GPS Software Development for Monitoring of Landslides

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Key words: GPS, realtime monitoring, landslides, normal point computation, tropospheric model.

ABSTRACT

Natural disasters caused by landslides are frequent phenomena in alpine regions. For the investigation of landslide motions a GPS-based continuous monitoring system has been developed. The goal of the related research project is to discover possible precursors of mass movements.

We present the development of the GPS software GRAZIA which is designed to monitor and visualize slow deformations online. We describe the sequence of data processing steps with the main focus on special algorithms for obtaining high accuracy results: (a) normal point computation of double differenced phase data, (b) covariance model of the phase data, and (c) tropospheric bias model.

We have surveyed the Gradenbach landslide (Austria) several times during the past three years, using the GPS monitoring system. Data obtained from this project is used to demonstrate the excellent performance of the software GRAZIA. We show that the implemented correction models achieve, with respect to standard methods, a significant improvement of accuracy, reliability and time resolution of the deformations.

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1. INTRODUCTION

Natural disasters caused by landslides are frequent phenomena in alpine regions. The Austrian Academy of Sciences funds a research project which aims at the detection of possible precursors of mass movements. Our institute contributes to this project with the development of a GPS-based continuous deformation monitoring system (CODMS) for the investigation of landslide motions.

Continuous monitoring requires reliable data transmission from the observation sites to the processing site, online data processing and reliable power supply at all GPS stations which is not easily accomplished in the mountains. Various CODMS concepts have been proposed by other authors, e.g. Manetti and Knecht (2000). We have reported about the hardware issues of our CODMS in Hartinger and Brunner (2000) and Hartinger (2002). In this paper we present an overview of the GPS processing software GRAZIA, which we have developed for this project.

We will focus on algorithms and procedures which have been implemented in GRAZIA to meet the requirements of continuous monitoring in alpine regions. The following features shall be discussed:

- A high data rate of 3s is used to facilitate the reliable detection of cycle slips and outliers. For final data processing and storage the observations are compressed using a normal point technique.
- The newly developed SIGMA-*F* weight model was implemented to detect and mitigate signal distortion effects which may be caused by trees or other obstacles.
- A particular problem of GPS landslide monitoring in mountainous areas (large height differences) is the atmospheric effect on GPS signal propagation. A special calibration model helps to reduce the detrimental effect of residual tropospheric delays associated with steep slopes and large height differences.

At the Gradenbach landslide area in Austria, our primary test site, the maximum height difference between the GPS stations is about 900m for a baseline length of 5km. Processing results of the Gradenbach landslide campaigns will be used to demonstrate the performance of the software GRAZIA.

2. DATA PROCESSING USING GRAZIA

The original version of GRAZIA was developed from GPSoft written by Joseph Czompo at the University of Calgary. Based on the I/O routines and on the Kalman filter of this program, a processing software with a graphical user interface (GUI) was developed. Fig. 1 shows a screenshot of the GUI which allows online viewing of the deformations at several selected GPS sites.

