Pricing long-term options with stochastic volatility and stochastic interest rates

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CHAPTER 7

Accounting for Stochastic Interest Rates, Stochastic Volatility and a General Correlation Structure in the Valuation of Forward Starting Options

*This chapter is based on:


7.1 Introduction

Forward starting options belong to the class of path-dependent European-style contracts in the sense that they not only depend on the terminal value of the underlying asset, but also on the asset price at an intermediate point (often dubbed as ’strike determination date’). Typically, a forward starting contract gives the holder a call (or put) option with a strike that is set equal to a fixed proportion of the underlying asset price at this intermediate date. A special form of these options are those on the (future) return of the underlying, which can be seen as a call option on the ratio of the stock price at maturity and the intermediate date. The latter form is often being used by insurance companies to hedge unit-linked guarantees embedded in life insurance products. Additionally, structured products involving forward starting options (like cliquet and ratchet structures) are often tailored for investors seeking for upside potential, while keeping protection against downside movements.

Though forward starting options seem quite simple exotic derivatives, their valuation can be demanding, depending on the underlying model. Our pricing takes into account two important factors in the pricing of forward starting options: stochastic volatility and stochastic interest rates, whilst also taking into account the correlation between those processes explicitly. It is
hardly necessary to motivate the inclusion of stochastic volatility in a derivative pricing model. Stochastic interest rates are crucial for the pricing of forward starting options because securities with forward starting features often have a long-dated maturities and are therefore much more interest rate sensitive, e.g. see Guo and Hung (2008) or Kijima and Muromachi (2001). The addition of interest rates as a stochastic factor has been the subject of empirical investigations most notably by Bakshi et al. (2000). These authors show that the hedging performance of delta hedging strategies of long-maturity options improves when taking stochastic interest rates into account.

The pricing of forward starting options was first considered by Rubinstein (1991) who provides a closed-form solution for the pricing of forward starting options based on the assumptions of the Black and Scholes (1973) model. Lucic (2003), Hong (2004) and Kruse and Nögel (2005) relax the constant volatility assumption and consider the pricing of forward starting options under Heston (1993) stochastic volatility. The pricing of forward starting options under stochastic volatility with independent stochastic interest rates was considered by Guo and Hung (2008), Ahlip and Rutkowski (2009) and Nunes and Alcaria (2009). The framework employed in this chapter distinguishes itself from these models by a closed form pricing formula and an explicit, rather than implicit, incorporation of the correlation between underlying and the term structure of interest rates. The flexibility of stochastic volatility model with (correlated) stochastic rates and the pricing of vanilla call options in such a framework was covered in Ahlip (2008) and Chapter 3.

The main goal of this work is performing a quantitative analysis on the pricing of forward starting options under stochastic volatility and stochastic interest rates. In particular we want to investigate the impact of stochastic volatility, stochastic interest rates as well as a realistic dependency structure between all the underlying processes on the valuation of these securities. The analysis is made possible by developing a closed-form solution for the price of a forward starting option in a model in which the instantaneous stochastic volatility is given by the Schöbel and Zhu (1999) model and the interest rates follow Hull and White (1993) dynamics. We explicitly incorporate the correlation between underlying stock and the term structure of interest rates, which is an important empirical characteristic that needs to be taken into account for the pricing and hedging of long-term options, e.g. see Bakshi et al. (2000) or Piterbarg (2005). The setup of this chapter is as follows: we discuss the modelling framework and the corresponding forward starting option problem in Section 7.2 and 7.3. Using the characteristic function of the log-asset price under the stock price measure (derived in Section 7.4), we derive in Section 7.5 the main pricing formulas of the chapter. In Section 7.6 we consider the implementation of these formulas and analyze the valuation and risk management of forward starting option under stochastic volatility, stochastic interest rates and a general correlation structure. Finally, we conclude in Section 7.7.

### 7.2 The modelling framework

To analyze the pricing of forward starting options under stochastic volatility and stochastic interest rates, we use the SZHW model of see Chapter 3. For clarity we will here repeat these
dynamics: in the SZHW model, the stock price $S(t)$ is governed by the following dynamics

$$dS(t) = r(t)S(t)dt + \nu(t)S(t)dW_Q^S(t), \quad S(0) = S_0,$$

(7.1)

$$\nu(t) = \kappa(\psi - \nu(t))dt + \tau dW_Q^\nu(t), \quad \nu(0) = \nu_0,$$

(7.2)

where $r$ follows an Hull and White (1993) process, see Chapter 2. For an explanation of the model parameters, see Chapter 3. The simulation of the SZHW model is discussed in Chapter 6.

### 7.3 Forward starting options

Forward starting options are contracts which not only depend on their terminal value of the underlying asset, but also on the asset price at an intermediate time between the current time and its expiry time. Kruse and Nögel (2005) consider two types of forward starting options under the Heston (1993) model: European forward starting call options on the underlying asset and on the underlying return. The first structure is prevalent in Employee stock option schemes, while the second category forms a building block for cliquet, ratchet and Unit-Linked insurance options. In both contracts a premium is paid on the purchase date, however the option’s life will only start on an intermediate date (in between the purchase and expiry date, dubbed as the strike determination time). Thus, the terminal payoff of these options depends on the underlying asset price at both the maturity and the start date of the underlying option. The next definition formalizes these option types.

**Definition** The terminal payoff of a European forward starting call option on the underlying asset price $S$, with a percentage strike of $K$, strike determination time $T_{i-1}$ and maturity $T_i$ is given by

$$\left[ S(T_i) - KS(T_{i-1}) \right]^+. \quad (7.3)$$

The terminal payoff of a European forward starting call option on the return of the underlying asset price $S$, with an absolute strike of $K$, determination time $T_{i-1}$ and maturity $T_i$ is given by

$$\left[ \frac{S(T_i)}{S(T_{i-1})} - K \right]^+. \quad (7.4)$$

### 7.3.1 The option pricing framework

We can express the price of the forward starting call option price $C_F(T_{i-1}, T_i)$ on the underlying asset, $t \leq T_{i-1} \leq T_i$ and with terminal payoff (7.3), in the following expectation under the risk-neutral measure $Q$

$$C_F(T_{i-1}, T_i) = \mathbb{E}^Q\left[e^{-\int_{T_{i-1}}^{T_i} r(u)du} \left( S(T_i) - KS(T_{i-1}) \right)^+ \right| F_{T_{i-1}}]. \quad (7.5)$$

Instead of evaluating the expected discounted payoff under the risk-neutral bank account measure, we can also change the underlying probability measure to evaluate this expectation under
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the stock price probability measure $Q^S$ (e.g. see Geman et al. (1996)), i.e. with the stock price $S$ as numeraire. Hence, starting from time $t$, we can evaluate the price of the forward starting option (7.5) as

$$C_F(T_{i-1}, T_i) = S(t) \mathbb{E}^{Q^S} \left[ \frac{1}{S(T_i)} \left( S(T_i) - KS(T_{i-1}) \right)^+ \right| \mathcal{F}_i \right]$$

$$= S(t) \mathbb{E}^{Q^S} \left[ (1 - K \frac{S(T_{i-1})}{S(T_i)})^+ \right| \mathcal{F}_i \right]$$

$$= S(t) K \mathbb{E}^{Q^S} \left[ \left( \frac{1}{K} - \frac{S(T_{i-1})}{S(T_i)} \right)^+ \right| \mathcal{F}_i \right], \quad (7.6)$$

where the last line can be interpreted as put option with strike $\frac{1}{K}$ on the ratio $\frac{S(T_{i-1})}{S(T_i)}$.

