Stochastic Volatility Models and Simulation
Applied Stochastic Processes (FIN 514)

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2019-20 Module 1 (Fall 2019)

Stochastic Volatility (SV) Models

- The price process (martingale):

$$\frac{dF_t}{F_t^\beta} = \sigma_t dW_t = \sigma_t(\rho dZ_t + \rho_* dX_t), \quad \text{for} \quad \rho_* = \sqrt{1-\rho^2}.$$

BSM-base: $\beta = 1$, normal-base: $\beta = 0$.
For the models except SABR, the base model is BSM (i.e., $\beta = 1$).

- The (stochastic) volatility process may vary:

$$\sigma_t = a(t, \sigma_t)dt + b(t, \sigma_t)dZ_t,$$

- The correlation between the two Brownian motions:

$$dW_t \, dZ_t = \rho \, dt.$$

The correlation explains the *leverage effect*: equity volatility increases as price goes down.

Various SV models

The SDE for volatility is defined for volatility σ_t or variance $v_t = \sigma_t^2$.

- SABR model [Hagan et al., 2002]:

$$d\sigma_t / \sigma_t = \alpha\, dZ_t.$$

- Heston [1993] model (CIR process):

$$dv_t = \kappa(\theta - v_t)dt + \xi\sqrt{v_t}dZ_t.$$

- 3/2 model [Heston, 1997, Lewis, 2000]:

$$dv_t = \kappa v_t(\theta - v_t)dt + \xi v_t^{3/2}\, dZ_t.$$

- GARCH diffusion model (relatively new):

$$dv_t = \kappa(\theta - v_t)dt + \xi v_t\, dZ_t.$$

- OU volatility model [Li and Wu, 2019]:

$$d\sigma_t = \kappa(\theta - \sigma_t)dt + \xi\, dZ_t.$$

Simulation scheme for the SV models

- Time discretization (Euler/Milstein):
  - Almost no restriction but computationally expensive.
- Conditional MC:
  - Can skip the simulation of price F_t. (Simulate volatility σ_t only)
  - The final price F_T should be expressed by σ_T and $V_T = \int_0^T \sigma_t^2 dt$.
- Exact Simulation:
  - No need for time-discretization: jump from $t = 0$ to T.
  - The conditional MC condition + should be able to sample σ_T and V_T.
  - σ_T follows a well-known distribution and the (conditional) Laplace transform of $V_T \,|\, v_T$ should be analytically available (Heston, 3/2, SABR)

    $$E(e^{-sV_T}|v_T = x) = f(s, x)$$

    If Laplace transform is known, the CDF of $V_T \,|\, v_T$ can be obtained by (numerical) inverse-transform although it may be computationally expensive.
  - There are other lucky cases too (e.g. normal SABR).

Conditional and exact MC

Conditional MC:

1) Simulate path of σ_t for $(0 \le t \le T)$
2) Obtain σ_T and V_T (trapezoidal / Simpson's rule)

Exact MC:

1) Sample v_T from the (well-known) distribution
2) Sample V_T from the (numerical) CDF of $V_T \,|\, v_T$.

In Common:

3) Obtain $E(F_T|v_T)$ and effective volatility (usually $\rho_* \sqrt{V_T/T}$)

4-1) Price sampling: draw normal / log-normal distribution

4-2) Call option: BSM formula

Heston model (conditional MC)

$$dv_t = \kappa(\theta - v_t)dt + \xi\sqrt{v_t}dZ_t \quad (v_t = \sigma_t^2)$$

Integrating v_t,

$$v_T - v_0 = \kappa(\theta T - V_T) + \xi \int_0^T \sqrt{v_t} dZ_t$$

$$\int_0^T \sigma_t \, dZ_t = \frac{1}{\xi}\Big(v_T - v_0 - \kappa(T\theta - V_T)\Big).$$

F_T is expressed by v_T and V_T (conditional MC possible)!

$$\log\left(\frac{S_T}{S_0}\right) = \frac{\rho}{\xi}\big(v_T - v_0 - \kappa(\theta - V_T)\big) - \frac{1}{2}V_T + \rho_* \sqrt{V_T}\, X_1$$

$$E(S_T) = S_0 \exp\left(\frac{\rho}{\xi}\big(v_T - v_0 - \kappa(\theta - V_T)\big) - \frac{\rho^2}{2}V_T\right)$$

