Karlsruhe Integrated Displacement Analysis Approach Towards a rigorous combination of different geodetic methods

Bernhard HECK, Michael MAYER, Malte WESTERHAUS, and Karl ZIPPELT (Germany)

Key words: Deformation analysis, InSAR, leveling, permanent GNSS sites, recent crustal motions, Upper Rhine Graben

SUMMARY

In recent years, dense GNSS (Global Navigation Satellite Systems) permanent networks have been established widely, the new PS-InSAR (Persistent Scatterer SAR Interferometry) method became operable and multiple repeated precise leveling lines are available to estimate recent displacements of the Earth's surface. Simultaneously, geodetic reference frames and processing models have been greatly improved. The available data provide a unique opportunity to derive detailed maps of surface movements. However, a joint interpretation is not straight forward since each method relies on its own characteristics (e.g. internal database, sampling interval, spatial resolution, reference frame and processing model). A stringent integration and unification of the various data types and their homogeneous combined analysis is still missing today. The available analysis models are fully formulated only for single methods.
Our aim is the development of a methodology to consistently link all geodetic observation methods such as GNSS, leveling and PS-InSAR in a multi-techniques approach and to facilitate a joint rigorous geodetic displacement analysis. Problems to be solved are inherent to (i) major differences in the temporal and spatial resolution of the involved methods, (ii) different time-dependant reference systems, and (iii) changing geometry of the Persistent Scatterer networks as well as the imprecisely known dimensions and locations of the PS points. A mutual cross validation of the involved methods in order to assess the reliability of (apparent) movements obtained by either method will be implemented in the future. As a result, the integrated geodetic displacement analysis will deliver homogeneous, temporarily and spatially dense maps of surface movements with improved accuracy and reliability. These maps can either be inverted with respect to subsurface deformation processes or define important boundary conditions for a refined geophysical numerical modeling. The paper will present the first steps to implement our approach in the border region between Germany, France and Switzerland where dense, overlapping multi-sensor networks are available.

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1. MOTIVATION

In recent years, substantial progress in various geodetic techniques was made. This holds for satellite geodetic sensors as well as data processing strategies, where models are getting more and more realistic (e.g. time and spatial resolution). In addition, increasing processing power enables to improve the quality of achievable results. The most prominent satellite geodetic sensors – which are taken into account within the here described research project – are

- continuously operating GNSS (Global Navigation Satellite Systems) networks and
- advanced InSAR-based techniques like PS-InSAR (Persistent Scatterer SAR Interferometry).

In addition to these techniques, modeling within the traditional highly precise geodetic technique leveling also benefits from recent advance of computer performance. These facts provide a unique opportunity to derive revised detailed maps of surface movements by means of combining synergistic benefits and cross-validating approaches based on a stringent integration and unification of various data types and their homogeneous combined analysis. However, the available analysis models are fully formulated only for single geodetic techniques. Within the new KIDDA (Karlsruhe Integrated Displacement Analysis Approach) project, the Geodetic Institute (GIK) of the Karlsruhe Institute of Technology (KIT, Karlsruhe/Germany) carries out geo-scientific research in order to overcome this remedy.

The geographical area under research within the KIDAA project is the Upper Rhine Graben (URG). The KIDAA project is embedded in the transnational project TOPO-WECEP (Western and Central European Platform; link: http://www.topo-wecep.eu/; CLOETINGH ET AL. 2007), which succeeded the former project URGENT (Upper Rhine Graben Evolution and NeoTectonics; link: http://comp1.geol.unibas.ch/; BEHRMANN ET AL. 2005) of the EUCOR universities (European Confederation of Upper Rhine Universities). Within these programs various and promising experiences were gained using the above mentioned sensors independently.

The Rhine Graben is the central, most prominent segment of the European Cenozoic rift system which extends from the North Sea through Germany and France to the Mediterranean Sea over a distance of some 1000 km (ZIEGLER 1992; BOURGEOIS ET AL. 2007). Within the here described geo-scientific multi-sensor project, the focus will be on the Upper Rhine Graben (URG). The URG is a 300 km long and 40 km wide SSW-NNE trending rift, extending from Basel (Switzerland) to Frankfurt (Germany). It is bounded to the west by the Vosges Mountains and to the east by the Black Forest, while the uplifted area of the Rhenish Massif terminates the rift to the north. To the south, the Leymen, Ferrette, and Vendlincourt folds represent the northern-most structural front of the Jura fold and Thrust belt. Preceded by late Cretaceous volcanism, the rifting was initiated during Late Eocene to early Miocene (42-

31 Ma) starting with broadly E-W resp. ENE-WSW extension and lasted until Aquitanian time (20 Ma). Today, the southern end of the Rhine Graben is characterized by small uplift and subsidence rates and by a quasi-compressive, left-lateral strike-slip tectonic regime, with a maximum stress-axis oriented NW-SE. The URG is considered to be the most seismically active region of northwest Europe with significant probability for the occurrence of large earthquakes (MEGHRAOUI ET AL. 2001; see Fig. 1).

