Some Aspects of Geodetic Time Series Modelling

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The radical technological development of sensors, communication techniques and high-performance computers has increased the importance of permanent fully automatised monitoring systems, also geodetical, and promoted, encouraged or even required the development and testing of enhanced modelling algorithms in order to extract all of the information from the data available. The implementation of mathematical techniques prioritizes the models which enable the assimilation of all of the information available, an estimation of essential parameters of dynamic modelling in real time, the processing of measurements with data gaps and methods to handle the complexity of adopted functional models. As such these models can provide an additional supportive tool for safety assessment with decision-making and can distribute more reliable results for alarming procedures. In the contribution an overview of some methods, which were presented in detail in referenced manuscripts, is given. Long-term time series of monitoring data were used to implement and analyse regression analysis and Bayesian probabilistic approach for model class selection, two models of Kalman filtering for (near) real-time assessment, and two frequency methods - Least Squares Spectral Analysis and Lomb-Scargle normalised periodogram, for analysing periodicities in time series with unevenly distributed data.

Keywords – Bayesian probabilistic approach, frequency analysis, Kalman filter, multiple linear regression, time series analysis

1. Introduction

The development of sensors, communication techniques and high-performance computers has increased the importance of permanent fully automatised monitoring systems, also geodetical. This radical technological development has also promoted, encouraged or even required the development and testing of enhanced modelling algorithms and evaluation concepts in order to extract all of the information from the data available precisely and instantaneously, and to improve the understanding of the spatial-temporal processes, i.e. behaviour of the object, deformation patterns, distribution of influential forces and parameters, interaction between influential forces and object reaction.

The implementation of mathematical techniques prioritizes the models which enable the assimilation of all of the information available, an estimation of essential parameters of dynamic modelling in real time, the processing of measurements with data gaps and methods to handle the complexity of adopted functional models. As such these models can provide an additional supportive tool for safety assessment with decision-making and can distribute more reliable results for alarming procedures.

Methods and sensors adopted nowadays for high-precision tasks in engineering geodesy permit fully automated data collection, with even very short sampling intervals. Long- and midterm high-rate time series of measured displacements and other parameters enable testing of algorithms which could potentially be integrated into an automatization of the alarming process. In continuation, displacement time series captured by two geodetic systems - tachymetric and satellite based measurement systems

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which play an important role in automatic and continuously operating monitoring networks, designed as a combination of different sensors, will be used. Furthermore, it should be stressed that there is still an open space or even a necessity to ascertain models for geodetic observations of processes in civil engineering or of natural processes, which are captured pointwise. This comprises the processing of kinematic observations in a near real-time, involving a time component in data modelling, analysis of geodetic time series, parametric modelling of static and dynamic processes for different applications, integration of all the available measurement data captured by different sensors in space and time domain, or even an automatic response during the measurement process.

In the contribution and referenced manuscripts, long-term time series were used to implement and analyse different algorithms for time series analysis. *Regression analysis*, *Bayesian probabilistic approach* and two models of *Kalman filtering* were tested on relative coordinate time series captured by tachymetric observations as a part of monitoring system on a rock-fill embankment dam and its surrounding. For analysing periodicities, two *frequency methods*, both proposed for time series with unevenly spaced data, were tested. *Least Squares Spectral Analysis* was implemented on daily long-term coordinate time series of permanent GPS stations as a part of geodynamic observations. In one case, displacements captured by a geotechnical sensor - pendulum system were analysed for periodicities of an arch dam behaviour by *Lomb-Scargle normalised periodogram*.

The attempts to answer the questions such as how to control and appropriately model the complexity of available, primary geodetic data, uncertainty modelling of dynamic processes, noise reduction or removal, the possibility of detecting statistically significant residuals and deformations in near real-time, modelling and propagation of quality parameters in engineering geodesy, will be discussed.

