

The Volatility Surface

A Practitioner's Guide

JIM GATHERAL

Foreword by Nassim Nicholas Taleb



WILEY

John Wiley & Sons, Inc.

Further Praise for *The Volatility Surface*

“As an experienced practitioner, Jim Gatheral succeeds admirably in combining an accessible exposition of the foundations of stochastic volatility modeling with valuable guidance on the calibration and implementation of leading volatility models in practice.”

—Eckhard Platen, Chair in Quantitative Finance, University of Technology, Sydney

“Dr. Jim Gatheral is one of Wall Street’s very best regarding the practical use and understanding of volatility modeling. *The Volatility Surface* reflects his in-depth knowledge about local volatility, stochastic volatility, jumps, the dynamic of the volatility surface and how it affects standard options, exotic options, variance and volatility swaps, and much more. If you are interested in volatility and derivatives, you need this book!

—Espen Gaarder Haug, option trader, and author to *The Complete Guide to Option Pricing Formulas*

“Anybody who is interested in going beyond Black-Scholes should read this book. And anybody who is not interested in going beyond Black-Scholes isn’t going far!”

—Mark Davis, Professor of Mathematics, Imperial College London

“This book provides a comprehensive treatment of subjects essential for anyone working in the field of option pricing. Many technical topics are presented in an elegant and intuitively clear way. It will be indispensable not only at trading desks but also for teaching courses on modern derivatives and will definitely serve as a source of inspiration for new research.”

—Anna Shepeleva, Vice President, ING Group

Founded in 1807, John Wiley & Sons is the oldest independent publishing company in the United States. With offices in North America, Europe, Australia, and Asia, Wiley is globally committed to developing and marketing print and electronic products and services for our customers' professional and personal knowledge and understanding.

The Wiley Finance series contains books written specifically for finance and investment professionals as well as sophisticated individual investors and their financial advisors. Book topics range from portfolio management to e-commerce, risk management, financial engineering, valuation, and financial instrument analysis, as well as much more.

For a list of available titles, please visit our Web site at www.WileyFinance.com.

The Volatility Surface

A Practitioner's Guide

JIM GATHERAL

Foreword by Nassim Nicholas Taleb



WILEY

John Wiley & Sons, Inc.

Copyright © 2006 by Jim Gatheral. All rights reserved.

Published by John Wiley & Sons, Inc., Hoboken, New Jersey.
Published simultaneously in Canada.

No part of this publication may be reproduced, stored in a retrieval system, or transmitted in any form or by any means, electronic, mechanical, photocopying, recording, scanning, or otherwise, except as permitted under Section 107 or 108 of the 1976 United States Copyright Act, without either the prior written permission of the Publisher, or authorization through payment of the appropriate per-copy fee to the Copyright Clearance Center, Inc., 222 Rosewood Drive, Danvers, MA 01923, (978) 750-8400, fax (978) 646-8600, or on the Web at www.copyright.com. Requests to the Publisher for permission should be addressed to the Permissions Department, John Wiley & Sons, Inc., 111 River Street, Hoboken, NJ 07030, (201) 748-6011, fax (201) 748-6008, or online at <http://www.wiley.com/go/permission>.

Limit of Liability/Disclaimer of Warranty: While the publisher and author have used their best efforts in preparing this book, they make no representations or warranties with respect to the accuracy or completeness of the contents of this book and specifically disclaim any implied warranties of merchantability or fitness for a particular purpose. No warranty may be created or extended by sales representatives or written sales materials. The advice and strategies contained herein may not be suitable for your situation. You should consult with a professional where appropriate. Neither the publisher nor author shall be liable for any loss of profit or any other commercial damages, including but not limited to special, incidental, consequential, or other damages.

For general information on our other products and services or for technical support, please contact our Customer Care Department within the United States at (800) 762-2974, outside the United States at (317) 572-3993 or fax (317) 572-4002.

