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Vorwort

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Darüber hinaus bietet die Reihe ein Forum für die Berichterstattung über die zahlreichen Kooperationsprojekte des Instituts mit Partnern aus Industrie und Wirtschaft.

Berichterstattung heißt hier Dokumentation des Transfers aktueller Ergebnisse aus mathematischer Forschungs- und Entwicklungsarbeit in industrielle Anwendungen und Softwareprodukte – und umgekehrt, denn Probleme der Praxis generieren neue interessante mathematische Fragestellungen.

Prof. Dr. Dieter Prätzel-Wolters
Institutsleiter

Kaiserslautern, im Juni 2001

Quanto Option Pricing in the Parsimonious Heston Model

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23rd September 2009

In this work we use the Parsimonious Multi–Asset Heston model recently developed in [Dimitroff et al., 2009] at Fraunhofer ITWM, Department Financial Mathematics, Kaiserslautern (Germany) and apply it to Quanto options. We give a summary of the model and its calibration scheme. A suitable transformation of the Quanto option payoff is explained and used to price Quantos within the new framework. Simulated prices are given and compared to market prices and Black–Scholes prices. We find that the new approach underprices the chosen options, but gives better results than the Black–Scholes approach, which is prevailing in the literature on Quanto options.

Contents

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1. Introduction

In this work we apply a multi–asset Heston Model developed in [Dimitroff et al., 2009] to the pricing of Quanto Options. The advantage of the proposed model is that it can reasonably explain market features like volatility smiles, as it is based on Heston's stochastic volatility model. The model features a parsimonious correlation structure. Assuming this structure, the model can be calibrated using plain vanilla options and a correlation parameter, which can be obtained from time series data. We give a summary of the model in section 2.
We apply this model to the pricing of Quanto options. These are options whose payoff is in another currency as the underlying is traded. The term Quanto is short for quantity adjusted. The (fixed) exchange rate incorporated in these options is called Quanto rate and is usually set to 1. An investior can use Quanto options when he wants to participate in gains in the underlying, but without carrying risks from the foreign exchange (FX) rate. The Quanto feature can also be applied to other derivatives like futures. In section 3 we explain how to apply the model to Quanto options. We then price two different options on two different dates with the model and compare the obtained prices with market and Black–Scholes prices in section 4.

2. Parsimonious Heston Model

We summarise the work of [Dimitroff et al., 2009] in this section. They propose a multi–asset Heston Model, which can be calibrated to market data easily. It is parsimonious in the sense that it does not allow all Brownian motions in the model to be correlated, reflecting the fact that the correlation of latent variables (such as volatilities) are not observable in contrast to the asset-asset correlation.
For each asset $S_i(t), i = 1, 2, \ldots, d$, a single Heston model is proposed, i.e.

$$\begin{pmatrix} dS_i(t) \\ d\nu_i(t) \end{pmatrix} = \begin{pmatrix} S_i(t)(r(t) - q_i(t)) \\ \kappa_i\left(\overline{\nu}_i - \nu_i(t)\right) \end{pmatrix} dt + \begin{pmatrix} S_i(t)\sqrt{\nu_i(t)} & 0 \\ 0 & \eta_i\sqrt{\nu_i(t)} \end{pmatrix} \begin{pmatrix} 1 & 0 \\ \rho_i & \sqrt{1-\rho_i^2} \end{pmatrix} \begin{pmatrix} dW_i(t) \\ d\widetilde{W}_i(t) \end{pmatrix}, \quad (1)$$

where $W_i(t)$ and $\widetilde{W}_i(t)$ are independent Wiener processes. For each $i = 1, 2, \ldots, d$, the correlation between the asset's price process $S_i(t)$ and its variance $\nu_i(t)$ is described by ρ_i. The variance process $\nu_i(t)$ is mean–reverting with mean–reversion level $\overline{\nu}_i$, mean-reversion speed κ_i and so-called volatility of volatility η_i. The parameters describing each single model are collected in $\theta_i = (\rho_i, \kappa_i, \overline{\nu}_i, \nu_i(0), \eta_i)$. It should be pointed out that the representation above is usually used for the representation under the risk–neutral measure $\mathbb{Q}$, and we interpret $r(t)$ as the risk–free rate, and $q_i(t)$ as a continuous dividend yield. Under the physical measure $\mathbb{P}$, which we would observe in empirical studies on time–series data, the drift $r(t) - q_i(t)$ is interpreted as the expected long–term growth of the stock, which is not directly linked to the interest rate. We will specify the underlying