2. Regression Analysis and Bayesian Probabilistic Approach

In the first task, we try to find a solution for predicting a dam behaviour at one monitoring point from the previous observations, to find a solution for detrending reversible deformations in order to estimate a long-term trend of irreversible deformations, and to propose a solution for a (near) real-time assessment of the dam behaviour. The main presumption made for all the items was that the algorithm would demand a very low level of initial tuning, would be as simple as possible, and will be computationally inexpensive.

The control point analysed is located in the middle of the upstream side on a dam crest and is a part of a permanent geodetic deformation network, which is designed for monitoring of a rock-fill embankment dam and its surrounding. The geodetic monitoring system is fully-automatised and based on the measurements with a high precision total station. The result of the geodetic network adjustment is the coordinates of points in the geodetic network in three perpendicular directions of a predefined local coordinate system. Seasonal variations, a strong correlation with the water level and an underlying long-term trend of irreversible deformations can be detected in coordinate time series of the analysed point, Gamse et al. (2017), where the reversible and irreversible deformations are of the utmost significance in the radial direction (i.e. longitudinal direction along the water reservoir).

2.1. Multiple Linear Regression

The availability of high-rate data has fostered the application and further development of statistical, also called empirical models, which enable the prediction of the structure behaviour under similar loads based on the experience and information from previous measurements of the influences and the object behaviour. In a statistical model, the influences of measurable variables on the observed object are described by basic mathematical functions, which are rather easier to handle as functions in deterministic models.

In order to propose a solution which could be easy to understand and would be based on best practises, which have already been proven to lead to reliable results, a hydrostatic-seasonal-time (HST) model, which was originally developed and proposed for analyzing of monitoring data on concrete dams and has been proven to be a powerful tool in safety procedures, was adopted to assess geodetically captured long-term relative coordinate time series of the case study. A further aspect which strongly encouraged a decision to implement the HST-model on the available data, was a strong correlation of measured relative displacements to the water level in the impounding reservoir.

Whereas the hydrostatic and temperature (i.e. seasonal) reversible effect are always modelled with a polynomial up to 4th degree and a linear combination of four sinusoidal functions respectively, different, strictly monotone functions are proposed for the modelling of long-term irreversible deformations. According to a long period of available data and changeable long-term trend within the analysed period, the sum of a linear, a positive exponential and a negative exponential function of reduced time was used to model the influence of various processes, whose effects are irreversible or not fully reversible deformations, and thus accumulate in the lifetime of the dam (Gamse et al. 2017).

For an estimation of unknown model parameters, several techniques can be used, whereas again a very-well know multiple linear regression (MLR) was adopted. The HST-model with the MLR solution is simple and computationally inexpensive. After a statistical calibration and estimation of unknown coefficients, it enables detrending of reversible deformations and assessment of a long-term trend.

But, is it necessary or even correct to include all parameters? The main challenge of the MLR is to select the *correct* parameters for a given model, in our case the HST-model. Namely, including all of the parameters, also those that could be unnecessary or involve (strongly) correlated variables, could lead to a problem of overfitting the model. Consequently, the significant measurement residuals, significant influences or deformations can be overlooked, and the model also does not fulfil some mathematical assumptions.

The extensive tests of the iterative procedure of inclusion/exclusion of regression coefficients by a backwards elimination and a forward search confirmed that only observing the coefficient of determination, R^2, and the root-mean square error, $RMSE$, which are the most widely and common used metrics of model accuracy in the process of defining an optimal model, are not sufficient and can even result in a model, which is unreliable for a prediction. In the case study, the process of finding an optimal model was primarily based on a backwards elimination of the coefficients by observing their statistical significance. Since the coefficients are interrelated, known practical experiences of engineers are taking into consideration for their exclusion/inclusion order. Namely, the influence of the water level in the impounding reservoir is much more significant than the influence of the temperature in the case of an embankment dam. Due to the main purpose of the dam, the water level in the impounding reservoir fluctuates with an annual (water management) cycle, which is conditioned by an annual temperature and rainfall period. In such cases it is especially demanding to separate and estimate two influences - a temperature influence and a hydrostatic pressure on the dam. Although the temperature influence is very low, at least one parameter of the seasonal component should be included into the model in order to reduce the correlation of data in time domain and to extract a deterministic pattern in the residual time series.

