# DEFORMATION INTEGRITY MONITORING FOR GNSS-POSITIONING SERVICES BY THE KARLSRUHE APPROACH (MONIKA) – CONCEPT, REALISATION AND RESULTS[1]

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## 0 Motivation and General Targets of the MONIKA-Concept

With the global process of the installation of GNSS-positioning services, such as *SAPOS*/**ascos** (www.sapos.de; www.ascos.eon-ruhrgas.com) in Germany (fig. 1), CZEPOS in Czech Republic (czepos.cuzk.cz), LATPOS in Latvia (www.latpos.lv, [11]), and many others in Europe and round the world, these services have become an interdisciplinary and indispensable application for a high precise geo-referencing.

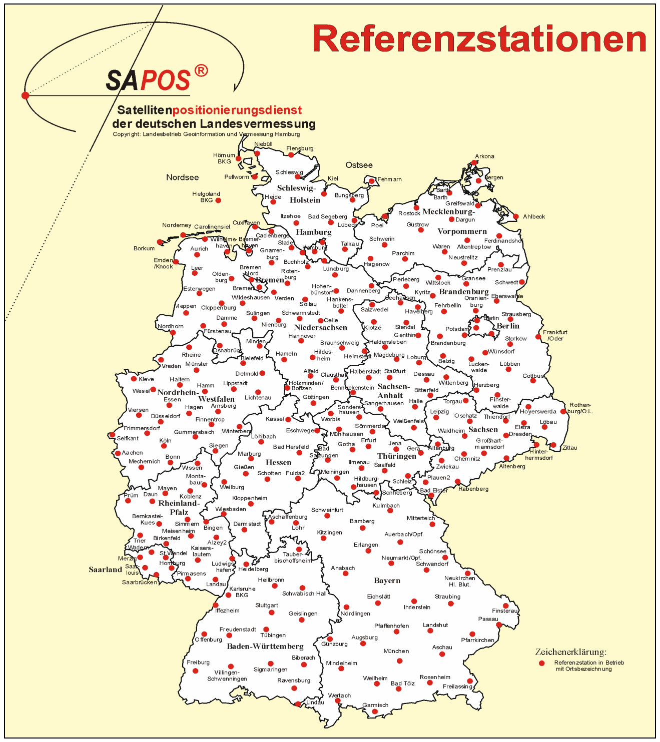


**Fig. 1:** German *SAPOS*®/**ascos** GNSS-reference-stations network.

[1] Contribution to the Proceedings of GEOSIBERIA 2007 (http://www.geosiberia.ssga.ru/). In press.



Fig. 1 shows as an example the GNSS-reference-stations network of the German state positioning service *SAPOS*® and the private **ascos**, cooperating in a private public partnership (PPP) and using more or less the same GNSS-reference-stations. These are set up in an online networking mode, in order to provide high accurate correction data. In that way *SAPOS*®/**ascos** enables a 3D online-positioning on a (1-3) cm accuracy level presently, which is still increasing due to improvements in the correction data modelling of the different networking software. The high accurate transformation of the ITRF-based (e.g. ETRF89) GNSS-position to the physical height system H and the plane position (N, E) in a classical national datum system of a country are also done online, e.g. by using high accurate DFHRS- and DFLBF-databases (www.dfhbf.de, www.geozilla.de, [10], [12]), either directly in the GNSS-controller or in future also set up by derived RTCM 3.0 transformation messages.

The capacity of an absolute positioning in such a GNSS-positioning service's network (fig .1) demands, that possible changes of the coordinates of the reference stations in the amount of a few millimetres are detected ad hoc. The reason for position changes of GNSS-reference-stations reaches from geological movements (fig. 2), over deformation due to mining, changes in the ground-water table, to local deformations of the building carrying the GNSS-antenna. Discrepancies in the coordinates may also be originated by the antenna calibration, and so as pseudo-deformation be followed by the change of an antenna

The development of GNSS-reference-station coordinate - or better deformation integrity - MONitoring provided by the KArlsruhe approach - briefly called MONIKA - is done in the frame of the research project GOCA (www.goca.info, [7]). The department for geodesy and SAPOS of the state survey agency of Baden-Württemberg, Germany is involved as cooperation partner. The MONIKA developments are further motivated by an official resolution of the state survey departments of Germany (Arbeitsgemeinschaft der Vermessungsverwaltungen Deutschland (AdV)) in 2006 [1] on the introduction of the coordinate monitoring as a quality-control duty of the GNSS-positioning provider.

