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The Effectiveness of the FX Market Interventions of the Bundesbank During the Louvre Period: An Options-Based Analysis

by

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Abstract:
The effectiveness of the foreign exchange market interventions conducted by the Deutsche Bundesbank during the Louvre period to alter either the level or the volatility of the $/DM spot rate is examined. Volatility quotes implicit in foreign currency options are employed to recover the impact of interventions on the variability of exchange rates. A contingent claims valuation framework allowing to highlight the implications of infrequent interventions for the valuation of options on foreign currency is constructed. The impact of interventions on FX option premia in a regime characterized by infrequent interventions and implicit intervention thresholds and in a pure managed float system is analyzed. A multifactor success criterion is developed to assess the effectiveness of the forex interventions of the Bundesbank empirically within the context of a qualitative dependent variable model.

Keywords: Central Bank Interventions, Foreign Currency Options, Implied Volatility, Ordered Probit Model
JEL Classification: F31, G13

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1 Introduction

Since the breakdown of the Bretton–Woods system, real–life exchange rates were often subject to central banks' foreign exchange market interventions. The present paper contributes to the literature devoted to the examination of the effectiveness of such foreign exchange market operations conducted by monetary authorities in influencing or changing either the time–path of spot rates and/ or the volatility of these asset prices. Volatility quotes implicit in actual foreign currency option premia are utilized to recover the impact of central bank interventions on the variability of exchange rates.

To establish a theoretical link between effective central bank interventions and changes in FX options implied volatilities, the second section of the paper is employed to examine within the context of a continuous–time model of exchange determination developed by Lewis (1995) how the impact of an effective central bank intervention policy on the dynamics of the exchange rate transmits onto the arbitrage–free premia of foreign currency options. The model to be laid out complements earlier work on FX option pricing under explicitly regulated asset price processes and examines the influence of both a non–zero probability of occasional central bank forex interventions and of implicit currency bands on the valuation of foreign currency options.

The theoretical discussion has clear–cut empirically testable implications. The employed set up predicts that, if compared to a free–float, an effective central bank intervention policy has the potential to reduce both the gap between the current exchange rate and its central parity and the variability of this important financial market variable. However, while the model utilized in the analysis simply assumes that the actions taken by central banks affect the level and the variability of spot rates, it remains a heavily discussed empirical question whether central bank interventions do indeed tend to stabilize the level of exchange rates around a central parity defined by economic policy and/ or to dampen the volatility of this asset price. This important issue will be addressed in the second part of the paper.

To perform the empirical analysis , the success of central bank intervention policy is measured in terms of an evaluation criterion which allows to simultaneously take into consideration both dimensions of the effectiveness of central bank foreign exchange market operations: their impact on the level and on the volatility of the spot rate. This multi–factor success criterion is then used to estimate an ordered qualitative response model to assess the success of interventions of the Deutsche Bundesbank in the $/DM spot market. The empirical analysis utilizes daily official German intervention data for the period of time following the Louvre Accord ranging from 01/02/1987 to 03/12/1990 which was characterized by frequent (and often coordinated) interventions. The so–called Louvre Accord was the main outcome of a G–7 meeting held at the Louvre in Paris on February 22, 1987 and was launched to stabilize exchange rates at or around the then prevailing levels (Funabashi 1988).

One of the main results of the theoretical study performed in the first part of the paper is that foreign currency option premia reflect the impact of monetary authorities' FX market operations on the level and the variability of exchange rates. In the empirical study, we use this finding and resort to volatilities implicit in FX options to test for the effectiveness of central bank interventions with respect to expected exchange rate volatility (cf. also Bonser–Neal and Tanner (1996) and Madura and Tucker (1991)). The present paper, therefore, also contributes to the literature examining how market participants and central banks can exploit the informational content implicit in foreign currency options to gain deeper insights into the functioning of FX markets and into the impact of monetary policy actions on the time–path of spot rates.

The analysis is structured as follows. In section 2, the exchange rate model of Lewis (1995) is briefly reviewed and the foreign currency option valuation model is constructed. The impact of infrequent central bank forex interventions on FX option premia is analyzed in both a policy regime featuring implicit intervention thresholds and in a managed float system. The empirical part of the analysis in contained in section 3. The research strategy designed to examine the effectiveness of central bank foreign exchange market interventions is laid out, results reported in the related literature are discussed, and the results of our own empirical work are presented. A final section summarizes the main findings of the analysis and offers some suggestions for future research.

2 Interventions, Implicit Bands, and FX Option Pricing

The arbitrage free valuation of European style FX options in stochastic continuous–time economies is frequently based on the first generation valuation frameworks introduced into the literature by Grabbe (1983), Giddy (1983), Biger and Hull (1983), and Garman and Kohlhagen (1983) (henceforth abbreviated as GK). As in the pioneering work of Black and Scholes (1973) and Merton (1973), a characteristic feature of these models is that in the derivation of the option pricing formula it is presumed that the underlying exchange rate on which the option is written follows an exogenously given unconstrained geometric Brownian diffusion process. The implicit convention behind this assumption is that real–life exchange rates are allowed to float freely and can, in principle, assume any numerical value on the positive real line. The experience of the post Bretton Woods era, however, suggests that this presupposition might be overly simplistic and might in certain historical situations provide only a poor description of the numerous variants of empirically observed exchange rate systems allowing for varying degrees of exchange–rate flexibility. In reality, governments often try to manage exchange rates in an attempt to cope with the "open–economy trilemma" (Obstfeld and Tayler 1998) expressing the impossibility to establish free cross–border capital flows, exchange rate flexibility, and monetary autonomy simultaneously. Active exchange rate policy is frequently implemented either by conducting occassional FX market interventions or by constraining spot rates to evolve within explicit or implicit fluctuation intervals. The so–called Plaza Communiqué agreed upon by G–5 central banks governors and finance ministers on September 22, 1985 and the Louvre Accord proclaimed at a G–7 summit held in Paris on February 22, 1987 are examples for political events marking attempts to implement exchange rate systems characterized by occassional interventions and implicit fluctuation bands. An example for a policy regime aiming at invoking an explicit exchange rate target zone is given by the former European Monetary System.[1] Clearly, the ad hoc specification of exchange rate dynamics underlying the first generation FX option pricing set ups neglects the potential influence of such economic policy strategies on the timepath of the exchange rate and thus on the premium of currency options.

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1 Explicit bands have also been envoked within the context of the European Monetary System II to target the spot rates between the Euro and the currencies of the so–called pre–ins. See Kempa (1998) for a detailed description.

Very recently, modeling strategies which take some of the implications of limited exchange rate flexibility into consideration have been proposed in the literature on currency option pricing in explicit exchange rate target zones. Ingersoll (1997) models the impact of credible and irrevocable exchange rate thresholds on the pricing of currency options by introducing a reflected Brownian exchange rate process. Sorensen (1996) and Ekvall et al. (1993) suggest to capture the impact of bounds on exchange rates on the pricing of currency options by assuming that the state variable of the economy follows an exogenously specified unbounded Ornstein–Uhlenbeck process. While these approaches allow to derive closed form solutions for European style FX options, they do not take into account the nonlinearities of the exchange rate path described in the literature on exchange rate target zones.[2] In exchange rate target zone models, the nonlinearity of the exchange rate function arises due to economic agents' expectations regarding the state contingent monetary policy intervention mechanism activated as the exchange rate reaches either the upper or the lower reflecting boundary of its explicit fluctuation interval.[3] Based on the first–generation target zone model developed by Krugman (1991) applicable to describe exchange rate dynamics within explicit and credible exchange rate bands, Dumas et al. (1993) demonstrate how to integrate this nonlinearity of the exchange rate function into a currency option valuation model. Since the integration of the nonlinearity of the exchange rate path into the option pricing model makes it impossible to derive closed form solutions for the premium of the derivative security, they implement the model numerically and show that the nonlinearity of the exchange rate path translates onto the mapping describing the premium of European style FX options as a function of regulated economic fundamentals. This baseline setting has been extended by Dumas et al. (1995) by modeling exchange rate dynamics as a composite process consisting of a Gauss–Wiener component for economic fundamentals and a Possion jump process reflecting occassional realignments of central parities. Kempa et al. (1998) have further modified this framework in two respects. They have introduced stochastic realignment risk as suggested in Bertola and Svensson (1993) to account for the limited credibility problem often beleaguering real world currency bands and mean reversion in fundamentals along the lines of Lindberg and Söderlind (1994) to reflect intramarginal interventions

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2 For a survey of the literature on exchange rate determination in exchange rate target zones, cf. Svensson (1992), De Argangelis (1994), and Kempa and Nelles (1999).

3 The nonlinearity of the exchange rate paht might be caused either by stabilizing or by destabilizing exchange rate expectations. For the latter case, see e.g. Bertola and Caballero (1992).

of central banks. A contingent claims valuation model featuring endogenous realignment risk has been proposed by Christensen et al. (1998). In their two–factor target zone model with the current and hypothetical free–float or shadow exchange rates being the state variables of the system, the realignment risk increases as the current exchange rate approaches the boundaries of its fluctuation range and as the gap between the current and the shadow spot rate widens.

The contingent claims valuation models mentioned so far have primarily been designed as theoretical tools to price European style FX options in *explicit* exchange rate target zones. The empirical analysis contained in the second part of the paper, however, examines the impact of intervention policy on the level and on the volatility of the $/DM exchange rates during the Louvre period which was characterized by *occasional* interventions and *implicit* bands. To derive empirically testable hypotheses regarding the impact of such an intervention regime on the level of exchange rates and the *expected* volatility of this asset price as implied in foreign currency options, the present section draws on work by Lewis (1995) to develop an FX option pricing framework featuring infrequent central bank FX market operations and implicit fluctuation bands. The model complements the valuation frameworks applicable to the evaluation of European style price contingent claims under regulated fundamentals briefly reviewed above in several interesting respects:

- The underlying exchange rate model features an implicit rather than an explicit target zone. While the technical tools employed by Dumas et al. (1993, 1995) can still be used to price FX options in implicit exchange rate bands, it has to be taken into account when performing comparative static analyses that the width of the implicit exchange rate band varies as the structural parameters of the model are altered.
- Harmonizing with the data used in the empirically observed intervention policy of major central banks during the Louvre regime, the exchange rate model of Lewis (1995) implies that the direction, the size and the timing of occasional interventions are itself stochastic variables. This is in contrast to FX option pricing frameworks built on the Krugman (1991) model in which central bank FX market interventions occur if and only if the exchange rate reaches the boundaries of its fluctuation interval. This also implies that the model departs from the assumption made in valuation set ups in which intramarginal interventions take place continuously and are an increasing deterministic function of the deviation of the exchange rate from its central parity.

- ♦ In the special case of an infinite width of the exchange rate band, the present option pricing model converges to the GK framework with appropriately adjusted default–free domestic and foreign interest rates and a modified exchange rate volatility parameter if the probability of a central bank intervention is the same for all exchange rate realizations. In contrast, models based upon the Krugman (1991) set up converge in the limit case of an infinite band width to the baseline version of the unadjusted GK model and, depending upon whether UIP is assumed to hold, models featuring an Ornstein–Uhlenbeck process for economic fundamentals degenerate either to the Ekvall et al. (1993) or to the Lo and Whang (1995) option pricing set up. While these latter frameworks are also special cases of the original GK model, they presume that the unbounded exchange rate follows a stationary mean–reverting stochastic process. In the present model, the unbounded exchange rate in such a managed float scenario is driven by a geometric Gauss–Wiener process with drift and diffusion coefficients modified to account for the probability of infrequent central bank foreign exchange market operations.
- ♦ In the exchange rate model of Lewis (1995), central bank interventions affect both the drift and the volatility of the fundamentals used to price foreign exchange. In models resorting to an Ornstein–Uhlenbeck process to depict interventions continuously affecting the spot rate, central banks' foreign exchange market operations only affect the drift component of the stochastic process driving economic fundamentals.

This section is structured as follows. Subsection 2.1 is utilized to outline the exchange rate model employed in the analysis. Subsection 2.2 is devoted to the presentation of the contingent claims valuation framework and to the analysis of the impact of infrequent FX market interventions and implicit currency fluctuation bands on the premia of foreign currency options. Section 2.3 abstracts from the presence of implicit bands and focuses exclusively on the implications of occasional interventions for FX option pricing. This simplified version of the intervention model is used to take a closer look at the sign of the impact of central bank foreign exchange market interventions on the volatility implicit in foreign currency option prices.

2.1 *The Underlying Exchange Rate Model*

The stochastic continuous–time flex–price monetary model of exchange rate determination exerts that the logarithm of the value of foreign currency can be expressed as the sum of a set of economic fundamentals and the expected rate of change of the nominal exchange rate over the time–span $\mathrm{d}t$ conditioned on the information set available in the current period *t*:

(1) $$e(t) = f(t) + \upsilon \mathrm{E}_t(\mathrm{d}e)/\mathrm{d}t$$

where υ denotes the interest–semi elasticity of money demand. The implicit assumptions underlying equation (1) are that capital is perfectly mobile internationally, that economic agents are risk–neutral, and that the condition of UIP holds in its logarithmic form so that the Siegel (1972) paradox does not apply. Economic fundamentals f^* net of changes in the monetary base due to central bank FX market interventions are assumed to follow the stochastic differential equation given below:

(2) $$\mathrm{d}f^* = \mu \mathrm{d}t + \sigma \mathrm{d}W$$

In equation (2), μ reflects a drift parameter, the constant σ denotes the diffusion coefficient of the process, and $\mathrm{d}W$ is the differential of a standard Gauss–Wiener process with expected value zero and unit variance.

To move from equation (2) to the process driving fundamentals in the presence of infrequent central bank FX market interventions, Lewis (1995) relies on the following assumptions regarding the exchange rate policy conducted by monetary authorities:

- To mimic the exchange rate policy established under the Louvre Accord, monetary authorities are assumed to restrict the intervention–augmented fundamentals f to the interval $f \in (\underline{f}, \overline{f})$.[4] Because equation (1) stipulates that the exchange rate is a deterministic function of fundamentals, this assumption implies that economic policy affects spot rate fluctuations by invoking an implicit fluctuation band for the exchange rate defined over economic fundamentals.