In principle it also possible, following the lines of Rubinstein (1991), Guo and Hung (2008) and Ahlip and Rutkowski (2009), to express the forward starting option price as the expected value of a future call option price, i.e.

$$C_F(T_{i-1}, T_i) = S(t) \mathbb{E}^{Q^S} \left\{ \frac{1}{S(T_{i-1})} \mathbb{E}^{Q^S} \left[ \left( S(T_i) - KS(T_{i-1}) \right)^+ \right| \mathcal{F}_{T_{i-1}} \right] \right| \mathcal{F}_i \right\}. \quad (7.7)$$

The above expectation can be evaluated using similar techniques as the evaluation of formula (7.6), and results in a pricing formula containing two integrals. On the other hand, working out the equivalent expectation (7.6) results in a pricing formula which only contains one integral. Not only does this make the corresponding implementation more efficient, but even more importantly it has been shown in Andersen and Andreasen (2002) and Lord and Kahl (2008) that the double integral formulation suffers from numerical instabilities whereas the single integral can be implemented in a numerically very stable way. Hence though both approaches are mathematically equivalent, we prefer to work with expectation (7.6) over the expression in formula (7.7).

We therefore express the option (7.6) with log strike $k := \ln \frac{1}{K}$, in terms of the $(T$-forward) characteristic function $\phi_F(T_{i-1}, T_i, v)$ of the log ratio $\ln \frac{S(T_{i-1})}{S(T_i)}$, i.e.

$$C_F(T_{i-1}, T_i, k) = \frac{1}{\pi} \int_0^\infty \Re \left( e^{(\alpha - iv)k} \phi_F(T_{i-1}, T_i, v) \right) dv, \quad (7.8)$$

with

$$\psi_F(T_{i-1}, T_i, v) := \frac{\phi_F(T_{i-1}, T_i, v + (\alpha - 1)i)}{(iv - \alpha)(iv - \alpha + 1)}$$

with $\phi_F(T_{i-1}, T_i, v) := \mathbb{E}^{Q^S} \left[ \exp(iu \ln \frac{S(T_{i-1})}{S(T_i)}) \right| \mathcal{F}_i \right]$ and where $\alpha > 1$ has been introduced for Fourier
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Transform regularization, see Section 2.5.

**Remark 7.3.1** For the pricing of the forward starting option on the underlying asset, it suffices to know the characteristic function \( \phi_F(T_{i-1}, T_i, v) \) of \( \ln \frac{S(T_i)}{S(T_{i-1})} \) under the stock price probability measure \( Q^S \). For the derivation of this characteristic function, see Section 7.5.1.

For the price \( C_R(T_{i-1}, T_i) \) of the forward starting call option on the return of the underlying asset, i.e. with terminal payoff (7.3), the following expectation expectation under the \( T_i \)-forward measure holds

\[
C_R(T_{i-1}, T_i) = P(t, T_i) \mathbb{E}_{Q^{T_i}} \left[ \left( \frac{S(T_i)}{S(T_{i-1})} - K \right)^+ \right].
\]

i.e. the corresponding numeraire is now the (pure) discount bond \( P(t, T_i) \) maturing at time \( T_i \). One can again write the option (7.6) with log strike \( k = \ln K \), in terms of the \( (T_i) \)-forward characteristic function \( \phi(T_{i-1}, T_i, v) \) of the log ratio \( \ln \frac{S(T_i)}{S(T_{i-1})} \), i.e.

\[
C_R(T_{i-1}, T_i, k) = \frac{1}{\pi} \int_0^\infty \text{Re} \left( e^{-(\alpha+iv)k} \psi(T_{i-1}, T_i, v) \right) dv,
\]

with

\[
\psi_R(T_{i-1}, T_i, v) = \frac{\phi_R(T_{i-1}, T_i, v - (\alpha + 1)i)}{(\alpha + iv)(\alpha + 1 + iv)},
\]

with \( \phi_R(T_{i-1}, T_i, v) := \mathbb{E}_{Q^{T_i}} \left[ \exp \left( iu \ln \frac{S(T_i)}{S(T_{i-1})} \right) \right] \) and where \( \alpha \in \mathbb{R}^+ \) has been introduced for Fourier Transform regularization.

**Remark 7.3.2** For the pricing of the forward starting option on the return of the underlying asset, it suffices to know the characteristic function \( \phi_R(T_{i-1}, T_i, v) \) of \( \ln \frac{S(T_i)}{S(T_{i-1})} \) under the \( T_i \)-forward probability measure \( Q^{T_i} \). For the derivation of the characteristic function, see Section 7.5.2.

The remainder of the chapter hence focusses on the derivation of the above characteristic functions.

### 7.4 Characteristic function of the log asset price

As a preliminary step towards the general valuation results presented in Section 7.5, we derive in this section the characteristic function of the log asset price \( F(t, T) \) under the stock price measure \( Q^S \) and under the \( T \)-forward measure \( Q^T \). To this end, define the \( T \)-forward asset price at time \( t \) as

\[
F(t, T) = \frac{S(t)}{P(t, T)},
\]

(7.11)
where \( P(t, T) \) denotes the the price of a (pure) discount bond at time \( t \) maturing at time \( T \), hence note that \( F(T, T) = S(T) \). Under the risk-neutral measure \( Q \) (where we use the money market bank account as numeraire) the discount bond price follows the process \( dP(t, T) = r(t)P(t, T)dt - \sigma B_{tw}(t, T)P(t, T)dW_r(t) \), where \( B_{tw}(t, T) := \frac{1}{a}(1 - e^{-a(T-t)}) \). Hence, by an application of Itô’s lemma, one has the following result for the \( T \)-forward stock price process:

\[
dF(t, T) = \left( \rho_S \nu(t) \sigma B_{tw}(t, T) + \sigma^2 B_{tw}^2(t, T) \right) F(t, T)dt + \nu(t)F(t, T)dW_S^Q(t) + \sigma B_{tw}(t, T)F(t, T)dW_r^Q(t). \tag{7.12}
\]

We will use these dynamics in the following two sections to determine the characteristic function of \( \ln F(T) \) under respectively the stock price measure and the \( T \)-forward measure.

