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GNSS/GPS/LPS based Online Control and Alarm System (GOCA)

- A Geodetic Contribution to Natural and Geotechnical Deformation Monitoring and Hazard Prevention -

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Summary

The research and development project GOCA (GNSS/LPS-based Online Control and Alarm System) aims at the use of GNSS (Global Navigation Satellite Systems) sensors (e.g. GPS, GLONASS and in futire GALILEO) together with classical terrestrial sensor, so-called local positioning sensors (LPS) for the real-time and the near online monitoring of movement processes at the earth's surface.

The GOCA system development is done as a cooperation project between the GOCA-team Karlsruhe (www.goca.info) and the companies GeoNav (www.geonav.de) and DrBertges Vermessungstechnik (www.drbertges.de). GOCA may be set up online as an early-warning-system for natural hazards (landslides, glaciers, volcanoes, earthquake zones, etc.), for mining areas, for the monitoring of geo-technical installations (dams, locks, dumps, etc.), for buildings and structures (bridges, towers, etc.) and for a GPS/GNSS reference station network deformation integrity monitoring (chap. 3.2).

The GOCA system and the GOCA deformation analysis concept and the mathematical models implemented in the GOCA software are discussed in the chap. 1 and 2. Special features are treated in chap. 3, and further applications in chap. 4.

Finally some application sceneries (a dam monitoring, and the long-term monitoring of the area of the largest European railway tunnel, the 57 km Gotthard tunnel, Switzerland) are shown and user references are given in chap. 5. The chap. 5 also points out some data analysis examples of GOCA software referring to mathematical models chap. 2.2.

1 GOCA System Hardware and Software Components

The GOCA system consists of a set of GPS sensors and communication units set up in the monitoring area and two software components, namely the GOCA sensor communication software and the GOCA deformation analysis software. The GOCA computation unit, called the "GOCA-Center", consists accordingly of a computer, where these two software components are running. Based on the GKA data interface, the GOCA communication software packages of the GOCA cooperation partners, namely MONITOR of GeoNav company [11], (www.geonav.de) and GOCA_DC3 of the company Dr. Bertges (www.drbertges.de) [7], are able to control any array of GPS/GNSS and LPS sensors (fig. 1), and to provide the GPS/GNSS and LPS data for the GOCA deformation analysis software (briefly GOCA software). The structure of the GPS/GNSS and LPS data interface for the GOCA deformation analysis software, the so-called GKA files, are adapted to the standard of the GPS/GNSS baseline output and the standard of LPS data (zenith angles, distances, directions, height differences; see [7]).

Any local GOCA-Center may be linked over a long distance to another PC, which serves as a remote control station, e.g. by Internet or a telephone link. In this way several separate local or regional projects can be monitored simultaneously. The further evaluation of the GKA baseline and LPS data and respective online modeling of a three-dimensional displacement, velocity and acceleration field and related deformation functions are performed by the GOCA software, which has been developed by the GOCA team Karlsruhe (http://www.goca.info) starting in 1999. The GOCA software sounds alarm, if a specified critical state becomes significant during an online monitoring. The complete deformation analysis functionality is also provided in a near online or in a post-processing mode respectively. So the GOCA system may be set up in an object area as a permanent array or as a mobile "task force system" in areas, where danger becomes imminent.