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4 In subsection 2.3, we also analyze the implications of occassional interventions on option premia when the exchange rate is not confined to fluctuate within implicit bands.

- Central banks intervene in the FX market occasionally. The function $0 \le \pi(f) < 1$ depicts the probability that a central bank intervention will take place as a function of economic fundamentals. The function is assumed to be continuous and continuously differentiable over the admissible range of fundamentals $\left(\underline{f}, f\right)$ defined above. The central bank chooses the size of interventions so as to exactly compensate the change in the fundamental which would have occurred had the drift and diffusion component given in equation (2) unfolded their impact on f. This implies that in the interior of the implicit fluctuation band, the central bank might either purchase or sell foreign currency when the exchange rate is above (below) its central parity. Harmonizing with the empirical facts documented in section 3 below, the direction of the intervention is thus itself stochastic.[5]

In order to derive the stochastic process reflecting the dynamics of the intervention–augmented economic fundamentals f, Lewis (1995) starts with a discrete time version of the model, utilizes a first–order expansion to depict changes in the intervention probability as a function of movements in fundamentals, and finally computes the continuous–time limit of the conditional mean and of the conditional variance of the discrete–time process by forcing the size of time–steps to converge to zero.[6] Upon carrying out these manipulations, she obtains the following process for the intervention–augmented fundamentals:

(3) $$\mathrm{d}f = \left\{\mu(1-\pi(f)) - \sigma^2 \pi_f(f)\right\}\mathrm{d}t + \sigma\sqrt{1-\pi(f)}dW$$

Applying the rules of stochastic calculus, equation (3) results in the following stochastic differential equation describing exchange rate dynamics in the presence of infrequent central bank forex interventions:

(4) $$\mathrm{d}e = \left\{e_f\left[\mu(1-\pi(f)) - \sigma^2 \pi_f(f)\right] + \frac{1}{2}\sigma^2 e_{ff}(1-\pi(f))\right\}\mathrm{d}t + e_f \sigma\sqrt{1-\pi(f)}\,\mathrm{d}W$$

Defining the anti–log of the exchange rate employed in the FX option pricing models outlined in the proceeding subsections as $E \equiv \exp(e)$ to get:

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5 As long as the intervention probability is an increasing function of the deviation of the exchange rate from its central parity, it follows that the probability of an intervention in the direction of the target rate is higher than an intervention away from the central parity. See Lewis (1995: p. 696 and p. 710).

6 For a detailed description of this procedure, cf. the technical appendix of Lewis (1995: pp. 709).

(5) $$\mathrm{d}E=\left\{e_f\left[\mu(1-\pi(f))-\sigma^2\pi_f(f)\right]+\frac{1}{2}\sigma^2 e_{ff}(1-\pi(f))+\frac{1}{2}e_f{}^2\sigma^2(1-\pi(f))\right\}E\,\mathrm{d}t$$
$$+e_f\sigma\sqrt{1-\pi(f)}E\,\mathrm{d}W$$

Taking conditional expectations of the process in equation (4), substituting the resulting expression into equation (1), and rearranging terms gives the following second–order inhomogeneous ordinary differential exchange rate equation with variable coefficients:

(6) $$e=f+\upsilon\left[\mu(1-\pi(f))-\sigma^2\pi_f(f)\right]e_f+\frac{1}{2}\upsilon\sigma^2(1-\pi(f))e_{ff}$$

A solution to equation (6) can be pinned down by enforcing the following set of smooth pasting conditions:

(7a) $$e_f\left(\overline{f}\right)=0$$

(7b) $$e_f\left(\underline{f}\right)=0$$

which rule out one–way bets and, thus, unbounded arbitrage opportunities as the exchange rate reaches the upper and lower reflecting boundaries of its implicit fluctuation band (see Krugman (1991)). The economic arguments motivating this set of boundary conditions are the same as those utilized in the literature to justify the imposition of the high–contact condition applying in the valuation of American style options (see e.g. Merton (1973); for a more recent discussion, cf. Kim (1990)). Figure 1 plots examples for exchange rate functions obtained by solving the boundary value problem formalized in equations (5) – (6) numerically for the case of $\mu=0$.[7] The intervention probability is computed as $\pi(f)=\overline{\pi}f^2$ with $\overline{\pi}$ being a scaling factor.

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7 Because the subsequent study of the FX option pricing model is greatly alleviated by constructing an analytical approximation to the exchange rate function, the numerical simulations of the model are based on the technique of collacation discussed in Kempa et al. (1997) rather than on one of the finite difference schemes commonly used in the numerical treatment of differential equations.

To interpret the figure, compare first the function e_0 with the free float exchange rate solution which obtains by assuming implicit bands and occasional central bank interventions away. The exhibit shows that the exchange rate path which obtains when the spot rate is allowed to float freely is a straight ray through the origin of the depicted plane with a slope coefficient of unity. This free–float spot rate solution expresses that there exists a one–to–one relation between the exchange rate and its fundamentals and can be computed by solving equation (6) subject to appropriate boundary conditions ruling out extrinsic bubbles. The exchange rate solution in the presence of infrequent intramarginal central bank interventions and an implicit bands depicted by the mapping e_0, in contrast, assumes a cubic shape with a slope converging to zero as the boundaries of the implicit spot rate fluctuation band are reached. As in the baseline target zone model of Krugman (1991), invoking implicit bands fosters expectations of marginal central bank interventions at the boundaries of the fluctuation interval defined over economic fundamentals which, in turn, are immediately discounted and incorporated into the current exchange rate. As compared to the free–float solution, the expectations regarding central banks' sales (purchases) of foreign currency to prevent economic fundamentals from crossing $\overline{f}$ ($\underline{f}$) result in a negative (positive) interest rate differential in the upper (lower) half of the implicit exchange rate band and require an appreciation (a depreciation) of the domestic currency. The exchange rate paths e_0 and e_1 demonstrate that the magnitude of this effect depends upon the width of the fluctuation interval assigned to economic fundamentals. As can be seen in the exhibit, a wider explicit fluctuation band for economic fundamentals translates into a wider implicit exchange rate band.

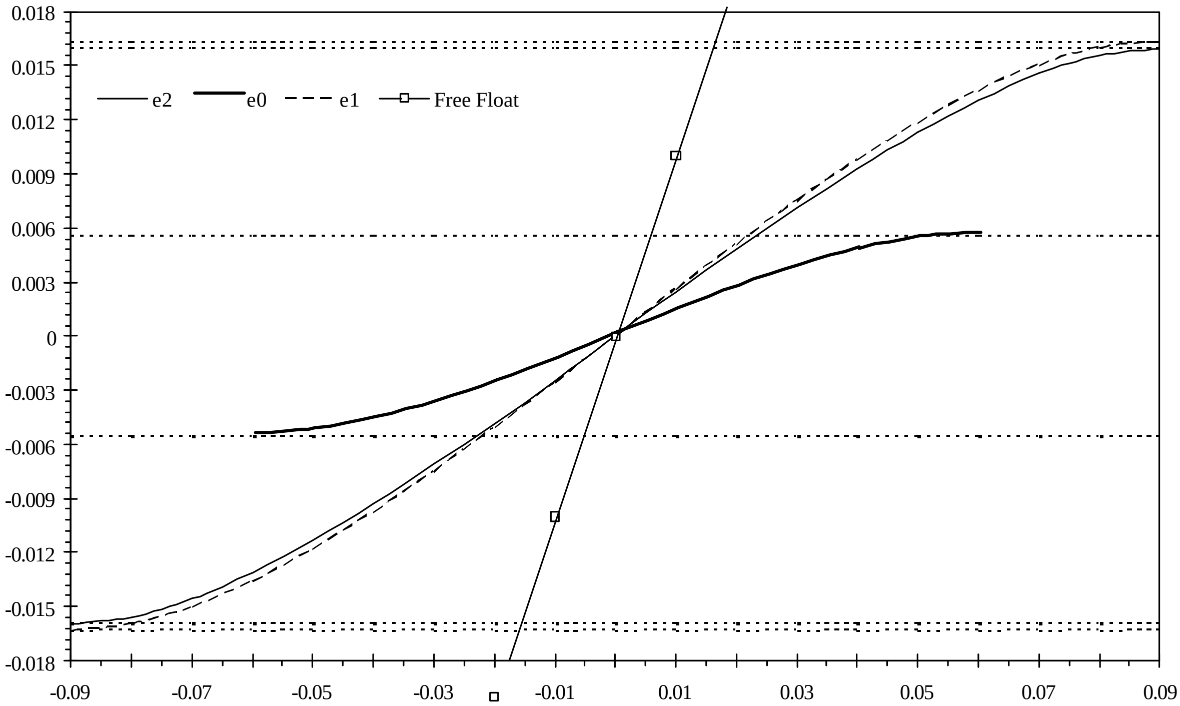


Figure 1 — Infrequent Interventions, Implicit Bands, and Exchange Rates

Note: The figure plots the logarithm of the exchange rate as a function of fundamentals. The numerical parameter values utilized to compute the figure are: $\mu = 0$, $\upsilon = 1$ and $\sigma = 0.15$. The function e_0 obtains by setting a symmetric fluctuation band for fundamentals with $\bar{f} = 0.06$ while the functions e_1 and e_2 represent the case of $\bar{f} = 0.09$. The function chosen to depict the intervention probability is $\pi(f) = \bar{\pi} f^2$ with $\bar{\pi} = 15$ for e_0 and e_1 and $\bar{\pi} = 25$ for e_2.

To elucidate the relevance of the intervention probability for the shape of the exchange rate function, figure 1 confronts the function e_1 with the mapping e_2. The impact of a variation in $\pi(f)$ on the exchange rate path is isolated by assuming the interval $(\underline{f}, f)$ assigned to economic fundamentals to be the same for both functions. The difference between the exchange rate paths arises because the scaling parameter $\bar{\pi}$ entering into the function used to compute intervention probabilities assumes the numerical value 15 for e_1 and 25 for e_2. It can be attributed to the assumed parabolic form of the mapping $\pi(f)$ that this constellation implies that the probability of intramarginal central bank interventions is relatively higher for the function e_2 as compared to the function e_1 for all realizations of economic fundamentals belonging to the admissible fluctuation interval $(\underline{f}, f)$.[8] Figure 1 shows that this increase in the intervention probability induces a counterclockwise shift of the exchange rate path and a concomitant narrowing of the implicit exchange rate fluctuation band. This finding is due to the

8 The intervention probability is equal for both functions whenever the current exchange rate is equal to the prevailing central parity.

fact that a variation in the intervention probability affects both the drift and the volatility of economic fundamentals. Equation (3) highlights that raising π dampens the variability of the diffusion term of the stochastic differential equation driving the intervention–augmented fundamentals and, at the same time, results in a stronger tendency of this process to mean–revert to its long–run base level. The latter corresponds to the central parity of the implicit exchange rate fluctuation band. While both effects contribute to a decline in the overall volatility of fundamentals, the second effect additionally implies that the within–band exchange rate density becomes more centered around the central rate of the implicit target band. The result is that the expected value of the integral of the entire path of future risk–free interest rate differentials declines. This, in turn, requires that the admissible deviation of the current nominal exchange rate from its steady state value is smaller for the function e_2 than for the mapping e_1.

2.2 *The FX Option Pricing Framework*

To integrate infrequent central bank interventions and implicit exchange rate fluctuation intervals into a foreign currency option valuation framework, the first step is to define a valuation function $C(E,t)$ twice–differentiable in E and once in t. Upon resorting to the familiar no–arbitrage argument, the following fundamental contingent claims valuation equation obtains:

(8) $$\frac{1}{2}C_{EE}\left(E^2 e_f{}^2\sigma^2(1-\pi(f))\right)+(r-r^*)C_E E - rC - C_\tau = 0$$

where we have used the definition $\tau \equiv T-t$ which implies $C_\tau = -C_t$. Upon defining a new valuation function $G(f,t)$ satisfying $C(E,t)\equiv G(f,t)$ and upon carrying out the necessary substitution of variables, we follow Dumas et al. (1993, 1995) and re–express the contingent claim valuation equation in terms of economic fundamentals as:

(9) $$\frac{1}{2}\sigma^2(1-\pi(f))G_{ff} - \left[\frac{1}{2}\sigma^2(1-\pi(f))\left(e_{ff}+e_f{}^2\right)-(r-r^*)\right]\frac{1}{e_f}G_f - rG - G_\tau = 0$$

As it stands, the fundamental partial differential valuation equation (9) must be satisfied by any foreign exchange contingent claim continuously traded in an arbitrage–free continuous–time economy with frictionless international capital markets. In order to pin down a particular solution to equation (9) applying in the case of European style foreign currency options, the valuation framework is closed by specifying an appropriate set of boundary conditions:

(10) $$G_f\left(\underline{f},\tau\right)=0$$

(11) $$G_f\left(\overline{f},\tau\right)=0$$

(12) $$G(f,0)=[E-X]^+$$

Finally, one can exploit the fact that the interest rate differential and conditional exchange rate expectations have been linked in an economically meaningful way by resorting the logarithmic specification of the condition of UIP to model the international no–arbitrage asset market equilibrium. Using equation (4), the differential between domestic and foreign risk–free interest rates can be written as:

(13) $$r - r^* = e_f\left[\mu(1-\pi(f)) - \sigma^2\pi_f(f)\right] + \frac{1}{2}\sigma^2 e_{ff}(1-\pi(f))$$

In order to fix not only the differential between but also the level of the domestic and the foreign riskless interest rates, we follow Dumas et al. (1993, 1995) in assuming that the international interest rate differential can be decomposed in the following manner:

(14a) $$r = \bar{r} + k(r - r^*)$$

(14b) $$r^* = \bar{r} + (1-k)(r - r^*)$$

Collecting information, the fundamental contingent claim valuation equation can be transformed into its final form given below:

(15) $$\frac{1}{2}\sigma^2(1-\pi(f))G_{ff} - \left\{\bar{r} + ke_f\left[\mu(1-\pi(f)) - \sigma^2\pi_f(f)\right] + \frac{1}{2}k\sigma^2 e_{ff}(f)(1-\pi(f))\right\}G$$

$$-\left\{\frac{1}{2}\sigma^2(1-\pi(f))e_f - \mu(1-\pi(f)) + \sigma^2\pi_f(f)\right\}G_f - G_\tau = 0$$

The valuation problem consisting of the boundary conditions (10) – (12) and the partial differential equation presented in (15) can now be set up numerically.