measure where appropriate.
Under the risk–neutral measure, we can obtain the single Heston parameters by a calibration on plain vanilla options as described in [Nögel and Mikhailov, 2003].
In the following, we restrict the presentation of the model to the two–asset case. In the more general, say d-asset case, model calibration reduces to calibrating $d(d-1)/2$ two asset submodels and a regularisation of the resulting correlation matrix as described in [Dimitroff et al., 2009].
In the two asset case, three cross–correlations[1] are involved: asset–asset, asset–volatility, and volatility–volatility. The latter two are hard to estimate from market data, as volatility is usually not a traded asset. Moreover, derivatives dependend on these correlations are, if available at all, usually not liquid enough and not traded for a suitable number of strikes and maturities. Therefore they can not be used for calibration.
The proposed model can be calibrated using the single Heston parameters $\theta_i, i = 1, 2$, and an empirical asset–asset correlation only. The following assumptions are made (see [Dimitroff et al., 2009, Assumption 2.1]):

Assumption 1. *The Wiener processes $W(t)$ and $\widetilde{W}(t)$ satisfy:*

1. $dW_1(t)dW_2(t) = \rho\ dt$
2. $d\widetilde{W}_1(t)d\widetilde{W}_2(t) = 0\ dt$
3. *$W(t)$ and $\widetilde{W}(t)$ are independent*

The first statement models the asset–asset correlation in the model. The second statement is that the additional Brownian motions contributing to the driving noise of the volatility are independent. This does not result in independent variance processes, as

$$d\nu_1(t)\, d\nu_2(t) = \rho\, \rho_1\, \rho_2\, \eta_1\, \eta_2 \sqrt{\nu_1(t)\, \nu_2(t)}\, \mathrm{d}t, \tag{2}$$

[Dimitroff et al., 2009, Proposition 2.2]
The third assumption is that on the cross–correlations asset–volatility, which results in $(i, j = 1, 2)$

$$dS_i(t)dv_j(t) = \rho\rho_i S_i(t)\eta_j \sqrt{v_i(t)v_j(t)}\ dt,$$

[Dimitroff et al., 2009, Proposition 2.2]
i.e. the price process of an asset and the volatility process of another asset are not independet. Their correlations are carried by the single Heston correlations and the asset–asset correlation.
The instananeous correlation ρ in the two–dimensional Wiener Process $W(t)$ is *not* directly observable from the market. However, it can be calculated using the estimated correlation of the log–returns.

[1] The term *cross–correlations* is used if the factors belong to different single Heston models.

Definition 2 (Log–returns)**.** *Consider a fixed time interval* $[0,T]$ *and a partition* $\Pi = (t_k), k = 0,1,\ldots,K$*. Suppose we have stock price data* $S(t_k)$ *for each* $k = 0,1,\ldots,K$*. Define* $X(t_k), k = 1,2,\ldots,K$*, to be the* Log–returns *of* S *(with respect to* Π*), i.e.*

$$X(t_k) = \ln\left(\frac{S(t_k)}{S(t_{k-1})}\right) = \ln S(t_k) - \ln S(t_{k-1}).$$

Definition 3 (Correlation Estimator)**.** *The* estimator for correlation between S^1 and S^2*,* $\hat{\rho}$*, is given by*

$$\hat{\rho} = \hat{\rho}(\rho) = \frac{\frac{1}{K-1}\sum_{k=1}^{K}(X_1(t_k) - \bar{X_1})(X_2(t_k) - \bar{X_2})}{\sqrt{\frac{1}{K-1}\sum_{k=1}^{K}(X_1(t_k) - \bar{X_1})^2 \frac{1}{K-1}\sum_{k=1}^{K}(X_2(t_k) - \bar{X_2})^2}},$$

where ρ *is the correlation between the Brownian motions driving* S^1 *and* S^2 *in the parsimonious Heston model,* X_i *the Log–returns of asset* S_i *with respect to* Π*, and*

$$\bar{X_i} = \frac{1}{K}\sum_{k=1}^{K} X_i(t_k)$$

the mean value of X_i*,* $i = 1,2$*.*

[Dimitroff et al., 2009] prove the following theorem.

