

Stochastic-alpha-beta-rho (SABR) Model Applied Stochastic Processes (FIN 514)

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The project overview

SABR Model

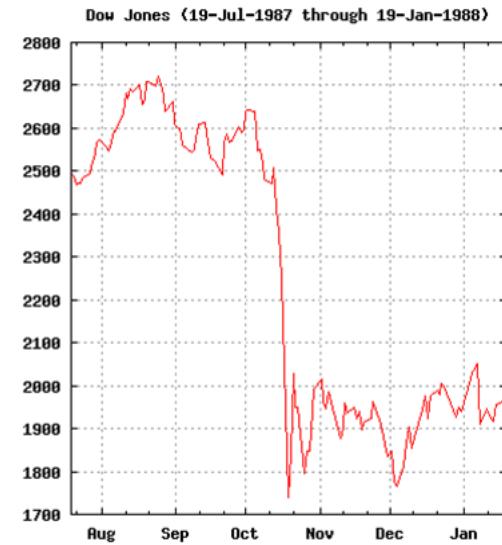
- One of the most popular stochastic volatility (SV) model.
- Heavily used for pricing and risk-managing options in interest rate and FX.
- Explains volatility skew/smile with minimal and intuitive parameters.

Project Goal

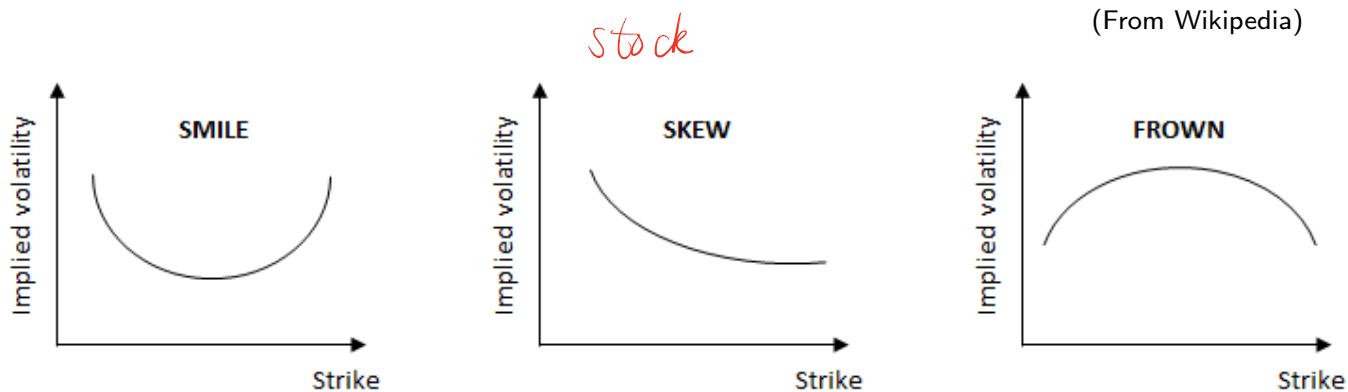
- Implement option pricing with Euler/Milstein scheme
- Implement conditional MC method (and check the variance reduction)
- Compare to the approximation formula by Hagan (code provided)
- Implement a smile calibration routine

Background: volatility skew/ smile

- Black Monday crash in 1987:
DJIA – 22.6% in one day!
- Overall ‘short gamma’ due to the *portfolio insurance* (put on equity index)
- Market values (down-side) tail event higher than before.
- Market sees volatility skew/ smile



(From Wikipedia)



Why need model for smile? challenges in risk management

- Option trading desk (market-making/sell-side) usually accumulates option positions with different strikes.
- Under BSM model,
 - Vol σ fixed under spot change $S_0 \rightarrow S_0 + \Delta$.
 - Risk-management is easy: delta and vega clearly defined
 - One can hedge delta (with underlying stock) and vega (with ATM option)
 - However, the OTM option prices/risks are not correct!
- BSM model with different σ to each option K ?
 - How do we fix the volatilities?
 - Sticky strike rule $\sigma = \sigma(K)$ vs sticky delta rule $\sigma = \sigma(S_0 - K)$.
 - Need to characterize the smile with a few minimal parameters.
- For better risk management, we need models which can capture the volatility smile.