Figure 2 depicts examples for FX option valuation functions obtained by solving the boundary value problem formalized in equation (15) and (10) – (12) numerically. The exhibit serves to highlight the impact of a variation in the interval $\left(\underline{f}, f\right)$ and in the probability of an intervention on the option valuation function. The parameter values are the same as in figure 1. Therefore, the depicted option valuation function c_j also correspond to the respective exchange rate functions e_j with $j = 0,1,2$ plotted in figure 1.

The figure reveals three interesting aspects of foreign currency option pricing in a setting featuring infrequent central bank interventions and implicit exchange rate bands. In the first place, a comparison between the functions c_0 and c_1 illustrates that the value of FX options is an increasing function of the fluctuation interval $\left(\underline{f}, f\right)$. Widening the interval defined over economic fundamentals from $(-0.06, 0.06)$ used to compute the mapping c_0 to $(-0.09, 0.09)$ applying in the case of c_1 also widens the implicit exchange rate fluctuation range. This, in turn, raises the implied instantaneous volatility of the exchange rate process and enhances the upside potential of the derivative contract. As can be seen in figure 2, both effects tend to increase the premia of foreign currency options.

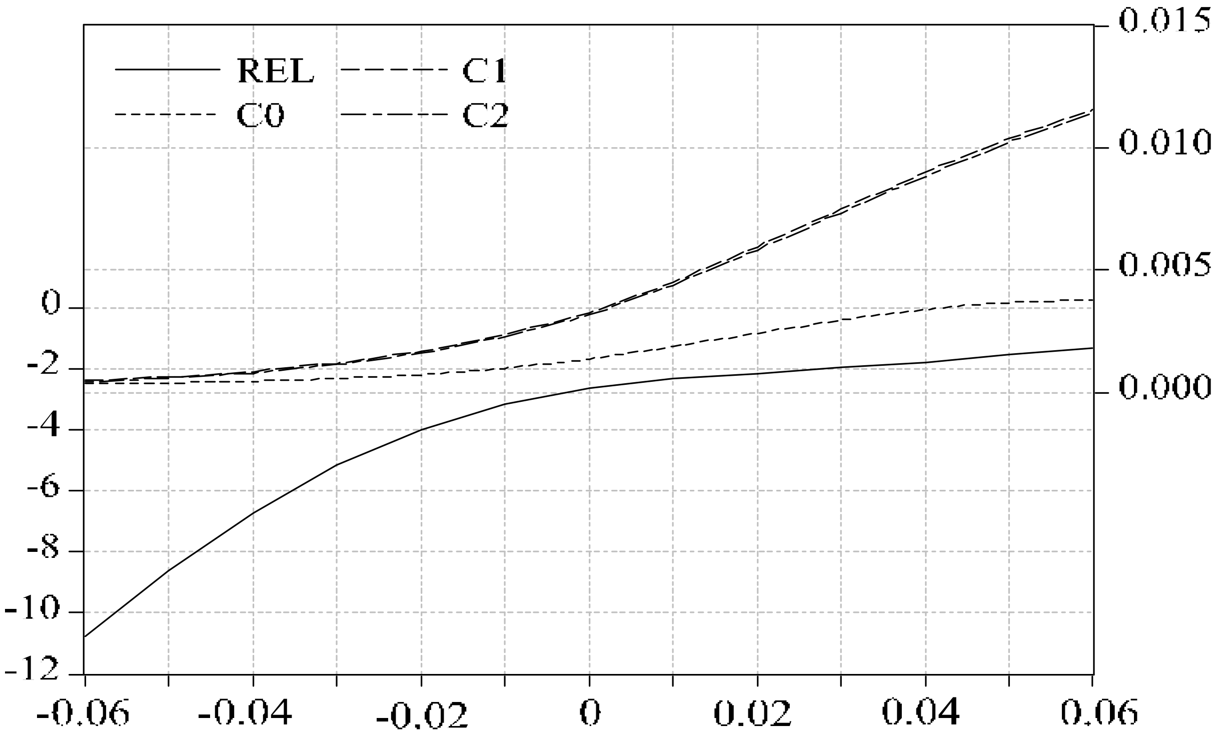


Figure 2 — Infrequent Interventions, Implicit Bands, and FX Option Values

Note: The figure plots option premia (right scale) and the relative pricing error $100 \times (c_2 - c_1)/c_1$ (left scale) on the vertical axis as a function of fundamentals on the horizontal axis. For parameter values, cf. figure 1. The time to maturity is one month in all cases. The exercise price of the option has been fixed at $X = 1$ and the parameter employed to decompose the international interest rate differential assumes the numerical value $k = 0.5$.

The second point highlighted by the figure is that the shape of the option valuation function is altered in the presence of an implicit exchange rate target interval. While the function c_1 and c_2 computed for a relatively wide implicit exchange rate band exhibit near–the–money the characteristic convex shape known from the theory of foreign currency pricing under unregulated fundamentals, the function c_0 can be seen to mimic the cubic shape of the exchange rate paths depicted in figure 1. This finding confirms results reported in Dumas et al. (1993, 1995) and shows that the non–linearity of the exchange rate function transmits onto the option valuation mapping. This effect becomes more pronounced as the interval $(\underline{f}, f)$ and, thus, the implicit exchange rate band is narrowed. Also note that the option pricing function becomes completely insensitive to movements of the underlying asset price when economic fundamentals reach the upper and lower boundaries of the fluctuation interval $\left(\underline{f}, f\right)$. This result reflects that the exchange rate volatility implied by the process driving fundamentals which can be computed by using equation (5) as $e_f{}^2\sigma_2(1-\pi(f))E^2$ converges to zero as the exchange rate reaches the boundaries of its implicit fluctuation band.

The third point illustrated by figure 2 is that an increase in the probability of an intervention tends to depress foreign currency option premia. To visualize this implication of the model, the exhibit confronts the functions c_1 obtained by assuming a relatively low intervention probability with the option valuation mapping c_2 resulting when the probability of a central bank foreign exchange market operation assumes relatively high numerical values. The higher intervention probability cuts off the upside potential of the option by reducing the implicit spot rate fluctuation band (see figure 1) and reduces the volatility of the exchange rate process. Both factor contribute to lower the premium of the foreign currency option. While a direct comparison of the mappings c_1 and c_2 suggests that the impact of a variation in the intervention probability on option premia is rather small, the function *rel* obtained by computing $100\times\left(c_2 - c_{12}\right)/\,c_1$ unearths that the resulting relative pricing differences can be substantial.

2.3 *The Managed Float Regime*

The valuation model derived in the preceding subsection provides a theoretically elegant framework to unearth the impact of infrequent central bank foreign exchange market interventions and implicit exchange rate bands on the arbitrage–free premia of European style FX options. However, its practical tractability is hampered by the fact that FX option premia can only be figured out numerically. In this subsection, we therefore derive a watered–down version of the model upon invoking the additional assumptions that (i) the width of the band over economic fundamentals goes to infinity, and (ii) the intervention probability is an exogenously specified constant $0 \le \pi < 1$ for all realizations of f.

In this scenario, the differential equation (6) describing the evolution of the exchange rate simplifies to:

(16) $$e = f + \upsilon\mu(1-\pi)e_f + \frac{1}{2}\upsilon\sigma^2(1-\pi)e_{ff}$$

Ruling out extrinsic bubbles by imposing appropriate transversality conditions, it follows that the particular and the general solution to this equation coincide and the exchange rate function can be written as:

(17) $$e(t) = f(t) + \upsilon\mu(1-\pi) \qquad \text{so that} \qquad \mathrm{d}e = \mathrm{d}f$$

Equation (17) implies that the fundamental parabolic partial differential contingent claims valuation equation applying in this economy can be specified as:

(18) $$\frac{1}{2}\sigma^2(1-\pi)G_{ff} + \left\{(1-\pi)\left(\mu - \frac{1}{2}\sigma^2\right)\right\}G_f - \left\{\bar{r} + k\mu(1-\pi)\right\}G - G_\tau = 0$$

Equation (18) can be re–written in terms of the anti–log of the exchange rate to obtain:

(20) $$\frac{1}{2}C_{EE}E^2\sigma^2(1-\pi) + \mu(1-\pi)C_E E - \left(\bar{r} + k\mu(1-\pi)\right)C - C_\tau = 0$$

In the case of European style FX options, this equation must be solved subject to:

(21) $$C(E,0) = [E - X]^+$$

(22) $$\lim_{E \to 0} C(E,\tau) = 0$$

(23) $C(E,\tau) \leq E$

The valuation problem stated in equations (20) – (23) consists of an appropriately modified version of the fundamental contingent claims valuation equation and the corresponding set of boundary and terminal conditions also applying in the case of the first–generation FX option pricing model of GK. The solution to this boundary value problem giving the premium of European style FX options in the absence of implicit exchange rate bands under the assumption of a constant probability of infrequent central bank forex interventions can thus be pinned down as:

(24) $$C^{MF}\left(E, X, r, r^*, \sigma\sqrt{1-\pi}, \tau\right) = C^{GK}\left(E, X, r, r^*, \tilde{\sigma}, \tau\right)$$

with $\tilde{\sigma} \equiv \sigma\sqrt{(1-\pi)}$ so that the diffusion coefficient utilized to price the option is a decreasing function of the intervention probability. The valuation formula provided in equation (24) can be stated more explicitly as:

(25) $$C^{MF}\left(E, X, r, r^*, \tilde{\sigma}, \tau\right) = E\exp\left[\left(-\bar{r} - (1-k)\mu(1-\pi)\right)\tau\right]\Phi\left(\tilde{d}_1\right)$$

$$-X\exp\left[\left(-\bar{r} - k\mu(1-\pi)\right)\tau\right]\Phi\left(\tilde{d}_2\right)$$

with

$$\tilde{d}_1 \equiv \frac{\ln\left(\frac{E}{X}\right) + \left(\mu(1-\pi) - 0.5\tilde{\sigma}^2\right)\tau}{\tilde{\sigma}\sqrt{\tau}}$$

$$\tilde{d}_2 \equiv \tilde{d}_1 - \tilde{\sigma}\sqrt{\tau}$$

To examine the impact of a variation in the probability of no interventions on the premium of the FX option contract, take the partial derivative of the augmented GK valuation formula provided in equation (25) with respect to $1-\pi$ to get:

(26) $$\frac{\partial C^{MF}\left(E, X, r, r^*, \tilde{\sigma}, \tau\right)}{\partial(1-\pi)} = -(1-k)\mu\tau E\exp\left[\left(-\bar{r} - (1-k)\mu(1-\pi)\right)\tau\right]\Phi\left(\tilde{d}_1\right)$$

$$+k\mu\tau X\exp\left[\left(-\bar{r} - k\mu(1-\pi)\right)\tau\right]\Phi\left(\tilde{d}_2\right) + E\exp\left[\left(-\bar{r} - (1-k)\mu(1-\pi)\right)\tau\right]\Phi'\left(\tilde{d}_1\right)\frac{\partial\tilde{d}_1}{\partial(1-\pi)}$$

$$-X\exp\left[\left(-\bar{r}-k\mu(1-\pi)\right)\tau\right]\Phi'\left(\tilde{d}_2\right)\frac{\partial\tilde{d}_2}{\partial(1-\pi)}$$

which can be simplified to give:

(27) $$\frac{\partial C^{MF}\left(E,X,r,r^{*},\tilde{\sigma},\tau\right)}{\partial(1-\pi)}=-\mu\tau X\exp\left[\left(-\bar{r}-k\mu(1-\pi)\right)\tau\right]\Phi\left(\tilde{d}_2\right)$$

$$+k\mu\tau\left(E\exp\left[\left(-\bar{r}-(1-k)\mu(1-\pi)\right)\tau\right]\Phi\left(\tilde{d}_1\right)+X\exp\left(-\bar{r}-k\mu(1-\pi)\right)\Phi\left(\tilde{d}_2\right)\right)$$

$$-\mu\tau C\left(E,X,r,r^{*},\tilde{\sigma},\tau\right)+\frac{1}{2}\Phi'\left(\tilde{d}_2\right)X\sigma\exp\left[\left(-\bar{r}-k\mu(1-\pi)\right)\tau\right]\sqrt{\frac{\tau}{1-\pi}}$$

From equation (27) it follows that the effect of an increase in the probability that the central bank will not intervene in the foreign exchange market unambiguously inflates the option premium if the drift term of the fundamentals process is zero and/or if the effect of occasional interventions on the foreign interest rate can be neglected. In all other cases, the impact of a variation in the intervention probability on option premia is ambiguous.