### 7.4.1 Characteristic function under the stock price measure \( Q^S \)

To determine the dynamics of the forward asset price under the stock price measure, we need to change from the money market account numeraire to the stock price numeraire, see Chapter 2. The corresponding Radon-Nikodým derivative is given by

\[
\frac{dQ^S}{dQ} = \frac{S(T)B(0)}{S(0)B(T)} = \exp\left[ -\frac{1}{2} \int_0^T \nu^2(u)du + \int_0^T \nu(u)dW_S^Q(u) \right]. \tag{7.13}
\]

The multi-dimensional version of Girsanov’s theorem (e.g. see Brigo and Mercurio (2006)) implies that in our model

\[
\begin{align*}
    dW_S^{Q^S}(t) &\mapsto dW_S^Q(t) - \nu(t)dt, \tag{7.14} \\
    dW_r^{Q^S}(t) &\mapsto dW_r^Q(t) - \rho_S \nu(t)dt, \tag{7.15} \\
    dW_y^{Q^S}(t) &\mapsto dW_y^Q(t) - \rho_S \nu(t)dt. \tag{7.16}
\end{align*}
\]

are \( Q^S \) Brownian motions. Hence under \( Q^S \) we have the following model dynamics for the volatility and interest rate process

\[
\begin{align*}
    dF(t, T) &= \left( \nu^2(t) + 2\rho_S \nu(t) \sigma B_{tw}(t, T) + \sigma^2 B_{tw}^2(t, T) \right) F(t, T)dt \\
    &\quad + \nu(t)F(t, T)dW_S^Q(t) + \sigma B_{tw}(t, T)F(t, T)dW_r^Q(t) \tag{7.17} \\
    dx(t) &= \left( -ax(t) + \rho_S \nu(t) \right)dt + \sigma dW_r^{Q^S}(t), \tag{7.18} \\
    dv(t) &= \left( \kappa(\psi - v(t)) + \rho_S \tau \nu(t) \right)dt + \tau dW_y^{Q^S}(t). \tag{7.19}
\end{align*}
\]

We can simplify (7.17) by switching to logarithmic coordinates and rotating \( W_S^Q(t) \) and \( W_r^{Q^S}(t) \) to a Brownian motion \( W_r^{Q^S}(t) \). Defining \( y(t, T) := \ln(F(t, T)) \) and an application of Itô’s lemma
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yields the following dynamics:
\[
\begin{align*}
    dy(t) &= +\frac{1}{2}v^2_F(t)dt + v_F(t)dW^Q_F(t), \\
    d\nu(t) &= \kappa(\psi - \nu(t))dt + \tau dW^Q_S(t)
\end{align*}
\]
(7.20)

where \( \kappa := \kappa - \rho_S\tau, \psi := \frac{\kappa}{\kappa} \) and with
\[
v^2_F(t) := v^2(t) + 2\rho_Sv(t)\sigma B_{\text{inv}}(t, T) + \sigma^2 B^2_{\text{inv}}(t, T).
\]
(7.22)

Note that we now have reduced the system (7.17) of the three variables \( S(t), x(t) \) and \( \nu(t) \) under the risk-neutral measure, to the system (7.20) of two variables \( y(t) \) and \( \nu(t) \) under the stock price measure. It remains to find the corresponding characteristic function in the reduced system of variables, which is the subject of the now following lemma.

**Lemma 7.4.1** Under the stock price measure \( Q^S \), the characteristic function of the \( T \)-forward asset price \( \ln F(T, T) = \ln S(T) \) conditional on the \( \sigma \)-algebra \( \mathcal{F}_t \) is given by the following closed-form solution:
\[
\mathbb{E}^Q\left[\exp\left(iu \ln F(T, T)|\mathcal{F}_t\right)\right] = \exp\left[A(u, t, T) + B(u, t, T)\ln F(t, T) + C(u, t, T)\nu(t) + \frac{1}{2}D(u, t, T)\nu^2(t)\right],
\]
(7.23)

where:
\[
\begin{align*}
    A(u, t, T) &= \frac{1}{2}u(i - u)V(t, T) \\
    &\quad + \int_t^T \left[ \kappa\psi + \rho_Siut\sigma B_{\text{inv}}(s, T) \right] C(s) + \frac{1}{2}\tau^2\left(C^2(s) + D(s)\right) ds, \\
    B(u, t, T) &= iu, \\
    C(u, t, T) &= u(i - u)\left(\gamma_3 - \gamma_4e^{-2\gamma(T-t)} - \gamma_5e^{-a(T-t)} - \gamma_6e^{-2(\gamma+a)(T-t)} - \gamma_7e^{-\gamma(T-t)}\right) / \gamma_1 + \gamma_2e^{-2\gamma(T-t)}, \\
    D(u, t, T) &= u(i - u)\frac{1 - e^{-2\gamma(T-t)}}{\gamma_1 + \gamma_2e^{-2\gamma(T-t)}},
\end{align*}
\]
(7.24-7.27)
with:

\[ \gamma = \sqrt{(\kappa - \rho_S \tau \text{i}u)^2 - \tau^2 u(i - u)}, \]

\[ \gamma_1 = \gamma + (\kappa - \rho_S \tau \text{i}u), \] \hspace{1cm} (7.28)

\[ \gamma_2 = \gamma - (\kappa - \rho_S \tau \text{i}u), \]

\[ \gamma_3 = \frac{\rho_S \sigma \gamma_1 + \kappa \psi_\text{f} + \rho_r \sigma \tau \text{i}u}{a \gamma}, \]

\[ \gamma_4 = \frac{\rho_S \sigma \gamma_2 - \kappa \psi - \rho_r \sigma \tau \text{i}u}{a \gamma}, \]

\[ \gamma_5 = \frac{\rho_S \sigma \gamma_1 + \rho_r \sigma \tau \text{i}u}{a (\gamma - a)}, \]

\[ \gamma_6 = \frac{\rho_S \sigma \gamma_2 - \rho_r \sigma \tau \text{i}u}{a (\gamma + a)}, \]

and:

\[ V(t, T) := \frac{a^2}{2} \left( (T - t) + \frac{2}{a} e^{-\alpha(T-t)} - \frac{1}{2a} e^{-2\alpha(T-t)} - \frac{3}{2a} \right). \] \hspace{1cm} (7.29)

**Proof** To determine the characteristic function of \( \ln F(T, T) \), we can apply the Feynman-Kac theorem and reduce the problem of finding the characteristic of the forward log-asset price dynamics to solving a partial differential equation. The Feynman-Kac theorem implies that the characteristic function

\[ f(t, y, \nu) = \mathbb{E}^{\mathbb{Q}^T} \left[ \exp(\text{i}uy(T)) | \mathcal{F}_t \right], \] \hspace{1cm} (7.30)

is given by the solution of the following partial differential equation,

\[ 0 = f_t + \frac{1}{2} \nu^2 f_{yy} + \kappa (\xi(t) - \nu(t)) f_y \]

\[ + (\rho_S \tau \nu(t) + \rho_r \tau \sigma B_{\text{rw}}(t, T)) f_{yy} + \frac{1}{2} \tau^2 f_{yy}, \] \hspace{1cm} (7.31)

\[ f(T, y, \nu) = \exp(\text{i}uy(T)), \] \hspace{1cm} (7.32)

where the subscripts denote partial derivatives and to ease the notation we dropped the explicit \((t, y, \nu)\)-dependence for \( f \). Furthermore we have taken into account that the covariance term \( dy(t) dv(t) \) is equal to

\[ dy(t) dv(t) = (\nu(t) dW^T_r(t) + \sigma B_{\text{rw}}(t, T) dW^T_i(t)) (\tau dW^T_i(t)) = (\rho_S \tau \nu(t) + \rho_r \tau \sigma B_{\text{rw}}(t, T)) dt. \] \hspace{1cm} (7.33)

