Fractional Brownian Motion as a Model in Finance

Tommi Sottinen, University of Helsinki

Esko Valkeila, University of Turku and University of Helsinki
Black & Scholes pricing model

In the classical Black & Scholes pricing model the randomness of the stock price $S$ is due to Brownian motion $W$:

$$dS_t = S_t(\mu dt + \sigma dW_t), \quad S_0 > 0.$$  

The bond price is $B_t = e^{rt}$.

Parameters $\mu \in \mathbb{R}$, $r, \sigma \in \mathbb{R}_+$ supposed to be known.

Traditionally one assumes that there are no dividends, no transaction costs, same interest rate $r$ for lending and saving on the bond and no limitations on short-selling of the stock.
B-S model, cont.

Some properties of this pricing model:

- The model is arbitrage free.

- One can give a unique price for options on the stock \( S \), e.g. the fair price of an European call-option \((S_T - K)^+\) is

\[
S_0 \Phi(y_1) - Ke^{-rT} \Phi(y_2),
\]

where

\[
y_1 = \log \frac{S_0}{K} + rT + \frac{\sigma^2 T}{2} \sigma T^{1/2},
\]

\[
y_2 = \log \frac{S_0}{K} + rT - \frac{\sigma^2 T}{2} \sigma T^{1/2}.
\]

- One can hedge options using the Ito-Clark-Ocone formula.
Discussion

According to the B & S model the log-returns

\[ R_t := \log \frac{S_t}{S_{t-1}} \]

should be independent normal variables.

- The dependence structure of the log-returns have been studied using the Hurst parameter \( H \). In the independent case one should have \( H = \frac{1}{2} \). However, some studies show that \( H \sim .6 \).

- There are empirical studies indicating that the log-returns are not normal.

To overcome with the first critical point, it has been proposed that one should replace the Brownian motion \( W \) by fractional Brownian motion.

[We will ignore completely the second critical point in what follows.]
Fractional Brownian motion

Fractional Brownian motion $Z$ is a continuous and centered Gaussian process with stationary increments and variance

$$\mathbb{E}Z_t^2 = t^{2H}.$$ 

The parameter $H$ allows us to model the statistical long-range dependence of the log-returns. In financial modeling it is assumed that $\frac{1}{2} < H < 1$.

Replace $W$ with $Z$ and consider the following dynamics for the stock price $S$

$$dS_t = S_t(\mu dt + \sigma dZ_t). \quad (2)$$

The solution to (2) is called a geometric fractional Brownian motion.
Fractional B-S model

Problems:

(a) How to define the stochastic integral (2)?

(b) Is the modified pricing model arbitrage free?

(c) Is the modified pricing model complete, i.e. is there a fractional analogue of the Ito-Clark-Ocone formula?

For the problem (a) two possible definitions: path-wise definition and definition based on generalized stochastic processes.
fractional B - S model, cont.

Path-wise solution to (2) is

\[ S_t = S_0 \exp(\mu t + \sigma Z_t) \]

and generalized solution is

\[ S_t = S_0 \exp(\mu t - \frac{\sigma^2}{2} t^{2H} + \sigma Z_t). \]

With generalized solutions to (2) the fractional pricing model is arbitrage free and complete, i.e. problems (b) and (c) are solved [HØ]. However, it seems to be difficult to give an economical interpretation to the formulas.

With path-wise solutions to (2) and with continuous trading one can do arbitrage in the fractional pricing model [C,Sh]. Surprisingly, the arbitrage arises in a modified binomial approximation [So].
European options in fractional models

Using a weak pricing principle one can compute the prices of European options in the path-wise fractional model [V]. These prices coincide with the ones obtained in the generalized model [HØ].

E.g. the price of an call-option \((S_T - K)^+\) is

\[
S_0 \Phi(y_1(H)) - Ke^{-rT} \Phi(y_2(H)),
\]

(3)

where

\[
y_1(H) = \log \frac{S_0}{K} + rT + \frac{\sigma^2 T^{2H}}{2 \sigma T^H},
\]

\[
y_2(H) = \log \frac{S_0}{K} + rT - \frac{\sigma^2 T^{2H}}{2 \sigma T^H}.
\]

Note that (3) converges to (1) as \(H \to \frac{1}{2}\).
Other topics

- Mixed models: $W \rightarrow W + Z$ [C, MV].

- Regularizations of the fractional Brownian motion [C].
Literature


