Set-up and application of multisensor-referencestations (MSST) for levelling, GNSS and InSAR in the former mining regions Saarland and Ruhrgebiet within Germany

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ABSTRACT

In 2017 the Mining Authorities *Oberbergamt des Saarlands* (OBA), the *State Office for Survey, Geoinformation and Land Consolidation Saarland* (LVGL) of the German federal state Saarland and the former mining company *RAG Aktiengesellschaft* (RAG) planned and set up a project to realize a modern network of so called multisensor-reference stations (MSST) for the monitoring of ground movements in post-mining and tectonically active regions. The MSST will serve as reference for the combined GNSS, Levelling and InSAR-based "*Bodenbewegungskataster Saarland (SaarBoBeKa)*", the ground movement cadaster of LVGL. A MSST consists of a solid heavy double corner reflector (D-CR) suitable for X-, C- and L-Band ascending and descending orbit data, a calibrated permanent registering GNSS chokering antenna and levelling points, all founded in a heavy reinforced concrete block. Additional components are weather-sensors and data transmission units. The MSST will be included into the German SAPOS GNSS framework and height measurements to official levelling points are attached to the German Height Reference System DHHN2016. LVGL operates a network of five MSST, RAG added six MSST distributed over the mining affected area. All LVGL stations are prepared to serve as stations of the German SAPOS GNSS framework and for this have to be supplied by the power network and the data transfer has to be done by LAN or LTE. All of RAG's MSST are powered by solar-cells and a small wind energy converter. The data transfer is performed by mobile communication to the GLOMON portal of ALLSAT. In GLOMON the RAG measurements are calculated by the program WapNet and sent to LVGL to be integrated in SaarBoBeKa. For the mining district of the Ruhr Area in the federal state of North Rhine-Westphalia (NRW) RAG is currently planning to construct and operate 10 MSST in 2022. The status of the MSST projects are presented.

I. Introduction

In Germany several centuries of near surface and underground mining activities led to changes and impacts to the earth surface of several meters in position and height. Subsidence troughs and discontinuous movement behavior led to damages to the infrastructure and to the environment that had to be compensated and regulated. The active mining ended in the Saar Area in the year 2012 and in NRW in 2018, so that the mining induced ground movements meanwhile nearly completely faded away.

Now that the hard coal production has expired, RAG is still accountable for the mining legacies. These are long-term liabilities like polder measures, mine water management and groundwater purification as well as classical legacies, e. g. reclamation and environmental protection, the processing of mining damage as well as post-mining activities (Hager and Wollnik, 2016). One part of the post-mining activities is the geometric monitoring of surface openings, near-surface old mining areas and the surveillance of the earth surface whilst the ordinance, controlled partial flooding of the former mine buildings (Spreckels *et al.,* 2018; 2020; Rudolph *et al.,* 2020).

For the three main hard coal mining regions in Germany, the Ibbenbueren Area, the Ruhr Area and the Saar Area up to now the classical precision levelling is still the official and most resilient survey method by ordinance of the federal mining- and survey-authorities.

During the past four decades GNSS-methods and since about two decades modern satellite based interferometric radar methods (InSAR) developed from research status to the use in day-to-day business. Now the connection between terrestrial high precision point and line measurements to area-wide distributed point determination is possible by targets that can be determined in each surveying method:

- Levelling points build the bridge to the official federal state height reference systems;
- GNSS-measurements are integrated into federal GNSS-reference networks for height and position;

- InSAR results can be referenced to the federal height and position networks by using multisensor-reference stations (MSST).

Following these requirements, a MSST consists of the components:

- Permanent GNSS-station;
- Double corner reflector (D-CR);
- Levelling points in the D-CR and founding;
- Additional needed sensors.

II. Surveillance Areas

For all mining regions a nearly indissoluble mixture of each other overlapping and interfering effects over the time appeared and have to be monitored in the post-mining era. The coal mining in the Ruhr area is supposed to start around the 13th century, for the Saar Area in the 15th century and in Ibbenbueren in the 16th century.

So overlaying effects like tectonics, active and post-mining activities, mine-water- and ground water management, large construction projects, climate change, water withdrawal, erosion, washout and possible sinkhole development characterize these regions.

A. *Saarland*

In the year 2017 Saarland's federal mining authority OBA and federal survey authority LVGL agreed together with RAG upon a common development of an MSST-based network within the official reference networks for building up an InSAR-based ground motion cadaster, SaarBoBeKa.

