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ANTICIPATIONS OF FOREIGN EXCHANGE VOLATILITY AND BID-ASK SPREADS

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ABSTRACT

The paper studies the effect of the market's perceived exchange rate volatility on bid-ask spreads. The anticipated volatility is extracted from currency options data. An increase in the perceived volatility is found to widen bid-ask spreads. The direction of the effect is consistent with an option model of the spread, but the magnitude is smaller. An increase in trading volume of spot exchange rates also widens the spread. The omission of the trading volume, however, does not bias the estimate of the effect of the volatility on the spreads. Although the spread-volatility relation implied by the option model of the spread is close to linear, some form of nonlinearity can still be detected from the data.

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1. Introduction

Bid-ask spreads and other microstructure of foreign exchange trading are understudied. Notable exceptions are Glassman (1987), Boothe (1988), Black(1989) and Lyons (1993). Among those studies on the bid-ask spreads, the *ex post* standard deviations in foreign exchange rates are typically used as a measure of exchange risk[1]. Presumably, when one talks about the effect of exchange rate risk on the transaction costs, one is thinking of the effect of the market's perception of the risk. Therefore, an important extension to be made is to examine directly the impact of the market's ex ante perceptions of exchange rate risk on the bid-ask spread.

This paper makes four main contributions. First, we derive a theoretical relationship between the spread and market's anticipated volatility. The key idea is to express the spread as a portfolio of options. Copeland and Galai (1983) also relate the spread to options. However, their model is an equilibrium one, and the spread in their model depends on, among other things, the percentage of traders who are liquidity traders. In contrast, our model links the spread with options from a different perspective. Consequently, we are able to derive a spread-volatility relation without the need to specify an equilibrium model.

Second, we are able to examine the effect of the market's *ex ante* anticipation of exchange rate volatility on the bid-ask spread, as opposed to the effect of the *ex post* exchange rate volatility that has been examined in previous papers. This measure of the market's anticipated volatility is extracted from observed option data on foreign currencies. The data used in the paper cover four major exchange rates: the British pound, German mark, Japanese yen and Swiss Franc, all in units of the U.S. dollars, from February of 1983 to February of 1990.

Because we have a measure of the market's perceived risk, we can decompose ex post exchange rate volatility into anticipated and unanticipated components. Then, we can examine whether the two components have differential effects on the bid-ask spread.

Third, previous studies acknowledge the potentially important impact of trading volume on bid-ask spreads, but do not examine it directly because of a lack of data on spot market trading volume. This paper utilizes actual trading volume of the spot exchange rate for one of the currencies, and thus is able to assess explicitly the effect of trading volume on the spread-uncertainty relationship.

Fourth, the relationship between the bid-ask spread and exchange rate volatility could, in principle, be a non-linear one. Previous studies either have run linear regressions without justifying the choice of functional form, or have not dealt with possible non-linearities beyond taking some simple (and arbitrary) transformations of the variables in linear regressions. The spread-volatility relation in our model appears to be nonlinear in its general form, but the results of simulations turn out to be very close to linear. This may provide a theoretical justification for the linear functional specifications. However, nothing guarantees that the empirical relationship is indeed linear. Therefore, we also apply a nonparametric method to study the possible nonlinearity in the spread-volatility relationship.

The next section provides a simple theoretical model demonstrating that the spread tends to widen as the market's perceived exchange rate volatility goes up. Section 3 describes the data source and the methods used in extracting the market's anticipated volatility and in computing the percentage bid-ask spreads. Section 4 reports the empirical findings (linear regressions) concerning the effect of anticipated volatility on the spreads. The empirical effects of unanticipated volatility and spot trading volumes are also discussed. Section 5 is devoted to studying the nonlinearity in the spread-volatility relationship. In particular, the locally weighted regression technique is used to determine whether the functional relation between the spread and volatility varies with volatility. Concluding remarks are provided in Section 6.

2. Theoretical discussions

A bid quote is the price at which customers can sell foreign currency to a specialist, whereas an ask quote is the one at which customers can buy foreign currency from a specialist. The difference between the ask and bid quotes is the spread. The bid-ask spread is an important part of transactions costs for international trade and investment[2]. A widening of the spread decreases the profit of a firm and thus discourages it from engaging in international trade or investment (See Appendix A for a formal demonstration).

What are the effects of increased exchange rate volatility on the bid-ask spread itself? There have been several qualitative reasons proposed for the determination of the spread. Part of the spread covers overhead costs (e.g. staffing and office supplies) incurred by specialists. To analyze how the perceived exchange rate volatility can affect the bid-ask spread, Black(1989) develops a simple model in which the spread is proportional to the ratio of exchange rate volatility to expected trading volume. To reach this result, it is assumed that liquidity traders' buy and sell orders have the same mean, that speculative traders' demand functions are exactly linear in the prices and that dealers are risk-neutral. These assumptions appear stringent.

The model in this paper relates the spread to a portfolio of options. Copeland and

Galai(1983) pioneered the use of options theory in a model of bid-ask spreads. But my model and theirs link the spread with options from different perspectives. In Copeland and Galai(1983), the offer to buy at the bid by a specialist is thought of as a put option with the strike price equal to the bid quote. Similarly, to a trader, the offer to sell at the ask is a call option with the strike price equal to the ask quote. Because the options always have positive values, and because the announcement of the bid and ask quotes are free of charge, the bid and ask quotes yields a net loss to a specialist. To derive a spread-volatility relation, Copeland and Galai need to specify an equilibrium model with heterogeneous traders. The specialist's loss from offering options (the bid and ask quotes) without charge can be compensated by the expected gains from trading with liquidity traders. In this story, assumptions on the preferences of specialists, speculators and liquidity traders are needed. The resulting spread-volatility relationship depends, among other things, on the proportion of traders that are liquidity traders and the preferences of the market participants.

This paper presents a second way of linking the spread with options. I will argue that the size of a spread is equal to the values of a call option and a put option. In contrast with the first view, the call option here has a strike price equal to the bid quote, and the put option has a strike price equal to the ask quote. In this story, the model is completed by using the options analogy alone. Because options are priced by a no-arbitrage argument, this model thus eliminates the need to specify an equilibrium model.

As in any economic model, to make the idea explicit, I have to make some audacious assumptions. First, assume that the central rate of exchange, E, is some "true" exchange rate. Information about this true rate is revealed to specialists only through trading. In other words, specialists do not have private information. Second, when a specialist announces a pair of bid and ask quotes, she is committed, for the next T minutes, to buy at the bid and sell at the ask. She can only change the quotes after some transactions[3].

To illustrate the idea, let us look at Figure 1. A customer in the foreign exchange market may view a specialist's bid and ask quotes as options. Consider someone who buys a foreign currency at the ask, E+0.5s. She makes a profit (in domestic currency) as E goes up, and loses money as E goes down. However, her loss has a lower bound, because she can sell the foreign currency back to the specialist at the bid, E-0.5s, as long as the bid-ask quotes have not been changed. The payoff diagram for this position resembles that of a call option.

Consider now a trader who has just sold a unit of foreign currency to a specialist at the bid, E-0.5s. Her profit increases linearly as E does down, and decreases linearly as E goes up. Her loss also has a lower bound, since she can buy back the foreign currency from the specialist at the ask, E+0.5s. This is an implicit put option[4].

