "Current Model" describes the behaviour with data up to this moment, while the "Optimal Model" is computed afterwards, *i.e*. with all available data. The current model converges asymptotically to the optimal model. It can be seen that a sufficient approximation is achieved, even if sometimes some offsets appear.

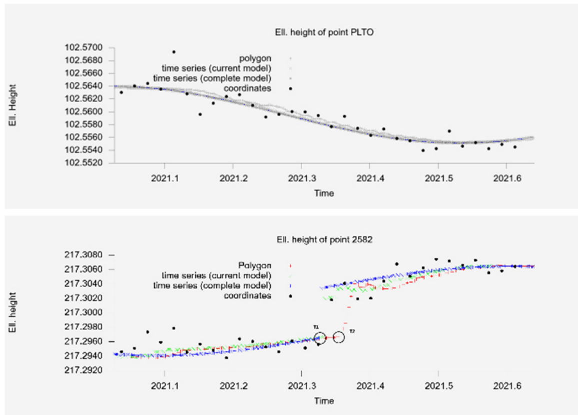

Figure 10. Approximation of the movement behaviour for height components of stations PLTO and 2582. Comparison of different computational steps.

IV. CONCLUSION

The here presented strategies and numerical concepts are a consequent extension of the classical deformation analysis of networks, but now applicable for continuous data.

At first, we look after a stable geodetic datum by a detailed analysis of the stability of the external reference stations. Even if some movement pattern can be encountered, in general these stations can remain within the group of datum defining stations. Of course, during the setup of each long-term monitoring project, the datum problems have to be taken into account by an adequate design resp. extension of the network.

We allow all permanent stations a linear and seasonal movements and consider offsets.

A more detailed description of displacement pattern would include reliable data on acting forces and/or external effects, an information, that was not available in the study area.

As second fundamental step we developed a concept to define and derive time-variant coordinates, which are more flexible and better suited for the approximation of continuous movements, than any other concept.

The results for the RUHR area demonstrate, that this concept really can be used for defining continuous coordinate representations, which then have to be included into the data-base concepts, what already is done by a different group, see Schulz and Schäfer (2022).

These time-variant coordinates allow the derivation of day-by-day coordinates, what is necessary to have a more consistent coordinate basis, if other sensors and methods are included in the complete monitoring task.

Finally, the here developed methods and concepts are not restricted to continuous GNSS-data. They allow the inclusion of continuous monitoring data of all applicable sensors, *e.g*. InSAR, UAV, total station and levelling data. Practical work in this direction is left for the future.

V. Acknowledgements

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