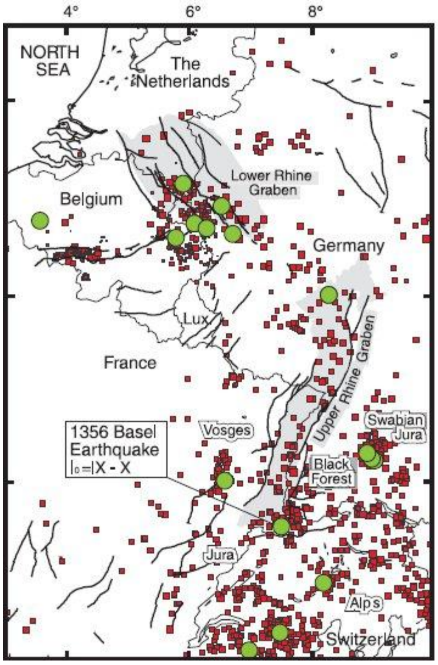

Fig. 1: Seismotectonic framework of the Lower / Upper Rhine Graben. Squares depict instrumental seismicity from 1910 to 1990 (1<M<5.5). Circles correspond to historical seismicity (MEGHRAOUI ET AL. 2001).

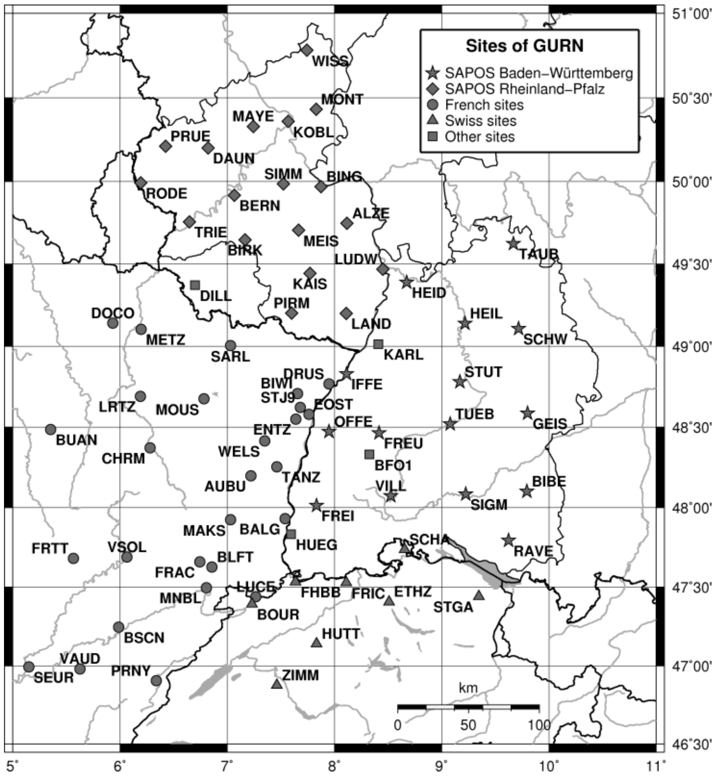

Fig. 2: Sites of GURN, status: July 2009.

For a better understanding of the processes that lead to seismic activity in the URG, it is necessary to study not only the location of the faults but also their kinematics. Seismic hazard assessment in the URG is hindered by a lack of information on the time-dependent and high resolution behavior of active structures. Within KIDAA, the GIK will contribute to remedy this regional defect by using synergistic benefits of a rigorous combination of different geodetic methods.

2. CONTRIBUTION OF VARIOUS OBSERVATION TECHNIQUES

Within this section the three contribution observation techniques (Sect. 2.1 GNSS, Sect. 2.2 leveling, Sect. 2.3 PS-InSAR) are described. A special focus is on the URG, which is the area of research.

2.1 The GNSS Upper Rhine Graben Network GURN

In September 2008, the Ecole et Observatoire des Sciences de la Terre (EOST, CNRS and Strasbourg University, Strasbourg/France) and the GIK established a transnational co-operation called GURN (GNSS Upper Rhine Graben Network). Within the GURN initiative these institutions are cooperating in order to carry out geo-scientific research in the frame-work of the transnational project TOPO-WECEP. The research within GURN is actually based on observation data of continuously operating GNSS sites in order to establish a highly precise and highly sensitive terrestrial network for the reliable point-wise detection of recent crustal movements (3d, horizontal, vertical) in the URG region.
Geodetic measurements using satellite techniques (e.g. GPS) have a long tradition in the URG, e.g. within the project EUCOR/URGENT, GPS campaigns have been carried out in 1999, 2000, and 2003. These campaigns were suffering from the small number of occupied sites (approx. 30) as well as from poor and inhomogeneous spatial resolution. In addition, the amount of GPS data (2 x 24h) and therefore the temporal resolution was poor. Nevertheless, the results and experiences gained were quiet promising (see ROZSA ET AL. 2005a, 2005b). These data, as well as an analysis of data from permanent GPS stations between 1996 and 2001 (NOCQUET AND CALAIS 2003) set an upper bound of 0.6 mm/a on horizontal movements across the URG. A more detailed analysis was not possible at that time since the spatial resolution of the data sets exceeded 100 km.
At the beginning GURN consisted of German and French continuously operating GNSS sites. Most data of the German sites were provided from SA*POS*®-Baden-Württemberg. SA*POS*® is a service hosted by the German state surveys, see WEGENER AND STRONK (2005). Most sites were recently (2008-2009) enabled to track GLONASS data. All SA*POS*® antennas are calibrated on absolute and individual level. In contrast to the German GNSS sites, the GNSS data of the French sites have several origins: RENAG (network hosted by universities and research institutes, including EOST; http://webrenag.unice.fr/), RGP (network of Institut Géographique National), Teria (private company, see GAUDET AND LANDRY 2005), and Orpheon (private company). The antennas of the French sites are not calibrated individually. Additionally, other continuously operating sites existing in and around the URG were included, e.g. IGS (DOW ET AL. 2005) resp. EPN (BRUYNINX 2004) sites like HUEGelheim and ZIMMerwald as well as the GNSS site BFO1 of the Black Forest Observatory (LUO AND MAYER 2008).
In June 2009, GURN was extended to the north and to the south when SA*POS*®-Rheinland-Pfalz (http://www.lvermgeo.rlp.de/indexsapos.html) and the Federal Office of Topography swisstopo (http://www.swisstopo.ch) joined GURN.
The resulting network covers the whole URG region homogeneously. The mean distance between the network sites is 40-60 km. GURN actually consists of approx. 75 permanently operating reference sites, see Fig. 2, which are delivering data in near real-time. SA*POS*®-Baden-Württemberg archives GNSS data since 2002, while SA*POS*®-Rheinland-Pfalz collects data since 2004. Tab. 1 gives an overview of the data history of GURN.