This ambiguity arises due to the fact that in the present model the probability that a central bank foreign exchange market operation will take place simultaneously affects three variables important for the pricing of FX options:

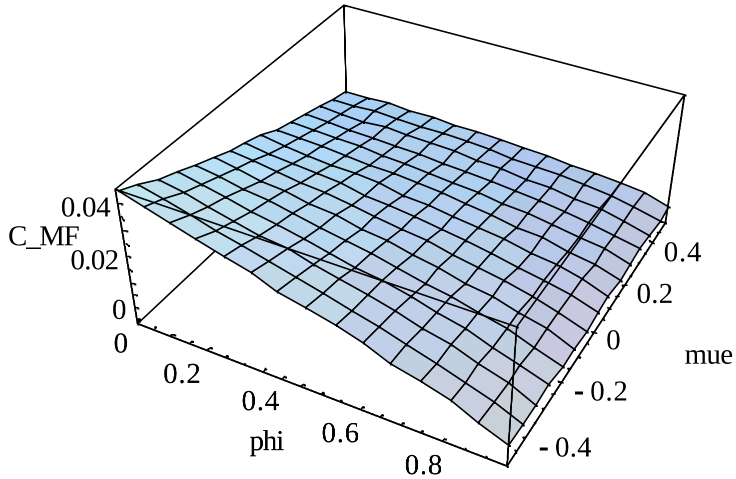
- Equation (11a) states that raising the parameter π sets the domestic interest rate on the increase. A higher intervention probability raises the foregone interest earnings accruing from investing in domestic risk–free assets and, thus, inflates the opportunity costs of writing the option. For this reason, investors tend to require a higher compensation for selling options and this, in turn, implies that the option premium increases.
- A variation in the parameter π affects the foreign interest rate. Equation (11b) stipulates that raising the intervention probability sets the foreign risk–free interest rate on the increase. This effects exerts a depressing effect upon the option premium because the interest accrued by holding foreign default–free assets plays a similar part in the valuation of FX options as the continuous leakage of value from holding the underlying in valuation models for European options on stocks yielding a dividend rate proportional to the level of the stock price.

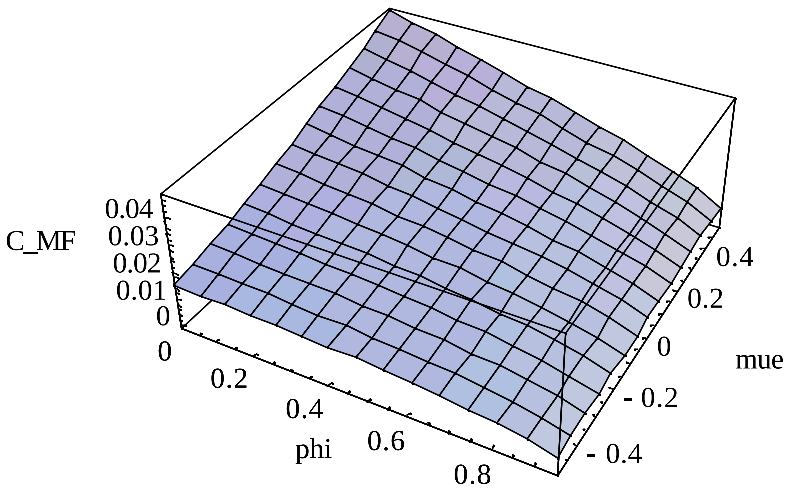
- Increasing the parameter π lowers the volatility parameter utilized to price options. Raising the intervention probability, thus, also affects the option price through the Vega of the contract. As the GK valuation formula states that the option price is an increasing function of the volatility parameter, this effect results in a decline of the premium of the contract.

To summarize, while the effect of a rise in the probability that a central bank FX market intervention will take place on the volatility of the spot rate and on the foreign interest rate tend to depress the value of the option, the effect exerted on the domestic risk–less interest rate raises the premium of the contract. Hence, whether a higher intervention probability π results in a lower option premium depends on the specific numerical parameter values plugged into the modified GK option pricing formula $C^{MF}(E, X, r, r^*, \tilde{\sigma}, \tau)$ outlined in equation (25).

The sign of the effect of a variation of the intervention probability on the premium of the FX option depends critically upon the parameter k reflecting how the international interest rate *differential* is decomposed to compute the *level* of the domestic and of the foreign risk–less interest rates. Figure 3 serves to highlight this feature of the model. The figure plots at–the–money option prices computed by resorting to the modified GK formula presented in equation (25) as a function of the intervention probability π and the drift μ of the process driving economic fundamentals. Figure (3a) assumes that the parameter k is relatively small so that the international interest rate differential corresponding to a given probability of central bank interventions is mainly opened by an appropriate adjustment of the foreign risk–free interest rate. Figure (3b), in contrast, is derived by presuming that the parameter k is relatively large so that the bulk of variations in the interest rate differential can be attributed to changes in the riskless domestic rate of interest. Both graphs plot at–the–money option values under the assumption that the drift–parameter μ is of a moderate size.

The depicted surfaces show that the sign of the effect of an increase in the drift of economic fundamentals on the premium of the at–the–money FX option depends upon the magnitude of the parameter k. For a relatively small k the option price turns out to decline as the drift of the fundamentals becomes larger, whereas for an interest rate differential allocation parameter k close to unity the option price is increasing in μ.





(b)

Figure 3— The Impact of the Intervention Probability on

At–the–money FX Options in the Managed Float: Part I

Note: The numerical parameter values selected to compute the option price surfaces are: $\bar{r} = 0.1$, $\sigma = 0.25$, $\pi = 0.5$ and $E = X = 1$. The time–to–maturity was fixed at one month. Figure (3a) obtains by setting $k = 0.1$ and Figure (3b) results by choosing $k = 0.9$. The above graph as well as all following figures presented in this subsection plot option prices for intervention probabilities up to 0.95.

A small k might capture the fact that the domestic economy is relatively large as compared to the rest of the world capital market so that the risk–free interest rate r can almost be viewed as an exogenous parameter. As the drift of the fundamentals μ becomes smaller and even negative in such an environment, the resulting appreciation expectations for the domestic currency tend to exert a relatively stronger depressing impact on the foreign risk–free interest rate as compared to the domestic rate of interest. Figure (3a) reveals that for a relatively small k, the decline in the level of the domestic interest–rate requiring a decrease in the option premium tends to be dominated by the effect of the lower proportional „dividend" rate on holding foreign assets ensuing a rise in the price of the FX option.

Figure (3b) reveals that for a relatively large k the situation is just reversed. In this situation, the domestic economy is relatively small in relation to the size of the world capital market. Therefore, expectations regarding changes in the level of the exchange rate must be accommodated mainly by an adjustment of the domestic risk–free interest rate. For example, the depreciation expectations fostered by a relatively large positive drift parameter μ result in a positive international interest rate differential. If the numerical value assumed by the parameter k is relatively large, this requires a strong rise in r and a comparatively moderate increase in r^*. This, in turn, implies that the rise in the opportunity costs of writing the option caused by the higher domestic interest rate dominates the increase in the opportunity costs of holding the contract attributable to the higher foreign interest rate.

The figure also suggests that at least for drift parameters μ of a relatively small absolute size at–the–money FX option premia are strictly decreasing in the intervention probability π. This finding indicates that for absolutely small values for μ the effect of a raise in π on the volatility of stochastic process driving the intervention–augmented fundamentals is stronger in terms of at–the–money option premia than the impact on the drift rate of this process. This result harmonizes with economic intuition because the Vega of the option attains a global maximum for contracts which are at–the–money.

Figure 4 demonstrates that the ordering of these effects might be reversed if at–the–money options are priced in an economic environment displaying a relatively large positive drift of fundamentals. The figure reveals that for a sufficiently large μ and for small and medium sized intervention probabilities the premium of the at–the–money FX option might be an increasing function of π. The economic reasoning motivating this finding is that for a large positive drift of fundamentals and a rather small probability that the central bank will step into the market the volatility affect is dominated by the impact of the intervention probability on the foreign–interest rate. Under these conditions, only rather high intervention probabilities ensure that the volatility effect dominates and the option premium begins to decline as π increases.

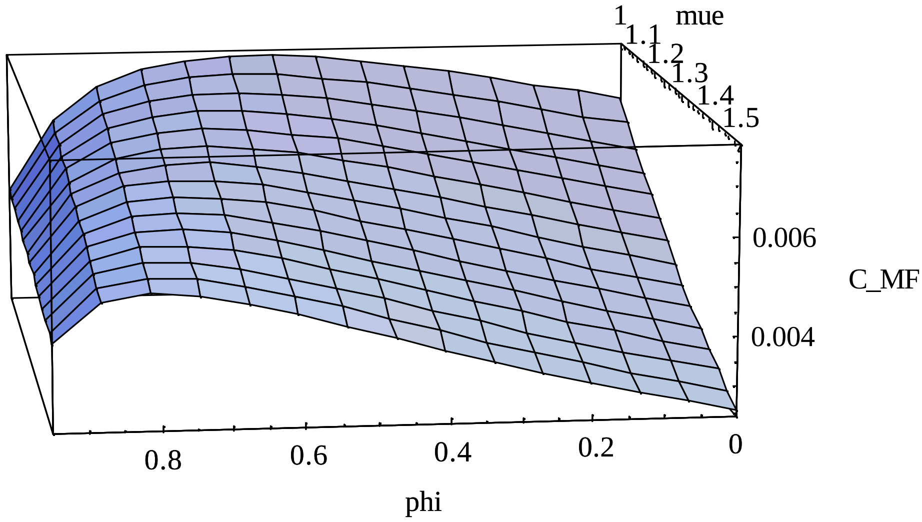


Figure 4 — The Impact of the Intervention Probability on

At–the–money FX Options in the Managed Float: Part II

Note: The numerical parameter values utilized to compute the figure are the same as in figure (3a).

The previous results demonstrate that for at–the–money options with a base currency issued by a relatively large domestic economy (which is characterized by a relatively small k) the volatility effect tends to dominate the interest rate effect as long as the drift of the process driving economic fundamentals is of a moderate size. Figure 5 highlights that a corresponding proposition does not hold in the case of in–the–money options. For such contracts, assigning even small positive numerical values to the parameter μ can change the relative magnitude of the effects. The economic reason behind this finding is that the interest rate sensitivity of the option is an increasing function of the moneyness of the contract (see e.g. Kolb 1997: p. 170) so that for in–the–money FX options the effect of a variation of the intervention probability π on Vega tends to be more easily outperformed by the simultaneous impact on the Rho of the option.[9]

9 Note that the Rho of the FX option with respect to both the domestic and the foreign interest rate must be considered.

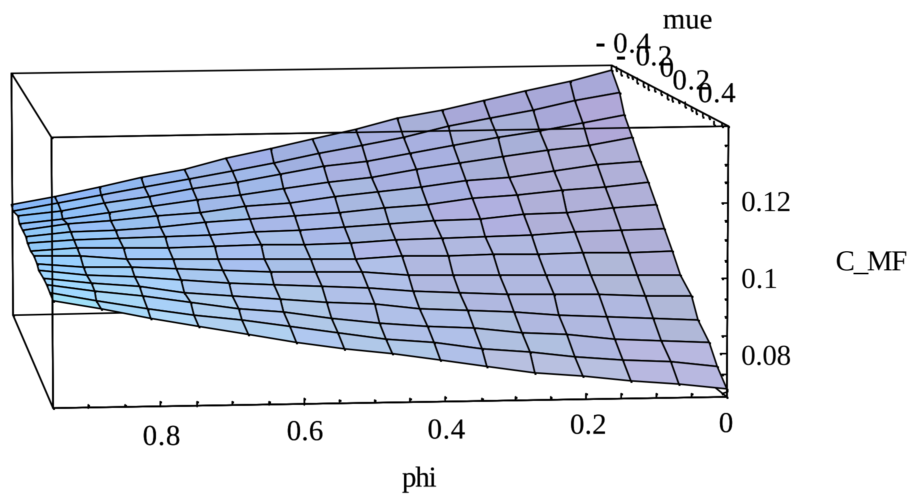


Figure 5 — The Impact of a Variation in the Intervention Probability on In–the–money Options

Note: The figure is based on the following set of numerical parameter values: $\bar{r} = k = 0.1$, $\sigma = 0.25$, $E = 1.1$, $X = 1$.

The conclusion to be drawn from the results reported in this section is that in empirical analyses the sign of the effect of central bank interventions on the expected variability of exchange rates as implied in options prices depends upon the characteristics of the economic environment. While this feature of the model might provide an explanation for the conflicting results documented in the literature analyzing the effects of central bank foreign exchange market interventions reviewed below, it also poses the question of how to disentangle effective from ineffective central bank FX market operations in the empirical study outlined in the proceeding section of this paper.

To make the point, suppose economic agents resort to the historical record of central bank interventions to conjecture a probability π that such a foreign exchange market operation will also take place during the next instant of time. Suppose further that interventions effectively alter the drift and lower the volatility of the exchange rate process. If the interest rate effect of this policy dominates its volatility effect, FX options prices might tend to increase and so do the implied volatilities backed out of these premia. If a researcher did not know that interventions have been assumed to be effective, it would be tempting to interpret the rise in the volatility implicit in foreign currency options as a hint that the central banks' exchange rate policy is ineffective in the sense that it does not contribute to calm disorderly markets.

This problem can only be resolved by taking a closer look at the international economic environment in which central banks' foreign exchange market operations take place. In the empirical section below, we examine the effectiveness of interventions conducted by the Deutsche Bundesbank in the $/DM spot market during a period ranging from 01/02/1987 to 03/12/1990. Using daily observations, the mean and the median of the differential between the domestic U.S. and the foreign German one month Eurodollar rates can be calculated as 2.7780 per cent per anno and 3.1920 per cent per anno, respectively.[10] During the time period under investigation the Bundesbank intervened on 167 days in the $/DM spot market. According to Dominguez and Frankel (1993), only 87 of these FX market operations were reported in the financial press. These figures can be utilized to compute an objective (a proxy for a subjective) unconditional probability of a Bundesbank intervention as $167/803 \approx 0.21$ ($87/803 \approx 0.11$). The above model can now be employed to define a virtual drift of economic fundamentals as $\mu_{virtual} \equiv (r - r^*)/(1-\pi)$. A back of the envelope calculation based on the objective unconditional probability of an intervention gives $\mu_{virtual} \approx 0.0352$ if the mean of the interest rate differential and $\mu_{virtual} \approx 0.0404$ if the corresponding median is utilized. Carrying out the same computations with the proxy for the subjective probability of an intervention, the virtual drift rate of fundamentals is $\mu_{virtual} \approx 0.0312$ when the mean of the interest rate differential is used and $\mu_{virtual} \approx 0.0359$ when the median is plugged into the above formula. These figures and visual inspections of the exchange rate series plotted in figure 6 below indicate that during the sample period under investigation the volatility effect can safely be expected to dominate at least for the at–the–money options employed in the empirical analysis presented in the next section.