How to model smile? Local volatility (LV)

- Volatility depending on the 'current location' of S_t :

$$\text{BSM: } \frac{dS_t}{S_t} = \sigma_{\text{BS}} f_{\text{BS}}(S_t) dW_t$$

$$\text{Normal: } dS_t = \sigma_{\text{N}} f_{\text{N}}(S_t) dW_t$$

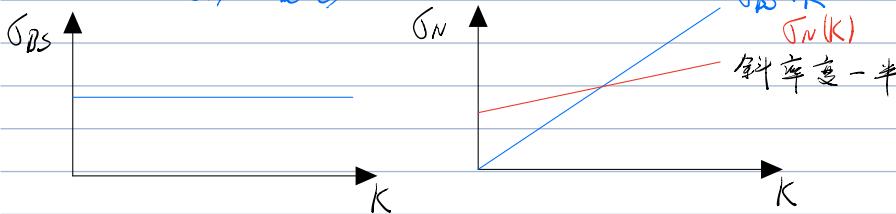
- BSM model:** a trivial case with $f_{\text{BS}}(x) = 1$. However, it is a local vol model under normal volatility ($f_{\text{N}}(x) = x$).
- Normal model:** a trivial case with $f_{\text{N}}(x) = 1$. However, it is a local vol model under BSM volatility ($f_{\text{BS}}(x) = 1/x$).
- What is the implied normal volatility of the Black-Scholes price on varying K ? What is the relation between the implied volatility and the local vol?
- The implied volatility is the volatility average of the in-the-money paths
- Exercise 1:** Chart the normal implied vol of the prices under BSM model for typical parameter sets. Measure the slope, $\partial\sigma(K)/\partial K$, at the money.

$$dS_t = \sigma_N dW_t$$

$$dS_t = \sigma_{BS} S_t dW_t$$

$$S_0 = 100 \quad \sigma_{BS} = 0.2 \quad \text{constant}$$

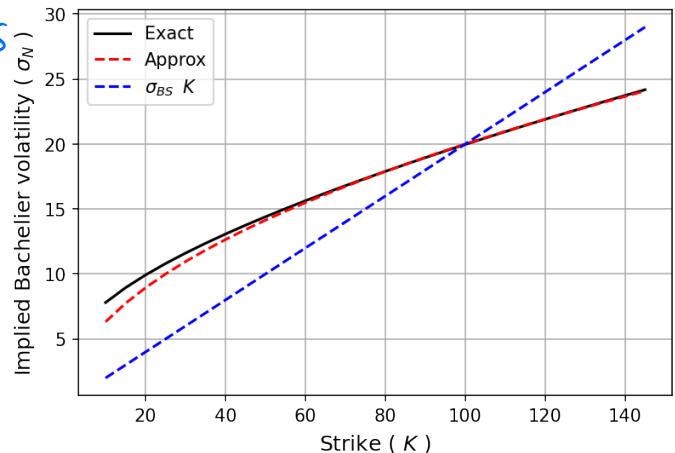
$$\sigma_N^2 = \sigma_{BS}^2 S_t^2$$



Parameters: $S_0 = 100$, $\sigma_{BS} = 20\%$ ($\sigma_N = 20$), $r = q = 0$:

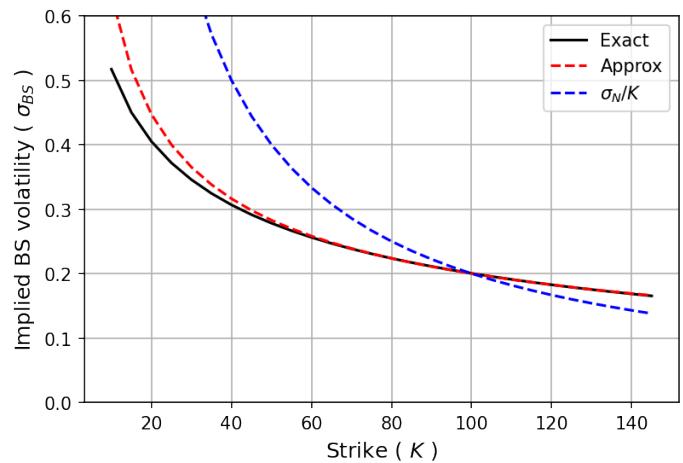
$$\sigma_N = f(\sigma_{BS}) \approx \sqrt{S_0 K} \sigma_{BS}$$

- Implied normal vol for constant BSM vol ($\sigma_{BS} = 20\%$)
- Approx: $\sigma_N \approx \sigma_{BS} \sqrt{S_0 K}$
- Local vol: $\sigma_N \approx \sigma_{BS} K$



$$\sigma_{BS} = f(\sigma_N) = \sigma_N / \sqrt{S_0 K}$$

- Implied BSM vol for constant normal vol ($\sigma_N = 20$):
- Approx: $\sigma_{BS} \approx \sigma_N / \sqrt{S_0 K}$
- Local vol: $\sigma_{BS} \approx \sigma_N / K$



