GLOMON-Monitoringportal for storage, management, advanced processing and intelligent visualization of GNSS- and other sensors data

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ABSTRACT

The earth is constantly exposed to endogenous and exogenous forces that cause temporally variable movements and deformations of varying degrees. The Global Monitoring (GLOMON) solution supports the monitoring of infrastructure or large areas such as mining regions using GNSS and other sensors, in order to detect deformations or surface movements. The GNSS reference stations enable the integration of other geodetic and geotechnical sensors in a global coordinate reference frame. Three dimensional coordinates are generated for each GNSS monitoring station with a precise time stamp, allowing for the web-based visualization of time series. One of the new developments presented here is the integration of the program system suite PANDA from GEOTEC GmbH into GLOMON, which supports a dynamic network adjustment. This procedure revolutionizes the approach of stable reference points for geodetic monitoring tasks, which has been valid and used for decades. The classic approach to such measurements is the assumption of a stable reference frame over a long period of time (zero measurement). Local measurements are connected to higher-level, supposedly stable reference points, such as first order GNSS reference stations. But these external reference points can also be subject to movements which, assuming stability, are projected onto the local measurements. To solve this problem, all GNSS stations are handed over to a deformation analysis after post-processing and network adjustment in order to detect displaced points. Furthermore, the concept of time-invariant reference station coordinates should be reconsidered. This means that those reference stations detected as displaced are not fundamentally excluded from the network evaluation, but their movement behavior is described by time-variant coordinates. With the introduction of movement models for reference stations, their movements are no longer projected onto local measurements of monitoring stations. This information can be used in the areas of interest, *e.g.* for the optimization of existing movement and deformation models. In this way, predictions about expected deformations can be made reliably.

I. INTRODUCTION

The ground movement monitoring in areas affected by underground hardcoal mining in Germany is an obligation of RAG Aktiengesellschaft (RAG). Due to the extensive hardcoal mining in large areas in North Rhine-Westphalia and Saarland over centuries, the ground is still moving even after the end of active hardcoal mining. For the monitoring of ground movements, various sensors and methods such as levelling, GNSS, aero photogrammetry and InSAR are used. These measurement methods require a stable reference frame in order to be able to compare measurements and generate time series. The fundamental problem here is that the surface geometry changes continuously and supposedly stable reference points are exposed to ground movements as well.

Especially for GNSS monitoring it is common practice to assume that the reference stations are stable over a long time period. Due to the need of short baselines between reference and monitoring stations the area considered stable is often located near the monitoring area. Changes of the reference station coordinates can remain undetected, with the result that their movements are projected onto the monitoring stations.

From this point of view, RAG started a R&D project in 2019 (Spreckels, 2022). The aim of the project was the realization and maintenance of a consistent and long-term stable reference frame for the GNSS station network and later other sensors.

RAG has been operating local GNSS reference and monitoring stations together with ALLSAT GmbH (ALLSAT) since 2014. These networks have grown steadily in recent years and now include over 30 GNSS stations within three networks in Ruhr area and Saarland (Spreckels *et al.*, 2020). The networks are extended by SAPOS GNSS reference stations (German satellite positioning service). In the monitoring portal GLOMON developed by ALLSAT, the data of all GNSS stations are fully automated edited, processed and the results are visualized. The enhancements made in the above-mentioned R&D project were integrated in this fully automated and proved process.

GLOMON and the fully automated process of GNSS data processing are shown in Section II. The new approaches of dynamic network adjustments are

shown in Section III. A conclusion and future prospects are shown in Section IV.

II. GLOMON (GLOBAL MONITORING)

The idea for the GLOMON-Portal is to combine three megatrends for monitoring tasks: The Digitization of sensors allows to continuously measure and automatically record data. The Internet is used to transfer the measurements to our central processing and storage servers. This Big Data recorded is then analyzed, processed and reduced to the important information and stored in our database. The GLOMON-Portal (www.GLOMON.de) supports the monitoring of man-made structures or large areas such as steep slopes and mining regions for the detection of deformations or surface movements using GNSS and other sensors.