In Figure 1, the dotted line and the solid line are the payoff diagrams of the associated call and put options, respectively. The value of the announcement of the bid-ask quotes is equal to the call, plus the put, and minus the spread. We know that the announcement is free of charge. Therefore, the bid-ask spread must equal to the values of the call and put options.

To summarize, announcing a pair of bid and ask prices by a specialist is equivalent to selling, for the price of s, a put option with a strike price equal to the ask quote, E+s/2, and simultaneously selling a call option with a strike price equal to the bid quote, E-s/2.

In order to derive an explicit expression, more assumptions are needed. (1) I treat the spread as a (short-lived) European option. I have already assumed earlier that when a spread is announced, the specialist is committed to do transactions at theses prices for the next T minutes. Here, I assume further that T is exogenous. (2) The effective domestic and foreign interest rates, for these T minutes, are zero. (3) Other assumptions of the Black-Scholes formula are satisfied.

The assumption of an exogenous T is motivated to apply the Black-Scholes formula. In examining the spread-volatility relation numerically, we will vary the value of T from 10 seconds to 5 minutes. They do not make a qualitative difference. The assumption on zero interest rates is not essential either, since the qualitative feature of the model is preserved with nonzero interest rates.

Let $\mu = s/E$ be the percentage bid-ask spread, and σ be the market anticipated exchange rate volatility over the time interval between when the bid-ask spread is announced and when it is changed. Then, we have the following result.

Lemma: (The option model of the spread) The relationship between the percentage spread, μ, and the anticipated volatility, σ, is given by the following equation:

$$\mu = \{N(h_{c1})-(1-\mu/2)N(h_{c2})\} + \{N(h_{p1})-1-(1+\mu/2)[N(h_{p2})-1]\}$$

where

$$h_{c1} = [-\ln(1-\mu/2)+0.5\sigma^2T]/[\sigma T^{0.5}],$$

$$h_{c2} = [-\ln(1-\mu/2)-0.5\sigma^2T]/[\sigma T^{0.5}],$$

$$h_{p1} = [-\ln(1+\mu/2)+0.5\sigma^2T]/[\sigma T^{0.5}],$$

$$h_{p2} = [-\ln(1+\mu/2)-0.5\sigma^2T]/[\sigma T^{0.5}],$$

and N(.) is the cumulative distribution function of a normal random variable.

[Proof]: Let C and P be the value of the call and put options associated with the bid-ask spread. From figure 1, we see that $0=C+P-s$. Or, $\mu=s/E=C/E + P/E$. The terms in the first curly bracket is the Black-Scholes' value of the call option (divided by the central rate of exchange E), and the term in the second curly bracket is the Black-Scholes' value of the put option.

The lemma gives at least two impressions. First, we may think that an increase in perceived volatility widens the spread since the values of both the call and the put options are increasing functions of the volatility. However, this result is not as straightforward as the above. The complication arises from the fact that the the percentage spread, μ, also appears on the right hand side of the equation; it is not obvious that the two are necessarily positively associated. Second, the relationship between the spread and the perceived volatility, in principle, is non-linear. In fact, no simple transformation (e.g., logarithmic transformation) is able to make the relationship linear.

Since it is difficult to express μ as an explicit function of the volatility, we turn to numerical simulations. Based on the lemma, for a given value of μ, the value of the volatility can be solved by the Newton-Raphson method. Appendix A records the values of volatility corresponding to different values of the percentage spreads. The range of the percentage spread is chosen so that it encompasses the actual range of the spreads observed in the data. We try four different values for the duration of the bid and ask offers: five minutes, two minutes, thirty seconds and ten seconds.

Figure 2 plots the results of the simulation. First, we note that the spread is a monotonically increasing function of the volatility. In other words, the option model of the spread does imply that the spread unambiguously widens as the anticipated volatility increases.

Second, perhaps more surprisingly, the relationship between the spread and the volatility is close to linear. This provides a theoretical justification for using linear regressions in the empirical sections. However, whether there is a nonlinear relationship in the data will be formally investigated later in the paper.

3. Estimating the anticipated volatility and bid-ask spreads

The key variable that we desire to obtain is a measure of the market's *ex ante* estimate of one-month-ahead exchange rate volatility. It is usually difficult to obtain a measure of market expectations. However, based on observed option trading on foreign currencies, we can get a reasonably good estimate. Lyons(1989) and Wei and Frankel(1991) have also extracted such measures for purposes which are different from each other and different from the current paper.

The basic idea is the following. To price a currency option properly, market participants use some version of the Black-Scholes formula. The inputs needed for the formula are time-to-maturity of the contract, interest rates in the two countries, the current spot exchange rate and an estimate of the future volatility over the lifetime of the option contract. The market estimate of the volatility is the only variable unknown to an econometrician. All the other inputs are readily available from newspapers or the indenture of the option contracts. By solving a nonlinear function, we can obtain an estimate of the market's anticipated volatility of the exchange rate in question.

We obtain these measures of anticipated volatility for four exchange rates: British pound, German mark, Japanese yen and Swiss franc, all in units of US dollars. The estimation method and the justification for the choice of the option formula are detailed in Wei and Frankel(1991). The source of the data is described in Appendix B. Because the option contracts, by regulation, always expire on the third Wednesday of each month, we choose options that are written on the third Wednesday of each month. The implied standard deviation (isd) from the options can be thought of as a market's anticipation of the average daily volatility over the lifetime of the contract (typically a month in this sample). The estimates of the market's anticipated volatility are plotted in Figure 3a.

The realized volatility is computed from daily exchange rates from the third Wednesday of the month to the third Wednesday of the following month. It is the sample standard deviation of the changes in logarithms of daily exchange rates. Such a measure of realized volatility is consistent with the definition of the market anticipated volatility that is used in option pricing. The unanticipated volatility is the difference between the realized volatility (rsd) and the anticipated one of the corresponding month. The realized volatility for the four currencies are plotted in Figure 3b.

The percentage bid-ask spreads for the four exchange rates are the actual bid-ask spreads as percentages of the ask quote. Alternatively, we could compute the bid-ask spreads as percentages of the middle rates; it makes little difference with respect to the empirical results in the next two sections. The data are the closing quotes in the London market on the day the options are written. Figure 4 plots the percentage bid-ask spreads. By inspecting Figure 4, we suspect that one of the observations (August 17,1988) on the spread for the dollar/pound rate may be an outlier. In the empirical testing, we will make sure that no result is entirely driven by this single observation.

4. Empirical results: Does volatility widen the spread?

III.A. Market anticipated volatility and bid-ask spreads

To examine the effect of anticipated volatility on percentage bid-ask spreads, we run the following regressions:

$$pspread_t = c + b \; isd_t + e_t$$

where pspread is the percentage bid-ask spread, and isd is the market perceived one-month-ahead exchange rate volatility implied by the currency options data.

Note that such a regression does not prove or disprove any causal relationship, but does indicate correlation, which is what the model predicts. To take advantage of the similar structure of the regressions for the four exchange rates, I use the seemingly unrelated regression (SUR) technique. The basic results are summarized in Table 1. Panel A presents the estimation results when no cross-equation parameter constraints are imposed. We first note that the intercept terms for the four currencies are all positive and statistically significant. Glassman (1987) argues that the intercept gives an estimate of the cost-overhead component of the transaction cost, which includes costs of office supplies, staff salaries etc., that are not directly related to risks in foreign exchange transactions. The point estimates of the intercepts range from 0.032 per cent for the German mark to 0.057 per cent for the Swiss Franc. [A fomal chi-square test rejects the null hypothesis that the intercepts are equal.]

