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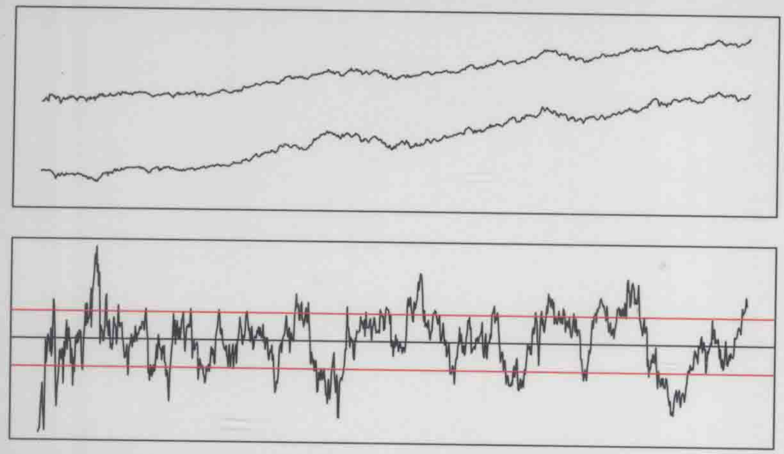
Analysis of
FINANCIAL TIME SERIES

THIRD EDITION



RUEY S. TSAY

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Analysis of Financial Time Series

Third Edition

RUEY S. TSAY

The University of Chicago
Booth School of Business
Chicago, IL

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To Teresa and my father, and in memory of my mother

Preface

As many countries struggle to recover from the recent global financial crisis, one thing clear is that we do not want to suffer another crisis like this in the future. We must study the past in order to prevent future financial crisis. Financial data of the past few years thus become important in empirical study. The primary objective of the revision is to update the data used and to reanalyze the examples so that one can better understand the properties of asset returns. At the same time, we also witness many new developments in financial econometrics and financial software packages. In particular, the Rmetrics now has many packages for analyzing financial time series. The second goal of the revision is to include R commands and demonstrations, making it possible and easier for readers to reproduce the results shown in the book.

Collapses of big financial institutions during the crisis show that extreme events occur in clusters; they are not independent. To deal with dependence in extremes, I include the extremal index in Chapter 7 and discuss its impact on value at risk. I also rewrite Chapter 7 to make it easier to understand and more complete. It now contains the expected shortfall, or conditional value at risk, for measuring finanical risk.

Substantial efforts are made to draw a balance between the length and coverage of the book. I do not include credit risk or operational risk in this revision for three reasons. First, effective methods for assessing credit risk require further study. Second, the data are not widely available. Third, the length of the book is approaching my limit.

A brief summary of the added material in the third edition is:

1. To update the data used throughout the book.
2. To provide R commands and demonstrations. In some cases, R programs are given.
3. To reanalyze many examples with updated observations.
4. To introduce skew distributions for volatility modeling in Chapter 3.
5. To investigate properties of recent high-frequency trading data and to add applications of nonlinear duration models in Chapter 5.

6. To provide a unified approach to value at risk (VaR) via loss function, to discuss expected shortfall (ES), or equivalently the conditional value at risk (CVaR), and to introduce extremal index for dependence data in Chapter 7.
7. To discuss application of cointegration to pairs trading in Chapter 8.
8. To study applications of dynamic correlation models in Chapter 10.

I benefit greatly from constructive comments of many readers of the second edition, including students, colleagues, and friends. I am indebted to them all. In particular, I like to express my sincere thanks to Spencer Graves for creating the FinTS package for R and Tom Doan of ESTIMA and Eugene Gath for careful reading of the text. I also thank Kam Hamidieh for suggestions concerning new topics for the revision. I also like to thank colleagues at Wiley, especially Jackie Palmieri and Stephen Quigley, for their support. As always, the revision would not be possible without the constant encouragement and unconditional love of my wife and children. They are my motivation and source of energy. Part of my research is supported by the Booth School of Business, University of Chicago.

