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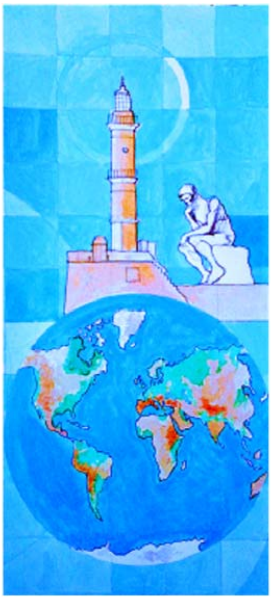
Book of Abstracts

Scientific Workshop: Space-time Stochastic Models and their Applications



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A Quick Review of Local-Interaction Energy Functionals and their Applications in Space-Time Data Analysis

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http://www.geostatistics.tuc.gr/4933.html

Abstract

This presentation will focus on statistical models of space-time random fields generated by energy functionals that involve local interactions. I will explain the motivation for generating such models and the connections that exist with statistical physics and machine learning. I will then summarily refer to advances that were made during the project in terms of theoretical ideas, new covariance functions, and statistical models. I will discuss the advantages of the new families of covariance functions, the use of locality to generate scalable models that can handle large data sets, and the possibility to generate new forms of spatiotemporal dependence within an expanded local interaction framework.

Spatiotemporal Stochastic Models Inspired by Statistical Physics

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Abstract

The growing availability of spatiotemporal data has drawn the attention to the theory of Random Fields (RFs) and their applications abound in physical sciences and engineering e.g. in astrophysics, material sciences, neurosciences, environmental and civil engineering. In this context, it is also very important to have efficient representations of RFs in order to overcome dimensionality problems that appear in numerical computations involving RFs, including polynomial chaos and high-dimensional Response-Excitation Liouville equations.

Statistical field theory can compactly express correlations in terms of suitable energy functionals which can be used as models of spatial data. We shall show that the Spartan Spatial Random Fields (SSRFs) can be derived by the maximum entropy principle. The resulting models incorporate “interactions” between the sample locations and involve three parameters that include the scale and rigidity coefficients and the characteristic length. Thus, they are more flexible than the classical, two-parameter covariance models such as the exponential and modified exponential. Moreover, the obtained models, which include oscillating covariance functions, can be represented using the Karhunen- Loève expansion which is amenable to analytic expression in one dimension. In fact, different combination of the parameters may allow controlling the size of the KL basis for given correlation length [1].

The equilibrium model is extended to the space-time domain by means of the associated Langevin equation obtained within the relaxation approximation. The Langevin equation is used to derive a general equation of motion for the two point correlation function of this space-time model. The derived fourth order partial differential equation is solved explicitly in different approximation regimes providing new types of space-time correlation functions without the simplifying assumption of space-time separability [2].

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Non-stationary Covariance Functions Based on Local Interaction Models

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Abstract

The study of spatially distributed physical processes usually relies on irregularly sampled data due to cost, time constraints, and instrumental limitations. Interpolation or prediction of missing values in spatial data sets, especially those involving extreme values, is a mathematical problem of practical interest in signal processing, remote sensing, and environmental risk assessment.

Random field theory is a mathematical framework for modeling spatial data. In this framework, it is assumed that measurements of a physical property correspond to a sample path of a multidimensional Gaussian joint probability distribution function. The spatial correlations are described by means of covariance functions which are determined from the data, usually under the assumption of statistical stationarity. Spatial interpolation is then performed via the stochastic optimal linear predictor.

Spartan spatial random fields (SSRFs) are a class of Gibbs random fields in which the spatial dependence is derived from local interactions instead of a model covariance. The probability of a given field configuration is determined by an effective local energy functional (ELEF). This formulation is inspired from statistical physics and provides a conceptually attractive framework for treating non-stationary and spatiotemporal problems.

In modeling localized extreme values, e.g., radioactivity emergencies due to an accidental release, the stationarity assumption no longer holds. In this talk, we propose new, non-stationary SSRF covariance functions for the interpolation of such data sets. We treat the extreme values by means of an ELEF perturbation, and we derive approximate but explicit non-stationary covariance functions using the leading-order perturbation expansion.