Second, the slope estimates are positive for all the four currencies. They are statistically significant for the British pound and Japanese yen at the five percent level, for the German mark at the ten percent level. This indicates that, as our model predicts, increases in the perceived volatility of the exchange rates are associated with widening of the bid-ask spreads. As noted before, one of the observation on the bid-ask spread for the pound (August 17, 1988) appears to be an outlier. We carry out an OLS regression for the pound omitting this observation and find that the sign and significance of the estimates are not changed, although the point estimate becomes slightly smaller. This means that the result for the pound in Panel A is not driven by that one observation. We omit the result of this regression to save space.

Since the point estimates of the slope coefficient in the unconstrained estimation are quite close, we perform an explicit Wald test on the hypothesis that all four slope parameters are equal. Under the null, the statistic has a Chi-square distribution with 3 degrees of freedom. The critical value at the five percent level is 7.815. Since the value of the statistic in the sample is only 0.956, we do not reject this null hypothesis. In fact, three individual t-tests also fail to reject pairwise equality of the four slope parameters. To improve the efficiency of our estimation, we redo the SUR procedure after imposing the restriction that the slope parameters are equal in the four equations. The results are in Panel B of Table 1. The point estimate for the coefficient associated with the market's anticipated volatility is 2.670, and is statistically different from zero at the five percent level.

Before October 1985, option contracts were only available at four maturity dates: the third Wednesdays in March, June, September and December. The monthly series of the market's anticipated volatility thus contain observations from contracts with overlapping time periods. This could cause serial correlation in the error terms of the above regressions. To make sure that this does not contaminate our results, we redo the SUR estimation in the subsample that excludes data from overlapping contracts. Again, because a Chi-square test fails to reject the hypothesis that the slope parameters are the same for the four currencies, we impose this constraint in our estimation. The results are reported in Panel C. As before, the slope parameter for the market's anticipated volatility is positive and statistically significant at the five percent level. The point estimate (3.242) becomes somewhat larger.

We repeat the above regressions after taking a logarithmic transformation of the anticipated volatility. This serves two purposes. First, it indicates whether the spread-volatility relationship in table 1 is robust to a small perturbation of the model specification. Second, it facilitates the quantitative interpretation of the estimates. That is to say, we are able to say by how much the bid-ask spread changes in response to a one percent increase in the market's perceived volatility.

Table 2 presents the results of this exercise. In the unconstrained SUR estimation, the parameters associated with the market's anticipated volatility are positive for all four currencies and statistically different from zero at the ten percent level for three of the exchange rates. A Chi-square test once again fails to reject the hypothesis that the slope paramters are the same in the four equations. [The value of the Wald statistic is 0.717, well below the critical value at the five percent level.] When this parameter constraint is imposed in the estimation, the slope parameter has a point estimate of 0.0151 and is statistically different from zero at the five percent level. Based on this point estimate, we conclude that a one percent increase in the market's perceived exchange rate volatility is associated with a widening of the bid-ask spread by about 0.015 percentage points.

As far as the direction of the spread-volatility association is concerned, the positive estimates of the slope parameter in Table 2 are good news for the option model of the spread. We now go one step further to compare the magnitude of the association implied by the lemma with these point estimates. The second half of Appendix A computes the theoretical response of the spread to changes in volatility. When the anticipated volatility increases by one unit, the increment of the spread varies from 69.67 percentage points, if the spread is assumed to last for five minutes, to 12.73 percentage points, if the spread lasts for 10 seconds. In comparison, the actual response in Table 1 is between 2 to 4 percentage points. Therefore, the model seems to have overpredicted the response.

Examine now the percentage response reflected in the estimation in logarithms. For a one percent increase in the volatility, the model predicts that the spread widens by about 0.084 percentage points. According to Table 2, the actual increase in the spreads is about 0.015 percentage point. Again, the model has overpredicted, though the difference between the theoretical and empirical responses is much smaller. Of course, economic models should not be taken too literally. Nevertheless, it is important to bear in mind that the option model of the bid-ask spread does not capture all the aspects regarding the spread-volatility relationship.

It should be pointed out that the market-anticipated-volatility could have been measured with error[5]. This error-in-variable problem can potentially give rise to a downward bias in the estimated response of the spread to a given change in the anticipated volatility. Unfortunately, this problem is not resolved in this paper as we not aware of any good instruments for the anticipated volatility. Nevertheless, we may derive some sense of plausibility for the measurement error to be an explanation for the gap between the option model and our point estimates.

Suppose our measure of the anticipated volatility (or its logarithm) is equal to the true anticipated volatility (or its logarithm) plus an error term which is independent of the error term in the original equation and of the true volatility, then the size of the bias is positively related to the ratio of the variance of the measurement error and the variance of the true anticipated volatility (See, for example, Johnston, 1984, p430). If the measurement error is large such that its variance is the same as that of the anticipated volitility, then the true response of the spread to a given change in the volatility would be twice as large as the point estimates here. This would still be smaller than the prediction of the option model. Indeed, in order for the model-predicted spread-volatility relationship to match up with our point estimates in Table 2, the variance of the measurement error is required to be at least four times as big as the variance of the true anticipated volatility. This seems implausibly large. To summarize, the option model does predict correctly the sign of the spread-volatility relationship, but may overpredict the magnitude of the association.

One may worry about the impact of possible non-normal distributions of the error terms. We note first that in a large sample, the slope estimator is consistent and asymptotically normal. In a small sample, however, nothing guarantees *a priori* the performance of the estimator. Wei and Frankel (1991, Table 5) have conducted simulation exercises to examine the effect of nonnormality on the point estimate and size of the t-test. With a sample size of 85, they have considered a wide range of non-normal distributions for the error term, the skewness parameter of the error term varying from -6.2 to 6.2, the kurtosis parameter from 3 to 113. Even with this wide range of non-normality, the point estimate of the slope parameter and the "true" size of the t-test in an OLS regression are hardly affected. This indicates that our results here are not likely to be an artifact of non-normal error terms.

III. Anticipated versus unanticipated volatility

Given a measure of the market's *ex ante* anticipation of volatility, we can decompose the *ex post* exchange rate volatility into anticipated and unanticipated components. The difference between the *ex post* volatility and the market's anticipation is defined to be the unanticipated volatility. With this decomposition, we can examine their possibly differential effects on the bid-ask spreads. One expects that the effect of exchange rate volatility comes entirely from the anticipated component, since the dealers should choose bid-ask spreads based on their perception of exchange rate volatility in the near future. We first run the following type of regression:

$$pspread_t = c + b_1\, isd_t + b_2\, (rsd_{t+1} - isd_t) + e_t$$

where $pspread_t$ is the percentage bid-ask spread on day t, isd_t is the market's anticipation on day t of the one-month-ahead exchange rate volatility, rsd_{t+1} the *ex post* volatility of the following month starting from day t. The results are in Table 3.

