PFG – Journal of Photogrammetry, Remote Sensing and Geoinformation Science
https://doi.org/10.1007/s41064-024-00273-3

ORIGINAL ARTICLE

German and European Ground Motion Service: a Comparison

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Received: 12 July 2023 / Accepted: 14 January 2024

Abstract

Since the end of 2022, two ground motion services that cover the complete area of Germany are available as web services: the German Ground Motion Service (*Bodenbewegungsdienst Deutschland*, BBD) provided by the Federal Institute for Geosciences and Natural Resources (BGR), and the first release of the European Ground Motion Service (EGMS) as part of the Copernicus Land Monitoring Service. Both services are based on InSAR displacement estimations generated from Sentinel-1 data. It would seem relevant to compare the products of the two services against one another, assess the data coverage they provide, and investigate how well they perform compared to other geodetic techniques. For a study commissioned by the surveying authority of the state of Baden-Württemberg (*Landesamt für Geoinformation und Landentwicklung Baden-Württemberg*, LGL), BBD and EGMS data from different locations in Baden-Württemberg, Saarland, and North Rhine-Westphalia (NRW) were investigated and validated against levelling and GNSS data. We found that both services provide good data quality. BBD shows slightly better calibration precision than EGMS. The coverage provided by EGMS is better than that of BBD on motorways, federal roads, and train tracks of the *Deutsche Bahn*. As an example, where both services have difficulties in determining the correct displacements, as they cannot be described well by the displacement models used for processing, we present the test case of the cavern field at Epe (NRW). Finally, we discuss the implications of our findings for the use of the products of BBD and EGMS for monitoring tasks.

Keywords InSAR · Sentinel-1 · Monitoring · Geodesy · Validation

1 Introduction

During the past two decades, Interferometric Synthetic Aperture Radar (InSAR) techniques have experienced rapid development. According to Crosetto et al. (2020), this is mainly due to the following factors: SAR data availability has improved a lot, with an increasing number of SAR systems and easy access to datahubs via the internet; new acquisition modes as well as new methods and algorithms have extended the range of applications and improved the density, quality, and reliability of results; with the launch of the first two Sentinel-1 satellites, large-area coverage with a short revisit time of 6 days had been available until the malfunction of Sentinel-1B and will again be available after the launch of Sentinel-1C; and with freely available ESA data and diverse freely available InSAR software (Sentinel Application Platform, Toolbox for Reducing Atmospheric InSAR Noise, Stanford Method for Persistent Scatterers, Delft Object-Oriented Radar Interferometric Software, ...), the research and user communities could grow fast and take part in an accelerating development. In addition, computing continues to become more performant, which allows the processing of ever greater datasets with algorithms of growing complexity. Methods have been developed to apply atmospheric corrections and to use Global Navigation Satellite System (GNSS) data to calibrate InSAR measurements, i.e., to transfer the displacements properly into geodetic reference frames. This allows the combination of multiple frames to large-area ground motion products. Regional monitoring systems (Del Soldato et al. 2019; Raspini et al. 2018) and national ground motion maps (Bischoff et al. 2020; Costantini et al. 2017; Cuenca et al. 2011; Dehls et al. 2019; Di Martire et al. 2017; Ferretti et al. 2019), in particular the German Ground Motion Service BBD (Kalia et al. 2017) and, recently, the European Ground Motion Service (EGMS), were created. The latter two, BBD and EGMS, are the subject of this study.

The latest release of BBD was provided in September 2022 by BGR. In March 2023, the latest release of the

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Published online: 27 February 2024

EGMS as part of the Copernicus Land Monitoring Service became available. Both services are based on InSAR displacement estimations generated from Sentinel-1 data and cover the whole area of Germany. It seems pertinent to ask if there are differences in quality or coverage between BBD and EGMS and to assess how well the two releases perform compared to other geodetic techniques. For this study, BBD and EGMS data from different locations in Baden-Württemberg, Saarland, and NRW were investigated and validated against levelling and GNSS data. In addition, an assessment of the coverage of the train tracks of the *Deutsche Bundesbahn*, the motorways, and federal roads in northern Baden-Württemberg between Karlsruhe and Stuttgart is given. The results show good agreement and confirm the high quality of the products of both services in standard situations. As an example for where surface displacements cannot be described well by the displacement models of either of the two services, we investigated how BBD or EGMS perform at the cavern field Epe (NRW). Comparisons with levelling and GNSS data show that both services have problems with capturing the ground motion in the area of strongest displacement at Epe (NRW).

Although it has recently been announced that the EGMS products will in future be the data basis for BBD (Kalia et al. 2023), we hope that our results can help in making decisions for the future development of both BBD and EGMS.

All spatial plots were created with Quantum-GIS (QGIS; QGIS Association) using OpenStreetMap (OpenStreetMap) as background. The depicted information was derived from data provided by partners or downloaded from BBD or EGMS.

2 BBD and EGMS

Although for Germany the products of both services were processed by GAF AG (Munich, Germany) with software developed by the Earth Observation Center (EOC), which is part of the German Aerospace Center (DLR News Archive), there are a number of differences. After calibration with GNSS data, displacements in ETRS89/DREF91 for BBD (Kalia 2022; Parizzi et al. 2020) or ETRF2000 for EGMS (Larsen et al. 2021) were obtained. Hence, the reference frames used by both services are essentially the same. For calibration, BBD uses the GNSS time series of the *Integriertes Geodätisches Referenznetz Deutschland* (GREF) and the *Satellitenpositionierungsdienst der deutschen Landesvermessungen* (SAPOS; Kalia et al. 2021), while EGMS uses as the main source the EUREF Permanent Network Densification Product (EPND; EUREF is the Reference Frame Sub-Commission for Europe of the International Association of Geodesy), as a secondary source the data provided by the Nevada Geodetic Laboratory (NGL), and some supplementary sources (Larsen et al. 2021). Downloadable products comprise calibrated line of sight (LoS) displacement time series for the processed paths as well as gridded vertical and east–west horizontal displacement time series. A 50 m × 50 m grid is used by the BBD for the vertical and east–west horizontal displacements. The grid of EGMS is 100 m × 100 m. Besides calibration, there are other differences in processing between the products of the two services (Kalia 2022; Ferretti et al. 2021): BBD time series run from April 2015 to December 2021 (fourth release), those of the second release of EGMS from January 2016 to December 2021. BBD uses persistent scatterers (PS). For Germany, EGMS uses PS. For other regions, EGMS also uses distributed scatterers (DS). For the final selection of points based on time series, BBD requires temporal coherence better than 0.75 and EGMS requires root mean square (RMS) smaller than 5 mm (Kotzerke et al. 2022). The default displacement model of BBD and that of EGMS in Germany is linear + sinusoid, while EGMS uses cubic + sinusoid or piece-wise linear in other regions (Ferretti et al. 2021). Time series of both services are sampled in steps of 6 days, but are shifted about 3 days against each other. The main characteristics are listed in Table 1. More details on processing are described in the subsections on BBD and EGMS.

Table 1 Basic information on BBD and EGMS

	BBD	EGMS for Germany
Calibration with	GREF, SAPOS	EPND, NGL
Grid	50 m × 50 m	100 m × 100 m
Period	04.2015–12.2021	01.2016–12.2021
Scatterers	PS	PS
Point selection	Coherence ≥ 0.75	RMS ≤ 5 mm
Model	Linear + sinusoid	Linear + sinusoid

2.1 BBD

Processing for BBD is done with the Interferometric Wide Area Product (IWAP) Processor, which was developed at DLR's Earth Observation Center (DLR News Archive). Some general information can be found in Kalia 2022. From personal communication with Andre Kalia (BGR), we obtained the following information regarding the processing of the previous BBD release (status 29.09.2022): correction of atmospheric effects was done as described in Adam 2019. To reduce the tropospheric effect on phase European Centre for Medium-Range Weather Forecasts (ECMWF) ERA5 data with 3 months latency, 31 km spatial resolution, 137 vertical levels, and 1-hour output sampling (ERA5) were used. The effect of ionosphere on phase was reduced based on global ionospheric Total Electron Content (TEC) maps with latency of 5 days, 2–8 TECU precision, spatial resolution of 5° longitude × 2.5° latitude, and temporal resolution of 2 h (CODE). InSAR results were calibrated with GNSS data following the approach of Parizzi et al. 2020. For reasons of visualization, plate movement was subtracted from the motion derived from InSAR and GNSS using the ITRF 2014 model (Altamimi et al. 2017). Consequentially, movements provided by BBD are given relative to the Eurasian plate. The velocities and displacements of BBD are given in ETRS89/DREF91, while the coordinates of the PS are provided in ETRS89/GRS80 (Kalia 2022). The products in vertical and east–west horizontal direction are spatially sampled on a 50 m × 50 m grid and temporally with 6 days' time difference. A value is assigned to a grid cell if at least one PS from the ascending orbit and one PS from the descending orbit are contained in the cell. Evaluations of the techniques applied for BBD can be found in Gonzalez et al. 2018 and Parizzi et al. 2021. The number of PS has increased with the latest release of BBD (30.09.2022), as a criterion for PS selection has been changed: the threshold for temporal coherence has been lowered from 0.85 to 0.75.

BBD provides data in the form of several products: calibrated LoS data and gridded products with displacements in vertical as well as east–west horizontal directions. In the viewer (BBD Viewer 2023), a product for the ascending and one for the descending orbit can be displayed. These have been merged from several paths with different incidence angles. Nevertheless, calibrated LoS products for each relevant path are accessible via data download. Among other information, the downloaded data comprise displacement time series and coordinates of the measurement points (MP).

2.2 EGMS

The products of EGMS are generated by a consortium of four companies, the OpeRatIonal Ground motion INsar ALliance (ORIGINAL) based on data of the Sentinel-1 satellites. The participating partners are e-GEOS, TRE Altamira, NORCE, and GAF AG. GAF AG is responsible for the processing over German territory and uses the IWAP processor of DLR under license. EGMS is well documented (EGMS Documentation).

A keyword-style overview of the applied algorithms is found in Ferretti et al. (2021), p. 61. In particular, corrections with external data are described:

1. Tropospheric delays are corrected based on ERA5 data,
2. Ionospheric delays are corrected based on data of the Center for Orbit Determination in Europe of Bern University (CODE),
3. Solid earth tides are corrected based on parameters provided by the NASA Navigation and Ancillary Information Facility (NAIF) database.

