GNSS/GPS/LPS based Online Control and Alarm System (GOCA) - Mathematical Models and Technical Realisation of a System for Natural and Geotechnical Deformation Monitoring and Hazard Prevention

R. Jäger and F.González,

Institute of Applied Research (IAF), Hochschule Karlsruhe für Technik und Wirtschaft - University of Applied Sciences. Moltkestrasse 30, D-76133 Karlsruhe. URL: www.goca.info

Abstract. The research and development project GOCA (GNSS/GPS/LPS based Online Control and Alarm System) applies GNSS/GPS as well as classical local positioning sensors (LPS) such as e.g. total stations for a real-time deformation monitoring. The GOCA system may be set up as an early-warning-system for natural hazards, such as landslides, mining and tunneling activities, volcano monitoring, and also for the monitoring of geotechnical structures and buildings. The GOCA system consists of GNSS/GPS/LPS sensors, which are set up in the monitoring area as a permanent array or as a mobile monitoring system. The GOCA hardware-control and communication software modules collect in different kind of communication modes the GNSS/GPS/LPS data in a user defined sampling rate. The GOCA deformation-analysis software is responsible for a further processing of that data in a three steps sequential adjustment procedure. The 1st step initializes the monitoring reference frame – the coordinates and covariance matrix – consisting of stable reference points. The 2nd and 3rd step comprise the georeferencing of the three-dimensional object-point coordinates in the reference frame, and the simultaneous deformation analysis respectively. Both least squares and robust estimation techniques (L1-norm and other so-called bounded influence M-estimators) are applied. The mathematical models of the above three adjustment steps are presented. A first focus is set on the robust online displacement estimation, statistical testing and alarm setting. Further the algorithmic scheme of a L2- and a robust L1-norm Kalman filter are treated, which are related to the object-point state vector of displacements, velocities and accelerations. With respect to the deformation monitoring in geotechnics and of constructions, one of the further developments of the deformation algorithms will be set on the integration both of further parameters (e.g. material parameters, damage models), as well as of additional geotechnical sensors (e.g. strain-meters) by means of so-called system analysis, which is based on deformation FEM-approaches for static and dynamics processes. Typical project applications are shown as examples for the GOCA-system.

Keywords: GNSS (GPS, GLONASS, GALILEO) and LPS (total stations, levelling) online and real-time monitoring system, environmental monitoring, geodetic deformation analysis, robust estimation and Kalman-filtering, natural hazard and disaster prevention.

1 Introduction

The GOCA system consists of a set of GPS sensors and communication units set up in the monitoring area and two software packages, 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 the GeoNav company, (www.geonav.de) and GOCA_DC3 of the company Dr. Bertges (www.drbertges.de), 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 G-PS/GNSS baseline output and the standard of LPS data (zenith angles, distances, directions, height differences. 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 starting in 1998 (www.goca.info). The GOCA software sounds alarm, if a specified critical state becomes significant during an online monitoring. The complete deformation analysis functionality is 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 (Borchers and Heer, 2002; Bulowski, 2001; Korittke and Palte 2001; Lauterbach and Krauter 2002; Schäfer, 2004; Kälber and Jäger 1999-2005) .

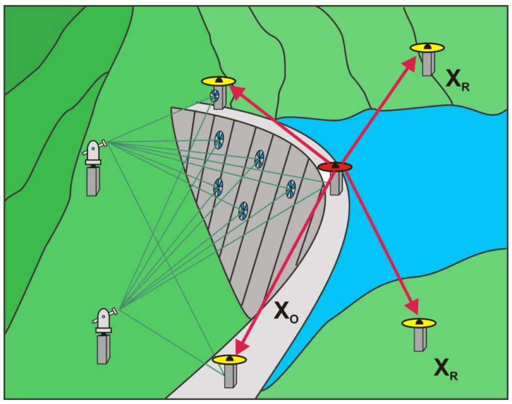

Fig. 1 Design of a classical absolute deformation network realized by the GOCA system.

The GOCA sensor array (fig. 1) consists of a stable reference point frame $\mathbf{x}_R$ and the domain of moving object points $\mathbf{x}_O$. The sensor observations $\mathbf{l}$, in the dam example fig.1 GPS-baseline observations and the total stations observations, enable the permanent estimation of the deformation state vector $\mathbf{y}(t)$ in dependence of time t.

