SZÉKFOGLALÓ ELŐADÁSOK A MAGYAR TUDOMÁNYOS AKADÉMIÁN

Bernhard Heck

POTENTIAL OF GEODETIC APPROACHES TO THE DETERMINATION OF RECENT CRUSTAL MOVEMENTS AND DEFORMATIONS

Tekintetes Nagygy

fennálló szabályainak 32-§a így szól:
újonnan választott tag, a külsők kivéte-
ztályába tartozó dolgozat felolvasásával,
zemélyes megnem jelenhetés esetén beküldé-
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SUMMARY

Repeated geodetic observations relating to points of the Earth's surface have become an indispensible tool in geodynamics for delivering precise values of recent crustal movements. Besides terrestrial geodetic observations, like spatial distances, horizontal angles and levelled height increments along levelling lines, satellite observations have become more and more feasible within the past decades. In particular, positioning procedures using GNSS (Global Navigation Satellite Systems) and radar interferometry have reached a very high level of precision.

In the paper, an analysis of the properties and error sources affecting the most commonly used geodetic observation procedures such as levelling, GNSS positioning, and InSAR (Interferometric Synthetic Aperture Radar), is presented. While every geodetic approach possesses its own spatial and temporal characteristics, the optimal information content in the various types of observations can be extracted by combining these approaches in regions where all data types are available. In this way, the advantages of every observation procedure can be used, while the disadvantages are mitigated. As a result, highly precise and more or less continuous displacement fields in time and space can be produced, which provide an ideal basis for further geodynamic studies, where the geodetic results are used as boundary data and restrictions for geodynamic modelling.

PREFACE

I am very happy and proud to have been elected as honorary member of the Hungarian Academy of Sciences, and I appreciate very much the recognition of my scientific work by my Hungarian colleagues.

For my inaugural lecture I have chosen a topic which has kept me busy and raised my interest from the very first days of my scientific life: the detection and monitoring of motions and deformations of the Earth's crust. It is also a topic which provided the major scientific relations to my Hungarian colleagues from geodesy:

First, to the late Prof. Dr. Ákos Detrekői; already at the end of the seventies we cooperated within an international group working in statistical approaches to the analysis of deformation measurements. Later, it was Prof. Dr. Péter Bíró; we collaborated in investigating the impact of the gravity field on the analysis of deformations of the Earth's surface. Finally, with Prof. Dr. József Ádám we have had various projects in studying the potential of satellite navigation systems for detecting deformations in small-scale geodynamic networks.

As a result of these bilateral efforts, a number of joint papers have been published in peer-reviewed journals. In my presentation and the related paper, I have tried to point out some new developments and trends in this field and to demonstrate the respective challenges by some recent projects worked on at my institute.

1. INTRODUCTION

Recent deformations of the Earth's surface, detectable by precise geodetic observations, are a consequence of geodynamic processes driven by external and internal forces acting inside and on the Earth. These deformations cause displacements of geodetic benchmarks, which can be detected by repeated geodetic observations, realized either by campaign measurements or by permanent monitoring. In this way uplift/subsidence and deformation rates can be quantified, providing constraints for modelling ongoing geodynamic processes. Recently, these geodynamic models have become an indispensable tool in practical applications, such as design of underground nuclear waste depository, geothermal energy production or CO2 sequestration.

In Chapter 2 three geodetic procedures for monitoring deformations of the Earth's surface – repeated precise geometric levelling, permanent GNSS observations, and interferometric SAR – are considered in detail, presenting their intrinsic properties, advantages and drawbacks. The practical examples are mostly taken from projects elaborated within the recent years by the working groups at the chair of Physical and Satellite Geodesy at KIT. Most of the case studies refer to the tri-national region of the Upper Rhine Graben, one of the seismically most active regions in Central Europe, situated in the surroundings of Karlsruhe. As a synthesis, in Chapter 3, a multi-sensor fusion approach is proposed for exploiting and combining the strengths of the single-sensor solutions and avoiding their disadvantages. Finally, the specific challenges in creating a rigorous, consistent, unified evaluation model are pointed out.

2. GEODETIC PROCEDURES FOR MONITORING DEFORMATIONS

Geodetic observations on the Earth's surface have been performed over various decades or even centuries. Sometimes they were dedicated to the purpose of land surveying, systematically collected by state surveying authorities. Classical terrestrial geodetic measurements often have been combined into geodetic networks; due to the principle of over-determination these networks have been evaluated by least squares adjustment in order to take into account random observation errors. In this way, some “snapshot” of the geometry of the Earth’s surface is obtained, related to a well-defined time instant, called “epoch”. In forming networks and attributing them to specified epochs it is presupposed that there are no deformations of the Earth’s surface within the time period needed for performing the measurements. If the observed region is rather large and it takes a long time to complete a network, or if there are comparably fast motions in the region under survey, this basic assumption is no longer valid. In this case, the classical procedure of comparing networks at various epochs (“static” deformation analysis) has to be replaced by a kinematic evaluation procedure, considering the geodetic observations scattered in space and time. Similar principles are also valid for modern space geodetic techniques covering large areas and producing very large data sets.