Theorem 4 (Properties of $\hat{\rho}$)**.** *Let* $(S_i(t), v_i(t)), i = 1,2$*, be the processes defined in* (1) *and suppose Assumption 1 holds. Let* $\Pi_n = (t_k), k = 0,1,\ldots,K_n$ *be partitions of* $[0,T]$ *with* $t_0 = 0$*,* $t_{K_n} = T$*, and* $\max_{i=1,\ldots,K_n(T)} |t_{i,n} - t_{i-1,n}| \to 0$ *for* $n \to \infty$ *and suppose* $\mathbb{E}v_i(\infty) \neq 0, i = 1,2$*. We then have*

$$\lim_{T\to\infty}\lim_{n\to\infty}\hat{\rho}(\rho) = \rho\frac{\mathbb{E}\left(\sqrt{v_{12}(\infty)}\right)}{\sqrt{\mathbb{E}v_1(\infty)\mathbb{E}v_2(\infty)}} \text{ in probability,} \tag{3}$$

where $v_i(\infty), i = 1,2$*, and* $v_{12}(\infty)$ *are random variables with the stationary distribution of* $v_i(t), i = 1,2$*, and* $v_1(t)v_2(t)$*, respectively. Note that* $v_{12}(\infty)$ *depends on* ρ*. [Dimitroff et al., 2009, Theorem 2.3, (2)]*

Using the result in equation (3), we are able to recover the instananeous correlation ρ from the empirical correlation $\rho^{emp} = \hat{\rho}$. At this point it is important how we obtained ρ^{emp}. [Dimitroff et al., 2009] discuss the following two cases:

Case 1 ρ^{emp} is the correlation from historical asset price data, i.e. observed under the physical measure $\mathbb{P}$ using the estimator from definition 3.

Case 2 ρ^{emp} is the correlation under the risk–neutral measure $\mathbb{Q}$, for instance given by an experienced trader.

This distinction is important as it influences the calibration procedure. In our empirical study, we have no given value for the asset–asset correlation ρ^{emp} and therefore have to estimate it from historical data, i.e. in this work we have to follow the procedure for case 1, which is outlined in detail in [Dimitroff et al., 2009, Section 3.2].
The main idea is to adjust the correlation ρ in $W(t)$ such, that the empirical correlation of generated paths (measured as in definition 3) matches the historical correlation ρ^{emp}. The simulations can be done e.g. using a simple Euler–scheme with full truncation in case of negative variance (see [Lord et al., 2006]). The paths have to be generated under the physical measure $\mathbb{P}$, as ρ^{emp} comes from historical data[2]. However, the calibration routine for the single Heston model gives us the risk–neutral parameters only. We therefore have to suitably transform the parameters for a model representation under the physical measure.
[Dimitroff et al., 2009, 3.2] argue that for our purpose we can assume a market price of risk equal to zero, i.e. we need not to make changes in the parameters of the asset price process. However, we have to adjust the parameters in the variance process. Denote the physical parameter set by θ^* (ommiting the index i, as this is a one–dimensonal problem) and the risk–neutral parameter set by θ. Under the assumptions in [Heston, 1993], especially on the shape of the market price of risk, we have the following relations:

$$\begin{aligned} &\rho = \rho^*, \;\; \eta = \eta^* \\ &\kappa = \kappa^* + \lambda \\ &\bar{\nu} = \frac{\kappa^* \bar{\nu}^*}{\kappa^* + \lambda} = \frac{\kappa^* \bar{\nu}^*}{\kappa}. \end{aligned} \tag{4}$$

It is therefore sufficient to estimate $\bar{v}^*$, the mean reversion level of the variance process under the physical measure $\mathbb{P}$, in order to obtain θ^* from θ. [Dimitroff et al., 2009, Proposition 5.1] prove the following estimator for partitions $\pi_n = (t_{k,n})_{k=1,\dots,K_n(T)}$ of $[0,T]$ with $\max_{i=1,\dots,K_n(T)} |t_{i,n} - t_{i-1,n}| \to 0$, for $n \to \infty$, and the log returns $X(t_k) = \log \frac{S(t_k)}{S(t_{k-1})}$:

$$\lim_{T \to 0} \lim_{n \to \infty} \frac{1}{T} \sum_{k=1}^{K_n(T)} X^2(t_k) = \bar{\nu}^* \text{ in probability} \tag{5}$$

To conclude this section, we give an overview on the calibration steps. We will use this in section 4 to measure the performance of the model on Quanto options.