2 GOCA Deformation Analysis Software – Basic Concepts

The deformation analysis concept implemented in the GOCA software is due to a classical deformation analysis (Kälber and Jäger, 2001; Feldmeth et. al, 2004; Jäger and Bertges, 2004). 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 adjustment 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 $\mathbf{x}_R$ 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 = Initialization (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. 2 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 $\mathbf{u}(t)$ ((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 (Bickel, 1975; Jäger et al. 2005].

3 Mathematical Models implemented in the GOCA software

3.1 Adjustment steps 1 and 2 – Reference Point Initialisation and Georeferencing of the Object Points

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

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

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 synchronic 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

$$\Delta t \leq \Delta T \qquad (2a)$$

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:

$$\Delta T(t_i) = [t_i - \tfrac{\Delta T}{2}, t_i + \tfrac{\Delta T}{2}] \qquad (2b)$$

According to (2b) the time dicretisation of the object point's 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 general 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 linearization of (1) the following system of an in general over-determined so-called system of observation equations:

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

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

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 demanding the stability constraint $\mathbf{x}_{Ri} = \mathbf{x}_{Rj} = \mathbf{x}_R$ for the reference points (fig. 1), we obtain as the basic state vector of the deformation process modeling **y** in the 1st and 2nd step for two general epochs t_i and t_j reading

$$d\mathbf{y} = (d\mathbf{x}_R \mid d\mathbf{x}_O(t_i), d\,\mathbf{x}_O(t_j))^T \qquad (4a)$$

$$\text{and} \quad \mathbf{y} = \mathbf{y}^0 + d\mathbf{y} \,. \qquad (4b)$$

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 of m monitoring epochs.

3.2 Least Squares Adjustment and Robust M-Estimation

The so-called M-estimation (Jäger et al., 2005) applied to n observations l_k (k=1,n) in all m monitoring epochs reads

$$\sum_{k=1}^{n} \rho(\bar{v}_k) =$$

$$= \sum_{k=1}^{n} \rho\left(\left(\mathbf{C}_l^{-\frac{1}{2}} \cdot \mathbf{A}\right)_k \cdot d\hat{\mathbf{y}} - \left(\mathbf{C}_l^{-\frac{1}{2}} \cdot (\mathbf{l} - \mathbf{l}(\mathbf{y}^0))\right)_k \right) =$$

$$\sum_{k=1}^{n} \rho(\bar{\mathbf{A}}_k \cdot d\hat{\mathbf{y}} - (\bar{\mathbf{l}} - \bar{\mathbf{l}}(\mathbf{y}^0))_k) = \mathrm{Min}\big|_{d\hat{y}} \qquad (5a)$$

and leads to the the state vector **y** (4a), (4b) by minimizing the total sum of the so-called loss function $\rho(\bar{v}_k)$ of the standardized residuals $\bar{v}_k$. With $\bar{\mathbf{A}}$ and $\bar{\mathbf{l}}$ we introduce the so-called homogenized design matrix and homogenized observations, respectively. The algorithmic solution of (5a) and the determination of the estimation $\hat{y}$ and the covariance $\mathbf{C}_{\hat{y}}$ are described in Jäger et. al (2005). Depending on the type of the loss-function $\rho(\bar{v}_k)$ the estimation of the parameters **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 (Jäger et al. 2005, Holland 1975, Bickel 1975):

- Least squares estimation (L2-norm)

$$\rho(\bar{v}_i) = \frac{1}{2}\bar{v}_i^{\,2} \qquad (5b)$$

- Robust L1-norm estimation

$$\rho(\bar{v}_i) = \frac{1}{2}\,|\,\bar{v}_i\,| \qquad (5c)$$

Weak robust Huber-Estimation

$$\rho(\bar{v}_i) = \begin{cases} \frac{1}{2}\bar{v}_i^2 & \forall\ |\bar{v}_i| \le k \\ |\bar{v}_i| & \forall\ |\bar{v}_i| > k \end{cases} \qquad (5d)$$

The loss function $\rho(\bar{v}_k)$ (5b) is optimal for normal distributed observation errors and (5c) and (5d) are robust against gross observation errors ∇l_k (Bickel 1975, Jäger et al. 2005).