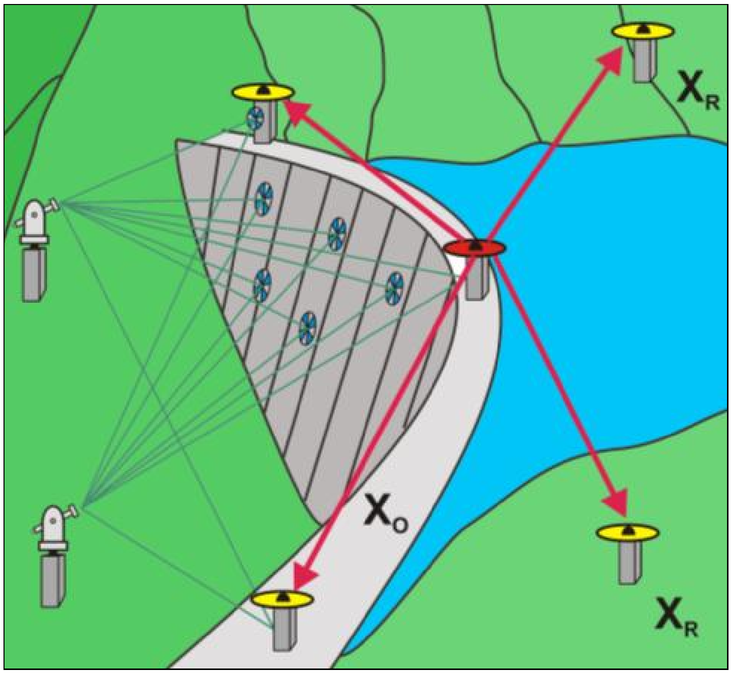

Fig. 1: **Design of a classical absolute deformation network realized by the GOCA system. The sensor array consists of a stable reference point frame $\mathbf{x}_R$ and the domain of moving object points $\mathbf{x}_O$. The sensor observations l, in the dam example GPS-baseline observations (red) and the total stations observations (green) enable the permanent estimation of the deformation state vector $\mathbf{y}(t)$ in dependence of time t.**

2 GOCA Deformation Analysis Software

2.1 Georeferencing and Deformation Modelling of the Object-Points

The deformation analysis concept implemented in the GOCA software is due to a classical deformation analysis [7], [8], [12], [14], [15]. It is based on a strict network adjustment and is realized in three subsequent adjustment steps (1st, 2nd and 3rd step). The monitoring network is physically realized by an array of GPS/GNSS and LPS sensors, while the respective deformation network design has to be specified in the initialization step (1st step).

The 1st step provides the initialization of the so-called reference or stable point frame of the monitoring network. As concerns GPS it holds, that independent of being set up either as a GPS/GNSS base station or as a rover station, any GPS/GNSS receiver has to be specified to be either a (stable) reference point or a (moving) object point. So an optimum design of a GPS/GNSS monitoring array - e.g. with respect to short baselines - is enabled. In the context with an adjustment concept behind all steps of the GOCA deformation analysis, the deformation network design may be set up as a redundant (e.g. by using two GPS/GNSS reference stations or additionally LPS sensors (total stations; automatic levelling) or as a non-redundant configuration.

The initialization namely the 1st adjustment step, is based on a least squares (L2-norm) free network adjustment of the GPS/GNSS baseline and LPS data with respect to a user-defined starting epoch, and is robustified with respect to gross errors by an automatic iterative data snooping including a stepwise variance component estimation. By the aim of realizing a classical deformation analysis in a permanent online mode, this 1st step has to precede the deformation monitoring, as it provides the network datum $\mathbf{x}_R$ (fig. 1) for the permanent georeferencing of the object points $\mathbf{x}_O$ (fig. 1) and the deformation analysis, which run parallel in the following 2nd and 3rd adjustement step.

The 2nd step performed by the GOCA software is again based on the above mentioned GKA baseline and LPS data and is running completely automatically during the online monitoring. Any online monitoring project can however also be processed in a post-processing mode. The 2nd step comprises the permanent L2-norm adjustment of the GPS/GNSS baselines and LPS data (distances, zenith angles, directions, height differences) and the mathematical model provides the georeferencing of the 3D object-point position time series $\mathbf{x_o}(t_i)$. The reference frame $\mathbf{x}_R$ (fig. 1) is constituted by the stable reference points, while both the coordinates and the covariance matrix of the reference points - as the result of the 1st step - are considered in the mathematical model. Based on a L2-norm adjustment and including automatic data-snooping, the 2nd step works automatically, both for redundant or for non-redundant GPS/GNSS and LPS array configurations.

The 3rd step, the deformation analysis itself, implemented in the GOCA software, deals with the estimation of the parameters of different so-called deformation functions and runs parallel online to the 2nd step. The parameter estimation is related to the results of the 2nd step, namely the 3D object-point position time series $\mathbf{x}(t_j)$ and the stochastic model. The 2nd and the 3rd step are handled online as seamless consecutive adjustment processes. The estimation of respective deformation functions and parameters can be performed in the 3rd step online either as a

- L2-norm estimation, (5b) or a
- Robust L1-norm estimation (5c), or a
- Robust M-Estimation (5d) .

The estimation principle can be chosen by the GOCA software user. The following object-point related deformation functions and respective parameter estimation algorithms are available in the online monitoring mode of the GOCA software:

- Moving average including the detection of critical displacements

- Automatic displacement estimation ((8a), (8b), fig. 4) between different epochs (each epoch is individually specified by an interval length, e.g. 3 hours)
    - 1st epoch = Initialisation (1st step) and 2nd epoch is moving in a defined cycle
    - 1st epoch = Fixed by user definition and 2nd epoch is moving in defined cycle
    - 1st epoch = Dynamically moving´and 2nd epoch is moving in defined cycle
    -
- Kalman-Filtering (9a), (9b) with the state vector of three-dimensional
    - displacements $\mathbf{u}(t)$,
    - velocities $\dot{\mathbf{u}}(t)$ and
    - accelerations $\ddot{\mathbf{u}}(t)$.