The monitoring technique ordinated by OBA up to then only included precision levelling over the more local areas of responsibility of mine sites. For the regional post-mining influences that are expected by the flooding of the underground hard coal mining buildings (Rosner *et al.*, 2014) an area-based monitoring backed on MSST and a thinned out precision levelling to a 5-year-cycle was ordinated that started in 2019. The northern parts of the Saarland are affected by recent tectonic effects caused by the still active underground volcanism due to the Eifel plume located in 45 km to 400 km depth below the earth surface.

B. *NRW: Ruhr area and Ibbenbueren*

In NRW the large area precision levelling, so called "Leitnivellement" (LN), first installed in 1873, will still be the common standard measurement technique but it will be thinned out to a 5-year-cycle from 2025 on. The ordinance survey Geobasis NRW is looking for operating the planned InSAR-based "*Bodenbewegungskatster NRW*" in 2022 (Riecken *et al.,* 2019).

For the Ruhr Area the challenge is the wide-spread region that had been under excavation for several centuries.

Even Ibbenbueren has a long mining history since the 16th century as a local mining region with specific tectonic structures (Goerke-Mallet, 2000).

III. Multisensor Reference Stations (MSST)

For the three surveillance areas different kinds of MSST are realized or planned. The MSST shall serve as reference station for several decades and have to be specially designed for their monitoring purpose – simple, robust, durable, low maintenance, suitable for all radar sensors and orbits, easy to build and handle, and, as far as possible, forward looking to be prepared for coming sensors and techniques.

The current design has been chosen in consideration of the long operation time: the foundation is easy to build, the D-CR can easily be strictly aligned in east-west direction and equipped with different additional sensors.

The decision for non-adjustable CR is due to the experience in the Ruhr- and the Saar Area with the high expenditure of time and personnel for the re-orientation of CR to different satellite's orbits, as well for ascending and for descending orbits, see Figure 1 in Spreckels *et al.* (2008).

Figure 1. LVGL's MSST Hellendorf for Saarland's SaarBoBeKa on a deep and solid grounded reinforced concrete foundation 2 m x 2 m x 2 m, Leica AR25 GNSS chokering antenna, D-CR Ø2,0m and levelling points in foundation. Image courtesy LVGL.

The dimensions for the diameter of the D-CR and the steel plates had been calculated in analogy to optical reflectors taking into account the effective reflection area and the deviation of the reflector center (Joeckel and Stober, 1995) according to different radar satellite orbits's incidence and azimuth angles.

Additionally the experience with CR in the analyses of X-, C- and L-band radar sensor data within RAG's R&D projects since 2005 and even the mean lifespan of about ten to fifteen years for adjustable CR made of perforated sheet rounded up the final D-CR design: the D-CR consist of 1 cm solid stainless steel plates at a diameter of 2 m and 1 m edge length. Measurement marks in the D-CR and the foundation allow to adapt and survey the D-CR in position and height. The reinforced concrete foundation contains measurement marks and is able to carry pillars or masts for permanent GNSS stations.

A. *Saarland*

In the Saarland the MSST of LVGL are part of the official federal geodetic reference system and in following special requirements are given (Figure 2). The MSST shall serve as a reference network for some decades and have to fulfill long life requirements. Since March 2022 LVGL operates five MSST for InSAR monitoring. The MSST are equipped with calibrated Leica AR25 chokering GNSS antennas, LAN connection and plugged to the power net. The heavy 2 m x 2 m x 2 m reinforced concrete foundation has been connected to the solid ground by concrete pillars where needed. The founding and the solid 2 m D-CR of 1 cm stainless steel plates bear several levelling points (see Figure 1).

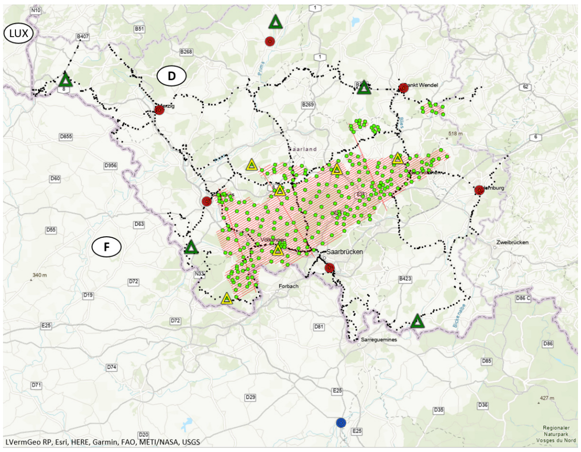

Figure 2. Monitoring concept of LVGL, OBA and RAG in the Saarland: LVGL-MSST (green triangles), RAG-MSST (yellow triangles), SAPOS GNSS stations (red circles), RGP-France GNSS station (blue circle), LN 2019 (black dots), aerial flight strips (red lines), GCP (green dots). Mapped area ~ 90 km x 70 km. Image courtesy RAG.

