Divine Intervention? Speculators and Central Banks in the Foreign Exchange Market*

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Using high frequency data this paper finds strong evidence that, on average, by creating market uncertainty central bank interventions lead to increased volatility and a widening of bid-ask spreads in the foreign exchange market. These results are consistent with predictions from standard models of market microstructure with heterogenous information sets across agents. The evidence suggests that traders' perceptions about the fundamentals can be combined with their interpretation of the signal conveyed by central bank behavior to determine pricing responses in the inter-bank market for foreign exchange. The analysis has implications for the market power of central banks as well as the payoff generated by trading large amounts of international reserves.

Keywords: exchange rates, microstructure, central banks, intervention announcements, high frequency data, GARCH, ordered probit.

1 Introduction

Central banks intervene on a frequent and substantial basis in foreign exchange markets. The motives of central bank authorities range from calming excessively volatile markets and discouraging destabilizing speculation to maintaining the spot rate about a target level and conveying information about future monetary policy. However, in an increasingly complex and fast paced environment of electronic trading, the ability of central banks to influence the market through intervention has been challenged, and often defeated.

Using high frequency data this paper tests the hypothesis that by creating price uncertainty central bank interventions lead to increased volatility and a widening of bid-ask spreads in the foreign exchange market. This holds if speculators as a group percieve the the signal conveyed by the the central bank's target to be inconsistent with the fundamentals. In addition, if individual traders recieve private information signals related to fundamentals then the market response to an intervention episode depends on the aggregation of individual trader responses.

These predictions are consistent with standard asymmetric information models with heterogenous information sets across agents such as Bhattacharya and Speigel (1991) and Kyle (1985). These models can be used to motivate the nature of the strategic interaction between central banks and speculative traders in response to intervention operations. Theoretical explanations such as Bhattacharya and Weller (1997) and Vitale (1999) suggest that the market reaction to a central bank intervention depends on the degree of heterogeneity across trader beliefs about the fundamentals as well as the intervention signal. An increase in the incongruence between prior beliefs about the fundamentals and the intervention signal lead to spot rate volatility increases following intervention episodes. Additionally, the link between the volatility of an asset and the spread on the asset is well-known in the market microstructure literature and implies that increased volatility leads to more adverse selection and greater inventory risk. For example, Glosten and Milgrom (1985) show that the bid-ask spread is positively related to the spread between the high and low values of the asset (which is like a volatility as the asset in their model has a two-point distribution). Similarly, Kyle (1985) shows that 'lambda', a measure of liquidity, is positively related to the volatility of the asset. See Ho and Stoll (1983) and Subrahmanyam (1991) for explanations related to increased inventory carrying costs.

These propositions imply that the variability of the spot rate is directly related to the precision with which traders' interpret the intervention signal. If an intervention announcement creates uncertainty about future monetary policy or other fundamentals and hence the future spot rate, bid-ask spreads should widen. However, if the central bank can credibly transmit a signal to the market designed to reduce uncertainty about the short-run variability about the target exchange rate, we should witness a narrowing of spreads. This prediction suggests that traders' signals about the fundamentals can be combined with their interpretation of the signal conveyed by central bank intervention to determine price responses in the inter-bank market for foreign exchange. In summary, two sources of differentiated information can be inferred. First, central banks and bank traders as a group can vary in their interpretation of the fundamentals and second, individual traders' private signals about fundamentals contain dispersion. Together or individually, these two effects lead to an increase in market uncertainty if the target spot rate implied by the intervention signal is not consistent with fundamentals.

Information asymmetries around earnings announcements have been examined extensively in equity markets. See Morse and Ushman (1983), Venkatesh and Chiang (1986), Skinner (1991), Daley, Hughes and Rayburn (1991), Barclay and Dunbar (1991), Seppi (1992) and Lee, Mucklow and Ready (1993). Collectively, their results suggest that liquidity providers are sensitive to information asymmetry risk and use both spreads and depths to actively manage this risk. Alternatively, Kim and Verrecchia (1991) outline a theoretical argument to suggest that information asymmetry will be higher after earnings announcements because the announcements are noisy signals and certain traders have a superior ability to process the earnings information so that spreads should widen after an announcement. In their specification, the asymmetric information risk arises from the public disclosure of the earnings. The model also predicts a drop in post announcement liquidity which would also lead to a widening of bid-ask spreads.

The following testable implications emerge from the arguments outlined above. First, increases in the uncertainty associated with an intervention signal would lead to an increase in the volatility of the equilibrium spot rate. Second, if information sets about fundamentals differ across individual traders in the foreign exchange market, this would result in further increases in spot rate volatility and bid-ask spreads following an intervention. This paper tests these implications using intra-day data in the Yen/Dollar market[1]. Specifically, it askes the following question. Does intervention activity create asymmetric information or increased inventory carrying costs amongst traders as evidenced by increased inter-bank bid-ask spreads?[2]. Since the distribution of the bid-ask spreads is discrete, an ordered probit model is used to correlate intervention news arrival to movements in the spread. The data set contains 0.56 million Yen/Dollar spot rate quotes distinguished by different banks in the inter-bank market for foreign exchange. The sample period covers the period between October 1, 1992 to September 30, 1993.[3]

The analysis combines the tick by tick spot rate data with time stamped Reuters reports to examine the impact of central bank order signals in the foreign exchange market. Since the database includes market survey expectations from the Reuters FXNB page, the model distinguishes between anticipated and unanticipated intervention. Only unexpected central bank activity is considered to be a 'news' item. The results are also broken down by major bank traders in order to study the price responses of the top traders in the Yen/dollar market following central bank interventions.

The paper finds strong evidence of greater aggregate market uncertainty following central bank trading activity, with increases in spot rate volatility and a widening of individual market maker bid-ask spreads. Marginal effects from the ordered probit analysis that allow us to evaluate shifts in the bid-ask spread distribution conditional on news of central bank intervention. These estimates show that if the probability of an intervention by the FED increases by one standard deviation the probability of the bid-ask spread taking on a value of less than 10 basis points falls by 8.14Consequently, they can maintain the threat of intervention while at the same time economizing on reserves, by only occasionally intervening in circumstances when they might want to influence exchange rates. Contrary to this, the evidence suggests that the explosive turnover growth in foreign exchange markets has rendered the task of central banks far more difficult. Neither the threat nor the actual act of intervention remain effective in this context.

[1]See Chang and Taylor, 1998; Goodhart and Hesse, 1993 and Peiers, 1997 for other studies on central bank interventions using intra-daily data.

[2]See Campbell, Lo and MacKinlay (1997) and Huang and Stoll (1997) for a survey of the literature on disentangling spread components. Flood et al.(1998) adds to this literature by offering evidence for the search cost component in addition to costs associated with processing orders, carrying inventories and adverse selection arising from asymmetric information

[3]I thank Olsen and Associates, Zurich, Switzerland for making the data available.