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10 The empirical analysis outlined in the next section uses Philadelphia Stock Exchange contracts to compute options implied volatilities. For this reason, the U.S. Eurodollar rate is defined as the domestic interest rate.

3 Using Options Implied Volatilities to Assess the Effectiveness of Central Bank Interventions

In this section, daily official data are utilized to shed light on the effectiveness of the interventions of the Deutsche Bundesbank in the $/DM spot market during the three years following the Louvre Accord ranging from 01/02/1987 to 03/12/1990. The interest in this period is fostered by the fact that the Bundesbank and other major central banks frequently participated in foreign exchange trading during this period. The effectiveness of interventions is examined by constructing a multifactor success criterion which allows to model the impact of this type of FX market operations on the level and on the expected volatility of the $/DM spot rate within a unified framework. The success criterion is derived from the insights provided by the theoretical analyses performed in the preceding section. The criterion forms the dependent variable in an ordered qualitative response model estimated to gauge the significance of the potential relation between the spot market interventions conducted by the Bundesbank and the following change of the level and of the volatility of the exchange rate. As suggested by Bonser–Neal and Tanner (1996) and Madura and Tucker (1991), daily implied volatility quotes backed out of Philadelphia Stock Exchange American style options are employed to capture anticipated exchange rate volatility.

To construct a success criterion, we use the two main results of the theoretical analyses contained in the preceding section. Based on the intervention model of Lewis (1995) discussed in the second section of this paper, it can be concluded that an effective intervention policy induces the exchange rate to exhibit a tendency to mean–revert towards the central parity of its implicit fluctuation band. This result also holds even if the influence of implicit exchange rate bands on spot rate dynamics can be neglected as long as the intervention probability is an increasing function of the gap between the exchange rate and its central parity. Furthermore, the study of the option pricing models has revealed that, for the sample period and exchange rate under investigation, volatilities implicit in foreign currency options should tend to decrease as the intervention probability increases. Using this intervention probability as a measure of the intensity of central banks FX market operations, the efficacy of this policy strategy can thus be measured by analyzing its impact on the volatility implicit in foreign currency options.

The success criterion applied to analyze the efficacy of the intervention policy of the Bundesbank during the Louvre period summarizes these results. According to the criterion used in the empirical analysis, an intervention is classified as effective if it tends to close the gap between the current exchange rate and an implicit target level and, at the same time, serves to lower the expected volatility of the $/DM spot price as implied in foreign currency options premia. If one of these conditions is not satisfied, the intervention is rated as partially effective. If both conditions do not hold, the intervention is identified as completely ineffective.

The research methodology utilized in the present section draws on an idea recently formulated by Humpage (2000) who suggests a dichotomous success criterion to study the effectiveness of central banks' FX market interventions. According to his two–state rule, an intervention is classified as successful if a sale (a purchase) of foreign currency is followed by an appreciation (a depreciation) of the domestic currency or if this policy action contributes to lower the rate of appreciation (depreciation) of the home currency. Focusing on the Louvre period, Humpage (2000) finds that the amount and the international coordination of interventions positively affected the probability of success of the FX market operations conducted by the Federal Reserve Bank of New York.

The work contained in the present section extends the study of Humpage (2000) in two important respects. Firstly, an alternative success criterion is used which allows to model the impact of central bank FX market interventions on the level of the spot rate and on the expected volatility of this asset price simultaneously. Secondly, to fully exploit the advantages of the success criterion used in the empirical analysis, we employ an alternative and potentially richer econometric methodology. While the success criterion constructed by Humpage (2000) allows to examine the effectiveness of FX market operations by means of bivariate binary dependent variable models, the success criterion developed in the present study makes a qualitative response model with ordered categories the natural candidate to be used in the empirical analysis.

The analysis is organized as follows. Subsection 3.1 is devoted to a discussion of the results reported in the related literature. In subsection 3.2, the multivariate success criterion utilized to assess the effectiveness of central bank foreign exchange market interventions is developed and the applied econometric research strategy is discussed in detail. The data utilized in the empirical analyses are described in subsection 3.3. The results of the estimations are presented and interpreted in the final subsection.

3.1 *Results Reported in the Related Literature*

In the literature concerned with the effectiveness of central banks' foreign exchange market interventions, the debate on the issue whether such operations tend to stabilize or to destabilize or even do not affect market prices at all has not been settled so far. Most contributions to this area of research analyze the effectiveness of interventions either in terms of their effect on the level of the spot rate or in terms of their impact on the volatility of exchange rates.

Regarding the impact of interventions on the level of exchange rates, Weber (1996) estimates a vectorautoregression and finds that the FX market operations of the G–3 were ineffective in that this policy did not help to stabilize exchange rates in the long–run.[11] Using a univariate regression approach, Dominguez and Frankel (1993) find that exchange rate policy announcement served to smooth exchange rates during the Louvre period. For the Plaza period, it is found that the intervention amount did not significantly affect exchange rate movements and that interventions reported in the financial press tended to aggravate exchange rate fluctuations.[12] For the Louvre period, in contrast, the opposite is found. While for this period of time the coefficient of the intervention amount turned out to be significant in their regressions, the variable capturing whether or not an intervention was publicly known is not significantly different from zero.

A descriptive study decisively arguing in favor of the effectiveness of G–3 central banks' foreign exchange market interventions is Catte et al. (1992). According to their success criterion, an intervention is ranked as effective whenever (i) the FX market operation reversed the trend of the $/DM spot rate, and, (ii) the following intervention took place with an opposite sign. Given this success criterion, the authors report that interventions were successful in breaking and reversing trends of the dollar. Moreover, it is documented that episodes during which interventions took place are also often periods during which turning points of the $/DM exchange rate can be observed. Though it is tempting to interpret this latter result as a hint indicating the effectiveness of interventions in breaking trends in the $/DM rate, Weber (1996: p. 258) emphasizes that it is also possible to identify

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[11] A comprehensive description of early research on this issue as well as an elucidating survey of this strand of the literature is provided by Edison (1993). See also Almekinders (1995: pp. 78 and ch. 6).

[12] Dominguez and Frankel (1993) attribute the „incorrect" sign of the effect to the feedback relation between effective interventions and exchange rate movements and the resulting simultaneity problems beleaguering their estimates. We will deal with this problem in section 3.3.2 below.

a substantial number of turning points in the spot rate series which do not fall into periods characterized by central bank forex interventions.

Recent evidence presented in Humpage (2000) suggests that interventions conducted by the U.S. central bank during the Louvre period effectively smoothed the $/DM and the $/Yen spot rates. Using a binary dependent variable model, he reports that the probability of a successful U.S. intervention was higher whenever the Federal Open Market Committee coordinated FX market operations with other major central banks. According to the binary success criterion used in this study, central banks' FX market interventions are identified as effective if a sale (a purchase) of foreign currency is either followed by an appreciation (a depreciation) of the domestic currency or a in slowdown of the rate of appreciation (depreciation) of the home currency.

Kaminsky and Lewis (1996) also report that interventions affected exchange rates. However, they emphasize that U.S. interventions convey information that future monetary policy moves in the opposite direction suggested by the sign of the intervention. Consequently, interventions are also found to induce an exchange rate change in the opposite direction indicated by the sign of the intervention.

Concerning the impact of central banks' foreign exchange market operations on exchange rate volatility, Bonser–Neal and Tanner (1996) use volatilities implicit in foreign currency options to analyze the impact of interventions on market participants' sentiment regarding the future variability of the spot market. Controlling for the influence of macroeconomic announcements, they find that both U.S. and Bundesbank interventions either did not affect implied volatility significantly or even contributed to inflate the expected variability of the spot rate. Options implied volatilities have also been used by Madura and Tucker (1991) to study the impact of interventions on exchange rate volatilities during the years following the Louvre Agreement. They find that the central bank foreign exchange market interventions conducted during this period of time were unsuccessful in dampening exchange rate volatility. Their findings thus corroborate the results documented in Bonser–Neal and Tanner (1996).

Taking a noise trader approach, Hung (1997) points out that the impact of interventions on exchange rate volatility might change over time. Using data on U.S. interventions, he finds that interventions during the mid–eighties intended to bring the strong dollar down tended to decrease volatility. In contrast, interventions mainly motivated by the goal to stabilize rates around prevailing levels in the aftermath of the Louvre Accord are found to raise exchange rate volatility. He motivates his results by resorting to arguments put forward in the noise trader literature. According to his line of argumentation, volatility decreasing interventions serve to foster chartists trend–line based demand for foreign currency. In contrast, volatility increasing interventions enhance trading uncertainty and contribute to make momentum–based trading strategies less appealing to FX market participants. These arguments imply that even interventions which raise exchange rate volalatility can be viewed as effective as long as (i) these FX market operations are intended to stabilize exchange rates around a prevailing fundamental level, and, (ii) chartists are suspected to drive a gap between the spot rate and this target level.

Though the noise trader hypothesis might in some circumstances provide a useful theoretical explanation for the positive effect of interventions on exchange rate volatility often found in empirical work, Hung's (1997) line of reasoning can be criticized for at least two theoretical reasons. Firstly, following De Long et al. (1990), it is possible to argue that volatility increasing interventions could discourage risk–averse fundamentalists to counter the speculative demand of noise traders. Depending on the net effect on the demand for foreign currency, volatility enhancing intervention therefore need not necessarily serve to bring the spot rate back to its fundamental value and would, therefore, be ineffective. Secondly, work of Krugman and Miller (1993) suggests that interventions which drive noise traders adhering to a trend–enforcing stop–loss strategy out of the market should result in a stabilization of exchange rates. This implies that FX market operations which effectively alter the speculative position taking of noise traders should result not in an increase but in a decline of exchange rate volatility.

The contributions mentioned so far examine the impact of interventions either on the level *or* on the variability of exchange rates. The analyses performed in the present section differ from these approaches in that our research strategy renders it possible to model the effect of central bank forex interventions on the level and on the expected volatility of the exchange rate simultaneously within a unified framework. In the literature devoted to the study of the effectiveness of interventions, a comparable approach has been chosen by Dominguez (1998). However, she uses a Generalized Autoregressive Conditional Heteroscedasticity (GARCH) model pioneered by Engle (1982) and generalized by Bollerslev (1986) to examine the success of interventions empirically.[13] Thus, the econometric approach chosen by Dominguez (1998) to perform the empirical analyses differs substantially from the research strategy adopted in the present section. As concerns the intervention policy of the Bundesbank, Dominguez (1998) finds that the FX market operations of the German central bank reduced the volatility of the $/DM exchange rate. This contrasts the results obtained for U.S. interventions which are found to decrease (increase) the conditional variability of the $/DM spot rate during 1985–1987 (1987–1994). Interestingly, secret interventions are found to inflate exchange rate volatility. Complementing this analysis with an implied volatility based least squares regression approach, she further finds that the results of the GARCH analysis are not robust insofar as Bundesbank interventions are now found to decrease exchange rate variability only during the mid–eighties but tended to induce an increase in expected spot rate volatility during the Louvre period.

13 Fatum and Hutchison (1999) employ a similar technique to assess the informational role of U.S. foreign exchange market interventions as a signal of future monetary policy. To accomplish this exercise, they estimate the effect of interventions on federal funds futures price changes. In their analysis, only the coefficients in the conditional variance equation are significant and positive.

3.2 *Discussion of the Research Strategy*

The effectiveness of a central bank intervention is measured by analyzing its impact on the absolute deviation of the exchange rate from a central parity defined by monetary authorities and on the volatility of this asset price as implied in the prices of foreign currency options. Both variables are typically considered in empirical studies elaborating on the factors influencing the propensity of central banks to step into the foreign exchange market.[14] It is therefore only consequent to evaluate the efficacy of such policy actions in terms of this set of variables. Over and above, both criteria are selected as they serve to reflect the convention documented in the fourth article of the Articles of Agreement of the International Monetary Fund that central banks should seek to counter „disorderly market conditions“.[15] Examining the absolute deviation of the exchange rate from an implicit central parity to measure the impact of interventions policy on the level of the exchange rate is motivated by the goal agreed upon by G–7 authorities at the Louvre Summit which took place on 02/22/1987 to stabilize spot rates around the then prevailing levels. In specifying an implicit central parity $\overline{E}$ established under the Louvre Agreement, we follow Funabashi (1988: p.183) who reports a more or less official baseline rate of approximately 0.55 $/DM. The absolute deviation of the current exchange rate from this target level is computed as:

(28) $$dev_t = \left| E_t - \overline{E} \right|$$

In a next step, we introduce a latent continuous variable $S_t *$ to designate joint movements of the change in the deviation of the exchange rate from its central parity and the change in the expected volatility of this asset price as implied in foreign currency option prices. The continuous index variable $S_t *$ is defined on the real–line and is assumed to depend linearly on a $(m \times 1)$ dimensional vector $\mathbf{x}_t$ of explanatory variables determining the conditional mean of $S_t *$ as formalized below:

(29) $$S_t * = \mathbf{x}_t ' \mathbf{b} + \varepsilon_t$$

where $\mathbf{b}$ denotes a $(m \times 1)$ vector of coefficients to be estimated and ε_t is a normally distributed error term with mean zero and variance σ_ε.

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14 See also the references presented in the section on the construction of an instrument for interventions.

15 See also IMF Execution Board, Decision No. 5392–(77/63) [April 1977].

The motivation to employ the ordered probit model pioneered by Aitchison and Silvey (1957) to analyze the effectiveness of central bank interventions stems from the fact that S_t* has a continuous state space and is, therefore, in general not observable. To develop an empirically meaningful model, we follow the line of argumentation suggested by Hausman et al. (1992) and assume that it is only possible to observe a discrete variable S_t which assumes a known numerical value if the unobservable index variable S_t* falls into a certain interval of its state space. The ordered probit model can now be used to relate the observable realizations of S_t and the unobservable continuous variable S_t* via the following rule (see Campbell et al. (1997: p. 123):

(30) $$S_t = j \quad \text{if} \quad S_t* \in s_j \quad , \qquad j = 0,1,\ldots,N$$

where the sets s_j form an ordered partition of the state space of S_t* into j non–overlapping intervals. In the following analysis, it suffices to set $N = 2$ as this implies that the state space is subdivided into three disjoint intervals which allow to discriminate between effective, partially effective, and ineffective central bank interventions.