2.1 Repeated terrestrial levelling

The principle of geometric levelling is very simple: a horizontal sight is produced by the instrument horizon of a levelling instrument, enabling readings at two level rods in backsight and foresight – the difference of these readings is the local height difference between both standpoints of the level rods. Summing up these local height differences observed between any two benchmarks levelling lines are formed, which can be combined to closed loops and finally, to levelling networks. An adjustment of these over-determined sets of observations according to the least squares method, founded by C.F. Gauß, is then applied for error control. Considering the precision of the measurements, it is usual to discriminate between levelling lines of 1st to 3rd order. For the region of the Upper Rhine Graben (URG), repeated historical and recent precise levelling data - recorded by the national surveying authorities in South-West Germany, Switzerland, and France - have been merged into a regional network covering a time span of more than 80 years *(Fig. 1)*. This offers the possibility of detecting small secular, and episodic vertical movements of the Earth's surface with high precision. As the data are measured by different surveying agencies and varying instrumentation, they are inhomogeneous in space and time.

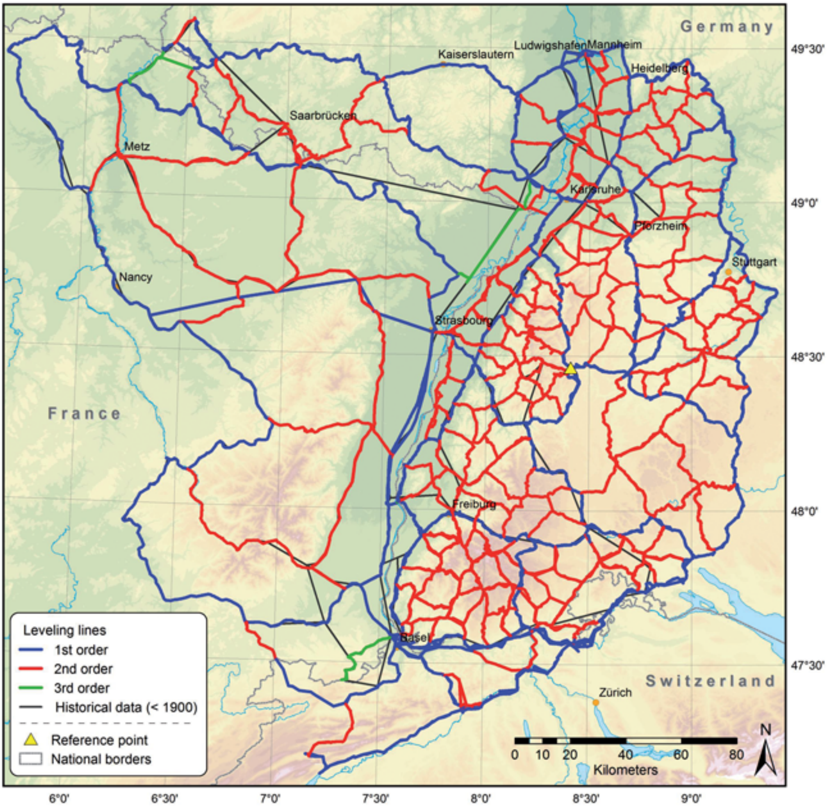

Fig. 1: Merged tri-national levelling network in the Upper Rhine Graben region (Fuhrmann et al., 2014)

It should be stressed that levelling is strongly related to the direction of the vertical, and thus to the Earth's gravity field. Therefore, the results depend in some way on local and regional variations of the gravity field, producing some kind of non-uniqueness; this non-uniqueness can be eliminated by forming geopotential numbers, combining the levelling results with gravity observations along the levelling lines, and performing the least squares adjustment in terms of geopotential numbers (Heck 2003, 281).

Although geometric levelling is one of the most precise geodetic observation procedures, reaching accuracies of 0.2 – 0.5 mm per km double-run levelling, it is subject to various systematic error sources if it is performed over larger areas. These error sources comprise e.g. mislevelling of the instrument, magnetic effects on the compensator, rod graduation and inclination errors, temperature effects on the equipment, Earth tides effects, vertical movements of instrument and rods during the observation, and, in particular, vertical refraction.

Due to the long time span of more than 80 years and considering the fact that motions of the order of only about 0.5 mm/year are expected in the URG area, the levelling observations have to be considered as scattered in space and time and cannot be attributed to fixed epochs. Therefore, a kinematic adjustment approach has to be applied to the data in order to extract vertical displacement rates. In the kinematic adjustment, any benchmark height is modelled as a time-dependent polynomial of low degree, related to its elevation at a chosen reference epoch and linear, accelerated and higher order terms (Zippelt 1988). After performing a quality check of the original observations, the respective polynomial coefficients have been estimated by an adjustment procedure based on a Gauß-Markov model (Fuhrmann et al. 2013a). Since levelling is a relative observation procedure, resulting in height differences, some stable reference benchmark has to be selected, assuming that no motion takes place at that point. As a result, maps of line-wise vertical displacement rates are produced, which can be transferred to surface models by some extrapolation procedure. In *Fig. 2* an example covering part of the northern URG network is illustrated.

Most of the displacement rates are small, concluding that the area behaves stable in general. A small tectonic uplift, amounting to about 0.3 mm/year, is visible in the northwest of the URG, while the subsidence in the Mannheim/ Ludwigshafen and Landau regions is of anthropogenic origin. Possibly the subsidence in the region of Mannheim is caused by groundwater withdrawal, while the strong subsidence signal of up to 4 mm/year near the city of Landau is due to oil extraction (Fuhrmann et al. 2013c).