The specifications of EGMS and its products can be found in the End User Requirements (Proietti and Cerri 2021). Via a WebGIS application, products can be visualized and accessed (EGMS Viewer). Among other information, time series and point coordinates in ETRS89-LAEA are provided. EGMS distinguishes between a calibrated product and an orthoproduct. The calibrated product consists of path-wise LoS data that were transferred to ETRF2000 via calibration with GNSS data. As for the calibrated product, the orthoproduct gives displacements in ETRF2000, but in vertical and east–west horizontal direction. The calibration of EGMS (Ferretti et al. 2021) is different from that of BBD (Parizzi et al. 2020). The calibrated product is provided burst-wise, while the orthoproduct can be downloaded in the form of 100 km × 100 km tiles. The orthoproduct covers the whole area of the member states of Copernicus as well as Great Britain.

3 Methods

In order to compare the time series from different data sources, the differences of linear displacement rates and standard deviations between the signals are calculated.

Before doing so, the InSAR time series have to be preprocessed. First, they are smoothed with robust quadratic regression (RLOESS) over a window of 7 data points' length. This way, while preserving the shape of the time series, a large part of the intrinsic noise is removed and, hence, it does not have a big effect on the statistical characteristics given in the study. Note that the intrinsic noise is of little value for the assessment of BBD or EGMS, as it depends on the data processing, the details of which are not publicly known. The next step is to interpolate the time series to the acquisition times of the dataset to which it shall be compared. This is done via shape-preserving piecewise cubic interpolation. Finally, the pair of time series that shall be compared is truncated to the same period. If one of the time series is from levelling, this means that the InSAR data are interpolated to the epochs of levelling. The GNSS time series of Baden-Württemberg have only been corrected for offsets at times of certain events (e.g., antenna changes). No further filtering was applied. The GNSS time series of Epe have been used without changes. If GNSS time series are compared to LoS data, the pointwise LoS vector provided together with the data of BBD or EGMS is used to project the GNSS data to LoS.

For the preprocessed time series, differences in displacement rates and standard deviations σ_P of the differences of time series were calculated and are given below in form of spatial plots and histograms. In order to put qualitative numbers to the histograms of differences in displacement rates, the median and median absolute deviation of median (MAD) are calculated. As it is here more important to detect systematic biases, the median has been preferred to the mean. The MAD is multiplied by 1.4826. If data are normally distributed, this has the effect that it approximately becomes an estimator of the standard deviation (MAD derivation). In addition, an overall standard deviation σ for differences in displacement is calculated by the formula

$$\sigma = \sqrt{\frac{1}{N-1}\sum_{P}(N_P - 1)\cdot {\sigma_P}^2} \tag{1}$$

The sum is taken over all points P that were taken into account for the evaluation, σ_P is the standard deviation between time series at point P, N_P is the number of data values evaluated for point P, and N is the sum of the N_P taken over the P. Formula 1 is based on the usual formula for unbiased estimation of the standard deviation. As the different datasets are relative to different references, the mean difference μ_P between two time series at P has no meaning and it can be assumed that $\mu_P = 0$. With this assumption, $\mu = \sum_P \mu_P = 0$. Hence, σ can be interpreted as the standard deviation between all measurements of differences.

The values of σ are plotted in the corresponding histograms.

4 Data and Comparison Results

For the comparisons, vertical and east–west horizontal products of BBD and EGMS as well as calibrated LoS data from both services are used. An overview of the datasets used for validation in this work is given in Table 2.

Table 2 Datasets used for validation

Dataset	Provided by	Used in section
GNSS data of Baden-Württemberg	LGL	SAPOS
Shapefiles of motorways and federal roads in Baden-Württemberg	LGL	Shapefiles of Linear Infrastructure
Shapefile of train tracks of German Railways	Open ESRI	Shapefiles of Linear Infrastructure
Levelling data of Primsmulde (Saarland)	RAG	Levelling at Primsmulde
Levelling data of Western NRW	Geoportal NRW	Levelling Western NRW
Levelling data of Epe (NRW)	SGW	Levelling and GNS near Epe

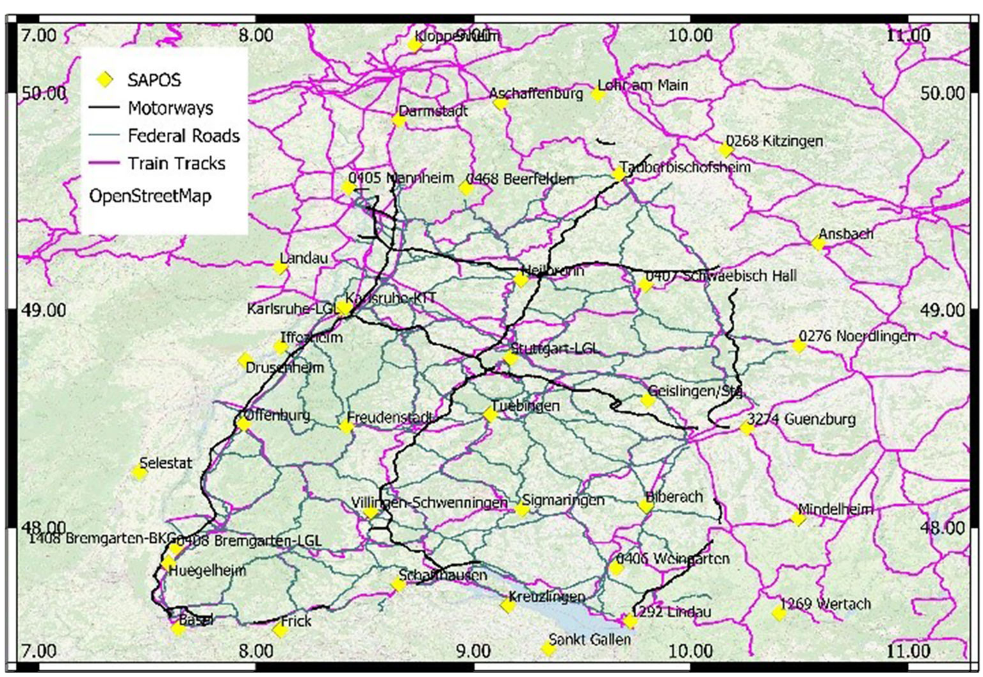


Fig. 1 Data overview Baden-Württemberg: locations of GNSS stations, motorways, federal roads, and train tracks

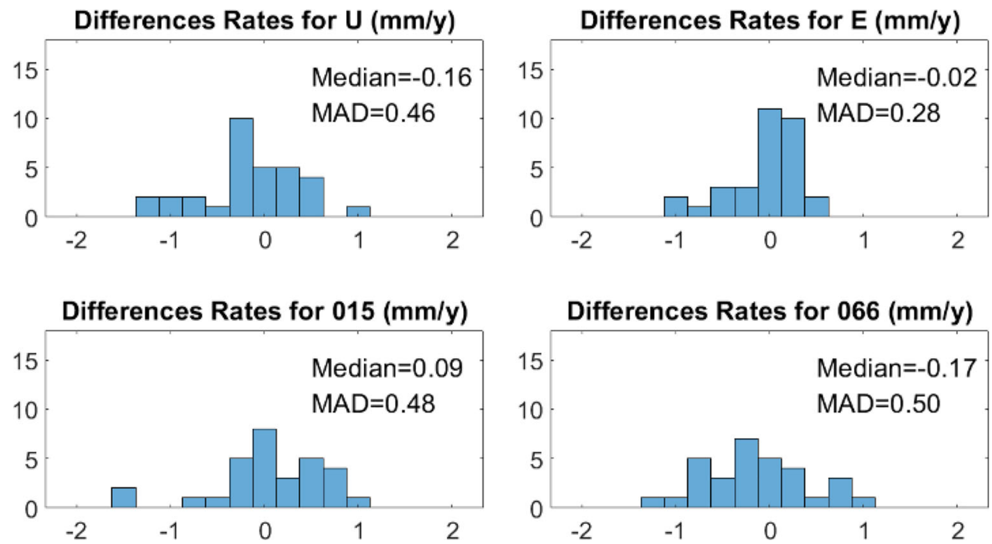


Fig. 2 Differences between displacement rates of BBD and SAPOS (Baden-Württemberg). *U* vertical, *E* east–west, *015* path 015 (ascending), *066* path 066 (descending), *MAD* Median Absolute Deviation of Median

4.1 Baden-Württemberg

For Baden-Württemberg, three types of investigations were performed that are described in detail in the following subsections:

1. Time series of GNSS stations of the SAPOS network (SAPOS) in Baden-Württemberg and in bordering regions were compared to BBD and EGMS data in vertical, east–west horizontal, and LoS directions. The LoS data stem from paths 015 (ascending) and 066 (descending), as these provide the best coverage of the region. The GNSS data were provided by LGL.
2. The coverage of linear infrastructure with data of BBD and EGMS was studied based on shapefiles that describe the motorways and federal roads in Baden-Württemberg (provided by LGL) and the train tracks of the *Deutsche Bahn* in all of Germany (downloaded 19 February 2023 from Open ESRI). In the shapefiles, each lane and each track are represented by line elements. For the analysis, an area in northern Baden-Württemberg was selected that extends from the Oberrheingraben with Karlsruhe in the west to Stuttgart in the east. It also includes the northernmost part of the Black Forest, which is a difficult area for InSAR, as a large part of the region is covered by vegetation. Again, LoS data from paths 015 (ascending) and 066 (descending) and vertical displacements were used. The shapes were subdivided in segments of different lengths (25 m, 50 m, 100 m). To assess the coverage of the different InSAR products, we determined the percentage of segments that contain an MP in a perpendicular distance of less than 10 m of each segment, as relevant movements may be visible at adjacent points not directly on the road or track. The total length of the in-

