NONLINEAR AND NONSTATIONARY SIGNAL PROCESSING

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Introduction

The programme "Nonlinear and Nonstationary Signal Processing" was held at the Isaac Newton Institute from July to December 1998. This programme was motivated by the observation that the whole field of signal processing and time series analysis has by now moved far beyond its roots in the theory of linear stationary processes, but many of the new techniques to handle nonlinear and nonstationary processes have developed in individual areas of statistics, engineering or more specialised fields such as environmental science or mathematical finance, with limited interaction between different groups. This programme brought together researchers from many different areas and with a wide range of expertise, resulting in a very successful synthesis of ideas. Particularly noteworthy achievements were new methodological developments and applications of wavelets, a wider appreciation of Bayesian methods, the interaction between nonlinear time series analysts and dynamical systems experts, and the development of new areas of application such as risk management in insurance and finance.

As part of the programme activities, five open workshops and a host of more informal meetings were held. The open workshops were on Bayesian statistics in signal processing, environmental modelling, the interaction between time series analysis and dynamical systems, statistical methods in finance, and data analysis with a particular emphasis on wavelet methods.

The chapters of this volume were all originally presented as talks at one of the workshops (and are divided into subsections according to the themes of those workshops), or are research contributions by long-stay participants in the programme.

Following the development of fast computers and sophisticated Monte Carlo simulation methods, the Bayesian community has been able to address more complex problems of Bayesian inference than was possible before. The chapter by Christophe Andrieu, Arnaud Doucet, Bill Fitzgerald and José Miguel Pérez, on Bayesian Computational Approaches to Model Selection, which is co-authored by the Programme's main organiser, Bill Fitzgerald, discusses some of the computational issues of this new approach and provides two examples which demonstrate how the resulting methodology can be used in stochastic model selection. The chapter first considers the state-of-the-art approaches to the problem of choosing prior distributions in the context of model selection. And it then goes on to describe numerical methods for computing Bayes factors and posterior model probabilities, concentrating on Markov Chain Monte Carlo (MCMC) methods and, in particular, the reversible jump MCMC method. The chapter concludes with two interesting examples that illustrate well the application of the methods: the detection of sinusoids in noise and the identification of the components in a Gaussian mixtures model.

There is much current interest in the development of sequential simulation methods with particular applications to Bayesian inference. Many of these ideas can be traced back to the control literature of the 1960s but due to computational restrictions at this time the methods were not really developed. The chapter by Neil Gordon, Alan Marrs and David Salmond, on sequential analysis of dynamic sytems using particle filters and mixtures, describes some of the theory, within a Bayesian framework, and introduces the ideas associated with particle filters and sequential MCMC methods. The chapter then goes on to consider three applications, concerning target tracking, in-situ ellipsometry for monitoring the growth of SiGe alloys and finally, the monitoring of chemical and nuclear agents as a function of space and time. These applications show the power of particle filters and sequential methods.

The current worldwide interest in environmental issues was reflected in the first workshop of the programme on Environmental Modelling and Data Analysis. The chapter by another of the programme organisers, Peter Young, gives excellent coverage of dynamic modelling for time variable and state dependent parameter estimation. This chapter starts by reviewing some of the author's previous and fundamental work concerning time variable and recursive parameter estimation and it is shown that if changes in parameters are functions of the state or input variables then the system can exhibit complex nonlinear behaviour, and this then requires state dependent modelling techniques, which are then covered in great detail in the chapter. The ideas associated with transfer function models and fixed interval smoothing for instrumental variable equations are introduced and the methodology is supported by various simulation examples starting with a simple first order time varying parameter model, then a forced logistic growth equation model, a chaotic logistic growth model and finally the so-called cosine map model, before moving onto the application of the methodology to the famous Nicholson blowfly data set where a totally new interpretation of the data is given.

One feature of the environmental workshop was the wide-ranging background of the participants. The chapter by Keith Beven, Jim Freer, Barry Hankin and Karsten Schulz is typical of the presentations made by scientists from different disciplines at the Workshop. Less mathematical than most of the chapters in the book, the authors concentrate on the important issues of uncertainty and over-parameterisation in large, mechanistic simulation models, with particular emphasis on hydrological systems. In relation to such large models, the chapter questions the concept of an optimum parameter set and proposes that this should be replaced by a concept they call 'equifinality'. This is intended to focus attention on the multiple possibilities for producing simulations that are, in some sense, 'acceptable', rather than optimum. The authors suggest that Beven's Bayesian Generalised Likelihood Uncertainty Estimation (GLUE) methodology allows the model builder and user to live with the problems of equifinality, and they present two practical examples which illustrate its application: the modelling of land surface to atmosphere fluxes, and dispersion in open channel flows.

The chapter by Richard Smith provides a very useful, partly tutorial, review of spatial statistics, but it has particular emphasis on the use of such methods in environmental applications. The first part of the chapter provides a general overview of the subject that covers specific methods of current interest. These include geostatistics and kriging, nonstationary models, models defined by conditional probabilities, the design of spatial experiments and spatio-temporal data issues. The second part of the chapter introduces a simplified, hierarchical model for spatially varying temporal trends and presents two applications of this approach. The first is concerned with spatial analysis of trends in global temperature series, and the second is based on sulphur dioxide measurements at 35 locations in the eastern US over the period 1989–1995.