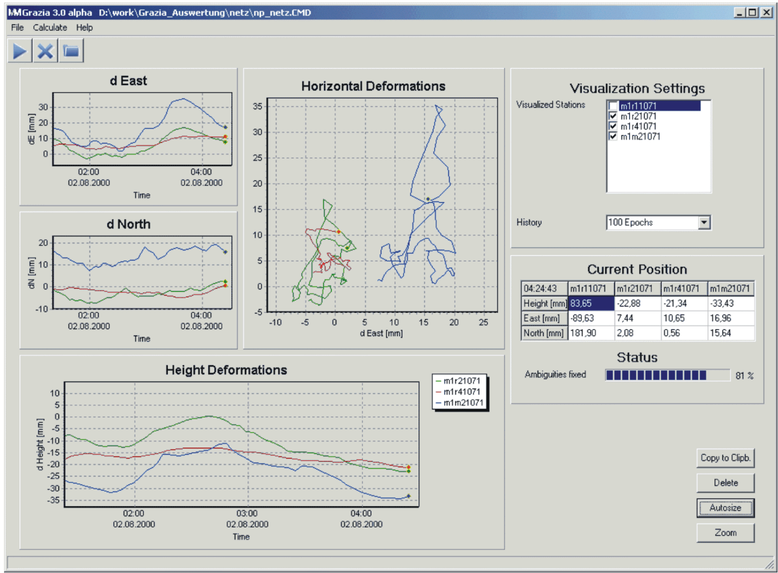

Figure 1: Screenshot of GRAZIA's main window

A flow chart of the processing steps is given in fig. 2. The software listens at the serial ports of the computer to receive the data which are recorded by the GPS receivers and immediately broadcast to the processing site by radio modems. The first processing step involves the selection of a reference satellite for each epoch and the computation of double differenced phase observations. The reference satellite selection is performed by a rule based fuzzy system, Wieser (2002). The rules integrate several parameters like the satellite elevation and the signal-to-noise ratio (S/N) of the received GPS signals. Next, the observations are scanned for cycle slips and outliers, based on triple differences. Outliers are eliminated. If a cycle slip cannot be fixed, the corresponding satellite data is disregarded for this epoch and a new integer ambiguity parameter is introduced for the following epoch. The preprocessed observations are reduced to a data rate of 30s using a robust normal point estimation procedure, which identifies and eliminates outliers that may have gone unnoticed so far. This procedure is described in section 3.1. To avoid diffraction effects of rising and setting satellites at ridges, an azimuth dependent elevation mask is used. The tropospheric delay is taken into account using a combination of the Saastamoinen model (Saastamoinen, 1973) and the Niell mapping function (Niell, 1996).

Once the observations have been reduced for satellite orbits and tropospheric propagation effects, the stochastic model needs to be established before the coordinates and ambiguities can be estimated. The variances of the double differenced phase observations are computed using a fuzzy system, SIGMA-*F*, which is described in section 3.2. Next, the positions and the float ambiguities are estimated in the Kalman filter. The LAMBDA method, e.g. Teunissen (1994), is used for ambiguity fixing. If the ambiguities can be fixed to their integer values, the positions are again estimated which yields ambiguity-fixed results of highest precision. For all subsequent epochs the integer ambiguities are kept fixed.
Finally, the heights of the monitoring points are corrected for unmodeled tropospheric effects using the results of a dedicated GPS reference station, Rührnössl et al. (1998). This algorithm is described in section 3.3.

To facilitate the online interpretation of the coordinate results, the actual deviations from the starting values are printed numerically and time series are plotted in dynamic charts by GRAZIA, fig. 1. The chart allows zooming and panning for better visualization. Finally the positions and their variances are stored to a file for archiving purposes and for the possible analysis of the results using different software.