Fig. 1: Example of a GPS receiver and telemetric equipment within a GOCA sensor array in case a slope monitoring in open cast mining at RWE Power AG (see, tab. 1) using the GOCA system

The deformation functions and the respective parameters described above can be referred either to critical values or to significant changes, e.g. in the displacements **u**(t) ((7a), (7b); (8a), (8b); (9a), (9b); fig. 4; fig. 5), so that an automatic alarm can be sounded according to the user-defined priorities and alarm modes (email, SMS, fax, etc).

The above online deformation functions can also be used in a near-online or a post-processing mode (e.g. in a daily processing of the data). In the near-online and post-processing of the 3rd step the complete spectrum of the above mentioned online deformation functions is again available, and additionally the deformation functions of a

- Polynomial based trend-estimation, a
- Leap detection and the estimation of
- Displacements between two epochs defined by an individual interval length (e.g. one day).

Here the estimation principles are besides L2-norm and the robust L1-norm extended with respect to the robust Huber-estimator [10].

2.2 Mathematical Models implemented in the GOCA software

In the 1st and in the 2nd step all GNSS and LPS observations **l,** which may according to the sensor design (fig. 1) either take place between the reference points $\mathbf{x}_R$ or between the object points $\mathbf{x}_O$ or between reference points $\mathbf{x}_R$ and object points $\mathbf{x}_O$ are included in an online geodetic network adjustment. The observations $\mathbf{l}$ - like shown in fig. 1 at the example of the GNSS baseline vectors and/or the LPS observations of total-stations (distances, zenith angles and distances) - are collected and provided by the GKA data interface together with their respective covariance matrices $\mathbf{C}_{li}$. In general the relation

$$\mathbf{l} = \mathbf{l}(\mathbf{y}) \tag{1}$$

between the sensor observations **l** and the state vector **y** of the deformation monitoring network is nonlinear, and the so-called functional model (1) has to be linearised by introducing approximate parameters $\mathbf{y}^0$. This is done automatically by the GOCA software.

The observations $\mathbf{l}$ (1) are collected at a tracking rate Δt (e.g. $\Delta t = 1\,\mathrm{sec}$ for GPS (fig. 2)), which may be synchron or different for the different sensor types in the monitoring array (fig. 1). The definition of discrete periods or epochs for the descretisation of the object point movements is referring to the so-called sampling interval ΔT, and it must hold

$$\Delta t \le \Delta T \quad . \tag{2a}$$

The lower and upper border of the discrete sampling interval $\Delta T(t_i)$, which refers to the epoch t_i and has a duration of ΔT, reads:

$$\Delta T(t_i) = [t_i - \frac{\Delta T}{2}, t_i + \frac{\Delta T}{2}] \quad . \tag{2b}$$

According to (2b) the time dicretisation of the object points displacements is done in subsequent intervals (2b) of duration ΔT. So all observations $\mathbf{l}_i$ within the time borders of the sampling interval $\Delta T(t_i)$ (2b) refer to a constant state vector $\mathbf{x}_O(t_i) = \mathbf{x}_{Oi}$ of the object point coordinates at epoch t_i. Observation sets $\mathbf{l}_i$ and $\mathbf{l}_j$ belonging to two generel different epochs t_i and t_j accordingly refer to two different sets of coordinates $\mathbf{x}_{Oi}$ and $\mathbf{x}_{Oj}$, which are be set up in the time invariant coordinate frame $\mathbf{x}_R$ of the reference points (fig. 1). For two general epochs t_i and t_j we get after the linearisation of (1) the following system of an in general overdetermined so-called system of observation equations:

$$(\mathbf{l}_i - \mathbf{l}_i(\mathbf{y}^0)) + \mathbf{v}_i = \mathbf{A}_{Ri} \cdot d\mathbf{x}_{Ri} + \mathbf{A}_{Oi} \cdot d\mathbf{x}_{Oi} + \mathbf{0} \cdot d\mathbf{x}_{Oj} \quad \text{and} \quad \mathbf{C}_{li} \tag{3a}$$

$$(\mathbf{l}_j - \mathbf{l}_j(\mathbf{y}^0)) + \mathbf{v}_j = \mathbf{A}_{Rj} \cdot d\mathbf{x}_{Rj} + \mathbf{0} \cdot d\mathbf{x}_{Oi} + \mathbf{A}_{Oj} \cdot d\mathbf{x}_{Oj} \quad \text{and} \quad \mathbf{C}_{lj} \tag{3b}$$