Panel A of Table 3 presents the result of an unconstrained estimation. The point estimates of the intercept terms and the slope parameters are quite close to the corresponding ones in Table 1. The parameter estimates of the unanticipated volatility are not statistically different from zero for any exchange rate, as expected.

A Wald test is performed on the hypothsis that the two slope parameters are the same across the four equations. The statistic has a Chi-square distribution with 6 degrees of freedom. The value of the statistic in the sample is 2.352, which is well below the critical value at the five percent level (12.59). Hence, the null hypothesis is not rejected.

In Panel B, the two slope paramters are restricted to be equal across the four equations. The slope parameter for the unanticipated volatility is not statistically different from zero, while that for the anticipated volatility is 2.393 and significant. Panel C reports the estimation result over the subsample that excludes contracts with overlapping maturities. [A Chi-square test fails to reject the hypothesis that the slope parameters are the same for the four currencies for this subsample.] The qualitative results are the same as in Panel B, although the point estimate for the anticipated volatility is slightly larger (2.990).

We repeat this set of regressions with logarithmic transformation of the right-hand-side variables:

$$pspread_t = c + b_1 \log(isd_t) + b_2 [\log(rsd_{t+1}) - \log(isd_t)] + e_t$$

The results are reported in Table 4. In the unconstrained SUR estimation, none of the parameters for the unanticipated volatility has any effect on the bid-ask spreads at even the twenty percent level. In comparison, all four parameters for the anticipated volatility are positive and two of them are significantly different from zero at the ten percent level. In the two constrained regressions over the whole sample and over the subsample of non-overlapping observations, the parameters for the unanticipated volatility are not different from zero at even the twenty percent level, while the parameters for the anticipated component are statistically greater than zero at the five percent level. Based on the constrained SUR estimations, we conclude that a one percent increase in the anticipated volatility widens the bid-ask spread by about 0.015 to 0.016 percentage points.

Previous studies on the effect of volatility typically use *ex post* volatility as a proxy for market's anticipated volatility. Doing so would not alter point estimate of slope parameter if market's anticipated volatility is an unbiased estimate of the *ex post* realized volatility. Unfortunately, Wei and Frankel(1991) have shown that the unbiasedness hypothesis is rejected for the four exchange rates. Therefore, the magnitude of the effect of the market's anticipated volatility on the bid-ask spread need not be reflected by the point estimate of the parameter associated with measures of *ex post* volatility.

III.C. The effect of trading volume on bid-ask spread

The literature suggests that, in theory, the trading volume of spot exchange rates has an effect on the bid-ask spread. Most suggest that the relationship should be negative in the long run(Copeland and Galai, 1983; and Black, 1989), although it could be positive in the short run(Copeland and Galai, 1983).

Due to lack of the data, few previous empirical studies have actually included the spot trading volume in their regressions. Glassman(1987, footnote 4) even suggests that "such data probably will never be available since the trading does not take place in a centralized marketplace and since banks resist revealing what they perceive to be confidential information about their business". Interestingly, spot trading volume is available for the interbank yen/dollar trading in Tokyo. The data is obtained from Nihon Kazai Shibun (Japanese Economic Daily). This provides a chance to examine directly the impact of the spot trading volume on the spreads.

In her study, Glassman(1987) cleverly uses the volume of currency futures trading at the Chicago Mercantile Exchange as a proxy for the volume of spot currency trading. She finds that the coefficient estimate on the proxy of spot volume is generally positive. The question is how well the trading volume of the futures contracts approximates that of spot trading. As noted by Glassman herself(1987,p482), the growth rate of the futures trading was more than 200% higher than that of the spot trading during the period 1977-1983. Consequently, the movement of the two may diverge substantially from each other. Therefore the effect of spot trading volume may not be adequately reflected by estimates derived from futures trading volume.

Black (1989) uses three years of annual data on spot trading volume of seven currencies: 1980, 1983 and 1986. He then calculates the annual average of the daily spread and the annual standard deviation of daily percentage changes for these three years. With a small sample of 21 observations, the spot trading volume variable enters a regression of the spread on volatility with a negative sign and a t-statistic equal to 1.31. The sign of the volume variable is opposite to what Glassman (1987) obtained.

One may want to improve the Black's result for two reasons. First, the sample in his study is very limited. Second, the interaction among the spread, volatility and trading volume is likely to be short-run in nature, and may not be adequately reflected in annual average data.

With seven years of monthly data on the actual spot trading volume, this paper hopes to provide more insights on the issue. It should be clear that the data in this section have their own limitations. The main one is the slight mismatching in time and space for the spread (from

London market) and volume (from Tokyo market) variables. The maintained assumption here is that the spot trading volumes are highly positively correlated across the major dollar/yen markets. The following results should be cautiously interpreted with this qualification in mind.

Table 5 presents the results of regressions for the Japanese yen, with the spot trading volume included as an additional explanatory variable. To avoid possible simultaneity problem, each regression is also run with one month lagged values of the trading volume used as the regressor. Panel A reports the estimation results with the anticipated volatility and spot trading volume in levels. The parameter estimate for the trading volume is about 0.00013 to 0.00015. It is statistically significant at the ten percent level for the whole sample with the lagged trading volume and significant at the fifteen or twenty percent levels in other instances.

Panel B reports the estimation with the anticipated volatility and trading volume in logarithms. The parameter estimates are positive and statistically different from zero at the fifteen or twenty percent levels. These results offer some support for the positive association between the spread and volatility and suggest that using futures volume as a proxy does give an qualitatively correct answer[6]. Based on Panel B, a one percent increase in the trading volume leads to a widening of the spread by approximately 0.005 percentage point. This estimate of the effect of the volume appears much larger than the estimate obtained using futures volume as a proxy for the spot volume (Glassman, 1987, Table 1).

Another thing that we can learn from Table 5 relates to the effect of omitting the spot trading volume. The point estimates in Panels A and B of Table 5 are very close to the corresponding ones in Tables 1 and 2 (the yen equations in the unconstrained SUR estimation with the whole sample). Indeed, one cannot reject the hypotheses that they are the same at the five percent level. This suggests that the omission of the spot volume variable does not seriously bias the parameter estimation for the market's anticipated volatility.

5. Empirical results: Is there a nonlinear relation?

The simulation exercise on our option model of the spread-volatility association implies a nearly linear relationship. But the relationship in the actual data could potentially be non-linear. This section is devoted to investigating the possibility of nonlinearity. The basic tool used is locally weighted regression.

Locally weighted regression (LWR) is a procedure for fitting a regression surface to data through smoothing in a moving average fashion. Suppose $\mu = g(x) + e$, where x is a p-dimentional vector, and g is a smooth (and possibly nonlinear) function of the independent variables. e is a normally distributed disturbance term. LWR provides an estimate of g(x) at any value x^*. The estimate of g at x^* uses a fraction, f, of observations whose x_i values are closest to x^*. That is, a neighborhood of the independent variables is defined. Each point in the neighborhood is weighted according to its distance from x^*; points close to x^* have large weight, and points far from x^* have small weight. A linear or a quadratic function of the independent variables is fitted to the dependent variable using weighted least squares with these weights. The resulting estimate of g(x) is taken to be the value of this fitted function at x^*. Cleveland and Devlin(1988) provide a comprehensive discussion of this procedure.