Historical Correlation Calculate the historical correlation ρ^{emp} between $S_1(t)$ and $S_2(t)$ using definition 3.

Heston Calibration Calibrate the single Heston models for $S_i(t), i = 1, 2$ and obtain the $\mathbb{Q}$–parameters $\theta_i, i = 1, 2$.

Physical Parameters Estimate $v_i^*, i = 1, 2$, and obtain the $\mathbb{P}$–parameters $\theta_i^*, i = 1, 2$.

[2] If we were in case 2 above, we would have to simulate under the risk–neutral measure.

Calibration Simulate paths of $(S_i(t), \nu_i(t)), i = 1, 2$, under the physical measure $\mathbb{P}$ (using an Euler–scheme) and adjust ρ such, that the empirical correlation of the generated paths (using definition 3) matches ρ^{emp}. This is done using a bisection algorithm.

Monte-Carlo Simulation Simulate paths of $(S_i(t), \nu_i(t)), i = 1, 2$ under the risk–neutral measure $\mathbb{Q}$ and obtain the fair price of the derivative as the mean payoff from the simulated paths (Monte–Carlo method).

3. Quanto Options in the Model

In this section we show how to apply the Parsimonious Heston model to the pricing of Quanto options. This is a multi–asset problem, as we need to model the stock price and the exchange rate. Research on Quanto options has focussed on the Black–Scholes setup, which is for example discussed in detail in [Baxter and Rennie, 1996].
We assume a domestic and foreign market. The domestic market uses domestic currency DOM and the foreign market foreign currency FOR, respectivly. Suppose a Quanto European call option with payoff

$$P(S(T)) = C^*(S(T) - k)^+ \text{ DOM}, \tag{6}$$

where $S(t)$ denotes the price of the underlying at time t, C^* the Quanto rate (in $\frac{\text{DOM}}{\text{FOR}}$), and k the strice price. We suppose the option has been written at time 0 with maturity T, i.e. $t \in [0.T]$. Note that the underlying $S(t)$ is traded on the foreign market and therefeore $S(t)$ and k are denoted in foreign currency FOR.
The Quanto option with payoff (6) is for a domestic investor. For pricing the option, we consider the payoff from a foreign investor's point of view[3], i.e.

$$\tilde{P}(S(T)) = C(T)C^*(S(T) - k)^+ \text{ FOR}, \tag{7}$$

where $C(t)$ is the FX rate at time t quoted as foreign currency per unit of domestic currency, i.e.

$$C(t) \equiv \frac{\text{foreign currency}}{\text{domestic currency}}.$$

The following proposition connects the two payoff functions.

Proposition 5. *Denote the value at time $0 \leq t \leq T$ of an option with payoff (6) by $V(t)$ and the value of an option with payoff (7) by $\tilde{V}(t)$. We then have*

$$C(t)V(t) = \tilde{V}(t) \ \forall t \in [0, T].$$

Proof. The proof follows a no–arbitrage argument[4]. We call option with payoff (6) Q and option with payoff (7) $\tilde{Q}$ and denote their values $V(t)$ and $\tilde{V}(t)$, respectively.

[3] In [Reiner, 1992], this is called the *foreign market method*.

[4] As there exists a risk–neutral measure in Heston's model (see [Wong and Heyde, 2006]), the model must be arbitrage free (first fundamental theorem of arbitrage-free pricing).