A. GLOMON Architecture

The core software technology developed for the GLOMON monitoring portal is the service kernel, that parses the incoming data streams of GNSS stations and other sensors (Figure 1). These data streams are decoded and written in a dedicated file and directory structure to a network array storage (NAS). The multiple thread technology allows to define post processing jobs that can be scheduled in parallel for the automatic processing of GNSS data for results with highest precision and accuracy in the range of a few mm. The post processing results are automatically synchronized with the SQL database. For the simple interaction of the user with the GLOMON monitoring portal, a webserver allows for a secure password protected access and control of multiple projects, supporting all kinds of up-to-date web browsers. All user specific settings are stored in the SQL database. The chart analysis tools allow for the detection of smallest deformations in the time series, which is compared to predefined limits and handled by the alarming management module, so that preventive measures for humans and infrastructure can be initiated as fast as possible.

B. GLOMON Functions

The GNSS stations are often the highest order reference points, which are locally densified by other geodetic or geotechnical sensors. The GLOMON-portal integrates all these different sensors into a single platform and supports a graphical overview of all relevant data in the monitoring region. In many cases, reliable interpretation of the data can only be made if different data sources are overlayed (*e.g.* GNSS time series with seasonal meteorological data).

The overview page (see Figure 2) shows all GNSS stations and other sensors included in a project. Each sensor is represented by a colored marker. The color indicates the connection state of the station and so the user gets a quick overview about the connection activity within the network. Furthermore, there are a variety of

functions clicking on a station marker, like links to the coordinate time series of this station or charts with information of connected sensors, like temperature or rainfall sensors.
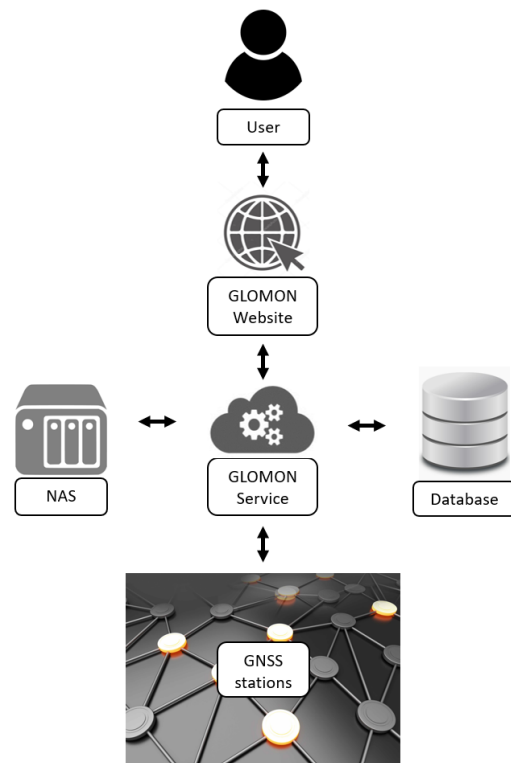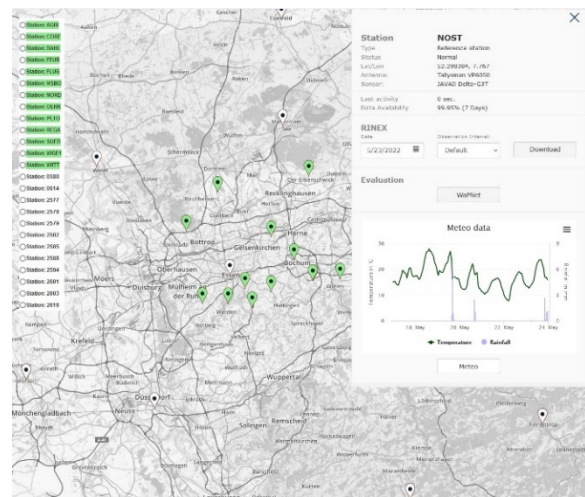

Figure 1. GLOMON Architecture.