Displaced BM (DBS) model

$$\text{set } \frac{dD(S_t)}{D(S_t)} = \frac{\beta dS_t}{D(S_t)} = \beta \sigma_D dW_t$$

- A simple local vol model with analytic solution (i.e., Black-Scholes formula)
- *Displaced* asset price $D(S_t) = \beta S_t + (1 - \beta)S_0$ follows a GBM:

$$\frac{dS_t}{D(S_t)} = \sigma_D dW_t \quad \text{where} \quad D(S_t) = \beta S_t + (1 - \beta)S_0.$$

- Calibration of σ_D (ATM option price on target):

$$\sigma_N \approx \sigma_D D(S_0) \approx \sigma_{BS} S_0 \Rightarrow \sigma_D = \sigma_{BS}$$

pivot

- Bridges the Bachelier ($\beta = 0$) and BS ($\beta = 1$) models.

$\beta=1$ BS

$\beta=0$ W

Displaced BM (DBS) model

- Final asset price S_T :

$$S_T = \left(S_0 + \frac{1-\beta}{\beta} S_0 \right) \exp \left(\beta \sigma_{\text{D}} W_T - \frac{\beta^2 \sigma_{\text{D}}^2 T}{2} \right) - \frac{1-\beta}{\beta} S_0,$$

- Option price:

$$C_{\text{D}}(K) = \frac{D(S_0)N(d_{1\text{D}}) - D(K)N(d_{2\text{D}})}{\beta},$$

where $d_{1\text{D},2\text{D}} = \frac{\log(D(S_0)/D(K))}{\beta \sigma_{\text{D}} \sqrt{T}} \pm \frac{\beta \sigma_{\text{D}} \sqrt{T}}{2}$.

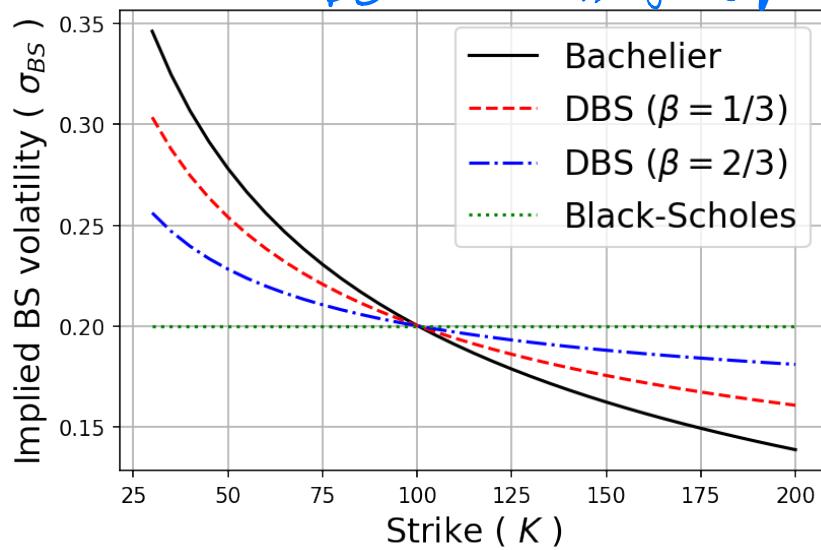
- We can reuse BS formula with the following substitutions:

$$F_0 \Rightarrow D(F_0), \quad K \Rightarrow D(K), \quad \sigma_{\text{BS}} \Rightarrow \beta \sigma_{\text{D}}, \quad C_{\text{BS}} \Rightarrow \beta C_{\text{D}}$$

BS vol skew of the DBS model

Exercise 2: Chart the BS implied volatility of the prices under the DBS model.

$$\sigma_{BS} = \sigma_N / \sqrt{S_0 K}$$



How to model smile? Stochastic volatility (SV)

- Volatility changing over time:

$$\text{BSM: } \frac{dS_t}{S_t} = \sigma_t dW_t \quad \text{Normal: } dS_t = \sigma_t dW_t$$