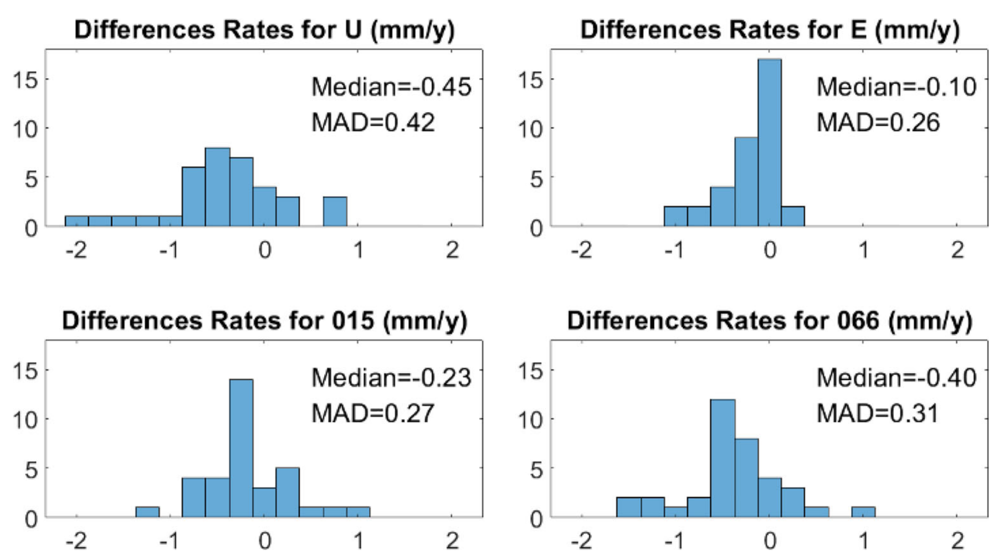


Fig. 3 Differences between displacement rates of EGMS and SAPOS (Baden-Württemberg). *U* vertical, *E* east–west, *015* path 015 (ascending), *066* path 066 (descending), *MAD* Median Absolute Deviation of Median

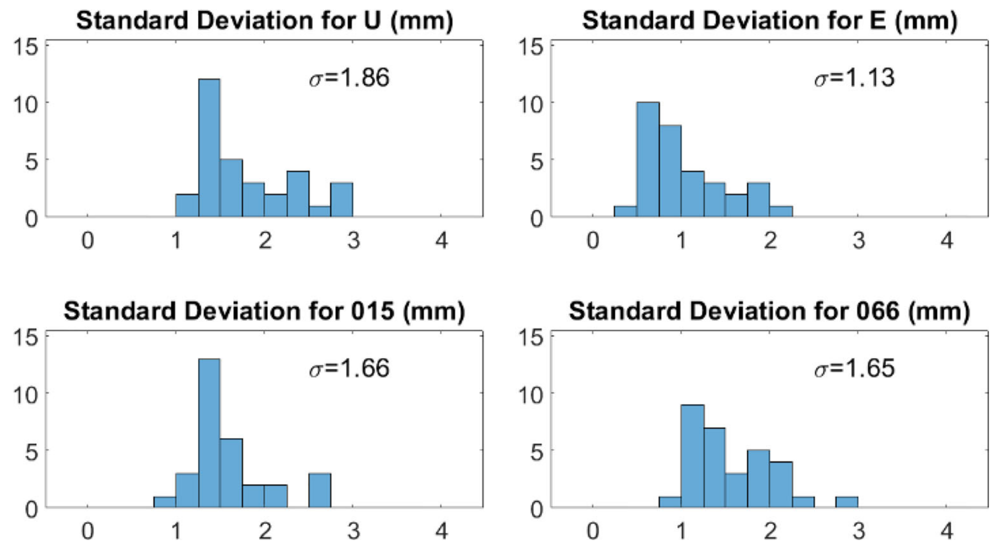


Fig. 4 Standard deviation of differences between displacement of BBD and SAPOS (Baden-Württemberg). *U* vertical, *E* east–west, *015* path 015 (ascending), *066* path 066 (descending)

Table 3 Coverage for BBD and EGMS in percent depending on segment length

Object	Length	U (BBD)	015 (BBD)	066 (BBD)	U (EGMS)	015 (EGMS)	066 (EGMS)
TT	25 m	5.4	25.3	28.2	3.7	62.3	52.8
TT	50 m	10.5	38.2	41.6	7.2	74.4	62.6
TT	100 m	16.3	46.4	50.2	11.8	79.2	67.0
Mw	25 m	2.9	12.8	14.3	3.6	37.7	38.1
Mw	50 m	5.0	18.6	21.2	6.4	47.5	48.3
Mw	100 m	7.7	23.9	27.5	10.3	54.3	55.5
FR	25 m	3.1	8.9	9.2	2.9	29.8	24.6
FR	50 m	5.1	12.8	13.2	4.9	37.1	30.9
FR	100 m	7.0	15.9	16.3	7.1	41.4	34.7

TT train tracks, *Mw* motorways, *FR* federal roads, *U* vertical, *015* ascending path 015, *066* descending path 066

vestigated train tracks is about 1450 km, of motorways about 1500 km, and of federal roads about 2800 km.

3. Finally, for the BBD and EGMS data downloaded to determine the coverage of linear infrastructure (vertical and paths 015 [ascending] and 066 [descending]), we performed comparisons of BBD and EGMS.

The locations of GNSS stations and linear infrastructure are depicted in Fig. 1.

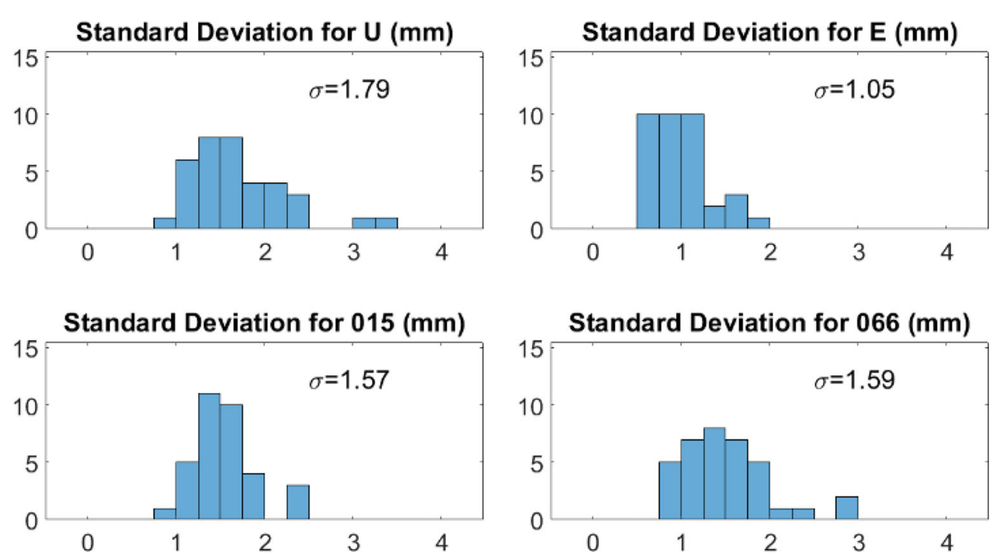


Fig. 5 Standard deviation of differences between displacement of EGMS and SAPOS (Baden-Württemberg). *U* vertical, *E* east–west, *015* path 015 (ascending), *066* path 066 (descending)

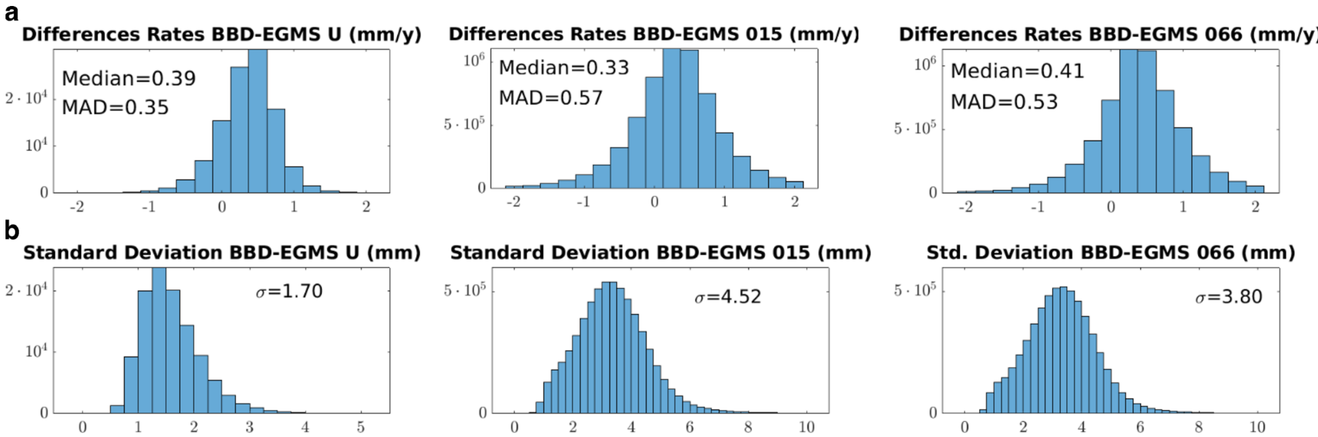


Fig. 6 Baden-Württemberg. **a** Differences of displacement rates of BBD and EGMS; **b** standard deviations of differences between displacement of BBD and EGMS. *U* vertical, *015* path 015 (ascending), *066* path 066 (descending), *MAD* Median Absolute Deviation of Median

4.1.1 SAPOS

Time series of GNSS stations of the SAPOS network in Baden-Württemberg and in bordering regions were provided by LGL; 32 stations were nearby points of BBD and 36 (32 plus 4 French or Swiss stations) nearby points of EGMS. The data cover different periods of time depending on the station. At three locations the time series are rather short, three more cover only 2 years. All others cover the complete period of the InSAR data. Beside vertical displacements also displacements in the east–west horizontal direction and LoS were compared. For this purpose, the SAPOS time series were projected to LoS of those paths of Sentinel-1 that include a significant number of stations (ascending path 015 and descending path 066). The overall agreement between SAPOS and InSAR results from both services is good (Figs. 2, 3, 4 and 5). In accordance with the error characteristics of GNSS, the agreement is best in the east–west horizontal direction and worst in the vertical direction, with the quality of agreement in LoS in between these two. EGMS data show a slightly bigger bias than BBD data. As the method of calibration used for BBD (Parizzi et al. 2020) assumes that the difference in displacement rates of BBD and GNSS consists of a space variant error screen, the displacement rate of the reference point, and random noise, a perfect agreement between the displacement rates of BBD and GNSS cannot be expected. Furthermore, use of GNSS time series required some preprocessing that presumably differs between our work and that done for the calibration of BBD. This is a second contribution to the observed biases.

4.1.2 Shapefiles of Linear Infrastructure

The calculated percentages of coverage are given in Table 3. Because the parts of the shapefiles that were checked for coverage were determined by intersection with the convex hull of the InSAR points, the actual percentages are even a bit higher than those given in Table 3, as the sets of InSAR points are not perfectly convex. The first important observation is that percentages in LoS are several times as high as for the vertical product. This is mostly because the vertical products are gridded and, hence, datapoints are sparse. Together with bad positioning accuracy of the gridded points, this has direct implications for the selection of products for monitoring purposes. The second important observation is that the coverages in LoS for EGMS are much higher than for BBD, giving EGMS a distinct advantage for monitoring applications. Presumably, this is the consequence of different pixel selection criteria. The larger percentages of coverage of train tracks by the vertical product of BBD compared to the vertical product of EGMS can be explained by the use of larger grid cells by EGMS. Finally, for obvious reasons, the percentages increase with increasing segment length.