We restrict our attention to days on which the absolute intervention amount I_t takes on a strictly positive numerical value and assume that the unobservable continuous variable S_t* is in interval j whenever we observe:

(30) $$S_t = \begin{cases} 2 & \text{if} \quad I_t > 0 \quad \text{and} \quad \sigma_{t+1}/\sigma_t < 1 \ \wedge \ dev_{t+1}(1-L) < 0 \\ 1 & \begin{cases} \text{if} \quad I_t > 0 \quad \text{and} \quad \sigma_{t+1}/\sigma_t < 1 \ \wedge \ dev_{t+1}(1-L) > 0 \ \vee \\ \text{if} \quad I_t > 0 \quad \text{and} \quad \sigma_{t+1}/\sigma_t > 1 \ \wedge \ dev_{t+1}(1-L) < 0 \end{cases} \\ 0 & \text{if} \quad I_t > 0 \quad \text{and} \quad \sigma_{t+1}/\sigma_t > 1 \ \wedge \ dev_{t+1}(1-L) > 0 \end{cases}$$

where L denotes the lag–operator. Equation (30) states that S_t* is in state 2 whenever we observe a decrease in both the expected volatility of the exchange rate backed out of FX option prices and in the deviation of the exchange rate from the target level $\overline{E}$. The latent variable S_t* can be found in state 1 whenever the change in the implied volatility and in dev_t move in opposite directions. In a similar vein, the unobservable continuous process assumes a realization belonging to state 0 if implied volatility increases and the exchange rate moves farther away from its central parity.

Equation (30) is a convenient tool to separate perfectly and partially effective interventions from ineffective central bank FX market operations. An intervention is classified as fully effective if it tends to lower implied exchange rate volatility and serves to close the gap between the current exchange rate and its central parity. Thus, if the intervention series is included in the vector $\mathbf{x}_t$ and it is found that this explanatory variable tends to increase the probability that S_t* assumes a realization belonging to state 2 the exchange rate policy of the central bank can be claimed to be effective. If, in turn, foreign exchange market operations primarily tend to raise the probability that S_t* falls into the interior state space, a trade–off between the impact on expected exchange rate volatility and the deviation from the target level exists and the intervention policy can be claimed to be only partially effective. Finally, a completely ineffective intervention policy can be identified by analyzing whether this policy instrument inflates the probability that S_t* falls into the partition of its state space indicated by $S_t = 0$.

For estimation purposes, equation (30) can be re–formulated in terms of the latent variable as follows:

(31) $$S_t = \begin{cases} 0 & \text{if } S_t* \leq S_1 \\ 1 & \text{if } S_1 < S_t* \leq S_2 \\ 2 & \text{if } S_2 < S_t* \end{cases}$$

with S_1 and S_2 being threshold parameters separating the non–overlapping states s_j. Given that ε_t has been assumed to be normally distributed, the probability that S_t* can be found in state j can be written as (see e.g. Greene 1997, ch. 19):

(32) $$Prob(S_t = 0) = \Phi(S_1 - \mathbf{x}_t'\,\mathbf{b})$$

$$Prob(S_t = 1) = \Phi(S_2 - \mathbf{x}_t'\,\mathbf{b}) - \Phi(S_1 - \mathbf{x}_t'\,\mathbf{b})$$

$$Prob(S_t = 2) = 1 - \Phi(S_2 - \mathbf{x}_t'\,\mathbf{b})$$

where $\Phi(\cdot)$ denotes the standard normal distribution function. The unknown parameters of the ordered probit model can be efficiently estimated by maximizing the following log–likelihood function (cf. Aitchison and Silvey (1957), Campbell et al. (1997)):

(33) $$LL = \sum_{t=1}^{n} \sum_{j=0}^{2} N_j \ln Prob(S_t = j)$$

where N_j denotes the number of realizations in category j.

3.3 *The Data*

3.3.1 The Time Series Used in the Empirical Analysis

The time period under investigation ranges from January 1987 to March 1990 and covers the period following the G–7 summit which took place at the Louvre in Paris on February 22, 1987. Daily official intervention data provided by the Deutsche Bundesbank are utilized to assess the effectiveness of the interventions of the German central bank in the $/DM spot market during this period of time. Figure (6a) plots the daily intervention data series. Positive interventions (+) denote a purchase of U.S. dollar and negative interventions (-) capture sales of foreign currency by the German central bank. The intervention amount is measured in millions of DM. During the analyzed sample period the Bundesbank carried out 167 interventions in the $/DM spot market. The fluctuation of the daily exchange rate series employed in the empirical analysis around the implicit target level of 0.55 $/DM reported in Funabashi (1988) are shown in figure (6b). The expected variability of the spot rate is measured in terms of volatility quotes implicit in at–the–money DM/$ Philadelphia Stock Exchange (PHLX) American style foreign currency options. Implicit volatilities measure market participants' sentiment regarding the average variability of the underlying exchange rate over the remaining time to maturity of the option. The $/DM implied volatilities employed in the present study are plotted in figure (6c). The series is identical to the time–series utilized by Bonser–Neal and Tanner (1996).[16]

When modeling the impact of central banks' foreign exchange market interventions on the level and on the volatility of the spot rate, it is important to account for the potential influence of other variables. The control variables considered in the present study can be subsumed under three broad categories.

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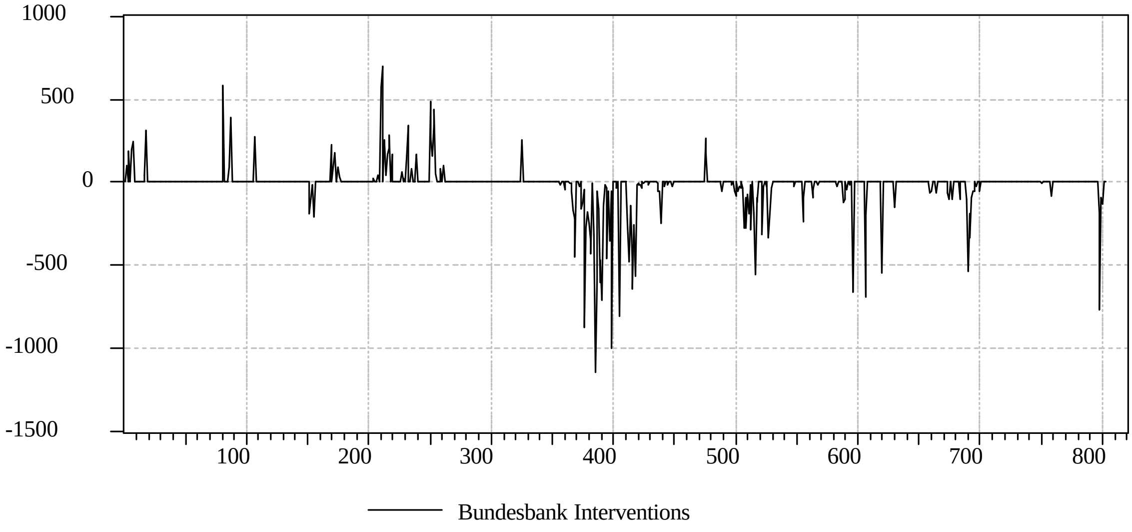
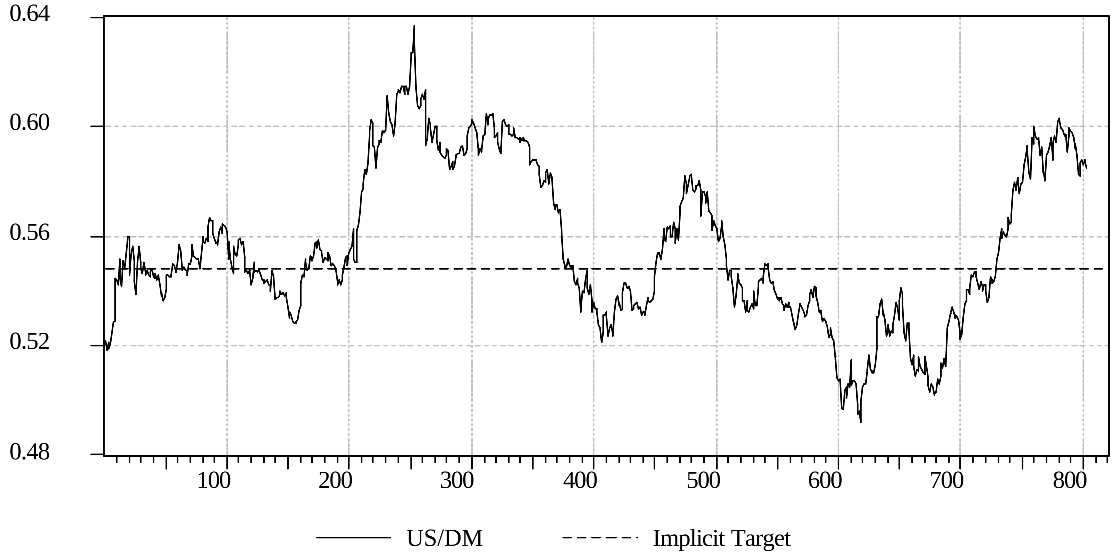
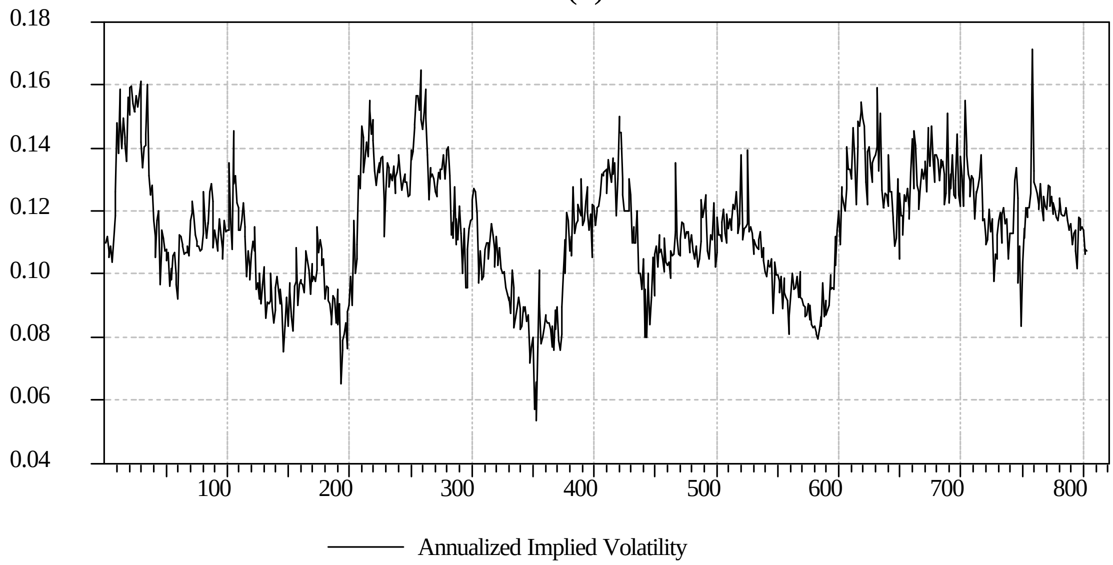
[16] I thank Catherine Bonser–Neal and Glenn Tanner for sharing their implied volatility data with me. They employed the Barone–Adesi and Whaley (1987) quadratic approximation technique to back volatilities out of observed option prices. In their data set, implied volatilities are missing for the period 08/26/1988 – 10/03/1998. To close this gap, I utilized daily closing prices for options with a moneyness between 0.98 and 1.02 and with a time to expiry of at least one week and at most three months as documented on the transactions data tapes of the PHLX. To be consistent with the strategy adopted by Bonser–Neal and Tanner (1996), the missing implied volatilities were also computed by implementing the Barone–Adesi and Whaley (1987) approach. I also thank the Deutsche Bundesbank for generously providing me with the daily data on foreign exchange market interventions.



(a)



(b)



(c)

Figure 6 — Time Series Used in the Empirical Analyses

- The first category contains variables capturing the *characteristics of the intervention*.

Dominguez and Frankel (1993) and Humpage (2000) report that the effectiveness of U.S. interventions tends to be higher whenever major central banks coordinated their FX market operations. To test whether a similar proposition also holds in the case of the Bundesbank, a dummy variable is constructed which assumes the value one whenever interventions were coordinated. Upon confronting the German data with the corresponding U.S. intervention series, it was verified that 88 of the 167 Bundesbank where coordinated.

A further possibly informative characteristic of an intervention is its sign. Because figure (6a) indicates that the direction of Bundesbank interventions has changed several times during the sample period under investigation, a dummy variable is defined which is 1 for positive and -1 for negative interventions and zero else.

In the literature elaborating on the effectiveness of central bank interventions, it is often considered to be important to distinguish between secret and publicly known interventions (see e.g. Dominguez (1998)). To take this argument into consideration, we compute a dummy variable which takes on the value one whenever FX market participants might have known that a central bank intervention is going on. Publicly known interventions are identified by confronting the Bundesbank data with the time schedule reported in Dominguez and Frankel (1993) in which reports in the financial press that an intervention had taken place are documented.

As can be seen by scrutinizing figure (6a), the Bundesbank frequently intervened on successive days. Humpage (2000) argues that the intervention marking the beginning of such an intervention cluster might be more informative for market participants and might, therefore, be more effective than the predecessor interventions. To account for this aspect, a dummy variable is defined which assumes the value zero whenever an intervention is immediately preceded by another FX market operation and one else.

- The second category considered has been filled with two variables indicating other aspects of German *monetary policy*.