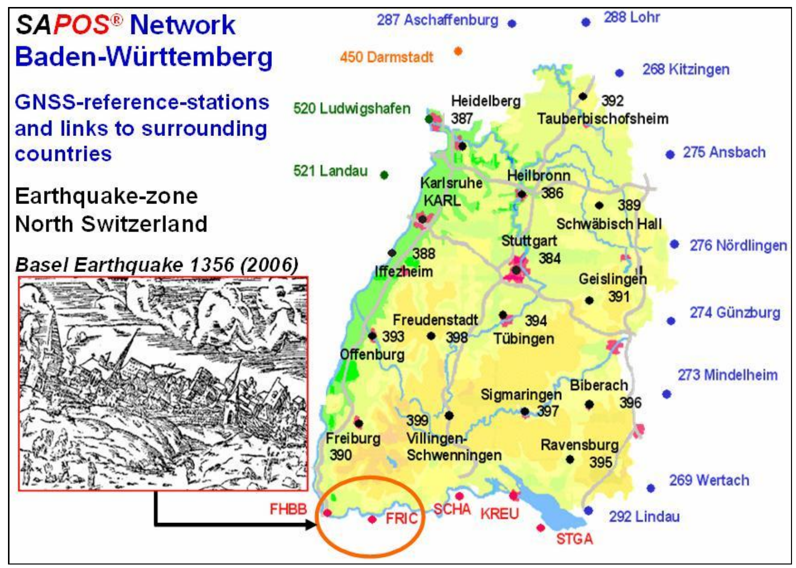


**Fig. 2:** Baden-Württemberg's part of the German *SAPOS*/**ascos** GNSS-reference-stations network. Network links to stations of surrounding countries including the earthquake endangered zone of North Switzerland and South Baden-Württemberg.

So far, the MONIKA approach perceives itself as a general prototype and reference for such a GNSS--reference-station coordinate monitoring, and was realized recently by the MONIKA software.

The MONIKA GNSS-reference-station deformation integrity approach is based on epoch state-information of the coordinates and covariance matrices at epoch time t. The “epoch” t has a duration-time $\Delta t$ and is centred around t. As concerns the network design, MONIKA is both multi-variate and multi-epochal. The epoch-state information results from a baseline- or network-wise processing of the GNSS-network or network parts within the interval $\Delta t$ of epoch t. The strict three-dimensional coordinate-related deformation-analysis is based on the hypothesis of a multi-epochal congruency of all single epoch states in a total duration $\Delta T$. A list of a-priori moving points can be handled. Incongruent points are detected by a single-point testing and added to the list of moving points. The displacements of the moving points, as well as estimated deformations of statistically congruent points, can be submitted to a time-series and trend-analysis. The case of a free-network and an absolute ITRF (International Terrestrial Reference Frame)-embedded one are considered, as well as the geodynamic trends of plate-tectonic movements and a datum-change.

Besides the theoretical background, the contribution is dealing with the results of the application of the MONIKA-software on the GNSS-reference-station network SAPOS Baden-Württemberg including the northern part of the Switzerland GNSS network SWIPOS. The investigations are based on a MONIKA-processing of daily RINEX files with a $\Delta t$ of one day and a duration $\Delta T$ of several months The sensitivity for the detection of displacements is presented, and trend estimations are shown.

It is evident, that the presented high sensitive deformation-analysis approach of MONIKA can - besides the above quality-control task for GNSS-positioning services - also be used for an included area-wide and large scale geodynamical and natural disaster-prevention service, as shown in fig. 2. Fig. 2 shows in this context the earthquake endangered zone of North Switzerland and South Baden-Württemberg, where a big earthquake took place in Basel 1356, and a recent one in that region in 2006, which happened during the installation of a regional geothermal power-station. The so-called Rhinegraben, which is flanking the western part of Germany and Baden-Württemberg along the French border belongs to the same continental rupture zone, and the sinistral movement of the graben-edges is in still active [9]. That geodynamical situation to be monitored by including the RINEX data of the French reference stations into the GNSS-reference-stations deformation integrity with MONIKA.

# 1 Introduction and Characteristics of the MONIKA-Concept

## 1.1 Coordinate-related Deformation Analysis

The mathematical model of MONIKA is based on the data interface of the GNSS RINEX files as original observations $\mathbf{l}$, which is followed after the adjustment steps 1 (GNSS-data processing) and 2 (three-dimensional epoch adjustment), and a transformations step, by step 3, which is a coordinate-related deformation analysis in a multi-epoch and multivariate network design as the final step (Fig. 3).

Coordinate-related means, that the deformation analysis is based on the epoch coordinates $\mathbf{x}(t_i)$, i = i-th epoch, and their covariance matrices $\mathbf{C}_X(t_i)$. These epoch states are derived basically from the processing of the raw GNSS data ($\mathbf{l}, \mathbf{C}_l$), which was observed at epoch time $t_i$, in the adjustment steps 1 and 2, according to the flowchart for MONIKA (Fig. 3). Multivariate means, that no common points over all epochs are required. In that way, MONIKA enables conceptually also a long-term monitoring. The basic model of the deformation analysis is the assumption of the congruency of the GNSS network over all epochs, considering of course splitting off the geodynamic trends, e.g. plate movements, within deformation analysis time window $\Delta T$.