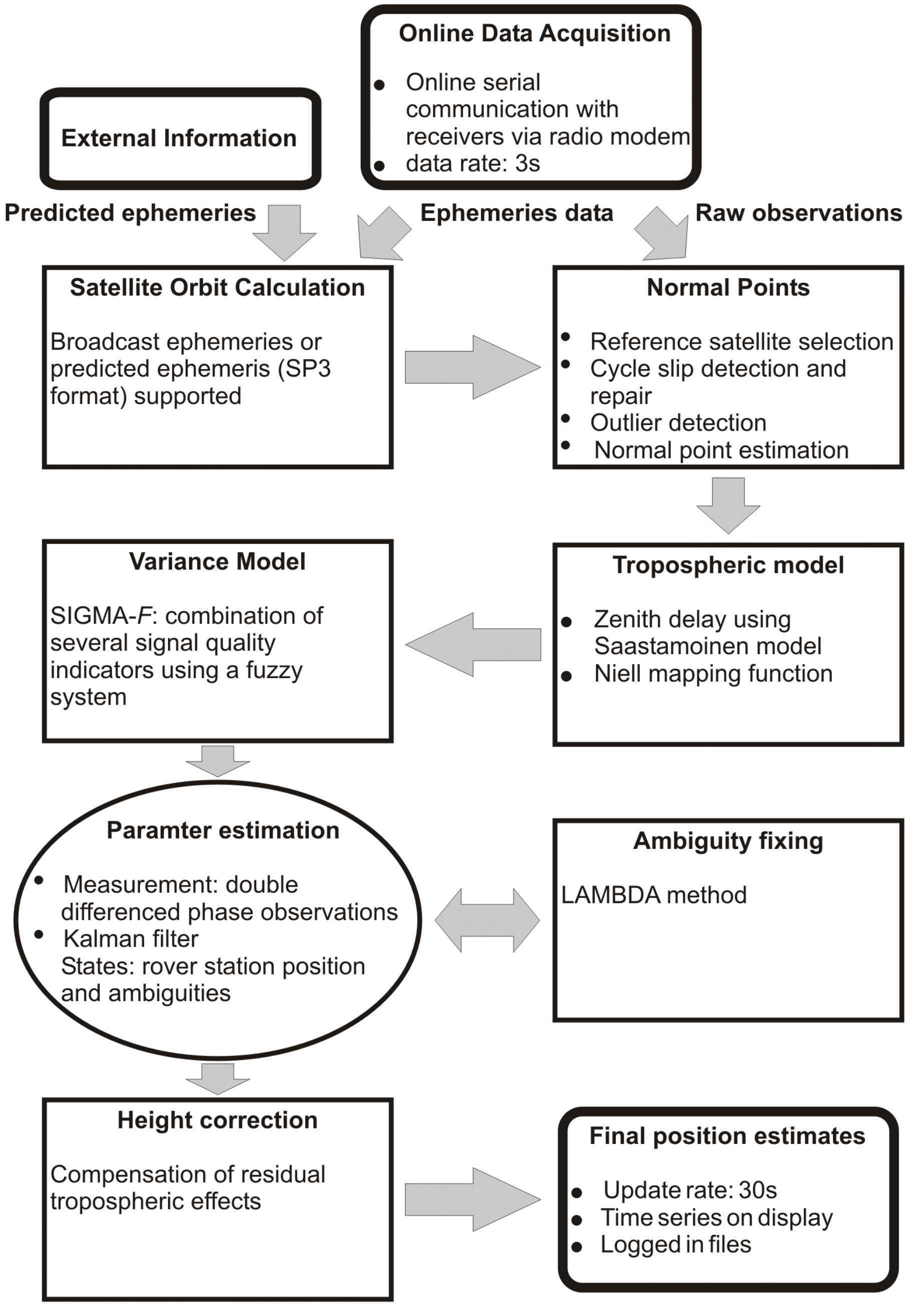

Figure 2: Data processing steps in GRAZIA

3. SPECIAL ALGORITHMS

3.1 Normal Points

For the reliable detection of cycle slips and outliers a high data rate is useful in order to increase the ratio of the phase difference value to the one cycle slip or outlier value. However, processing the data at a lower data rate is an advantage as GPS measurements are highly time correlated. Data compression using the normal point (NP) technique is well known from SLR. A sequence of N original data points is represented by a single normal point using an estimation technique which fits a suitable model to every consecutive N epochs of data, the normal point interval.

Leick (1995, p. 373) has discussed the suitability of the normal point approach to the time series of GPS double differenced (DD) phase observations, $\varphi_{jk}^{pq}(t)$, between the satellites p and q and the stations j and k. Introducing the term 'observed-minus-computed' for the phase observations, $\Phi_{jk}^{pq}(t)$, the time series of the linearized observation equations for the residual DD phase can be expressed as

$$\begin{aligned} e_{jk}^{pq}(t) = & \frac{\partial \varphi_{jk}^{pq}(t)}{\partial u_j} du_j + \ldots + \frac{\partial \varphi_{jk}^{pq}(t)}{\partial w_k} dw_k \\ & + \lambda N_{jk}^{pq}(1) - \Phi_{jk}^{pq}(t) \\ & + \left[T_{jk}^{pq}(t) - I_{jk}^{pq}(t) + m_{jk}^{pq}(t) \right] \end{aligned} \tag{1}$$

where the partial derivatives and Φ_{jk}^{pq} are functions of time. This time dependence is caused by the satellite motion. The DD of the ambiguity N is only unknown for the initial epoch. λ is the wavelength of the carrier wave, T, I and m are the propagation effects due to the troposphere, ionosphere and multipath, respectively.