Wiley also publishes its books in a variety of electronic formats. Some content that appears in print may not be available in electronic formats. For more information about Wiley products, visit our Web site at www.wiley.com.

ISBN-13 978-0-471-79251-2

ISBN-10 0-471-79251-9

Library of Congress Cataloging-in-Publication Data:

Gatheral, Jim, 1957–

The volatility surface : a practitioner's guide / by Jim Gatheral ; foreword by Nassim Nicholas Taleb.

p. cm.—(Wiley finance series)

Includes index.

ISBN-13: 978-0-471-79251-2 (cloth)

ISBN-10: 0-471-79251-9 (cloth)

1. Options (Finance)—Prices—Mathematical models. 2. Stocks—Prices—Mathematical models. I. Title. II. Series.

HG6024. A3G38 2006

332.63'2220151922—dc22

2006009977

Printed in the United States of America.

10 9 8 7 6 5 4 3 2 1

To Yukiko and Ayako

Contents

| | |
|--|--------------|
| List of Figures | xiii |
| List of Tables | xix |
| Foreword | xxi |
| Preface | xxiii |
| Acknowledgments | xxvii |
| CHAPTER 1 | |
| Stochastic Volatility and Local Volatility | 1 |
| Stochastic Volatility | 1 |
| Derivation of the Valuation Equation | 4 |
| Local Volatility | 7 |
| History | 7 |
| A Brief Review of Dupire's Work | 8 |
| Derivation of the Dupire Equation | 9 |
| Local Volatility in Terms of Implied Volatility | 11 |
| Special Case: No Skew | 13 |
| Local Variance as a Conditional Expectation of Instantaneous Variance | 13 |
| CHAPTER 2 | |
| The Heston Model | 15 |
| The Process | 15 |
| The Heston Solution for European Options | 16 |
| A Digression: The Complex Logarithm in the Integration (2.13) | 19 |
| Derivation of the Heston Characteristic Function | 20 |
| Simulation of the Heston Process | 21 |
| Milstein Discretization | 22 |
| Sampling from the Exact Transition Law | 23 |
| Why the Heston Model Is so Popular | 24 |

| | | |
|---|--|-----------|
| CHAPTER 3 | | |
| The Implied Volatility Surface | | 25 |
| Getting Implied Volatility from Local Volatilities | | 25 |
| Model Calibration | | 25 |
| Understanding Implied Volatility | | 26 |
| Local Volatility in the Heston Model | | 31 |
| Ansatz | | 32 |
| Implied Volatility in the Heston Model | | 33 |
| The Term Structure of Black-Scholes Implied Volatility in the Heston Model | | 34 |
| The Black-Scholes Implied Volatility Skew in the Heston Model | | 35 |
| The SPX Implied Volatility Surface | | 36 |
| Another Digression: The SVI Parameterization | | 37 |
| A Heston Fit to the Data | | 40 |
| Final Remarks on SV Models and Fitting the Volatility Surface | | 42 |
| | | |
| CHAPTER 4 | | |
| The Heston-Nandi Model | | 43 |
| Local Variance in the Heston-Nandi Model | | 43 |
| A Numerical Example | | 44 |
| The Heston-Nandi Density | | 45 |
| Computation of Local Volatilities | | 45 |
| Computation of Implied Volatilities | | 46 |
| Discussion of Results | | 49 |
| | | |
| CHAPTER 5 | | |
| Adding Jumps | | 50 |
| Why Jumps are Needed | | 50 |
| Jump Diffusion | | 52 |
| Derivation of the Valuation Equation | | 52 |
| Uncertain Jump Size | | 54 |
| Characteristic Function Methods | | 56 |
| Lévy Processes | | 56 |
| Examples of Characteristic Functions for Specific Processes | | 57 |
| Computing Option Prices from the Characteristic Function | | 58 |
| Proof of (5.6) | | 58 |