The workshop on dynamical systems is represented by the chapter written by Alistair Mees. Mees's chapter addresses the problem of determining which components of an apparently unpredictable time series can be identified with a deterministic nonlinear system as opposed to stochastic noise. A particular feature of his approach is the use of criteria based on information theory. The concept of code length, originally due to Kolmogorov but developed independently by Wallace and Rissanen, is introduced as a unifying theme. This is first applied in the case of symbol strings, where the whole system can be represented as series of symbols from a finite alphabet. A key step here is the use of context trees to allow the system to be represented as a Markov chain, followed by estimation of the transition probabilities of that chain. The discussion then moves on to real-valued time series, including the use of embedding to allow this kind of system to be represented as a Markov chain, then estimating the transition relations through either local linear approximations or a radial basis function representation. As an example, a time series of firing voltage measurements from a squid giant axon is analysed using both the finite-alphabet and real-value methods. For finite-alphabet methods, Mees concludes that information theory is the key tool allowing efficient identification of the system. For real-valued time series, information-theoretic methods are also valuable but appreciation of the geometry of the system is another essential part of the reconstruction.

The workshop on statistical methods in finance is represented by two chapters. Tina Rydberg and Neil Shephard focus on the use of compound Poisson processes to model trade-by-trade data. Such data consist of jumps between discrete levels and so render traditional models for financial time series, such as geometric Brownian motion, inappropriate. Their proposal is to model the point process of jump times as a Cox process, together with a random process for the price changes which occur at the jumps. To illustrate their methods, they use electronically recorded IBM share price data from the New York Stock Exchange. Their basic model assumes an Ornstein–Uhlenbeck process to define the random intensity of the point process of trading times, combined with a first-order moving average process for the price changes. A particular feature is the use of signal-extraction methods to infer the unobserved random intensity process from the observed sequence of trading times. They also consider the consequences of their model for the distribution of returns over various time periods. They conclude that there are many features of the observed data which are well described by their model but they also highlight some aspects where more sophisticated modelling is required.

The second chapter on finance, by Richard Davis and Thomas Mikosch, focusses on the behaviour of sample autocorrelations in time series which may have both non-linear and heavy-tailed features. Examples such as the GARCH model, well-known in econometrics, often have both these features. For linear heavy-tailed processes, the sample autocorrelation function generally has attractive properties, for example, converging rapidly to a well-defined quantity even when the population autocorrelation does not exist. For nonlinear processes, however, there is no guarantee that the sample autocorrelation converges to anything as the sample size tends to infinity. The authors illustrate this possibility especially for ARCH and GARCH models, which they treat as a special case of the more general class of models satisfying stochastic recurrence equations. On the other hand, for stochastic volatility models, the behaviour of the sample autocorrelations is far more satisfactory. The results may provide some grounds for preferring the stochastic volatility models in practice, though the authors are careful to stress that conclusions of this nature need further research.

Time-frequency and wavelet methods formed an important theme in the programme.

Long-stay participant Patrick Flandrin illustrates in a clear and interesting way how tools for non-parametric time-frequency analysis can be motivated in a large number of different contexts, by considering representations of the signal, its energy or power, distribution or correlation, or by making use of probabilistic or geometrical properties. There are few existing time-frequency methodologies that are not covered in this comprehensive survey.

Metin Bayram and Richard Baraniuk (elected as Rosenbaum Fellow for the programme) give a new non-parametric method for estimating the time-varying spectrum of a nonstationary random process. The method extends Thomson's multiple window spectrum estimation method and works by averaging over sets of orthogonal, optimally concentrated windows – the Hermite functions for time-frequency analysis and the Morse wavelets for time-scale analysis. Nonstationary line components are detected and extracted by approximating them as piecewise linear chirps.

David Thomson, originator of the multiple window (or multitaper) spectrum estimation method, made two visits to the programme.

His chapter gives a number of multitaper approaches to the analysis of nonlinear and nonstationary time series with a viewpoint between those of statistics and signal processing; included are detailed analyses of the Central England temperature series and space physics data (magnetic fields and electron fluxes).

The data analysis workshop is further represented by two chapters on wavelet methods. The first, by Vasily Strela and Andrew Walden, looks at signal and image denoising via wavelet thresholding in the context of scalar and multiple wavelet transforms, using both scalar and vector thresholding. Multiwavelets outperform scalar wavelets for three out of four noisy 1D test signals, and are similarly generally preferable for the four 2D image denoising problems. Chui–Lian scaling functions and wavelets combined with repeated row preprocessing appears to be a good general method.

Don Percival, Sylvain Sardy and Anthony Davison consider the problem of decorrelating random processes using wavelet methods. They achieve this by adaptively selecting an orthonormal transform from a wavelet packet table using a series of white noise tests. Having thus obtained transform coefficients with very low correlations, they create new sets of coefficients by bootstrapping; these are then inverse transformed to create bootstrapped time series, from which distributions of statistical quantities of interest can be calculated. This innovative procedure is given the name 'wavestrapping'.

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