Assuming now that the receivers do not move, then the coordinate corrections for the stations j (du_j, dv_j, dw_j) and k (du_k, dv_k, dw_k) are constant. If, however, the coordinates of the stations are accurately known, then the partial derivative terms do not contribute to the phase residuals $e_{jk}^{pq}(t)$. In that case, one would expect its DD time series to be a smooth curve with a slope close to zero due to the unmodeled DD of ionospheric, tropospheric, and multipath delays. If the coordinate corrections are non-zero, a residual curve with almost constant slope will be the result. Hence it is possible to fit straight lines through short sections of the DD time series, leading to the computation of representative normal point values.

Frequently, the estimates of the regression lines are computed using the least-squares (LS) estimator. However, the LS estimate is very sensitive to outliers, which may yield erroneous normal point estimates. Therefore, gross error detection needs to be considered. We suggest a normal point method using robust estimation, which combines estimation and the gross error detection into one single process, see fig. 3.
We use an iteratively reweigthed LS procedure (RLS), similar to the Danish method (DM), suggested by Krarup et al. (1980). The principle of the RLS method is the reweighting of the

observations as a function of the size of the residuals. Outliers become evident by large normalized residuals. If such observations occur, they are “down-weighted” i.e., their influence in the following estimation process is reduced. The resulting estimates are based on the largest group of consistent observations, Kubik (1982). In the absence of outliers the DM yields the same results as a LS estimator.

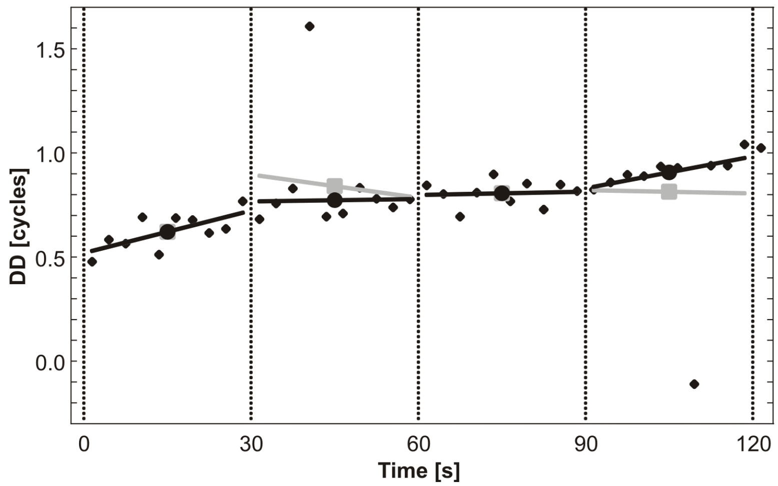

Figure 3: Normal point estimation in presence of outliers; original data points (black diamonds), linear regression and normal point estimated by LS (gray line and square) and linear regression and normal point estimated by RLS (black thick line and dot)

3.2 SIGMA-*F*

Signal distortions by multipath and diffraction are hardly avoidable in GPS. With kinematic GPS or short static sessions these effects, if not taken into account properly, may result in cm-level biases in the estimated coordinates.

A fuzzy system was developed by Wieser and Brunner (2002), which controls the parameter estimation by iteratively reweighted least squares. It combines conventional outlier detection with additional information on the data quality i.e., the S/N ratios.