At this point it should be stressed that in practical implementation, the model should be checked at regular intervals, depending on the frequency of observations, whether the estimated model is still valid. The reanalysis includes an estimation of included regression coefficients with new data. Any inclusion of other regressors or even changing the influence functions should be done with caution and supported by an interpretation of changed loads on the object.

2.2. Bayesian Probabilistic Approach

In comprehensive analyses in Gamse et al. (2017), several HST-model candidates were validated as reliable for a given data set, with a good prediction for a time span of three years. Furthermore, the computations showed that observing only the R^2 and $RMSE$ metrics can even result into a false future prediction. Since the process of variable selection and model building by methods of backwards elimination and forward search is very challenging to make a final decision which model is the optimal and demands a previous knowledge of the process, the continuing research work was focused on an optimisation of the model selection process and a more objective solution of finding an accurate and robust model, which could be even completely automatised. In the work Gamse et al. (2018), the authors adopted a Bayes interference in the model selection process. The implementation of the Bayesian probabilistic modelling for the structural reliability analysis is becoming tremendously popular, with the main focus on the implementation of Bayesian networks. In our case, with a fixed parameter set in the HST-model, and measured input and output values, the Bayesian probabilistic approach can provide a framework for parametric identification in a prescribed functional model and uncertainty quantification. In the Gamse et al. (2018), the Bayesian probabilistic approach was used to define a reliable HST-model for displacement time series analysis and to analyse the pattern of included coefficients in top n-models.

While the accuracy measures such as R^2 and $RMSE$, which are based on minimising a norm of the fitting error between the output/measured data and the corresponding estimated prediction, select an optimal model class, often with many parameters included, the crux of the Bayesian probabilistic approach is to select *the most plausible model* within a set of model class candidates.

In the Bayesian approach to model class selection (Bayesian model class selection, BMCS), the concept of model evidence provided by the data has been incorporated. The goal is to use information given by dynamic data in $\mathcal{D}$, in which an unknown noise is present, to select the most plausible, suitable class of models representing the observed physical phenomenon among a set of N_C model classes $\mathcal{C}_1$. The model, which maximises the posterior probability, is selected as the most plausible one. The conditional posterior probability of a model class $\mathcal{C}_j$ is obtained by using the Bayes' theorem, which incorporates the evidence for the model class $\mathcal{C}_j$ provided by the data $\mathcal{D}$, the user's judgement on the prior plausibility of the model class $\mathcal{C}_j$, and the probability of the data as a normalizing constant. If the prior probabilities are uniform, this is equivalent to maximising the evidence for the model class $\mathcal{C}_j$ provided by the data. The model evidence for $\mathcal{C}_j$ is given by the law of total probability, with an integral over all possible parameters. In the work Gamse et al. (2018), Laplace's method of asymptotic expansion was adopted for solving a high-dimensional integral for computing the model evidence for $\mathcal{C}_j$. The expression includes two factors: the maximum value of a likelihood function attained at the optimal vector of uncertain parameters and the Ockham factor, which represents a penalty against complicated parametrization and a measure of robustness to modelling error and measurement noise.

For the case study, we have $N_C = 2^{12-1} - 1 = 2047$ HST-model class candidates, which were computed and ranked according to the evidence provided by the data $\mathcal{D}$. Several tests with different prior probabilities of the uncertain parameters and a weighting between sub-groups of parameters (i.e. hydrostatic / seasonal / time term) were performed. In order to keep the model selection process as objective as possible, the same prior probabilities of the included parameters, which are included in the model $\mathcal{C}_j$, were finally chosen.

In the case of a large number of observations N, computational problems can encounter in direct calculation of the likelihood function, Ockham factor and model evidence provided by the data, which was also the case for the analysed data and the HST-model. The problem was numerically solved by using the logarithm function. Furthermore, instead of computing the absolute plausibility of a model class by using the exponential of the log-evidence, the relative plausibility between different model classes was computed. All model class candidates of the HST-model were finally ranked according to the value of evidence for the model classes $\mathcal{C}_j$ given the data $\mathcal{D}$ or relative plausibility, with the highest value for the top model.