Tab. 1: History of GURN observation data.

year	2002	2003	2004	2005	2006	2007	2008
number of GURN sites	13	17	42	44	46	48	65

The first results of GURN are described in KNÖPFLER ET AL. (2010) and MAYER ET AL. (2009) in detail. A special focus is hereby on the verification of the achievable quality with respect to the various origins of the data, especially.
Due to the fact that GURN is a project aiming for the long-time monitoring of the slow moving (sub-mm per year; ILLIES 1977, 1979) URG, a special focus has to be set on sites showing significant horizontal or vertical displacements. The behavior of these sites has to be checked in detail in order to distinguish between representative and not representative resp. local and regional displacements, as example in Fig. 3 the EOST times series (northing, easting, up) of site 0391 established on a building's roof top is shown. The continuously decreasing of the vertical coordinate component is clearly visible.

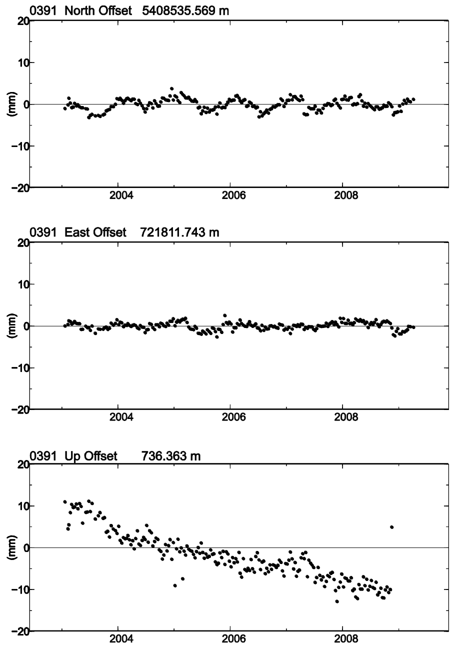

Fig. 3: Detrended time series (10-day-mean; northing, easting, up) of the site 0391 showing a significant vertical displacement.

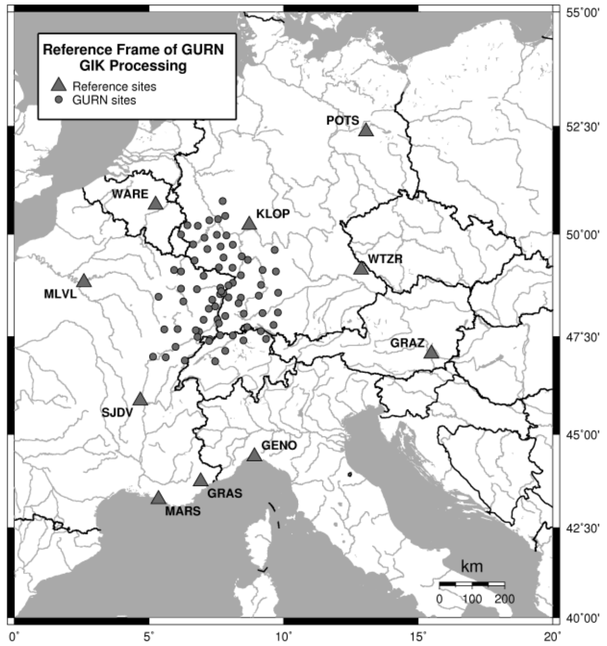

Fig. 4: Framework realization of the GIK working group. Site selection based on geometrical distribution, data history, and data quality.

In contrast to the EOST data processing strategy, the GIK uses the Bernese Software V5.0 (DACH ET AL. 2007). Within this analysis the observations of ~9 IGS-EUREF sites were included in order to link the regional GURN to the global ITRF2005 (see Fig. 4). In order to derive coordinate time series which are easily interpretable, the Eurasian trend is eliminated and the absolute coordinates are transformed into local topocentric coordinate increments.
Fig. 5 is showing the detrended time series (northing, easting, up) calculated by the GIK working group of site 0392 as an example for discontinuities of coordinate time series due to instrumentation replacement. A step within the three time series of site 0392 at the beginning of the year 2004 is clearly visible. Such steps are actually removed in order to gain a continuous data base. Therefore, a careful and detailed analysis of the history of the GURN sites is necessary.