Stochastic Local Interaction Model as Alternative to Kriging for Missing Data Problems

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Abstract

Kriging methods are widely used in geostatistics for spatial interpolation including the estimation of mineral reserves and occasionally for addressing missing data problems. It can be proved that kriging methods are the best linear estimators for normally distributed data. However, this condition is not always sufficiently satisfied by the available datasets. A possible remedy is the use of nonlinear transformations of the data when possible. Herein we illustrate the use of the Stochastic Local Interaction method for discrete data, which is not limited by the normality requirement.

Ordinary kriging is used for a comparison with the Stochastic Local Interaction method. Interpolation studies of three different datasets will be presented and used to compare these two methods. The first dataset is composed of drill-hole data taken from a lignite mine. The second dataset is composed from a 2-D diffusion model with non-Gaussian (binary) data that have values of 0 and 1. The third dataset is a discrete dataset from a grayscale image of the dwarf planet Pluto, with integer values in the range between 0 and 255. In the last two datasets, results from the comparison with the nearest neighbors interpolation method will also be presented.

Sparse Matlab Implementation of SLI Model

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Abstract

High-level programming languages to which *Matlab* belongs allow the integration of computationally demanding tasks in a more user-friendly way than traditional programming languages such as *C*, *C ++*, and *Fortran*. However, *Matlab* is limited in speed of execution and memory that is required for the execution of tasks.

Spatiotemporal prediction is often limited in size by the inversion of large matrices. This shortcoming can be remedied by using models with sparse spatial or temporal structures. This paper presents two techniques to implement sparse representations of the stochastic local interaction model in Matlab. The first approach involves the utilization-exploitation of sparse structures, and the second approach implicit and explicit parallelism within the *Matlab* programming environment. The combination and implementation of these two techniques in time series (*1D*), for a validation set which comprises 3000 points, reduces the execution time by 80 % compared to the straightforward (non-explicitly sparse) implementation.

Application of Local Interaction Models to Precipitation Data on the Island of Crete

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Abstact

Understanding and predicting the spatiotemporal patterns of precipitation in the Mediterranean islands is an important topic of research, which is emphasized by alarming long-term predictions for increased drought conditions [4]. Geostatistical methods have been applied to environmental data for more than two decades in order to provide reliable simulations and estimations which could contribute to sustainable management of environmental resources. The analysis of records from drought-prone areas around the world has demonstrated that precipitation data are non-Gaussian. Typically, such data are fitted to the gamma distribution function and then transformed into a normalized index, the so-called Standardized Precipitation Index (SPI) [2, 5]. Precipitation maps can be constructed using the stochastic method of Ordinary Kriging [1]. Such mathematical tools help to better understand the space-time variability and to plan water resources management.

We present results of a geostatistical analysis of the space-time precipitation distribution on the island of Crete (Greece). The study spans the time period from 1948 to 2012 and extends over an area of 8.336 km^2. The data comprise monthly precipitation measured at 56 stations. Analysis of the data showed that the most severe drought occurred in 1950 followed by 1989, whereas the wettest year was 2002 followed by 1977. A spatial trend was observed with the spatially averaged annual precipitation in the West measured at about 450mm higher than in the East. Analysis of the data also revealed strong correlations between the precipitation in the western and eastern parts of the island. In addition to longitude, elevation (masl) was determined to be an important factor that exhibits strong linear correlation with precipitation. The precipitation data exhibit wet and dry periods with strong variability even during the wet period. Thus, fitting the data to specific probability distribution models has proved challenging. Different time scales, e.g. monthly, biannual, and annual have been investigated. Herein we focus on annual precipitation data which are fitted locally to a normal probability distribution, after the trend is removed based on topographic parameters. We use the Spartan variogram function to model space-time correlations, because it is more flexible than classical models [3]. The performance of the variogram model is tested by means of leave-one-out cross validation. The variogram model is then used in connection with ordinary kriging to generate precipitation maps for the entire island. In the future, we will explore the joint spatiotemporal evolution of precipitation patterns on Crete.