The paper proceeds as follows. Section 2 presents a brief theoretical motivation of asymmetric information frameworks with the central bank being the strategic 'informed insider'. Section 3 describes the data. Section 4 outlines the empirical methodology employed and discusses the results from our analysis. Section 5 presents concluding remarks.

2 Asymmetric Information, Central Banks and Agent Heterogeneity

The traditional view in the literature suggests that sterilized interventions operate through a signaling channel if they cause private agents to change their expectations about the exchange rate by altering their views about the likely future actions of the central bank or of other private agents. Alternatively, although perceptions of the future actions of the central bank remain unchanged agents might alter their views about the likely impact of present actions on future values of the exchange rate.[4,5] Although there has been considerable debate in both academic and policy circles about the effectiveness of sterilized interventions, the signalling channel has received ambiguous empirical support in studies using daily data or more generally data at lower frequencies (Baillie and Humpage,1992; Bosner-Neal and Tanner,1996; Baillie and Osterberg,1997). While Domiguez and Frankel (1989) use survey data on exchange rate expectations and report quantitatively significant results, Humpage (1989) concludes that systematic intervention has no apparent impact on exchange rates. He argues that it is plausible that an intervention can have a short-lived impact if it provides new information to the market.[6]

Asymmetric information explanantions can be used to operationalize the signalling hypothesis as follows. Asset pricing models with a strategic informed insider (such as Bhattacharya and Speigel (1991), Kyle (1985) and Bhattacharya and Weller (1997)) assume that the central banks are informed insiders, with an informational advantage about spot rate fundamentals. In particular, central banks have inside information about the course of fu-

[4]The existing literature offers two channels through which sterilized interventions can affect exchange rates-the 'portfolio balance' channel and the 'signaling' channel. Since the former explanation has received poor empirical support, subsequent studies have emphasized the signaling hypothesis (Rogoff (1984), Lewis (1988), Dominguez and Frankel (1990), Mussa (1981)).

[5]The effectiveness of this signal constitutes an important policy issue with respect to foreign exchange interventions made by governments to maintain exchange rate target zones in particular and monetary stability in general.

[6]Edison (1993) provides a detailed overview of the literature.

ture monetary policy in addition to other fundamental determinants of spot rates. Further, central bank utility functions differ from standard profit maximizing agents in that they can choose to make losses on their intervention operations by leaning against the wind. Central banks attempt to balance the expected loss on currency transactions against their success in achieving targeting objectives or reducing the volatility of exchange rates. In addition, rational speculators in the foreign exchange market have their own private information with respect to central bank objectives. A combination of asymmetric information and Bayesian learning can be used to describe central bank interventions signals that communicate information about future monetary policy and hence the fundamentals process governing the spot rate.

A modified version of the timeline in Bhattacharya and Weller(1997) can be applied to the spot market for foreign exchange as follows:

Timeline

- t=-2: Speculators have a common prior about the fundamentals process, $\tilde{\epsilon}_p$, distributed normally about mean zero and precision τ_p ($\tilde{\epsilon}_p$, $\sim$ N(0,τ_p)).[7] Plus, each speculator i has private information about the fundamentals process given by $\tilde{\gamma}_i \sim$ N(0,τ_γ). Finally, speculators have a common prior associated with the prevailing exchange rate target level described by $\tilde{\epsilon}_T \sim N(\mu, \tau_T)$ where μ is the observable component of the fundamentals process. The central bank's prior about the fundamentals is given by; $\tilde{\zeta}_p \sim$ N(0,τ_{ζ_p}) and for its target is $\tilde{\epsilon}_T \sim N(\mu, \tau_T)$[8].
- t=-1: each speculator $i \in [0, 1]$ observes a private signal about fundamentals, S_i=$\tilde{\epsilon}_p$+$\tilde{\gamma}_i$, and updates prior about fundamentals and the central bank observes ϵ_T.
- t=0: The central bank intervenes. Speculators update priors for a second time about fundamentals and the central bank's target rate, $\tilde{T}_0$=μ + $\tilde{\epsilon}_T$ for i=1......N. If signal correlation across speculators about the fundamentals and the central bank's target is low (τ_γ and τ_T), spot rate volatility increases with trading and bid ask spreads widen.

[7]The inverse of the precision, τ^{-1} is the variance.

[8]$\tilde{\epsilon}_p$ can be decomposed as $\tilde{\epsilon}_p$=$\tilde{\zeta}_p$ + $\tilde{\delta}_p$, where: $\tilde{\zeta}_p \sim$ N(0,τ_{ζ_p}) and $\tilde{\delta}_p \sim$ N(0,τ_{δ_p}). In order to explicitly model the central bank's superior information about the fundamentals assume that the central bank observes $\tilde{\zeta}_p$ so that the only uncertainty for the central bank with respect to the fundamentals process lies with the realization of the second unobserved component $\tilde{\delta}_p$. Speculators, on the other hand do not observe either $\tilde{\zeta}_p$ or $\tilde{\delta}_p$.

- t=1: All uncertainty is resolved and the spot market clears.

The first order condition for the optimal choice of this period's spot rate, P_0, in Bhattacharya and Weller (1997) is given by:

$$P_0 = b_4 + b_5\tilde{\epsilon}_p + b_6\tilde{\epsilon}_T \tag{1}$$

where:

- $\tilde{\epsilon}_p$, is the speculators common prior about the fundamentals, and
- $\tilde{\epsilon}_T$, is the speculators common prior about the prevailing exchange rate target

The first order condition for P_0 implies that the variance of the spot rate can be written as:

$$Var(P_0) = b_7 Var(\tilde{\epsilon}_p) + b_8 Var(\tilde{\epsilon}_T) \tag{2}$$

where

- ω is the weight placed by the central bank on its targeting objective,
- b_7=$(b_5)^2$,
- b_8=$(b_6)^2$,
- $Var(\tilde{\epsilon}_p)$ depends on τ_p, the prior precision of speculators about the fundamentals process and
- $Var(\tilde{\epsilon}_T)$ depends on τ_T, the prior precision of speculators about the central bank's objective.

This implies that the volatility of the spot rate depends both on the speculator's priors about the volatility of the fundamentals and the variability of the target rate. An increase in the dispersion across speculators in their prior beliefs about the fundamentals as well as the central bank's target rate would lead to an increase in the volatility of the spot rate. Further, the link between the volatility of an asset and the spread on the asset suggests that increased volatility leads to more adverse selection and greater inventory risk (Glosten and Milgom(1985), Kyle(1985), Ho and Stoll(1983) and Subrahmanyam(1991)) and hence increased bid-ask spreads (See appendix). The following empirical investigation tests the hypothesis that agents widen bid-ask spreads to manage asymmetic information and inventory control risks if faced with increased spot rate volatility following intervention activity.