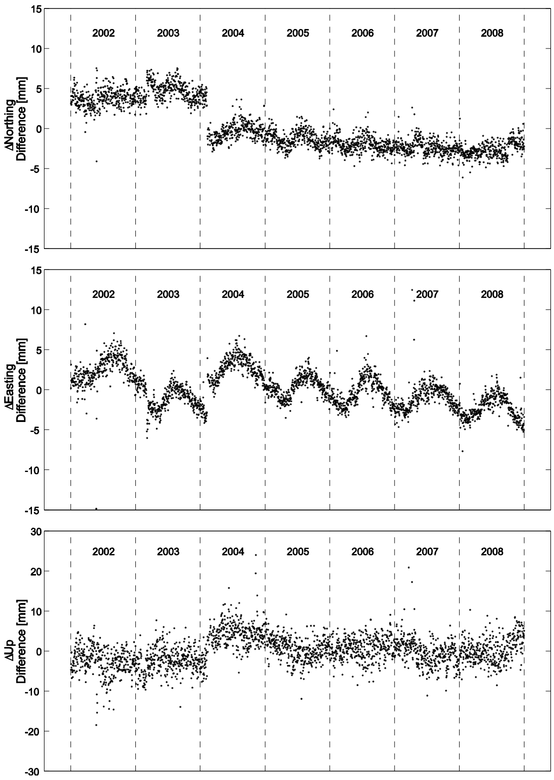

Fig. 5: Detrended time series (GIK, daily solution; northing, easting, up) of site 0392.

2.2 Leveling: Database and GIK expertise in the Upper Rhine Graben

As discussed above, the URG as well as southwest Germany are regions of increased seismicity, which is linked to recent tectonics. The active tectonic motions are very small in horizontal and in vertical direction. Measurements with high accuracy and over a period as long as possible are necessary to detect resp. investigate these motions.

Leveling is most appropriate to investigate surface vertical motions, e.g. caused by neotectonics. These data are available over a long time – in some URG regions up to 85 years – and they have been collected carefully with a very high precision. Since precise leveling is a time-consuming observation method – regional observation campaigns are lasting for years, the data are scattered in time and therefore require special analysis procedures to provide reliable estimates of height changes.

The recent investigation carried out at the GIK combines leveling data of 1st and 2nd order from different countries (e.g. Germany (Baden-Württemberg, Bavaria), Switzerland), see ZIPPELT AND DIERKS (2006). The accumulated data form a network consisting of more than 4000 leveling points. The locality of the points in Switzerland and a numerous points in the region of southern Black Forest and Lake Constance were classified by geological evaluation in view of reliability resp. stability. The leveling data were converted to a common height system and analyzed using a kinematic modeling approach. Along the evaluated leveling lines the very promising results show a detailed pattern of vertical movement rates, which is widespread in the range of ±0.4 mm/a. Rising outside this range, the estimated movements become statistically significant. ZIPPELT AND DIERKS (2006) found ascertained subsidence of the southern Rhine Graben and the Dinkelberg area, compared to the crystalline Black Forest, whereas the area of Hegau in the north of Lake Constance presents variable and mostly not significant movement rates (Fig. 6). Additionally, it was shown that the Swiss molasses basin is a stable area with very small and alternating rates of subsidence and uplift. The analysis of highly precise leveling data will be extended starting in 2010 to the northern URG and towards France.