- Many models proposed (mostly for BSM). For $dW_t dZ_t = \rho dt$,

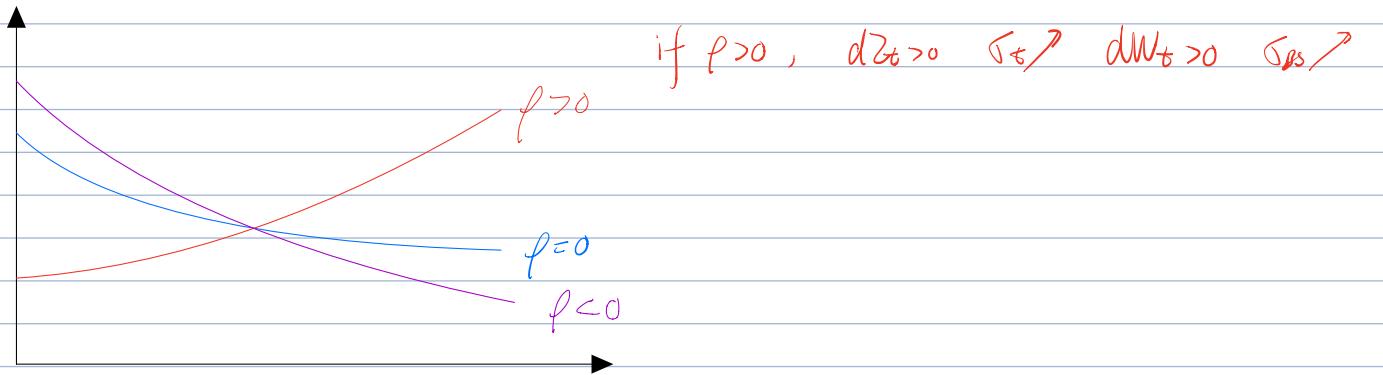
- Hull-White and SABR:

$$\frac{d\sigma_t}{\sigma_t} = \nu dZ_t$$

- Heston: $V_t = \sigma_t^2$ follows Cox-Ingersoll-Ross (CIR) process,

$$dV_t = \kappa(V_\infty - V_t)dt + \nu \sqrt{V_t} dZ_t$$

- SV model correctly captures the smile, ν for curvature and ρ for skewness.



SABR model: LV + SV

Stochastic-alpha-beta-rho model SDE:

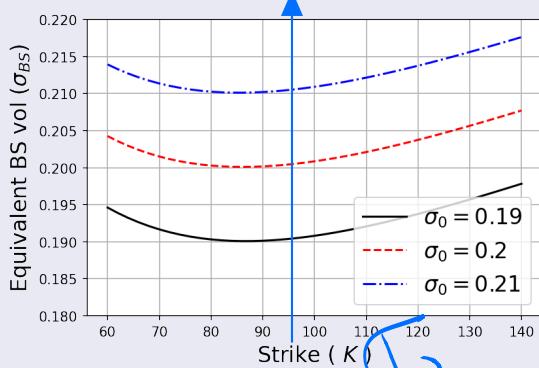
$$\frac{dS_t}{S_t^\beta} = \sigma_t dW_t \quad \text{and} \quad \frac{d\sigma_t}{\sigma_t} = \nu dZ_t \quad (dW_t dZ_t = \rho dt)$$

- Parameters: $\sigma_0, \nu, \beta, \rho$.
- σ_0 : overall volatility, calibrated to ATM implied vol
- β : elasticity or 'backbone'. (Normal: $\beta = 0$, BSM: $\beta = 1$)
- ν : volatility of volatility, σ following a GBM
- ρ : correlation between asset price and volatility

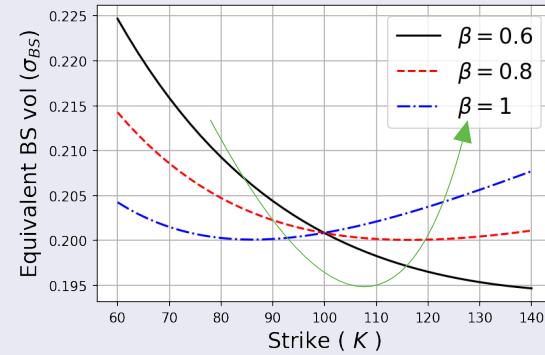
The impact of parameters

Base parameters: $\sigma_0 = 0.2$, $\nu = 0.2$, $\rho = 0.1$, $\beta = 1$.