Heston model (exact MC)

- It is known that v_T is distributed as a noncentral chi-square distribution, $\textsc{ncx2}(\delta,\lambda)$:

$$v_T \;=\; \frac{\xi^2(1-e^{-\kappa T})}{4\kappa}\textsc{ncx2}(\delta,\lambda) = \frac{e^{-\kappa T/2}}{2\phi(\kappa)}\textsc{ncx2}(\delta,\lambda),$$

where the degrees of freedom δ and the noncentrality λ are

$$\delta = \frac{4\kappa\theta}{\xi^2}, \quad \lambda = \frac{4v_0\kappa\, e^{-\kappa T}}{\xi^2(1-e^{-\kappa T})} = 2v_0 e^{-\kappa T/2}\phi(\kappa) \text{ for } \phi(\kappa) = \frac{2\kappa/\xi^2}{\sinh(\kappa T/2)}$$

Standard library is available for drawing $\textsc{ncx2}$ random number.

- The conditional Laplace transform of V_T is also known [Pitman and Yor, 1982].
- Reference: Broadie and Kaya [2006] and Glasserman and Kim [2011] (improvement)

SABR model (conditional MC)

$$\frac{d\sigma_t}{\sigma_t} = \alpha\, dZ_t \quad \Rightarrow \quad \sigma_T = \sigma_0 \exp\left(-\frac{1}{2}\alpha^2 T + \alpha Z_T\right)$$

Integrating σ_t,

$$\alpha \int_0^T \sigma_t dZ_t = \sigma_T - \sigma_0 = \sigma_0 \exp\left(-\frac{1}{2}\alpha^2 T + \alpha Z_T\right) - \sigma_0$$

F_T is expressed by σ_T and V_T (conditional MC possible) !

$$S_T = S_0 + \frac{\rho}{\alpha}(\sigma_T - \sigma_0) + \rho_* \sqrt{V_T}\, X_1$$

$$\log\left(\frac{S_T}{S_0}\right) = \frac{\rho}{\alpha}(\sigma_T - \sigma_0) - \frac{1}{2}V_T + \rho_* \sqrt{V_T}\, X_1$$

SABR Model (exact MC)

- σ_T is distributed by log-normal distribution. Sampling is trivial.
- The conditional Laplace transform of $1/V_T$ is also known:

$$E\left(e^{-s/V_T}|v_T\right) = \exp\left(-\frac{\phi_x(s)^2 - x^2}{2T}\right)$$

  where $\phi_x(s) = \text{acosh}(se^{-x} + \cosh(x))$ and $v_T = \exp(\alpha x)$
- From above, we can sample $1/V_T$ and get V_T.
- Reference: Cai et al. [2017]

$$dv_t = \kappa v_t(\theta - v_t)dt + \xi v_t^{3/2}\, dZ_t.$$

The change of variable, $x_t = 1/v_t$ yields (good Itô calculus exercise!)

$$dx_t = (\kappa + \xi^2 - \kappa\theta\, x_t)dt - \xi\sqrt{x_t}\, dZ_t.$$

This is same as v_t in Heston model with new parameters:

$$\xi' = -\xi, \quad \kappa' = \kappa\theta, \quad \text{and} \quad \theta' = (\kappa + \xi^2)/(\kappa\theta).$$

We can F_T as a function of V_T and v_T (conditional MC possible)!

$$d\log(x_t) = \left(\frac{\kappa + \xi^2/2}{x_t} - \kappa\theta\right) dt - \frac{\xi}{\sqrt{x_t}}\, dZ_t$$

$$\int_0^T \frac{1}{\sqrt{x_t}}\, dZ_t = \frac{1}{\xi}\left(\log\left(\frac{x_0}{x_T}\right) + (\kappa + \xi^2/2)V_T - \kappa\theta T\right),$$

$$\log\left(\frac{F_T}{F_0}\right) = \frac{\rho}{\xi}\left(\log\left(\frac{v_T}{v_0}\right) - \kappa\left(T\theta - \left(1 + \frac{\xi^2}{2\kappa}\right)V_T\right)\right) - \frac{1}{2}V_T + \rho_*\sqrt{V_T}\, X_1$$