In conclusion, the characteristics of repeated geodetic levelling as a procedure for the determination of recent crustal motions can be summarized as follows: results are available only along the levelling lines, due to line-wise registration of displacements, and only the vertical components are observable. In many regions, the data sets comprise a long time basis of several decades, up to nearly one century. In the evaluation of levelling data, the fact has to be considered that, in general, no fixed observation epoch exists, the measurements being scattered over time. For this reason, kinematic evaluation models have to be applied. Furthermore, it has to be kept in mind that uplift/subsidence rates are only available along the levelling lines, while no information exists within the levelling loops. Since levelling is a relative procedure, a stable reference point has to be selected showing no motions over the period of evaluation. Still challenging is the choice of the stochastic model within the least-squares adjustment; this problem can be solved e.g. by variance component estimation (Fuhrmann et al. 2014).

2.2 Permanent GNSS observations

Positioning by the aid of the electromagnetic signals transmitted by satellites of Global Navigation Satellite Systems (GNSS) has become an indispensable tool for about two decades for many applications in science and practical life. Present-day GNSS are based on the ranging principle, i.e. the propagation time between the transmission of the microwave signal at the satellite and the recep-

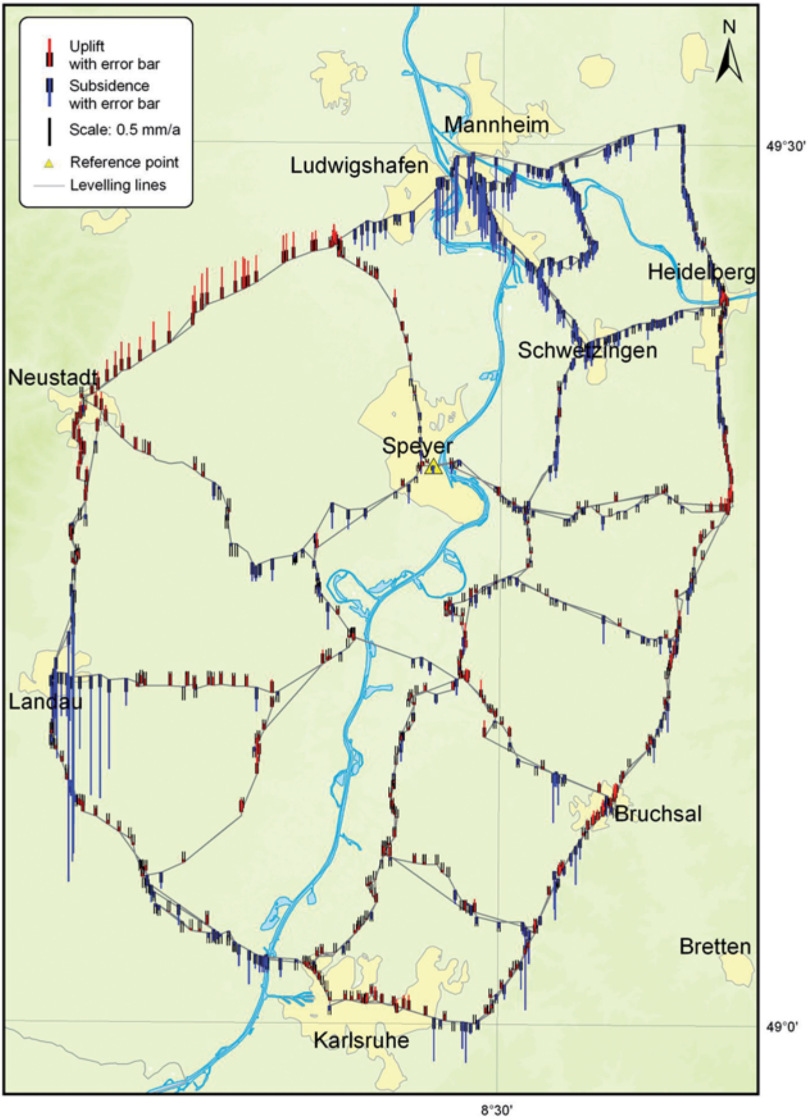

Fig. 2: Levelling results in the test network Speyer, in the northwestern part of the URG

tion time measured at the antenna of the user/receiver on the Earth's surface (or on ships, airplanes, or satellites) is the principal quantity. Multiplication of the observed propagation time with the velocity of light provides the distance between the positions of the satellite and the ground station; if the positions of three simultaneously observed satellites with respect to some well-defined reference system are available, the position of the user can be derived in the same reference frame, in principle. Due to the fact that the atomic clocks in the satellites and the quartz crystal clocks in the receivers work independently, another simultaneous observation of a fourth satellite is necessary to solve for the synchronisation unknown (Xu 2007).

Besides the propagation time measurements, providing the three-dimensional position of the user with meter to sub-meter precision, also the phase of the microwave carrier can be observed after reconstruction of the original signal. In order to exploit the high accuracy of phase measurements, the so-called phase ambiguity, corresponding to the full integer number of wavelengths within the distance to the satellite at the initialisation of the measurements, has to be resolved. By this procedure relative positions with respect to some reference point can be derived with centimetre to millimetre precision (Hofmann-Wellenhof et al. 2008), allowing multiple applications in geodynamic research.

The first GNSS with full operational capability was the US NAVSTAR-GPS (Navigation with Time and Ranging – Global Positioning System), followed by the Russian GLONASS. At present, some more GNSS arise, like the European Galileo and the Chinese Beidou/Compass systems. Some of these systems or parts of them are compatible and can be jointly used in future (Hofmann-Wellenhof et al., 2008).

GNSS in general are composed of three segments (Kaplan 1996; Seeber 2003): The space segment consists of the satellites orbiting the Earth and transmitting coded microwave signals. The control segment is built up by a number of permanently observing sites on the Earth's surface, receiving and processing all satellite signals; these observations are used to calculate and predict the orbits of the satellites and to transmit this and other information to the users via the satellite message. Finally, the user segment consists of the receiver, antenna and further equipment of the user for determining his position.