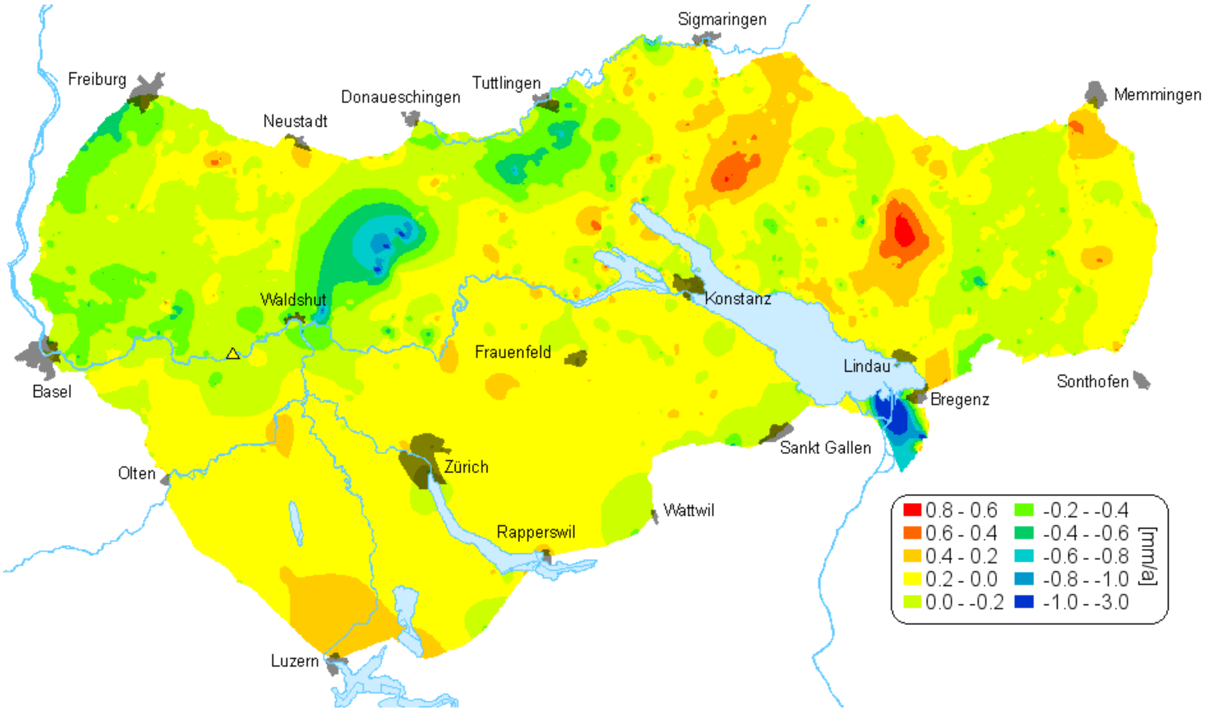

Fig. 6: Vertical displacement rates after ZIPPELT AND DIERKS (2006).

2.3 InSAR: Principles and first results from Upper Rhine Graben

Radar satellites (e.g. ERS1/2, ENVISAT) emit monochromatic radar signals. A small fraction of the signal energy is scattered back by the ground and reaches the radar antenna with a certain time delay. The time delay is expressed as a phase shift between the original and the back scattered signals. After 35 days, the C-band satellite ENVISAT crosses the same region again and obtains a 2^{nd} radar image of the ground. Displacements of the ground surface between the two passes of the satellite will lead to a different phase of the 2^{nd} image. Subtraction of both images gives the phase difference (e.g. interferometric phase), which can be directly converted into areal ground displacement.
The interferometric approach relies on temporarily stable back scattering conditions of the ground. This condition is supposedly violated for regions with agriculture, forests or lawn, as it is the case for the URG area. To test the interferometric conditions in this area, 24 C-band scenes of ERS1/2 and ENVISAT have been processed computing the coherency and inter-

ferometric phase. The processing was done using the inteferometric processor DORIS (Delft Object-orientated Radar Interferometric Software, KAMPES ET AL. 2003). A SRTM digital terrain model (U.S. Geological Survey, USGS) was used to remove topography effects.
Coherency is a measure of the quality of a SAR interferogram. Low coherency indicates de-correlation and high phase noise. Among others, this occurs if the back scattering conditions of the ground are not stable over time. As anticipated, the investigated region in the URG south of Mannheim/Germany shows an 'urban' coherency pattern (Fig. 7). Coherency values above 0.3 are obtained over urban areas and sometimes along roads. Only in these regions the interferometric phase can be exploited with respect to surface displacements (Fig. 8). For the rural parts coherency is very low. A comparison of several successive interferograms shows that the coherency pattern does not change with time. This first application of SAR interferometry in the URG area proves that an investigation of the interferometric phase with respect to surface movements is possible for limited regions only. However, the test also shows that it will be possible to apply the Persistent Scatterer method in urban areas. This will give refined time series of ground displacement and will significantly densify the information obtainable from GNSS and leveling alone. Thus, even for a 'difficult' region like the URG, InSAR is supposed to contribute considerably to an improved assessment of surface displacements via the envisioned multi-sensor approach.