4.1.3 BBD Versus EGMS

As the investigation of coverage involved downloading a large amount of data, these were also used for comparing BBD versus EGMS. Differences between displacement rates and standard deviations between time series were considered for this purpose. Histograms are shown in Fig. 6. The most notable observations are a bias of about 0.3 mm/y of the differences between displacement rates and standard deviations of 4.52 mm (ascending path 015) and 3.80 mm (descending path 066) between time series for the LoS products. A possible explanation may be a slightly less optimal calibration of EGMS because of a worse GNSS data basis (see section “SAPOS”). This hypothesis is supported by the long wavelength signals visible in the three maps of differences of displacement rates in the first column of Fig. 7.

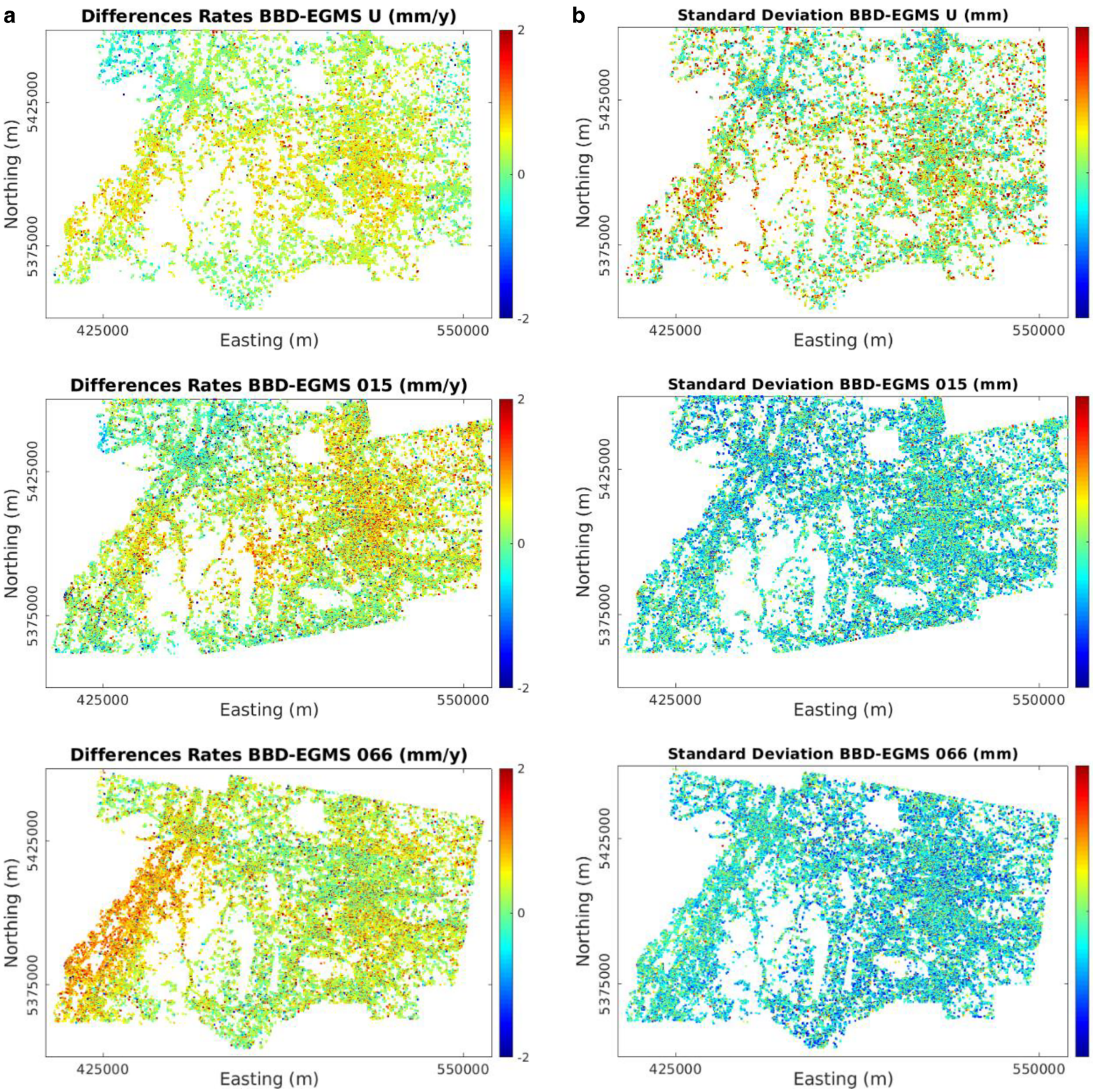


Fig. 7 Baden-Württemberg. **a** Differences of displacement rates of BBD and EGMS; **b** standard deviations of differences between displacement of BBD and EGMS. *U* vertical, *015* path 015 (ascending), *066* path 066 (descending)

4.1.4 Conclusions Baden-Württemberg

The comparison of BBD and EGMS with GNSS data shows that the calibration of BBD is somewhat better than that of EGMS. The coverage of linear infrastructure is better for EGMS than for BBD. This is due to the less strict point selection criterion and the shorter time period covered by the data of EGMS. An important observation is that the coverage of linear infrastructure by the LoS products is several times better than that of the vertical products, as the vertical products are gridded and, hence, datapoints are sparse. Together with the bad positioning accuracy of the gridded points, this has the implication that LoS products are preferable for monitoring purposes. The comparison BBD versus EGMS shows small biases of differences of displacement rates. The standard deviation of differences of displacement is only 1.7 mm for the vertical products, but more than twice this number for paths 015 (ascending) and 066 (descending). The smaller standard deviation between the vertical products compared to that of the LoS products could be

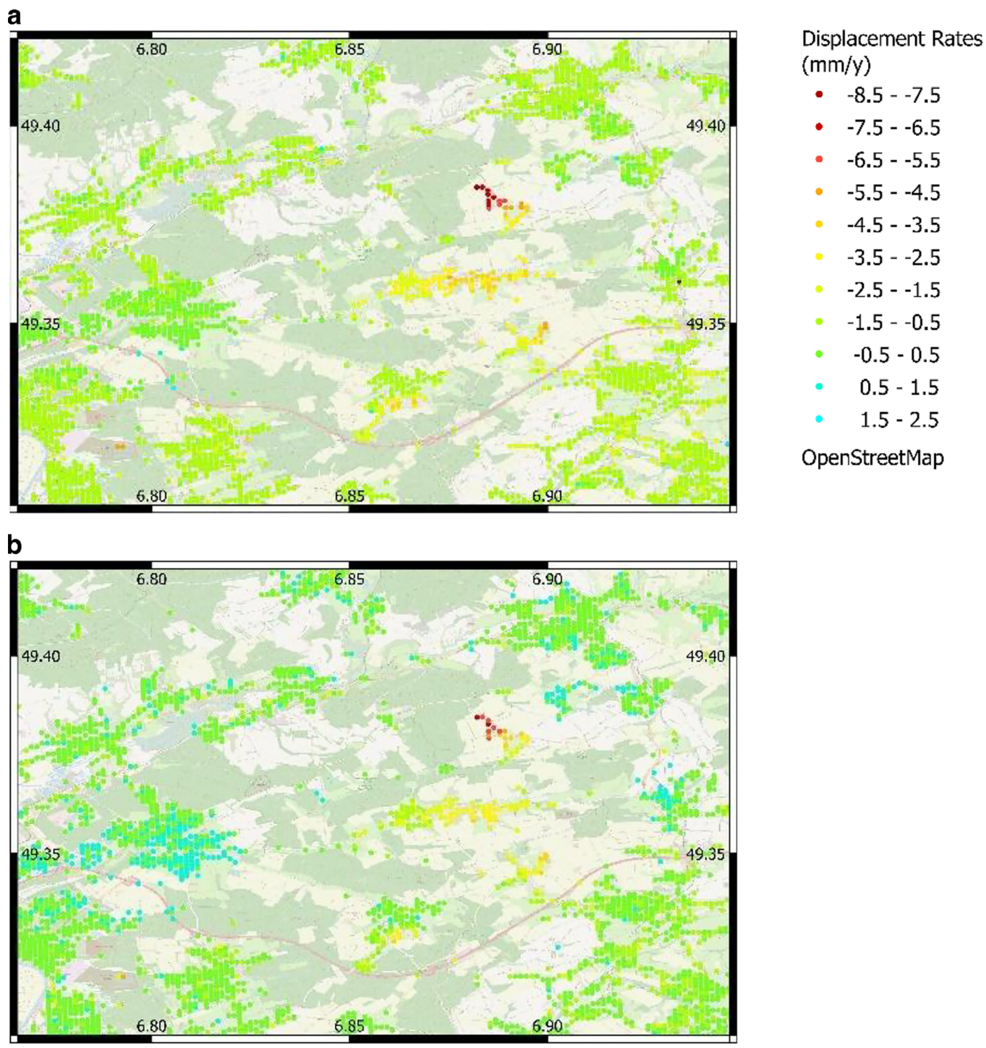


Fig. 8 Saarland: vertical displacement rates of BBD (**a**) and EGMS (**b**) for the period January 2016 to December 2021

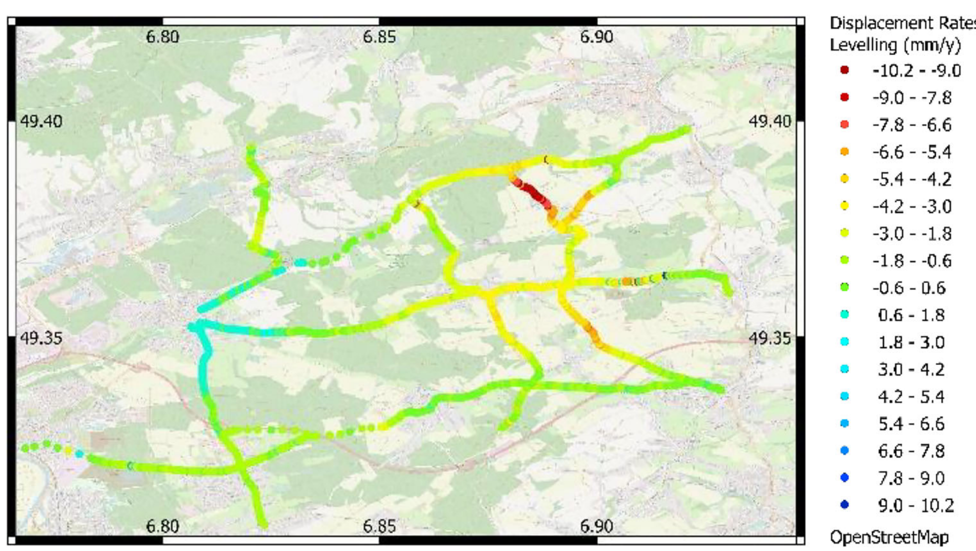


Fig. 9 Saarland: levelling points colored according to the displacement rates during the period April 2016 to April 2021