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Space-Time Modelling of Groundwater Level Using the Spartan Covariance Function and Bayesian Bootstrapping

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Abstract

Space-time geostatistical approaches can improve the reliability of dynamic groundwater level models in areas with limited spatial and temporal data. As it has been shown in previous research the estimation of a spatial trend that incorporates auxiliary information improves the predictions of groundwater level. Therefore, it is proposed the spatiotemporal trend to be approximated by involving a product of temporal and spatial components. The temporal trend is approximated by using an exponentially weighted moving average filter, whereas for the spatial term is based on a physical law that governs the groundwater flow under pumping conditions.

The correlation of the spatiotemporal residuals is modeled using a non-separable space-time variogram based on the Spartan covariance family. The space-time Residual Kriging (STRK) method is applied to combine the estimated trend and residuals for the final prediction of the groundwater level.

The spatiotemporal trend variance is also carefully investigated due to the complex nature of its calculation. This is necessary in order to calculate STRK estimations variance. Therefore, a Bayesian approach based on the bootstrap idea is applied for the characterization of the prediction uncertainty. This approach considers the uncertainty of the spatiotemporal trend parameters and of the estimated spatiotemporal covariance function, by performing a simulation of the parameters and calculation in respect to STRK of the 5 and 95% prediction intervals.

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Functional Kriging for Probability Density Functions: A Bayes Space Approach

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Abstract

Functional Kriging for probability density functions: a Bayes space approach. We present a novel approach to kriging for probability density functions which combines the viewpoints of Functional Data Analysis and Compositional Data Analysis in Bayes spaces. Our theoretical framework allows characterizing and predicting random fields valued in the Bayes Hilbert space of functional compositions, possibly spatially non-stationary. We illustrate the potential of our approach through its application to a real case study dealing with particle-size data collected within a heterogeneous aquifer near Tubingen, Germany. Unlike traditional approaches, our methodology allows to transfer the entire information embedded within the densities to unsampled locations in the system.

Efficient Uncertainty Assessment Methods in Spatially Distributed Hydrogeological Models of Flow and Transport

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Abstract

In hydrogeological applications involving flow and transport of in heterogeneous porous media the spatial distribution of hydraulic conductivity is often parameterized in terms of a lognormal random field based on a histogram and variogram model inferred from data and/or synthesized from relevant knowledge. Realizations of simulated conductivity fields are then generated using geostatistical simulation involving simple random (SR) sampling and are subsequently used as inputs to physically-based simulators of flow and transport in a Monte Carlo framework for evaluating the uncertainty in the spatial distribution of solute concentration due to the uncertainty in the spatial distribution of hydraulic conductivity [1] Realistic uncertainty analysis, however, calls for a large number of simulated concentration fields; hence, can become expensive in terms of both time and computer resources. A more efficient alternative to SR sampling is Latin hypercube (LH) sampling, a special case of stratified random sampling, which yields a more representative distribution of simulated attribute values with fewer realizations [2]. Here, term representative implies realizations spanning efficiently the range of possible conductivity values corresponding to the lognormal random field.

In this presentation, we provide a brief overview of the research conducted in one of the work packages of the research project (2269) ``Advances in Geostatistics for Environmental Characterization and Natural Resources Management'' (GEOSTATENV), implemented within the framework of the Action «Aristeia I» of the Operational Program ``Education and Lifelong Learning'' (Action's Beneficiary: General Secretariat for Research and Technology), and co-financed by the European Social Fund (ESF) and the Greek State.

More precisely, we introduce a novel LH sampling method for efficiently generating realizations of second-order stationary lognormal random fields on large (order of million pixels) regular grids, thus overcoming the simulation domain limitations of existing LH sampling approaches, In addition, we present two alternative LH sampling methods, stratified likelihood (SL) [6,3] and minimum energy (ME) sampling [5] in which attribute realizations are generated using the polar simulation method by exploring the geometrical properties of the multivariate Gaussian distribution function. These latter sampling methods are further enhanced in a dimensionality reduction context by defining flow-controlling points over which representative sampling of hydraulic conductivity is performed, thus also accounting for the sensitivity of the flow and transport model to the input hydraulic conductivity field [4]. Via synthetic case studies, these different methods are compared to SR sampling in terms of reproduction of ensemble statistics of hydraulic conductivity and solute concentration for different sample sizes (numbers of simulated realizations). The results indicate that the proposed approaches are more efficient than SR sampling, in that they can better reproduce statistics of the conductivity and concentration fields, yet with smaller sampling variability than the latter.