The functional and stochastic model of a coordinate-related deformation analysis (step 3, Fig. 3), which is also part of the software MONIKA, reads:

$$\mathbf{x}(t_i) + \mathbf{v}_{x(t_i)} = \mathbf{D}_R^i \cdot d\hat{\mathbf{x}}_r + \mathbf{D}_O^i \cdot d\hat{\mathbf{x}}_O^i + \mathbf{x}_0^i , \quad \text{with } \mathbf{C}_X(t_i) \ . \qquad \text{(1a,b)}$$

The final epoch states ($\mathbf{x}(t_i), \mathbf{C}_X(t_i)$) (Fig. 3) are used as observations and stochastical models in the coordinate-related deformation analysis. The Gauss-Markov-Model (GMM) (1a, b) includes all epochs (i = 1,m) within the total duration $\Delta T$ of the deformation analysis window. With null hypothesis $H_0$ of congruency, the coordinate-related monitoring concept MONIKA means to introduce the assumed non-deformed parts of the GNSS-reference-station network in the i-th epoch as so-called reference points $\mathbf{x}_R^i$ with identical coordinates in all epochs. Points, which are a-priori assumed to be moving, and those, which show significant displacements during the testing procedure (see chap. 3, (5a,b)) receive time-dependent epoch coordinates. In terms of deformation analysis they are called object-points $\mathbf{x}_O(t_i)$. With $d\hat{\mathbf{x}}_R^i$ and $d\hat{\mathbf{x}}_O^i$ (1a, b) we introduce the coordinate unknowns as increments to the approximates $\mathbf{x}_0$. The design-matrices $\mathbf{D}_R^i$ and $\mathbf{D}_O^i$ are filled with 0 or 1 as coefficients, as $\mathbf{x}(t_i)$ are direct observations in (1a, b). The test strategy for the detection of in-congruencies by means of a three-dimensional significance test for the estimated displacements $\hat{\nabla}\mathbf{x}_R^k(t_i)$, leads to an extended GMM referring to (1a, b). It is treated in details in chap. 3.

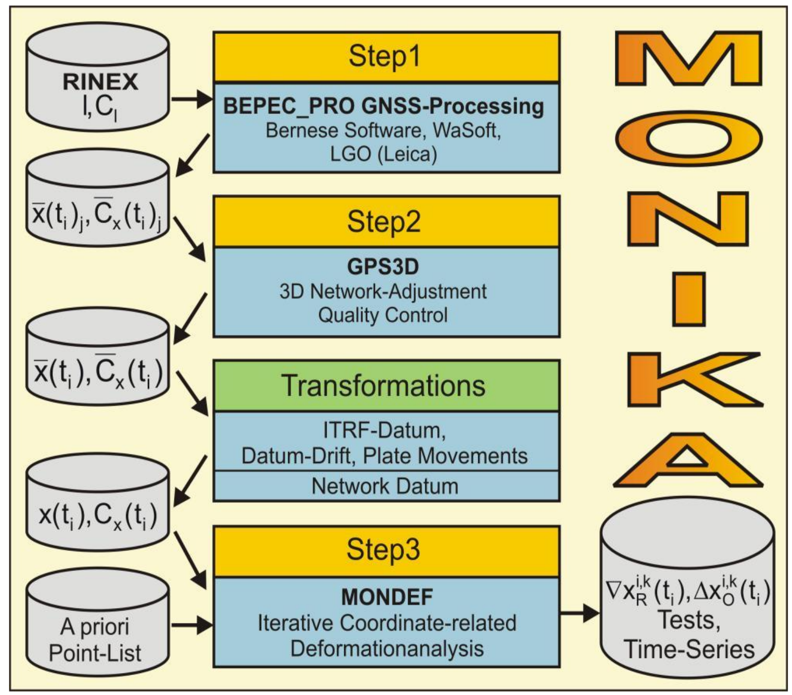


**Fig. 3**: Data-input/-output and adjustment- and transformation steps in MONIKA.

In case of a large deformation analysis window $\Delta T$ or a wide network area the so-called primary epoch states $(\bar{\mathbf{x}}(t_i), \bar{\mathbf{C}}_x(t_i))$ resulting from the epoch adjustment step 2 (module GPS3D), which follows the GNSS data processing in step 1 (module GOCA_BPEC_PRO), have to be submitted to different transformations (Fig. 3). These transformations are at first due to a common ITRF-datum and for the second in order the remove the geodynamic trends of a common datum-drift of all plates together and of individual plate-rotations. In case of processing the GNSS-data $(\mathbf{l}, \mathbf{C}_l)$ in a free network and deformation analysis concept, an additional datum-transformation procedure has to follow with respect to the network-datum set up by the approximate coordinates $\mathbf{x}_0$ (1a, b) of the coordinate-related deformation analysis in step 3 (module MONDEF) (Fig. 3).