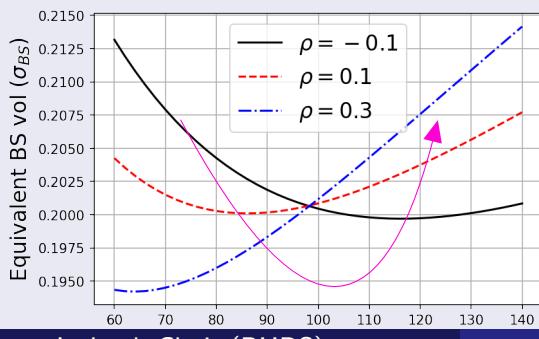
Initial vol σ_0



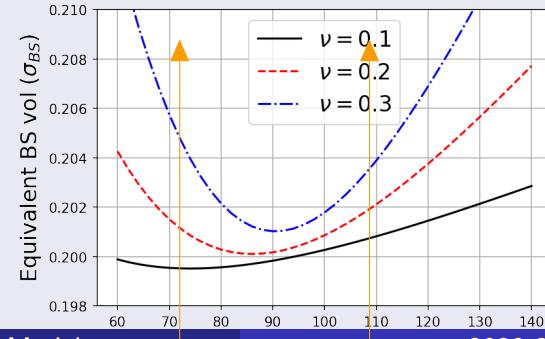
Backbone β



Correlation ρ



Vol-of-vol ν



Equivalent BSM-volatility formula (Hagan et al, 2002)

The leading-order and first-order terms of Taylor's expansion around $\nu\sqrt{T} \approx 0$.

$$\sigma_{\text{BS}}(K) = H(z) \frac{\alpha}{k^{\beta_*/2}} \frac{1 + \left(\frac{\beta_*^2}{24 k^{\beta_*}} \alpha^2 + \frac{\rho\beta}{4 k^{\beta_*/2}} \alpha\nu + \frac{2-3\rho^2}{24} \nu^2 \right) T}{1 + \frac{\beta_*^2}{24} \log^2 k + \frac{\beta_*^4}{1920} \log^4 k},$$

where,

$$\beta_* = 1 - \beta, \quad \alpha = \frac{\sigma_0}{F_0^{\beta_*}}, \quad k = \frac{K}{F_0}, \quad z = \frac{\nu}{\alpha} k^{\beta_*/2} \log k,$$

$$H(z) = \frac{z}{x(z)}, \quad x(z) = \log \left(\frac{V(z) + z + \rho}{1 + \rho} \right), \quad \text{and} \quad V(z) = \sqrt{1 + 2\rho z + z^2}.$$

The option price can be obtained by plugging $\sigma_{\text{BS}}(K)$ in to the Black-Scholes formula.

$$C_{\text{SABR}} = C_{\text{BS}}(K, F_0, \sigma_{\text{BS}}(K), T)$$

Success of the SABR model

- Volatility smile information encoded into three parameters σ_0, ν, ρ .
- These three parameters are parsimonious (minimal) and intuitive.
- Equivalent BSM volatility is available although not accurate for wide parameter range.
- Vega (volatility) risk managed by the three parameters rather than each individual vol.
- Three implied vols (or option prices) on the smile can calibrate the parameters. → An effective interpolation method for implied volatility (or option price)

Limitation of Hagan's formula

- Arbitrage is equivalent to some event happening with negative probability.
The price of a derivative paying \$1 on that event is negative (should be free at most)!



- Probability (digital call option price) from the call spread:

$$\mathbb{P}(S_T > K) = D(K, \sigma(K))$$

$$= \frac{C_{\text{BS}}(K, \sigma(K)) - C_{\text{BS}}(K + \Delta K, \sigma(K + \Delta K))}{\Delta K} = -\frac{\partial C_{\text{BS}}(K, \sigma(K))}{\partial K}$$

- Probability density from the second derivative: *regardless of model*

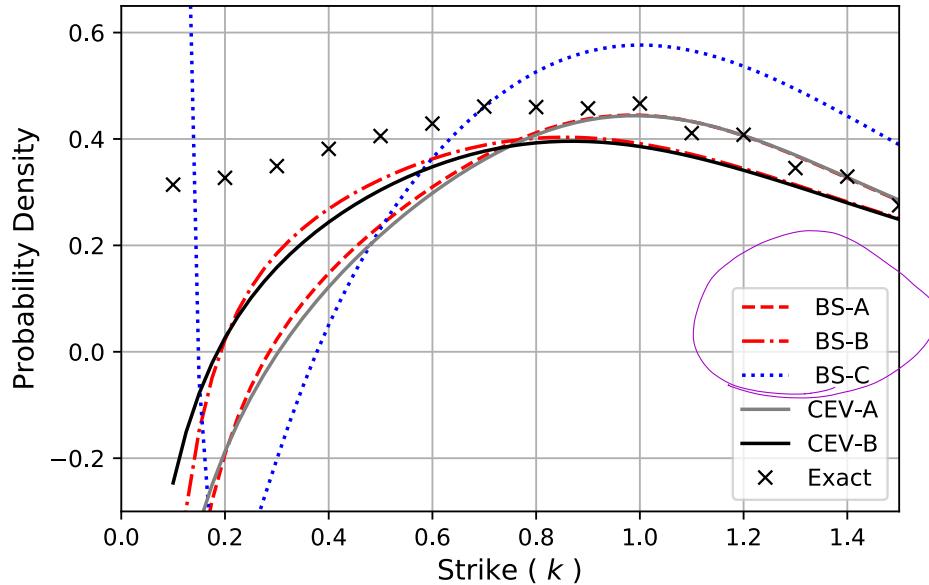
$$f_{SABR}(K) = \frac{\partial^2 C_{\text{BS}}(K, \sigma(K))}{\partial K^2} \geq 0.$$