It has been argued by Lastrapes (1989) that exchange rate volatility might depend upon the prevailing monetary policy regime. To take this argument into consideration, the level of the discount rate has been chosen to control for the overall stance of monetary policy. The second variable in this category has been labeled *news* and assumes the value one whenever an event is reported in Dominguez and Frankel (1993) which is not an intervention but which might be informative with respect to an evaluation of the overall stance of monetary or of exchange rate policy.

- Finally, a third category of variables has been designed to account for the potential influence of other *financial market variables* on the evolution of $s_t *$.

To account for possible weekend and day–of–the–week effects documented for exchange rates in e.g. Baillie and Bollerslev (1989), we have also constructed two dummy variables assuming the value one on every Monday and Friday, respectively.

Using a regression approach, Bonser–Neal and Tanner (1996) report that movements in expected exchange rate volatility are significantly related to contemporaneous changes in stock market volatility which is interpreted as a measure of overall financial market volatility. Motivated by this result, we have computed an annualized time–varying conditional stock market volatility series by estimating a GARCH(1,1) model for the returns of the German stock market index published by the Frankfurter Allgemeine Zeitung with a constant as the regressor in the mean equation.

The system of equations forming the GARCH model can be efficiently estimated simultaneously using a non–linear maximum likelihood routine. The results of implementing this procedure as well as several important diagnostic tests performed to check for the adequacy of the framework are summarized in table 1. The figures reported in the table indicate that the coefficients of the GARCH model are all significant at the one per cent level. Moreover, the result of the Wald test (WALD) presented in the first column of the table reveals that the sum of the ARCH and the GARCH terms entering into the conditional volatility equation is significantly different from one. This result suggests that the unconditional stock market volatility is a stationary process and that the unconditional variance exists. Langrange multiplier (LM) tests championed by Breusch (1978) and Godfrey (1978) indicate that it is not possible to reject the null hypothesis of no remaining autocorrelation in the standardized residuals. The LM–test (ARCH) introduced by Engle (1982) witnesses that the Null of no further GARCH effects in the squared standardized residuals of the GARCH (1,1) framework cannot be rejected. A few influential outliers mainly attributable to the stock market crashes of 1987 and 1990 are responsible for the striking significance of the test statistic suggested by Bera and Jarque (1982) (abbreviated as JB). The significance of this test indicates that it is not possible to retain the assumption that the standardized residuals of the GARCH model are standard normally distributed. To account for this departure from normality, robust standard errors (reported in brackets) have been computed by using the quasi-maximum likelihood method developed by Bollerslev and Woolridge (1992).

Mean equation	*Variance equation*			*TARCH coefficient*
Intercept[a]	Constant	ARCH–coef.[c]	GARCH–coef.	
0.001534*** (2.95)[b]	0.00001*** (2.66)	0.27528*** (2.26)	0.68480*** (10.06)	0.35049 (1.13)
Diagnostic Tests	LM(5)	WALD	ARCH(5)	JB
	8.30	0.37	0.28	22403.87***

Table 1 — Modeling Conditional Stock Market Volatility

Note: [a] Figures in brackets are standard normally distributed *z*–statistics computed as the ratio of the respective coefficients and the corresponding standard deviations. Robust standard errors have been obtained by implementing the technique of Bollerslev and Woolridge (1992). [b] Three asterisks indicate that the test statistic is significant at the 1 per cent level. [c] Abbreviation for co-efficient.

As a final exercise, we have tested for significant leverage effects in conditional stock market volatility by estimating the asymmetric Threshold–ARCH model suggested by Glosten, Jagannathan and Runkle (1993) and by Rabenmananjara and Zakoian (1993). However, the corresponding TARCH coefficient presented in the fifth column of table 1 turned out to be insignificant.

Taken together, the evidence summarized in table 1 indicates that the baseline GARCH(1,1) model captures the dynamics of conditional stock market volatility very well. This suggests that it is reasonable to employ the conditional stock market volatility series obtained from this model in the empirical analysis out-lined below.

3.3.2 Constructing an Instrument for Interventions

Authors contributing to the strand of the literature examining the objectives of central bank forex interventions often report that both swings in the level of the exchange rate and a rise in its volatility might play a prominent role in explaining the propensity of central banks to step into FX markets.[17] These results suggest that a potential simultaneity problem resulting in spurious parameter estimates might arise if the original Bundesbank intervention series is utilized to estimate the ordered probit model outlined in the preceding section. To resolve this problem, the model should only be estimated after the original intervention series has been replaced by an appropriate instrumental variable. Humpage (2000) suggests to construct such an instrumental variable by specifying a full–fledged reaction function to model the intervention policy of the Bundesbank.[18]

The first step in estimating a reaction function is to identify an appropriate set of variables which serves to explain central banks' interventions policy.[19] We employ the lagged change of the absolute deviation of the exchange rate from its central parity (denoted as $factor_1$) to capture the impact of swings in the level of the $/DM spot rate on the intervention propensity of the Bundesbank. The second factor ($factor_2$) presumed to affect the intervention probability reflects the overall tendency of trading uncertainty to rise or to fall and is formed by a five–day moving average of lagged implied volatility changes. Defining the central banks' propensity to intervene by I_t*, these assumptions allow us to write:

(34) $$I_t* = \beta_0 + \beta_1 factor_1 + \beta_2 factor_2 + \varepsilon_t*$$

where ε_t* is an independently and identically distributed error term with standard deviation $\sigma*$.

The next step is to formulate a quantitative model allowing to shed light on the relation between this set of independent variables and the amount of interventions. In this respect, we utilize the reaction function model suggested by Almekinders and Eijffinger (1994). In line with the intervention series plotted in figure 6, these authors point out that it is not reasonable to presume that every arbitrarily small deviation of the explanatory variables of the model from their target levels implicitly defined by the central bank triggers an intervention. Rather, it

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17 See i.a. Eijffinger and Gruijters (1991), Almekinders and Eijffinger (1994), Baillie and Osterberg (1997a, 1997b), and Döpke and Pierdzioch (1999).

18 Humpage (2000) departs from the research strategy adopted in the present section in that he uses the sample selection model develpoed by Heckman (1979) to construct an instrument.

19 A comprehensive survey of the numerous early contributions to this area of research can be found in Almekinders (1995: ch. 4 and ch. 5). See also the references presented in the footnote before last.

can be expected that central banks only decide to step into the foreign exchange market when the momentum of the movement of the exchange rate away from its central parity and/or of options implied volatilities exceeds a certain critical level.

Assuming that the absolute intervention amount I_t is proportional to the central banks' propensity to intervene I_t*, one can conclude:

(35) $$I_t = \begin{cases} I_t* & \text{if} \quad I_t* > 0 \\ 0 & \text{else} \end{cases}$$

where, for ease of exposition, the critical propensity to step into the market triggering an intervention has been set equal to zero.

Equation (35) implies that interventions are truncated from below and that the reaction function should not be estimated by least squares. Rather, the truncated regression model tracing back to Tobin (1958) turns out to offer an appropriate econometric technique to reveal the link between the intervention propensity of the Bundesbank and the set of explanatory variables defined above.

Tobit model	Coefficient	Standard Deviation	*z*-Statistic
Constant	-0.3260***	0.0317	-10.2935
$factor_1$	9.9453**	4.7329	2.1013
$factor_2$	31.5777***	7.4882	4.2170
$\sigma*$	0.3775***	0.0242	15.6174
Adjusted R^2	0.0254	Standard Error	0.1259
Log likelihood	-300.6904	Uncensored Observations	633
Restricted Log likelihood	-312.6064	Censored Observations	164
LR–test	23.8320****	Marginal Probability	<0.0001

Table 2 — Reaction Function Derived by Estimating a Tobit Model

Note: The significance of a regressor is analyzed by using the standard normally distributed ratio of the coefficient and its respective standard deviation (z-statistic).

Table 2 provides maximum likelihood estimates of the Tobit model as well as some diagnostic statistics. All coefficients can be seen to be significant at the one per cent level. To assess the overall explanatory power of the model, a likelihood ratio (LR) statistic has been computed. To compute the *LR*–test, both the unrestricted model and a model only containing an intercept are estimated. Taking the difference between the respective log likelihood functions to compute (see Greene 1997: p. 886):

(35) $$LR = -2\left(LL_{restricted} - LL_{unrestricted}\right) \sim \chi^2_{number\ of\ restrictions}$$

gives a test statistic which is χ^2 distributed with degrees of freedom equal to the number of imposed restrictions. Table 2 shows that the *LR*–test is highly significant with a marginal probability smaller than 0.0001.

Given that the Tobit model turns out to exhibit significant explanatory power, we are now in a position to follow Humpage (2000) in utilizing the predicted values obtained from the reaction function model as an instrumental variable in the model constructed to analyze the effectiveness of central bank foreign exchange market interventions

3.4 *The Effectiveness of Bundesbank FX Market Interventions*

This section presents maximum likelihood estimates of the parameters of the ordered probit model discussed in subsection 3.2.2. The model is estimated over the 167 intervention days contained in the sample period under investigation.

Table 3 reports results for models constructed by including the various explanatory variables separately into the vector $\mathbf{x}_t$. The table allows to examine the individual effects of the explanatory variables on the probability that $S_t = j$ and $S_t{*} \in s_j$ and to identify potential candidates for building a more complex model. The information needed to evaluate the various models are contained in the rows of the table. The first column depicts the respective explanatory variables. While the variable *buba* is defined as the absolute amount of actual Bundesbank interventions, the series *bubaexpected* contains the predicted absolute intervention amounts obtained from the Tobit model outlined in the previous subsection. The second, fourth, and sixth columns report the element β_1 of the coefficient vector $\mathbf{b}$ and the threshold parameters S_1 and S_2, respectively. The corresponding *z*–statistics indicating the individual significance of the estimated parameters are depicted in the third, fifth, and seventh columns of the table. A likelihood ratio test statistic used to evaluate the overall explanatory power of the respective models is contained in the most left column of the table.

	β_1	*z*-statistic	S_1	*z*-statistic	S_2	*z*-statistic	*LR*–test
			Interventions				
bubaexpected	6.1784	1.9616	-0.3439	-1.8299	0.9981	5.01906	3.8687
buba	-0.2282	-0.5665	-0.6970	-5.2593	0.6255	4.7693	0.3212
			Characteristics of Interventions				
coordination	-0.0926	-0.5371	-0.0926	-5.0100	0.6216	4.4924	0.2886
sign	0.0810	0.8142	-0.6932	-5.9226	0.6309	5.4538	0.6634
reported	-0.2434	-1.4085	-0.7827	-5.5541	0.5480	4.0235	1.9869
first	0.1324	0.7530	-0.5995	-4.7874	0.7242	5.6612	0.5673
			Monetary Policy				
discount	0.0354	0.3666	-0.5270	-1.4877	0.7946	2.2300	0.1345
news	0.3333	1.1369	-0.6223	-5.7634	0.7052	6.4081	0.1345
			Financial Market Variables				
fazvola	0.8689	1.2062	-0.4625	-2.4607	0.8659	4.4608	1.4617
monday	0.3157	1.4336	-0.5960	-5.3329	0.7350	6.3831	2.0623
friday	-0.2601	-1.2495	-0.7124	-6.1378	0.6162	5.4164	1.5649

Table 3 — Ordered Probit Model for Individual Effects of Explanatory Variables

Note: The critical values for the *LR*–test with one degree of freedom are 3.84146 at the 5 % level and 2.70554 at the 5% significance level. See Judge et al. (1988: p. 987).

The results reported in table resemble those obtained by Humpage (2000) for U.S. data. Only the variable *bubaexpected* exhibits a statistically significant power to influence the probability that the dependent variable S_t* settles in state j. Though the arguments outlined below indicate that the coefficients of the ordered probit model must be interpreted with care, the positive sign of β_1 shows that the probability of a simultaneous decline in both the expected exchange rate volatility and in the gap between the current level of the spot rate and its target level increases with the absolute amount of Bundesbank interventions. Also, the probability that $S_t = 0$ which indicates that a FX market operation of the central bank induces options implied volatilities to rise and the exchange rate to move farther away from the central parity turns out to be a decreasing function of *bubaexpected*. Also note that the coefficient of the variable *buba* is insignificant and has the "wrong" sign. This outcome underscores the severity of the simultaneity problem and highlights the importance of taking care to construct an instrumental variable for the original intervention series.

Other variables than *bubaexpected* do not contribute to explain movements in the dependent variable. Significant in a broader sense are the financial market variables and the variable *reported* indicating whether an intervention was secret or publicly known. Notice that the coefficient capturing the influence of the latter variable exhibits a negative sign, a result which confirms findings of Dominguez and Frankel (1993: pp.114). This result signals that the interventions conducted by the Bundesbank tended to be less effective whenever market participants were aware that the central bank participated in the trading of foreign exchange. This finding might indicate that known Bundesbank interventions either created trading uncertainty or provoked speculative position taking against the central bank. Also note that in contrast to the findings of Dominguez and Frankel (1993: p.116) and Humpage (2000) but in line with the results reported in Baillie and Osterberg (1997b) for U.S. interventions, the *coordination* dummy turns out to be insignificant.

In a next step, the vector of explanatory variables $\mathbf{x}_t$ has been enlarged by estimating the joint effects of *bubaexpected* and an additional series on the dependent variable. Table 4 reports the results of this exercise. The most striking finding is that the effect of the instrumental variable *bubaexpected* on S_t* remains significant in all estimated models at least at the 10 % significance level. Thus, enriching the set of independent variables with one of the other series considered to be potentially important in explaining the variation in S_t does not affect the explanatory power of the absolute intervention amount very much.

The table further provides weak evidence that the effectiveness of the intervention policy of the Bundesbank might have depended on whether the FX market intervention was secret or publicly known. The negative sign of the corresponding coefficient shows that the effectiveness of an intervention tended to be higher whenever the Bundesbank succeeded to keep the FX market operation secret. Focusing attention on the model including the *reported* variable shows that the *z*–statistic of the coefficient reflecting the influence of the *reported* series assumes a numerical value of -1.36 so that the null hypothesis that the coefficient is not significantly different from zero can be rejected at a marginal significance level of 17%.