## 1.2 Estimation of the primary epoch state

The information of the so-called primary epoch states is represented by the epoch coordinates $\bar{\mathbf{x}}(t_i)$ and their covariance matrix $\bar{\mathbf{C}}_x(t_i)$ of the GNSS-reference-stations network at epoch time $t_i$ resulting from step 2 of the MONIKA approach (Fig. 3). The reference time $t_i$ and the epoch duration $\Delta t(t_i)$ specify the epoch time window $[t_i - \Delta t(t_i)/2, t_i + \Delta t(t_i)/2]$. The primary epoch state information recruits itself from the coordinates and the covariance matrices $(\bar{\mathbf{x}}(t_i)_j, \bar{\mathbf{C}}_x(t_i)_j, j = 1, n(t_i)$; $n(t_i) \geq 1)$ of the baseline-wise or network-like processing of original GNSS observations $\mathbf{l}(t_i)_j$ (e.g. daily RINEX files), which were observed in the epoch window $\Delta t(t_i)$, and resulted from the GNSS-data processing as the adjustment step 1 (Fig. 3). Hereby the GNSS data $\mathbf{l}(t_i)_j$ can extend either over the entire interval $\Delta t(t_i)$ or over only a part $\Delta t(t_i)_j$. As concerns the independent single solutions $\bar{\mathbf{x}}(t_i)_j$ a common congruent state vector $\bar{\mathbf{x}}(t_i)$ is presupposed. That assumption holds, if (usually) the epoch-duration $\Delta t$ is limited, otherwise the geodynamic transformations (Fig. 3) have to be performed also within the epoch.

The determination of the final primary epoch state $(\bar{\mathbf{x}}(t_i), \bar{\mathbf{C}}_x(t_i))$ of the GNSS network is done in step 2 as a three-dimensional so-called epoch adjustment of all single network parts $(\bar{\mathbf{x}}(t_i)_j, \bar{\mathbf{C}}_x(t_i)_j, j = 1, n(t_i))$, which are available in $\Delta t(t_i)$, using the module GPS3D. It provides all quality control standards of a three-dimensional network adjustment. In case of $n(t_i) = 1$, step 1 and step 2 coincide, and a quality check for that epoch $t_i$ not possible.

The practical difference between an observation-related deformation analysis (like e.g. realized in the software GOCA [7]) and the coordinate-related deformation analysis MONIKA [6] is evident, while the deformation analysis results are identical [4]: In a single-step observation-related deformation analysis, the original observations are in one step directly part of the functional model of the deformation analysis (1a, b) with individual observation related design-matrices. In the coordinate-related case, the primary epoch states $(\bar{\mathbf{x}}(t_i), \bar{\mathbf{C}}_x(t_i))$ serve – eventually after additional transformations (Fig. 3; chap. 2.1 and 2.2) - as observations of the deformation analysis model (1a, b) as second or third step of the procedure. In spite of these intermediate steps, the results of all final parameter and displacement estimations $\nabla\hat{\mathbf{x}}_O^{i,k}(t_i)$ and $\nabla\hat{\mathbf{x}}_R^{i,k}(t_i)$ (chap. 3) for the object- and reference-points, and respective test statistics are however identical according to the theory of a two-step adjustment, provided that the stochastical models are ported subsequently through all steps [4].



## 1.3 Estimation of the epoch states – rigorous and non-rigorous procedures

Independently of whether the GNSS-data processing is done network-like or in baseline-wise, already linear independent sets of baselines observations $\mathbf{l}(t_i)_j$ in step 1 (Fig. 3) imply a fully occupied covariance matrix $\mathbf{C}_l(t_i)_j$ of these derived GNSS observations, because the same original GNSS data $\mathbf{l}(t_i)$ is multiply used for a number of different GNSS-reference stations. Respective mathematical correlations in the baseline-observations $\mathbf{l}(t_i)_j$ are taken into account in rigorous working network-like GNSS-processing-software, e.g. Bernese (www.bernese.unibe.ch) or WaSoft/Netz (www.wasoft.de) and others. GNSS-processing-software, which is restricted to a baseline-processing („baseline-software“) contrarily neglects these correlations, and it can further not provide the covariance blocks $\mathbf{C}_{x_k, x_l}$ between the coordinates of the rovers k and l of the different baselines. So a GNSS-baseline-processing contributes twice to a neglect in the stochastical model of the resulting block-diagonal matrix $\bar{\mathbf{C}}_x{}'(t_i)_j$ of a processed GNSS-reference-station network. Besides that, rigorous network-like GNSS-software is also more efficient in the estimation of atmospheric parameters and ambiguities.

All neglects in the stochastical models of step 1 and 2 imply biased stochastical models. The neglect of physical correlations in GNSS-processing [8] is in general unavoidable. It leads together with the neglect of the mathematical correlations above, principally to unfavourable covariance matrices $\bar{\mathbf{C}}_x{}'(t_i)$ for the epoch states $\bar{\mathbf{x}}(t_i)$ [4], [8].