3 The Data

This section briefly describes the data and provide an analysis of the nature of the distribution of the spread data in the foreign exchange market. A GARCH (1,1) model is estimated in order to be used as the measure of volatility in the empirical analysis that follows.

3.1 High Frequency Real-Time Yen/Dollar Spot Rate Quotations

The data-set consists of all Yen/Dollar quotes that appeared on the Reuter's screen between the 1st October 1992 and the 30th September 1993. During this period a total of 5,67,718 quotes were posted on the screen by approximately 125 banks. Each observation on a quote lists the time of the day, the Reuters's code for the name of the bank making the quote, the city where the bank is located along with the bid and the ask prices. To illustrate, consider the following five consecutive quotes for Tuesday 23rd June 1993:

No.	Time	Bank	City	Bid-Ask Quotes
1.	7:50:04	Chemical Bank	London	110.28/110.38
2.	7:50:10	Dresdner Bank	Frankfurt	110.35/110.40
3.	7:50:22	Lloyds Bank	London	110.35/110.39
4.	7:50:38	Citibank	Tokyo	110.40/110.45
5.	7:51:04	Tokai Bank	Tokyo	110.38/110.45

The time of day is GMT or Greenwich Mean Time; for the first observation it is 7:50:04. That is 7:50 A.M. and 4 seconds while the second observation is 7:50:10 or just 6 seconds later. The second column represents the bank making the quote and the third column maps the corresponding location of the quoting bank as the major banks participating in the foreign exchange market have branches all over the world. The final column gives the bid and the ask prices. In short, at 7:50:04 A.M., Chemical Bank in London was willing to buy yen at 110.38 per dollar, and sell yen at 110.28 per dollar. For the five observations listed above the absolute spreads are 10,5,4,5 and 7, respectively.

The theoretical explanation in Section 2 links intervention announcements to changes in the bid-ask spread via changes in the volatility of the spot rate. Bollerslev and Melvin (1994) note that the bid and the ask may move together, so that there is no change in the spread when the signal conveyed by news of an intervention is perceived by traders as being unambiguously 'good' or 'bad'. For example, if market-makers are receiving one-sided buy (sell) orders, they may increase (decrease) the bid and ask by the same amount in response to the market pressure. The analysis focuses on variations in quoted spreads as a function of spot rate volatility and the arrival of intervention news.[9] If an intervention announcement creates further uncertainty about future monetary policy and/or the fundamentals and hence the target/actual future spot rate, theory suggests that the spread should widen. However, if the central bank can credibly transmit a signal to the market designed to reduce uncertainty about the short-run variability about the target exchange rate, we should witness a narrowing of spreads.[10]

3.2 Event Windows

News about central bank intervention was collected from the Reuters's AAMM headline news screen. An electronic search was conducted for all reports of Bank of Japan (BOJ) and Federal Reserve Bank (FED) intervention over the one year sample period. Each report consists of a date and time stamp to the nearest second the announcement was made allowing it to be precisely matched with spot rate data.

Next, sub-samples of the spot rate data around intervention reports were constructed as follows. Goodhart and Hesse (1989) claim that the time lag between an intervention and the report on the Reuter's news screen is approximately 15 to 30 minutes. Conversations with traders suggest a lag of at most 10 to 15 minutes (Peiers, 1994). The estimations trace intervention activity up to 60 minutes prior to the time stamp associated with the Reuters's announcement. The data sub-samples were initiated at 120 minutes prior to the announcements in order to allow for a distinction between intervention versus non-

[9] It is also well known that imbalances in buy or sell orders could affect the magnitude of quoted spreads as market-makers attempt to create more balanced order flows.

[10] Bollerslev and Melvin (1994) present evidence that for 8.0 percent of the observations, the bid and the ask move up together with no change in the spread while for 8.3 percent of the observations, the bid and the ask move down together resulting in no change in the spread in the DM/dollar market. Thus, the majority, or 83.7 percent, of the observations involve a change in the spread compared with the previous pair of quotes.

intervention data dynamics.

Since financial markets react quickly to new information[11], we hypothesize that most foreign exchange intervention effects die out 120 minutes following an intervention report. Thus, the sub-sample time windows extend from -120 to +120 minutes surrounding the time-stamped Reuters's announcements. A variety of window sizes were experiemented with before arriving at the present estimate. Our choice represents a length of time that is long enough for traders to observe and respond to a news announcement and is short enough so that other news arrival does not contaminate our results. Based on these criteria 71 BOJ and 6 FED intervention announcements, reported by Reuters's over the 10/1/92 to 9/30/93 time period were selected as relevant events for this study (see Table 1). Note, from Table 1 that multiple interventions within any given day are not uncommon. Intervention windows in these cases begin two hours prior to the first intervention and end two hours after the last reported intervention of the day. The time of day is GMT.

In addition to examining the data across all quoting banks, the data-set allows us to analyze the behavior of major market-makers individually around intervention announcements. Table 2 lists the ten banks with the most quotes posted around FED intervention announcements. Chemical Bank is seen as being the leading market maker with 604 quotes around these intervention announcements. The next five banks are Credit Suisse, Tokai Bank, Dresdner Bank, Morgan Guaranty and Citibank. These six banks account for 33 percent of overall quote activity during intervention episodes. Table 3 presents the distribution of quotes by location in the yen/dollar market and shows that the largest volume of quotes emanates from the United Kindom followed by Japan, the United States and Switzerland.

3.3 GARCH(1,1) Volatility Estimation

The empirical investigation of the relationship between the bid-ask spread and the exchange rate uncertainty associated with the arrival of news about central bank intervention requires an explicit proxy for the time-varying volatility of the spot rate.[12] The paper employs a standard two-stage estimation procedure in which the conditional variance for the spot

[11]Edison (1993) claims that intervention effects on the exchange rate are short-lived.

[12]An extensive body of literature demonstrates that the GARCH procedure may be used in order to best describe the volatility process followed by asset prices including exchange rates. See Bollerslev et al. (1992) for details.

exchange rate is first estimated as a GARCH process. This volatility series is then used as a proxy for exchange rate volatility in the second-stage model to analyze the temporal behavior of the spread around intervention announcement windows.

A theoretical explanation for correlations in price changes can be associated with the dispersion of beliefs (see Shalen (1993) for a two-period noisy rational expectations model of a futures market). When new information arrives, different prior beliefs about the news create incentives to trade and lead to price changes. As traders observe the new price, they may revise their prior beliefs in response to new information, which leads to continued trading and future price changes. If it takes time for the market to resolve these heterogeneous beliefs when traders revise their prior beliefs in response to new information, this process of searching for the information price may lead to volatility clustering around the arrival of new information.