Figure 2. GLOMON Overview.

The GNSS post processing software packages of WaSoft (wasoft.de) and Geo++ (geopp.de) are integrated in GLOMON. The user is able to start manual or plan automatic jobs that are repeated in specific time intervals. A job includes for example the converting of the GNSS raw data on the NAS, the post processing of the GNSS data and the storage of the results into the database. Using the example of post processing a GNSS station network with WaPNet (WaSoft), usually 24 h of multi-frequency GNSS observations are collected. After the observation and orbit data as well as the antenna

correction files are checked, WaPNet processes baselines between the network stations including cycle-slip detection and repair as well as ambiguity fixing. When all stations are connected, all zero-differenced observations are on the same ambiguity level. The final network solution consists of an iterative process with outlier detection and estimation of variance components. In the end, a set of unknowns is determined which includes: station coordinates, tropospheric parameters and GLONASS inter-frequency biases. The three-dimensional coordinate time series can be shown and analyzed in GLOMON (see Figure 3).
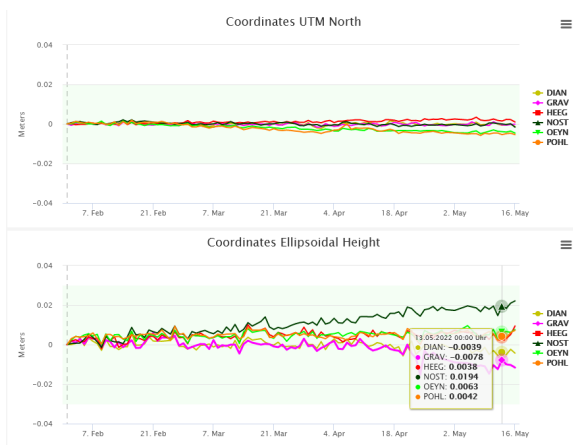

Figure 3. UTM-North and ell. Height time series of several GNSS monitoring stations in NRW Germany.

GLOMON uses a modern and intuitive charts library and offers some tools for data filtering and analysis. Furthermore, csv- and pdf-exports can be realized.

In addition to the fully automatic processing of GNSS data and a modern visualization of the results, GLOMON offers data quality analysis for reference station networks. For that, Leica SpiderQC GNSS data analysis software is integrated in GLOMON and can be used for a range of tests and analysis regarding data completeness, multipath, cycle slip and much more.

Furthermore, GLOMON supports the integration of geotechnical sensors, like triaxial tilt sensor, weather sensors including wind and rainfall as well as energy sensors. The information of the meteorologic sensors can help to interpret GNSS time series. Often there are correlations between the movement of a reference station and the temperature or soil water. In rural areas a permanent power line to the monitoring stations is not available in many cases, so that renewable energies must be used. Our solutions include energy sensors that are used on self-sufficient solar- and wind-powered monitoring stations. The voltage values of solar and wind energy supply can be monitored via these energy sensors. In GLOMON the voltage values can be shown as time series and are now also displayed on the overview page.

Moreover, GLOMON offers a multi-level alarming system, a download function for the RINEX observation data of the GNSS station and an online post processing service by which users can upload their GNSS observation data and receive a precise position.

III. DYNAMIC NETWORK ADJUSTMENT (DNA)

A. New Approach

The conventional approach for geodetic deformation monitoring is to create a reference frame from a certain number of reference points classified as stable (zero-epoch). As outlined in Figure 4 local measurements (orange) are repeated quite frequently in order to record the expected movements as completely as possible. These local measurement points are connected to near local reference points (green) which are usually connected in longer time intervals to high-level reference points like SAPOS GNSS reference stations at a larger distance.
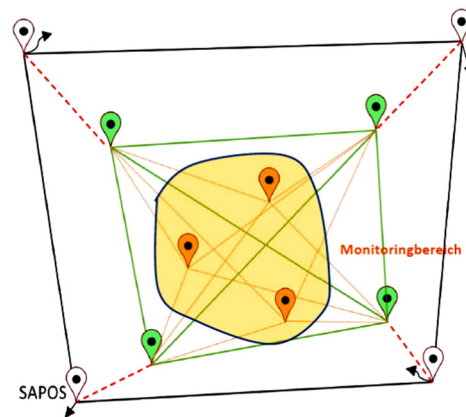

Figure 4. Cascading groups of monitoring and reference points in a conventional monitoring project.