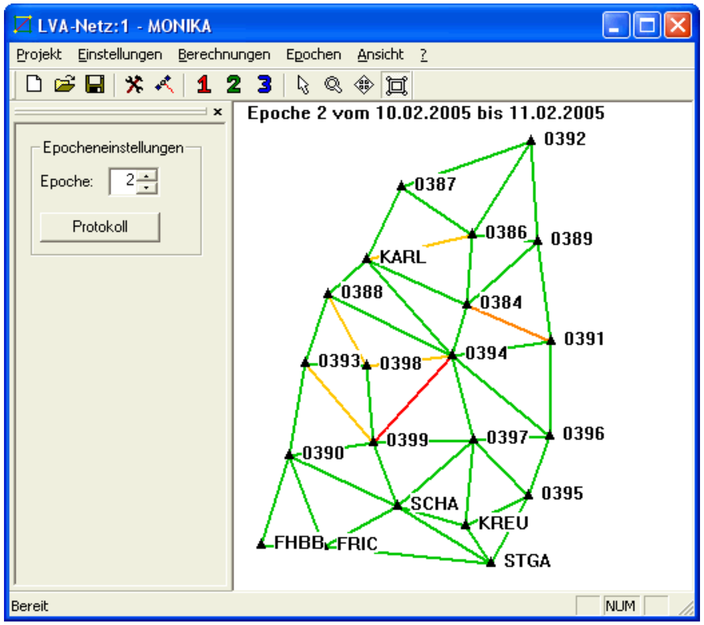


**Fig. 4:** SAPOS-network Baden-Württemberg linked with additional GNSS-reference stations from Switzerland. Graphics for the adjustment (step 2) of the primary epoch state $\bar{\mathbf{x}}(t_i)$ with a detected gross error (red) in one baseline $\bar{\mathbf{x}}(t_i)_j$. A baseline-wise GNSS-adjustment was used in step 1.

This implies accordingly a reduced sensitivity [3] for all tests and biased test statistics, for the parameters of the GMM (1a, b) (e.g. object-point displacements $\Delta\mathbf{x}_O^{i,k}(t_i)$) as well as for the parameters $\hat{\nabla}\mathbf{x}_R^k(t_i)$ of the extended GMM (5a, b) in the deformation analysis step 3 (Fig. 3)So the application of a rigorous network-like GNSS-processing-software combines all advantages for achieving a high sensitive GNSS-reference-station deformation integrity monitoring based on the GNSS observations $\mathbf{l}(t_i)_j$.

The loss of accuracy in the neglect case $\overline{\mathbf{C}}_x'(t_i)$, and so the loss of sensitivity for the detection of object-and reference points displacements in step 3 (fig. 3), can be reduced at first with the choice of the shortest path of linear independent baselines in the GNSS-reference-station-network. The inclusion of additional linear dependent baselines would supply no new contributions on considering rigorously the above mentioned mathematical correlations, what is however not done in the case of a baseline-wise adjustment. So additional baselines could - in principle - contribute to regain a better accuracy for the epoch states ($\overline{\mathbf{x}}(t_i)$, $\overline{\mathbf{C}}_x(t_i)'$). Because of the lack of a theoretical concept concerning the choice of the number and design of additional linear dependent baselines, this proceeding is not adequate as a replacement of a strict GNSS network-wise GNSS-adjustment.

## 2 Transformations of the primary epoch states in MONIKA

The estimation of the primary epoch states ($\overline{\mathbf{x}}(t_i)$, $\overline{\mathbf{C}}_x(t_i)$) in the adjustment steps 1 and 2 (Fig. 3) can either be based on a free or on an ITRF-embedded network adjustment concept. Anyway, the strict realization of the subsequent coordinate-related deformation analysis requires additionally different transformations, which leads to the final input ($\mathbf{x}(t_i)$, $\mathbf{C}_x(t_i)$) of the deformation analysis adjustment step 3 ((1a, b), (5a, b)). In any case a common ITRF-datum for the epochs is required. If step 3 covers a long time-window $\Delta T$ and a wide GNSS-reference-station network area, known geodynamic trends affecting the ITRF positions have to be removed by respective transformations (Fig. 3), both for a free and for an ITRF-embedded deformation analysis concept. The MONIKA deformation integrity monitoring concept has hereby not to mind the question, how the GNSS-reference-stations coordinates and correction data are set up by the positioning service. In case of a free network concept an additional geodetic network-datum transformation procedure has to take place. Both different types of transformations are treated in the following.

### 2.1 ITRF-Datum and geodynamic transformations in MONIKA

Besides a continuous ITRS (International Terrestrial Reference System) parameter estimation the responsible IERS (International Earth Rotation Service) carries out, presently about every five years, the readjustment of the core network of GNSS and VLBI permanent stations. This defines by the new ITRF-coordinates a respective new ITRF datum (ITRFzzzz), which is related to January 0.0 of the new year zzzz of reference. In addition a first set of 14 parameters is estimated, namely the seven parameters of the global datum transition to the preceding ITRF datum (ITRFyyyy), and further seven parameters of global datum drift-rates. And in addition 16 sets of 3 rotation rate parameters for the IERS 16-plates-model of the lithosphere are estimated. The pure datum transition between two ITRF datum realizations, yyyy and zzzz, for an ITRF-based primary epoch position at epoch time $t_i$ reads:

$$\overline{\mathbf{x}}(t_i)_{ITRFzzzz} = (1+\Delta m)\cdot\mathbf{R}(\varepsilon_x,\varepsilon_y,\varepsilon_z)\cdot\overline{\mathbf{x}}(t_i)_{ITRFyyyy} + \mathbf{t} \quad . \tag{2}$$