With $\mathbf{A}(\mathbf{y}^0)$ we introduce the type of the so-called design matrices, which relate to the first derivatives of the observations **l** with respect to the unknown parameters **y**. With $\mathbf{v}_i$ and $\mathbf{v}_j$ we describe the vectors of observation corrections of the observation vectors $\mathbf{l}_i$ and $\mathbf{l}_j$. Upon imposing the stability constraint $\mathbf{x}_{Ri} = \mathbf{x}_{Rj} = \mathbf{x}_R$ for the reference points (fig. 2), we obtain as the basic state vector of the deformation process modelling **y** in the 1st and 2nd step for two general epochs t_i and t_j reading

$$d\mathbf{y} = (d\mathbf{x}_R \mid d\mathbf{x}_O(t_i), d\mathbf{x}_O(t_j))^T \quad \text{and} \quad \mathbf{y} = \mathbf{y}^0 + d\mathbf{y} \ . \tag{4a), (4b}$$

According to (3a), (3b) and (4a), (4b) the mathematical model and the basic deformation process related state vector **y** can easily be extended to any number m of monitoring epochs.

The so-called M-estimation [10] applied to n observations l_k (k=1,n) in all m monitoring epochs reads

$$\sum_{k=1}^{n} \rho(\overline{v}_k) = \sum_{k=1}^{n} \rho\left((\mathbf{C}_l^{-\frac{1}{2}} \cdot \mathbf{A})_k \cdot d\hat{\mathbf{y}} - (\mathbf{C}_l^{-\frac{1}{2}} \cdot (\mathbf{l} - \mathbf{l}(\mathbf{y}^0)))_k \right) = \mathrm{Min}\,|_{\mathbf{y}} \tag{5a}$$

and leads to the the state vector **y** (4a), (4b) by minimizing the total sum of the so-called loss function $\rho(\overline{v}_k)$ [10] of the standardized residuals $\overline{v}_k$. The algorithmic solution of (5a) and the determination of the estimation $\mathbf{y}$ and the covariance $\mathbf{C}_y$ are described in [10]. Depending on the type of the loss-function $\rho(\overline{v}_k)$ the estimation of the parameters $\mathbf{y}$ in the 1st , 2nd and 3rd GOCA-adjustment step is either due to a least squares (L2-Norm), a L1-Norm or a Huber estimation. The respective loss functions read:

$$\rho(\overline{v}_i) = \frac{1}{2}\overline{v}_i^{\,2} \qquad \text{- Least squares estimation (L2-norm)} \tag{5b}$$

$$\rho(\overline{v}_i) = \frac{1}{2}|\,\overline{v}_i\,| \qquad \text{- L1-norm estimation} \tag{5c}$$

$$\rho(\overline{v}_i) = \begin{cases} \frac{1}{2}\overline{v}_i^2 & \forall\ |\overline{v}_i| \le k \\ |\overline{v}_i| & \forall\ |\overline{v}_i| > k \end{cases} \qquad \text{- Weak robust Huber-Estimation [10]} \tag{5d}$$

The loss functions $\rho(\overline{v}_k)$ (5b) is optimal for normal distributed observation errors and (5c) and (5d) are robust against gross observation errors ∇l_k [10].

The 1st adjustment step (initialization) is based on a L2-norm (5b) and is robustified by the procedure of iterative datasnooping. The 1st step provides the reference point frame information for all the subsequent monitoring steps. The steps 2 and 3 are running parallel. The essential result of the initialization is the information about the reference point frame $\mathbf{x}_R$ (fig. 1), which is completely represented by adjusted coordinates $\mathbf{x}_R$ and the covariance matrix $\mathbf{C}_{x_R}$. Both are stored in the GOCA project database.