In the presented case study, the BMCS for the parametric identification and model class selection in the HST-model was introduced for the first time. Based on comprehensive analyses, it was concluded that the Bayesian probabilistic approach presents a more objective solution than the combination of backwards elimination and forward search used in the work Gamse et al. (2017). The method offers high potential for controlling the complexity of any functional model and for further implementations in even more complex models, for example, in the hydrostatic-temperature-time model, where temperature observations are directly modelled.

3. Kalman Filtering

In presented works so far, we try to find the best model for a longer data set or period. Is it possible to learn an algorithm on a much shorter data set and assess the dam behaviour after each epoch the new observations enter into the system?

The Kalman filter is a well-known one-step back / one-step forward algorithm for filtering data and the analysis of errors, systematical influences and blunders. The algorithm considers all of the available measurement data and previous knowledge about the system and instrumentation to get the system state estimation for a given epoch in a manner, which statistically minimizes the errors. The efficiency of the filter can be used especially in tasks of time series analysis, where no redundant measurements are available; in geodesy in tasks of navigation or continuous measurements of object movements and deformations. Already at this point it should be stressed that the output results depend strongly on the initial values of input model parameters.

3.1. Dynamic Modelling by Kalman Filtering

In a first attempt of implementing the Kalman filtering for the time series of geodetically measured relative displacements at the point on the embankment dam, an one-step back / one-step forward modelling as a dynamic stochastic process was proposed. A third-order discrete Wiener process acceleration model as a formulation of the Kalman filtering, described and evaluated in Gamse (2017), was implemented.

The main parameters of interest to be estimated are monthly median values of relative displacements, which can be considered as time-varying parameters and their dynamics can be described with simple equations of motion. The system state vector of the functional model involves displacement, velocity, and acceleration in one direction of a predefined local coordinate system. Under the presumption that the changes in relative displacements are slow (i.e. constant acceleration during each sampling period), which should be the case for any dam, they can be modelled as acceleration disturbances in the stochastic model. In the Kalman filtering, different stochastic process models can be implemented to account for effects that are difficult to model or are subject to random disturbances. In the contribution, a discrete-time Wiener process acceleration model was implemented, where the acceleration is modelled as a zero-mean white sequence. The acceleration enters into the dynamic equation through a noise gain and zero-mean white noise scalar, which is defined by a process noise variance or process noise intensity scalar. In the processing, we are interested in the integrated effect of the random walk on the velocity and displacement as the second and first system state component respectively.

To perform the Kalman filtering, some a priori information has to be known sufficiently to provide an optimal a posteriori estimate of the system state components. In the case study, the initial values of the system state components - position, velocity, acceleration, and initial error covariance matrix were defined from the first few measurements. The covariance matrix of observations is usually defined externally using a known standard uncertainty of a used measurement system or earlier observations. Since the standard deviations of monthly median values of measured relative displacements, which present the Kalman filter measurements, were not available, the Allan variance for monthly median values of relative displacements was used to estimate the noise. One of the main challenges by Kalman filtering is to define the process noise covariance matrix and the corresponding process noise intensity scalar, which defines weighting between the process and measurement noise and influences the results most significantly. The value was defined from the initial measurements and several repetitions. The verification of a filter design and choosing an appropriate value of the process noise intensity scalar, as the main parameter for a Kalman filter tuning, was controlled primarily with the achieved congruence between the statistical tests in the domain of measurements and in the system state domain. For a chosen confidence level, both tests resulted approximately in the same percentage of the points - relative displacements, at similar epoch, as statistically significant anomalies. Furthermore, the autocorrelation function of system state corrections and innovations were used to check the randomness and to detect possible time correlations, where the confidence bounds enclosed most of the time lags. The procedures and parameters for the evaluation of the Kalman filter model, which can be used in (near) real-time tasks, are described in detail in Gamse et al. (2014).