Of utmost importance for the determination of a precise position is an ultra-precise reference frame accessible to the user. A global reference frame with centimetre precision is provided by the International Earth Rotation and Reference Systems Service (IERS), operated by the International Union of Geodesy and Geophysics (IUGG) and the International Astronomical Union (IAU). The primary results of IERS are celestial and terrestrial reference frames, as well as transformation parameters depending on the Earth's rotation. The latest issue of the International Terrestrial Reference Frame (ITRF) is ITRF2008 (Altamimi et al. 2011), based on GPS observations and other geodetic space methods like Very Long Baseline Interferometry (VLBI), Satellite Laser Ranging (SLR) and DORIS (Doppler Orbitography and Radio Positioning Integrated by Satellite). Any of these space geodetic procedures is managed by a respective service operated by the International Association of Geodesy (IAG), being part of the IUGG. For an overview of the sites contributing to ITRF2008, see *Fig. 3*.

Another important aspect of precise GNSS positioning is the effect of the Earth's atmosphere on the propagation of the microwave signal. Two regions in the atmosphere have to be discriminated: The ionosphere consists of electrically charged particles and extends from about 50 km to 1500 km above the Earth. For microwave frequencies above 30 MHz the ionosphere behaves as a dispersive medium, producing frequency-dependent effects in code and carrier phase observations. This phenomenon is exploited in order to experimentally derive the first order ionospheric refraction effects by using two car-

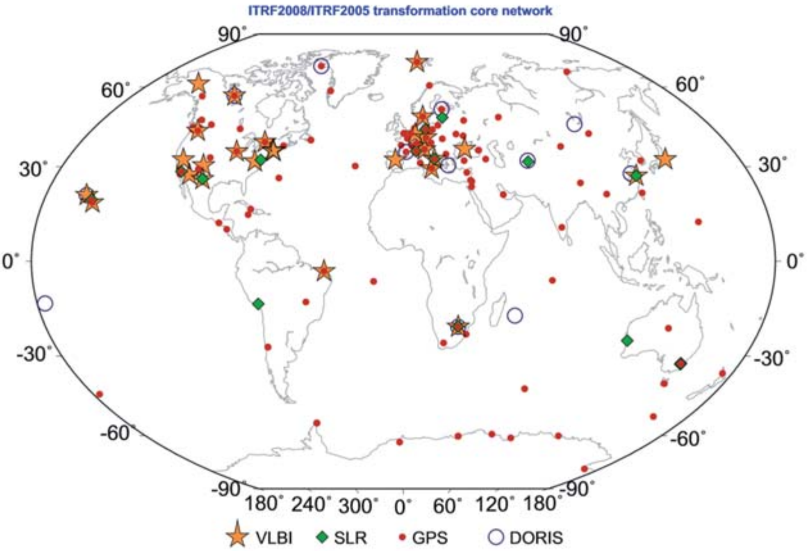

Fig. 3: Site distribution of the ITRF2008 global network highlighting VLBI, SLR and DORIS sites co-located with GPS (Altamimi et al. 2011)

rier frequencies in the transmitted signal, providing a possibility to reduce the observations for the ionospheric effects. The second part of the atmosphere, the electrically neutral neutrosphere, covers the troposphere and parts of the stratosphere and extends from the Earth's surface to about 50 km. The refractivity within the neutrosphere depends on the meteorological parameters of temperature, air pressure, and humidity and is described by neutrospheric models. While the "dry" part of neutrospheric refraction is rather stable in time and produces effects in the distance between receiver and satellite of about 2.6 metres in vertical direction, the water vapour contribution amounts only to about 60 centimetres, but is strongly variable in space and time (Hofmann-Wellenhof et al. 2008). The "wet" component in the neutrospheric delay can be exploited for deriving the integrated water vapour content in the atmosphere (Mayer 2006; Luo et al. 2007; Fuhrmann et al. 2010).

GNSS positioning at various epochs with respect to a stable global reference frame such as ITRF2008 provides the opportunity to detect displacements of geodetic benchmarks caused by geodynamic processes or anthropogenic activities. Until about the year 2000, when sufficient receiver equipment was not available, it was usual to perform campaign measurements of local or regional GNSS networks connected to a few reference stations (Rózsa et al. 2005a, b). This procedure was applied e.g. in a joint Hungarian-German endeavour to derive displacements and deformations in the geodynamic test network of Sóskút in the Buda mountains near Budapest (Ádám et al. 2003). As an effect of various error sources the precision of these campaign measurements was not high enough to detect small motions and deformation rates such as those occurring in the Sóskút network or in the URG area, although advanced-level statistical analysis procedures had been developed and used (Heck 1989). This situation changed with the installation and operation of permanent GNSS sites, enabling to derive and analyse time series of coordinates and displacements.

In the framework of a cooperation between the Geodetic Institute of KIT Karlsruhe and Institut de Physique du Globe, Ecole et Observatoire des Sciences de la Terre (EOST) of the University of Strasbourg, France, and further partners, the data of permanent GNSS stations in the area of the URG are collected and evaluated on a regular basis (Knöpfler et al. 2010; Mayer et al. 2012; Fuhrmann et al., 2013a). The respective GURN (GNSS Upper Rhine Graben Network) network comprises actually about 80 GNSS sites situated in South-West Germany, France and Switzerland; the data series reach back to 2002, partially also to earlier years *(Fig. 4)*. The data sets are made available by various institutions and are automatically downloaded once per day, providing daily coordinate solutions of all network points by the aid of the

Bernese GNSS Software (Dach et al. 2007). A further extension of GURN to the north is planned.