With improvements in the ITRS parametric models, the datum-transition (2) tends to zero. So the current transition from ITRF2000 to ITRF2005 is with $\mathbf{t}^T = (-0.1\text{mm}, +0.8\text{mm}, +5.8\text{mm})$ for the translations, a scale-change $\Delta m = -0.4\cdot 10^{-9}$, and rotation angles $\varepsilon_x = \varepsilon_y = \varepsilon_z = 0$ [2] - contrary to earlier ones, e.g. ETRF89 to ITRF93 - very small. .



For the transformation of an ITRF-position $\overline{\mathbf{x}}(t_1)_{ITRFzzzz}$ of a j-th point at epoch time $t_i$ to the reference time $t_0$ of the deformation analysis ((1a, b) and (5a, b)) the common datum drift rates ($\Delta\dot{m}$, $\dot{\mathbf{R}}$, $\dot{\mathbf{t}}$) of all plates, and in addition the rotation rate matrix $\dot{\mathbf{R}}_{P(k)}$ of the plate P(k) concerning the j-th point in regard, become relevant. So we have all in all for that geodynamical transformation:

$$\begin{aligned} \mathbf{x}(t_1) &:= \overline{\mathbf{x}}(t_1 \mid t_o)_{ITRFzzzz} \\ &= \overline{\mathbf{x}}(t_1)_{ITRFzzzz} + \left((\Delta\dot{m} + \dot{\mathbf{R}})\cdot\overline{\mathbf{x}}(t_1)_{ITRFzzzz} + \dot{\mathbf{t}}\right)\cdot(t_o - t_1) \\ &\quad + \left(\dot{\mathbf{R}}_{P(j)}\cdot\overline{\mathbf{x}}(t_1)_{ITRFzzzz}\right)\cdot(t_o - t_1) \quad . \end{aligned} \tag{3}$$

Values for the parameters in (3) are found in [2] and [5]. In case of an expanded time window $\Delta T$ of the coordinate-related deformation analysis (1a, b), as well in a wide area GNSS-reference-stations network, the physically caused geodynamic transformation (3) becomes relevant. So both transformations (2) and (3) of the primary epoch states ($\overline{\mathbf{x}}(t_i)$, $\overline{\mathbf{C}}_x(t_i)$) have to be considered, together with an arbitrary definition of a common reference time $t_0$, for all epochs in (1a, b). The transformations of the epoch state vectors from $\overline{\mathbf{x}}(t_i)$ to $\mathbf{x}(t_i)$ are followed by a respective transformation of $\overline{\mathbf{C}}_x(t_i)$ and lead to

$$\mathbf{C}_x(t_i) = \overline{\mathbf{C}}_x(t_i) + \Delta\mathbf{C}((2),(3)) \tag{4}$$

on applying the law of error propagation to (2) and (3) using the covariance matrices of, all in all, 17 parameters. The application of the transformations (2) and (3) also causes covariances between the epoch states. In regional GNSS-networks, like SAPOS/ASCOS in Germany, the transformations (3) and (4) can be avoided by the choice of small and overlapping time windows $\Delta T$ for the standard monitoring case. So the missing part $\Delta\mathbf{C}((2),(3))$ (4) leads to an increase of the deformation sensitivity (chap. 3).

The transformations (2), (3) and (4) are relevant both for an ITRF-embedded as well as for a free network based coordinate-related deformation analysis in the concept of MONIKA (fig. 3). We arrive at first commonly at the transformed states ($\mathbf{x}(t_i)$, $\mathbf{C}_x(t_i)$). In case of a free network concept applied in the MONIKA approach (Fig. 3), the epoch states have each a singular covariance matrix $\mathbf{C}_x(t_i)$ and the coordinates $\mathbf{x}(t_i)$ are not unique with respect to the occurence of a datum translation defect d=3. So they to be submitted further to the datum transformation procedure treated in chap. 2.2.

Alternatively, and possibly with an increase of the sensitivity, the transformations (3) and (4) could be replaced by an appropriate parametric extension of the GMM (1a,b) with respect to the estimation of additionally seven or - in case of free network concept used in MONIKA of four - common drift rate parameters. In that case the primary epoch states ($\overline{\mathbf{x}}(t_i)$, $\overline{\mathbf{C}}_x(t_i)$) could - except the additional datum transformation in the free network case (chap. 2.2) - be used directly in (1a, b).

