Springer Series in Statistics

Peter J. Brockwell, Richard A. Davis

Time Series: Theory and Methods

Second Edition

时间序列的理论与方法

第2版

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To our families .

Preface to the Second Edition

This edition contains a large number of additions and corrections scattered throughout the text, including the incorporation of a new chapter on state-space models. The companion diskette for the IBM PC has expanded into the software package *ITSM: An Interactive Time Series Modelling Package for the PC*, which includes a manual and can be ordered from Springer-Verlag.*

We are indebted to many readers who have used the book and programs and made suggestions for improvements. Unfortunately there is not enough space to acknowledge all who have contributed in this way; however, special mention must be made of our prize-winning fault-finders, Sid Resnick and F. Pukelsheim. Special mention should also be made of Anthony Brockwell, whose advice and support on computing matters was invaluable in the preparation of the new diskettes. We have been fortunate to work on the new edition in the excellent environments provided by the University of Melbourne and Colorado State University. We thank Duane Boes particularly for his support and encouragement throughout, and the Australian Research Council and National Science Foundation for their support of research related to the new material. We are also indebted to Springer-Verlag for their constant support and assistance in preparing the second edition.

Fort Collins, Colorado
November, 1990

P.J. Brockwell
R.A. Davis

* *ITSM: An Interactive Time Series Modelling Package for the PC* by P.J. Brockwell and R.A. Davis. ISBN: 0-387-97482-2; 1991.

Note added in the eighth printing: The computer programs referred to in the text have now been superseded by the package ITSM2000, the student version of which accompanies our other text, *Introduction to Time Series and Forecasting*, also published by Springer-Verlag. Enquiries regarding purchase of the professional version of this package should be sent to pjbrockwell@cs.com.

Preface to the First Edition

We have attempted in this book to give a systematic account of linear time series models and their application to the modelling and prediction of data collected sequentially in time. The aim is to provide specific techniques for handling data and at the same time to provide a thorough understanding of the mathematical basis for the techniques. Both time and frequency domain methods are discussed but the book is written in such a way that either approach could be emphasized. The book is intended to be a text for graduate students in statistics, mathematics, engineering, and the natural or social sciences. It has been used both at the M.S. level, emphasizing the more practical aspects of modelling, and at the Ph.D. level, where the detailed mathematical derivations of the deeper results can be included.

Distinctive features of the book are the extensive use of elementary Hilbert space methods and recursive prediction techniques based on innovations, use of the exact Gaussian likelihood and AIC for inference, a thorough treatment of the asymptotic behavior of the maximum likelihood estimators of the coefficients of univariate ARMA models, extensive illustrations of the techniques by means of numerical examples, and a large number of problems for the reader. The companion diskette contains programs written for the IBM PC, which can be used to apply the methods described in the text. Data sets can be found in the Appendix, and a more extensive collection (including most of those used for the examples in Chapters 1, 9, 10, 11 and 12) is on the diskette. Simulated ARMA series can easily be generated and filed using the program PEST. Valuable sources of additional time-series data are the collections of Makridakis et al. (1984) and Working Paper 109 (1984) of Scientific Computing Associates, DeKalb, Illinois.

Most of the material in the book is by now well-established in the time series literature and we have therefore not attempted to give credit for all the results discussed. Our indebtedness to the authors of some of the well-known existing books on time series, in particular Anderson, Box and Jenkins, Fuller, Grenander and Rosenblatt, Hannan, Koopmans and Priestley will however be apparent. We were also fortunate to have access to notes on time series by W. Dunsmuir. To these and to the many other sources that have influenced our presentation of the subject we express our thanks.

Recursive techniques based on the Kalman filter and state-space representations of ARMA processes have played an important role in many recent developments in time series analysis. In particular the Gaussian likelihood of a time series can be expressed very simply in terms of the one-step linear predictors and their mean squared errors, both of which can be computed recursively using a Kalman filter. Instead of using a state-space representation for recursive prediction we utilize the innovations representation of an arbitrary Gaussian time series in order to compute best linear predictors and exact Gaussian likelihoods. This approach, developed by Rissanen and Barbosa, Kailath, Ansley and others, expresses the value of the series at time t in terms of the one-step prediction errors up to that time. This representation provides insight into the structure of the time series itself as well as leading to simple algorithms for simulation, prediction and likelihood calculation.