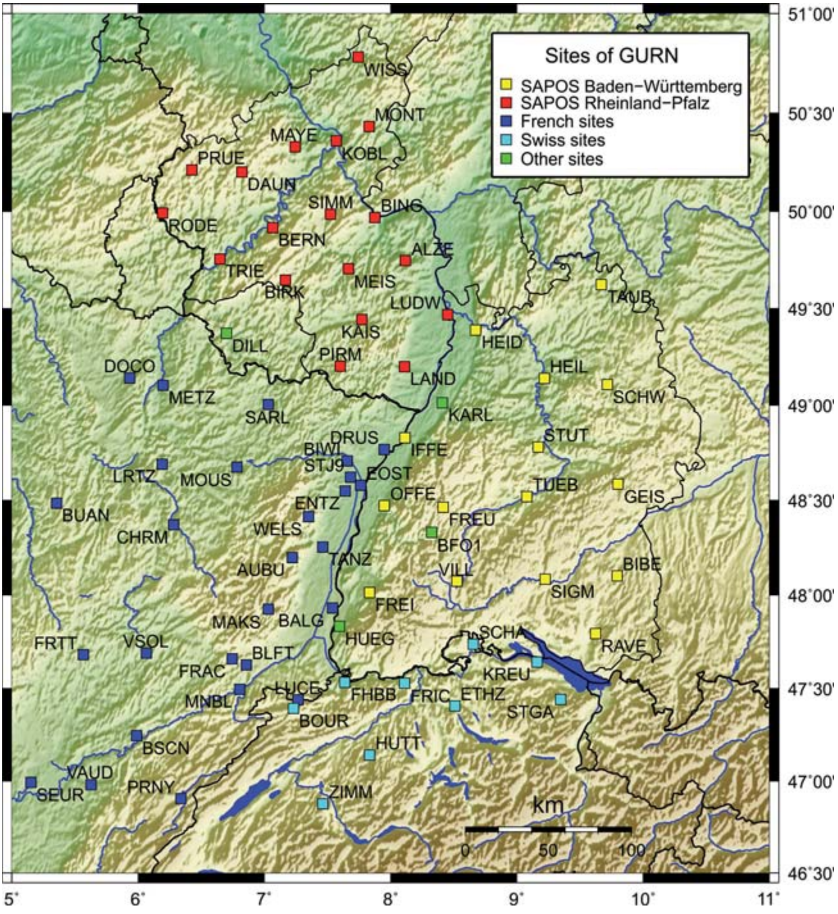

Fig. 4: Site map of GURN (GNSS Upper Rhine Graben Network)

As a consequence of the observation geometry and the effect of tropospheric refraction, the precision of the vertical displacement component is worse than the horizontal components by a factor of about two. The first results of the time series of daily solutions reveal interesting details about the short- and long-term behaviour of the sites *(Fig. 5)*. In some cases, changes of equipment such as GNSS antennae, can be detected in the time series of displacements (e.g. site RAVE, red lines), while the effect of snow cover on the antenna is clearly visible in the time series of some sites in the mountains (e.g. site AUBU in the Vosges mountains, see *Fig. 5*). Annual variations, in particular in the height component, may be due to the foundation of the sites and antennas.

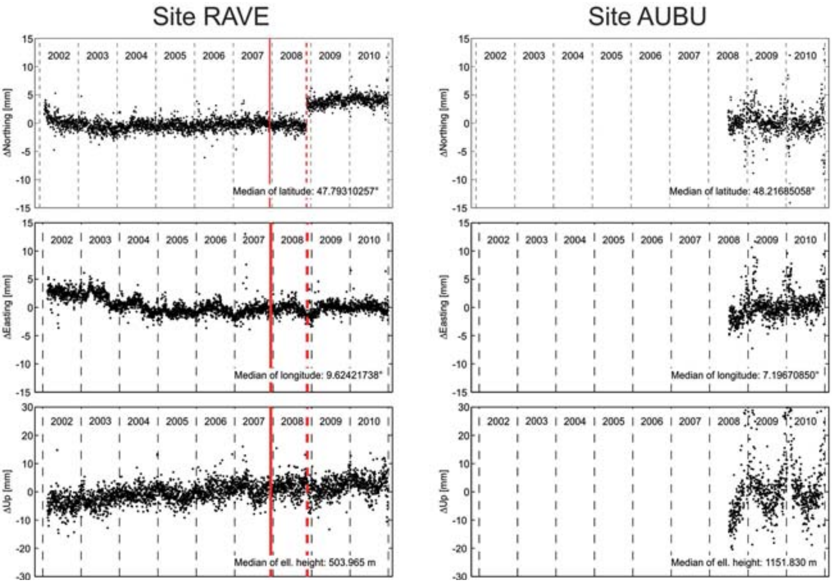

Fig. 5: GNSS Upper Rhine Graben Network, first results of coordinate time series

Using different software and independent analysis at EOST and KIT in the processing of GNSS observations, a comparison of the results enables getting insight into the external precision of the derived velocity estimates. Preliminary results show that the GNSS data are sensitive to resolve small surface displacement rates down to an order of magnitude of 0.4 mm/year (Fuhrmann et al. 2013a). Apart from some minor inconsistencies between the EOST and KIT solutions, the preliminary results concerning the strain field in general fit well into the overall recent tectonic picture. Some refinements related to the processing of the GURN data, such as the use of stacking procedures for the mitigation of some error components, are being tested for further improvement.