The problem of simultaneity has been raised frequently in the context of measuring the effectiveness of interventions. It is argued that interventions are not exogenous to current market conditions. Hence estimations may yield inconsistent and biased estimates. Several studies argue that this presence of endogeneity between interventions and changes in the spot rate require an instrumental variables estimation(e.g. Frankel and Dominguez (1990)). However, Goodhart and Hesse (1989) and Almekinders (1995) both suggest that there is at least a two day lag between the time that spot rates become excessively volatile or deviate from target levels and the time that central banks intervene because of the institutional features of central bank decision making. As a consequence, any particular intervention episode is exogenous to spot rate behavior on that particular day. In other words, they argue that since the intervention is in response to events that took place about two days ago they are exogenous to the spot rate on the day that intervention takes place. This is especially true in the context of high frequency data since we study spot rate behavior during a two-three hour window around the time the intervention is reported.

The paper uses the first difference of the logarithm of the mid-price (DLMID) of the spot rate for estimation purposes. The log of the mid-price (LMID) is calculated as follows:

$$\text{LMID} = LOG[(ASK + BID)/2] \tag{3}$$

Furthermore, a MA (1)-GARCH (1,1) specification found to fit the data takes the form:

$$\text{DLMID}_t = \mu + \theta\epsilon_{s,t-1} + \epsilon_{s,t} \tag{4}$$

$$\sigma^2_{s,t} = \omega + \alpha\epsilon^2_{s,t-1} + \beta\sigma^2_{s,t-1} \tag{5}$$

$$\epsilon_{s,t} \mid I_{t-1} \sim N(0, \sigma^2_t) \tag{6}$$

where I_{t-1} denotes the t-1 information set, DLMID is the first difference of the log of the mid-price, and μ,θ,ω,α and β are the parameters that are estimated. Since the second to second movements in the mid-price are typically very small, we scaled the logarithmic first differences by 10,000 for numerical reasons. For a more complete description of the quasi-maximum likelihood estimation procedure employed see Bollerslev et al. (1992). The time t subscript refers to the place in the order of the series of quotes, so that provides an estimate of the price volatility between quotes.

Nelson (1990,1992) presents theoretical arguments to support the specification for the conditional variance estimation above. Intuitively, if the sample path for the true unobservable volatility process is continuous, it follows that interpreting the GARCH (1,1) model as a non-parametric estimator, or a one-sided filter, results in estimates for the conditional variance that are generally consistent as the length of the sampling interval goes to zero.[13]

Table 4 reports the maximum likelihood estimates from the GARCH model outlined above for all quotes contained in the sub-sample windows (-120 to +120 minutes) surrounding FED intervention announcements. In order to avoid discontinuities between different sub-samples, the estimation was conducted for each sub-sample date separately. Examining the table reveals that the results are extremely robust across the different sub-samples (different rows). The GARCH effect is positive and highly significant at the 1% level, and the coefficient estimates are quite similar across all of the sub-samples in size, sign and significance. Standard diagnostic tests indicate that this relatively straightforward procedure does a particularly good job of tracing temporal dependencies in the conditional mean of the continuously recorded spot exchange rate. The same exercise was conducted for BOJ intervention announcements and resulted in a similar pattern of coefficient estimates. In the interest of brevity results here for all 71 sample dates are not reported here.[14]

[13] See Bollerslev and Melvin (1994) for further details. For the entire data set the average time interval between new quotes is only about 17 seconds.

[14] Details are available from the author upon request.

3.4 Frequency Distribution of the Spread

The choice of the estimation strategy used in examining the statistical relationship between the spreads and the volatility estimates from the previous section and the intervention announcements is predicated upon the nature of the spread data. The distribution of the foreign exchange market spreads is clearly not continuous. The values of 3, 4, 5, 7, 10 and 11 basis points account for 98.53% of the data suggesting that the bid-ask quote pairs tend to take on only a few distinct values. This feature of the quotes is evident from the frequency distribution presented in Table 1, which lists the frequency distribution for the complete set of quotes, for the sub-samples around intervention windows.[15] (See Table 5).

The 'normal' spreads in the Yen/dollar market are 5 and 10 basis points. In the entire data set 273409 observations accounting for 48.2% of the data and 232082 observations accounting for 40.9% of the observations took on a value of 10 and 5, respectively. This is almost exactly the same proportion for the individual bank quotes. This lack of continuity suggests that utilizing continuous state space processes will not represent the spread data accurately. Addressing this issue of discreteness in US stock market data, Hausman et al. (1992) suggest an ordered probit model in their analysis of continuously recorded transactions price changes.[16]

4 Ordered Probit Analysis

Several theories[17] suggest that bid-ask spreads exist because of order processing costs, inventory costs, adverse selection and specialist market power. According to Hausman et al (1992), this implies that a stochastic model for prices is a essential to decomposing spreads into its different components. First, the costs and benefits of specific aspects of a market's microstructure such as margin requirements, the degree of competition faced by dealers, the frequency with which orders are cleared and intra-day volatility depend closely on the particular stipulation of price dynamics. Second, a distinguishing feature

[15] The raw spreads are converted into basis points by multiplying them by 10,000.

[16] Hausman et al. (1992) do not include contemporaneous trading volume in their model of tick-by-tick stock price movement for simultaneity reasons, thereby effectively eliminating important information from the analysis. In our case, only indicative quotes for foreign exchange data are available in the public domain while volume data although collected by the Reuters's 2000-2 matching system is limited in coverage.

[17] See Huang and Stoll (1995), George, Kaul and Nimalendran (1991), Glosten and Harris (1988) for examples.

of transactions prices is that their timing is irregular and random. Therefore, such prices may be modeled by discrete time processes only if we ignore the information contained in waiting times between trades.

Third, what is of economic interest is the conditional distribution of price changes, conditioned on the arrival of news, time between trades and the sequence of past price changes. Ordered probit is perhaps the best specification that can take account of both price discreteness and irregular trade times[18].

4.1 Empirical Methodology

We now briefly outline the ordered probit methodology[19] employed in subsequent estimations. As noted earlier the observed spread, S_t assumes only a fixed number of discrete values, a_1, a_2,...., a_N. The unobservable continuous random variable, S_t^*, is given by

$$\mathrm{S}_t^* = \beta_0 + \beta^{'} X_t + \epsilon_{S,t} \tag{7}$$

The vector X_t represents the set of predetermined variables that affect the conditional mean of S_t^*, and $\epsilon_{S,t}$ is conditionally normally distributed with mean zero and variance, $\sigma^2_{S,t}$,

$$\epsilon_{S,t} \mid I_{t-1} \sim N(0, \sigma^2_{S,t}) \tag{8}$$

To allow for conditional heteroskedasticity in the spread, we parameterize the logarithm of $\sigma^2_{S,t}$ as a linear function of the same explanatory variables that enter the conditional mean of S_t^*. We obtain the following form for our multiplicative heteroskedasticity correction:

$$\sigma^2_{S,t} = [exp(\delta^{`} X_t)]^2 \tag{9}$$

In the GARCH model in subsection 3.3, the time subscript t refers to the place in the order of the series of posted quotes, in contrast to actual clock time.