If the functional relationship between the spread and the anticipated volatility depends on the size of the volatility, LWR is ideal to capture this. In choosing the fraction of data, f, to do the local fitting, one faces certain tradeoffs. As f approaches one, the estimated regression surface tends to a regular linear regression. The sampling variability is reduced, but the chance of detecting nonlinear relation is also reduced. On the other hand, as f moves away from one, the flexibility of the regression (and thus the chance of finding the nonlinearity) increases, but the influence of the sampling errors on the estimates also increases. To balance the flexibility with low sampling errors, we pick f=0.98, 0.90 and 0.85 respectively.

Figure 5 reports the smoothed scatter plots resulting from applying the LWR procedure. Each plot has the estimates of the regression surface on the vertical axis and the anticipated volatility on the horizontal axis. The four columns correspond to the four currencies, and the three rows correspond to the three values of the f. From Figure 5, we may notice two things. First, the positive association between the spread and the anticipated volatility are profound. Furthermore, for most of the data range, the relationship between the two appears to be linear. This is certainly consistent with the option model of the bid-ask spread. However, there is some systematic nonlinear pattern in at least three currencies. The slope of the curves appears to be smaller in the lower tails. This becomes more obvious as we choose smaller fractions of observations to do the local fitting. Therefore, the bid-ask spreads become less elastic when the anticipated volatility is low. Although there is no formal statistical test available for this particular pattern of non-linearity, the similarity of the pattern in the three of the four exchange rates suggests this to be a systematic phenomenon. This feature of the data is not well captured by the option model the bid-ask spread (the lemma).

6. Conclusions

This paper studies whether and how the perception of foreign exchange risk may affect the bid-ask spreads in foreign exchange market. In the theoretical section, we have derived a model of the spread-volatility relationship which is solely based on a no-arbitrage argument. Based on the model, numerical simulations indicate that an increase in the volatility widens the spread. Furthermore, the spread-volatility relationship derived from the simulations is close to linear.

The empirical part of the paper has sought to make further contributions. The key variable used in the empirical part is a measure of the market's anticipated volatility of foreign exchange. It is extracted from observable currency option trading for four major currencies from February of 1983 to February of 1990. There are three major empirical findings. First, the bid-ask spread in foreign exchange does increase as the market's perception of the volatility increases. This is consistent with the option model of the spread. Based on the constrained SUR estimations in Section 4, a one percent increase in the volatility typically leads to a widening of the spread by 0.015 to 0.016 percentage points. This magnitude of the point estimate appears to be smaller than that implied by the option model of the spread. Furthermore, the *ex post* realized volatility in foreign exchange rates is decomposed into unanticipated and anticipated components. The regression results show that the unanticipated component of volatility does not have any impact on bid-ask spreads.

Second, the effects of spot trading volume on the spread and on the possible bias of the volatility parameter are examined. The spot trading volume (of dollar/yen) is positively related with the bid-ask spread. The parameter for the volatility variable is unaffected by the addition or omission of the trading volume variable. This suggests that omitting the trading volume may not generate much bias in the estimation of the spread-volatility relation. These findings lend direct support to the results by Glassman(1987), who uses a proxy for the spot trading volume.

Third, the locally weighted regression technique is employed to investigate whether the relationship between the spread and the volatility is nonlinear in the data. It is found that the relationship is indeed nearly linear for most of the data range. However, nonlinearity is still there: in plots of the regression surface against the volatility terms, the slopes for smaller values of the volatility are smaller for three currencies. Therefore, when exchange rate volatility is small in the market's perception, the bid-ask spreads are much less responsive to changes in the volatility.

Appendix A:

Bid-ask Spread and Incentive to Engage in International Trade

This appendix illustrates that a widening of the spread decreases the profit of a firm in international trade, thus discouraging it from engaging in the trade. Consider a firm that uses both domestic and foreign inputs and exports all of its output to the foreign market. Let w_d be the domestic price of the domestic input, p and w_f be the foreign price of the output and imported input. Let E be the central rate of exchange (units of domestic currency per unit of foreign currency) and s be the bid-ask spread. E-s/2 and E+s/2 are the bid and ask prices respectively. We use $\pi(s) = \pi(E, s, p, w_d, w_f)$ to denote the profit function of the firm.

Result: The profit function $\pi(s)$ is decreasing and convex in s.

[Proof]: Define (y,x_d,x_f) to be the profit-maximizing production plan for the exchange rate- price vector (E,s,p,w_d,w_f), and (y',x_d',x_f') the corresponding optimal plan for (E,s',p,w_d,w_f). The profit function is

$$\pi(s) = (E-s/2)py - (E+s/2)w_f x_f - w_d x_d.$$

It is easy to see that the profit function is decreasing in s. Let s' > s, then

$$\begin{aligned}\pi(s) &> (E-s'/2)py - (E+s'/2)w_f x_f - w_d x_d \\ &\geq (E-s'/2)py' - (E+s'/2)w_f x_f' - w_d x_d' \\ &= \pi(s'), \text{ as was to be shown.}\end{aligned}$$

The first inequality comes from the assumption that s'>s. The second inequality follows from the definition of (y',x_d',x_f') as the optimal plan for (E,s',p,w_d,w_f).

To show that $\pi(s)$ is also convex in s, define $s''=ts+(1-t)s'$, where $0\leq t \leq 1$. We need to show that $\pi(s'') \leq t\pi(s) + (1-t)\pi(s')$.

By definition,

$$\pi(s'')= (E-s''/2)py'' - (E+s''/2)w_f x_f'' - w_d x_d''$$

$$= t[(E-s/2)py''-(E+s/2)w_f x_f''-w_d x_d''] + (1-t)[(E-s'/2)py''-(E+s'/2)w_f x_f''-w_d x_d'']$$

$$\leq t[(E-s/2)py-(E+s/2)w_f x_f-w_d x_d] + (1-t)[(E-s'/2)py'-(E+s'/2)w_f x_f'-w_d x_d']$$

$$= t\pi(s) + (1-t)\pi(s)\text{, as was required.}$$

Appendix B:

Simulation Results Based on the Option Model of the Spread.

This appendix presents some simulation results on the relationship between the percentage bid-ask spread and the anticipated exchange rate volatility.

A1. Values of σ (implied by the lemma) corresponding to values of μ.

percentage spread (100μ)	volatility σ (T=5 minutes)	volatility σ (T=2 minutes)	volatility σ (T=30 seconds)	volatility s (T=10 seconds)
0.001	0.000014	0.000023	0.000045	0.000079
0.005	0.000072	0.000114	0.000227	0.000393
0.009	0.000129	0.000204	0.000409	0.000708
0.04	0.000581	0.000899	0.001798	0.003147
0.06	0.000871	0.001363	0.002725	0.004672
0.08	0.00116	0.001817	0.003634	0.006294
0.10	0.00145	0.002271	0.004542	0.007867
0.12	0.00172	0.002725	0.005450	0.009440
0.14	0.00201	0.003179	0.006359	0.01113
0.16	0.00230	0.003597	0.007267	0.01259
0.18	0.00259	0.004088	0.008261	0.01416
0.20	0.00287	0.004542	0.009084	0.01573

Notes:

(1) Based on the lemma, for a given value of μ, a value of σ is computed using the Gauss-Raphson method.
(2) The volatility σ is on per day basis. μ is the percentage bid-ask spread.
(3) T is the time duration of the bid-ask spread. 5 minutes, 2 minutes, 30 seconds and 10 seconds correspond to T=1/288, 1/720, 1/2880 and 1/8640, respectively.