In conclusion, GNSS approaches for determining recent crustal motions are characterized by point-wise registration of the site displacements with respect to a global precise reference frame, providing three-dimensional time series of coordinate variations; the precision of the vertical displacement rates is worse than the horizontal components by a factor of two. The discrete displacement field given in the vertices of a geodetic GNSS network can be interpolated, e.g. by linear prediction within triangular meshes, allowing to calculate local strain and strain rates on a regional basis (Heck 1989), in particular when permanent GNSS sites are involved. In order to consider and mitigate the influence of small systematic disturbances, a consistent scientific evaluation and analysis of the observation data is necessary, sometimes requiring a complete re-processing of the total multi-year data set. Either differential GNSS positioning based on the evaluation of baselines, or the method of precise point positioning (PPP) is applied to the observed carrier phases. Still challenging is the selection of a stochastic model for the adequate statistical description of the precision of the measurements; the rather simple models applied in most processing software have to be replaced by advanced stochastic models considering spatial and temporal correlations of the phase observations (Luo 2013).

It should be noted that as a side product valuable information about the atmospheric water vapour content can be extracted from the evaluation of precise GNSS carrier phase observations collected in a dense network of permanent sites (Fuhrmann et al. 2010; Alshawaf 2014).

2.3 Interferometric SAR

Synthetic Aperture Radar (SAR) is an imaging radar technique using frequency modulated microwave pulses transmitted in slant direction to the ground from an antenna carried by a satellite, flying at a typical altitude of about 800 km above the Earth's surface. E.g. for the ERS-1/2 remote sensing satellites the altitude is 785 km, the look angle is fixed to 23°, the swath width is 52 km, and the frequency (wavelength) of the transmitted signal is 5.3 GHz (5.66 cm). An analysis of the back-scattered echoes, received by the same antenna, allows determining the amplitudes and – in the interferometric mode – the phases of these electromagnetic signals (Hanssen 2001; Cumming and Wong 2005). SAR interferometry (InSAR) is based on phase differences between images related to repeated tracks of the satellite. For so-called persistent scatterers (Hooper et al. 2007), i.e. permanently coherent resolution cells, this analysis can be performed point- resp. pixel-wise, if some larger number of SAR images covering the same region are available and a time series approach is feasible.

The observed interferometric phase is composed of several contributions, a reference phase, a component induced by topography (look angle error), the atmospheric contribution, the effect of any displacement having occurred between the recordings of the SAR images, and some stochastic noise, see *Fig. 6*. For previous missions like ERS-1/2 also the orbit error plays a major role. In order to split the deformation signal from the other components, additional information is required, in particular, a precise digital elevation model for subtracting the topographic phase contribution. Atmospheric effects can be averaged out if stacks of some 15 or more scenes taken at different atmospheric conditions are available (Hooper et al. 2007). Furthermore, since the phase measurements are ambiguous with respect to the number of full wavelengths within the distance between the SAR antenna and the ground, the integer number of phase ambiguities has to be resolved by phase unwrapping (Chen and Zebker 2001).

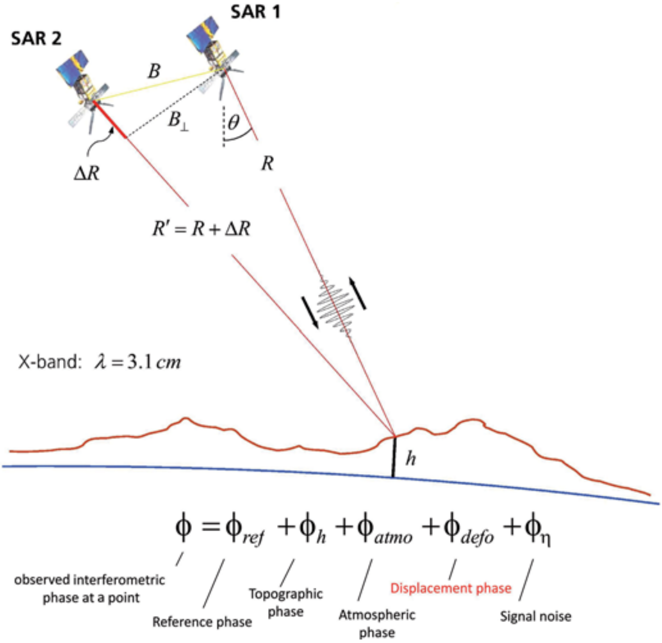

Fig. 6: SAR interferometry geometry and decomposition of the interferometric phase (according to Bamler et al., 2008)

Due to the fact that the radar signal is emitted in a single direction, just a one-dimensional component of the three-dimensional displacement of a resolution cell or pixel on the Earth's surface, namely in the direction of the line of sight (LOS) between the satellite and ground, can be detected. Using images of the same region taken on ascending and descending orbits helps to mitigate this deficiency, but complete information on the three-dimensional displacement is only available by a fusion with other external types of observation, e.g. results from repeated levellings or permanent GNSS observations (Hu et al. 2011).