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

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

According to (3a, (3b) the time series $\mathbf{x}_O(t_i)$ (6a) (see fig. 3) 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

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

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

3.3 Online Displacement Estimations

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. The object points $\mathbf{x}_O(t_i)$ (6a) and $\mathbf{u}_O(t_i)$ (7a) 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.

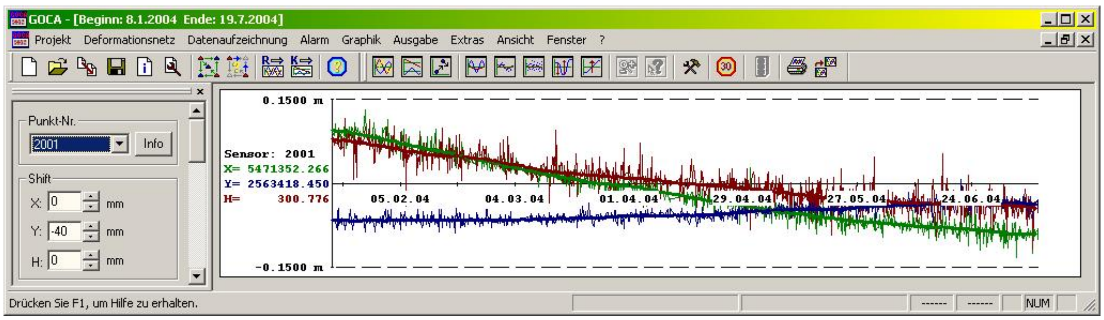

Fig. 3 GOCA object-point time series $\mathbf{x}_0(t_i)$ as result of the 2nd adjustment step of the GOCA-software. The thick lines show the smoothing by a robust moving average estimation applying the M-estimation (5c).

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 (see e.g. fig 4).

The functional model of the GOCA object point displacement estimation $\mathbf{u}(t)$ (Jäger und Bertges, 2004) at a time t with respect to the reference time t_0 and state vector $\mathbf{y}(t)$ reads:

$$\begin{bmatrix} \mathbf{l}_{t0} \\ \mathbf{l}_t \end{bmatrix} + \begin{bmatrix} \mathbf{v}_{t0} \\ \mathbf{v}_t \end{bmatrix} = \begin{bmatrix} \mathbf{E}_1 & \mathbf{0} \\ \mathbf{E}_2 & \mathbf{E}_2 \end{bmatrix} \cdot \begin{bmatrix} \mathbf{x}_0 \\ \mathbf{u}(t) \end{bmatrix} \qquad (8a)$$

$$\mathbf{y}(t) = (\mathbf{x}_0, \mathbf{u}(t))^T \qquad (8b)$$

The reference time t_0 is again defined with respect to an extended time interval Δt_0 (fig. 4, 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 $\mathbf{y}$ (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.

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.

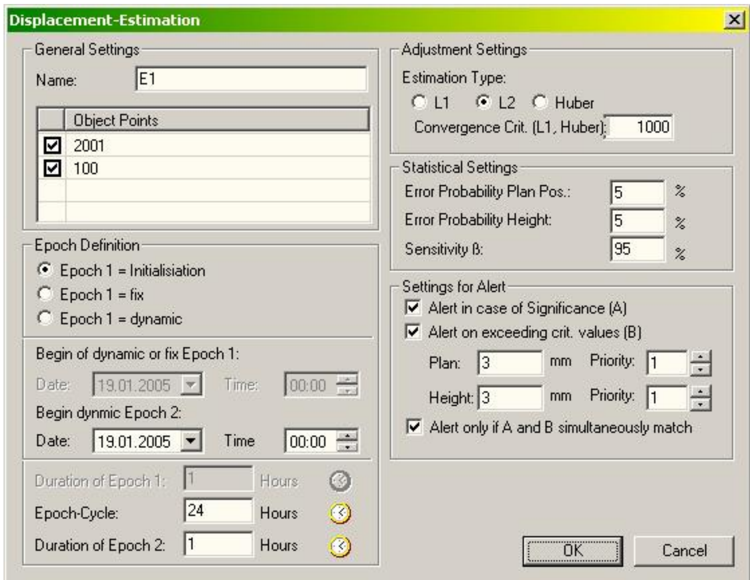

Fig. 4. GOCA online deformation (3rd step). Settings for the online displacement estimation and alerting.