as long as $[S_T - K]_+$

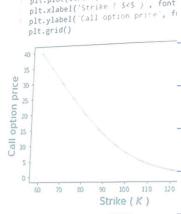
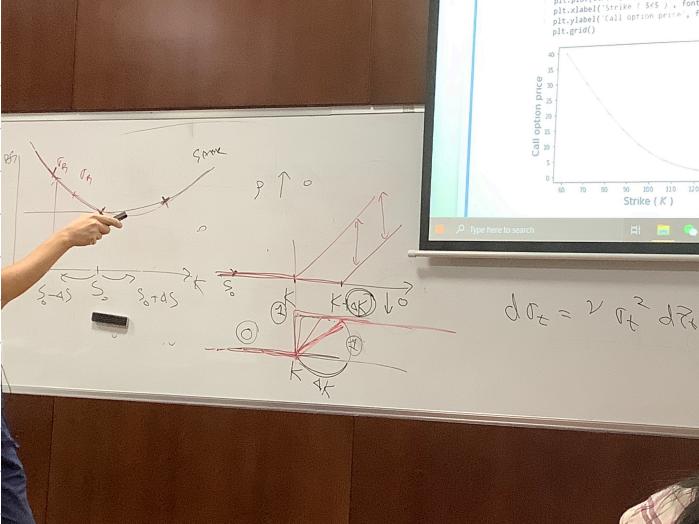
- The PDF from the exact SABR solution should be positive. When $\nu\sqrt{T} \gg 1$, however, Hagan's approximation formula often implies negative PDF.

$$D(K, \sigma(K)) < D(K + \Delta K, \sigma(K + \Delta K)).$$

The volatility effect $\sigma(K + \Delta K)$ dominates (should NOT!) the moneyness effect $K + \Delta K$.



- Parameters: $\sigma_0 = 0.25$, $\nu = 0.3$, $\rho = -0.2$, $\beta = 0.6$, $T = 20$
- Many volatility approximation methods imply negative PDF at low K .
- Reference: Choi, J., & Wu, L. (2019). The equivalent constant elasticity of variance (CEV) volatility of the stochastic-alpha-beta-rho (SABR) model. ArXiv:1911.13123 [q-Fin]. <http://arxiv.org/abs/1911.13123>



$$d\sigma_t = \nu \sigma_t^2 dZ_t$$

Euler method (MC with time-discretization)

- Unlike normal or BSM model (as in spread/basket option project), we can not jump the simulation directly from $t = 0$ to T .
- Divide the interval $[0, T]$ into N small steps, $t_k = (k/N)T$ and $\Delta t_k = T/N$ and simulate each time step with

$$S_t : \begin{cases} \beta = 0 : S_{t_{k+1}} = S_{t_k} + \sigma_{t_k} W_1 \sqrt{\Delta t_k} \\ \beta = 1 : \log S_{t_{k+1}} = \log S_{t_k} + \sigma_{t_k} \sqrt{\Delta t_k} W_1 - \frac{1}{2} \sigma_{t_k}^2 \Delta t_k, \end{cases}$$
$$\sigma_t : \sigma_{t_{k+1}} = \sigma_{t_k} \exp \left(\nu \sqrt{\Delta t_k} Z_1 - \frac{1}{2} \nu^2 \Delta t_k \right),$$

where $W_1, Z_1 \sim N(0, 1)$ with correlation ρ .