The mathematical model of the 2nd adjustement step is also based on a L2-norm estimation (5c) and iterative datasnooping and provides the time series $\mathbf{x}_0(t_i)$ of the object points and the covariance matrices $\mathbf{C}_{x_O(t_i)}$ as

$$\mathbf{x}_O(t_i) \quad \text{and} \quad \mathbf{C}_{x_O}(t_i) \ . \tag{6a,b}$$

According to (3a, (3b) the time series $\mathbf{x}_O(t_i)$ (6a) are georeferenced in the reference point frame $\mathbf{x}_R$. In order to increase essentially the real-time performance of the 2nd step adjustment the coordinates $\mathbf{x}_R$ of the reference points resulting of the initialization are held fix on setting $d\mathbf{x}_R = \mathbf{0}$. The covariance matrix $\mathbf{C}_{x_R}$ is however taken into account for the computation of the covariance matrices $\mathbf{C}_{x_O}(t_i)$ (6b) of the object point time series $\mathbf{x}_0(t_i)$. The raw object point displacements t_0 are resulting by defining a discrete reference epoch t_0, and we have

$$\mathbf{u}_O(t_i) = \mathbf{x}_O(t_i) - \mathbf{x}_O(t_0) \quad \text{and} \quad \mathbf{C}_{u_O}(t_i) \quad . \tag{7a,b}$$

The covariance matrices $\mathbf{C}_{u_O}(t_i)$ (7b) are resulting by applying the so-called law of error propagation to (7a).

The mathematical model of the object-point related deformation functions (chap. 2.1) and the respective parameter estimation algorithms in the 3rd step of the GOCA deformation analysis are referring to the object points $\mathbf{x}_O(t_i)$ (6a) and $\mathbf{u}_O(t_i)$ (7a) respectively. These are used as observations $\mathbf{l}(t_i)$ together with the stochastical models $\mathbf{C}_{x_O}(t_i)$ (6b) and $\mathbf{C}_{u_O}(t_i)$ (7b), respectively. The different M-estimation principles (5b), (5c) and (5d) can be selected arbitrarily be the user in the GOCA settings dialogs for the deformation function estimations of the 3rd step.

The functional model of the GOCA object point displacement estimation $\mathbf{u}(t)$ [9] at a time t with respect to the reference time t_0 and state vector $\mathbf{y}(t)$ read:

$$\begin{bmatrix} \mathbf{l}_{t_0} \\ \mathbf{l}_t \end{bmatrix} + \begin{bmatrix} \mathbf{v}_{t_0} \\ \mathbf{v}_t \end{bmatrix} = \begin{bmatrix} \mathbf{E}_1 & \mathbf{0} \\ \mathbf{E}_2 & \mathbf{E}_2 \end{bmatrix} \cdot \begin{bmatrix} \mathbf{x}_0 \\ \mathbf{x}_0 + \mathbf{u}(t) \end{bmatrix} \quad \text{and} \quad \mathbf{y}(t) = (\mathbf{x}_o, \mathbf{u}(t))^T \quad . \tag{8a,b}$$

The reference time t_0 is again defined with respect to an extended time interval Δt_0 (fig. 5, left) for the observations taken from the time series $\mathbf{x}_O(t_i)$ (6a). The same holds for the time t referring also to an extended interval Δt_t (fig. 5, right). Accordingly the two observations groups $\mathbf{l}_{t_0}$ and $\mathbf{l}_t$ (8a) taken from the time series vector $\mathbf{x}_O(t_i)$ (6a) provide in general redundancy with respect to the state vector **y** (8b) of the displacement model (8a) with only 6 parameters for each object point $\mathbf{x}_O$. The six parameters $\mathbf{y}(t)$ are the 3-dimensional position $\mathbf{x}_0$ at the reference time t_0 and the 3-dimensional displacement $\mathbf{u}(t)$ at the estimation epoch time t. The matrices $\mathbf{E}_1$ and $\mathbf{E}_2$ are column matrices composed of (3 x 3)-unit matrices for each three-dimensional observation in the respective group.

The GOCA Kalman-Filtering [4], [5], [6], [11], [12], [13] as a second example for the deformation parameter estimation in the 3rd step is related to the following so-called transition equation (9a), and to the state vector **y** (9b) reading:

$$\mathbf{y}(t) = \begin{bmatrix} \mathbf{u}(t) \\ \dot{\mathbf{u}}(t) \\ \ddot{\mathbf{u}}(t) \end{bmatrix} = \begin{bmatrix} \mathbf{I} & [\Delta t] & \left[\frac{1}{2}\Delta t^2\right] \\ \mathbf{0} & \mathbf{I} & [\Delta t] \\ \mathbf{0} & \mathbf{0} & \mathbf{I} \end{bmatrix} \cdot \begin{bmatrix} \mathbf{u}(t-\Delta t) \\ \dot{\mathbf{u}}(t-\Delta t) \\ \ddot{\mathbf{u}}(t-\Delta t) \end{bmatrix} \quad \text{and} \quad \mathbf{y}(t) = (\mathbf{u}, \dot{\mathbf{u}}, \ddot{\mathbf{u}})^T \quad . \tag{9a,b}$$