| | |
|---|----|
| Computing Implied Volatility | 60 |
| Computing the At-the-Money Volatility Skew | 60 |
| How Jumps Impact the Volatility Skew | 61 |
| Stochastic Volatility Plus Jumps | 65 |
| Stochastic Volatility Plus Jumps in the Underlying Only (SVJ) | 65 |
| Some Empirical Fits to the SPX Volatility Surface | 66 |
| Stochastic Volatility with Simultaneous Jumps in Stock Price and Volatility (SVJJ) | 68 |
| SVJ Fit to the September 15, 2005, SPX Option Data | 71 |
| Why the SVJ Model Wins | 73 |

CHAPTER 6**Modeling Default Risk 74**

| | |
|--|----|
| Merton's Model of Default | 74 |
| Intuition | 75 |
| Implications for the Volatility Skew | 76 |
| Capital Structure Arbitrage | 77 |
| Put-Call Parity | 77 |
| The Arbitrage | 78 |
| Local and Implied Volatility in the Jump-to-Ruin Model | 79 |
| The Effect of Default Risk on Option Prices | 82 |
| The CreditGrades Model | 84 |
| Model Setup | 84 |
| Survival Probability | 85 |
| Equity Volatility | 86 |
| Model Calibration | 86 |

CHAPTER 7**Volatility Surface Asymptotics 87**

| | |
|--|-----|
| Short Expirations | 87 |
| The Medvedev-Scaillet Result | 89 |
| The SABR Model | 91 |
| Including Jumps | 93 |
| Corollaries | 94 |
| Long Expirations: Fouque, Papanicolaou, and Sircar | 95 |
| Small Volatility of Volatility: Lewis | 96 |
| Extreme Strikes: Roger Lee | 97 |
| Example: Black-Scholes | 99 |
| Stochastic Volatility Models | 99 |
| Asymptotics in Summary | 100 |

| | |
|---|------------|
| CHAPTER 8 | |
| Dynamics of the Volatility Surface | 101 |
| Dynamics of the Volatility Skew under Stochastic Volatility | 101 |
| Dynamics of the Volatility Skew under Local Volatility | 102 |
| Stochastic Implied Volatility Models | 103 |
| Digital Options and Digital Cliquets | 103 |
| Valuing Digital Options | 104 |
| Digital Cliquets | 104 |
| CHAPTER 9 | |
| Barrier Options | 107 |
| Definitions | 107 |
| Limiting Cases | 108 |
| Limit Orders | 108 |
| European Capped Calls | 109 |
| The Reflection Principle | 109 |
| The Lookback Hedging Argument | 112 |
| One-Touch Options Again | 113 |
| Put-Call Symmetry | 113 |
| QuasiStatic Hedging and Qualitative Valuation | 114 |
| Out-of-the-Money Barrier Options | 114 |
| One-Touch Options | 115 |
| Live-Out Options | 116 |
| Lookback Options | 117 |
| Adjusting for Discrete Monitoring | 117 |
| Discretely Monitored Lookback Options | 119 |
| Parisian Options | 120 |
| Some Applications of Barrier Options | 120 |
| Ladders | 120 |
| Ranges | 120 |
| Conclusion | 121 |
| CHAPTER 10 | |
| Exotic Cliquets | 122 |
| Locally Capped Globally Floored Cliquet | 122 |
| Valuation under Heston and Local | |
| Volatility Assumptions | 123 |
| Performance | 124 |
| Reverse Cliquet | 125 |

| | |
|--|-----|
| Valuation under Heston and Local Volatility Assumptions | 126 |
| Performance | 127 |
| Napoleon | 127 |
| Valuation under Heston and Local Volatility Assumptions | 128 |
| Performance | 130 |
| Investor Motivation | 130 |
| More on Napoleons | 131 |