3.4 Kalman-Filtering as General M-Estimation

The GOCA Kalman-Filtering (Kälber and Jäger 2001, Feldmeth et al. 2004, Kälber et al. 2002) as a second example for the deformation parameter estimation in the 3rd step is related to the following so-called transition equation (9a,b), and to the state vector $\mathbf{y}$ (9c) reading:

$$\mathbf{y}(t) = \mathbf{T} \cdot \mathbf{y}(t - \Delta t) \quad , \qquad (9a)$$

$$\mathbf{y}(t) = \begin{bmatrix} \mathbf{u}(t) \\ \dot{\mathbf{u}}(t) \\ \ddot{\mathbf{u}}(t) \end{bmatrix} = \begin{bmatrix} \mathbf{I} & [\Delta t] & \left[\frac{1}{2}\Delta t^2\right] \\ \mathbf{0} & \mathbf{I} & [\Delta t] \\ \mathbf{0} & \mathbf{0} & \mathbf{I} \end{bmatrix} \cdot \begin{bmatrix} \mathbf{u}(t - \Delta t) \\ \dot{\mathbf{u}}(t - \Delta t) \\ \ddot{\mathbf{u}}(t - \Delta t) \end{bmatrix} \qquad (9b)$$

$$\text{with} \quad \mathbf{y}(t) = (\mathbf{u}, \dot{\mathbf{u}}, \ddot{\mathbf{u}})^T \quad . \qquad (9c)$$

The state vector $\mathbf{y}(t)$ 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. A Kalman-Filtering a time t is equivalent to the common adjustment of the prediction of the state vector $\mathbf{y}(t)$ (9a,b,c) and the state vector related observations $\mathbf{l}(\mathbf{y}(t))$ at time t. So the system of observation equations of a Kalman-Filtering generally reads:

$$\mathbf{y}(t) + \mathbf{v}_y = \hat{\mathbf{y}}(t) \text{ and } \mathbf{C}_y(t) \qquad (10a)$$

$$\mathbf{l}(t) + \mathbf{v}_l = \mathbf{l}(\hat{y}(t)) = \mathbf{A} \cdot d\hat{\mathbf{y}} + \mathbf{l}(\mathbf{y}(t)) \text{ and } \mathbf{C}_l \,. \qquad (10b)$$

The covariance matrix $\mathbf{C}_y(t)$ (10a) of the prediction is received by applying the law of error propagation to the system transition equation (9a,b). In case of GOCA the observations $\mathbf{l}(t)$ for the Kalman-Filtering are taken from the object point time series (2nd adjustment step) and relate only to the object point displacements $\mathbf{u}_O(t_i)$ (7a). So the design matrix $\mathbf{A}$ (10b) of the GOCA observations' component is filled with zero elements at the position of the velocity and acceleration parameters within $\hat{\mathbf{y}}(t)$. The linearization in (10b) is done with respect to the predition $\mathbf{y}(t)$ (9a,b). The generalized M-estimation of the parameters $\hat{\mathbf{y}}(t)^{(j)}$ of the Kalman-Filter model (10a,b) can be computed iteratively as:

$$\hat{\mathbf{y}}(t)^{(j)} = \mathbf{y}(t) + \mathbf{K}^{(j)} \cdot (\bar{\mathbf{l}}(t) - \bar{\mathbf{l}}(\mathbf{y}(t))) \text{, with} \qquad (11a)$$

$$\mathbf{K}^{(j)} = (\mathbf{C}_y^{-\frac{1}{2}} \mathbf{W}_y^{(j)} \mathbf{C}_y^{-\frac{1}{2}} + \bar{\mathbf{A}} \mathbf{W}_l^{(j)} \bar{\mathbf{A}})^{-1} \bar{\mathbf{A}} \mathbf{W}_l^{(j)} \,. \qquad (11b)$$