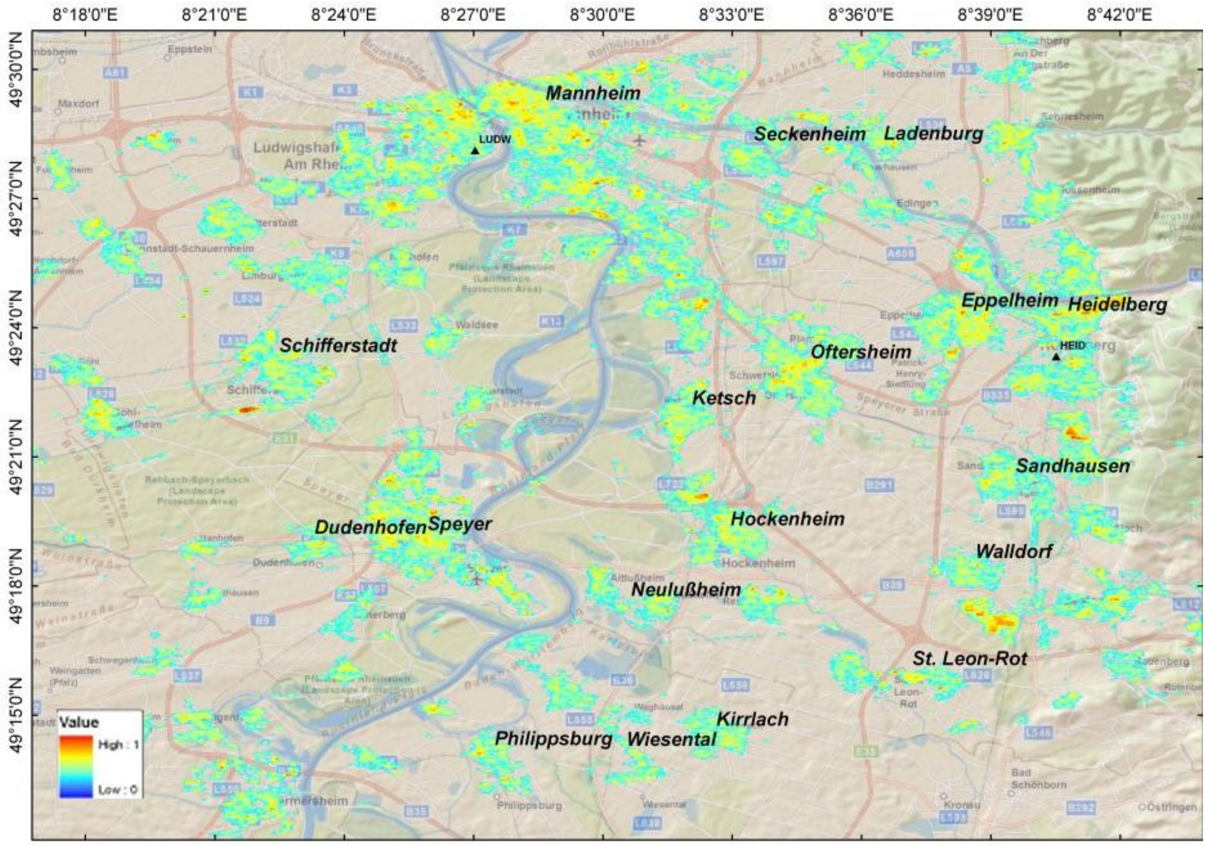

Fig. 7: Example for coherency obtained in the URG. The figure shows a stack of six ENVISAT scenes taken from an ascending orbit between August 1996 and July 2006. Coherency values below 0.3 have been masked out**.**

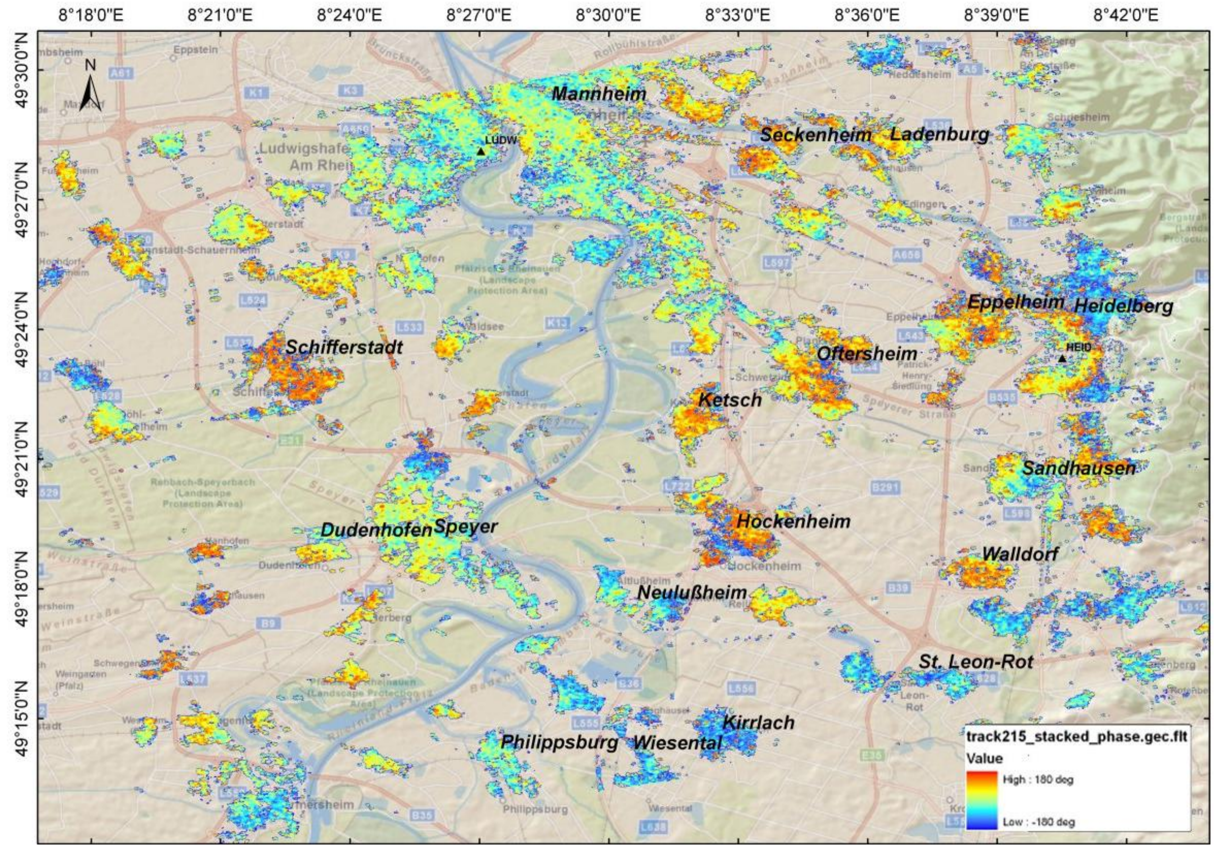

Fig. 8: Example for the SAR-interferometric phase obtained in the URG. The figure shows a stack of six ENVISAT scenes taken from an ascending orbit between August 1996 and July 2006. Phase values have been masked out where coherency is below 0.3.