A2. The response of the spread μ (implied by the lemma) to changes in volatility σ.

Average response of the percentage spread (100μ) to a one unit change in the volatility:

Time length	(T=5 minutes)	(T=2 minutes)	(T=30 seconds)	(T=10 seconds)
Response	69.67	44.11	22.05	12.73

Average response of the percentage spread (100μ) to a one percent change in the volatility:

Time length	(T=5 minutes)	(T=2 minutes)	(T=30 seconds)	(T=10 seconds)
Response	0.0848	0.0839	0.0846	0.0844

Appendix C. Data sources

The data on four exchange rates (the British pound, German mark, Japanese yen and Swiss Franc, all in units of US dollars) are used in this paper. The sample periods for all the data are from February of 1983 to February of 1990.

Daily spot exchange rates and the bid-ask spreads: The daily spot exchange rates used to compute the realized standard deviations for the four currencies are the daily closing bid quotes on the London Market. The units for the four exchange rates are units of US dollar per unit of foreign currency.The monthly series of the percentage bid-ask spread is computed from the closing quotes on the third Wednesday of each month on the London Market. The percentage spread used in the paper is defined as 100(ask-bid)/ask. The source is Data Resources, Inc.

Options data: The currency option data are used to extract the market's anticipated one-month-ahead exchange rate volatility. They are the closing quotes on the third Wednesday of each month on the Philadelphia Exchange. By regulation, currency options always expire on the third Wednesday of each month. The source is various issues of the Wall Street journal. The other aspects of the selection criteria of the option data are:

(1) Call options that are closest to being at the money.

(2) If possible, contracts that mature in the following month. Otherwise, contracts with the next nearest maturity.

Trading volume of the spot dollar/yen rate: The trading volume of the spot dollar/yen exchange rate is the volume of interbank transactions in Tokyo on the third Wednesday of each month. The source is Nikkei Telecom.

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Endnotes

1. Lyons (1993) employs an unusual one-week-long data set of transaction prices and inventories. His focus is on the effect of inventory on prices as opposed to the spread-volatility relationship. Melvin and Tan (1991) examined possible links between foreign exchange bid-ask speads and social unrest.

2. Many people may think that bid-ask spreads or transaction costs in foreign exchange markets are economically unimportant. A recent study by the European Economic Commission (1990) has challenged this view. According to its estimate, the transaction costs are on the order of 0.25-0.4% of EC's GDP per annum. The bulk of the transaction costs comes from bid-ask spreads and other fees paid to banks.

3. In reality, a specialist certainly does not have to trade at her quoted bid and ask prices. However, refusing to trade at the quotes too often is considered bad for reputation. Therefore, quoted bid and ask prices are usually honored by a specialist.

4. An alternative interpretation replaces the central rate E in the above story by the actual quotes. To obtain the result on the implicit put, consider someone purchasing the foreign currency at the ask quote. Her payoff depends on the movement of the next bid quote (in stead of E). Just as in the previous story, the payoff diagram resembles that of a call option with strike price equal to the bid. Similarly, for someone selling foreign currency to the specialist, her payoff depends on the movement of the next ask quote (in stead of E). It is still a put option with the strike price equal to the ask quote. When we evaluate the value of the spread, the resulting spread-volatility relationship is exactly the same as before. I thank David Gordon for pointing this out.

5. There are two principle reasons for the errors-in-measurement. First, the relevant anticipated volatility for the theoretical model is for the next few seconds or minutes after a given quote of the bid and ask prices, not for the next month. On the other hand, the error from this source is probably not very large since the set of new information regarding the next few seconds or minutes is likely to be close to that regarding the next 30 days.

The second reson for the measurement error that the Black-Scholes (or Garman-Kohlhagan) formula may not be the correct model to price currency options because the exchange rate volatility could be stochastic. Bates (1988) discusses the option pricing problem when the exchange rate follows a mixture of jump and diffusion processes. While the Black-Scholes formula may not be the best model to price currency options, there is one defence for our approach. Some financial consultants specializing in currency products as well as currency option traders have told me that the

Black-Scholes model is what is relied upon by the option traders to price currency options at least until recently. Regardless of what is the best model to price options in theory, the Black-Scholes formula is probably the most relevant model to use in order to back out market-anticipated volatilities.

6. It should be pointed out that if the volume variable is measured with error, the point estimate could be downward biased.

We have also run the regression with a specification similar to that in Black(1989). The result is as follows (standard errors are in parentheses):

$$\underset{}{psprd_t} = \underset{(0.0108)}{0.0276} + \underset{(22.69)}{7.50}\, isd_t/volume_t + \underset{(1.979)}{3.277} isd_t + \underset{(0.00015)}{0.00017} volume_t$$

adj.R^2=0.034 DW=2.35

This result is close to those in the text. In particular, the volume variable enters with a positive sign. Qualitatively similar results are obtained when one-period lagged value of the volume variable is used or a subsample excluding observations from overlapping contracts is used.

Table 1: Percentage spread and the anticipated volatility in levels
1983:2 - 1990:2
$pspread_t = c + b\ isd_t + e_t$

A. Unconstrained SUR estimation, whole sample (N=85)

Currency	c	b	adj.R^2	DW
BP	0.0424*	4.014*	0.05	1.85
	(0.0119)	(1.878)		
GM	0.0320*	2.072#	0.04	1.73
	(0.0072)	(1.080)		
JY	0.0368*	3.049*	0.04	2.27
	(0.0085)	(1.455)		
SF	0.0566*	2.353	0.02	1.71
	(0.0120)	(1.744)		

B. Constrained SUR estimation, whole sample (N=85)

Currency	c	b	adj.R^2	DW
BP	0.0504*	2.670*	0.051	1.86
	(0.0060)	(0.791)		
GM	0.0283*		0.040	1.73
	(0.0052)			
JY	0.0388*		0.042	2.27
	(0.0046)			
SF	0.0547*		0.020	1.72
	(0.0058)			

C. Constrained SUR estimation, excluding data from contracts with overlapping maturities (N=64)

Currency	c	b	adj.R^2	DW
BP	0.0459*	3.242*	0.047	1.91
	(0.0075)	(1.018)		
GM	0.0268*		0.068	1.70
	(0.0064)			
JY	0.0364*		0.048	1.50
	(0.0055)			
SF	0.0497*		0.012	1.25
	(0.0069)			

Notes:
(1) Standard errors are in parentheses.
(2) * denotes that the estimate is statistically different from zero at the five percent level.
(3) # denotes that the estimate is statistically different from zero at the ten percent level.