For the geometric monitoring of RAG's mining effected area six MSST operate since summer/autumn 2020. All MSST are equipped with weather-sensors, solar & wind energy power supply and with JAVAD RingAnt-G3T GNSS chokering antennas. The 2 m x 2 m x 2 m reinforced concrete foundation had been set as a solid block into the ground. The founding and the 2 m - D-CR, identical to LVGL, bear several levelling points (see Figure 3).

B. *Ruhr area NRW*

The Ruhr Area, like Ibbenbueren, see shapter C, lies in NRW where no official ordination of the mining authorities for an InSAR-based ground movement monitoring is given. But Geobasis NRW is working on the InSAR-based *Bodenbewegungskataster NRW* that is expected in 2022. So, for this large spread monitoring region the MSST have to fulfill long life requirements but they will not be parts of the official point reference in NRW (Figure 4).

Figure 3. RAG's MSST Primsschacht for Saarland's SaarBoBeKa. From left to right: wind & solar power supply, equipment box, reinforced concrete foundation block at size 2 m x 2 m x 2 m, D-CR Ø2,0 m, JAVAD RingAnt-G3T GNSS chokering antenna. Image courtesy ALLSAT.

The solid D-CR at a diameter of 2 m and 1 m edge length is identical to the Saarland D-CR. In contrast to the MSST used in the Saarland no heavy foundation is necessary and the D-CR can be founded on a transportable reinforced concrete plate where all needed equipment can be mounted. The advantages of this design are, that in a case of need, this platform can be hooked up and transported to some other place. Currently the static for the construction of the concrete platform of 2,3 m to 2,2 m is computed. Figure 5 shows sketches of the fully equipped transportable MSST.

In agreement with *Geobasis NRW* these MSST will operate with calibrated Leica AR 25 GNSS chokering antennas that are used on NRW's SAPOS GNSS stations.

C. *Ibbenbüren, NRW*

The geometric monitoring for the small Ibbenbueren area is done by standard precision levelling attached to the LN but even here no official ordination for an InSAR-based ground movement monitoring is given. RAG performs the geometric monitoring with five GNSS stations and a smaller type of MSST that is suitable for X- and C-band radar data. The DCR600 is commercially available by ALLSAT. It is a D-CR with 120 cm in diameter, a centered GNSS antenna and four 5/8" adapters for terrestrial targets. Weather-sensors complete the equipment. It has a mounting *e.g.* for terrestrial pillars or tripods and a special roof mount. The DCR600 is designed for a flexible use in smaller regions or for a local object monitoring (see Figure 6).