Finally, the website for the book is:

`http://faculty.chicagobooth.edu/ruey.tsay/teaching/fts3.`

Ruey S. Tsay

Booth School of Business, University of Chicago
Chicago, Illinois

Preface to the Second Edition

The subject of *financial time series analysis* has attracted substantial attention in recent years, especially with the 2003 Nobel awards to Professors Robert Engle and Clive Granger. At the same time, the field of financial econometrics has undergone various new developments, especially in high-frequency finance, stochastic volatility, and software availability. There is a need to make the material more complete and accessible for advanced undergraduate and graduate students, practitioners, and researchers. The main goals in preparing this second edition have been to bring the book up to date both in new developments and empirical analysis, and to enlarge the core material of the book by including consistent covariance estimation under heteroscedasticity and serial correlation, alternative approaches to volatility modeling, financial factor models, state-space models, Kalman filtering, and estimation of stochastic diffusion models.

The book therefore has been extended to 12 chapters and substantially revised to include S-Plus commands and illustrations. Many empirical demonstrations and exercises are updated so that they include the most recent data.

The two new chapters are Chapter 9, Principal Component Analysis and Factor Models, and Chapter 11, State-Space Models and Kalman Filter. The factor models discussed include macroeconomic, fundamental, and statistical factor models. They are simple and powerful tools for analyzing high-dimensional financial data such as portfolio returns. Empirical examples are used to demonstrate the applications. The state-space model and Kalman filter are added to demonstrate their applicability in finance and ease in computation. They are used in Chapter 12 to estimate stochastic volatility models under the general Markov chain Monte Carlo (MCMC) framework. The estimation also uses the technique of forward filtering and backward sampling to gain computational efficiency.

A brief summary of the added material in the second edition is:

1. To update the data used throughout the book.
2. To provide S-Plus commands and demonstrations.

3. To consider unit-root tests and methods for consistent estimation of the covariance matrix in the presence of conditional heteroscedasticity and serial correlation in Chapter 2.
4. To describe alternative approaches to volatility modeling, including use of high-frequency transactions data and daily high and low prices of an asset in Chapter 3.
5. To give more applications of nonlinear models and methods in Chapter 4.
6. To introduce additional concepts and applications of value at risk in Chapter 7.
7. To discuss cointegrated vector AR models in Chapter 8.
8. To cover various multivariate volatility models in Chapter 10.
9. To add an effective MCMC method for estimating stochastic volatility models in Chapter 12.

The revision benefits greatly from constructive comments of colleagues, friends, and many readers of the first edition. I am indebted to them all. In particular, I thank J. C. Artigas, Spencer Graves, Chung-Ming Kuan, Henry Lin, Daniel Peña, Jeff Russell, Michael Steele, George Tiao, Mark Wohar, Eric Zivot, and students of my MBA classes on financial time series for their comments and discussions and Rosalyn Farkas for editorial assistance. I also thank my wife and children for their unconditional support and encouragements. Part of my research in financial econometrics is supported by the National Science Foundation, the High-Frequency Finance Project of the Institute of Economics, Academia Sinica, and the Graduate School of Business, University of Chicago.

Finally, the website for the book is:

`gsbwww.uchicago.edu/fac/ruey.tsay/teaching/fts2.`

Ruey S. Tsay

University of Chicago
Chicago, Illinois

Preface to the First Edition

This book grew out of an MBA course in analysis of financial time series that I have been teaching at the University of Chicago since 1999. It also covers materials of Ph.D. courses in time series analysis that I taught over the years. It is an introductory book intended to provide a comprehensive and systematic account of financial econometric models and their application to modeling and prediction of financial time series data. The goals are to learn basic characteristics of financial data, understand the application of financial econometric models, and gain experience in analyzing financial time series.

The book will be useful as a text of time series analysis for MBA students with finance concentration or senior undergraduate and graduate students in business, economics, mathematics, and statistics who are interested in financial econometrics. The book is also a useful reference for researchers and practitioners in business, finance, and insurance facing value at risk calculation, volatility modeling, and analysis of serially correlated data.

