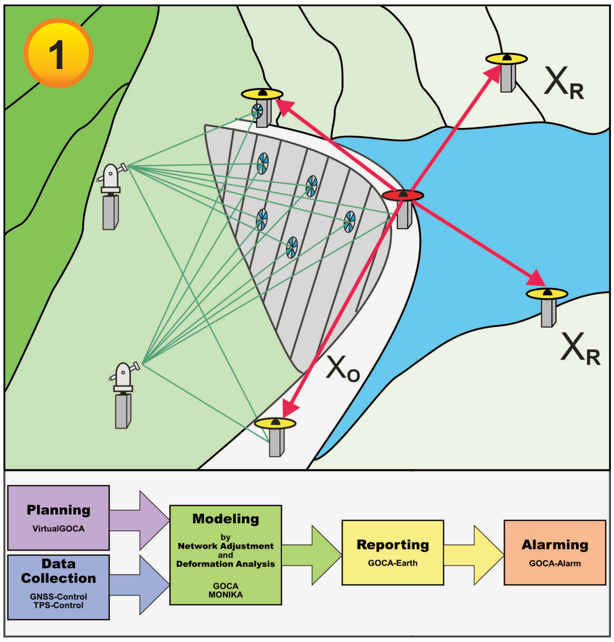
GOCA GNSS/LPS/LS Online Control and Alarm System

University of Applied Sciences Karlsruhe, Germany



Objectives and Application Domains of the GOCA-System: GOCA deals with the application of the global satellite navigation systems (GNSS), i.e. GPS/GLONASS/GALILEO, as well as local terrestrial positioning systems LPS as further sensor components, for the realtime monitoring of movements on the earths surface. Besides the application in the prevention of **natural disasters** (slopemovement-monitoring, mining-, flood-monitoring, etc.) GOCA is also well suited for the online monitoring of **safety relevant buildings** (e.g. dams (fig. 1), locks, bridges, etc.) and **geotechnical installations** (dumps, tunnels).

GOCA Input-Interface (GKA-Interface): The GOCA-monitoring is based on the GNSS-and LPS sensor data, which is both provided by a sensor-control- and communication software (e.g. MONITOR©Trimble-GeoNav, Spider©Leica-Geosystems). The GKA-interface is open and can be served by the data of arbitrary hardware. A complete GOCA dataset ***„gka-String"*** contains the information 1. identification of the sensor-type, 2. time of registration, 3. sensor data (e.g. GPS-baseline vectors $\Delta\mathbf{X}$ and covariance-matrices $\mathbf{C}_x$).

GOCA Systemanalysis and Interfaces: Both, the continuously registered object point time series $\mathbf{x}_O(t)$ of the GOCA adjustment step 2, as well as the state vector of parameters resulting from the parameter estimations of the deformationanalysis step 3 (formula table 3) can be used as general online or postprocessing interface for the research and development field of a so-called system-analysis oriented deformation-analysis (e.g. By a FEM based system modelling).

GOCA - Deformationanalysis: The GOCA software (fig. 2), which provides a comfortable graphical user interface and can be controlled remotely, performs a classical deformation-analysis by a three-dimensional adjustment of the hybrid observation data **l** (GPS raw data, GNSS baselines and LPS data (totalstations, spirit and hydrostatic levelling)), which is provided by the above mentioned hardware control software via the hardware-independent gka-string data input interface. By dividing the sensor array configuration into a stable area and a moving object area, the deformation analysis comprises an online, a near-online or a postprocessing parameter estimation in three steps.