These algorithms are used in the parameter estimation program (PEST) found on the companion diskette. Given a data set of up to 2300 observations, the program can be used to find preliminary, least squares and maximum Gaussian likelihood estimators of the parameters of any prescribed ARIMA model for the data, and to predict future values. It can also be used to simulate values of an ARMA process and to compute and plot its theoretical autocovariance and spectral density functions. Data can be plotted, differenced, deseasonalized and detrended. The program will also plot the sample autocorrelation and partial autocorrelation functions of both the data itself and the residuals after model-fitting. The other time-series programs are SPEC, which computes spectral estimates for univariate or bivariate series based on the periodogram, and TRANS, which can be used either to compute and plot the sample cross-correlation function of two series, or to perform least squares estimation of the coefficients in a transfer function model relating the second series to the first (see Section 12.2). Also included on the diskette is a screen editing program (WORD6), which can be used to create arbitrary data files, and a collection of data files, some of which are analyzed in the book. Instructions for the use of these programs are contained in the file HELP on the diskette.

For a one-semester course on time-domain analysis and modelling at the M.S. level, we have used the following sections of the book:

1.1–1.6; 2.1–2.7; 3.1–3.5; 5.1–5.5; 7.1, 7.2; 8.1–8.9; 9.1–9.6

(with brief reference to Sections 4.2 and 4.4). The prerequisite for this course is a knowledge of probability and statistics at the level of the book *Introduction to the Theory of Statistics* by Mood, Graybill and Boes.

For a second semester, emphasizing frequency-domain analysis and multivariate series, we have used

4.1–4.4, 4.6–4.10; 10.1–10.7; 11.1–11.7; selections from Chap. 12.

At the M.S. level it has not been possible (or desirable) to go into the mathematical derivation of all the results used, particularly those in the starred sections, which require a stronger background in mathematical analysis and measure theory. Such a background is assumed in all of the starred sections and problems.

For Ph.D. students the book has been used as the basis for a more theoretical one-semester course covering the starred sections from Chapters 4 through 11 and parts of Chapter 12. The prerequisite for this course is a knowledge of measure-theoretic probability.

We are greatly indebted to E.J. Hannan, R.H. Jones, S.I. Resnick, S.Tavaré and D. Tjøstheim, whose comments on drafts of Chapters 1–8 led to substantial improvements. The book arose out of courses taught in the statistics department at Colorado State University and benefitted from the comments of many students. The development of the computer programs would not have been possible without the outstanding work of Joe Mandarino, the architect of the computer program PEST, and Anthony Brockwell, who contributed WORD6, graphics subroutines and general computing expertise. We are indebted also to the National Science Foundation for support for the research related to the book, and one of us (P.J.B.) to Kuwait University for providing an excellent environment in which to work on the early chapters. For permission to use the optimization program UNC22MIN we thank R. Schnabel of the University of Colorado computer science department. Finally we thank Pam Brockwell, whose contributions to the manuscript went far beyond those of typist, and the editors of Springer-Verlag, who showed great patience and cooperation in the final production of the book.

Fort Collins, Colorado
October 1986

P.J. Brockwell
R.A. Davis

Contents

CHAPTER 1

Stationary Time Series

In this chapter we introduce some basic ideas of time series analysis and stochastic processes. Of particular importance are the concepts of stationarity and the autocovariance and sample autocovariance functions. Some standard techniques are described for the estimation and removal of trend and seasonality (of known period) from an observed series. These are illustrated with reference to the data sets in Section 1.1. Most of the topics covered in this chapter will be developed more fully in later sections of the book. The reader who is not already familiar with random vectors and multivariate analysis should first read Section 1.6 where a concise account of the required background is given. Notice our convention that an n-dimensional random vector is assumed (unless specified otherwise) to be a column vector $\mathbf{X} = (X_1, X_2, \ldots, X_n)'$ of random variables. If S is an arbitrary set then we shall use the notation S^n to denote both the set of n-component column vectors with components in S and the set of n-component row vectors with components in S.

§1.1 Examples of Time Series

A time series is a set of observations x_t, each one being recorded at a specified time t. A discrete-time series (the type to which this book is primarily devoted) is one in which the set T_0 of times at which observations are made is a discrete set, as is the case for example when observations are made at fixed time intervals. Continuous-time series are obtained when observations are recorded continuously over some time interval, e.g. when $T_0 = [0, 1]$. We shall use the notation $x(t)$ rather than x_t if we wish to indicate specifically that observations are recorded continuously.

EXAMPLE 1.1.1 (Current Through a Resistor). If a sinusoidal voltage $v(t) = a\cos(\nu t + \theta)$ is applied to a resistor of resistance r and the current recorded continuously we obtain a continuous time series

$$x(t) = r^{-1} a\cos(\nu t + \theta).$$

If observations are made only at times 1, 2, ..., the resulting time series will be discrete. Time series of this particularly simple type will play a fundamental role in our later study of stationary time series.