CHAPTER 11
Volatility Derivatives **133**

| | |
|--|-----|
| Spanning Generalized European Payoffs | 133 |
| Example: European Options | 134 |
| Example: Amortizing Options | 135 |
| The Log Contract | 135 |
| Variance and Volatility Swaps | 136 |
| Variance Swaps | 137 |
| Variance Swaps in the Heston Model | 138 |
| Dependence on Skew and Curvature | 138 |
| The Effect of Jumps | 140 |
| Volatility Swaps | 143 |
| Convexity Adjustment in the Heston Model | 144 |
| Valuing Volatility Derivatives | 146 |
| Fair Value of the Power Payoff | 146 |
| The Laplace Transform of Quadratic Variation under Zero Correlation | 147 |
| The Fair Value of Volatility under Zero Correlation | 149 |
| A Simple Lognormal Model | 151 |
| Options on Volatility: More on Model Independence | 154 |
| Listed Quadratic-Variation Based Securities | 156 |
| The VIX Index | 156 |
| VXB Futures | 158 |
| Knock-on Benefits | 160 |
| Summary | 161 |

Postscript **162**

Bibliography **163**

Index **169**

Figures

- 1.1 SPX daily log returns from December 31, 1984, to December 31, 2004. Note the -22.9% return on October 19, 1987! 2
- 1.2 Frequency distribution of (77 years of) SPX daily log returns compared with the normal distribution. Although the -22.9% return on October 19, 1987, is not directly visible, the x-axis has been extended to the left to accommodate it! 3
- 1.3 Q-Q plot of SPX daily log returns compared with the normal distribution. Note the extreme tails. 3

- 3.1 Graph of the pdf of x_t conditional on $x_T = \log(K)$ for a 1-year European option, strike 1.3 with current stock price = 1 and 20% volatility. 31
- 3.2 Graph of the SPX-implied volatility surface as of the close on September 15, 2005, the day before triple witching. 36
- 3.3 Plots of the SVI fits to SPX implied volatilities for each of the eight listed expirations as of the close on September 15, 2005. Strikes are on the x -axes and implied volatilities on the y -axes. The black and grey diamonds represent bid and offer volatilities respectively and the solid line is the SVI fit. 38
- 3.4 Graph of SPX ATM skew versus time to expiry. The solid line is a fit of the approximate skew formula (3.21) to all empirical skew points except the first; the dashed fit excludes the first three data points. 39
- 3.5 Graph of SPX ATM variance versus time to expiry. The solid line is a fit of the approximate ATM variance formula (3.18) to the empirical data. 40
- 3.6 Comparison of the empirical SPX implied volatility surface with the Heston fit as of September 15, 2005. From the two views presented here, we can see that the Heston fit is pretty good

- for longer expirations but really not close for short expirations. The paler upper surface is the empirical SPX volatility surface and the darker lower one the Heston fit. The Heston fit surface has been shifted down by five volatility points for ease of visual comparison. 41
- 4.1 The probability density for the Heston-Nandi model with our parameters and expiration $T = 0.1$. 45
- 4.2 Comparison of approximate formulas with direct numerical computation of Heston local variance. For each expiration T , the solid line is the numerical computation and the dashed line is the approximate formula. 47
- 4.3 Comparison of European implied volatilities from application of the Heston formula (2.13) and from a numerical PDE computation using the local volatilities given by the approximate formula (4.1). For each expiration T , the solid line is the numerical computation and the dashed line is the approximate formula. 48
- 5.1 Graph of the September 16, 2005, expiration volatility smile as of the close on September 15, 2005. SPX is trading at 1227.73. Triangles represent bids and offers. The solid line is a nonlinear (SVI) fit to the data. The dashed line represents the Heston skew with Sep05 SPX parameters. 52
- 5.2 The 3-month volatility smile for various choices of jump diffusion parameters. 63
- 5.3 The term structure of ATM variance skew for various choices of jump diffusion parameters. 64
- 5.4 As time to expiration increases, the return distribution looks more and more normal. The solid line is the jump diffusion pdf and for comparison, the dashed line is the normal density with the same mean and standard deviation. With the parameters used to generate these plots, the characteristic time $T^* = 0.67$. 65
- 5.5 The solid line is a graph of the at-the-money variance skew in the SVJ model with BCC parameters vs. time to expiration. The dashed line represents the sum of at-the-money Heston and jump diffusion skews with the same parameters. 67
- 5.6 The solid line is a graph of the at-the-money variance skew in the SVJ model with BCC parameters versus time to expiration. The dashed line represents the at-the-money Heston skew with the same parameters. 67