This cascading approach is also assumed for the point stabilities: outer reference points are considered to be stable over a very long period of time. The (middle) reference points for the local measurements should be outside the actual monitoring area and should be stable over a certain period of time. The local measurements are in an unstable area, that means continuous movements are assumed for these points.

However, higher-level reference points can also be subject to movements. If these movements remain undetected, this may result in a misinterpretation of these movements as deformations of a certain object.

Especially in GNSS monitoring, the assumption of stability of reference stations over a long period of time is common in day-to-day business, but should be regarded critically. Due to the need for shortest possible baselines between reference stations and monitoring stations, the area considered to be stable is often chosen much to close to the monitoring area.

The challenge in longer monitoring projects is that smaller point movements as well as larger changes for individual points can often be registered (Niemeier *et al.*, 2020). In the classic approach, these movements often lead to a critical reduction in the number of stable reference points. For this reason, the points detected as

shifted should not be excluded from the group of reference points. Instead, a methodical approach has been developed that derives movement patterns for unstable reference stations to maintain their usability for the reference frame. The concept used to recognize movement patterns for repeatedly determined reference points was first described in (Tengen *et al.*, 2019).

B. *Implementation in GLOMON*

In the last three years (2019-2021), the concept of time-invariant reference station coordinates has been fundamentally reconsidered, as part of a research and development project by RAG (Spreckels, 2022). The focus was set on a further development of the program system suite PANDA (Niemeier and Tengen, 2022) and its integration into GLOMON.

For more than 6 years, the data collected and stored from RAG's GNSS monitoring stations have been processed automatically within the GLOMON portal of ALLSAT. Over the years, numerous reference and monitoring stations have been added and until now three core GNSS networks have been established. In the former mining regions of the Ruhr Area and Ibbenbueren in the German federal state North-Rhine Westphalia (NRW), and in the federal state Saarland (Spreckels and Engel, 2022), the ground movements will be and have to be monitored alongside the rising of underground mine water levels (Hager and Wollnik, 2016).

The GNSS monitoring network in NRW currently includes various RAG-owned GNSS reference stations together with 10 SAPOS GNSS stations of NRW's surveying authority Geobasis NRW. The data is automatically processed on a daily basis with the post-processing software suite WaPNet from WaSoft. The post-processing results, specifically the 3-dimensional coordinates of all stations together with the respective covariance matrix, are used in weekly terms by PANDA for a deformation analysis, in order to detect relevant movements within the reference station network.

At the start of this PANDA algorithm, all daily solutions are merged into solution results for each week. Based on that, a strict deformation analysis is executed for each epoch. The individual points are either detected as stable, as outliers or as shifted. Then the deformation analysis is continued with all the stable points for the next epoch. This iterative process is cancelled, if the number of remaining points decreases below a defined minimum. All epochs processed are then transformed onto those stations detected to be stable and the changes in coordinates are calculated. For each station, the time series of coordinate changes is then analyzed and then subsequently a model of movement is estimated. If this model of movement fits within the accuracy limits defined, the respective station is set as a shifted point described by a movement model. The iteration is then started again

from the first remeasurement. In this second run the original zero-measurement coordinates, that were used in the first run, are replaced by the calculated coordinates from the model for all stations with movement model. A more detailed description of the whole process of PANDA-algorithm is given in (Niemeier and Tengen, 2022).