Suppose $C(t)V(t) < \tilde{V}(t)$ and consider a foreign investor. The arbitrage strategy is as follows: At time t, buy one option Q and sell one option $\tilde{Q}$. We then have a positive (foreign) cash flow at time t, which is given by

$$\tilde{V}(t) - C(t)V(t) > 0.$$

This is a risk–free position, as at terminal time T we have (in foreitgn currency)

$$-\widetilde{P}(S(T)) + C(T)P(S(T)) = 0,$$

which completes the argument.
For $V(t) > C(t)\tilde{V}(t)$ we choose an opposite strategy. Buy one option $\tilde{Q}$ and sell one option Q. The proof is an analogue of the above. □

In order to get the price $V(t)$ of option with payoff (6), we use the Parsimonious Heston model to obtain $\tilde{V}(t)$, the value of option with payoff (7), and then use Proposition 5. The model we work with is given in the following.

Model 6 (Parsimonious Heston model for Quanto options)**.** *Suppose the Parsimonious Heston model as outlined in section 2. Let $\overline{W}$ be an uncorrelated, 4-dimensional Brownian motion. Then the model in its risk–neutral representation takes the following form:*

$$\begin{pmatrix} dS(t) \\ d\nu_1(t) \\ dC(t) \\ d\nu_2(t) \end{pmatrix} = \begin{pmatrix} (u(t) - q(t))S(t) \\ \kappa_1(\bar{\nu}_1 - \nu_1(t)) \\ (u(t) - r(t))C(t) \\ \kappa_2(\bar{\nu}_2 - \nu_2(t)) \end{pmatrix} dt +$$
$$+ \; diag \begin{pmatrix} \sqrt{\nu_1(t)}S(t) \\ \eta_1\sqrt{\nu_1(t)} \\ \sqrt{\nu_2(t)}C(t) \\ \eta_2\sqrt{\nu_2(t)} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 & 0 \\ \rho_1 & \sqrt{1-\rho_1^2} & 0 & 0 \\ \rho & 0 & \sqrt{1-\rho^2} & 0 \\ \rho\rho_2 & 0 & \rho_2\sqrt{1-\rho^2} & \sqrt{1-\rho_2^2} \end{pmatrix} \begin{pmatrix} d\overline{W}_1(t) \\ d\overline{W}_2(t) \\ d\overline{W}_3(t) \\ d\overline{W}_4(t) \end{pmatrix}, \tag{8}$$

where $(S(t), \nu_1(t))$ models the stock price and its variance, and $(C(t), \nu_2(t))$ the FX rate and its variance with correlation ρ_1 and ρ_2, respectively. The parameters of the single Heston models are as in section 2. The instantaneous asset–asset correlation is ρ. The domestic risk–free rate is denoted by $r(t)$, the foreign risk free rate by $u(t)$, and the continuous dividend yield of the stock by $q(t)$.

The FX rate has drift $u(t) - r(t)$, as a foreign investor who owns domestic currency will not just keep the money in his deposit, but invest it in the domestic risk–free bond. The FX rate can therefore be regarded as an asset paying a continuous dividend of $r(t)$. Once the model is calibrated, we obtain a price for the Quanto European call option with payoff

$$P(S(T)) = C^*(S(T) - k)^+ \text{ DOM}$$

in two steps.

Issue	29.11.2007
Maturity	21.05.2010
Entitlement	0.1
Strike Price	800/1000 USD
Underlying	Gold per troy ounce, quoted in USD
Settlement Currency	EUR
Quanto Rate	1.00 EUR/DOL

Table 1: Parameters of ABN Amro Gold American Quanto Calls, (ISIN NL0006136715, NL0006136723).

Monte–Carlo Simulation Simulate a reasonable number of paths of Model 6 under $\mathbb{Q}$ and calculate

$$\widetilde{P}(S(T)) = C(T)C^*(S_T - k)^+$$

for each path. Take the mean value of the single payoffs as an approximation to the expected payoff $\mathbb{E}\widetilde{P}(S(T))$.

Transformation Using the current FX rate, $C(t)$ (which has already been observed in the calibration procedure), calculate the value of the option as

$$V(t) = \frac{1}{C(t)} e^{-\int_t^T u(s)ds} \mathbb{E}\widetilde{P}(S(T)),$$

with the approximation of $\mathbb{E}\widetilde{P}(S(T))$ from the Monte–Carlo step.

The first step is common in the calculation of option prices, for which no analytic solutions exist. The second step is due to the approach we have taken for valuating Quanto options.