The ordered probit model relates the observed spreads to S_t^* via

$$\mathrm{S}_t = a_N \tag{10}$$

where the a_N's form an ordered partition of the real line into N disjoint intervals. [20] The probabilities that enter the log-likelihood function for the maximum likelihood estimation

[18]See Hausman et al. (1992) for a complete discussion.

[19]See Maddala (1983) and Greene (1990) for a more thorough review of the ordered probit model.

[20]The variance of ϵ_i is assumed to be 1.0 since as long as y_i^*,β and ϵ_i are unobserved, no scaling of the underlying model can be deduced from the observed data. Since the $\mu' s$ are free parameters, there is no significance to the unit distance between the set of observed values of y-they merely provide a ranking. See Greene (1993) for a complete exposition.

are: $Prob[y_i = j] = Prob[y_i^*]$ is in the jth range. This means that:

$$\begin{aligned}
\mathrm{y}_i^* &= \beta' X_i + \epsilon_i, \\
\epsilon_i &\sim N[0,1], \\
\mathrm{y}_i = 0 &\quad if \quad y_i^* \leq \mu_0, \\
1 &\quad if \quad \mu_0 < y_i^* \leq \mu_1, \\
2 &\quad if \quad \mu_1 < y_i^* \leq \mu_2, \\
&\ldots. \\
J &\quad if \quad y_i^* > \mu_{J-1}
\end{aligned}$$

The probability that the spread takes on the value a_N is equal to the probability that S_t^* falls into the appropriate partition, a_N. Following Bollerslev and Melvin (1994), for tractability purposes we limit the empirical analysis on a classification of the spread into only four categories. From the discussion in subsection 3.3 the four most commonly observed spreads account for 98.5% of the total number of quotes. In the categorization, the group a_1 contains spreads with value less than or equal to five basis points; a_2 contains spreads greater than 5 but less than 10; a_3 represents the 'normal' value 10 basis points and a_4 is for spreads of a value of greater than 10 basis points. The corresponding intervals for the unobservable latent variable S_t^* are given by

$$\mathrm{a}_1 = (] -\infty, \mu_0]) \tag{11}$$

$$\mathrm{a}_2 = (]\mu_0, \mu_1]) \tag{12}$$

$$\mathrm{a}_3 = (]\mu_1, \mu_2]) \tag{13}$$

$$\mathrm{a}_4 = (]\mu_2, +\infty]) \tag{14}$$

The partition parameters, μ_I, are estimated jointly with the other parameters of the model. The ordered probit model described by the above equations allows the estimation of the probability of a particular spread being observed as a function of the predetermined variables X_t. In order to test the hypothesis that the spread is affected by the arrival of central bank intervention news while controlling for the volatility of the spot rate, an intervention dummy, $inter_t$ and the GARCH estimates of the conditional variance of the logarithm of the spot price, $\hat{\sigma}^2_{S,t}$, saved from section 3.3 are included as elements of X_t. Given the partition boundaries determined by the data, if a higher conditional mean $\beta^{‘} * X_t$ is caused by an intervention announcement while controlling for the conditional variance of the spot rate and this raises the probability of observing a higher spread, we will infer that the hypothesized theoretical link is supported by our empirical analysis.[21]

$$\mathrm{S}^*_t = \beta_0 + \beta_1 \hat{\sigma}^2_{S,t} + \beta_2 \mathrm{inter}_t + \beta_3 \mathrm{S}_{t-1} + \epsilon_{S,t} \tag{15}$$

$$\sigma_{S,t} = exp(\gamma_1 \hat{\sigma}^2_{S,t} + \gamma_2 \mathrm{inter}_t + \gamma_3 \mathrm{S}_{t-1}) \tag{16}$$

The intervention dummy takes the value negative one for the time prior to an intervention announcement being made within each sub-sample, a value zero for the time closest to the time when the announcement appears on the Reuters news screen and plus one for sub-sample data points following the news arrival. In addition to the parameters specified in the ordered probit specification above, we also estimated the threshold parameters, μ_1 and μ_2. Following standard practice, and without loss of generality, the value of μ_0 was normalized to zero.

4.2 Estimates of Intervention Windows

Maximum likelihood estimates of the ordered probit model for the pooled sub-samples surrounding FED intervention announcements are presented in Table 6. The boundaries for partitioning the data, μ_1 and μ_2, are estimated with a high degree of precision as seen by the large t-statistics. The coefficient on the intervention dummy variable, β_2, suggests that intervention announcements lead to a widening of the bid-ask spread implying that traders perceive an increase in uncertainty when the central bank enters the market. This is consistent with the implications from of theoretical explanation in Section 2. The estimate for β_3, the lagged spread variable, is indicative of the strong intra-day persistence in the spread process; if the current quoted spread is large, the following spread will also tend to be large. The $\gamma 1$ and $\gamma 2$ coefficients highlight the importance of heteroskedasticity in the

[21] As long as $\hat{\sigma}^2_{S,t}$ is a consistent estimator, the second stage ordered probit model generally yields consistent parameter estimates although the resulting standard errors may be downward biased compared to using the true underlying unobservable $\sigma^2_{S,t}$ process. Pagan (1984) provides a formal econometric analysis of issues related to the use of generated regressors.

spread equation. Both the conditional variance and of the exchange rate and the lagged spread have a positive influence on $\sigma^2_{S,t}$.

The likelihood ratio statistic provides an overall measure of the joint significance of the explanatory variables in the mean and variance part of the model given by β_1=β_2=β_3=γ_1 =γ_2=γ_3= 0 is reported at the bottom of the table. The test statistic takes the value 3444.66, which is significant in the corresponding chi-squared distribution with six degrees of freedom.

Since the actual magnitude of the ordered probit coefficients in Table 6 are not easily interpreted, in order to provide an indication of the economic significance of the model estimates for the ordered probit model marginal effects were estimated as follows:

$$\frac{\partial E(S|x, \beta, \Theta)}{\partial x} = \phi(x, \beta, \Theta) * \beta \tag{17}$$

This allows us to ascertain shifts in the probability distribution of the spread about different means as each explanatory variable was increased by one standard deviation holding everything else constant. We can therefore evaluate scenarios such as if the conditional variance is increased by one standard deviation by what percentage does the probability of being in the lowest categories fall and the highest categories increase thereby providing an indication of whether or not meaningful shifts in the spread take place following news of central bank intervention. As Table 7 shows if the incidence or probability of an intervention by the FED increases the probability of the spread falling in categories a_1 or a_2 falls by 0.34% and 7.8% respectively while the probability of the spread shifting to categories a_3 or a_4 increases by 7.81% and 0.35%. The same exercise reveals that increases in the volatility of the spot rate result in a similarly shifting pattern in the probability distribution of the spread. Table 8 confirms that a similar pattern of results is observed for interventions by the Bank of Japan.