The state vector **y**(t) of the GOCA-Kalman-Filtering comprises the individual three-dimensional displacement $\mathbf{u}(t)$, velocity $\dot{\mathbf{u}}(t)$ and acceleration $\ddot{\mathbf{u}}(t)$ of the object points between subsequent time intervals Δt. The observations **l**(t) for the Kalman-Filtering (9a), (9b) are taken from the object point time series $\mathbf{u}_O(t_i)$ (7a), and again the observation content is to be set by the GOCA-user by specifying an interval.

3 Further Features of the GOCA-Software

3.1 Congruency Testing and Detection of Instable References Points

A special feature of the GOCA deformation analysis software consists in the automatic procedure of a statistically strict testing of the congruency of the plan and height component of a GPS-array. In the context of setting up a classical deformation network, the stable point test procedure is applied to detect instable reference points [8], [11], [13], [14]. In this way distortions of the object-points or better “pseudo deformations”, which would in case of undetected instable reference points occur of the object space, are excluded of the deformation process modelling. With respect to a maximum sensitivity the detection of instable reference points between different epochs is performed as a "1:(n-m) process". This means, that - in analogy to the classical observation-related iterative data-snooping - a significant 3D displacement of each reference point is tested in the m^{th} step relative to (n-m) stable points, starting with m=1. The iterative stable point testing is again accompanied and robustified, respectively, by an iterative data snooping concerning the GPS/GNSS baseline observations (GKA files) and by a variance-component estimation.

3.2 Deformation Integrity Monitoring of Reference Station Networks

The GOCA software and the implemented stable point testing algorithm (chap. 3.1) can be applied for the statistically strict detection of possible movements of stations in GPS/GNSS positioning service such as ***SAPOS*** and ***ascos***. (www.sapos.de). This feature of the GOCA system is called deformation integrity monitoring of reference station network, and is applied in different states in the German ***SAPOS*** network.

4 Present Developments of the GOCA software

The present development of the GOCA software is dealing with the implementation of different so-called

- GPS/GNSS-baseline processing engines.

This kind of GPS-processing packages will enable the GOCA software to work in a near-online mode with respect to the integration of a GPS raw data processing (code and phase measurements), which is based on RINEX data. One application of the GPS/GNSS raw data processing capacity is the deformation integrity monitoring of reference station networks (chap. 3.2).

A third topic is concerning the further development of the GOCA software for a

- Monitoring in the higher frequency domain (e.g. 100 Hz for the monitoring a structural vibrations).

Further developments in the domain of deformation analysis theory are dealing with

- System analysis related deformation process modeling [11] and a respective sensor and system parameter integrating modeling [7] .

Appropriate approaches both for static and dynamic process modeling and system parameter estimation are provided by finite element models (FEM) of structures [7], [11], [12], [13]. Here the displacement-, velocity- and acceleration-field, which are resulting from the GOCA software in the 2^{nd} and 3^{rd} step, as well as data from other local sensors (e.g. strain- or tilt-meters), can be used as additional observation sources in a FEM approach [7], [12], [13].

5 Examples - GOCA-Software and GOCA Projects

Enterprises and Companies	**Universities and Research Institutions**
• **Deutsche Steinkohle AG (DSK), Germany** • **DMT, Essen, Germany** • **Rheinbraun Power AG (RWE), Germany** • **Open cast mining areas Garzweiler, Elsdorf and Hambach** • **Vattenfall Europe Mining, Germany** • **Rössing Mines, Namibia, Africa** • **Geo-International, Mainz, Germany** • **Swissphoto AG, Regensdorf, Switzerland** • **Morilia Mines, Mali, Africa** • **Dr Bertges Vermessungstechnik, Neunkirchen Germany** • **GeoNav, Wunstorf, Germany** • **Optron Ltd., South Africa** • **Landesvermessungsamt des Saarlandes**	• **University of Hannover, Geodetic Institute, Germany** • **University of Federal Forces, München, Germany** • **University Innsbruck, Austria** • **FH Karlsruhe – University of Applied Sciences, Germany**

Tab. 1: GOCA system users in the domains of enterprises (left) and research institutions (right)

The tab. 1 above gives an overview over the GOCA system users at different enterprises and research institutions all over the world.