- 5.7 The solid line is a graph of the at-the-money variance skew in the SVJJ model with BCC parameters versus time to expiration. The short-dashed and long-dashed lines are SVJ and Heston skew graphs respectively with the same parameters. 70
- 5.8 This graph is a short-expiration detailed view of the graph shown in Figure 5.7. 71
- 5.9 Comparison of the empirical SPX implied volatility surface with the SVJ fit as of September 15, 2005. From the two views presented here, we can see that in contrast to the Heston case, the major features of the empirical surface are replicated by the SVJ model. The paler upper surface is the empirical SPX volatility surface and the darker lower one the SVJ fit. The SVJ fit surface has again been shifted down by five volatility points for ease of visual comparison. 72
- 6.1 Three-month implied volatilities from the Merton model assuming a stock volatility of 20% and credit spreads of 100 bp (solid), 200 bp (dashed) and 300 bp (long-dashed). 76
- 6.2 Payoff of the 1×2 put spread combination: buy one put with strike 1.0 and sell two puts with strike 0.5. 79
- 6.3 Local variance plot with $\lambda = 0.05$ and $\sigma = 0.2$. 81
- 6.4 The triangles represent bid and offer volatilities and the solid line is the Merton model fit. 83
- 7.1 For short expirations, the most probable path is approximately a straight line from spot on the valuation date to the strike at expiration. It follows that $\sigma_{BS}^2(k, T) \approx [v_{loc}(0, 0) + v_{loc}(k, T)] / 2$ and the implied variance skew is roughly one half of the local variance skew. 89
- 8.1 Illustration of a cliquet payoff. This hypothetical SPX cliquet resets at-the-money every year on October 31. The thick solid lines represent nonzero cliquet payoffs. The payoff of a 5-year European option struck at the October 31, 2000, SPX level of 1429.40 would have been zero. 105
- 9.1 A realization of the zero log-drift stochastic process and the reflected path. 110
- 9.2 The ratio of the value of a one-touch call to the value of a European binary call under stochastic volatility and local

| | | |
|------|---|-----|
| | volatility assumptions as a function of strike. The solid line is stochastic volatility and the dashed line is local volatility. | 111 |
| 9.3 | The value of a European binary call under stochastic volatility and local volatility assumptions as a function of strike. The solid line is stochastic volatility and the dashed line is local volatility. The two lines are almost indistinguishable. | 111 |
| 9.4 | The value of a one-touch call under stochastic volatility and local volatility assumptions as a function of barrier level. The solid line is stochastic volatility and the dashed line is local volatility. | 112 |
| 9.5 | Values of knock-out call options struck at 1 as a function of barrier level. The solid line is stochastic volatility; the dashed line is local volatility. | 115 |
| 9.6 | Values of knock-out call options struck at 0.9 as a function of barrier level. The solid line is stochastic volatility; the dashed line is local volatility. | 116 |
| 9.7 | Values of live-out call options struck at 1 as a function of barrier level. The solid line is stochastic volatility; the dashed line is local volatility. | 117 |
| 9.8 | Values of lookback call options as a function of strike. The solid line is stochastic volatility; the dashed line is local volatility. | 118 |
| 10.1 | Value of the “Mediobanca Bond Protection 2002–2005” locally capped and globally floored cliquet (minus guaranteed redemption) as a function of <i>MinCoupon</i> . The solid line is stochastic volatility; the dashed line is local volatility. | 124 |
| 10.2 | Historical performance of the “Mediobanca Bond Protection 2002–2005” locally capped and globally floored cliquet. The dashed vertical lines represent reset dates, the solid lines coupon setting dates and the solid horizontal lines represent fixings. | 125 |
| 10.3 | Value of the Mediobanca reverse cliquet (minus guaranteed redemption) as a function of <i>MaxCoupon</i> . The solid line is stochastic volatility; the dashed line is local volatility. | 127 |
| 10.4 | Historical performance of the “Mediobanca 2000–2005 Reverse Cliquet Telecomunicazioni” reverse cliquet. The vertical lines represent reset dates, the solid horizontal lines represent fixings and the vertical grey bars represent negative contributions to the cliquet payoff. | 128 |
| 10.5 | Value of (risk-neutral) expected Napoleon coupon as a function of <i>MaxCoupon</i> . The solid line is stochastic volatility; the dashed line is local volatility. | 129 |