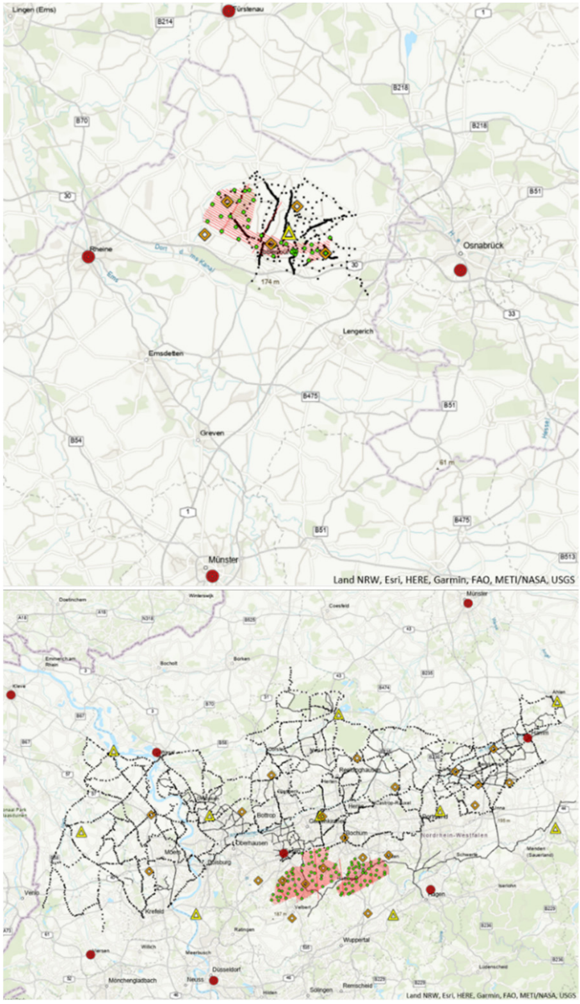

Figure 4. Monitoring concept of RAG in NRW. Ibbenbueren (top) and Ruhr Area (bottom): MSST-stations (yellow triangles), GNSS-stations (orange rhomb), SAPOS GNSS-stations (red circles), LN (black dots), aerial flight strips (red lines), GCP (green dots). Mapped area: ~ 64 km x 65 km (Ibb.) and ~ 145 km x 90 km (Ruhr). Image courtesy RAG.

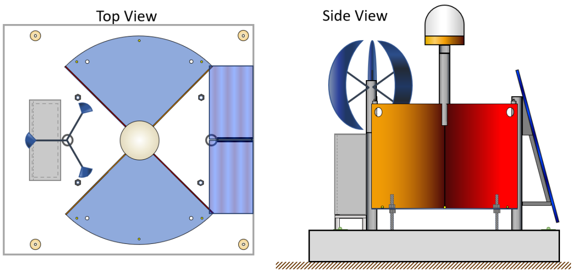

Figure 5. Top view (left) and side view sketches of a fully equipped and self-supplying transportable MSST, Ø2,0 m, to be installed in the Ruhr Area. Image courtesy RAG.

IV. GERMAN GROUND MOTION CADASTER

The availability of the free Sentinel-1A/B radar satellite data since 2014 pushed the development and applications for InSAR-based methods from research status into daily practice. The "*BodenBewegungsdienst Deutschland*" (BBD) is a Germany-wide InSAR-based ground motion service set up in 2019 by the Federal Institute for Geoscience and Natural Resources (BGR) and the German Aerospace Center (DLR) (BGR, 2019). But: the BBD has no sovereign, governing character.


Figure 6. DCR600, Ø1,2 m with GNSS-Antenna and targets. View from west (left) and south (right). Image courtesy ALLSAT & RAG.

The first operational and ordinative ground motion cadaster in Germany is LVGL's "*Saarlaendisches Bodenbewegungskataster SaarBoBeKa*" (SaarBoBeKa 2022), operating since March 2022.

The launch of the "*Bodenbewegungskataster NRW*" is scheduled in 2022 by Geobasis NRW.

A. *SaarBoBeKa*

SaarBoBeKa has been discussed since 2017 and was realized in 2022 with the participation of Saarland's authorities "Ministerium für Umwelt und Verbraucherschutz", the "Oberbergamt des Saarlands" (OBA) and LVGL. The already in Section III presented MSST and levelling serve as the geometric geometric reference (see Figure 7). SaarBoBeKa provides a dense-meshed area-wide ground motion cadaster for changes to the earth surface in the Saarland based on interferometric data from Sentinel-1A/B radar satellites of the European Space Agency (ESA) within the *European Union's Earth observation programme "Copernicus"*.

For this ground motion cadaster official, quality-assured and annually updated ground movements are derived and made publicly available as a web service. The process chain of the complete workflow can be seen in Figure 8.

The data and privacy protection has been guaranteed by generalizing the pointwise by persistent scatterer interferometry (PSI) derived information to 250 m x 250 m cells. For all persistent scatterer (PS) of each tile the relative movements will be averaged and presented in one geometric centered point element that can be chosen for the visualization of the ground motion time series. (see Figure 9).

To derive quality assured and reliable relative changes in height and in east-west – direction the InSAR-analyses of Sentinel-1A/B satellite data taken from ascending and descending orbits have been combined and processed in a decomposition approach (Yin and Busch, 20018). Whilst the postprocessing and quality assessment a data cleansing by blunder and outlier detection is performed for PS with *e.g.* high standard deviations in “Line-of-Sight” direction (LOS) and a trend analysis with best-fitting polynoms is performed for each PSI time-series (Busch and Linke, 2014).