3. CONCLUSIONS AND FUTURE WORK

Within Sect. 2 the three sensors GNSS, leveling, and PS-InSAR were discussed with a special focus on the region under research and the characteristic features of the proposed methods resp. sensors.

- *GNSS:* GNSS observations facilitate the determination of absolute 3-D coordinates and displacements, which can be separated into vertical and horizontal components. This is a unique feature compared to InSAR and leveling. Furthermore, GNSS is the sole method that can be operated with sampling rates of up to 100 Hz. The achievable accuracy for horizontal displacements is several mm; for vertical displacements the method is worse by a factor of about 2-3. In the years to come, the accuracy will be enhanced by additional global navigation systems like the European Navigation Satellite System GALILEO as well as similar efforts in other countries (e.g. COMPASS/China). However, GNSS requires distinct receiver stations at the ground, thus, information about surface movements is available only for single points.
- *Leveling:* Highly precise leveling still is the most precise method to determine height differences between two nearby points. Height changes of up to 0.1 mm on a distance of 1

km can be significantly determined. Since more than 80 years ordnance surveys in Europe carry out repeated precise leveling campaigns across the whole countries (temporal resolution: approx. 20 years). Taking into account the high precision of the method and the long time span of available data, this method is most suited to quantify even slow uplift and subsidence rates within the URG or other tectonically active regions. However, leveling campaigns require a lot of manpower, the obtainable time span between successive campaigns is of the order of weeks/months (local applications) up to years (regional applications), and information about height changes is available only on lines.

- *SAR Interferometry:* SAR interferometry (InSAR) is the sole method able to deliver areal information about surface movements. The achievable accuracy is of the same order as for GNSS. In contrast to GNSS, however, InSAR does not determine absolute 3-D coordinates but relative movements in the direction of the line-of-sight (LOS) between a ground resolution cell (about 10 m by 10 m) and the satellite. By stacking of several SAR-scenes taken from ascending and descending orbits, the LOS displacements can be separated into vertical and east-west components. Displacements in north-south direction are not observable by the current satellite-based SAR missions. Repeated measurement intervals are 35 days for the current C-band satellites like ENVISAT, and 11 days for the DLR X-band mission TerraSAR-X.

The next step of the initiated project will be to develop a multi-techniques joint rigorous geodetic displacement analysis concept. Therefore, a hybrid measurement concept, consisting of the components GNSS, leveling, and InSAR is going to be used. The components will be collocated at fundamental sites that realize an unambiguous reference and provide the observational basis for a stringent combination of the three methods. The mathematical approach to combine the three methods will be based on geodetic displacement analyses according the Karlsruhe Model (MAYER ET AL. 2000; ZIPPELT AND DIERKS 2007). This algorithm contains numerous statistical tools (e. g. tests to unravel stable blocks and significant single point movements within a network, estimation of realistic accuracies). So far, the model is fully formulated for single methods only (point-wise input data (e.g. GNSS) resp. leveling-line-related). For the envisioned multi-sensor displacement analysis, the functional as well as the stochastic model of the present concept have to be considerably improved. The approach has to overcome several problems like

- different reference systems for ground-based and space-born methods,
- combination of data with extremely different temporal and spatial resolution,
- the continuously varying geometry of Persistent Scatterer networks (network of opportunity) as well as the imprecisely known location of Persistent Scatterer points, and
- the development of an efficient uncertainty propagation method.

Another aim of the research project will be to mutually verify GNSS, PS-InSAR, and leveling data. The ultimate goal is to create an integrated data set with high spatial and temporal resolution, to quantify recent lateral and vertical crustal motions on regional scale, and to provide realistic estimates of accuracy in the URG.

Ultimately, a combination of horizontal motion from permanent GNSS and vertical motion from leveling/InSAR will facilitate maps of on-going deformation with unprecedented accuracy.

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REFERENCES

BEHRMANN, J., P. ZIEGLER, S. SCHMID, B. HECK, AND M. GRANET (2005). The EUCOR-URGENT Project. *Int. J. Earth Sciences (Geol. Rundschau)*, 94(4), 505-506.

BOURGEOIS, O., M. FORD, M. DIRAISON, C. LE CARLIER DE VESLUD, M. GERBAULT, R. PIK, N. RUBY, AND S. BONNET (2007). Separation of rifting and lithospheric folding signatures in the NW-Alpine foreland. *Int. J. Earth Sciences (Geol. Rundschau)*, 96, 1003-1031. DOI: 10.1007/s00531-007-0202-2.

BRUYNINX C. (2004). The EUREF Permanent Network: a multi-disciplinary network serving surveyors as well as scientists. *GeoInformatics*, 7, 32-35.