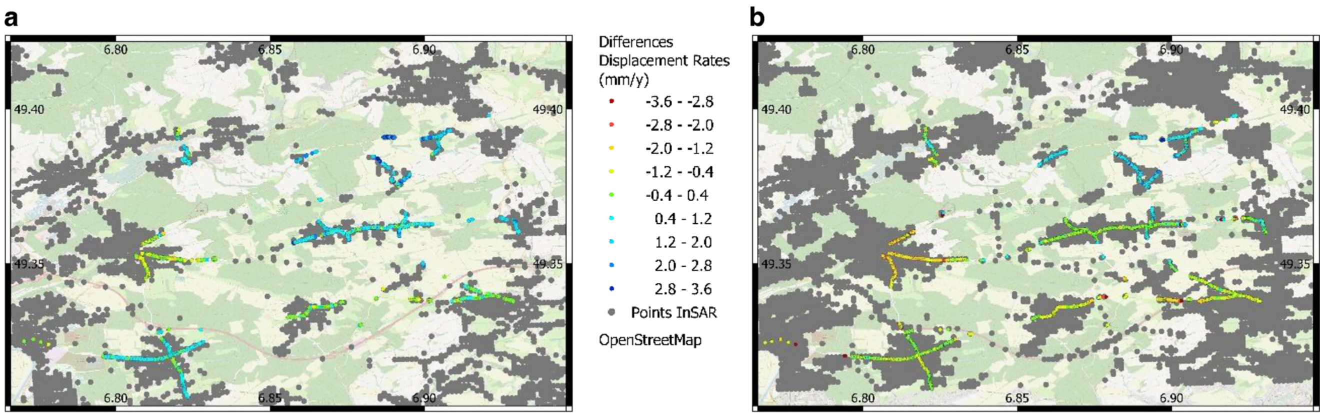


Fig. 10 Saarland: differences of vertical displacement rates between: **a** BBD and levelling, **b** and EGMS and levelling

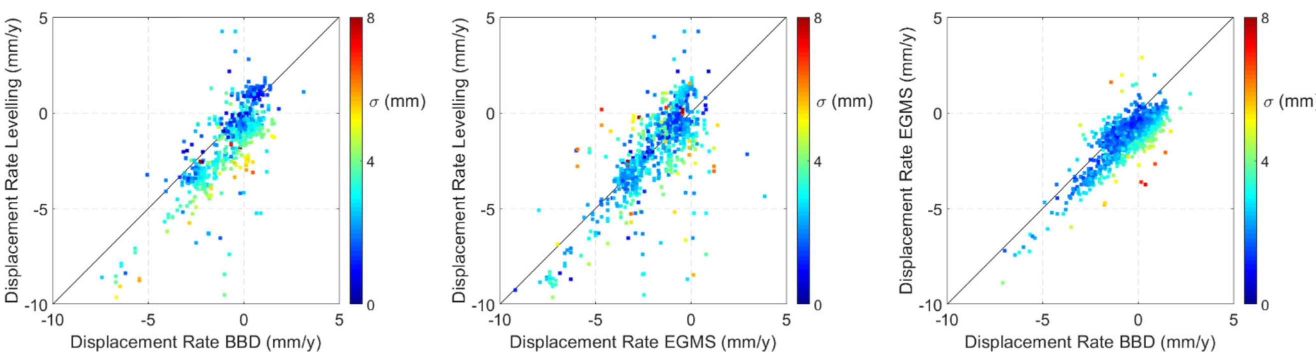


Fig. 11 Saarland: comparison of vertical displacement rates of BBD, EGMS, and levelling

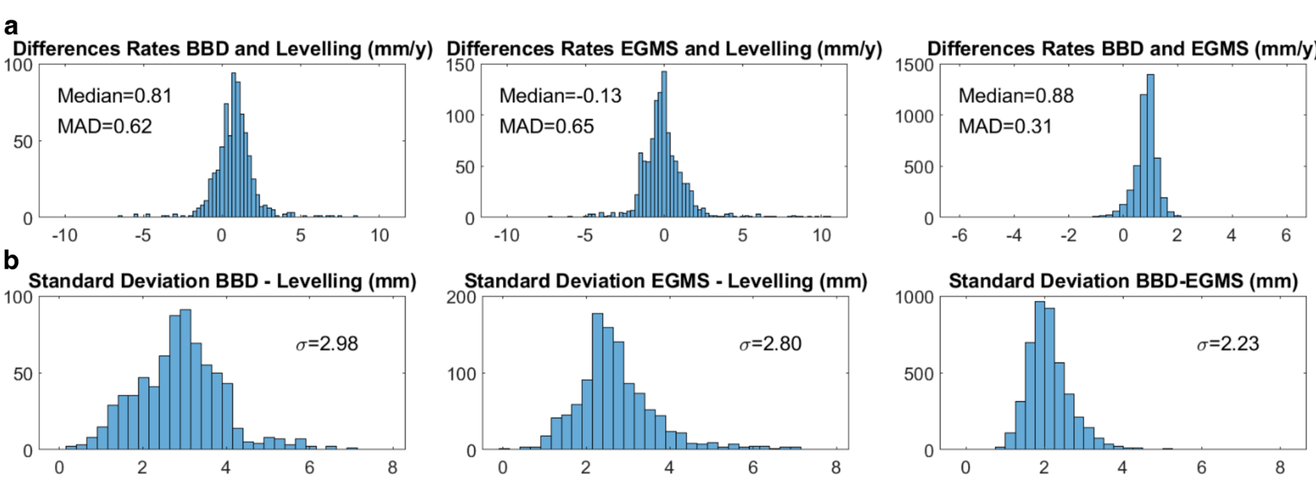


Fig. 12 Saarland: **a** differences of vertical displacement rates of BBD, EGMS, and levelling; **b** standard deviations of differences between vertical displacement of BBD, EGMS, and levellin. *MAD* Median Absolute Deviation of Median

due to the averaging and filtering done during orbit combination.

4.2 Saarland

For the Primsmulde, a former hard coal mining area in Saarland, RAG provided an impressive dataset with approximately half-annual measurement campaigns at 2436 levelling points. These are compared with the vertical products of BBD and EGMS. Furthermore, the vertical products are compared with each other. The vertical displacement rates of BBD and EGMS for points where a neighbor has been found are depicted in Fig. 8.

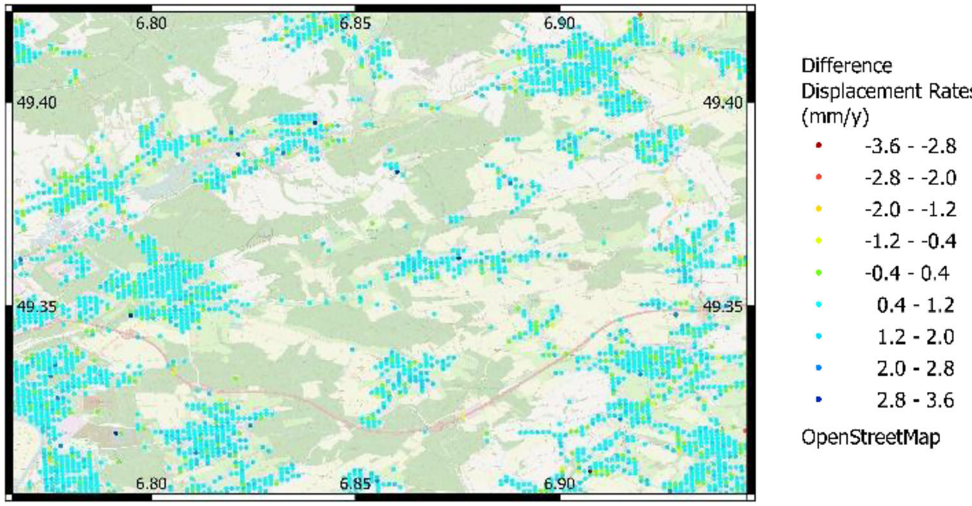


Fig. 13 Saarland: difference of vertical displacement rates between BBD and EGMS

4.2.1 Levelling at Primsmulde

During the period April 2016 to April 2021, for which data from both BBD and EGMS are available, ten measurement campaigns took place at Primsmulde. The levelling lines are shown in Fig. 9 and are colored according to the displacement rates during this period.

In order to perform the comparison, the time series of those levelling points contained in a grid cell of the respective data product were compared to the InSAR time series. Although this means that in the case of BBD (50 m × 50 m grid) the InSAR and levelling points are closer together on average than in case of EGMS (100 m × 100 m grid), we decided not to refine the grid of EGMS, as this would have reduced the number of comparisons significantly. This way, the time series of 727 levelling points could be compared with BBD data and 1095 with EGMS data. The comparison with both services was taken over the same period (April 2016 to April 2021), which means that the levelling campaigns in 2015 were not compared with BBD. Figure 10 shows the comparison between displacement rates of InSAR and levelling. The differences are mostly in a narrow range of ± 3 mm/y. Figure 11 shows the quality of agreement depending on displacement rates. Histograms and statistical numbers are given in Fig. 12. The agreement of EGMS with levelling is slightly better than that of BBD with levelling. The bias of displacement rates of BBD is about 0.7 mm/y worse than that of EGMS. The overall standard deviation between EGMS and levelling is only 2.80 mm, while that of BBD and levelling is 2.98 mm.

4.2.2 BBD Versus EGMS

Figure 13 shows the spatial comparison between displacement rates of BBD and EGMS. 4480 points were compared. Histograms and statistical values are given in Fig. 11. A significant bias of displacement rates of 0.88 mm/y and a very small variation around this bias (MAD 0.31 mm/y) were found. The overall standard deviation of 2.23 mm is moderate.