The numerical results confirmed the potential of the proposed third-order discrete Wiener process acceleration model for detecting statistically significant changes in geodetically measured relative displacements. The advantage of the model is that the process noise intensity can be well related to physical characteristics of the motion (acceleration). The results also expose a correlation between detected statistically significant displacements and larger adjacent differences in the water level. It should be stressed that the value of process noise intensity scalar should be chosen appropriately, otherwise the Kalman filter model can result in under- or over-estimated values of the system state components and associated errors.

3.2. Adaptive Parametric Identification by Kalman Filtering

The proposed third-order discrete Wiener process acceleration model can detect statistically significant or unexpected changes in monthly median values of relative displacements according to the previous behaviour (one-step back), but it cannot express any information on the underlying long-term trend or to detrend and estimate the influence of the water level in an impounding reservoir and of the temperature on the relative displacements.

In the second attempt, the Kalman filtering is used for an iterative estimation of unknown parameters of the HST-model (Gamse & Zhou 2019). The unknown parameters present a system state of the Kalman filter, which is iteratively improved by new information entering with new observations – in our case measured relative displacements. We are also interested in the estimation of unknown model parameter changes and capability of the stochastic model of the Kalman filter to detect statistically significant changes in the dam behaviour described by measuring relative displacements as a consequence of changeable influential forces on the dam. In order to reduce the complexity of the model as much as possible, we keep only sine and cosine terms with an annual period. Furthermore, for the time component only a constant term and a linear trend, are used in order to simplify the analysis of changes in the long-term trend.

The initial estimate of the system state components - parameters of the HST-model and the associated a priori error covariance matrix can be very well initialised from the first few measurements as well as from a few repetitions of the Kalman filter. They strongly influence the acceleration of the convergence of the estimated system state component standard deviations and of the learning process. Wrong initial values of standard deviations can even lead into the divergence of standard deviations. For the standard deviation of Kalman filter measurements, the average value of differences between adjacent monthly median values of relative displacements is taken.

How can we then recognise if the filter assumptions are met and that the filter is performing correctly in practice? A very informative measure of the filter performance is the measurement residual – innovation, d_i, defined as the difference between the observation (measurement) and its prediction made using the information available in time based on the previous knowledge of the process. It is a measure of the new information provided by entering of new measurements into the estimation process, and their values are an important measure of how well the estimator is performing. We can verify if the filter is consistent by applying the innovation magnitude bound test to check that the innovations are consistent with their covariance by verifying that the magnitude is bounded by σ- or $2 \cdot \sigma$-bound. This simple test is already quite sufficient to check the filter consistency. In practice, an additional test – χ^2-test of normalised innovations squared – is applied to check the consistency of innovations with their covariances and to analyse significant observations. To perform even more robust test, the normalised innovations squared can be compared to their moving average for each measurement epoch.

All tests denote three periods of significant innovations and normalized innovations squared after the stabilisation of the system state components and their standard deviations is achieved. Two of them are correlated with a drawdown of the annual water level below the reduced minimal water level. Another period relates to the period, for which the annual water level was kept higher than the average minimal water level. After the stabilisation, the parameter values expose changes only for the periods for which significant innovations and normalized innovations squared were also detected. Since the Kalman filter is implemented on the HST-model the algorithm enables detrending of reversible and irreversible deformations, and analysis of a long-term trend at each measurement epoch. The significant deviations in the water level influence not only changes in the amplitude of reversible deformation but causes also changes in the long-term trend. Defining an appropriate value of the process noise intensity scalar, which is the most influential initial parameter, is again the main challenge of the algorithm, where the convergence of the trace of the a posteriori error covariance matrix is used as the main criterion in the tuning process for the case study.

4. Frequency Methods

Time series - either of measurements generated from continuous observations or residual time series after adopting some model can expose systematic variations. The reasons can lie in systematic influences on a measurement system, a strong correlation of a dynamic behaviour of the object to the periodical external influences, or in an inadequate modelling. The three main goals of necessity to appropriately identify the periodical patterns in time series data could be emphasised: (a) to extract deterministic influences on the measurement system, which could otherwise be interpreted in the object behaviour, (b) to correctly decompose periodical influences on the measurement system and actual periodical-reversible deformations of the object as a consequence of periodical external forces, and (c) to improve mathematical modelling in order to fulfil the presumption that the residuals have a Gaussian distribution with zero mean and variance σ_ε^2, and are uncorrelated in time domain.