CLOETINGH, S.A.P.L., P.A. ZIEGLER, P.J.F. BOGAARD, P.A.M. ANDRIESSEN, I.M. ARTEMIEVA, G. BADA, R.T. VAN BALEN, F. BEEKMAN, Z. BEN-AVRAHAM, J.-P. BRUN, H.P. BUNGE, E.B. BUROV, R. CARBONELL, C. FACENNA, A. FRIEDRICH, J. GALLART, A.G. GREEN, O. HEIDBACH, A.G. JONES, L. MATENCO, J. MOSAR, O. ONCKEN, C. PASCAL, G. PETERS, S. SLIAUPA, A. SOESOO, W. SPAKMAN, R.A. STEPHENSON, H. THYBO, T. TORSVIK, G. DE VICENTE, F. WENZEL, M.J.R. WORTEL, and TOPO-EUROPE Working Group (2007). TOPO-EUROPE: The geoscience of coupled deep Earth-surface processes. *Global and Planetary Change*, 58(1-4), 1-118. doi:10.1016/j.gloplacha.2007.02.008

DACH, R., U. HUGENTOBLER, P. FRIDEZ, AND M. MEINDL (2007). Bernese GPS Software Version 5.0. *User Manual of the Bernese GPS Software Version 5.0*.

DOW, J.M., R.E. NEILAN, AND G. GENDT (2005). The International GPS Service (IGS): Celebrating the 10th Anniversary and Looking to the Next Decade. *Adv. Space Res.*, 36, 320-326. doi:10.1016/j.asr.2005.05.125

GAUDET A. AND J.C. LANDRY (2005). TERIA: The GNSS Network for France. Proceedings, *From Pharaohs to Geoinformatics, FIG Working Week 2005 and GSDI-8*, April 16th-21th 2005, Cairo, Egypt. Link: http://www.fig.net/pub/cairo/papers/ts_08/ts08_03_gaudet_landry.pdf.

ILLIES, J.H. (1977). Ancient and recent rifting in the Rhine graben. *Geologie en Mijbouw*, 56, 320-350.

ILLIES, J.H. (1979). Rhinegraben: Shear controlled vertical motions of the graben floor. *Allgemeine Vermessungs-Nachrichten*, 86, 364-367.

KAMPES, B.M., R.F. HANSSEN, AND Z. PERSKI (2003). Radar interferometry with public domain tools. In: *Third International Workshop on ERS SAR Interferometry, `FRINGE03'*, Frascati, Italy, 1-5 Dec 2003, 6 pp.

KNÖPFLER, A., F. MASSON, M. MAYER, P. ULRICH, AND B. HECK (2010). *GURN (GNSS Upper Rhine Graben Network) – Status and First Results*. Extended abstracts, 95th Journées

Luxembourgeoises de Géodynamique, 9.-11. November 2009, Echternach/Luxembourg, (submitted).

LUO, X. AND M. MAYER (2008). Automatisiertes GNSS-basiertes Bewegungsmonitoring am Black Forest Observatory (BFO) in Nahezu-Echtzeit. *Zeitschrift für Geodäsie, Geoinformatik und Landmanagement (ZfV)*, 133(6), 283-294.

MAYER, M., A. KNÖPFLER, B. HECK, F. MASSON, P. ULRICH, AND G. FERHAT (2009). *GURN (GNSS Upper Rhine Graben Network – Research Goals and First Results of a Transnational Geo-Scientific Network.* Proceedings of the 2009 IAG General Assembly, International Association of Geodesy Assembly, 31. August - 4. September 2009, Buenos Aires, Argentina (in review).

MAYER, M., K. LINDNER, H. KUTTERER, AND B. HECK (2000). Deformationsanalyse zur Aufdeckung von Punkt- und Blockbewegungen im Bereich der Antarktischen Halbinsel. In: DIETRICH, R. (Ed.): *Deutsche Beiträge zu GPS-Kampagnen des Scientific Committee on Antarctic Research (SCAR) 1995-1998*. DGK B 310, München 2000, 127-144.

MEGHRAOUI, M., B. DELOUIS, M. FERRY, D. GIARDINI, P. HUGGENBERGER, I. SPOTKE, AND M. GRANET (2001). Active normal faulting in the Upper Rine Graben and paleoseismic identification of the 1356 Basel earthquake. *Science*, 293, 2070-2073.

Noquet, J.-M. and E. Calais (2003). Crustal velocity field of western Europe from permanent GPS array solutions, 1996-2001, *Geophys. J. Int.*, 154, 72-88.

ROZSA, S., M. MAYER, M. WESTERHAUS, K. SEITZ, AND B. HECK (2005a). Towards the determination of displacements in the Upper Rhine Graben area using GPS measurements and precise antenna modelling. *Quaternary Science Reviews*, 24,425-438.

ROZSA, S., B. HECK, M. MAYER, K. SEITZ, M. WESTERHAUS, AND K. ZIPPELT (2005b). Determination of Displacements in the Upper Rhine Graben Area from GPS and Leveling Data. *Int. J. Earth Sci*, 94, 538-549.

WEGENER, V. AND M. STRONK (2005). SA*POS*®- A Satellite Positioning Service of the German State Survey. *GeoInformatics*, 8, 40-43.

ZIEGLER, P.A. (1992). European Cenozoic Rift System. *Tectonophysics*, 208, 91-111.

ZIPPELT, K. AND O. DIERKS (2006). *Auswertung von wiederholten Präzisionsnivellements im südlichen Schwarzwald, Bodenseeraum sowie in angrenzenden schweizerischen Landesteilen*. *NAGRA, NAB 07-27*.

BIOGRAPHICAL NOTES

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