The Persistent Scatterer InSAR (PS-InSAR, PSI) approach has been applied to the detection of motions in the city of Staufen near Freiburg/South Germany. The realisation of a new heating system for the historical city hall based on geothermal energy was accompanied by a leakage in a drill-hole, so that groundwater infiltrated into a subsurface anhydrite layer causing a volume growth of that layer and uplift of the Earth's surface. Before the groundwater infiltration was stopped, the ground in the city centre was uplifted by a rate of 1 cm per month; even two years after the infiltration process was stopped, the uplift rate is as large as 5 cm per year in the centre of motion. In the meantime more than 200 houses in the city centre show cracks and major damages. For the analysis, a stack of more than 40 radar images from the TerraSAR-X mission covering the period between January 2008 and July 2010, have been acquired. Due to the use of electromagnetic signals in the X-band (TerraSAR-X radar frequency 9.65 GHz) and the respective small wavelength (3.1 cm) the derived LOS displacements are very precise. A major number of persistent scatterers, which can be identified as roofs of houses, streets, etc., are available in the centre of the city. In addition to the PSI-analysis based on ascending and descending orbits, also the results of repeated levellings have been made available, allowing a comparison of these techniques for selected scatterers in the vicinity of levelling benchmarks. The levellings have been performed on a regular basis, every two weeks. *Fig.* 7 shows the stacked linear LOS displacements for the ascending and descending orbits, indicating a significant difference in the magnitude of the displacement signals.

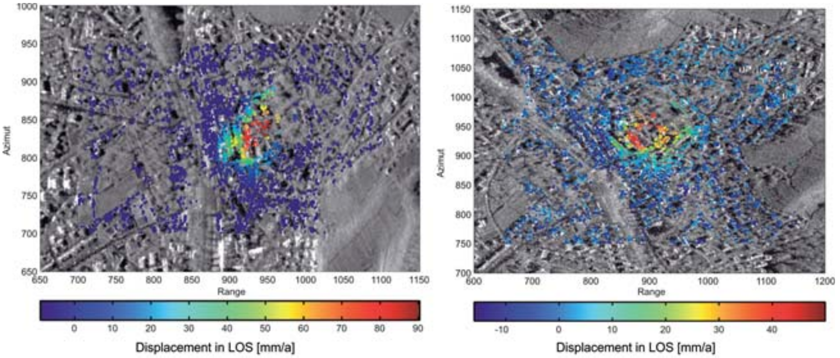

Fig. 7: Results of PSI processing of SAR images for the city of Staufen related to ascending and descending orbits (Schenk and Westerhaus, 2012)

Furthermore, *Fig. 8* illustrates the LOS displacements for ascending and descending orbits for a specific PS-point, jointly with the results of levelling of a close benchmark. The discrepancies between the three time series can easily be explained by the fact that the total displacement consists of horizontal and vertical components, but the observation geometry is different for the three measurement series. While repeated levellings provide the vertical component of motion, the projection of the spatial displacement on the respective lines of sight for ascending and descending orbits provides different views: as a result of the different observation geometry the LOS displacements derived from descending orbits are much smaller than those obtained from ascending orbits (Schenk and Westerhaus 2012).

On a larger scale, the potential of the PS-InSAR approach has also been investigated in the URG region, based on ERS-1/2 and Envisat data from ascending and descending orbits. These data, covering a period from 1992 to 2000 and 2002 to 2010, respectively, have been processed by the StaMPS (Stanford Method for Persistent Scatterers) software package (Hooper et al. 2007). As expected, the majority of PS points are located in urban areas. As the

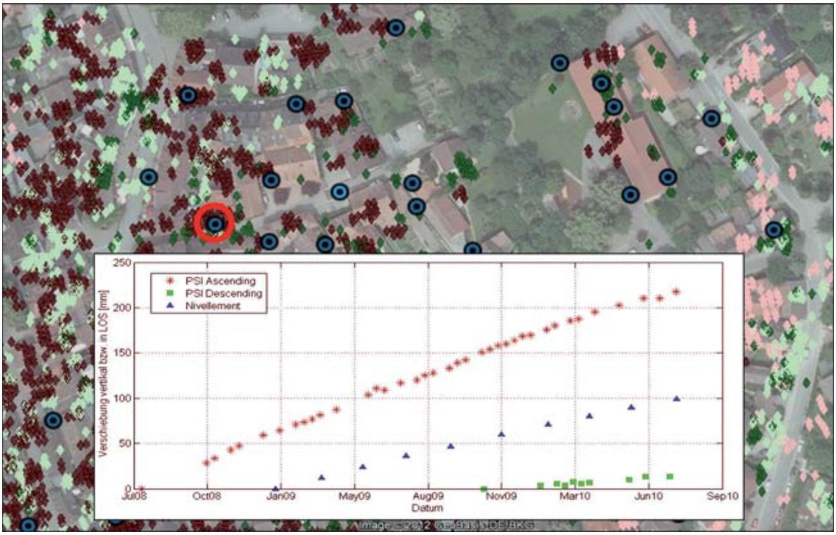

Fig. 8: Line of sight displacements in the city of Staufen resulting from ascending and descending TerraSAR-X orbits, and levelling results (Schenk and Westerhaus, 2012)

displacements in the URG area are rather small and the analysed SAR data cover a large area, the separation of atmospheric and orbit errors plays an important role (Fuhrmann et al. 2013b). These investigations are still going on; for the future, the use of TerraSAR-X and Sentinel data is envisaged.