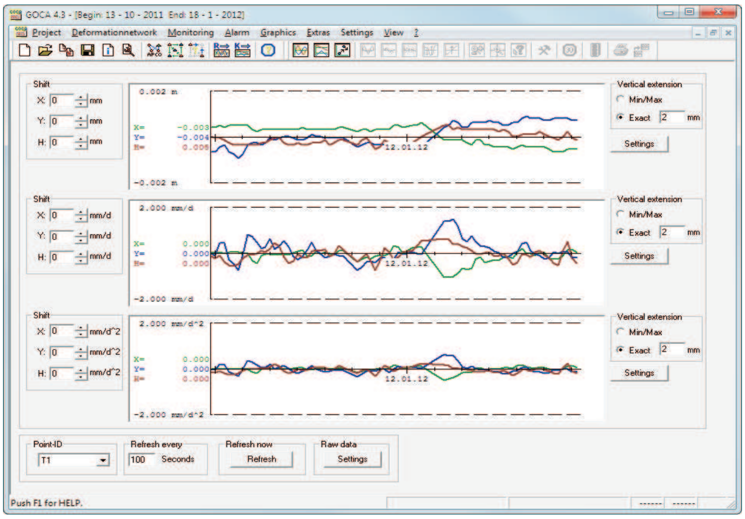
Step 1: Initialisation of the three-dimensional reference frame $\mathbf{x}_R$ and the covariance matrix $\mathbf{C}_{x,R}$ in a classical least-squares network adjustment of GNSS and LPS data (distances, azimuths, zenithdistances, height difference observations) in the datum of the reference points. The quality assurance is done by data snooping and variance component estimation. The observations equations, e.g. for LPS data are given in formula table 2.

With the congruency of the reference frame between all epochs, the coordinates of the reference points $\mathbf{x}_R$ and of the georeferenced object points $\mathbf{x}_O$ referring to the reference frame $\mathbf{x}_R$ are resulting (formula table 1). The congruency of the reference frame $\mathbf{x}_R$ is statistically analysed ans tested, and can in this context also be applied for the monitoring of the deformation integrity of GNSS reference station networks, such as e.g. SAPOS and ascos.

Step 2: Continuous Online Adjustment including datasnooping of the GNSS baselines and the LPS data in the GOCA array providing a threedimensional georeferencing of the object point positions $\mathbf{x}_O(t)$ in the datum of the reference points. The formula table 2 discribes the LPS direction observaion of a totalstation and the LPS height difference observation (total station observation, spirit or hydrostatic levelling instrumentation) at time t_k.

Step 3: Deformationanalysis based on the object points positions $\mathbf{x}_O$ and their covariance matrices resulting from step 2. Here several parameter estimation methods based on M-Estimation are realized (formula table 3) to get from the "low accurate" single positions of the object point time series an estimation and a statistical valuation (significancy proof) of the "accurate" geometrical state vector of **displacement, velocity and acceleration** of the object points $\mathbf{x}_O$.

Besides the classical least-squares estimation, different robust estimation methods are applied for the detection and elimination of gross errors. As mathematical models of the deformation analysis in the online, near-online and postprocessing mode are realised: **Displacement estimation** in three different modes (1. with respect to the initialisation (epoch 2 is moving cyclic); 2. with respect to a fix epoch 1 (epoch 2 is moving cyclic); 3. dynamic displacement estimation (cyclic moving of epochs 1 and 2)), **Moving average** and **Kalman-filtering.** For postprocessing applications additional **trend-estimations** based on **polynomials, spline estimations** and **leap detection** are realized. During the online deformation analysis an **alarm report** is sended by SMS, email, etc., if a given probability for **critical states** or user-defined **critical values** are exceeded.



Alerting: The alerting is based on the online-deformation-analyses displacement estimation, moving average and Kalman filteringinf GOCA step 3. For that purpose the current displacement, velocity and acceleration is continuously compared to the critical values. If a boundary value or a given probability is exceeded or if there is a significant change in the state-space-vector, then an alert string is written to a goca-alert-file. With the module GOCA-Alert (fig. 3) the different alerts are allocated to the responsible persons. These are either informed via SMS or by a siren.