In the case of deterministic pattern with underlying periodicities, frequency analysis methods can be adopted to detect statistically significant frequencies. Depending on the type of data, the Fourier transform can be used for the data sets with evenly spaced data, otherwise the Lomb-Scargle normalised periodogram and least squares spectral analysis are proposed.

4.1. Least Squares Spectral Analysis

Coordinate time series of continuously operating GNSS stations expose often periodic signal(s), which are caused by various influences that have a periodic nature. In order to get a more accurate estimate of unknown parameters of interest and their uncertainties, the periodic patterns - either in direct coordinate time series or in remaining residual time series should be appropriately analysed. In the work Nobakht-Ersi et al. (2016), a set of three-dimensional daily coordinate time series of selected 125 permanent GPS stations, which are part of the Southern California Integrated GPS Network, were analysed for a time span of nearly eight years. The main intention of the work was to iteratively improve a basic site motion model, which is used for analysing crustal deformations and other geophysical phenomena.

The least-squares spectral analysis was adopted since small data gaps are present in GPS time series. For computing the velocities (rates and directions) of the analysed permanent GPS stations as a main parameter of interest, a site motion model with a linear trend, trigonometric functions of periodic signals, and term of offset modelling was adopted. The unknown parameters of the model were estimated using a least-squares method. For computing underlying periodicities in direct coordinate time series and in remaining residual time series after adopting the site motion model, the least-squares spectral analysis was used, and the site motion model was iteratively extended for sinusoidal functions of particular statistically significant frequencies. The noise towards to random distribution, which is important for the validity of statistical conclusions and was controlled by the autocorrelation function of residuals. The post-fit $RMSE$ scatters of residuals were suppressed for factor up to ~ 2 in N- and E-direction.

The next step was the interpretation of statistically significant frequencies that were extracted by the least-squares spectral analysis. The results confirmed the presence of some dominant intervals of statistically significant frequencies, corresponding to annual and semi-annual period, in most of the coordinate time series. After removing the most powerful frequencies, an extension of less prominent components was undertaken. The noise periodograms exposed also a peak at the frequency corresponding to the Chandler wobble frequency with 435 day period. In all three directions, long-term period effects (for example, larger than 1000 $days$) were present in some analysed coordinate time series. Part of these long-term effects can be considered as a random walk noise. In the iterative computation of the statistically significant frequencies of unknown periodicities, it was also confirmed that the values strongly depend on the changes of input data, such as the frequency sampling size.

From the analyses, it can be concluded that by the iterative inclusion of statistically significant periodicities into the site motion model and extracting the periodic underlying signals, more realistic estimates of the unknown parameters, especially rates of GPS sites, (Nobakht-Ersi et al. 2016, Gamse et al. 2014), can be obtained. Due to a high correlation of different influences on the GPS/GNSS observations, the interpretation of significant periodicities is still one of challenging tasks and demands further research work.

4.2. Lomb-Scargle normalised periodogram

The comprehensive analyses in the case study of the embankment dam, (Gamse et al. 2017, Gamse et al. 2018, Gamse et al. 2016), showed that the residual time series can still expose small underlying periodicities after implementing an optimal HST-model. Since the monitoring system in the case study presented in Gamse et al. (2016) offers a high potential for a further research work to fully explore the potential of the frequency methods, i.e. to adopt the frequency method on the reading stations of all pendulum systems installed in the dam and to analyse the natural and other statistically significant frequencies for the whole dam, the Lomb-Scargle normalised periodogram was tested for analysing the deterministic pattern in the displacement measurements with unevenly spaced data in radial direction of the topmost reading station of the central pendulum system. In the first step, the optimal HST-model was estimated by a multiple linear regression using a backwards elimination and forward search method. The residual time series were further analysed for underlying periodicities and the optimal HST-model is iteratively extended for sinusoidal functions of statistically significant frequencies. The assessment of the statistical significance of periodogram peaks is performed by a False Alarm Probability approach.