### 2.2 Free network concept and datum-transformation in MONIKA

The primary epoch state vectors ($\overline{\mathbf{x}}(t_i)$, $\overline{\mathbf{C}}_x(t_i)$) may either result from the steps 1 and 2 in MONIKA, or may be imported from an external computation, and they are transformed by (2), (3) and (4) to ($\mathbf{x}(t_i)$, $\mathbf{C}_x(t_i)$). Due to $\varepsilon_x = \varepsilon_y = \varepsilon_z = 0$ (chap. 2.1) the transformation (2) can, except the scale, be neglected in a free network deformation analysis concept, as the translations $\mathbf{t}$ are not relevant due to the translation defect d=3. In case of a free network concept the resulting epoch state vector $\mathbf{x}(t_i)$ depends anyway on the network datum, and e.g. in case of an externally computed and imported primary state ( $\bar{\mathbf{x}}(t_i)$ , $\bar{\mathbf{C}}_x(t_i)$ ), the datum of the transforemd $\mathbf{x}(t_i)$ remains unknown.

To achieve however in the free network case of the coordinate-related deformation analysis approach MONIKA the same results as in the observation $\mathbf{l}(t_i), \mathbf{C}_l(t_i)$ related analogy, it is necessary, that the transformed epoch state presentations $(\mathbf{x}(t_i), \mathbf{C}_x(t_i))$ lead to the same normal-equation parts in (1a,b). This is provided in two steps of a respective datum transformation procedure. First $\mathbf{x}(t_i)$ is submitted to a defect-dependent parametrized three-dimensional un-weighted similarity transformation (Helmert-transformation) on the approximate coordinates $\mathbf{x}_0$ used in (1a, b). This concept also holds for higher defects (e.g. free three-dimensional terrestrial distance networks, d=6), but only for d>3 the law of error-propagation requires a subsequent finite similarity transformation (not a standard S-transformation) for $\mathbf{C}_x(t_i)$ . As second step a defect-dependent classical S-transformation [4] has to follow for $\mathbf{C}_x(t_i)$ . If the S-transformation is done with respect to the so-called ‚inner datum', the pseudoinverse $\mathbf{C}_x(t_i)^+$ has to be used for the computation of the weight matrix $\mathbf{P}(i) = \sigma_0^2 \cdot \mathbf{C}_x(t_i)^+$ in (1a, b). With $\sigma_0^2$ we decribe the a priori variance factor. If alternativey the S-tansformation is done due to an arbitrarily chosen datum point, correlated coordinate differences $\Delta\mathbf{x}(t_i)$ with a regular weight matrix $\mathbf{P}(i)$ , can be introduced as observations into (1a, b) in step 3.

In case of a free network concept in (1a, b) the above mentioned S-transformation removes the translation parts, which are contained in $\mathbf{C}_x(t_i)$ . So the sensitivity for the detection of the displacements $\Delta\mathbf{x}_O^{i,k}(t_i)$ and $\nabla\mathbf{x}_R^k(t_i)$ (chap. 3) will be higher in a free network related approach (1a, b).

## 3 Deformation analysis modelling and software MONIKA

In opposite to an observation-related $(\mathbf{l}, \mathbf{C}_l)$, one step and fast, online procedure for hybrid observation data, such as e.g. realized in the GOCA-software (www.goca.info; [7]), the three step coordinate-related ( $\mathbf{x}(t_i)$ , $\mathbf{C}_x(t_i)$ ) deformation analysis in MONIKA [6] is best suited for the (near-online) deformation integrity monitoring of GNSS-reference-station networks. Here MONIKA (Fig. 3) allows a flexible definition and computation of the primary epoch states in step 1. The adjustment step 2 allows a profound quality control of primary epoch states, and so of the deformation analysis input. Additionally the coordinate-related approach is directly accessible both to the above mentioned ITRF-datum (2) and the geodynamics transformation (3), as well as for the import of external and also coordinate-related epoch states.

The computation of the primary epoch state contributions ( $\bar{\mathbf{x}}(t_i)_j$ , $\bar{\mathbf{C}}_x(t_i)_j$ ) from the original RINEX data $(\mathbf{l}, \mathbf{C}_l)$ is done in the software MONIKA by the module GOCA_BEPEC_PRO, which permits the use and full control of different GNSS-data processing engines (Fig. 3). The three-dimensional epoch adjustment of the ( $\bar{\mathbf{x}}(t_i)_j$ , $\bar{\mathbf{C}}_x(t_i)_j$ ) with respect to the final primary epoch state ( $\bar{\mathbf{x}}(t_i)$ , $\bar{\mathbf{C}}_x(t_i)$ ) is done in MONIKA using the module GPS3D (www.geozilla.de), and ensures in step 2 the quality control of the GNSS data processing(s) in step 1.