(González 2005). Again the above homogenizition (5a) is used in (11a,b). The iterative Kalman matrix $\mathbf{K}^{(j)}$ has to be recomputed stepwise (j=j-th step). In the j-th step the diagonal weigth-matrices $\mathbf{W}_y^{(j)}$ and $\mathbf{W}_l^{(j)}$ within $\mathbf{K}^{(j)}$ are set up a weighting function related to the argument of the homogenized corrections $\bar{v}_{y,i}$ and $\bar{v}_{l,i}$ of the parameter and the observation component (10b,c). The specific weighting function $w(\bar{v}_i)$ of any M-estimator is strictly based its loss function $\rho(\bar{v}_i)$ (5b,c,d). It reads (Bickel 1975, Holland 1977, Jäger et al. 2005):

$$w_i = w(\bar{v}_i) = \frac{\partial\rho(\bar{v}_i)/\partial\bar{v}_i}{\bar{v}_i} = \frac{\partial\psi(\bar{v}_i)}{\bar{v}_i} \quad . \qquad (11c)$$

The first derivative $\psi(\bar{v}_i)$ of the loss function is the so-called influence function. In case of an L2-norm (least squares) Kalman-Filter (5b) it holds that $w_i = 1.0$. So the general iterative M-estimation computation (11a,b) is (only) in case of the classical least squares (L2 norm) Kalman filter already finished in one step j=1.

Like the online displacement estimation (8a,b), with the settings shown in fig. 4, right, the above GOCA-Kalman-Filtering can also be performed by setting either a least squares estimation (5b) or a robust L1-norm estimation (5c) principle by the user.

4 Further Features of the GOCA-Software

4.1 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 (Kälber and Jäger, 2001). 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.

4.2 Deformation Integrity Monitoring of Reference Station Networks

The GOCA software and the implemented stable point testing algorithm (chap. 4.1) can be applied for the statistically strict detection of possible movements of stations in GPS/GNSS positioning service such as ***SAPOS*** (www.sapos.de) and ***ascos***. (www.ascos.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.

5 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 (Kälber and Jäger 1999-2005). One application of the GPS/GNSSraw data processing capacity is the deformation integrity monitoring of reference station networks (chap. 4.2).

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 and a respective sensor and system parameter integrating modeling (Jäger and Bertges 2004).

Appropriate approaches both for static and dynamic process modeling and system parameter estimation are provided by finite element models (FEM) of structures (Jäger and Bertges, 2004). 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 tiltmeters), can be used as additional observation sources in a FEM approach (Kälber et al. 2000, Kälber und Jäger 2001, Jäger und Bertges 2004).

6 Examples - GOCA-Software and Projects

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 and downloads can be found at the GOCA homepage (Kälber and Jäger 1999-2005). The fig.3 shows the time series visualisation as result of the above mentioned 2^{nd} 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 (3^{rd} adjustment step). The example fig. 3 shows the vertical and the horizontal displacements of a GOCA monitoring of an underground coal mining in a depth of 800 m.

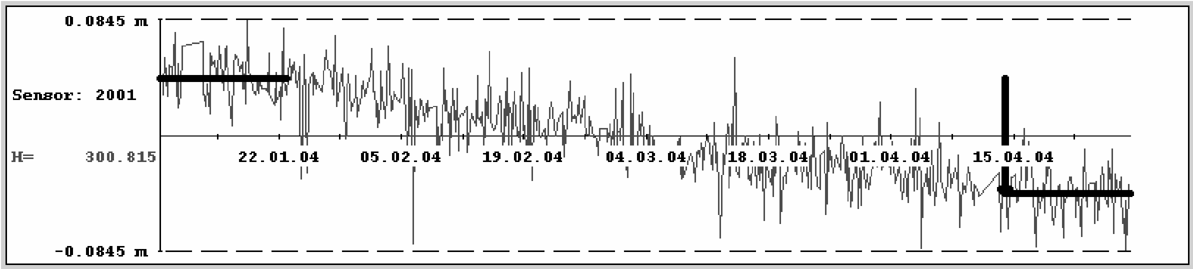

Fig.5 Visualization of the GOCA displacement estimation (3rd step). Thick horizontal line left shows the estimation of $\mathbf{x}_0$ (8a), (8b) by a number of observations $\mathbf{x}_O(t_i)$ belonging to the reference time t_0. The thick horizontal line right shows the estimated position $\mathbf{x}(t)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