For the frequency analysis processing, the frequency limits and the grid spacing of the periodogram should be defined. The frequency limit at the low end is usually set to zero or $f_{min} = 1/T$, with a time span T. The high-frequency limit should be chosen in order not to miss relevant information, where the Nyquist limit can be used. Furthermore, an appropriate oversampling interval or frequency grid has to be chosen for the periodogram to successfully detect all statistically significant frequencies in the predefined frequency range. Too coarse a grid can lead to a periodogram that entirely misses the relevant peaks. But if too fine a grid is chosen, it can lead to unnecessarily long computation times. The computations also confirmed that a larger value of the sampling factor does not significantly contribute to the precision of frequency detection.

The optimal HST-model was iteratively extended in two steps for the sinusoidal terms with lower frequencies, corresponding to the period 1.5 $years$ and 1.2 $years$, which were detected as statistically significant with the 10%- and 1%-confidence level respectively. The estimated frequencies are valid within the time period of modelling and were not detected directly in the time series of measured displacements. The metrics such as the coefficient of determination R^2, root mean square error $RMSE$ and signal-to-noise ratio SNR exposed slight statistical improvement of the extended HST-model and of modelling of amplitude peaks. The autocorrelation of residuals for the extended HST-model confirmed a lower correlation of residuals in the time domain. Since the maximal improvements amounted up to 1.5 mm at the amplitudes of approximately annual periodicity after adopting the extended HST-model, the extended HST-model presents predominantly the statistical improvement of the optimal HST-model, and does not influence the data interpretation and safety assessment on decision-making.

In future work, the proposed method could be adopted for all pendulum reading stations to extract the natural and other frequencies of a whole structure, to analyse similarities in response of different parts of a structure, and for an estimation of possible correlations between measured influences and measured responses of a whole structure.

5. Conclusions

In the contribution a short overview of some mathematical models for data processing is given and the Author kindly references the reader to further published manuscripts listed in the bibliography. In comprehensive analyses of published manuscripts, enhanced modelling algorithms and evaluation concepts were tested on time series data captured within real monitoring systems. Primarily, time series of geodetically measured displacements were used to adopt different assessment concepts.

For the Bayesian model class selection approach adopted for the hydrostatic-seasonal-time model it has been proven to be a very objective and prompt method for model class selection, and is strongly recommended to test the method for other functional models used for the geodetic data processing. In the case of a larger number of unknown model parameters and consequently a large number of model candidates the solution with parallel computing can be implemented.

Both models of Kalman filtering were used for an assessment of the dam behaviour in a stepwise manner, when new information/observations enter/- into the system. The Kalman filter can present a solution which could be used for a (near) real-time assessment of the parameters of interest and for detecting significant anomalies in the observed process. But the Author stresses that the initial values of the model, especially the process noise intensity scalar value, which defines weighting between the process and measurement noise and influences the results most significantly, should be chosen appropriately, otherwise the Kalman filter model can result in under- or over-estimated values of the system state components and associated errors. The Author suggests the implementation and testing of the Monte Carlo Simulation for the initial phase of defining the process noise intensity scalar to develop a more objective attempt.

A spectral analysis or frequency domain analysis can provide an alternative way of data processing. For both cases - Lomb-Scargle Peridogram for dam monitoring and Least Squares Spectral Analysis for GPS time series used for analysis of crustal deformations, it has been shown that the frequency algorithms are efficient methods for analysing periodic patterns either in observations or in the observed process itself described by time series with unevenly spaced data.

It can be concluded that the enhanced algorithms can extract more information from the data available precisely and instantaneously, and can improve the understanding of the spatial-temporal processes, i.e. behaviour of the object, deformation patterns, distribution of influential forces and parameters, assimilation of different data types, and interaction between influential forces and object reaction.

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