For the detection of unstable reference points the functional model (1a) is extended by the three-dimensional additional parameter vector $\nabla\mathbf{x}_R^{i,k}(t_i)$ as

$$(\mathbf{x}(t_i) - \mathbf{x}_0^i) + \mathbf{v}_{x(t_i)} = \mathbf{D}_R^i \cdot d\hat{\mathbf{x}}_R^i + \mathbf{D}_O^i \cdot d\hat{\mathbf{x}}_O^i + \mathbf{B}_i^k \cdot \hat{\nabla}\mathbf{x}_R^{i,k}(t_i) \qquad (5a)$$

and with



$$\mathbf{B}_i^k \cdot \hat{\nabla}\mathbf{x}_R^{i,k}(t_i) = \begin{bmatrix} \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \ldots \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \ldots \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \end{bmatrix}^T \cdot \hat{\nabla}\mathbf{x}_R^{i,k}(t_i) \quad . \qquad (5b)$$

The design-matrix $\mathbf{B}_i^k$ and the three-dimensional parameter vector of a displacement $\hat{\nabla}\mathbf{x}_R^k(t_i)$ are adressing the k-th reference point of the i-th epoch. The model (5a, b) is applied to all epochs and reference points $\mathbf{x}_R^{i,k}$ within each epoch. A generalized three-dimensional iterative datasnooping [4] provides the estimation of the displacement vector $\hat{\nabla}\mathbf{x}_R^{i,k}(t_i)$. The (3x3)-covariance-matrix of $\hat{\nabla}\mathbf{x}_R^{i,k}(t_i)$ can be computed from the results of the adjustment (1a, b). In that way the above extended GMM (5a, b) needs not to be set up and computed explicitly. Like in the case of the classical datasnooping, each k-th reference point in the i-th epoch is tested for the significance of the displacement $\hat{\nabla}\mathbf{x}_R^{i,k}(t_i)$ (5a, b) by a three-dimensional test-statistics [4], [8]. The test assumes the remaining (n-1) reference points $\mathbf{x}_R$ as congruent and unmoved. If we introduce with m the total number of epochs in the deformation analysis window $\Delta T$ , the relation between the number of free and fixed parameters is $1:(m-1)\cdot(n-1)$ , and it means a maximum of sensitivity for the detection of displacements $\nabla\mathbf{x}_R^{i,k}(t_i)$.

The results of the displacement estimation (5a, b) for the reference-points $\mathbf{x}_R$ , as well as the displacements of the a-priori or iteratively selected object-points $\mathbf{x}_O$ , can further be represented by the MONIKA software in a time series graphics (Fig. 5). If the test for $\hat{\nabla}\mathbf{x}_R^{i,k}(t_i)$ reveals a significantly distorted reference-point, the respective point is put automatically to the list of objects points $\mathbf{x}_O$ . That point can optionally be set back to the reference-point list $\mathbf{x}_R$ , if the displacements $\Delta\hat{\mathbf{x}}_O^{i,k}(t_i)$ in the next epoch (i+1) turns out as not significant. As concerns time series of estimation of the displacements of the reference point, as well as for object-points displacements, these can be visualized (Fig. 5), and further be submitted to different kind of trend estimations, time series analysis' and filtering procedures.

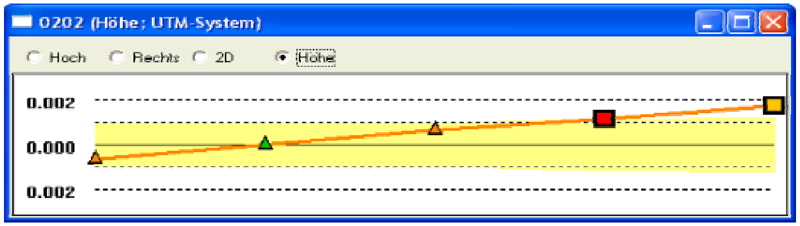


**Fig. 5:** Time series of estimated $\hat{\nabla}\mathbf{x}_R^{i,k}(t_i)$ concerning the height of a k-th reference point in a simulation study. In yellow the confidence intervals.

The present test-computations with daily RINEX files in Baden-Württemberg, Germany, using the baseline software WA1 (www.wasoft.de) in MONIKA step 1 point out, that already with baseline-software, displacements in plane and height positions of a few mm can already be detected. The statistical measure of the three-dimensional sensitivity-ellipsoid [3] concerning the displacements shows, that - on a sensitivity level of ß=95% - displacements $\nabla\mathbf{x}_R^{i,k}(t_i)_{(\alpha,\beta)}$ in plane and height of less than 5 mm and 20 mm can be detected on applying the three-dimensional test-statistics for $\hat{\nabla}\mathbf{x}_R^{i,k}(t_i)$ (5a,b) with a test error-probability of $\alpha$ =5%. The sensitivity measure is equivalent to accuracies of less than 1.2 mm and 4.8 mm in plan and height-components for the estimates $\hat{\nabla}\mathbf{x}_R^{k}(t_i)$ (5a, b).

The realization of the coordinate-related deformation analysis modelling (1a, b), (5a, b) has been implemented in the MONIKA software, version 1.0 (module MONDEF, fig 1) and tested successfully by real data and simulations. Alternatively the deformation analyis adjustment step 3 could be set up as a sequential adjustment procedure related to (1a, b) and (5a, b), or e.g. with regard to the prediction (3), in a Kalman-filtering related model. These are just two examples for future research and development work concerning the MONIKA approach within the GOCA project and in cooperation with the state survey agency of Baden-Württemberg, Karlsruhe [6].

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