Some tedious algebra shows that direct substitution of the ansatz

\[ f(t, y, \nu) = \exp \left[ A(u, t, T) + B(u, t, T) y(t) + C(u, t, T) \nu(t) + \frac{1}{2} D(u, t, T) \nu^2(t) \right], \] \hspace{1cm} (7.34)

solves the partial differential equation (7.31) and hence proves the theorem. \( \Box \)

### 7.4.2 Characteristic function under the \( T \)-forward measure \( \mathbb{Q}^T \)

For the derivation of the characteristic function of \( \ln S(T) \) under the \( T \)-forward measure we refer the reader to Chapter 3. For clarity, we here repeat this result.
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Lemma 7.4.2 Under the $T$-forward measure $Q^T$, the characteristic function of the $T$-forward asset price $\ln F(T, T) = \ln \frac{S(T)}{S(T)} = \ln S(T)$ conditional on the time $t$ filtration $\mathcal{F}_t$ is given by the following closed-form solution:

$$f(t, y, \nu) = \exp \left[ L(u, t, T) + M(u, t, T)y(t) + N(u, t, T)\nu(t) + \frac{1}{2}O(u, t, T)\nu^2(t) \right], \quad (7.35)$$

where:

$$L(u, t, T) = -\frac{1}{2}u(i + u)V(t, T)$$

$$+ \int_t^T \left( \kappa \psi + \rho_r(iu - 1)\tau \sigma B_{im}(s, T) \right) N(s) + \frac{1}{2}\tau^2 \left( N^2(s, t, T) + O(s, t, T) \right) ds,$$

$$M(u, t, T) = iu,$$  \quad (7.37)

$$N(u, t, T) = -u(i + u) \frac{\left( \delta_3 - \delta_4 e^{-2q(T-t)} \right) - \left( \delta_5 e^{-a(T-t)} - \delta_6 e^{-2q+a(T-t)} - \delta_7 e^{-q(T-t)} \right)}{\delta_1 + \delta_2 e^{-2q(T-t)}},$$  \quad (7.38)

$$O(u, t, T) = -u(i + u) \frac{1 - e^{-2q(T-t)}}{\delta_1 + \delta_2 e^{-2q(T-t)}},$$  \quad (7.39)

with:

$$\delta = \sqrt{(\kappa - \rho_S, \tau iu)^2 + \tau^2 u(i + u)}, \quad \delta_1 = \delta + (\kappa - \rho_S, \tau iu),$$  \quad (7.40)

$$\delta_2 = \delta - (\kappa - \rho_S, \tau iu), \quad \delta_3 = \frac{\rho_S, \sigma \delta \delta_1}{a \delta} + \frac{\kappa \psi + \rho_r, \sigma \tau (iu - 1)}{a \delta},$$

$$\delta_4 = \frac{\rho_S, \sigma \delta_2 - \kappa \psi - \rho_r, \sigma \tau (iu - 1)}{a \delta}, \quad \delta_5 = \frac{\rho_S, \sigma \delta_1 + \rho_r, \sigma \tau (iu - 1)}{a (\delta - a)},$$

$$\delta_6 = \frac{\rho_S, \sigma \delta_2 - \rho_r, \sigma \tau (iu - 1)}{a (\delta + a)}, \quad \delta_7 = (\delta_3 - \delta_4) - (\delta_5 - \delta_6),$$

and with $V(t, T)$ as in (7.29).

7.5 Valuation of forward starting call options

With the preliminary work of the previous sections, we can now present the general valuation results for the forward starting characteristic functions. The results are provided in the theorems of the following two sections.
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7.5.1 Forward starting characteristic function under the stock price measure

With the help of lemma 7.4.1, we are now ready to derive the characteristic function of \( \ln \frac{S(T_i)}{S(T_j)} \). This characteristic function, provided by the following theorem, can then directly be plugged into the Fourier inversion formula (7.8) to price the forward starting call option (7.6) in closed-form.

**Theorem 7.5.1** Under the stock price measure \( Q^S \), the characteristic function \( \phi_F(T_{i-1}, T, u) \) of \( \ln \frac{S(T_i)}{S(T_j)} \) is given by the following closed-form solution:

\[
\phi_F(T_{i-1}, T, u) = \exp \left[ a_0 + a_1 \mu_s + \frac{1}{2} a_1^2 \sigma_s^2 \left( 1 - \rho_{s,v}(t, T_{i-1}) \right) \right] \\
\times \frac{\exp \left[ a_2 \mu_v + a_3 \mu_v^2 + \frac{(a_1 \sigma_s \rho_{s,v}(t, T_{i-1}) + a_2 \sigma_v + 2a_3 \mu_v \sigma_v)^2}{2(1 - 2a_3^2 \sigma_v^2)} \right]}{\sqrt{1 - 2a_3^2 \sigma_v^2}},
\]

(7.41)

where:

\[
a_0 := iu \ln A_{tw}(T_{i-1}, T) + A(-u, T_{i-1}, T), \quad a_1 := -iu B_{tw}(T_{i-1}, T),
\]

(7.42)

\[
a_2 := C(-u, T_{i-1}, T) \quad a_3 := \frac{1}{2} D(-u, T_{i-1}, T).
\]

(7.43)

**Proof** Recalling the definition (7.11) for the forward asset price and using Lemma 7.4.1, one can write the following for the characteristic function \( \phi_F(T_{i-1}, T, u) \) of \( \ln \frac{S(T_i)}{S(T_j)} \):

\[
\phi_F(T_{i-1}, T, u) = \mathbb{E}_{Q^S} \left[ e^{iu \ln \frac{S(T_i)}{S(T_j)}} \big| \mathcal{F}_{T_{i-1}} \right] = \mathbb{E}_{Q^F} \left[ e^{iu \ln S(T_{i-1}) - iu \ln S(T_j)} \big| \mathcal{F}_{T_{i-1}} \right]
\]

\[
= \mathbb{E}_{Q^F} \left[ e^{iu \ln P(T_{i-1}, T_{i}) + iu \ln F(T_{i-1}, T) - iu \ln F(T_i)} \big| \mathcal{F}_{T_{i-1}} \right].
\]

Using the tower law of conditional expectations, i.e. conditioning on the time \( T_{i-1} \) filtration \( \mathcal{F}_{T_{i-1}} \), we have that

\[
\phi_F(T_{i-1}, T, u) = \mathbb{E}_{Q^F} \left[ e^{iu \ln P(T_{i-1}, T_{i}) + iu \ln F(T_{i-1}, T)} \mathbb{E}_{Q^S} \left[ e^{iu \ln F(T_i)} \big| \mathcal{F}_{T_{i-1}} \right] \big| \mathcal{F}_{T_{i-1}} \right],
\]

and note that the inner expectation is the characteristic function of \( \ln F(T_{i-1}, T) \) evaluated in the point \(-u\), i.e. given by lemma 7.4.1. Hence substituting for this the characteristic function in the above expression, we obtain:

\[
\phi_F(T_{i-1}, T, u) = \mathbb{E}_{Q^F} \left[ e^{iu \ln P(T_{i-1}, T_{i}) + A(-u, T_{i-1}, T) + C(-u, T_{i-1}, T) \sigma(T_{i-1}) + D(-u, T_{i-1}, T) \gamma(T_{i-1})} \big| \mathcal{F}_{T_{i-1}} \right].
\]