4.2.3 Conclusions Saarland

The comparison of BBD and EGMS with levelling data shows good agreement. The differences of displacement rates for EGMS are essentially unbiased, while for BBD a small but nonnegligible bias of 0.81 mm/y is observed. The bias of differences of displacement rates of BBD and EGMS for the vertical products has a similar value of 0.88 mm/y. The standard deviation of differences of displacements of BBD and EGMS is small, with 2.23 mm.

4.3 Western North Rhine-Westphalia

Displacements in the investigated region in Western North Rhine-Westphalia (NRW) stem from mining activity. Considerable linear displacements are caused by lowering the ground water table in the surroundings of open-pit mines, where lignite is exploited. In the West of the region, uplift is visible, which is a consequence of the flooding of former underground hard coal mines. We compared points of EGMS with nearby points of BBD. The displacement rates of the compared points are shown in Fig. 14. In addition, we downloaded levelling data from Geoportal NRW (Geoportal NRW), which comprise measurement campaigns in the area in 2017 and 2019. A 50 m × 50 m grid was used for the comparison of BBD data versus EGMS data and levelling data. If a grid cell contains a BBD point and an EGMS point, their displacements rates were compared. Analogously, levelling points near BBD or EGMS points were evaluated.

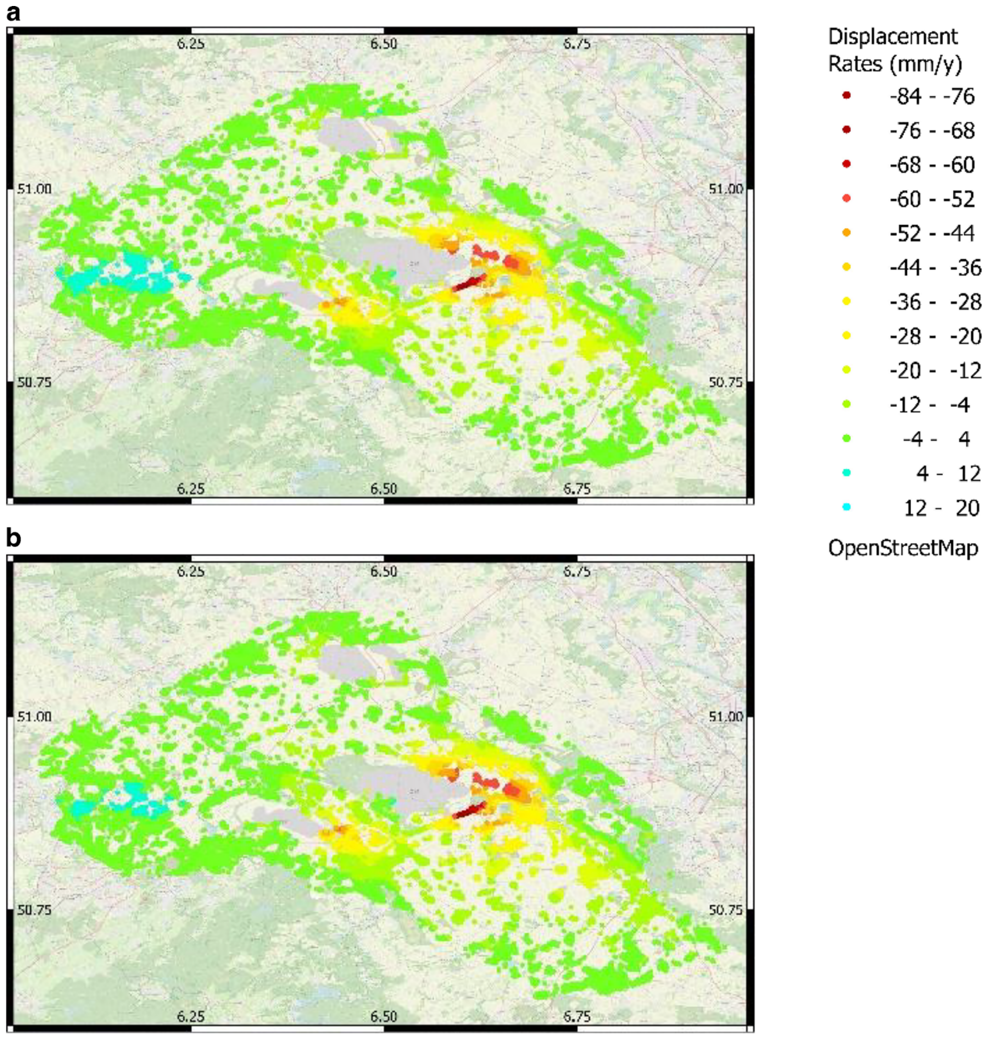


Fig. 14 Western NRW: vertical displacement rates of BBD (**a**) and EGMS (**b**; only EGMS points near BBD points are displayed) for the period January 2016 to December 2021

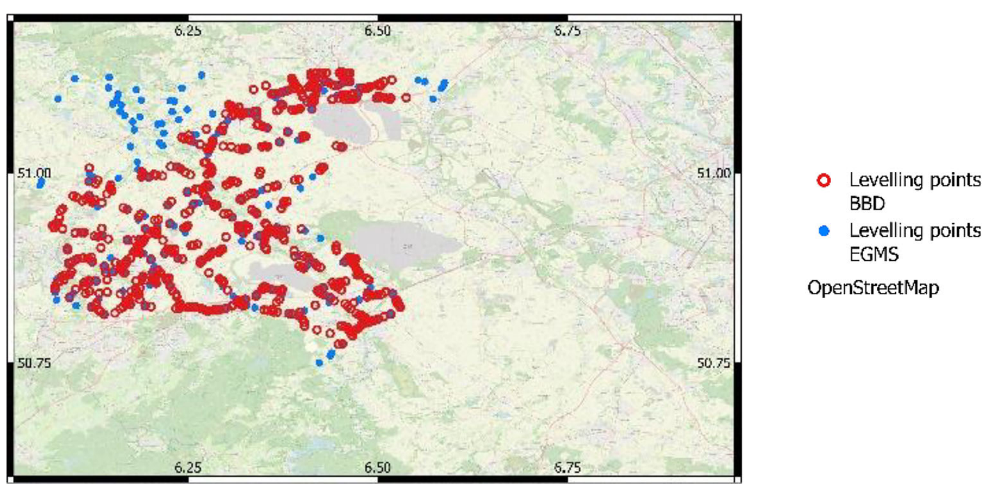


Fig. 15 Western NRW: locations of levelling points that were compared to InSAR

4.3.1 Levelling Western NRW

A total of 584 (BBD) or 279 (EGMS) levelling points are found in grid cells for which an MP from InSAR is also available. Their locations are shown in Fig. 15. Because the downloaded EGMS data cover a larger area than those of BBD, levelling points outside the area covered by BBD could be used as well. The overall agreement between levelling and InSAR results from both services is good. Histograms and statistical numbers are given in Fig. 16. The

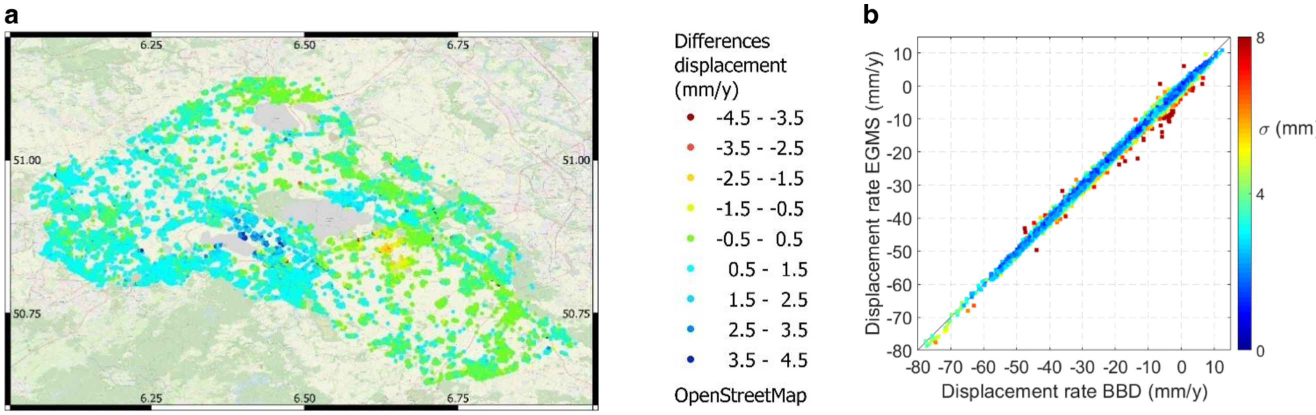
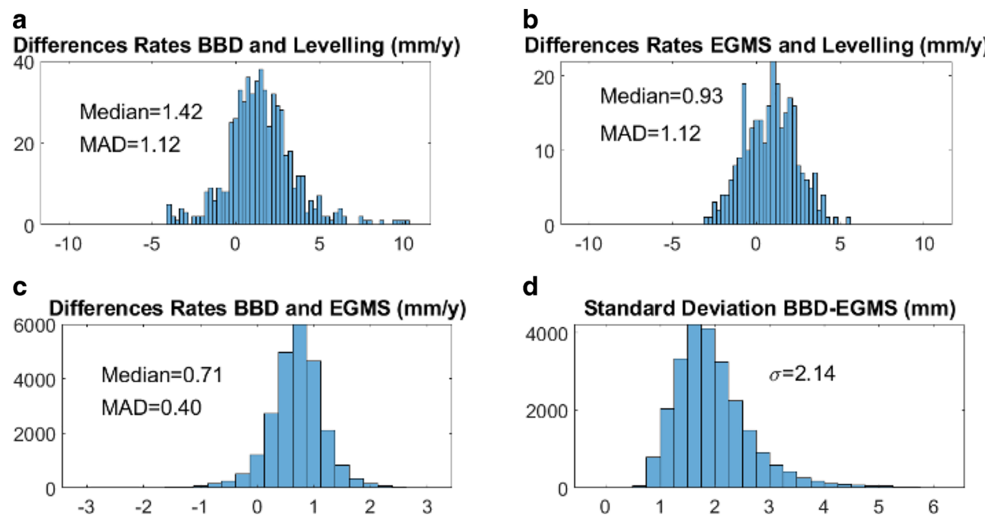


Fig. 16 Differences between vertical displacement rates of BBD and EGMS at Western NRW (**a**). The colors in (**b**) encode the standard deviation of the differences between the displacement time series of BBD and EGMS

Fig. 17 Western NRW: differences of vertical displacement rates of BBD (**a**) or EGMS (**b**) and levelling; differences of vertical displacement rates of BBD and EGMS (**c**) and standard deviations of differences between displacements of BBD and EGMS (**d**). *MAD* Median Absolute Deviation of Median



biases of 1.42 mm/y (BBD) and 0.93 mm/y (EGMS) are not negligible, but small compared to the magnitude of displacement rates. The agreement of EGMS with levelling is better than that of BBD with levelling. The bias of displacement rates of BBD is about 0.5 mm/y worse than that of EGMS. As only two levelling campaigns fell in the period for which BBD as well as EGMS data are available, the information given by differences of displacement and standard deviations of displacement is the same. Hence, we do not show the histograms of standard deviations. Nevertheless, the overall standard deviation between EGMS and levelling is only 1.76 mm, while that of BBD and levelling is 2.68 mm. As only two measurement campaigns fell in the period for which data from BBD and EGMS are available, this result should be treated with caution. Nevertheless, a better fit of EGMS with levelling than of BBD with levelling has was observed for Saarland.