Those movement models are calculated once a week, using a sliding window of about two years of preceding observation data. The application in GLOMON requires coordinate updates on a daily basis. Therefore, the calculated movements of each station are extrapolated for the following week at the end of the PANDA-algorithm. Due to the sliding data window, the movement model parameters slightly change from week to week. But that would cause inadmissible jumps within the time series. Furthermore, previously calculated reference station coordinates for a particular point in time would change, when new epochs are added to the time period analyzed before. To avoid such jumps and changes of coordinates due to future data, the movement model is not applied for the coordinate calculation directly, but with a third order polynomial approach. This polynomial is extrapolated for the respective next week, following the deformation analysis and the model calculation. At the start and end point of each polynomial, the function value and the slope are similar to the previous respectively the next polynomial. These polynomials combine the weekly movement models without any jumps and are used for the calculation of station coordinates for a particular point in time.

Figure 5 shows the time series of the UTM-East coordinates of one SAPOS reference station in NRW (red). The total range of the coordinate axes (vertical) is 4 mm. The time period (horizontal) is 30 days. The green graph shows weekly data, calculated by the PANDA algorithm. The slight differences between the red time series from post processing and the weekly data are caused by the different geodetic datum. The weekly data is transformed onto the stations detected as stable, while the post processing results are transformed onto the SAPOS reference stations. The blue time series shows the movement model, that includes linear and seasonal terms for this specific station. The purple time series shows the polynomials.

This approach required extensive changes within the SQL coordinate database. The classical zero-epoch coordinates to which the time series differences have been referenced, was replaced by a dynamic time dependent model that accounts for slow seasonal movements and for certain jumps in station coordinates.

The movement models and the polynomials can be visualized within the existing three-dimensional coordinate time series of the reference stations (see Figure 6).
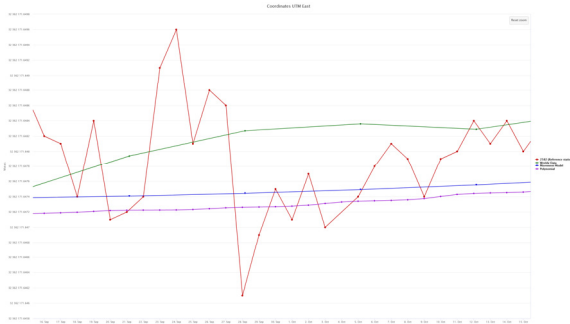
Figure 5. Coordinate times series (red), movement model (blue) and polynomials (purple) of a reference station in GLOMON.
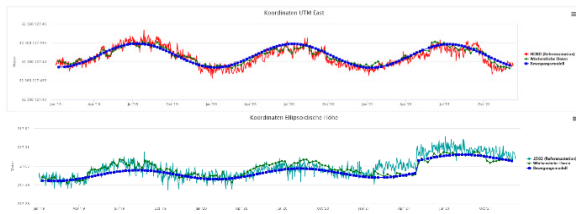

Figure 6. Above: time series of the UTM East coordinates (red) and below: time series of the ell. Height of SAPOS station 2582 (cyan), each with weekly data from the dynamic network adjustment (green) and motion model (blue).

Figure 6 shows the time series and the corresponding movement model of two different reference stations over a period of nearly three years. Figure 6 (above) shows an UTM-East coordinate times series with a significant movement with annual period. Figure 6 (bottom) shows the ellipsoidal Height of a SAPOS station with a detected jump at one point. Exactly at that time of this jump the GNSS antenna has been changed on this reference station. Although, individually calibrated antenna files were used for post processing of the GNSS observation data, the antenna change became obvious within the time series after processing with PANDA.

Furthermore, the time variant coordinates are used, for example, for post processing and adjustment of reference stations within the monitoring network and for downloading observation data (RINEX) from the GLOMON portal for post processing applications (Figure 7).