GOCA – Mathematical Model for GPS/GNSS and LPS - Adjustment Step 1 (1)

$$\mathbf{l}_i + \mathbf{v}_i = \mathbf{A}_{Ri}\cdot\mathbf{x}_{Ri} + \mathbf{A}_{Oi}\cdot\mathbf{x}_{Oi} \text{ and } \mathbf{C}_{li}$$

$$\mathbf{l}_j + \mathbf{v}_j = \mathbf{A}_{Rj}\cdot\mathbf{x}_{Rj} + \mathbf{A}_{Oj}\cdot\mathbf{x}_{Oj} \text{ and } \mathbf{C}_{lj}$$

$$\begin{bmatrix}\mathbf{x}_R\\ \mathbf{x}_{O,i}\\ \mathbf{x}_{O,j}\end{bmatrix} \text{ and } \mathbf{C}_x = \begin{bmatrix}\mathbf{C}_{R,R} & \mathbf{C}_{R,Oi} & \mathbf{C}_{R,Oj}\\ \mathbf{C}_{Oi,R} & \mathbf{C}_{Oi,Oi} & \mathbf{C}_{Oi,Oj}\\ \mathbf{C}_{Oj,R} & \mathbf{C}_{Oj,Oi} & \mathbf{C}_{Oj,Oj}\end{bmatrix}$$

GOCA – Functional Models for LPS-data - Adjustment Steps 1 and 2 (2)

$$r_{ij}^{t_k} = \arctan\left(\frac{\Delta\hat{y}_{ij}^{t_k}}{\Delta\hat{x}_{ij}^{t_k}}\right) - o$$

LPS direction observation $r_{ij}^{t_k}$. Totalstation at time t_k between array points i und j. Plan position $(\hat{x},\hat{y})_{ij}$ of the points $\mathbf{x}_O(t_k)$ as essential unknown. Orientation *o* as an auxiliary unknown.

$$\Delta H_{ij}^{t_k} = \Delta h_{ij}^{t_k} + A\cdot\Delta y_{init} + B\cdot\Delta x_{Init} + \Delta m\cdot\Delta h$$

LPS height-difference observation $\Delta H_{ij}^{t_k}$. Totalstations, spirit and hydrostatic levelling instruments. Time t_k between array points i und j. Ellipsoidal height differences $\Delta h_{ij}^{t_k}$ of the points $\mathbf{x}_O(t_k)$ as essential unknowns. Local datum parameters A, B and a scale-factor dm as auxiliary unknwon.

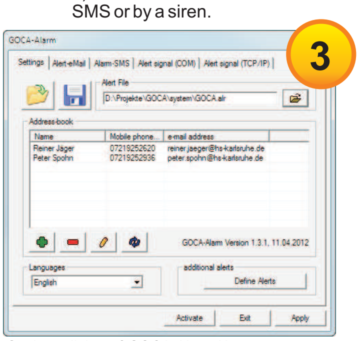
GOCA - M-Estimations - Adjustment Step 3 (Deformationparameter Estimation) (3)

Principle: $$\sum_{i=1}^{n}\rho(\bar{\mathbf{v}}_i) = \sum_{i=1}^{n}\rho\left((\mathbf{C}_l^{-\frac{1}{2}}\cdot\mathbf{A})_i\cdot\hat{\mathbf{x}} - (\mathbf{C}_l^{-\frac{1}{2}}\cdot\mathbf{l})_i\right) = \mathrm{Min}|_{\hat{x}} \quad \text{and} \quad \mathbf{v} = \mathbf{C}_l^{-\frac{1}{2}}\cdot\bar{\mathbf{v}}$$

$\rho(\bar{v}_i) = \bar{v}_i^2$ ***Least Squares Estimation (L2-Norm)***

$\rho(\bar{v}_i) = |\bar{v}_i|$ ***Robust L1-Norm***

$\rho(\bar{v}_i) = \begin{cases}\frac{1}{2}\bar{v}_i^2 & \forall\ |\bar{v}_i| \le k\\ |\bar{v}_i| & \forall\ |\bar{v}_i| > k\end{cases}$ ***Robust Huber-Estimation***



Settings dialog of GOCA-Alert. Alert management by the use of an address book and allocation of different kinds of alerts to the responsible persons. Alerting via SMS or by siren. Different languages are available for a better understanding of the dialogs.