Table 2: Percentage spread and the anticipated volatility in logarithms
1983:2 - 1990:2
$pspread_t = c + b \log(isd_t) + e_t$

A. Unconstrained SUR estimation, whole sample (N=85)

Currency	c	b	adj.R^2	DW
BP	0.1879*	0.02349*	0.048	1.86
	(0.0596)	(0.01147)		
GM	0.1156*	0.01384*	0.048	1.73
	(0.0360)	(0.00671)		
JY	0.1187*	0.01247#	0.030	2.26
	(0.0415)	(0.00718)		
SF	0.1509*	0.01558	0.022	1.70
	(0.0625)	(0.01127)		

B. Constrained SUR estimation, whole sample (N=85)

Currency	c	b	adj.R^2	DW
BP	0.144*	0.0151*	0.048	1.87
	(0.024)	(0.0046)		
GM	0.122*		0.048	1.73
	(0.024)			
JY	0.133*		0.030	2.25
	(0.025)			
SF	0.148*		0.022	1.70
	(0.024)			

C. Constrained SUR estimation, excluding data from contracts with overlapping maturities (N=64)

Currency	c	b	adj.R^2	DW
BP	0.146*	0.0158*	0.040	1.92
	(0.028)	(0.0054)		
GM	0.128*		0.077	1.71
	(0.028)			
JY	0.137*		0.036	1.50
	(0.029)			
SF	0.150*		0.010	1.25
	(0.028)			

Notes:
(1) Standard errors are in parentheses.
(2) * denotes that the estimate is statistically different from zero at the five percent level.
(3) # denotes that the estimate is statistically different from zero at the ten percent level.

Table 3: Differential effects of the anticipated and unanticipated volatility on the spreads
1983:2 - 1990:2
$pspread_t = c + b_1\, isd_t + b_2\, (rsd_{t+1} - isd_t) + e_t$

A. Unconstrained SUR estimation, whole sample (N=85)

Currency	c	b_1	b_2	adj.R^2	DW
BP	0.044*	3.785#	-0.140	0.051	1.86
	(0.013)	(2.201)	(1.074)		
GM	0.032*	2.152#	0.824	0.042	1.74
	(0.008)	(1.267)	(0.487)		
JY	0.043*	1.795	-0.658	0.055	2.29
	(0.009)	(1.750)	(0.526)		
SF	0.057*	2.370	0.044	0.021	1.70
	(0.013)	(2.104)	(0.818)		

B. Constrained SUR estimation, whole sample (N=85)

Currency	c	b_1	b_2	adj.R^2	DW
BP	0.0500*	2.393*	-0.195	0.050	1.86
	(0.0064)	(0.935)	(0.348)		
GM	0.0280*			0.038	1.74
	(0.0056)				
JY	0.0386*			0.044	2.26
	(0.0049)				
SF	0.0543*			0.021	1.72
	(0.0062)				

C. Constrained SUR estimation, excluding data from contracts with overlapping maturities (N=64)

Currency	c	b_1	b_2	adj.R^2	DW
BP	0.0470*	2.990*	-0.384	0.051	1.92
	(0.0081)	(1.106)	(0.656)		
GM	0.0286*			0.082	1.67
	(0.0070)				
JY	0.0380*			0.038	1.50
	(0.0062)				
SF	0.0517*			0.016	1.27
	(0.0078)				

Notes:
(1) Standard errors are in parentheses.
(2) * denotes that the estimate is statistically different from zero at the five percent level.
(3) # denotes that the estimate is statistically different from zero at the ten percent level.

Table 4: Differential effects of the anticipated and unanticipated volatility on the spreads
1983:2 - 1990:2

$$pspread_t = c + b_1 \log(isd_t) + b_2 [\log(rsd_{t+1}) - \log(isd_t)] + e_t$$

A. Unconstrained SUR estimation, whole sample (N=85)

Currency	c	b_1	b_2	adj.R^2	DW
BP	0.188*	0.023#	0.0002	0.048	1.86
	(0.064)	(0.012)	(0.004)		
GM	0.127*	0.016*	0.001	0.065	1.76
	(0.036)	(0.007)	(0.001)		
JY	0.107*	0.010	-0.001	0.039	2.32
	(0.040)	(0.008)	(0.001)		
SF	0.152*	0.016	0.0002	0.022	1.70
	(0.064)	(0.012)	(0.002)		

B. Constrained SUR estimation, whole sample (N=85)

Currency	c	b_1	b_2	adj.R^2	DW
BP	0.149*	0.0160*	0.0001	0.046	1.86
	(0.027)	(0.0052)	(0.0008)		
GM	0.127*			0.045	1.75
	(0.027)				
JY	0.137*			0.033	2.25
	(0.028)				
SF	0.153*			0.023	1.70
	(0.027)				

C. Constrained SUR estimation, excluding data from contracts with overlapping maturities (N=64)

Currency	c	b_1	b_2	adj.R^2	DW
BP	0.142*	0.0150*	-0.0019	0.041	1.92
	(0.033)	(0.0063)	(0.0043)		
GM	0.123*			0.084	1.69
	(0.032)				
JY	0.133*			0.033	1.51
	(0.033)				
SF	0.146*			0.012	1.25
	(0.032)				

Notes:
(1) Standard errors are in parentheses.
(2) * denotes that the estimate is statistically different from zero at the five percent level.
(3) # denotes that the estimate is statistically different from zero at the ten percent level.

Table 5: Trading volume, anticipated volatility and the spread (Japanese Yen)
1983:2 - 1990:2

A. OLS estimation in levels

$pspread_t = c + b_1 \, isd_t + b_2 \, volume_t + e_t$ OR
$pspread_t = c + b_1 \, isd_t + b_3 \, volume_{t-1} + e_t$

Sample	c	b_1	b_2	b_3	adj.R^2	DW
whole sample	0.0288* (0.0101)	3.6444* (1.6285)	0.00013+ (0.00009)		0.044	2.34
	0.0313* (0.0097)	3.0430# (1.6857)		0.00015# (0.00009)	0.042	2.33
excluding overlapping contracts	0.0348* (0.0102)	2.4447++ (1.7591)	0.00013++ (0.00010)		0.023	1.52
	0.0353* (0.0094)	2.0710 (1.778)		0.00016+ (0.00010)	0.041	1.52

B. OLS estimation in logarithm

$pspread_t = c + b_1 \log(isd_t) + b_2 \log(volume_t) + e_t$ OR
$pspread_t = c + b_1 \log(isd_t) + b_3 \log(volume_{t-1}) + e_t$

Sample	c	b_1	b_2	b_3	adj.R^2	DW
whole sample	0.1201* (0.0413)	0.01538# (0.0081)	0.00413++ (0.00313)		0.027	2.31
	0.1052* (0.0431)	0.0129+ (0.0081)		0.00466+ (0.00310)	0.027	2.31
excluding overlapping contracts	0.0852# (0.0444)	0.00949 (0.0080)	0.00498++ (0.00373)		0.017	1.52
	0.0812* (0.0468)	0.00878 (0.0081)		0.00501++ (0.00367)	0.024	1.51

Notes:
(1) Standard errors are in parentheses.
(2) *, #, + and ++ denote that the estimate is statistically different from zero at the five, ten, fifteen and twenty percent levels, respectively.