The estimation procedure was also extended to account for an irregular quote arrival pattern. We construct a variable, $\Delta \mathrm{T}_{t-1}$, where T is the number of seconds that have elapsed from a preceding quote. As the results in Tables 9 indicate the coefficient estimate for β_4, the time between quotes, is positive suggesting that spreads widen during periods of infrequent trading activity. Table 11 documents the total value of reserves expended by the

Federal Reserve for the interventions in our sample period. The results from our analysis suggest that the interventions represent non-trivial trading losses.

4.3 Individual Bank Estimates

While the results for all the quotes posted during intervention time windows support the hypothesis from the theoretical explanation in Section 2, it is useful to examine the quoting behavior of individual banks during the same period. This exercise allows us to ascertain the response across heterogeneous traders to the central bank entering the market. In order to analyze the individual behavior of banks a similar ordered probit model was estimated for four of the top ten banks in the Yen/Dollar market.

The estimates for quotes from Chemical Bank, Citibank, Dresdner Bank and Morgan Guaranty following the arrival about central bank activity are given in Table 12. The results are qualitatively similar (except for Chemical Bank which shows that spreads narrow in response to interventions) to those for the entire set of quotations around intervention time windows suggesting that on average market makers widen spreads when the central bank enters the market. The case of Chemical Bank gives credibility to the notion that there is heterogeneity in the manner in which different banks in the market interpret the intervention signal. Further analysis would require tests to assess whether the coefficient estimates for individual banks are significantly different from each other. We conducted the same exercise using the multiplicative heteroskedasticity correction and found that the coefficients for γ_1, γ_2 and γ_3 were insignificant indicating that time-varying heteroskedasticity appears to be absent in the individual cases we considered. This is in contrast to the previous section where all quotes posted around intervention incidences are utilized for estimation purposes. The likelihood ratio statistics for the joint significance of the explanatory variables in the mean part of the model are highly significant.

The marginal effects estimations indicate the economic significance of our results. The exercise reveals that increases in volatility as well as intervention episodes lead to an increase in the probability of the spread being observed in the higher categories of the probability distribution as compared to the entire data set. The probability of the spread falling in the third highest category of ten basis points increase by 8.1%, 8.5%,7.9% and 9.2% respectively for the four banks under consideration. Similar effects are observed for the lagged spread as well.

5 Conclusion

This paper tests the hypothesis that bid-ask spreads and the volatility of the spot rate following central bank interventions depend on the actual/perceived volatility of fundamentals and exchange rate target by speculators in the foreign exchange market. If the weight placed on targeting objective by the central bank as well as speculator information about fundamentals are both high, central bank interventions will on average lead to increased volatility and wider spreads if the target and/or intervention signal is not consistent with the market's perceptions about the fundamentals.

In addition, it is plausible that there are differences in the models that different banks employ to interpret public information signals. By analyzing the response of individual banks to observing the central bank in the market we are able to understand better the aggregate market response to intervention episodes. Although announced intervention activity could indicate future monetary policy, it is an expensive signal to interpret and market participants vary in their ability to discern the signal.[22] Varying perceptions about fundamentals along with perceived differences about the central bank's intentions could account for increased volatility and wider spreads following an intervention episode.

The analysis combines high frequency(tick by tick) data of quotes posted on the Reuter's FXFX screen by different banks in the inter-bank market for foreign exchange with time stamped news announcements of central bank interventions on the Reuter's news screen to test the hypothesis. Testing 71 interventions by the Bank of Japan and 6 by the Federal Reserve over the period between October,1992-September,1993 reveals that on average intervention announcements are followed by an increased volatility in the spot rate and wider bid-ask spreads quoted by traders suggesting that there is an increase in aggregate

[22]Unraveling the nature of the signal on each occasion may be rather a complex matter. "Perhaps, the key signal is not the occasion of the overt intervention itself, but the urgency and seriousness of the authorities' perceived resolve which may be a more complex amalgam of assessed frequency and accumulated amount of intervention, together with the market's appreciation of whether the authorities may be prepared to back their resolve with changes in monetary policy. As to why authorities intervene in circumstances where agents may well ignore their actions it can be argued that intervention may be a means for central banks to avoid making a more fundamental change in interest rates. However, while intervention as a 'signal' does indicate that the authorities are unhappy about the course of exchange rate movements, markets may just as easily interpret an intervention as a signal for an impending change in interest rates as a sign of weakness." (Goodhart and Hesse,1993)

market uncertainty following a central bank intervention. The results are borne out by estimations conducted for the four banks(Chemical Bank, Citibank, Dresdner Bank and Morgan Guaranty) with the highest quote frequency in the Yen/Dollar market individually with all four widening spreads following news of a central bank intervention. This suggests that aggregating individual market maker responses determines the total market response of higher volatility and wider spreads both signifying greater uncertainty following central bank intervention.

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Table 1: Intervention Announcements by FED in Yen/Dollar Market: 10/01/92-09/30/93