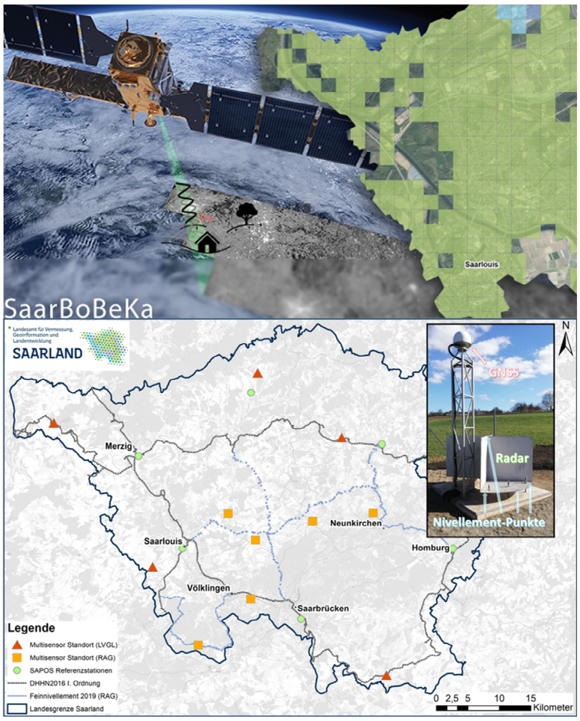

Figure 7. MSST and levelling lines as geometric reference for SaarBoBeKa.

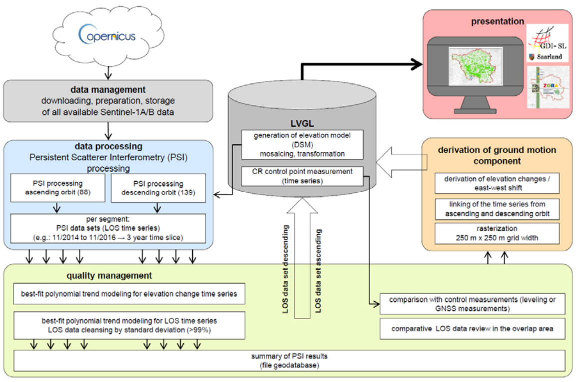

Figure 8. Process chain of the SaarBoBeKa-workflow.

For an early detection of possible ground movements an annual update is intended and if needed half-yearly updates can be processed and published.

The annual processing will be done with the radar data for a time span of three years so that the each other following analyses will have an overlapping time span of two years. By this, an optimum of dense PS will be saved for area-wide PSI- and decomposition results (Evers *et al.,* 2020; Gefeller *et al.,* 2016).

The link between geodetic and radar-interferometric data are the MSST that are used for the validation and verification of the InSAR results compared to geodetic measurements with the aim to transfer this high geometric quality from points into the area for an accurate and controlled ground motion service in position and height. Figure 10 givs an impression how future comparison in MSST can happen: here the time series of the relative vertical InSAR-related movements of the SaarBoBeKa 250 m x 250 m tile no. 19052 from June 2017 to June 2020 and the GNSS-height measurements on RAG’s MSST Primsschacht from July 2020 to February 2022 are presented together with levelling RAG performed to the MSST foundation. Unfortunately, the current measurements do not overlap but the spread of both the sensors movement behavior is at the same extent and fit to the levelling.