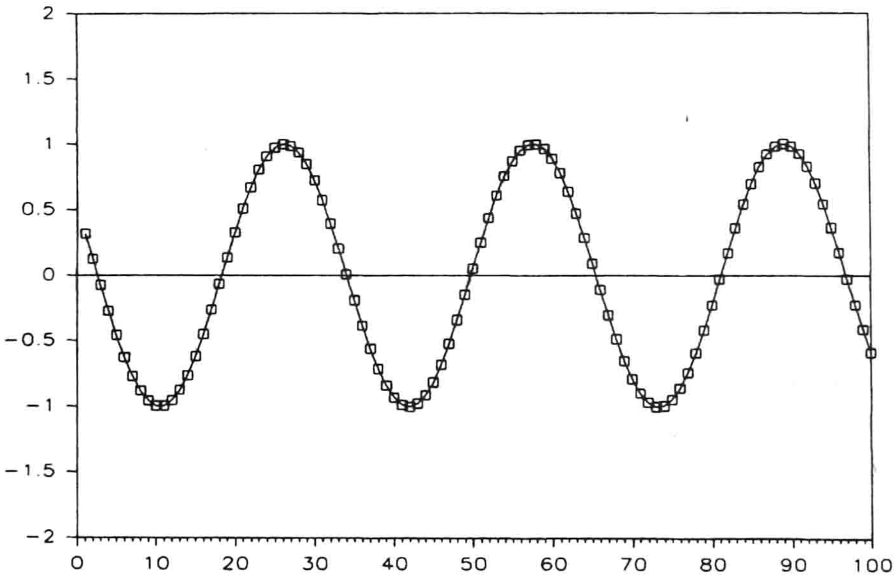

Figure 1.1. 100 observations of the series $x(t) = \cos(.2t + \pi/3)$.

EXAMPLE 1.1.2 (Population x_t of the U.S.A., 1790–1980).

t	x_t	t	x_t
1790	3,929,214	1890	62,979,766
1800	5,308,483	1900	76,212,168
1810	7,239,881	1910	92,228,496
1820	9,638,453	1920	106,021,537
1830	12,860,702	1930	123,202,624
1840	17,063,353	1940	132,164,569
1850	23,191,876	1950	151,325,798
1860	31,443,321	1960	179,323,175
1870	38,558,371	1970	203,302,031
1880	50,189,209	1980	226,545,805

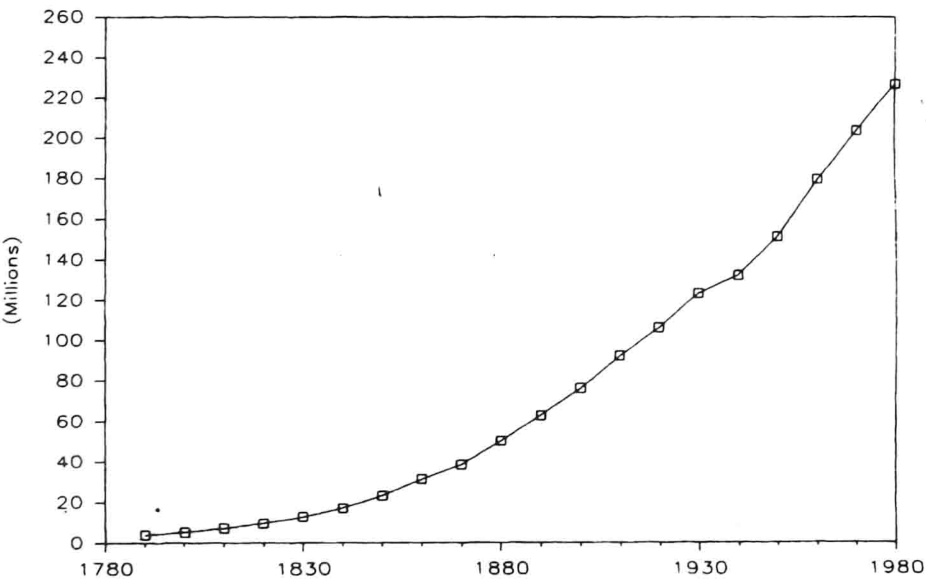

Figure 1.2. Population of the U.S.A. at ten-year intervals, 1790–1980 (U.S. Bureau of the Census).