In conclusion, the Persistent Scatterer InSAR approach provides one-dimensional displacement components in the LOS direction for permanently scattering resolution cells in the form of time series. A complete detection of three-dimensional displacements requires analysing data from ascending and descending orbits, as well as including further external information. The total time basis of this approach amounts to 1 – 2 decades, depending on the availability of respective SAR satellite missions. The temporal resolution of the InSAR technique is comparably low, being equivalent to the repeat orbit rate, which is e.g. 35 days for ERS-1/2 and Envisat, and 11 days for TerraSAR-X orbits. Since the InSAR technique is based on phase measurements, the problem of correct integer phase unwrapping has to be solved. Being a relative procedure, a reference point has to be selected, for which the hypothesis of no motion should hold. Varying vegetation produces problems due to loss of coherence; this property makes its application problematic in densely populated regions and intensive farming areas. While the precision of the calculated orbits is practically sufficient for recent missions, the elimination of atmospheric effects is still a challenging topic in repeat track SAR missions (Alshawaf 2014).

3. MULTI-SENSOR FUSION

As a general result from the presentation and discussion of the various procedures for the determination of recent crustal motions and deformations, it can be concluded that the space-time properties of the single-sensor approaches are strongly different. Displacements derived from continuous GNSS phase observations are obtained at single points on the Earth's surface, yet in three space dimensions, which can be decomposed in horizontal and vertical components. Based on daily solutions the precision of relative positioning in the horizontal direction is about 1 mm (standard deviation), while for the vertical component it is about 2.5 mm, due to peculiarities of error propagation. The total available time basis for GNSS observations covers a few decades; for the GURN network in the URG area it amounts to about 10 years for most sites.

Repeated levelling provides displacement components in the vertical direction only, referring to benchmarks along the levelling lines. A precision of the displacement rates of 0.2 mm/year can be achieved. Based on historical measurements, carried out by the national surveying authorities every 20 to 30 years, the total time span covered by precise levellings may reach up to 100 years.

In contrast, InSAR is a relatively new satellite-based approach, covering a time span of up to 20 years only. Depending on the back-scattering properties of the Earth's surface in the region, displacements of a large number of surface points can be simultaneously detected, producing a good spatial distribution. The temporal resolution of the InSAR measurements depends on the repetition rate of the satellite orbits and amounts to 11 days for the TerraSAR-X mission and 35 days for the ERS-1/2 and Envisat missions. Only one-dimensional displacements in the LOS direction can be detected, achieving a precision of about 2 mm/year with the PS-InSAR technique if at least 15 radar scenes of the considered region are available.

In order to exploit the positive characteristics and to mitigate the negative properties of the various geodetic approaches it will be advantageous to merge all types of data in regions where these are available. Multi-sensor fusion within a rigorous mathematical concept will allow first of all cross-validating the results of the single-sensor solutions, before exploiting the space-time information content in an optimal way for the estimation of deformation parameters (for the situation in the URG area see *Fig. 9*). For this purpose, suitable space-time representations and interpolation procedures have to be developed and investigated, forming the functional part of a unified, consistent evaluation model; potential candidates are approaches based on Kriging procedures (Stein 1999). The functional model part of this synergistic approach has to be completed by a suitable stochastic model, describing the stochastic properties of the observables. The ultimate product of this endeavour will be a homogeneous, highly precise and more or less continuous displacement and deformation field in time and space, which forms an ideal basis for further geodynamic studies, the geodetic results acting as boundary data and restrictions for geodynamic modelling.

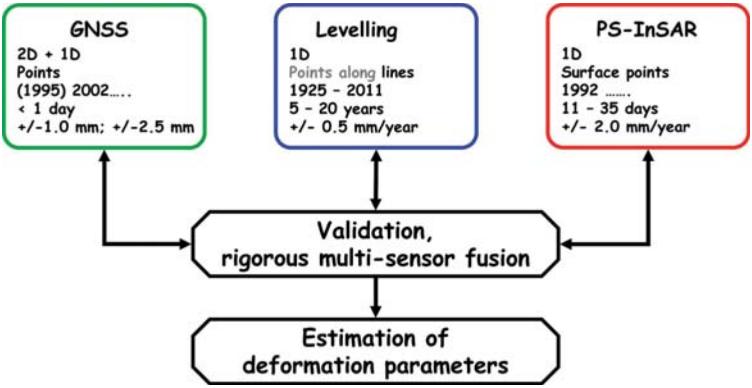

Fig. 9: Synergistic approach to the estimation of deformation parameters by multi-sensor fusion

4. CONCLUSIONS AND OUTLOOK

Repeated geodetic observations form an important basis for the determination of recent crustal motions and deformations. The considerations about various geodetic approaches such as precise levelling, continuous GNSS observations and InSAR have revealed that every procedure possesses its own space-time characteristics and sensitivity concerning the impact of random and systematic errors. Still challenging is the task of developing a unified evaluation model for multi-sensor fusion, delivering an optimal displacement field in space and time on the one hand, and separating signal and error components in an optimal way on the other hand.

Since geodetic space observations make use of electromagnetic signals propagated through the Earth's atmosphere, the observables are affected also by atmospheric effects, in particular by the water vapour in the troposphere. Thus, a natural extension of the unified approach for the determination of displacement and deformation fields consists in a simultaneous estimation of atmospheric parameters. The first steps in this direction, yet restricting to the derivation of integrated water vapour for improvement of weather prediction and climatological studies, have been undertaken in the past years by various groups, e.g. in Hungary (Rózsa et al. 2013) and Germany (Fuhrmann et al. 2010; Alshawaf et al. 2012; Alshawaf 2014). A cooperation project between the chairs of Higher Geodesy at the Budapest University of Technology and Economics (BUTE) and Karlsruhe Institute of Technology (KIT) has been formulated and started for the further development of this interesting and important research topic. In this way, the close relationships with the Hungarian colleagues from Geodesy and Earth Sciences will be continued and strengthened once more within the next years.

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