4. Empirical Performance

For our empirical analysis, we chose two **Gold American Quanto Calls**, issued by ABN AMRO Bank on 29th November 2007 with strike price 800 USD (ISIN: NL0006136715) and 1000 USD (ISIN: NL0006136723), respectively. In the following, we will call these options *Quanto800* and *Quanto1000*, where the number corresponds to its strike price. We summarised the option parameters in Table 1. A corresponding termsheet for the Quanto1000 option can be found in Appendix A. The underlying is Gold Bullion LBM USD/Troy Ounce, which pays no dividend, so $q(t) = 0\ \forall t$. For simplicity, we take the risk–free rates to be constant. We have chosen them as the (interpolated) zero rates at maturity.
Even though our theory is for European options only, we also can apply it to an American Call. This is from the well-known fact, that there is no advantage in an early exercise of an American Call (in case of no dividends in the underlying).

Product	DS Code	Date/Period
Quanto Option	1839KU	12.08.2009
Gold	GOLDBLN	13.08.2008 - 12.08.2009
EUR-DOL FX rate	USECBSP	13.08.2008 - 12.08.2009
EUR Zero Curve	EM00Y00, EM00Y01, ..., EM02Y00	12.08.2009 - 12.08.2011
DOL Zero Curve	US00Y00, US00Y01, ..., US02Y00	12.08.2009 - 12.08.2011
Call Options on EUR		various maturities and strikes
Call Options on Gold		various maturities and strikes

Table 2: Summary of the obtained Data from Thomson Datastream on 12.08.2009. An analogue dataset has been obtained on 28.08.2009.

	12.08.2009	28.08.2009
Quanto800 EUR	19.09	19.42
Quanto1000 EUR	8.48	8.45
Gold Bullion LBM USD/Troy Ounce	948.25	948.25
FX rate USD/EUR	1.417	1.436

Table 3: Spot prices on 12.08.2009 and 28.08.2009.

We obtained all relevant data from Thomson Datastream on 12.08.2009 and on 28.08.2009. A summary is given in Table 2. The relevant spot prices are given in Table 3.

In a first step we used the call options and their implied volatilities to calibrate the single Heston Models for the FX rate DOL/EUR and for Gold Bullion LBM USD/Troy Ounce. We left out all options maturing in less than three months time as the Heston model is not suitable for short maturities. We did the calibration using an internal tool developed at Fraunhoer ITWM, Dep. Financial Mathematics. Note that we obtain the parameters for the risk-neutral representation of the processes. Using the time series of FX rate and Gold, we obtain the physical mean reversion level by equation (5) and the physical mean reversion speed by equation (4). The calibration results are given in Tables 4 and 5. The empirical correlation ρ^{emp} and the correlation ρ of $W(t)$, the Wiener process driving the price processes, are given in Table 6.
The option prices are summarised in Table 7. We also calculated two Black-Scholes values for each Quanto (see appendix B for the Black-Scholes pricing formula) and summarised the results in Table 8 and 9. For the first calculation, we used the (square-root of) mean reversion level as volatility parameter in the Black-Scholes setup, in the second calculation we used the (square root of) inital variance. The second approach is reasonable due to the relatively short time to maturity in our examples. For the correlation parameter in Black-Scholes, we used the empirical correlation ρ^{emp}. It can be seen that the proposed model underprices the Quanto options in all cases. The

	12.08.2009	28.08.2009
Interest Rate USD	0.63 %	0.46 %
Interest Rate EUR	1.09 %	1.00 %
Initial Variance	4.03 %	1.43 %
Mean Reversion Speed	158.09 %	38.38 %
Mean Reversion Level	0.23 %	1.64 %
Volatility of Volatility	8.53 %	10.84 %
Correlation	30.51 %	35.60 %
Physical Mean Reversion Speed	12.84 %	22.16 %
Physical Mean Reversion Level	2.83 %	2.83 %

Table 4: Calibrated Heston Paramters for the FX rate EUR/USD * 100.