The distinctive features of this book include the combination of recent developments in financial econometrics in the econometric and statistical literature. The developments discussed include the timely topics of value at risk (VaR), high-frequency data analysis, and Markov chain Monte Carlo (MCMC) methods. In particular, the book covers some recent results that are yet to appear in academic journals; see Chapter 6 on derivative pricing using jump diffusion with closed-form formulas, Chapter 7 on value at risk calculation using extreme value theory based on a nonhomogeneous two-dimensional Poisson process, and Chapter 9 on multivariate volatility models with time-varying correlations. MCMC methods are introduced because they are powerful and widely applicable in financial econometrics. These methods will be used extensively in the future.

Another distinctive feature of this book is the emphasis on real examples and data analysis. Real financial data are used throughout the book to demonstrate applications of the models and methods discussed. The analysis is carried out by using several computer packages; the SCA (the Scientific Computing Associates) for building linear time series models, the RATS (regression analysis for time series)

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for estimating volatility models, and the S-Plus for implementing neural networks and obtaining postscript plots. Some commands required to run these packages are given in appendixes of appropriate chapters. In particular, complicated RATS programs used to estimate multivariate volatility models are shown in Appendix A of Chapter 9. Some Fortran programs written by myself and others are used to price simple options, estimate extreme value models, calculate VaR, and carry out Bayesian analysis. Some data sets and programs are accessible from the World Wide Web at http://www.gsb.uchicago.edu/fac/ruey.tsay/teaching/fts.

The book begins with some basic characteristics of financial time series data in Chapter 1. The other chapters are divided into three parts. The first part, consisting of Chapters 2 to 7, focuses on analysis and application of univariate financial time series. The second part of the book covers Chapters 8 and 9 and is concerned with the return series of multiple assets. The final part of the book is Chapter 10, which introduces Bayesian inference in finance via MCMC methods.

A knowledge of basic statistical concepts is needed to fully understand the book. Throughout the chapters, I have provided a brief review of the necessary statistical concepts when they first appear. Even so, a prerequisite in statistics or business statistics that includes probability distributions and linear regression analysis is highly recommended. A knowledge of finance will be helpful in understanding the applications discussed throughout the book. However, readers with advanced background in econometrics and statistics can find interesting and challenging topics in many areas of the book.

An MBA course may consist of Chapters 2 and 3 as a core component, followed by some nonlinear methods (e.g., the neural network of Chapter 4 and the applications discussed in Chapters 5–7 and 10). Readers who are interested in Bayesian inference may start with the first five sections of Chapter 10.

Research in financial time series evolves rapidly and new results continue to appear regularly. Although I have attempted to provide broad coverage, there are many subjects that I do not cover or can only mention in passing.

I sincerely thank my teacher and dear friend, George C. Tiao, for his guidance, encouragement, and deep conviction regarding statistical applications over the years. I am grateful to Steve Quigley, Heather Haselkorn, Leslie Galen, Danielle LaCouriere, and Amy Hendrickson for making the publication of this book possible, to Richard Smith for sending me the estimation program of extreme value theory, to Bonnie K. Ray for helpful comments on several chapters, to Steve Kou for sending me his preprint on jump diffusion models, to Robert E. McCulloch for many years of collaboration on MCMC methods, to many students in my courses on analysis of financial time series for their feedback and inputs, and to Jeffrey Russell and Michael Zhang for insightful discussions concerning analysis of high-frequency financial data. To all these wonderful people I owe a deep sense of gratitude. I am also grateful for the support of the Graduate School of Business, University of Chicago and the National Science Foundation. Finally, my heartfelt thanks to my wife, Teresa, for her continuous support, encouragement, and understanding; to Julie, Richard, and Vicki for bringing me joy and inspirations; and to my parents for their love and care.

R. S. T.

Chicago, Illinois

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