- Typically, $\Delta t_k \approx 0.25$. For $T = 30$, $N = 120$, quite time-consuming.
- Any good control variate?

$$C(K) = \frac{1}{N} \sum_{i=1}^N (S_T^{(i)} - K)^+$$

Euler method vs Milstein method

For a stochastic process,

$$dX_t = \mu(X_t)dt + \sigma(X_t)dW_t,$$

the Euler scheme is given as:

$$X_{t+\Delta t} = X_t + \mu(X_t)\Delta t + \sigma(X_t)W_1\sqrt{\Delta t} \quad \text{for } W_1 \sim N(0, 1).$$

In Milstein scheme, an higher-order correction is added:

$$\begin{aligned} X_{t+\Delta t} &= X_t + \mu(X_t)\Delta t + \sigma(X_t)\Delta W_t + \frac{\sigma(X_t)\sigma'(X_t)}{2}((\Delta W_t)^2 - \Delta t), \\ &= X_t + \mu(X_t)\Delta t + \sigma(X_t)W_1\sqrt{\Delta t} + \frac{\sigma(X_t)\sigma'(X_t)}{2}\Delta t(W_1^2 - 1). \end{aligned}$$

The idea is from the well-known stochastic integral

$$\int_0^{\Delta t} W_t dW_t = \frac{1}{2}((\Delta W_t)^2 - \Delta t) = \frac{\Delta t}{2}(W_1^2 - 1).$$

Milstein Scheme (continued)

For the time s , $t \leq s \leq t + \Delta t$, the dynamics of $\sigma(X_s)$ is

$$d\sigma(X_s) = \sigma'(X_s)dX_s + O(\Delta t) = \sigma'(X_s)\sigma(X_s)dW_s + O(\Delta t).$$

Applying the Euler scheme, we get

$$\sigma(X_s) = \sigma(X_t) + \sigma'(X_t)\sigma(X_t)(W_s - W_t) + O(\Delta t).$$

The Milstein scheme is derived as

$$\begin{aligned} X_{t+\Delta t} - X_t &= \mu(X_t) \int_{s=t}^{t+\Delta t} ds + \int_{s=t}^{t+\Delta t} \sigma(X_s) dW_s \\ &= \mu(X_t)\Delta t + \int_{s=t}^{t+\Delta t} (\sigma(X_t) + \sigma'(X_t)\sigma(X_t)(W_s - W_t)) dW_s \\ &= \mu(X_t)\Delta t + \sigma(X_t)\Delta W_t + \sigma'(X_t)\sigma(X_t) \int_{s=t}^{t+\Delta t} (W_s - W_t) dW_s \\ &= \mu(X_t)\Delta t + \sigma(X_t)\Delta W_t + \frac{\sigma'(X_t)\sigma(X_t)}{2}((\Delta W_t)^2 - \Delta t) \\ &= \mu(X_t)\Delta t + \sigma(X_t)W_1\sqrt{\Delta t} + \frac{\sigma(X_t)\sigma'(X_t)}{2}\Delta t(W_1^2 - 1). \end{aligned}$$

Stochastic integral of σ_t

From Itô's lemma,

$$\frac{d\sigma_t}{\sigma_t} = \nu dZ_t \quad \Rightarrow \quad d\log \sigma_t = -\frac{1}{2}\nu^2 dt + \nu dZ_t$$

we can solve the volatility process:

$$\sigma_T = \sigma_0 \exp \left(-\frac{1}{2}\nu^2 T + \nu Z_T \right).$$

We also know

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

which will be useful for the integration of S_t .

Stochastic integral of S_t (normal: $\beta = 0$)

Writing the SDE in a de-correlated form,

$$dS_t = \sigma_t \left(\rho dZ_t + \sqrt{1 - \rho^2} dX_t \right) \quad \text{with} \quad dX_t dZ_t = 0.$$

Integrating S_t , we get so far as

$$\begin{aligned} S_T - S_0 &= \rho \int_0^T \sigma_t dZ_t + \sqrt{1 - \rho^2} \int_0^T \sigma_t dX_t \\ &= \frac{\rho}{\nu} (\sigma_T - \sigma_0) + \sqrt{1 - \rho^2} \int_0^T \sigma_t dX_t \end{aligned}$$

From Itô's Isometry, the integration in blue is equivalent to

$$\int_0^T \sigma_t dX_t = X_1 \sqrt{I_T} \quad \text{where} \quad X_1 \sim N(0, 1), \quad I_T := \int_0^T \sigma_t^2 dt.$$

Here, the random variable X_1 is independent from I_T and σ_T . Note that $I_T = \sigma_0^2 T$ if $\nu = 0$ (i.e., volatility is not stochastic).