Reports of the GOCA system users are [1], [2], [3], [17], [18] and [19]. Further links and downloads can be found at the GOCA homepage [16]. The fig.3 shows the time series vizualisation as result of the above mentioned 2nd adjustment step implying the georeferencing of the object points $\mathbf{x}_0(t_i)$ in the datum of the stable points $\mathbf{x}_R$ together with the parallel running moving average estimator (3rd adjustment step). The example fig. 3 shows the vertical (red) and the horizontal displacements (green and blue) of a GOCA monitoring of an underground coal mining in a depth of 800 m.

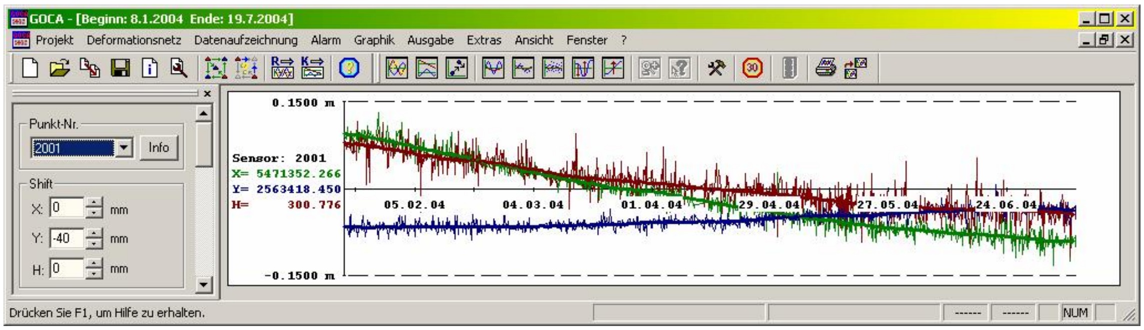

Fig.3: GOCA object-point time series $\mathbf{x}_0(t_i)$ as result of the 2nd adjustment step of the GOCA-software The thick lines show the smoothing of the object point series by a robust moving average estimation applying the M-estimation (5c).

Fig. 4 shows the GOCA-software settings dialog for the online displacement estimation according to the mathematical model (8a) (8b) in the deformation analysis (3rd step). The different settings concern the choice of the object points, the epoch definition for the displacement estimation $\mathbf{u}(t)$, the settings for adjustment and statistical testing, and the settings for an automatic alert.

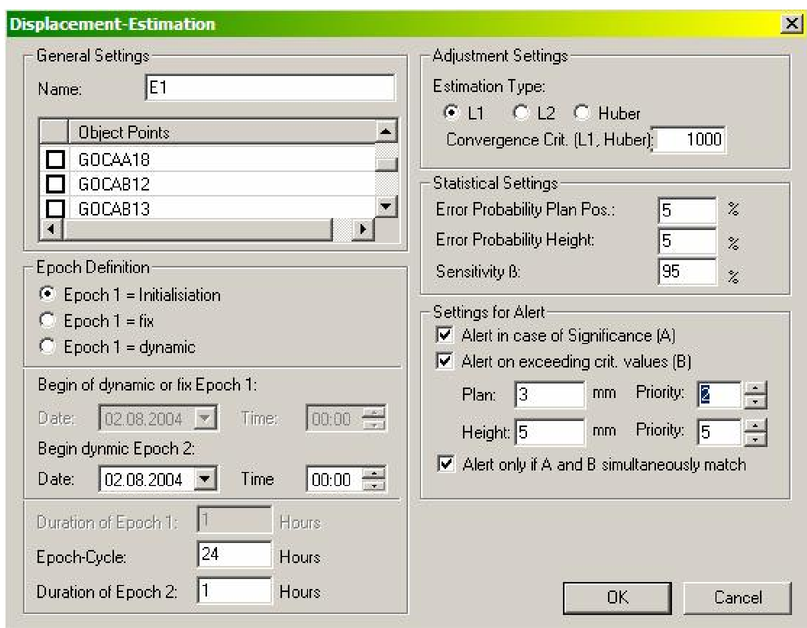

Fig. 4: GOCA online deformation (3rd step). Settings for the online displacement estimation and alerting.

The fig. 5 shows the visualization of the result of a displacment estimation $\mathbf{u}$(t) between a reference epoch t_0 (left) with a finite observation interval, and the estimation epoch t (right).