(7.44)

In the Gaussian rate model, one has the following expression for the time-\( T_{i-1} \) price of a zero-coupon bond \( P(T_{i-1}, T) \) maturing at time \( T_i \) (e.g. see Brigo and Mercurio (2006)):

\[
P(T_{i-1}, T_i) = A_{tw}(T_{i-1}, T_i) e^{-B_{tw}(T_{i-1}, T_i) \sigma(T_{i-1})},
\]

(7.45)
7.5. Valuation of forward starting call options

where

$$A_{\text{bw}}(T_{i-1}, T_i) = \frac{P^M(t, T_i)}{P^M(t, T_{i-1})} \exp \left[ \frac{1}{2} (V(T_{i-1}, T_i) - V(t, T_i) + V(t, T_{i-1})) \right]$$

(7.46)

$$B_{\text{bw}}(T_{i-1}, T_i) = \frac{1 - e^{-a(T_i-T_{i-1})}}{a}$$

(7.47)

$$V(T_{i-1}, T_i) = \frac{\sigma^2}{a^2} \left( (T_i - T_{i-1}) + \frac{2}{a} e^{-a(T_i-T_{i-1})} - \frac{1}{2a} e^{-2a(T_i-T_{i-1})} - \frac{3}{2a} \right).$$

(7.48)

Hence we can express the characteristic function \( \phi_F(T_{i-1}, T_i, u) \) completely in terms of the Gaussian factors \( x(T_{i-1}) \) and \( v^2(T_{i-1}) \), i.e.

$$\phi_F(T_{i-1}, T_i, u) = \mathbb{E}^Q \left[ \exp \left[ iu \ln A_{\text{bw}}(T_{i-1}, T_i) - B_{\text{bw}}(T_{i-1}, T_i)x(T_{i-1}) + A(-u, T_{i-1}, T_i) \right. \\
+ C(-u, T_{i-1}, T_i)v(T_{i-1}) + D(-u, T_{i-1}, T_i)v^2(T_{i-1}) \left. \right] \right|_{F_{T_i}}$$

(7.49)

where the last line defines the constants \( a_0, \ldots, a_3 \). Because the above expression is a Gaussian quadratic form of the variables \( x(T_{i-1}) \) and \( v(T_{i-1}) \), one can evaluate this expectation completely in terms of the means \( \mu_x, \mu_v \), variances \( \sigma_x^2, \sigma_v^2 \) and correlation \( \rho_{xv}(t, T_{i-1}) \) of these two state variables, e.g. see Feuerverger and Wong (2000) or Glasserman (2003). A straightforward evaluation (e.g. by completing the square or by integration the exponential affine function against the bivariate normal distribution) of this Gaussian quadratic expectation results in the characteristic function \( \phi_F(T_{i-1}, T_i, u) \) of (7.41) and hence proves the theorem. □

7.5.2 Forward starting characteristic function under the \( T \)-forward measure

Using lemma 7.4.2 and similar arguments as in the previous section, we can now also derive the characteristic function of \( \ln \frac{S(T)}{S(T_{i-1})} \) under the \( T \)-forward probability measure. This characteristic function can directly be used in the Fourier inversion formula (7.10) to price the forward starting call option (7.9) on the return of the underlying asset in closed-form.

**Theorem 7.5.2** Under the \( T \)-forward measure \( Q^T \), the characteristic function \( \phi_R(T_{i-1}, T_i, u) \) of \( \ln \frac{S(T)}{S(T_{i-1})} \) is given by the following closed-form solution:

$$\phi_R(T_{i-1}, T_i, u) = \exp \left[ b_0 + b_1 \mu_x + \frac{1}{2} b_1^2 \sigma_x^2 \left( 1 - \rho_{xv}^2(t, T_{i-1}) \right) \right] \\
\times \exp \left[ b_2 \mu_v + b_3 \mu_v^2 + \frac{(b_1 \sigma_x \rho_{xv}(t, T_{i-1}) + b_2 \sigma_v + 2b_3 \mu_v \sigma_v^2)^2}{2(1 - 2b_1 \sigma_x \sigma_v)} \right] \sqrt{1 - 2b_3 \sigma_v^2},$$

(7.50)
where:
\[
\begin{align*}
  b_0 & := -iu \ln A_{\text{fin}}(T_{i-1}, T_i) + L(u, T_{i-1}, T_i), \\
  b_1 & := iuB_{\text{fin}}(T_{i-1}, T_i), \\
  b_2 & := N(u, T_{i-1}, T_i), \\
  b_3 & := \frac{1}{2} O(u, T_{i-1}, T_i).
\end{align*}
\] (7.51)

Proof Using analogous arguments as in the proof of theorem 7.5.1, one can obtain the following expression for the characteristic function \( \phi_R \) of \( \ln S(T_i) \) under the \( T_i \)-forward probability measure. Using the tower law of conditional expectations, i.e. conditioning on the time \( T_{i-1} \) filtration \( \mathcal{F}_{T_{i-1}} \), we have that
\[
\phi_R(T_{i-1}, T_i, u) = \mathbb{E}^{\mathbb{Q}^{T_i}}[e^{-iu \ln P(T_{i-1}, T_i) - iu \ln F(T_{i-1}, T_i)} \mathbb{E}^{\mathbb{Q}^{T_i}}[e^{iu \ln F(T_i, T_i)} | \mathcal{F}_{T_{i-1}}] | \mathcal{F}_T].
\]
As the inner expectation is just the characteristic function of \( \ln F(T_i, T_i) \) evaluated in the point \( u \), we can substitute the closed-form expression of lemma 7.4.1 for this characteristic function in the above expression, i.e.
\[
\phi_R(T_{i-1}, T_i, u) = \mathbb{E}^{\mathbb{Q}^{T_i}}[e^{-(iu \ln P(T_{i-1}, T_i) + iu \ln F(T_{i-1}, T_i) + M(u, T_{i-1}, T_i)}} | \mathcal{F}_{T_{i-1}}] | \mathcal{F}_T]
\]
\[=\mathbb{E}^{\mathbb{Q}^{T_i}}[\exp\{b_0 + b_1 x(T_{i-1}) + b_2 v(T_{i-1}) + b_3 v^2(T_{i-1})\} | \mathcal{F}_T].
\] (7.53)

Note that the only difference with the Gaussian quadratic form (7.49) are the dynamics of the processes \( x(T_{i-1}) \) and \( v(T_{i-1}) \), which now instead need to be evaluated under the \( T_i \)-forward measure. Hence it can be evaluated in an analogous way as in the proof of theorem 7.5.1 resulting in the closed-form expression (7.50) for the characteristic function \( \phi_R(T_{i-1}, T_i, u) \) and hence proving the theorem. □

7.6 Numerical results

To investigate the impact of stochastic volatility and stochastic interest rates on the prices of forward starting options, we will consider the following numerical test cases. As the prices of forward starting options can be calculated in closed-form, a Monte Carlo benchmark against the pricing formulas (7.8)-(7.10) forms a standard test case for their implementation. We then explicitly investigate the impact and parameter sensitivities of stochastic interest rates and stochastic volatility on the prices of forward starting options. Finally, we tackle the issue of model risk and compare our framework with the Black and Scholes (1973) and Heston (1993) model, respectively considered in Rubinstein (1991) and Guo and Hung (2008) for the valuation of forward starters.