4.3.2 BBD Versus EGMS

A total of 24,358 points of EGMS were compared to nearby points of BBD. Apart from individual exceptions, the agreement between the two services is good, as can be expected when the actual displacement is compatible with the displacement models used for processing (Fig. 16 and 17). The bias is nonnegligible with 0.71 mm/y and the overall standard deviation is 2.14 mm (Fig. 16). Figure 17 shows the spatial distribution of differences of vertical displacement rates and Fig. 17b a scatter plot of the vertical displacement rates of BBD and EGMS.

4.3.3 Conclusions Western NRW

The comparison of BBD and EGMS with levelling shows biases of differences of displacement rates that are nonnegligible (1.42 mm/y for BBD and 0.93 mm/y for EGMS); however, given the magnitude of displacements, these are relatively small. In addition, the errors of the displacement

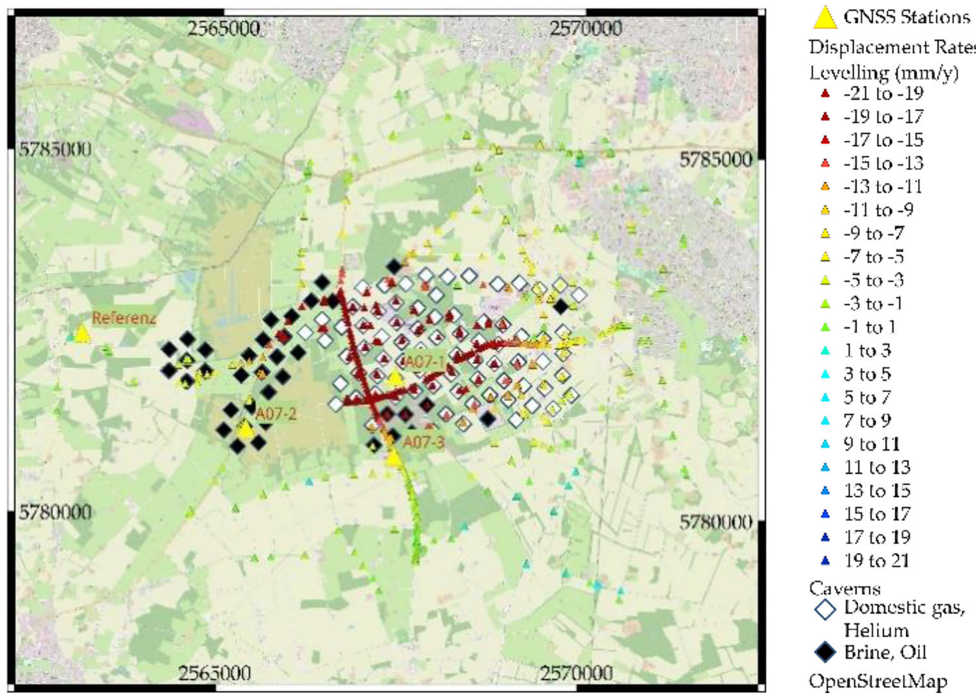


Fig. 18 Epe: caverns, levelling points, and GNSS stations

rates of levelling have to be taken into account as only two campaigns were used for the estimation. Likewise, the differences of displacement rates for the vertical products of BBD and EGMS, with a bias of 0.71 mm/y and overall standard deviation 2.14 mm (Fig. 17b), are relatively small.

4.4 Cavern Field Epe

Due to gas storage at Epe, nonlinear displacements occur that are not compatible with the displacement models of either service (Even et al. 2020, 2022). As anticipated, neither BBD nor EGMS are able to provide a correct description of the displacements in the area of strongest motion. This can be seen from levelling data that were provided by *Salzgewinnungsgesellschaft Westfalen* (SGW), the owner of the cavern field. In addition, SGW provided GNSS data from three stations (measured relative to a fourth reference station outside the area of displacement) that were recorded between June 2018 and October 2022. The locations of caverns, levelling points, and GNSS stations can be seen in (Fig. 18). Figure 19 shows the displacement rates of BBD and EGMS for the period January 2016 to December 2021.

4.4.1 Levelling and GNSS near Epe

The levelling data were collected during annual campaigns from 2015 to 2021 at 615 measurement points. In order to achieve comparability, the campaigns from 2016 to 2021 were used, for which data from both BBD and EGMS are available. We used 303 levelling points close to points of BBD and 447 levelling points close to points of EGMS. As not all levelling points were measured during each campaign, the comparisons are performed for different timespans. Nevertheless, 174 of the levelling points near BBD points and 279 levelling points near EGMS points were measured during all six campaigns. Although the biases and MAD values of differences of displacement rates between levelling and InSAR are unsuspicious (Fig. 20), the standard deviations show that levelling and BBD and EGMS time series do not fit well.

Fig. 21a shows an example time series of BBD, EGMS, and levelling for points close to GNSS station A071. BBD and EGMS do not follow a very strong subsidence in the winter 2017–2018 (visible in Fig. 21b). The time series of EGMS shows clear indication of an unwrapping error. The same misestimation concerns the whole area of strongest vertical displacement, as plots of differences of cumulated displacements between levelling and BBD or EGMS show (Fig. 22). A displacement model adapted to the phenomenon (Even et al. 2020, Even et al. 2022) would be needed to capture the strong gradients of the displacement field. The all-purpose models of the services are unable to describe the actual displacement satisfactorily.

4.4.2 BBD Versus EGMS

According to the statistics given in Fig. 20, the agreement between BBD and EGMS at Epe seems good, only that a nonnegligible bias of displacement rates of 0.91 mm/y is observed. This is due to the fact that most points that are

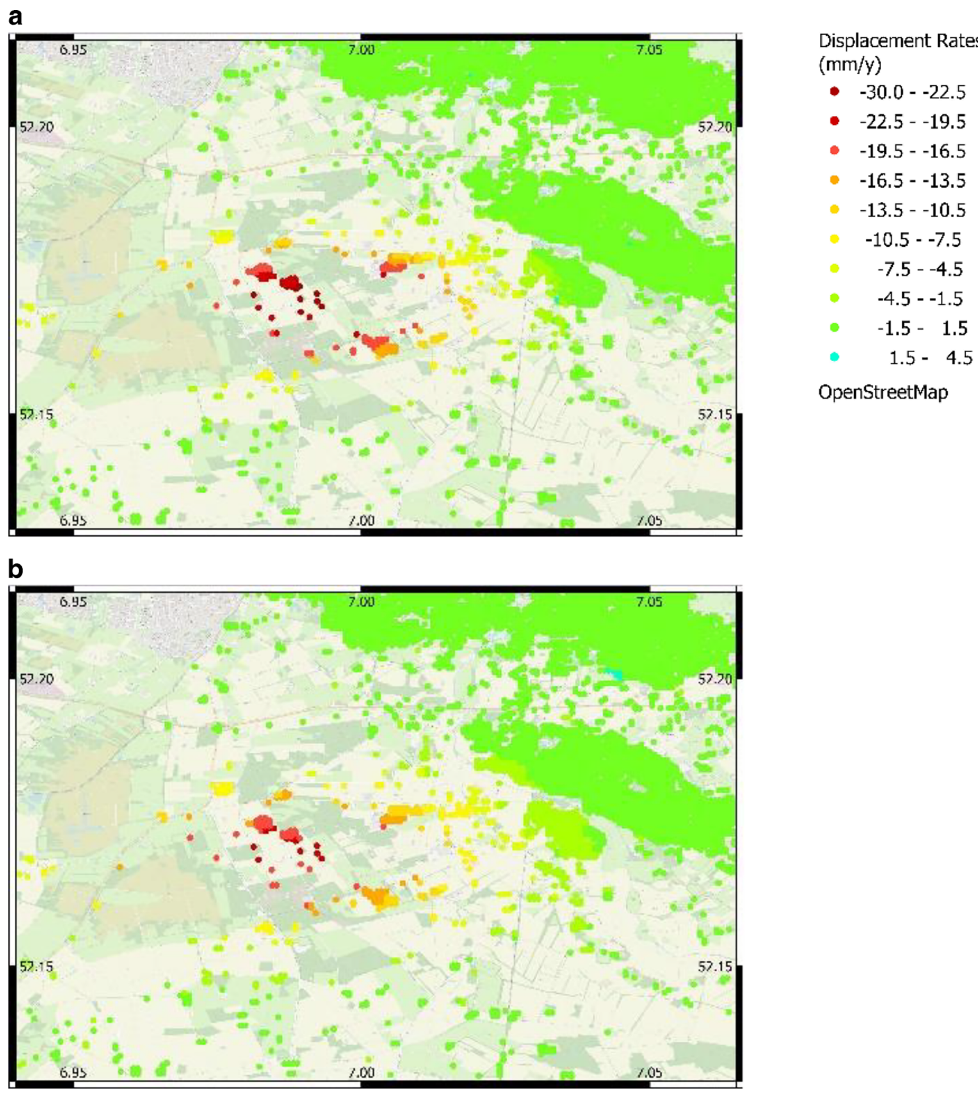


Fig. 19 Epe: vertical displacement rates of BBD (**a**) and EGMS (**b**) for the period January 2016 to December 2021