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Spatiotemporal Covariance Models as a Basis for the Design of Effective Risk Management Tools

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Abstract

The essence of space-time covariance models (STCMs) is to describe spatial and dynamic properties of a stochastic quantity. This makes them of particular practical relevance in environmental application domains, such as the prediction of flood concurrence events, the early warning of peak flows in a dam site or the analysis of pollution diffusion patterns, where there is a strong interaction between the space and time components of the process of interest. The growing interest in renewable energy has also created new perspectives on STCMs beyond the classical environmental risk assessment. In this application domain, the understanding of the spatial and temporal evolution of the process of weather patterns is crucial for predicting more accurately the amount of renewable energy that will be available at each node of an electrical grid at a particular time period.

The purpose of this talk is to discuss how the information provided by STCMs can be efficiently utilized in the design of risk assessment tools and the management of energy resources. Several practical issues are demonstrated through two real-life case studies on the optimal harvesting of wind/ solar resources and the economic appraisal of a wind farm project.

Keywords: Space-time covariance models, risk management, power portfolio, project risk-assessment.

Modified Spin Model for Efficient Spatial Prediction

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Abstract

We introduce a novel spatial prediction method inspired from statistical physics for efficient estimation of missing data with general non-Gaussian distributions on partially sampled Cartesian grids. The prediction model is based on a classical XY (also called planar rotator) spin model, which is modified in order to allow an appropriate one-to-one transformation between the data and spin values and which displays relevant short-range correlations at low temperatures. The spatial correlations present in the data are captured in terms of nearest-neighbor interactions between the spin variables. The only parameter of the present model is the reduced temperature, which is estimated from the sample-based correlations. Having inferred the temperature, conditional Monte Carlo simulations honoring the sample values are performed on the entire lattice to bring the system into thermal equilibrium and subsequently collect prediction statistics. Owing to the fact that the model does not show undesirable critical slowing down, the relaxation process is rather fast and, furthermore, the short-range nature of the interactions allows vectorization of the algorithm. Consequently, the proposed method achieves almost linear scaling with system size, thus being much more efficient than the conventional geostatistical approaches and applicable to huge datasets, such as satellite and radar images.

Measurements and Structural Analysis of Masonry Monuments

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Abstract

Using modern techniques, like digital photogrammetry, laser scanners, optical recognition and penetrating radars, we are able to measure with high accuracy the geometry, crack or interface data as well as material parameters for masonry monuments. This information can be used efficiently within linear and nonlinear finite element analysis and inverse, parameter identification procedures for the evaluation of strength and stability of existing monuments. We are working in this direction, in cooperation with various colleagues in Greece and abroad. The ultimate goal is the creation of an automatic and seamless procedure that will allow for the concurent usage of the available hardware and software.

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Numerical Simulation of Grain Coarsening and Coalescence Process

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Abstract

A kinetic nonlinear model of mass transfer, grain coarsening and coalescence with potential applications in sintering processes is presented and studied. The model involves nonlinear ordinary differential equations that determine the transport of mass between grains. The rate of mass transfer is controlled by a mass-dependent Arrhenius factor leading to a nonlinear model of mass transfer and grain coarsening. The equilibrium points, which constitute nullclines of model, are determined and lead to different dynamic regimes. The dynamical system of coupled nonlinear differential equations with a random initial grain configuration is solved by means of the fourth-order Runge-Kutta method. For a comparison, the explicit Euler scheme is employed as well. The convergence error is investigated for both Runge-Kutta and Euler numerical methods.

The influence of the activation energy parameter on the different regimes is illustrated. An effective mass transfer simulation algorithm that involves coalescence for the multi-grain system is proposed. We incorporate coalescence of smaller grains with larger neighbors using a cellular automaton step in the evolution of the system. The Ostwald ripening formula is fitted to the grain's mean radius obtained by the grain coalescence and coarsening model. Numerical experiments are carried out and discussed for both normal and lognormal initial grain distributions.

Acknowledgments

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