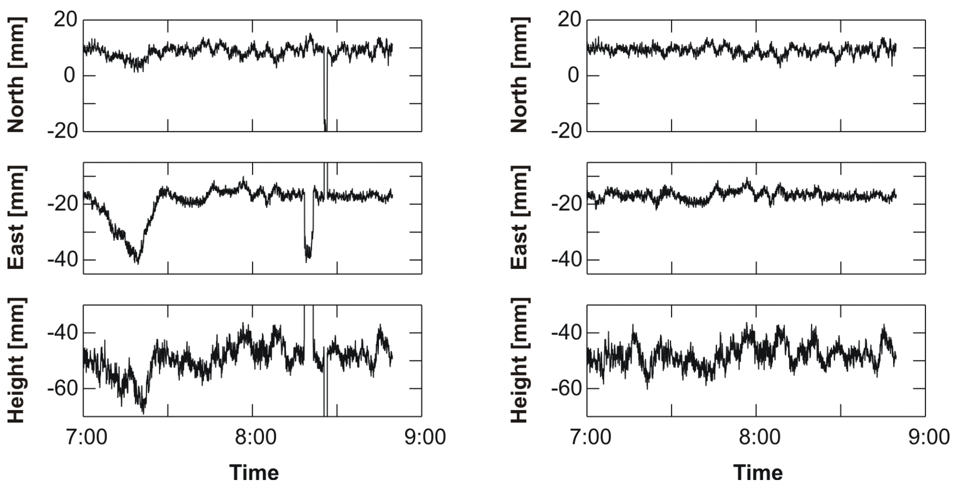

Figure 4: Epoch-by-epoch coordinate results of the static rover site as deviations from the ground truth in mm; LS and standard weight model left side; LS and SIGMA-*F* right side

An example shall explain the procedure. Fig. 4 shows the epoch-by-epoch processing results of a short baseline (100m). A building in the vicinity of the rover antenna causes signal diffraction, affecting the signals of one satellite. The time series of the standard processing results is contaminated by these signal distortion effects from 7:00 to 7:30hrs. Due to the receiver-obstacle-satellite geometry, mainly the east coordinate is affected. The maximum bias exceeds 20mm in this case. The strong offsets of the solutions from 8:15 to 8:30hrs are due to erroneously fixed ambiguity parameters of a low elevation satellite with several loss-of-lock occurrences.
Using the SIGMA-*F* variance model, the biases are successfully mitigated. SIGMA-*F* mitigates not only signal distortion effects but also biases caused by other unmodeled effects (e.g., erroneous ambiguity fixing) provided these effects are significant with respect to the random noise level.

3.3 Tropospheric Model

The tropospheric model used in GRAZIA is based on the idea that tropospheric anomalies can be derived from the time variations of the height values of one or multiple calibration stations. This model yields a practical correction term for the atmospheric model in a small area (Rührnössl et al. 1998).
The parameter estimation using a Kalman filter yields apparent height difference variations $\delta h_{RK}(t)$ between the reference *R* and the calibration point *K*, see fig. 5. If *K* is in fact a static point, then $\delta h_{RK}(t)$ should be zero for all epochs, and thus deviations from zero are mainly due to insufficiently modeled tropospheric effects. The height values of rover stations *i* may be improved using $\delta h_{RK}(t)$ due to the high spatial correlation of tropospheric effects in small areas, typical for landslide sites. Let us calculate the height difference ratio as k_i according to eq. (2) then the correction term $\delta h_{Ri}(t)$ for the station *i* is obtained by scaling $\delta h_{RK}(t)$ with k_i, see eq. (3). Details of the model are given by Rührnössl et al. (1998).

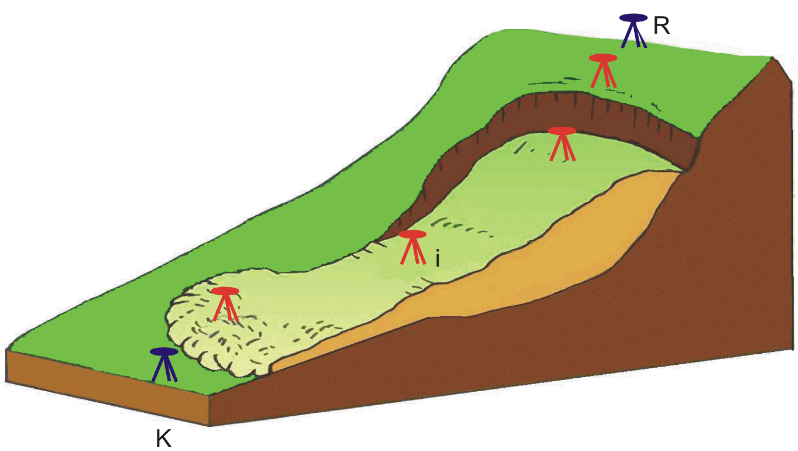

Figure 5: Monitoring scheme; reference stations (R, K) in stable area (blue); rover stations (i) in the deformation area (red)

$$k_i = \frac{\Delta h_{Ri}}{\Delta h_{RK}} \qquad (2)$$

$$\delta h_{Ri}(t) = k_i \, \delta h_{RK}(t) \qquad (3)$$

This model is based on the following assumptions in order to obtain accurate results:

- The height difference variation $\delta h_{RK}(t)$ is not affected by the landslide motion.
- The same satellites should be simultaneously tracked at all stations.
- The atmospheric processes must be the same for the whole monitoring network. So, tropospheric calibration may only be valid for one valley, perhaps even limited to one side of a valley.
- The layout of the stations is important. The height difference between the reference station and the calibration station should be the maximum height difference within the network. The best results are achieved if all stations are nearly situated on one line.
- The ambiguities must be fixed.
- Usually the height value of the calibration point is not exactly known at the initial GPS session, therefore only the precision of the heights of the monitoring stations can be improved.

So far, this model has proven to be very effective in reducing the atmospheric (tropospheric) propagation effects. Results using data of a landslide area are shown in the following section.

4. RESULTS OF A MONITORING CAMPAIGN

4.1 Description of the test area Gradenbach

The landslide area Gradenbach represents a severe threat to the village Putschall and the upper Möll-Valley in Carinthia, Austria. Previous studies investigated the kinematic behaviour of the deep-seated mass movements of the mountain slope Gradenbach (Weidner et al., 1998). The critical area consists of phyllites, calcareous schists, chlorite schists and quartzites from the ’Matrei zone’.

The GPS deformation network originally consisted of two reference stations and four rover stations. In August 1999, the first measurements were carried out to test the CODMS in this difficult terrain. Until now three campaigns of two days, one campaign of two weeks and one of three weeks duration were carried out. The results of the longest campaign (July 21st – August 12th, 2000) are used to demonstrate the performance of the software. During this campaign we used the configuration displayed in fig. 6. The data were analyzed using GRAZIA with system noise set to ±30mm/h in the Kalman filter. The guideline for the selection of this value was to set the system noise equal to the maximum motion that could be expected.

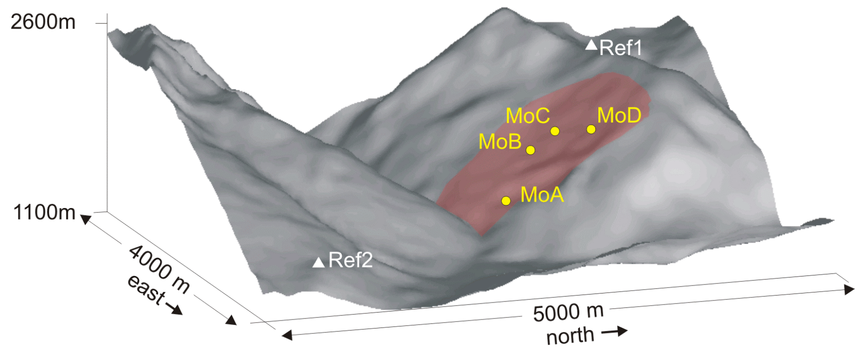

Figure 6: Terrain model of the Gradenbach monitoring site; the landslide area is shown in red

4.2 Sequence of Data Analysis

The accurate estimation of height differences is very important in landslide monitoring. For deep mass movements on steep slopes the height motion is usually a significant part of the total motion.