Kalmanfilter kinematic model (4)

$$\bar{y}_{k+1} = \begin{bmatrix}x_{k+1}\\ \dot{x}_{k+1}\\ \ddot{x}_{k+1}\end{bmatrix} = \begin{bmatrix}1 & \Delta t_{k,k+1} & \frac{1}{2}\Delta t_{k,k+1}^2\\ 0 & 1 & \Delta t_{k,k+1}\\ 0 & 0 & 1\end{bmatrix}\cdot\begin{bmatrix}x_k\\ \dot{x}_k\\ \ddot{x}_k\end{bmatrix} = T\cdot\hat{y}_k$$

State vector $\bar{y}_{k+1}$ at time t_{k+1} with displacement, velocity and acceleration; kinematic model $T\cdot\hat{y}_k$ with assumption $\ddot{x}_k = const.$ over a short period Δt.

Kalmanfilter algorithm (5)

$$\bar{y}_{k+1} = T\cdot\hat{y}_k + S\cdot a \qquad C_{\bar{y}\bar{y},k+1} = TC_{\hat{y}\hat{y},k}T^T + SC_{aa}S^T$$

$$d_{k+1} = (l - A_y\bar{y}_{k+1}) \qquad D = Q_{ll,k+1} + A_yQ_{\bar{y}\bar{y},k+1}A_y^T$$

$$K = Q_{\bar{y}\bar{y},k+1}A_y^TD^{-1}$$

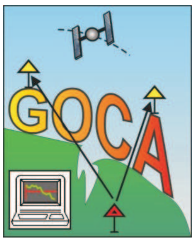
$$\hat{y}_{k+1} = \bar{y}_{k+1} + Kd \qquad Q_{\hat{y}\hat{y},k+1} = Q_{\bar{y}\bar{y},k+1} - KDK^T$$

Forecasting of the state vecor $\bar{y}_{k+1}$ with additional system noise C_{aa} within the stochastical model. Calculation of the innovation d_{k+1} with its covariance matrix D from the measured values l and the prediction $\bar{y}_{k+1}$. Estimation of the Kalman-Gain-Matrix K to obtain the optimal system status $\hat{y}_{k+1}$.

GOCA-Team Karlsruhe - Projektleitung

Prof. Dr. Ing. Reiner Jäger

Hochschule Karlsruhe - Technik und Wirtschaft
Studiengang Vermessung und Geomatik
Institut für angewandte Forschung (IaF)
Moltkestr. 30, D-76133 Karlsruhe
Tel.: ++ 49 721 925 2620 ; Fax: ++ 49 721 925 2591
Email: reiner.jaeger@goca.info



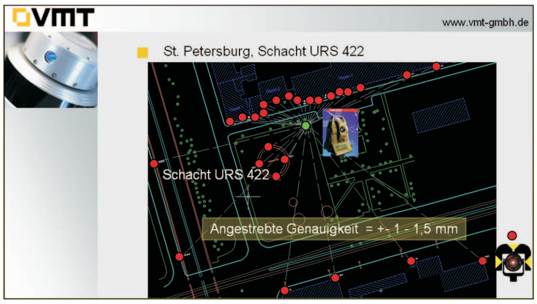
Forecasting and Kalmanfiltering: Base of the prediction of the displacement, velocity and acceleration is a kinematic modell (formula table 4), that calculates on the assumption of a constant object acceleration within a short time period the future state vector. The in step 3 of the GOCA concept as M-estimator realized Kalman filter (formula table 5) corrects the prediction with the aid of actuell measurements optimally. The deformation model acts on the assumption of a constant object acceleration, what not always corresponds with the reality (e.g. oscillating movements). This failure can be modeled within the stochastical model, because the real failure is unknown generally. With the forecasted state vector it is possible to alert before a critical state is reached in fact. Hence, retaliatory action can start before a risky situation arrives.