7.6.1 Implementation of the option pricing formulas

In this section we consider the practical implementation of the pricing formulas (7.8) and (7.10); both the implementation of the inverse Fourier transform, as well as the calculation of the char-
characteristic function underlying this transform, deserve some attention. For the calculation of the inverse Fourier transform we refer the reader to Lord and Kahl (2008), Kilin (2006) and Chapter 3, where this topic is covered in great detail. Instead we focus on the application specific calculation of the characteristic functions (7.41) and (7.50). The calculation of the characteristic functions (7.41) and (7.50) is trivial up to the calculation of the constants $A(u, t, T)$ of (7.24) and $L(u, t, T)$ of (7.36), which involves the calculation of a numerical integral. Hence we focus on the calculation of $A(u, t, T)$, but a completely analogous reasoning holds for the calculation of $L(u, t, T)$.

It is possible to write a closed-form expression for the remaining integral in (7.24). As the ordinary differential equation for $D(u, t, T)$ is exactly the same as in the Heston (1993) or Schöbel and Zhu (1999) model, it will involve a complex logarithm and should therefore be evaluated as outlined in Lord and Kahl (2007) in order to avoid any discontinuities. The main problem however lies in the integrals over $C(u, t, T)$ and $C^2(u, t, T)$, which will involve the Gaussian hypergeometric $\text{}_2F_1(a, b; c; z)$. The most efficient way to evaluate this hypergeometric function (according to Press and Flannery (1992)) is to integrate the defining differential equation. Since all of the terms involved in $D(u, t, T)$ are also required in $C(u, t, T)$, numerical integration of the second part of (7.24) seems to be the most efficient method for evaluating $A(u, t, T)$. Note that we hereby conveniently avoid any issues regarding complex discontinuities altogether. It remains to have a closer look at the implementation of the numerical integral of $A(u, t, T)$ and $L(u, t, T)$.

We compute the prices for short and long-term forward starting option for a range of strikes and where we use fixed-point Gaussian-Legendre quadrature to compute the numerical integral in (7.24) and (7.36). Hereby we vary the number of quadrature points to determine how many points are needed in the test cases to obtain a certain accuracy. The numerical results together with the corresponding Monte Carlo estimates (using $10^6$ sample paths) can be found in Table 1 and 2 below.

<table>
<thead>
<tr>
<th>strike level</th>
<th>CF(4)</th>
<th>CF(8)</th>
<th>CF(16)</th>
<th>CF(1024)</th>
<th>MC (±95% interval)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50%</td>
<td>65.31</td>
<td>65.26</td>
<td>65.26</td>
<td>65.26</td>
<td>65.30 (±0.31)</td>
</tr>
<tr>
<td>75%</td>
<td>53.94</td>
<td>53.85</td>
<td>53.85</td>
<td>53.85</td>
<td>53.89 (±0.29)</td>
</tr>
<tr>
<td>100%</td>
<td>44.97</td>
<td>44.85</td>
<td>44.85</td>
<td>44.85</td>
<td>44.90 (±0.27)</td>
</tr>
<tr>
<td>125%</td>
<td>37.80</td>
<td>37.65</td>
<td>37.65</td>
<td>37.65</td>
<td>37.71 (±0.25)</td>
</tr>
<tr>
<td>150%</td>
<td>32.00</td>
<td>31.82</td>
<td>31.82</td>
<td>31.82</td>
<td>31.89 (±0.24)</td>
</tr>
</tbody>
</table>

Table 1: Closed-form solution prices (CF(N)) using N quadrature points for $A(u, T_1, T_2)$ in (7.24) and Monte Carlo prices (MC) of the forward starting call option (7.6) for $t = 0$, $T_1 = 5$, $T_2 = 15$ and $P(t, T_1) = P(t, T_2) = 1.0$ and model parameters $\kappa = 1.00$, $\nu(0) = \psi = 0.20$, $a = 0.02$, $\sigma = 0.01$, $\tau = 0.50$, $\rho_{SV} = -0.70$, $\rho_{SR} = 0.30$ and $\rho_{rsv} = 0.15$. 
Table 2: Closed-form solution prices (CF(N)) using N quadrature points for $L(u, T_1, T_2)$ in (7.36) and Monte Carlo prices (MC) of the forward starting return call option (7.9) for $t = 0$, $T_1 = 1$, $T_2 = 2$ and $P(t, T_1) = P(t, T_2) = 1.0$ and model parameters $\kappa = 0.30$, $\nu(0) = \psi = 0.15$, $\tau = 0.20$, $\alpha = 0.05$, $\sigma = 0.01$, $\rho_{SV} = -0.40$, $\rho_{SR} = 0.20$ and $\rho_{rv} = 0.10$.

From the tables we see that the characteristic functions (7.41) and (7.50) underlying the option price formulas can be calculated very accurately, using only a small number of quadrature points; the prices of short term options (Table 1) and long-term options (Table 2) can be calculated within a base points accuracy by using respectively just two and eight quadrature points for the calculation of the integral in $A(u, t, T)$ and $L(u, t, T)$. Note hereby that the corresponding Monte Carlo confidence interval is also larger in test case of Table 2, due to the longer dated maturity. Combining the efficient calculation of characteristic functions (7.41) and (7.50) with the efficient Fourier inversion techniques, we can all in all conclude the pricing of forward starting options can be done fast, highly accurate and in closed-form using the latter methods.

### 7.6.2 Impact of stochastic interest rates and stochastic volatility

In this section we will cover the impact of stochastic volatility and (correlated) stochastic interest rates on the prices of forward starting options. That is, we investigate qualitative aspects of our extended framework in comparison to deterministic (or independent) interest rates and volatility assumptions. Rubinstein (1991) considered the pricing of a vanilla forward starting option in the Black and Scholes (1973) framework; as both interest rates and volatilities are deterministic in this model, the prices of a forward starting options are (up to deterministic discounting effects) equal for all forward starting dates. The constant volatility assumption has been relaxed by Lucic (2003), Hong (2004) and Kruse and Nögel (2005), who consider the pricing of forward starting options under Heston (1993) stochastic volatility. The impact of stochastic volatility is graphically shown in the graphs of Figure 1.
7.6. Numerical results

Figure 1: The figures plot, for different option maturities, the impact of stochastic interest rates on the forward implied volatility structure of an underlying call (left pictures) and return call option (right pictures). Parameters are $\kappa = 1.0$, $\nu(t) = \psi = 0.20$, $\tau = 0.5$, $\rho_{SV} = -0.70$, $\rho_{SR} = \rho_{RV} = 0$ and $P(t, s) = \exp(-0.04(s - t))$ for all $s > t$. The top figures plot the volatility structure for deterministic interest rates, whilst the bottom figures plot the volatility structure for stochastic interest rates case with parameters $a = 0.02$ and $\sigma = 0.01$.