Conditional MC method (normal $\beta = 0$)

Conditional on (σ_T, I_T) , S_T can be sampled from

$$S_T = S_0 + \frac{\rho}{\nu}(\sigma_T - \sigma_0) + \sqrt{(1 - \rho^2)I_T} X_1$$

and the option price is from the normal model:

$$C_N(K, S_0 := S_0 + \frac{\rho}{\nu}(\sigma_T - \sigma_0), \sigma_N := \sqrt{(1 - \rho^2)I_T/T})$$

Then, the price is obtained as an expectation over (σ_T, I_T) :

$$C_{\beta=0} = E(C_N(\sigma_T, I_T)), \quad \text{where} \quad I_T = \sum_k \sigma_{t_k}^2 \Delta t_k.$$

For I_T , we can use higher-order numerical integration methods
(**trapezoidal rule** or Simpson's rule)

$$I_T = \sum_{k=0}^{N-1} (\sigma_{t_k}^2 + \sigma_{t_{k+1}}^2) \frac{\Delta t}{2} = \left(\sigma_{t_0}^2 + 2\sigma_{t_1}^2 + \cdots + 2\sigma_{t_{N-1}}^2 + \sigma_{t_N}^2 \right) \frac{\Delta t}{2}$$

Conditional MC method (BSM $\beta = 1$)

Conditional on (σ_T, I_T) , S_T can be sampled from

$$\log \left(\frac{S_T}{S_0} \right) = \frac{\rho}{\nu} (\sigma_T - \sigma_0) - \frac{1}{2} I_T + \sqrt{(1 - \rho^2) I_T} X_1$$

and the option price is from the BSM formula:

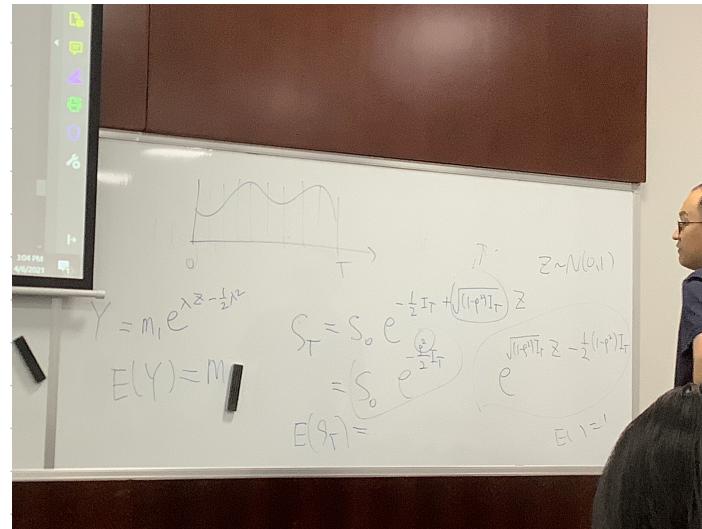
$$C_{\text{BS}} \left(K, S_0 e^{\frac{\rho}{\nu} (\sigma_T - \sigma_0) - \frac{\rho^2}{2} I_T}, \sqrt{(1 - \rho^2) I_T / T} \right)$$

Then, the price is obtained as an expectation over (σ_T, I_T) :

$$C_{\beta=1} = E (C_{\text{BS}}(\sigma_T, I_T)), \quad \text{where} \quad I_T = \sum_k \sigma_{t_k}^2 \Delta t_k$$

For I_T , we can use higher-order numerical integration methods
(trapezoidal rule or **Simpson's rule**)

$$I_T = \left(\sigma_{t_0}^2 + 4\sigma_{t_1}^2 + 2\sigma_{t_2}^2 + \cdots + 4\sigma_{t_{N-2}}^2 + 2\sigma_{t_{N-1}}^2 + \sigma_{t_N}^2 \right) \frac{\Delta t}{3} \quad \text{for even } N$$



Advantages of conditional MC method

- No need to simulate S_t : less computation, less memory use.
- Given (σ_T, I_T) , the option price is exact. Therefore, MC variance is much smaller than that of the MC simulating both σ_t and S_t .
- Can obtain correct option value for extreme strike values: If we have so simulate S_T , no simulation path arrives at $S_T > K$ for very big or small K , option value from MC is zero. The conditional MC method result in very small (correct) option value because the price comes from (analytic) BSM formula.

Smile Calibration

- When β is given (0 or 1), three parameters, σ_0 , ρ and ν , can be calibrated to three option prices (or implied volatilities), typically at $K = S_0$ (ATM), $S_0 - \Delta$ and $S_0 + \Delta$.

$$\text{SABR}(\sigma_0, \rho, \nu) \rightarrow \sigma(S_0), \sigma(S_0 - \Delta), \sigma(S_0 + \Delta)$$

- Write a calibration routine in R to solve σ_0 , ρ and ν in homework.