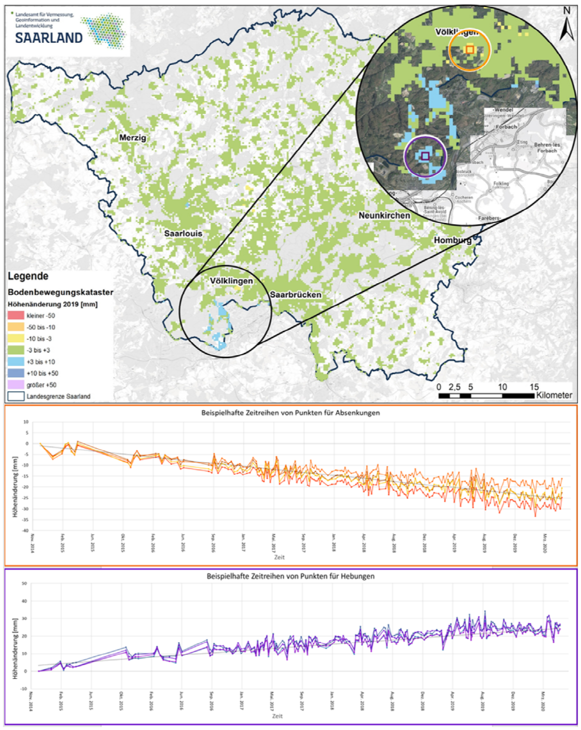

Figure 9. SaarBoBeKa: 250 m x 250 m tiles with colour-coded movement classification (top), time series of a cell showing subsidence (mid) and a cell showing uplift (bottom), Dec. 2014 – June 2020. Image courtesy LVGL.

Farther, LVGL’s MSST comply the requirements for a German SAPOS GNSS station and for this these ground bound MSST will be integrated into the SAPOS framework to additionally improve the position services for GNSS users.

B. *Bodenbewegungskataster NRW*

Different to LVGL, Geobasis NRW will back the geodetic reference of the “*Bodenbewegungskataster NRW*” only their SAPOS GNSS stations and on the very long and for large areas available time-series of the “Leitnivellement” (LN) in NRW.

The use of MSST for the whole federal state NRW, like in the Saarland, would lead to the installation of more than 100 MSST, what is technically and financially regarded not feasible.

V. CONCLUSION AND OUTLOOK

The development of InSAR-techniques for the geometric monitoring of the earth surface has come to daily practice and now face the demands of classic geodetic reference networks. Since more than 20 years RAG accompanies the InSAR developments first in R&D project and since several years more and more in day-to-day business. Due to the ordinances of the authorities all the results have to be mounted into the federal German reference networks for height and position. For the German federal state Saarland RAG's monitoring workflow has been developed in cooperation with the mining and survey authorities and now is completely based on the official SaarBoBeKa.

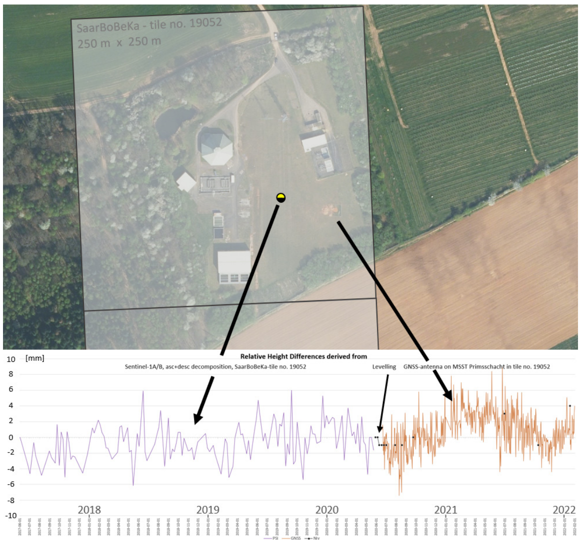

Figure 10. Time series (06/2017-02/2022) for relative vertical movements derived for a 250 m x 250 m tile, SaarBoBeKa - nr. 19052, height difference spacing: 2 mm. RAG's levelling measurements (black dots). Decomposition (height component) of Sentinel-1A/B ascending and descending orbit (06/2017-06/2020) by LVGL (purple). GNSS time series (06/2020-02/2022) derived from RAG's MSST station Primsschacht, LVGL nr. 6607 0 403 00, Saarland (orange). Mapped area ~ 550 m x 330 m. Image courtesy LVGL and RAG.

In NRW a slightly different kind of reference for the ground motion cadaster than in the Saarland will be operated. Consequently, RAG realizes the SaarBoBeKa workflow in the NRW post-mining regions in a comparable manner and installs an own high accurate MSST- and GNSS-station based network mounted within the SAPOS and LN networks. This network will contain 10 MSST and 30 GNSS stations for the Ruhr area. For Ibbenbueren five GNSS stations and one MSST have already been installed in 2021.

In RAG's latest R&D projects GEOTEC (Niemeier and Tengen, 2022) developed the "Dynamic Network Adjustment" (DNA) approach that is implemented in ALLSAT's GLOMON portal (Schulz and Schäfer, 2022). The current analyses show that RAG is able to check either the own networks and even the federal geodetic reference framework in position and height. Accordingly, the high demands of the authorities for the geometric monitoring can be faced and put into practice for RAG's post-mining era – and areas.

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