The fig. 5 shows the visualization of the result of a displacement estimation **u**(t) between a reference epoch t_0 (left) with a finite observation interval, and the estimation epoch t (right). 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 **l**(t) given by the time series $\mathbf{x}_O(t_i)$ on the deformation parameters **y**(t).

Table 1 GOCA-system and –software users at private and state institutions and at universities and research centers

Private companies and State Companies	
Deutsche Steinkohle AG (DSK), Germany	Sudsidence and horizontal deformations. Coal mining
Rheinbraun Power AG (RWE) at Hambach, Garzweiler, Elsdorf, Germany	Slopes. Open cast coal-mining
GeoInternational Mainz, Germany	3D landslide monitoring
Rössing Mines, Namibia, Africa	Slope-monitoring. Uranium-mining
Vorarlberger Illwerke, Austria	Dam-monitoring
Morila Mines, Mali, Africa	Slope-monitoring. Gold-mining
DMT, Germany	3D Monitoring in mining
SwissPhoto Group, Switzerland	Longterm 3D monitoring Gotthard railway tunnel
Vattenfall Europe, Germany	Slope, uplift, subsidence monitoring. Open cast mining
Landesvermessungsamt des Saarlandes	SAPOS GNSS reference station network monitoring
DrBertges Vermessungstechnik, Germany	Different Projects. GOCA cooperation partner
GeoNav-Trimble	Different Projects. GOCA cooperation partner
Palabora Mining, South Africa	Slope monitoring, Copper mining
Universities and Research Institutions	
Universität Hannover, Germany	
University of Federal Forces Munich, Germany	
Universität Innsbruck, Austria	
University of Applied Sciences (FH), Karlsruhe	

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.

The Fig. 7 above shows one of the 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.

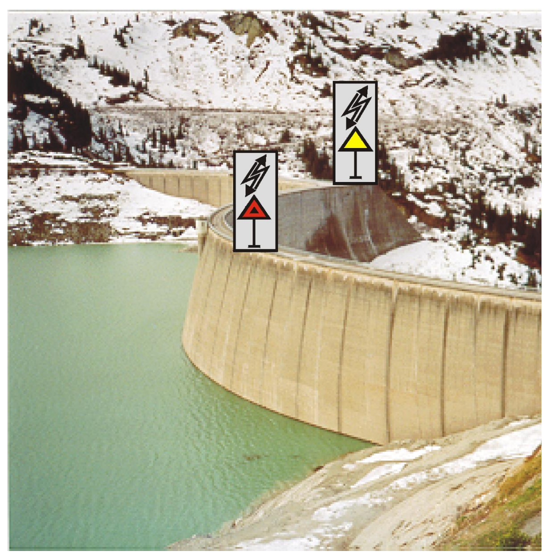

Fig. 6 GOCA installation at Kops dam, Austria.

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).

Conclusions

The contribution treats the GNSS/GPS/LPS-based Online Control and Alarm system (GOCA). The GOCA-software components set up an array of GNSS- and/or LPS-sensors, which are equiped with a telemetric, GSM, LAN or internet communication. GOCA can be used for a continuous monitoring of natural hazards (landslides, volcanos, water level), and for the monitoring of geotechnical structures (mining, tunneling) and buildings (constructions, dams). The deformation network points may be occupied both in a permanently mode as well as intermittently. All online computation steps can be performed also in a post-processing or a near-online mode. The GOCA-deformationanalysis-software is responsible for a further processing of the GPS/LPS data in a three steps sequential adjustment procedure, which models in total an online classical three-dimensional deformation network. The network adjustment concept behind the GOCA-deformationanalysis-software provides a unique georefercencing of the GNSS/LPS-occupied object point positions in the coordinate frame of the reference points. The online deformation analysis of the object-point can be set up as flexible user-defined displacement estimation or by a Kalman filter (displacements, velocities and accelerations). Both least squares and robust estimation techniques are applied, so that a reliable setting of an alarm is enabled, in case that a critical state is reached and proved by statistical testing. The worldwide use of the GOCA system in different domains of environmental monitoring and research is documented and shown by examples. The evaluation of continuous time series of the objects displacement field, provided by GOCA, opens new perspectives in deformation analysis and model calibration. This concerns the transition from the classical geometric deformation analysis to so-called system analysis based approaches, as required by the interests of geodesists and of other disciplines such as geodynamics, geotechnics and civil engineering.