3/2 model (exact MC)

- From Heston model, $1/v_T$ is distributed as a noncentral chi-square distribution, $\textsc{ncx}2(\delta', \lambda')$ where the degrees of freedom δ' and the noncentrality λ' are

$$\delta' = \frac{4\kappa'\theta'}{\xi^2}, \quad \lambda = \frac{4\kappa'\, e^{-\kappa' T}}{v_0 \xi^2 (1 - e^{-\kappa' T})}.$$

  Standard library is available for drawing $\textsc{ncx}2$ random number.
- The conditional Laplace transform of V_T is also known.
- Reference: Baldeaux [2012]

Project Suggestion

- General scheme:
  - Implementing existing paper is OK:
  - Improving Euler / Milstein scheme? or exact simulation?
  - Or try something new (see below):
- Simulation for GARCH diffusion:

$$dv_t = \kappa(\theta - v_t)dt + \xi v_t\, dZ_t.$$

  - Currently, there is no easy way to solve the SDE.
  - Conditional MC possible? Option pricing with conditional MC?
  - How to express F_T as a function of v_T and V_T (or something else)?
  - Exact simulation possible?
- *Almost* Exact MC (by Choi)

Project Suggestion: *Almost* Exact MC (by Choi)

Drawback of exact simulation (if existing):

- Inverse Laplace transform of $V_T|v_T$ is complicated.
- Drawing random number from numerical CDF is also slow.

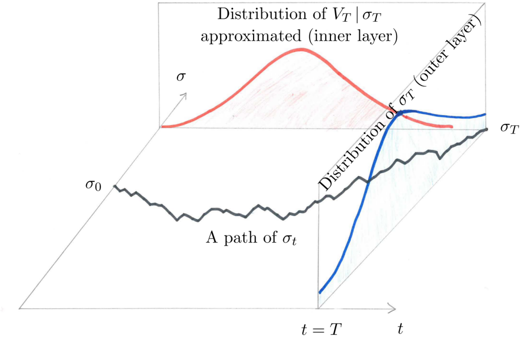
How can we simplify this step with some approximation?

- Approximate $V_T|v_T$ with a well-known distribution with easy sampling with moment matching, $E(V_T|v_T)$, $E(V_T^2|v_T)$, etc.
- Distribution candidates:
  - Log-normal:
  $$Y \sim e^X \quad \text{where} \quad X \sim N(\mu, \sigma^2)$$
  - Inverse-Gaussian:
  $$f_{\mathrm{IG}}(x \,|\, \gamma, \delta) = \frac{\delta}{\sqrt{2\pi x^3}}\, \exp\left(-\frac{(\gamma x - \delta)^2}{2x}\right) \quad \text{for} \quad \gamma \geq 0,\ \delta > 0.$$
  - First two moments are available. The sampling method for IG is available from Michael et al. [1976].
- A similar idea exists for SABR Kennedy et al. [2012]

Project Suggestion: *Almost* Exact MC (by Choi)

The illustration of the proposed double layer approximation method:

1. The outer layer distribution of σ_T (in blue) is typically known
2. The inner layer distribution of $V_T|\sigma_T$ (in red) is approximated as well-known distributions such as log-normal or inverse Gaussian.



(Continued) How to obtain the moments of $V_T|\sigma_T$?

Keep in mind for a random variable $X \geq 0$, the MGF and Laplace transform are same:

$$M_X(-s) = E(e^{-sX}) = \int_{x=0}^{\infty} e^{-sX} f_X(x)dx = f(s)$$

$$f(s) = 1 - M_1 s + \frac{1}{2} M_2 s^2 + \cdots,$$

where $M_1 = E(V_T|v_T)$ and $M_2 = E(V_T^2|v_T)$.

- Numerical method: Choudhury and Lucantoni [1996]
- Analytic method (obtaining Taylor expansion or else):
  - SABR: well-known Kennedy et al. [2012].
  - GARCH: Barone-Adesi et al. [2005](?)
  - Heston, 3/2, OU?

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