IV. Conclusion and future work

The concept of time-variant coordinates for reference stations has the potential to revolutionize the approach of long-term stable reference points in mine surveying and geodesy, which has been valid for decades. This accounts for the fact, that the Earth's surface is constantly exposed to endogenous and exogenous forces, that cause temporally variable movements and deformations of varying degrees. These movements and deformations can now be modelled by PANDA, and can be applied into the GLOMON post processing and adjustment routines in order to give better and more reliable results (Figure 8).
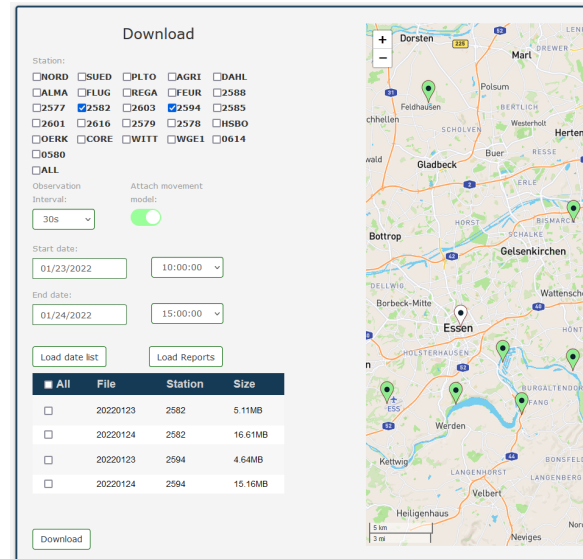

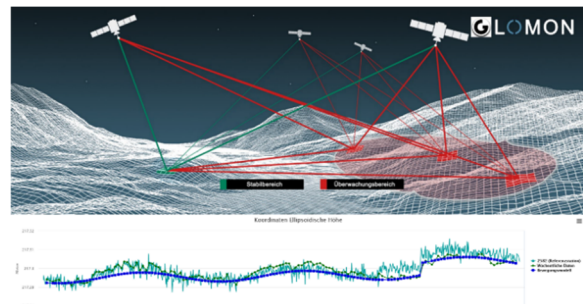Figure 7. GLOMON RINEX download with possibility to attach movement model to specific coordinates.

Figure 8. GLOMON Dynamic Network Adjustment.

Nevertheless, there are some points that have received little or no attention so far. The movement models currently generated as part of the dynamic network adjustment describe a linear trend, a seasonal component and, if necessary, offsets. However, the typical ground movements caused by former mining activities cannot only be described with these movements. Radial basis functions (RBF) are ideal for approximating such non-linear movement behavior. The approaches of using several RBFs have already been successfully tested in the area of the former Prosper-Haniel (NRW Germany) mine. An integration into the active dynamic network adjustment is still pending.

Another important aspect is the merging of the results from different sensors and measuring methods that are used for monitoring of ground movements. This will include also external sensors from free available sources, supporting the Open Data concept. Such an integration must take place time synchronized and spatially, since all sensors and the measurement methods used in monitoring have their characteristic strengths and weaknesses. A concept for combining different sensors for an easy 3D overview is the attribution of height changes to tiles (see Figure 9). In a first step, the integration of InSAR data should be tested in order to integrate area-related information for ground movements.
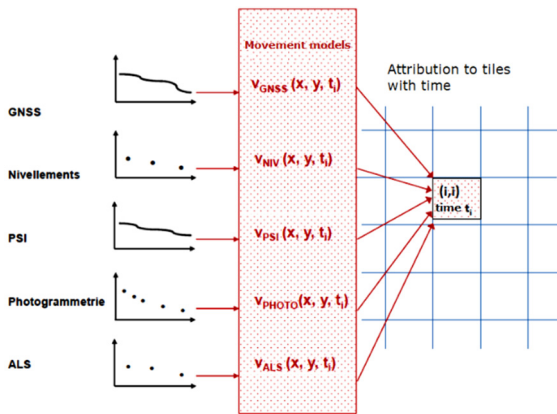
Figure 9. Concept for the integration of different sensors with non-linear movement behavior.

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