Date	Time	Reuter's News Headline
93/4/27	13:05:36	"FED BUYS U.S. DOLLARS AT 109.50/55 YEN – DEALERS"
93/4/27	13:35:14	"FED AGAIN BUYS U.S. DOLLARS FOR YEN – DEALERS"
93/4/27	14:15:54	"FED BUYS DOLLARS FOR YEN A THIRD TIME – DEALERS"
93/5/27	13:12:36	"FED BUYS DOLLARS FOR YEN – DEALERS"
93/5/27	13:47:18	"FED AGAIN BUYS U.S. DOLLARS FOR YEN – DEALERS"
93/5/27	17:43:46	"FED AGAIN BUYS U.S. DOLLARS FOR YEN - DEALERS"
93/5/27	17:47:46	"FED BUYS DOLLARS FOR YEN IN NEW ROUND - DEALERS"
93/5/27	18:00:32	"FED CONTINUES BUYING DOLLARS FOR YEN–DEALERS"
93/5/27	18:16:52	"FED BUYS DOLLARS FOR YEN AS DOLLAR RISES–DEALERS"
93/5/28	01:06:16	"FED AND BOJ BUYING DLRS AT 107.20 YEN AND ABOVE"
93/5/28	03:14:02	"DOLLAR UP VS YEN ON FED/BOJ ACTION AT TOKYO MIDDAY"
93/5/28	13:01:24	"FED BUYS U.S. DOLLARS FOR YEN – DEALERS"
93/5/28	13:14:24	"FED INTERVENTION LIFTS DOLLAR AFTER WEAK U.S. OPEN"
93/5/28	13:23:46	"FED BUYS DOLLARS MORE AGGRESSIVELY AT 107.30 YEN"
93/5/28	13:39:32	"FED CONTINUES BUYING DOLLARS FOR YEN – DEALERS"
93/5/28	13:46:40	"FED INTERVENES AGAIN AS DOLLAR RECOVERS – DEALERS"
93/5/28	14:33:04	"FED BUYS DOLLARS AGAIN FOR YEN – DEALERS"
93/5/28	15:10:00	"FED BUYS DOLLARS FOR YEN AS U.S. CURRENCY FALLS"
93/5/28	15:23:34	"FED BUYS DOLLARS FOR YEN AT 107.35 YEN"
93/5/28	15:53:44	"FED BUYS DOLLARS FOR YEN AT 107.17 YEN"
93/6/1	14:49:10	"FED SEEN BUYING DOLLARS AROUND 107 YEN – DEALERS"
93/6/8	15:25:42	"FED BUYS DOLLARS AT 106.20/25 YEN - DEALERS"
93/6/8	15:38:36	"FED BUYS DOLLARS AT 106.35 TO 106.37 YEN–DEALERS"
93/6/8	16:03:36	"FED BUYS DOLLARS AT 106.25 YEN"
93/8/19	14:39:44	"FED BUYS DOLLARS AT 101.60 YEN - DEALERS"
93/8/19	14:50:18	"TRADE TRAUMA ROCKS DOLLAR IN EUROPE, FED STEPS IN"
93/8/19	14:54:58	"FED BUYS DOLLARS AT 102.30 YEN - DEALERS"
93/8/19	14:57:10	"FED BUYS DOLLARS AT 102.70/80 YEN - DEALERS"
93/8/19	15:07:08	"FED BUYS DOLLARS AT 103.60 YEN - DEALERS"
93/8/19	15:52:06	"FED BUYS DOLLARS AGAIN AT 103.80 YEN - DEALERS"
93/8/19	15:58:18	"FED BUYS DOLLARS IN LARGER VOLUME - U.S. DEALERS"
93/8/19	16:00:20	"FED BUYS DOLLARS AT 104 AND 104.05 YEN - DEALERS"
93/8/19	16:52:18	"FED SWOOPS IN TO RESURRECT DOLLAR AT U.S. MIDDAY"

Table 2: Distribution of Quotes by Bank in Yen/Dollar Market: 10/01/92-09/30/93

Bank	Percent of Total Quotes
Chemical Bank	8.65
Credit Suisse	6.58
Tokai Bank	5.17
Dresdner Bank	4.32
Morgan Guaranty	4.19
Citibank	4.19
Banca Commerciale Italiana	3.94
Industrial Bank of Japan	3.67
Swiss Bank Corporation	3.67
Union Bank of Switzerland	3.29

Table 3: Distribution of Quotes by Location in Yen/Dollar Market: 10/01/92-09/30/93

Country	Percent of Total Quotes
United Kingdom	23.6
Japan	15.27
United States	14.99
Switzerland	11.96
Singapore	11.35
Hong Kong	8.14
Canada	4.07
Germany	3.27

Table 4: Frequency Distribution of Absolute Spreads in Yen/Dollar Market: 10/01/92-09/30/93

Spread	Frequency	Percent
$0 \leq x < 5$	20648	3.6
$x = 5$	232082	40.9
$5 < x < 10$	36657	6.4
$x = 10$	273409	48.2
$10 < x < 15$	2804	0.5
$15 \leq x < 20$	1057	0.2
$20 \leq x < 30$	848	0.1
$30 \leq x < 40$	129	0
$x \geq 40$	64	0
Total	567698	99.9

Table 5: GARCH(1,1)-MA(1) Volatility Estimates for Sub-sample Windows Surrounding FED Intervention Announcements

$$\text{DLMID} = \mu + \theta\epsilon_{s,t-1} + \epsilon_{s,t} \quad (18)$$

$$\sigma^2_{s,t} = \omega + \alpha\epsilon^2_{s,t-1} + \beta\sigma^2_{s,t-1} \quad (19)$$

$$\epsilon_{s,t} \mid I_{t-1} \sim N(0, \sigma^2_t) \quad (20)$$

Sub-sample Date	μ	θ	ω	α	β	N
04/27/93	0.0039**	0.167**	0.001**	0.012**	0.956**	954
	(47.91)	(5.90)	(9.93)	(10.49)	(52.47)	
05/27/93	0.00357**	0.096**	0.003**	0.018**	0.505**	1020
	(75.33)	(2.32)	(9.05)	(2.83)	(9.34)	
05/28/93	0.00306**	0.255**	0.001**	0.011**	0.975**	552
	(34.82)	(8.34)	(16.72)	(15.79)	(38.80)	
06/01/93	0.00246**	0.066	0.008**	0.006	0.557**	520
	(14.725)	(0.555)	(3.13)	(0.83)	(3.93)	
06/08/93	0.00226**	0.178**	0.001	0.012**	0.608	636
	(63.56)	(3.89)	(0.994)	(3.22)	(1.486)	
08/19/93	0.00593**	0.044**	0.001	0.301**	0.679**	821
	(20.91)	(2.01)	(0.936)	(14.14)	(36.99)	

Notes: T-Statistics reported in parentheses. (**) and (*) denote significance at the 1% and 5% levels, respectively.

Table 6: Ordered Probit Estimates

$$S^*_t = \beta_0 + \beta_1 \hat{\sigma}^2_{s,t-1} + \beta_2 \text{inter}_{t-1} + \beta_3 S_{t-1} + \epsilon_{SS,t} \quad (21)$$

$$\sigma_{SS,t} = exp(\gamma_1 \hat{\sigma}^2_{s,t-1} + \gamma_2 \text{inter}_{t-1} + \gamma_3 S_{t-1}) \quad (22)$$

Variable	FED	BOJ
β_0	2.737	1.497
	(13.667)	(14.782)
β_1	0.348	0.296
	(6.454)	(4.301)
β_2	0.233	0.0914
	(9.496)	(5.185)
β_3	0.356	0.021
	(8.228)	(2.937)
γ_1	-0.043	-0.112
	(-0.657)	(-1.599)
γ_2	-0.013	0.046
	(-0.064)	(2.572)
γ_3	0.091	-0.325
	(3.085)	(-0.566)
μ_1	2.729	1.514
	(14.68)	(13.958)
μ_2	5.771	3.693
	(16.34)	(13.204)
LR	-3444.662	-3084.467
N	4503	58,675

Notes: Maximum likelihood estimates are presented with t-statistics in parentheses. μ_1 and μ_2 define the partition parameters. LR represents the value for the likelihood ratio statistic for the test of joint significance that the explanatory variable coefficient estimates are jointly equal to zero.