	12.08.2009	28.08.2009
Interest Rate USD	0.63 %	0.46 %
Initial Variance	7.48 %	6.89%
Mean Reversion Speed	81.51 %	61.14 %
Mean Reversion Level	7.11 %	8.78 %
Volatility of Volatility	34.05 %	32.76 %
Correlation	46.47 %	33.90 %
Physical Mean Reversion Speed	60.82 %	58.17 %
Physical Mean Reversion Level	9.53 %	9.23 %

Table 5: Calibrated Heston Paramters for Gold Bullion LBM USD/Troy Ounce.

	12.08.2009	28.08.2009
Empirical Correlation ρ^{emp}	28.27 %	27.95 %
Model Correlation ρ	32.81 %	32.81 %

Table 6: Correlation Paramters for Quanto Pricing.

	12.08.2009	28.08.2009
Quanto800	18.13 EUR (-5.03 %)	17.70 EUR (-8.86 %)
Quanto1000	7.41 EUR (-12.62 %)	6.79 EUR (-19.64 %)

Table 7: Prices obtained using the Parsimonious Heston Model and error compared to market price (in brakets).

	12.08.2009	28.08.2009
Quanto800	16.82 EUR (-11.89 %)	17.12 EUR (-11.84 %)
Quanto1000	6.62 EUR (-21.93 %)	7.11 EUR (-15.86 %)

Table 8: Prices obtained using the Black-Scholes model and error compared to market price (in brakets). For volatility, we used the square-root of mean-reversion level.

	12.08.2009	28.08.2009
Quanto800	16.44 EUR (-13.88 %)	16.40 EUR (-15.55 %)
Quanto1000	6.25 EUR (-26.30 %)	6.09 EUR (-27.93 %)

Table 9: Prices obtained using the Black-Scholes model and error compared to market price (in brakets). For volatility, we used the square-root of inital variance.

corresponding Black–Scholes prices are mostly even worse, except for the Quanto1000 on 28.08.2009, where the Black–Scholes price with mean–reversion level as variance performs slightly better. In general it can be said that the Parsimonious Heston model does give better prices than the Black–Scholes approach. The higher market price can have various reasons:

- The market for these options is not liquid enough. This is supported by the fact that to our knowlege only ABN Amro offers Gold Quanto contracts at the moment.
- Traders do pay a premium for the 'American' feature of the option, even though theory tells them not to do so.

A. Termsheet

A summary of the product we were using as reference can be found in Figure 1. The termsheet can be found online at:

`http://www.abnamrozertifikate.de/MediaLibrary/Document/PDF/ProductDocuments/NL0006136749/NL0006136749\_DE\_Prospectus.pdf` (27.08.2009)

Summary of Offering

Issuer	ABN AMRO Bank N.V. (incorporated in The Netherlands with its statutory seat in Amsterdam), London branch
Series	Gold American Quanto Call Warrants Series D
Number of Securities	50,000
Underlying	Gold (Bloomberg code: GOLDS)
Issue Price	EUR 9.047
Entitlement	0.1
Strike Price	USD 1000.00
Expiration Date	21 May 2010
Issue Date	29 November 2007
Settlement	Cash
Settlement Date	5 Business Days following the Valuation Date
Settlement Currency	EUR
Calculation Agent	ABN AMRO Bank N.V., London branch
Principal Agent	ABN AMRO Bank N.V., London branch
Clearing	Clearstream Banking AG, Clearstream Banking S.A, Euroclear Bank S.A.
ISIN	NL0006136723
WKN	AA0SGT

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Figure 1: Termsheet for `NL0006136723`.

B. Quanto Options in a Black-Scholes Setup

In a Black-Scholes setup (i.e. log-normally distributed returns), the price for a European Quanto Call is given by the following formula.

$$V_0 = e^{-rT} C^* \left[S_0 e^{(u-\rho\sigma_C\sigma_S)T} \Phi\left(d\right) - k\Phi\left(d - \sigma_S\sqrt{T}\right)\right] \tag{9}$$

where

$$d = \frac{\ln\frac{S_0}{k} + \left(u - \rho\sigma_C\sigma_S + \frac{\sigma_S^2}{2}\right)T}{\sigma_S\sqrt{T}}$$

and r (u) is the domestic (foreign) risk-free rate, σ_S (σ_C) the volatility of the underlying (FX rate), respectively, and ρ the correlation parameter [Wilmott, 2006].

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