References

Bickel, P. (1975): One-step Huber estimates in the linear model. Journal of the American Statistical Association (70). 428-434.

Borchers, S. und R. Heer (2002): Bauwerksüberwachung mit GOKA (GPS-basiertes Online Kontroll- und Alarmsystem) an der Schleuse Uelzen I. Schriftenreihe des DVW, Band 44, Konrad Wittwer Verlag. ISBN 3-87919-281-2, ISSN 0940-4260, S. 65-84.

Bulowski, T. (2001): Kontinuierliche Überwachung von Tagebauböschungen mit dem System GOCA. 43. Wissenschaftliche Tagung der DMV (Deutsche Markscheider Vereinigung), Sept. 01, Trier. DMV Mitteilungen, 2001.

Feldmeth, I., Jäger, R. und R. Zischinsky (2004): GPS-based Online Control and Alarmsystem GOCA – Leistungsstandards am Einsatzbeispiel Staumauer Kops (Vorarlberger Illwerke AG, Österreich). Wasserwirtschaft - Zeitschrift für Wasser und Umwelt, Heft 1-2, 2004. Vieweg Verlag, Stuttgart, ISSN 0043-0978.

Holland, P.W. (1977): Robust Regression using iteratively reweighted Least Squares. Commun. Statist.-Theor. Meth. A6(9), S. 813-827.

González, F. (2005): Improvement, Redesign, C++-based Implementation and Testing of the GOCA-Kalmanfiltering Modules. Masterthesis im Masterstudiengang Geomatics der Fachhochschule Karlsruhe.

Jäger, R.; Müller, T.; Saler, H. and R. Schwäble (2005): Klassische und robuste Ausgleichungsverfahren - Ein Leitfaden für Ausbildung und Praxis von Geodäten und Geoinformatikern. ISBN 3-87907-370. Wichmann Verlag.

Jäger, R. und M. Bertges (2004): Integrierte Modellbildung zum permanenten Monitoring von Bauwerken und geotechnischen Anlagen. Beitrag zum 61. DVW-Fortbildungsseminar, 27./28. September 2004, Bauhaus-Universität Weimar. DVW-Schriftenreihe, Band 46/2004. ISBN 3-89639-451-7. S. 101-140.

Kälber, S. and R. Jäger (1999-2005): GOCA-Homepage. www.goca.info.

Kälber, S.; Jäger, R; Schwäble, R.: Heimberg, F. and K. Kast (2000): GPS-based Online Control and Alarm System (GOCA). Report presented to the 20. ICOLD-Congress, 2000, Peking. Int. Commission on Large Dams, Paris.

Kälber, S. und R. Jäger (2001): GPS-based Online Control and Alarm System (GOCA). Proceedings 10th FIG Internat. Symposium on Deformation Measurements. Orange, Californien, USA, 19.-22. March 01. CDROM.

Korittke, N. und G. Palte (2001): Real-Time-Monitoring von bergbaubedingten Gebäudebewegungen mit GPS. Schriftenreihe des DVW, Band 43, Konrad Wittwer Verlag. ISBN 3-87919-279-0, ISSN 0940-4260, S. 183-195.

Lauterbach, M. und E. Krauter (2002): Satellitengestütztes Monitoring einer Großrutschung im Bereich eines Autobahndammes bei Landstuhl/Pfalz. Messtechnik – Geotechnik, Nr. 25, 2002.

Schäfer, W. (2004): GPS-gestützte 3D-Permanent-Überwachung bewegungsempfindlicher Bergschadensobjekte. Zeitschrift Markscheidewesen.