Table 7: Marginal Effects of Ordered Probit Estimates: FED Interventions

Variable/Category	a_0	a_1	a_2	a_3
GVOL	-0.003	-0.063	0.0629	0.0028
IV	-0.0034	-0.0078	0.0781	0.0035
SPREAD1	-0.0052	-0.1192	0.1191	0.0053

Table 8: Marginal Effects of Ordered Probit Estimates: BOJ Interventions

Variable/Category	a_0	a_1	a_2	a_3
GVOL	-0.0922	-0.5783	0.6353	0.0352
IV	-0.0053	-0.0332	0.0365	0.0020
SPREAD1	-0.0015	-0.0093	0.0102	0.0006

Table 9: Ordered Probit Estimates:Irregular Trade Time Correction

$$\mathrm{S}_t^* = \beta_0 + \beta_1 \hat{\sigma}_{s,t-1}^2 + \beta_2 \mathrm{inter}_{t-1} + \beta_3 \mathrm{S}_{t-1} + \beta_4 \Delta \mathrm{T}_{t-1} + \epsilon_{SS,t} \tag{23}$$

$$\sigma_{SS,t} = exp(\gamma_1 \hat{\sigma}_{s,t-1}^2 + \gamma_2 \mathrm{inter}_{t-1} + \gamma_3 \mathrm{S}_{t-1} + \gamma_4 \Delta \mathrm{T}_{t-1}) \tag{24}$$

Variable	FED
β_0	2.157
	(20.605)
β_1	0.126
	(9.428)
β_2	0.113
	(3.886)
β_3	0.546
	(10.357)
β_4	0.0748
	(7.325)
γ_1	0.0004
	(0.000)
γ_2	-0.0879
	(-3.551)
γ_3	-.152
	(-15.231)
γ_4	0.0203
	4.747
μ_1	2.023
	(12.449)
μ_2	5.133
	(14.32)
LR	-3476.686
N	4550

Notes: Maximum likelihood estimates are presented with t-statistics in parentheses. μ_1 and μ_2 define the partition parameters. LR represents the value for the two sided likelihood ratio statistic for the test of joint significance that the explanatory variable coefficient estimates are jointly equal to zero.

Table 10: Marginal Effects of FED Interventions: Irregular Trade Time Correction

Variable/Category	a_0	a_1	a_2	a_3
GVOL	-0.0198	-0.0481	0.0482	0.0188
IV	-0.0027	-0.0666	0.0667	0.0026
SPREAD1	-0.0045	-0.1090	0.1092	0.0043
TIMDIF	0.000	-.002	0.002	0.000

Table 11: Size of FED interventions in Yen/Dollar Market (10/92-09/93): Against Yen

Date	Millions of $
27 April 1993	200
27 May 1993	200
2 June 1993	492
8 June 1993	374
19 August 1993	165

Table 12: Ordered Probit Estimates: Individual Banks

$$S_t^* = \beta_0 + \beta_1 \hat{\sigma}^2_{s,t-1} + \beta_2 \text{inter}_{t-1} + \beta_3 S_{t-1} + \epsilon_{SS,t} \quad (25)$$

Variable	Chemical Bank	Citibank	Dresdner Bank	Morgan Guaranty
β_0	0.460	9.541	0.992	0.886
	(2.664)	(4.539)	(4.478)	(3.697)
β_1	0.157	0.586	0.482	0.561
	(11.547)	(1.476)	(3.187)	(0.005)
β_2	-0.164	4.523	0.094	0.138
	(-3.236)	(4.535)	(0.174)	(2.633)
β_3	0.353	0.318	0.174	0.238
	(39.290)	(30.092)	(9.627)	(13.807)
μ_1	3.679	3.350	2.128	1.01
	(25.406)	(23.441)	(15.834)	(7.60)
μ_2	7.194	7.355	5.311	5.824
	(38.118)	(42.546)	(22.306)	30.57
LR	-1597.29	-1268.92	-648.950	-449.357
N	2069	1708	905	2750

Notes: Maximum likelihood estimates are presented with t-statistics in parentheses. μ_1 and μ_2 define the partition parameters. LR represents the value for the likelihood ratio statistic for the test of joint significance that the explanatory variable coefficient estimates are jointly equal to zero.

Part I

Appendix

Since we assume that the spot rate is a function of the traders' perception of the fundamentals

$$P_t = \mu_{t-1} + \epsilon_t \tag{26}$$

where: $E_{t-1}(\epsilon_t)$=0 and $E_{t-1}(\epsilon_t^2)$=σ_t^2

and $E_{t-1}(.)$ denotes the conditional expectation based on the information set generated by past values of P_t.

Further if we assume that at time $t-1$ traders set bid and ask quotes as for each trader i:

$$A_t^i = \mu_{t-1} + k_{t-1} \tag{27}$$

$$B_t^i = \mu_{t-1} - k_{t-1} \tag{28}$$

where the bid-ask spread is assumed to be set symmetrically around the known fundamental price prevailing at the time of quote formation.

This implies that the mid-price can be written as and serves as our proxy for the unobserved underlying spot rate in the empirical analysis:

$$\frac{A_t^i + B_t^i}{2} = \frac{\mu_{t-1} + \epsilon_t + k_{t-1} + \mu_{t-1} + \epsilon_t - k_{t-1}}{2} \tag{29}$$

which is equal to:

$$mid_t = \mu_{t-1} + \epsilon_t \tag{30}$$

Similarly the bid-ask spread can be written as

$$A_t^i - B_t^i = (\mu_{t-1} + \epsilon_t + k_{t-1}) - (\mu_{t-1} + \epsilon_t - k_{t-1}) \tag{31}$$

And this is equal to:

$$spread_t^i = 2k_{t-1} \tag{32}$$

Thus it is reasonable to assume that the current spread's mean is a function of previous period's volatility. The mechanism by which this can happen is as follows. This period's spread depends on the dealers' expectation of this period's volatility. But this expectation can depend on previous period's volatility if volatility is serially dependent (we can assume that dealers don't know current volatility but must form an estimate of it).

This can be written as:

$F(k_t)\sim$ G$(k_{t-1}, \sigma^2_{t-1})$

This means that if σ^2_{t-1} increases the expected value of the spread will widen or the spread distribution shifts right.

This implies that the reduced form equation utilized in the ordered probit analysis can be written as:

$$\mathrm{S}_t^* = \beta_0 + \beta_1 \hat{\sigma}^2_{m,t-1} + \beta_2 \mathrm{inter}_{t-1} + \beta_3 \mathrm{S}_{t-1} + \epsilon_{S,t} \tag{33}$$

$$\sigma_{S,t} = exp(\gamma_1 \hat{\sigma}^2_{m,t} + \gamma_2 \mathrm{inter}_t + \gamma_3 \mathrm{S}_{t-1}) \tag{34}$$

where:

- S_t^*=spread,
- $inter_t$=intervention dummy,
- S_{t-1}=lagged spread,
- $\hat{\sigma}^2_{m,t-1}$=time varying GARCH volatility measure.