Compared to constant volatility, the addition of stochastic volatility increases the future uncertainty about the underlying option price which is hence reflected in higher implied volatilities for longer forward starting dates. Intuitively this effect is rather appealing as this coincides with market prices for forward starting structures where the writer of such an option wants to be compensated for the extra (future) volatility risk he is exposed to. Furthermore it is interesting to note from the figures that these effects are more apparent where the underlying option has a short maturity, which effect may be explained by the mean reverting property of stochastic volatility that is less severe for a short term option hence increasing the future volatility risk. Finally note from the top two graphs of Figure 1 that with deterministic rates the long-term uncertainty approaches a limit (or a stationary state) as the forward starting date or the underlying option maturity increase. For example the implied volatilities for forward starting options with a forward date of ten and thirty years are exactly equal, which is counterintuitive as the term structure of implied
volatilities remains increasing for long-dated options and in general does not flatten out nor approaches a limit, for instance see the implied volatility quotes in long-maturity equity markets (readily available from MarkIT or Bloomberg) or the over-the-counter FX quotes in Piterbarg (2005) or Andreasen (2006).

The inconsistency in the way the market and the latter models look at long-dated implied volatility structures, more likely suggests that these models lack an extra factor in their pricing frameworks; this conjecture is supported by Guo and Hung (2008) and Kijima and Muromachi (2001), who claim that stochastic interest rates are crucial for the pricing of forward starting options as these securities are often much more interest rate sensitive due to their long-term nature. In fact if we look at the bottom graphs of Figure 1, where we add stochastic interest rates to the framework with stochastic volatility, we see that the implied volatilities increase for longer forward starting and maturity dates. These model effects also correspond with a general feature of the interest rate market: the market’s view on the uncertainty of long-maturity bonds is often much higher than that of shorter bond, reflecting the increasing impact of stochastic interest rates for long-dated structures. In this sense stochastic interest rates do seem to incorporate the larger uncertainty the writers of the forward starting options are exposed to.

The addition of stochastic interest rates as independent factor for the pricing of forward starting options has been investigated in Guo and Hung (2008) and Nunes and Alcaria (2009). Though one step in the right direction, the independency assumption is certainly not supported by empirical analysis (e.g. see Baur (2009)) nor do the exotic option markets (such as hybrid equity-interest rate options) price these derivatives in this way, e.g. see Andreasen (2007) or Antonov et al. (2008); from Figure 2 and 3 of Appendix 7.8.3, we see that correlated stochastic interest rates can have a big impact on the prices of forward starting options. From Figure 2 we can see that for a positive rate-asset correlation coefficient the prices of forward starting options increase and vice versa for a negative correlation coefficient. In particular note from Figure 2 that, though the correlation coefficient between the interest rates and the stock also affects the implied volatility structure of the current time vanilla options, the effects on the prices of forward starting options are much more pronounced. Forward starting options are thus not only more interest rate and volatility sensitive, but are also much more exposed to correlation risks. This is not surprising as a joint movement in both the interest rates as the asset price not only affects the future discounting, but more importantly also the (joint) asset price distribution. All in all, we can conclude that because forward starting options are very sensitive to future interest rate movements, volatility smiles as well as their dependency structure with the underlying asset, it is very important to take all these stochastic quantities into account for a proper pricing and risk management of these derivatives.

7.7 Conclusion

We performed a quantitative analysis on the valuation of forward starting options, where we explicitly accounted for stochastic volatility, stochastic interest rates as well as a general dependency structure between all underlying processes. The analysis was made possible by the development of closed-form formulas involving the pricing of the two main forward starting
structures, currently present in the literature and the financial markets. Using a probabilistic approach, we derived closed-form expressions for the characteristic functions of the assets underlying the forward starting options. We then demonstrated how forward starting options can be priced efficiently and in closed-form by Fourier inverting these forward starting characteristic functions. An additional advantage of this technique is that our modelling framework can include jumps as a trivial extension, since we already work in the Fourier option pricing domain.

Our results are of great practical importance as the derivative markets for long-dated dynamic securities such as forward starting options have grown very rapidly over the last decade; compared to vanilla options, these structures directly depend on future volatility smiles, the term structure of interest rates as well as their dependency structure with the underlying asset. Moreover, as these contracts often incorporate long-dated maturities, we found that it is of crucial importance to take stochastic interest rates, volatility and a general correlation structure into account for a proper valuation and hedging of these securities: not doing so leads to serious mispricings, not to mention the potential hedge errors. Compared to other models, the analysis performed in our framework stands out by modelling both the stochastic volatility and interest rates, as well as taking a general correlation structure between all underlying drivers explicitly into account.

Besides investigating the behaviour of these dynamic derivatives, our formulas can also be used to directly price or hedge financial contracts. For instance unit-linked guarantees embedded in life insurance products, being sold in large amounts by insurance companies, can be priced in closed-form relying on our formulas. The same applies for cliquet options, which are heavily traded in over-the-counter markets, and CEO/employee stock option plans. Furthermore, there is a big interaction between forward starting options considered here and over-the-counter exotic structures such as ratchet options and pension contracts, as these form the natural building blocks and hedge instruments for such contracts. Finally, as all the above-mentioned products explicitly depend on the future volatility smiles, the term structure of interest rates as well as their dependency structure with the underlying asset, we judge that a proper valuation framework should account for all these characteristics.
7.8 Appendix

7.8.1 Calculation of the moments for the rate processes under different measures

Stock price measure

For the computation of the characteristic functions from Theorem 7.5.1 one needs the first two moments of \( x(T_{i-1}) \) and \( v(T_{i-1}) \) (conditional on the \( \sigma \)-algebra \( F_i \)) under the stock price measure \( Q^S \). For completeness, we will therefore explicitly provide the analytical expressions for these moments: integrating the dynamics (7.17) and using Fubini’s theorem, results (after some algebra) in the following explicit solutions:

\[
v(T_{i-1}) = \tilde{\psi} + \left( v(t) - \tilde{\psi} \right) e^{-\tilde{x}(T_{i-1} - t)} + \tau \int_t^{T_{i-1}} e^{-\tilde{x}(T_{i-1} - u)} dW^Q_v(u),
\]

\[
x(T_{i-1}) = \rho_S \sigma \left[ \frac{\tilde{\psi}}{a} \left[ 1 - e^{-a(T_{i-1} - t)} \right] + \frac{v(t) - \tilde{\psi}}{a - \tilde{\kappa}} \left[ e^{-\tilde{x}(T_{i-1} - t)} - e^{-a(T_{i-1} - t)} \right] \right]
+ \rho_S \sigma \tau \int_t^{T_{i-1}} \left[ e^{-\tilde{x}(T_{i-1} - u)} - e^{-a(T_{i-1} - u)} \right] dW^Q_v(u) + \sigma \int_t^{T_{i-1}} e^{-a(T_{i-1} - u)} dW^Q_r(u).
\]