GOCA Homepage: http://www.goca.info

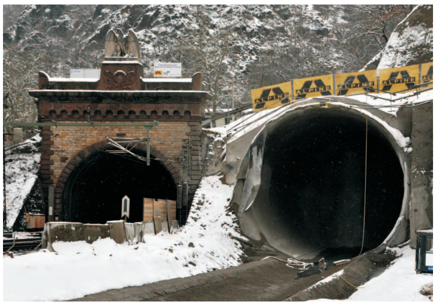
GOCA Project-Examples

University of Applied Sciences Karlsruhe, Germany

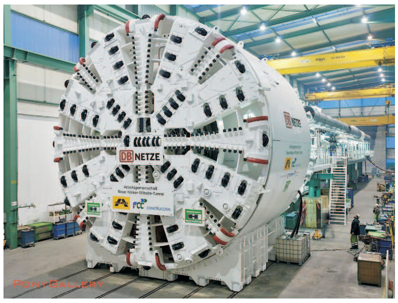
GOCA Projects of GOCA Cooperation Partner, VMT Bruchsal



Shaft Monitoring, Oldtown of St. Petersburg, Russia



GNSS/TPS-based Geomonitoring of the new Kaiser-Willhelm Tunnel in Cochem,

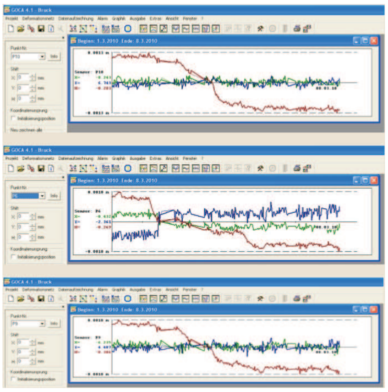


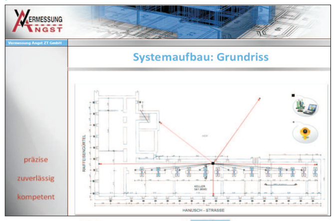
Herrenknecht Tunnel Boring Machine for Cochem Project

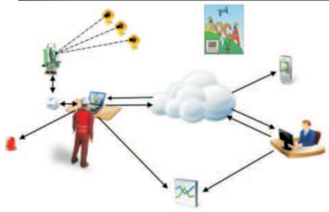
GOCA Projects of GOCA Cooperation Partner, Angst ZT Company, Austria

Upper, left and right: Geomonitoring of the New Construction of the Train Mainstation in Vienna, Right: Dam Monitoring in Bosnia

Monitoring of a Building Complex, Bruck, Austria





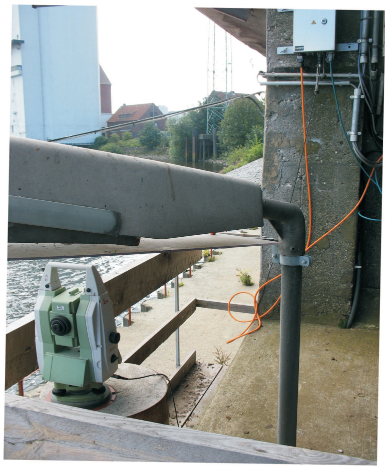


Monitoring of the Robert Bosch Hospital, Germany, E. Messmer, Germany

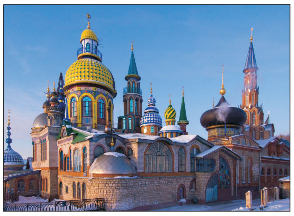
VERMESSUNGSBÜRO DIPL.-ING. E. MESSMER

Monitoring of the New Construction of the Rethe-Bridge, Hamburg Harbour Port (HPA), Germany

Hamburg Port Authority



GOCA Projects in Russia, Coop. Partner GNSSPlus, Moscow



Upper: Geodetic Monitoring of the new Youth Olympic Stadium in Kazan. Lower: GNSS-based Monitoring of Dams and Buildings in Russia

GNSS-based Monitoring in Mining and Hazard Areas

Right: GNSS-based Geomonitoring in Open-Cast Mining, Vattenfall Europe, Germany. Left: GNSS-based Monitoring of Palabora Copper Mine, South Africa

GOCA Homepage: http://www.goca.info