-
- 10.6 Historical performance of the STOXX 50 component of the “Mediobanca 2002–2005 World Indices Euro Note Serie 46” Napoleon. The light vertical lines represent reset dates, the heavy vertical lines coupon setting dates, the solid horizontal lines represent fixings and the thick grey bars represent the minimum monthly return of each coupon period. 130
- 11.1 Payoff of a variance swap (dashed line) and volatility swap (solid line) as a function of realized volatility Σ_T . Both swaps are struck at 30% volatility. 143
- 11.2 Annualized Heston convexity adjustment as a function of T with Heston-Nandi parameters. 145
- 11.3 Annualized Heston convexity adjustment as a function of T with Bakshi, Cao, and Chen parameters. 145
- 11.4 Value of 1-year variance call versus variance strike K with the BCC parameters. The solid line is a numerical Heston solution; the dashed line comes from our lognormal approximation. 153
- 11.5 The pdf of the log of 1-year quadratic variation with BCC parameters. The solid line comes from an exact numerical Heston computation; the dashed line comes from our lognormal approximation. 154
- 11.6 Annualized Heston VXB convexity adjustment as a function of t with Heston parameters from December 8, 2004, SPX fit. 160

Tables

| | | |
|------|---|-----|
| 3.1 | At-the-money SPX variance levels and skews as of the close on September 15, 2005, the day before expiration. | 39 |
| 3.2 | Heston fit to the SPX surface as of the close on September 15, 2005. | 40 |
| 5.1 | September 2005 expiration option prices as of the close on September 15, 2005. Triple witching is the following day. SPX is trading at 1227.73. | 51 |
| 5.2 | Parameters used to generate Figures 5.2 and 5.3. | 63 |
| 5.3 | Interpreting Figures 5.2 and 5.3. | 64 |
| 5.4 | Various fits of jump diffusion style models to SPX data. JD means <i>Jump Diffusion</i> and SVJ means <i>Stochastic Volatility plus Jumps</i> . | 69 |
| 5.5 | SVJ fit to the SPX surface as of the close on September 15, 2005. | 71 |
| 6.1 | Upper and lower arbitrage bounds for one-year 0.5 strike options for various credit spreads (at-the-money volatility is 20%). | 79 |
| 6.2 | Implied volatilities for January 2005 options on GT as of October 20, 2004 (GT was trading at 9.40). Merton vols are volatilities generated from the Merton model with fitted parameters. | 82 |
| 10.1 | Estimated “Mediobanca Bond Protection 2002–2005” coupons. | 125 |
| 10.2 | Worst monthly returns and estimated Napoleon coupons. Recall that the coupon is computed as 10% plus the worst monthly return averaged over the three underlying indices. | 131 |
| 11.1 | Empirical VXB convexity adjustments as of December 8, 2004. | 159 |