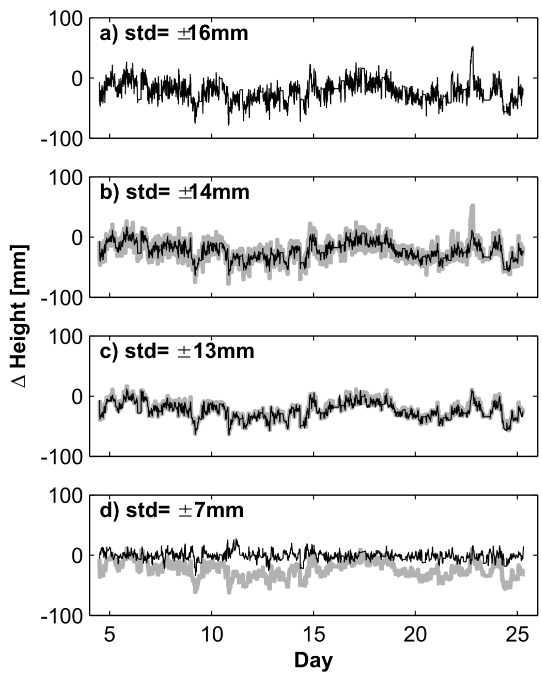

Figure 7: Sequence of data analysis for the height values of station MoB; Kalman filter results with a) original data, b) 30s normal points, c) SIGMA-*F* variance model, d) SIGMA-F and tropospheric model; for a comparison the results of the preceeding version are plotted in gray

Fig. 7 visualizes the impact of the individual processing modules on the height results of station MoB which has a height difference of 620m to the reference station Ref1. The results of processing the original data using the Kalman filter is plotted in fig. 7a, yielding a standard deviation (std) of ±16mm. The robust estimation of normal points helps to further reduce the noise and remove outliers from the original data, fig. 7b. If no outliers exist, each normal point is just the average over 10 data points. At this processing stage a standard weight model is used, resulting in a std value of ±14mm.

The solution obtained using SIGMA-*F* is, in the case of clear data and correct ambiguity fixing, close to that of the standard model (fig. 7c), which explains the nearly identical std value of ±13mm. However, when the signal is disturbed or falsely fixed ambiguities are used, SIGMA-*F* is a very important feature, which was already demonstrated in section 3.2.
The reduction by the application of the normal point technique and the SIGMA-F algorithm is only marginal because of the lack of serious data problems in the present example. Fig. 7d demonstrates that only the tropospheric correction removes the distinct signature which is imposed on the previous time series a to c. It reduces the standard deviation by 47 percent, yielding ±7mm. For comparison the std of the original data (fig. 7a) is ±16mm.

4.3 Results

The effectiveness of our tropospheric model for all four monitoring stations is between 47 and 60% yielding an average std value of ±7mm for the 21 day observation period. The final results of the monitoring station MoB are plotted in fig. 8. For the horizontal deviation a std value of about ±4mm can be achieved. Already during the 21 days of observation a slight motion of the landslide can be detected at MoB, clearly visible by the regression line plotted in fig. 8. The slopes of the regression lines are –0.4mm/d, 0.4mm/d, 0.2mm/d for North, East and Height respectively.

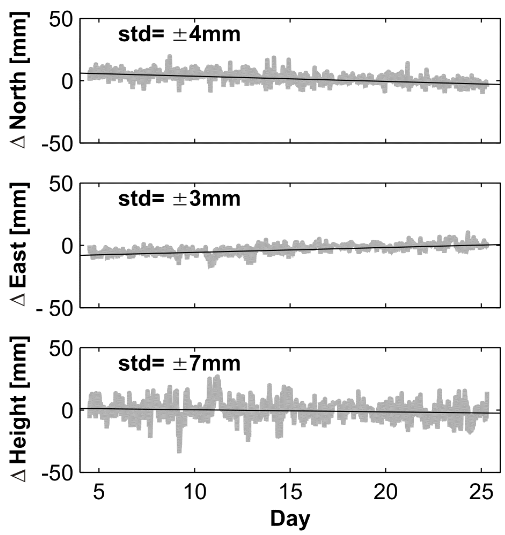

Figure 8: Results for station MoB with Kalman filter and SIGMA-*F* variance model, and the additional tropospheric model for heights; online results (gray thick line) and regression line (black thin line)

5. CONCLUSION

At this time GRAZIA is already a very useful tool for GPS monitoring. It has been specially designed for applications with steep slopes and large height differences. A standard deviation of about ±7mm for the height and ±3-4mm for the horizontal position can be achieved in near real-time. Next, the use of multiple reference sites with a new model for ionospheric and tropospheric propagation effects will be implemented.

ACKNOWLEDGEMENTS

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