Using Itô’s isometry, one therefore has that the pair \( (v(T), x(T)) \), under the stock price measure and conditional on \( F_i \), follow a bivariate normal distribution with means \( \mu_v, \mu_x \), variances \( \sigma_v^2, \sigma_x^2 \) and correlation \( \rho_{vx}(t, T_{i-1}) \) respectively given by

\[
\mu_v = \tilde{\psi} + \left( v(t) - \tilde{\psi} \right) e^{-\tilde{x}(T_{i-1} - t)} \tag{7.54}
\]

\[
\sigma_v^2 = \frac{\tau^2}{2\tilde{\kappa}} \left( 1 - e^{-2\tilde{x}(T_{i-1} - t)} \right) \tag{7.55}
\]

\[
\mu_x = \rho_S \sigma \left[ \frac{\tilde{\psi}}{a} \left[ 1 - e^{-a(T_{i-1} - t)} \right] + \frac{v(t) - \tilde{\psi}}{a - \tilde{\kappa}} \left[ e^{-\tilde{x}(T_{i-1} - t)} - e^{-a(T_{i-1} - t)} \right] \right], \tag{7.56}
\]

\[
\sigma_x^2 = \sigma_v^2 + \sigma^2 + 2\rho_x \sigma_1 \sigma_2, \tag{7.57}
\]

\[
\rho_{vx}(t, T_{i-1}) = \frac{\rho_{vx} \sigma^2}{\sigma_v \sigma_x (a + \kappa)} \left[ 1 - e^{-(a+\tilde{\kappa})(T_{i-1} - t)} \right], \tag{7.58}
\]

\]
7.8. Appendix

where

\[ \sigma_1 = \sigma \sqrt{1 - e^{-2a(T_i - t)}} \]

\[ \sigma_2 = \frac{\rho_{S_i}\sigma^\tau}{a - \kappa} \sqrt{\frac{1}{2\kappa} + \frac{1}{2a} - \frac{2}{(\kappa + a)} - \frac{e^{-2\kappa(T_i - t)}}{2\kappa} - \frac{e^{-2a(T_i - t)}}{2a} + \frac{2e^{-\kappa(x)(T_i - t)}}{(\kappa + a)}} \]

\[ \rho_{12} = \rho_{r\nu} \frac{\sigma_1^2 \rho_{S_i}\sigma^\tau}{\sigma_1 \sigma_2 (a - \kappa)} \left[ \frac{1 - e^{-2(x)(T_i - t)}}{(a + \kappa)} - \frac{1 - e^{-2a(T_i - t)}}{2a} \right] \]

**T-forward measure**

For computing the characteristic functions from theorem 7.5.2, the first moments of \( x(T_i - t) \) and \( \nu(T_i - t) \) under the \( T_i \)-forward measure \( Q^T_i \) are needed; one can obtain the following explicit solutions for \( x(T_i - t) \) and \( \nu(T_i - t) \) by direct integration of the corresponding \( T_i \)-forward dynamics, i.e.

\[ x(T_i - t) = x(t)e^{-a(T_i - t)} - MT_i(t, T_i - t) + \sigma \int_t^{T_i} e^{-a(T_i - t - u)} dW^T_i(u), \]

\[ \nu(T_i - t) = \nu(t)e^{-\kappa(T_i - t)} + \int_t^{T_i} \xi(u)e^{-\kappa(T_i - t - u)} du + \int_t^{T_i} \nu(t)e^{-\kappa(T_i - t - u)} dW^T_{\nu}(u), \]

where

\[ \xi(u) := \psi - \frac{\rho_{r\nu}\sigma^\tau}{ak}(1 - e^{a(T_i - u)}), \]

\[ MT_i(t, T_i - t) := \frac{\sigma^2}{a^2}(1 - e^{-a(T_i - t)}) - \frac{\sigma^2}{2a^2}(e^{-a(T_i - t)} - e^{-a(T_i + T_i - 2t)}). \]

Hence, from Itô’s isometry, we immediately have that the pair \( \left( \nu(T_i - t), x(T_i - t) \right) \), under the \( T_i \)-forward measure and conditional on \( F_i \), follows a bivariate normal distribution, respectively with means \( \mu_r, \mu_x \), variances \( \sigma^2_r u^2, \sigma^2_x \) and correlation \( \rho_{rx}(t, T_i - t) \) given by

\[ \mu_r = \nu(t)e^{-\kappa(T_i - t)} + \left( \psi - \frac{\rho_{r\nu}\sigma^\tau}{ak} \right)(1 - e^{-\kappa(T_i - t)}) \]

\[ -\frac{\rho_{r\nu}\sigma^\tau}{a(k + \alpha)} (e^{-a(T_i - t) - \kappa(T_i - t)} - e^{-a(T_i - T_i - t)}), \]

\[ \sigma^2_r = \frac{\tau^2}{2\kappa}(1 - e^{-2\kappa(T_i - t)}), \]

\[ \mu_x = x(t)e^{-a(T_i - t)} - MT_i(t, T_i - t), \]

\[ \sigma^2_x = \frac{\sigma^2}{2a^2}(1 - e^{-2a(T_i - t)}), \]

\[ \rho_{rx}(t, T_i - t) = \frac{\rho_{r\nu}\sigma^\tau}{\sigma_r \sigma_x (a + \kappa)} \left[ 1 - e^{-a\kappa)(T_i - t)} \right]. \]
7.8.2 Impact of the rate-asset correlation coefficient on the forward starting options

Figure 2: Impact of the rate-asset correlation $\rho_{Sr}$ on the (forward) implied volatility structure. for different underlying call option maturities. Parameters are $\kappa = 1.0$, $\nu(t) = \psi = 0.20$, $\tau = 0.5$, $a = 0.02$, $\sigma = 0.01$, $\rho_{S\nu} = -0.70$, $\rho_{r\nu} = 0$ and $P(t,s) = \exp(-0.04(s-t))$ for all $s > t$. The top figure shows the impact of this correlation on the volatilities of the current time (vanilla) options, whereas the bottom figure plots these volatility structures for forward starting call options with strike determination date $T_1 = 10$ year.
7.8. Appendix

7.8.3 Impact of the rate-volatility correlation coefficient on the forward starting options

Figure 3: Impact of the rate-volatility correlation $\rho_{rv}$ on the (forward) implied volatility structure. for different underlying call option maturities. Parameters are $\kappa = 1.0$, $\nu(t) = \psi = 0.20$, $\tau = 0.5$, $a = 0.02$, $\sigma = 0.01$, $\rho_{SV} = -0.70$, $\rho_{Sr} = 0$ and $P(t, s) = \exp(-0.04(s - t))$ for all $s > t$. The top figure graphs the impact of this correlation on the volatilities of the current time (vanilla) options, whereas the bottom figure plots these volatility structures for forward starting call options with strike determination date $T_1 = 10$ year.