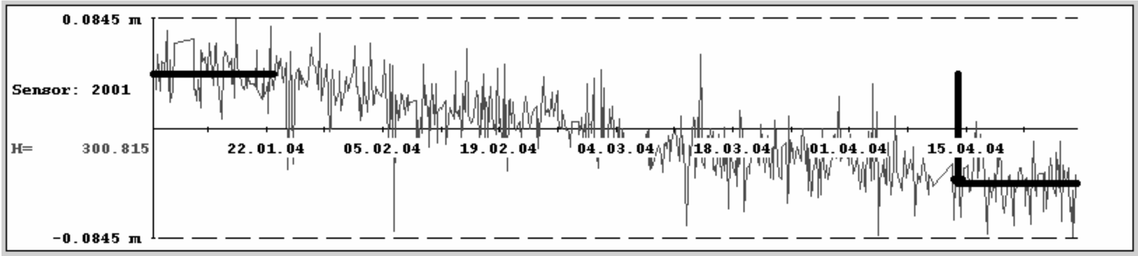

Fig.5: Visualization of the GOCA online displacement estimation (3rd step). Thick horizontal line left shows the estimation of $\mathbf{x}_0$ (8a), (8b) by a number of observations $\mathbf{x}_O(t_i)$ belonging to the reference time t_0. The thick horizontal line right shows the estimated position $\mathbf{x}(t) = \mathbf{x}_o + \mathbf{u}(t)$, and the thick arrow shows the estimation vertical displacement $\mathbf{u}(t)$.

The fig. 5 clearly reveals the benefits of an online monitoring, where - compared to a classical discrete monitoring – a large number of single positions $\mathbf{x}_O(t_i)$ contribute to the estimation of the state vector $\mathbf{y}(t) = (\mathbf{x}_o, \mathbf{u}(t))^T$ (8b), while at the same time a robust estimation (5c), (5d) is able to prevent the influence of gross errors in the observations $\mathbf{l}(t)$ given by the time series $\mathbf{x}_O(t_i)$ on the deformation parameters **y**(t).

Fig. 6 shows the location of the two object point GPS sensors during the Kops dam (Austria) monitoring as an example of a GOCA-installation aiming at the monitoring and deformation process modeling of buildings and geotechnical structures, respectively.

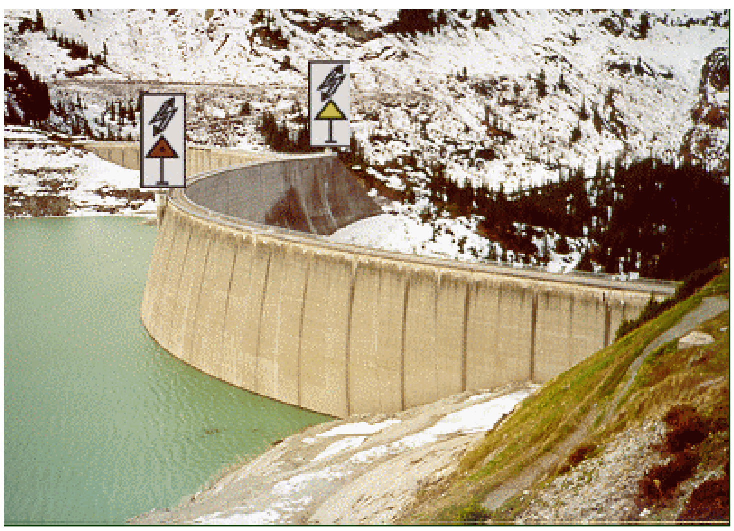

Fig. 6: GOCA GPS-based installation at Kops dam, Austria [4], [5], [6].

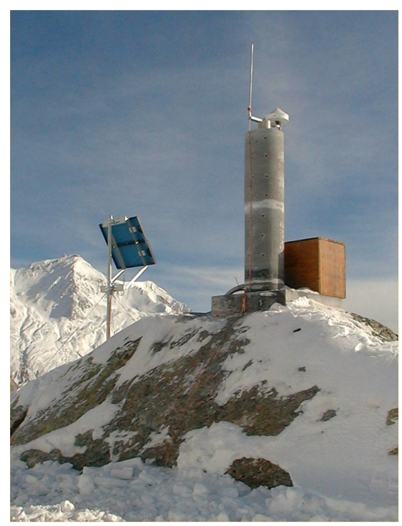

Fig. 7: GPS-receiver on pillar with solar panel energy supply as part of the GOCA array for the monitoring of the Gotthard railway tunnel construction (2002-2014).

The Fig. 7 above shows one of 5 GPS sensors of the Gotthard tunnel monitoring GPS array in the high Alps of Switzerland. Starting in 2002, the GOCA-system will be installed there for at least 12 years, namely during the complete duration of the construction of the 57 km long Gotthard railway tunnel.

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