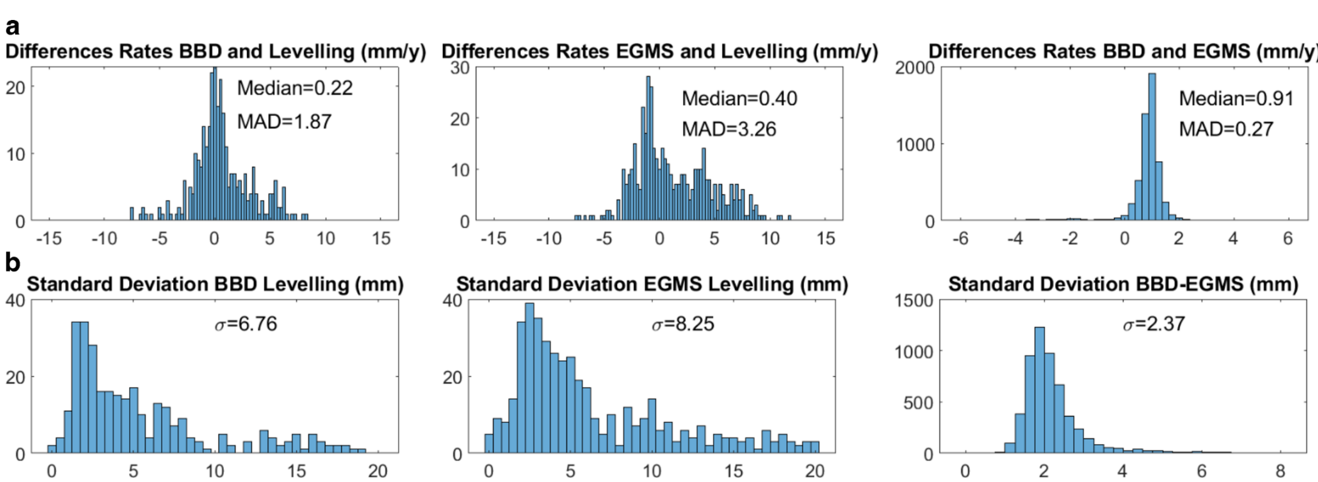


Fig. 20 Epe: **a** differences of vertical displacement rates of BBD and EGMS; **b** standard deviations of differences between vertical displacements of BBD and EGMS

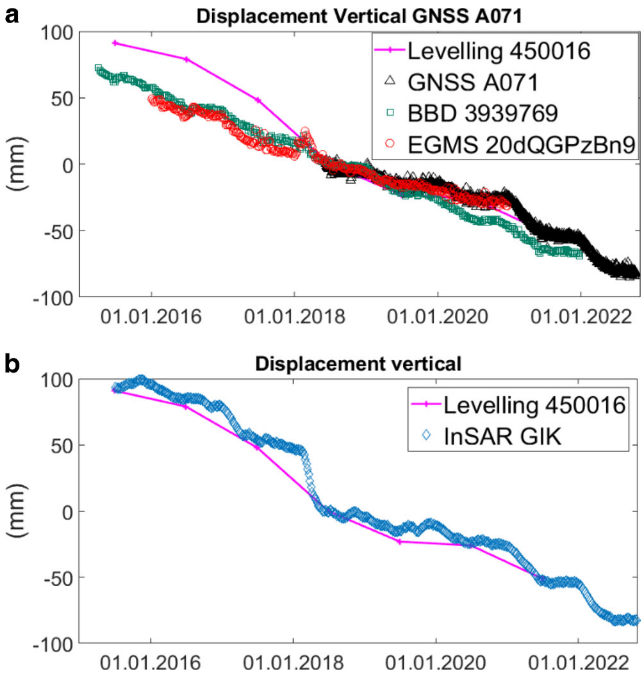


Fig. 21 Epe: vertical displacement near GNSS station A071 from levelling, GNSS, BBD, and EGMS (**a**) and InSAR processed by GIK (**b**)

used for the comparison are outside the area of strongest displacement; inside the area of strongest displacement, the differences of vertical displacement rates are bigger (Fig. 23).

4.4.3 Conclusions Cavern Field Epe

The comparison of BBD and EGMS with levelling or GNSS shows very considerable differences. These differences are due to a displacement pattern that cannot be well described by the displacement models of BBD or EGMS. The agreement between BBD and EGMS in the area of strongest displacement is also worse than in the surrounding area or at any of the other locations investigated for this study.

5 Discussion and Conclusion

We studied the quality and coverage of BBD and EGMS based on data from four locations. The comparison of BBD and EGMS data with SAPOS data of Baden-Württemberg shows slightly bigger biases of differences of displacement rates for EGMS. This might be due to a less optimal calibration caused by the less dense network of GNSS stations available to EGMS as well as to the use of the same SAPOS stations for BBD calibration and our validation. The coverage of linear infrastructure with MP from InSAR is distinctly higher for EGMS. It can be expected that the use of DS would further increase the coverage, which would be very valuable for monitoring. In addition, the gridded products show poor coverage compared to the LoS products. The agreement of EGMS with levelling in Saarland and western NRW is slightly better than that of BBD with levelling (smaller bias, smaller standard deviation). Currently, we have no explanation for this observation. A connection with the longer timespan processed for BBD seems possible. Nevertheless, both services show good agreement between InSAR and levelling for these locations. The agreement of BBD and EGMS is good for the investigated data from Baden-Württemberg, Saarland, and western NRW. An exception is the cavern field at Epe, which is challenging for InSAR because of the pronounced spatiotemporal gradients of the displacement field. In the area of strongest displacement, large deviations of BBD and EGMS data from levelling and GNSS data are observed. The mass processing of InSAR data performed by BBD or EGMS does not suffice in this situation to provide accurate measurements. Finally, we want to emphasize the value of LoS observations and of DS for monitoring purposes. The much better coverage and, in the case of LoS products, better localization precision, makes them indispensable.

Acknowledgements We are grateful to Jenny Uskow and Hans-Georg Dick of LGL for providing geodetic data of Baden-Württemberg. Furthermore, we want to thank RAG, namely Michael Drobniewski, Ute Kristin Weißenborn, Andreas Thoß, and Steffen Bechert, for pro-

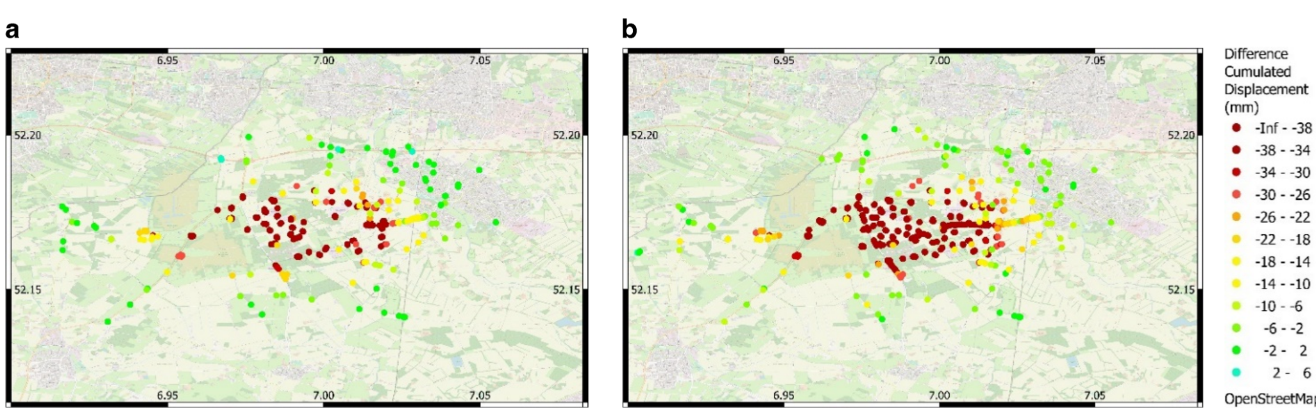


Fig. 22 Differences of cumulated vertical displacement at Epe. **a** BBD versus levelling; **b** EGMS versus levelling

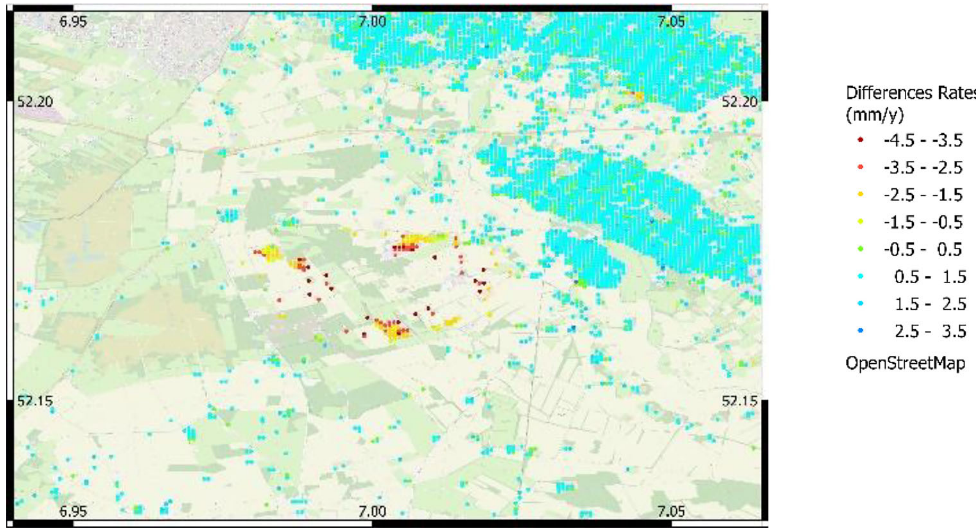


Fig. 23 Epe: differences of vertical displacement rates between BBD and EGMS

viding the levelling data of Saarland. For the levelling and GNSS data of Epe we want to thank SGW, in particular Stefan Meyer. Moreover, we are grateful to Andre Kalia of BGR for providing information on the processing of data for BBD and EGMS. Finally, we thank our colleague Alison Seidel for providing the InSAR time series of Epe.

Funding This work was partially funded by LGL.

Author Contribution Conceptualization, M. E.; methodology, M. E.; software, M. E.; validation, M. E.; formal analysis, M. E.; investigation, M. E.; resources, H.K.; data curation, M. E.; writing—original draft preparation, M. E.; writing—review and editing, M.W. and H.K.; visualization, M. E.; supervision, M.W. and H.K.; project administration, M.W.; funding acquisition, M.W. and H.K. All authors have read and agreed to the published version of the manuscript.

Funding Open Access funding enabled and organized by Projekt DEAL.

Availability of Data and Material The geodetic data used for this work were provided within the framework of projects and collaborations and cannot be made available to third parties.

Code Availability Upon request, parts of the code could be made available.

Conflict of interest M. Even, M. Westerhaus and H. Kutterer declare that they have no competing interests.

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