To further corroborate these results, models featuring a vector $\mathbf{x}_t$ containing *bubaexpected* and *reported* and a third series taken from the remaining subset of explanatory variable have been estimated. The overall impression which arises when the results of these estimations which are documented in table 5 are analyzed is that the findings obtained from the more parsimonious orderd probit models by and large turn out to be robust. As already detected when analyzing the figures presented in table 4, the significance of the intervention instrument is somewhat hampered only in the equation containing the stock markt variability *fazvola*. The other variables do not contribute to improve our understanding of the link between Bundesbank interventions and S_t*.

Added Variable	*Bubaexpected*		*Added Variable*		*Thresholds*				*LR–tests*		
	β_1	*z*-statistic	β_2	*z*-statistic	S_1	*z*-statistic	S_2	*z*-statistic	$H_0: \beta_1 = \beta_2 = 0$	$H_0: \beta_2 = 0$	$H_0: \beta_1 = 0$
Characteristics of Interventions											
coordination	6.3048	1.9966	-0.1135	-0.6551	-0.3986	-1.9378	0.9457	4.4122	4.2980	0.4294	4.0095
sign	6.0390	1.7900	0.0123	0.1153	-0.3573	-1.6169	0.9848	4.2843	3.8820	0.0133	3.2185
reported	6.0912	1.9294	-0.2362	-1.3630	-0.4762	-2.2479	0.8752	4.0073	4.1577	0.2891	3.7423
first	5.9916	1.8902	0.0953	0.5376	-0.3162	-1.6223	1.0275	4.9768	5.7292	1.8606	5.1620
Monetary Policy											
discount	6.3864	2.0152	0.0576	0.5902	-0.1321	-0.3260	1.2118	2.9313	4.2173	0.3486	4.0828
news	5.9689	1.8864	0.2952	1.0012	-0.3288	-1.7405	1.0182	5.0841	4.8749	1.0062	3.5765
Financial Market Variables											
fazvola	5.5301	1.6517	0.4401	0.5734	-0.2808	-1.2892	1.0630	4.6387	4.1979	0.3293	2.7362
monday	6.3012	1.9963	0.3271	1.4812	-0.2810	-1.4565	1.0726	5.2096	6.0704	2.2018	4.0081
friday	6.2754	1.9890	-0.2698	-1.2926	-0.4023	-2.0770	0.9473	4.6729	5.5441	1.6754	3.9792

Table 4 — Estimates of Joint Effects in Ordered Probit Model

Note: The critical values for the *LR*–test with one degree of freedom are 3.84146 at the 5 % level and 2.70554 at the 10% significance level. The critical values for the LR–test with two degrees of freedom are 5.99146 at the 5% level and 4.60517 at the 10% significance level. See Judge et al. (1988: p. 987).

Added Variable	*Bubaexpected*		*Reported*		*Added Variable*		*Thresholds*				*LR–test*	
	β_1	*z*-statistic	β_2	*z*-statistic	β_3	*z*-statistic	S_1	*z*-statistic	S_2	*z*-statistic	$H_0: \beta_1 = \beta_2 = \beta_3 =$	$H_0: \beta_1 = 0$
					Characteristics of Interventions							
coordination	6.1173	1.9319	-0.2279	-1.2003	-0.0205	-0.1078	-0.4814	-2.2165	0.8701	3.8932	5.7409	3.7524
sign	6.0173	1.7795	-0.2358	-1.3595	0.0065	0.0610	-0.4831	-2.0135	0.8683	3.5370	5.7330	3.1807
first	6.0779	1.9138	-0.2336	-1.2534	0.0074	0.0385	-0.4726	-2.0394	0.8788	3.6901	5.7307	3.6815
					Monetary Policy							
discount	6.3571	2.0016	-0.2531	-1.4482	0.0755	0.7670	-0.2078	-0.5083	1.1466	2.7552	6.3182	4.0277
news	5.9440	1.8760	-0.2093	-1.1818	0.2222	0.7364	-0.4497	-2.0911	0.9042	4.0691	6.2729	3.5369
					Financial Market Variables							
fazvola	5.4099	1.6126	-0.2386	-1.3761	0.4632	0.6038	-0.4108	-1.7266	0.9424	3.8391	6.0943	2.6075
monday	6.2128	1.9635	-0.2418	-1.3923	0.3338	1.5080	-0.4151	-1.9225	0.9479	4.2226	8.0119	3.8771
friday	6.1922	1.9580	-0.2354	-1.3567	-0.2691	-1.2858	-0.5333	-2.4611	0.8250	3.7186	7.3873	3.8553

Table 5 — Estimates of Joint Effects in Ordered Probit Model Including a Dummy for Reported Interventions

Note: The critical values for the *LR*–test with one degree of freedom are 3.84146 at the 5% level and 2.70554 at the 10% significance level. The critical values for the LR–test with three degrees of freedom are 6.25139 at the 5% level and 4.60517 at the 10% level. See Judge et al. (1988: p. 987).

It remains to quantitatively substantiate the impact of Bundesbank interventions on the probability that S_t * settles in state j. To accomplish this task, we compare the effects attributable to a small intervention with the effects induced by a large–scale FX market operation. A small (large) intervention is identified by fixing the absolute value of the intervention amount one standard deviation below (above) the mean absolute intervention amount computed over all Bundesbank FX market operations in the sample. Table 6 reports the respective probabilities that $Prob(S_t = j)$, the corresponding marginal effects $\partial Prob(S_t = j)/\partial \mathbf{x}$, and elasticities computed as $[\partial Prob(S_t = j)/\partial \mathbf{x}][\mathbf{x} / Prob(S_t = j)]$ for both the model with the intervention amount as the only explanatory variable and the ordered probit model with *bubaexpected* and *reported* included in the vector $\mathbf{x}_t$. While the marginal effects allow to identify the sign of an infinitesimal variation in the absolute intervention amount on the probability that S_t * falls into category j, the elasticities give the percentage response of the respective probabilities $Prob(S_t = j)$ to a one per cent change in the intervention amount.[20]

Model	*Category*	*Probability*		*Marginal Effect*		*Elasticity*	
		$\mu_b - \sigma_b$	$\mu_b + \sigma_b$	$\mu_b - \sigma_b$	$\mu_b + \sigma_b$	$\mu_b - \sigma_b$	$\mu_b + \sigma_b$
Scenario I							
Bubaexpected	0	0.3114	0.2034	-2.1839	-1.7473	-0.1681	-0.6751
	1	0.4910	0.4924	0.4665	-0.4141	0.0139	-0.0468
	2	0.1976	0.3041	1.7174	2.1615	0.0513	0.2441
Scenario II							
Bubaexpected + *Reported*=1	0	0.3498	0.2362	-2.2556	-1.8770	-0.1545	-0.6246
	1	0.4831	0.5004	0.7308	-0.1123	0.0210	-0.0120
	2	0.1672	0.2635	1.5248	1.9892	0.0439	0.2123
Scenario III							
Bubaexpected + *Reported*=0	0	0.2669	0.1698	-2.0024	-1.5403	-0.1798	-0.7129
	1	0.5001	0.4843	0.1397	-0.7061	0.0044	-0.0848
	2	0.2329	0.3459	1.8627	2.2464	0.0536	0.2397

Table 6 — Probabilities, Marginal Effects, and Elasticities in the Ordered Probit Model

Note: The variables μ_b and σ_b denote the mean and the standard deviation of the series *bubaexpected*, respectively.

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20 For a discussion of the advantages of such elasticities in interpreting the results of qualitative response models, see e.g. LeClere (1992). A recent application of this concept to evaluate problems in economics can be found in Krafft (1997).

The table provides several interesting insights. As already indicated by the discussion of the estimation results, the figures offered in the table demonstrate that the probability of an effective intervention is an increasing function of the absolute intervention amount. During the Louvre period, the FX market operations of the Bundesbank tended to be more effective whenever it was not publicly known that the German central bank participated in FX trading. Moreover, the marginal effects and the corresponding elasticities suggest that a small intervention raised the respective probabilities that $S_t = 2$ and $S_t = 1$ and lowered the probability that $S_t = 0$. The elasticities reveal that the probability that S_t* settles in category 2 increased by more in response to a small intervention than the probability that the intervention is only partially effective. Furthermore, a large–scale intervention served to allocate probability mass from the first category to category 2.

While these figures corroborate the impression that the intervention policy of the Bundesbank was a success, the relative magnitudes of the probabilities presented in table 6 are far less appealing. Comparing the magnitudes of the probabilities that S_t* falls into partition j of its state space, it can be seen that the probability that $S_t = 1$ dominates in all cases. In other words, when conducting an intervention the Bundesbank had a good chance that this FX market operation either served to narrow the gap between the actual exchange rate and its implicit target level *or* contributed to decrease the expected variability of the spot rate. For a small intervention, the relative magnitudes of the probabilities even indicate that the probability of a complete failure of the operation exceeds the probability that the intervention is effective. The figures in the tabel further reveal that switching from a small to a large intervention increases the probability that $S_t = 2$ by about ten percentage points and serves to depress the probability that $S_t = 0$ by approximately the same amount. Thus, though the intervention are found to be statistically significant in the ordered probit models estimated above, the magnitude of the effect on the probability that S_t* settles in category 2 is only moderate. This, in turn, casts doubts that the intervention policy conducted by the Bundesbank during the years following the Louvre Accord was successful rather in statistical than in economic terms.

4 Summary

In this paper, we have taken into account that since the breakdown of the Bretton–Woods system central banks often attempted to influence the dynamics of real–life exchange rates by intervening in foreign exchange markets. The theoretical section of the chapter has been utilized to offer a currency option pricing model featuring infrequent central bank interventions and implicit currency bands. In the second part of the chapter, the empirically testable predictions of the model have been used to evaluate the effectiveness of the intervention policy of the Bundesbank observed during the years following the Louvre Accord.

The exchange rate model developed by Lewis (1995) has been employed to discuss that an effective intervention policy influences not only both the gap between the level of the current exchange rate and ist central parity and the volatility of this asset price but also the premia of foreign currency options. The first model developed in section 2 complements existing work on FX option pricing under explicitly regulated asset price processes. The framework can be used to highlight the implications of both a non–zero probability of occasional central bank FX market operations and of implicit currency bands for the pricing of FX options. As in FX option valuation frameworks featuring explicitly regulated exchange rate bands, the non–linearity of the spote rate path translates onto the arbitrage–free prices of options on foreign currency. The response of the option pricing function to a variation in the structural parameters of the model of the set up with implicit bands is different from the reaction of option premia to a comparable shift in the parameter of a framework solved under explicit exchange rate target zones. Performing comparative static analyses under implicit bands, one has to take into account that the width of the implicit exchange rate band varies as the structural parameters of the model are altered.

At the second stage of the theoretical analysis, we have abstracted from the existence of implicit currency bands and have analyzed the impact of infrequent central bank interventions on the premia of foreign currency options within the context of an appropriately modified GK framework. It has been argued that a variation in the intervention probability might either increase or decrease the option premium. The ambiguity of the effect of infrequent intervention on foreign currency option prices arises due to the fact that an increase in the intervention probability does not only dampen exchange rate volatility but also affects the domestic and foreign risk–free rate of interest. Given the intervention and interest rate data collected for a three year period following the Louvre Summit, it has been shown that the model predicts that for the sample period investigated in the empirical part of the paper an effective intervention policy served to depress volatilities implicit in $/DM foreign currency option prices.

The second part of the paper has been devoted to an analysis of the effectiveness of the intervention policy of the Bundesbank in terms of a success criterion which allows to model the impact of central bank forex interventions on the level and on the expected volatility of the exchange rate simultaneously. Following Bonser–Neal and Tanner (1996) and Madura and Tucker (1991), exchange rate variability has been measured in terms of volatility quotes implicit in FX option premia. With this multifactor success criterion at hand, we have studied the success of interventions of the Deutsche Bundesbank in the $/DM spot market during a sample period ranging from 01/02/1987 to 03/12/1990.

The main results of estimating ordered probit models can be summarized as follows. First, the absolute amount of Bundesbank interventions increased the probability of a decline in both the gap between the actual exchange rate and the implicit target level narrow and the volatility of the spot rate implicit in foreign currency option prices. Second, foreign exchange market interventions were less effective when market participants were aware that the Bundesbank participated in FX trading. Third, the magnitude of the effect of raising the absolute intervention amount on the probability of on effective FX market operation was only moderate. Though the intervention variable turned out to be significant in the estimated ordered probit models, the overall impression is that the intervention policy of the Bundesbank was successful rather in statistical than in economic terms. All in all, this interpretation underscores that the results on the effectiveness of intervention policy reported in the present paper on the whole confirm the findings documented in earlier contributions to this area of research.

Future research could extend the present analysis in three interesting and important directions. Firstly, it is possible to adopt the research strategy chosen in the present paper to simultaneously model the impact of the interventions of other major central banks like the Fed or the Bank of Japan on the level and the volatility of exchange rates. Given that it is often found in the empirical literature that the sign and the significance of the effects of central banks' interventions depend upon the specific sample period under investigation, it would also be an important exercise to carry out the computations not only for the years following the Louvre Accord but also for the Post–Plaza and the Post–Louvre periods. Secondly, it would be interesting to adopt our success criterion and the ordered probit model to analyze the simultaneous impact of interventions on the level and the volatility of spot rates using high–frequency data. The insights obtained by carrying out such a plan could then be compared to the findings reported in the literature examining the effects of central bank interventions in the continuous–time (see e.g. Breiers (1998), Goodhart and Hesse (1993), and Dominguez (1999)). Thirdly, it would be interesting to use other options data to assess the effectiveness of central banks' forex interventions. For example, one could exploit the informational content embodied in the prices of risk–reversals to analyze whether or not interventions cause market participants' exchange rate expectations under the equivalent martingale measure to become skewed in the direction suggested by the FX market operation.

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