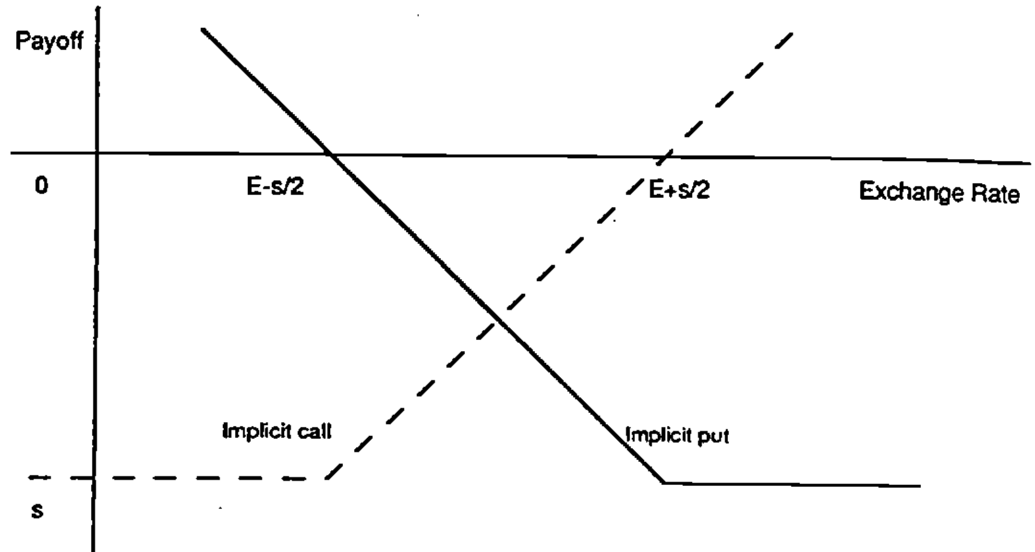


Figure 1: Spread as a portfolio of options

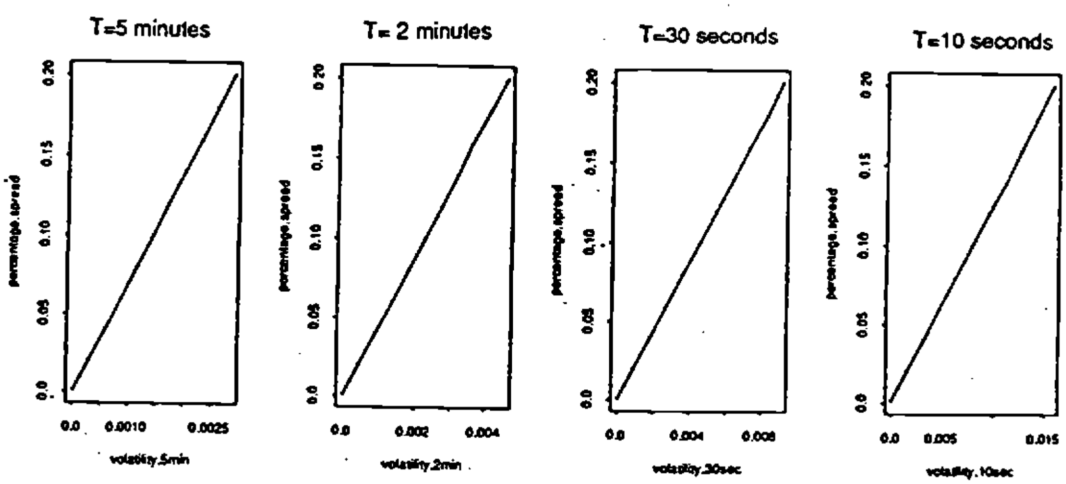


Figure 2: Spread-volatility relation: Simulation results

Figure 3a: Market's anticipated exchange rate volatility extracted from options data (1983:2-1990:2)

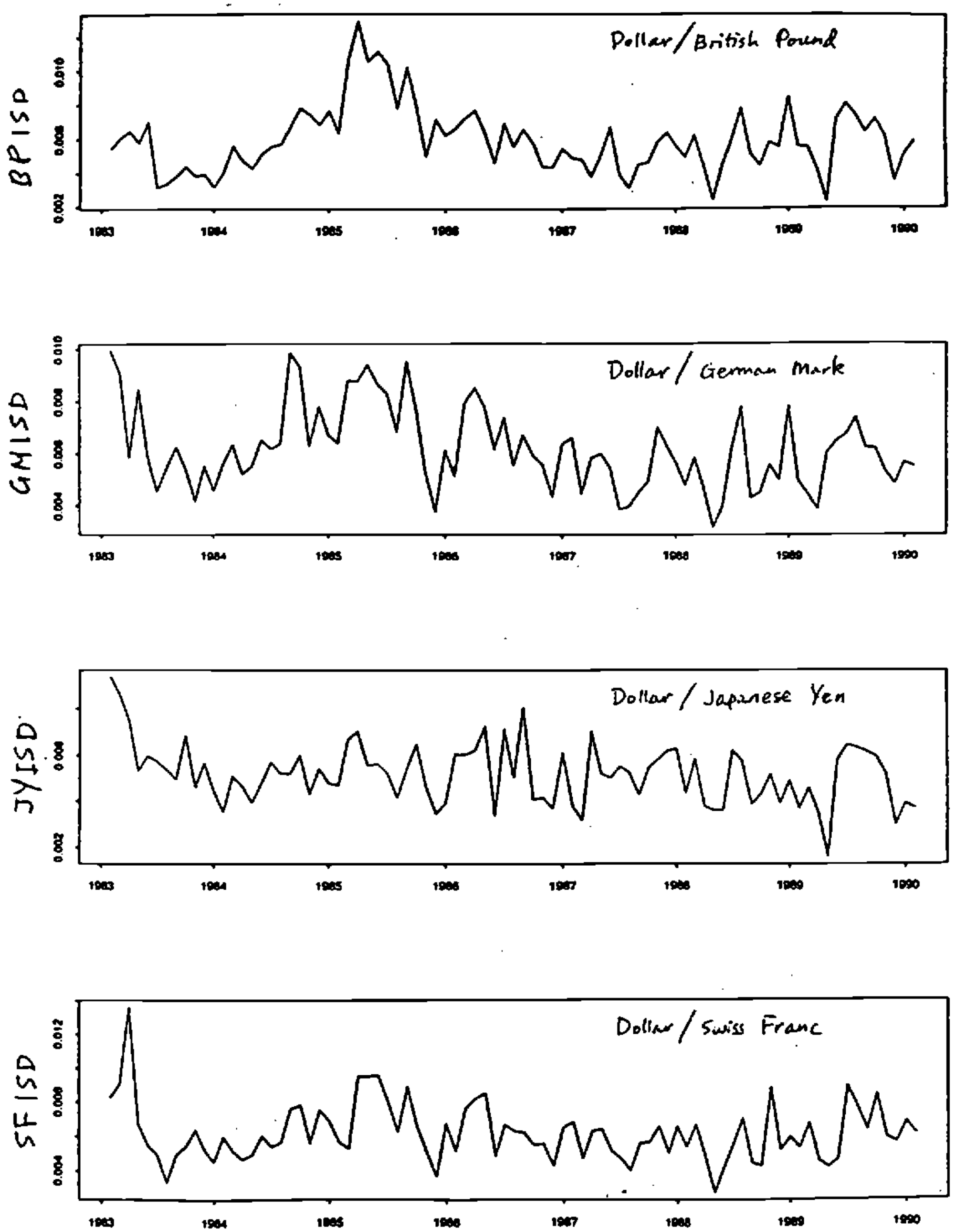


Figure 3b: Realized exchange rate volatility

(1983:2-1990:2)

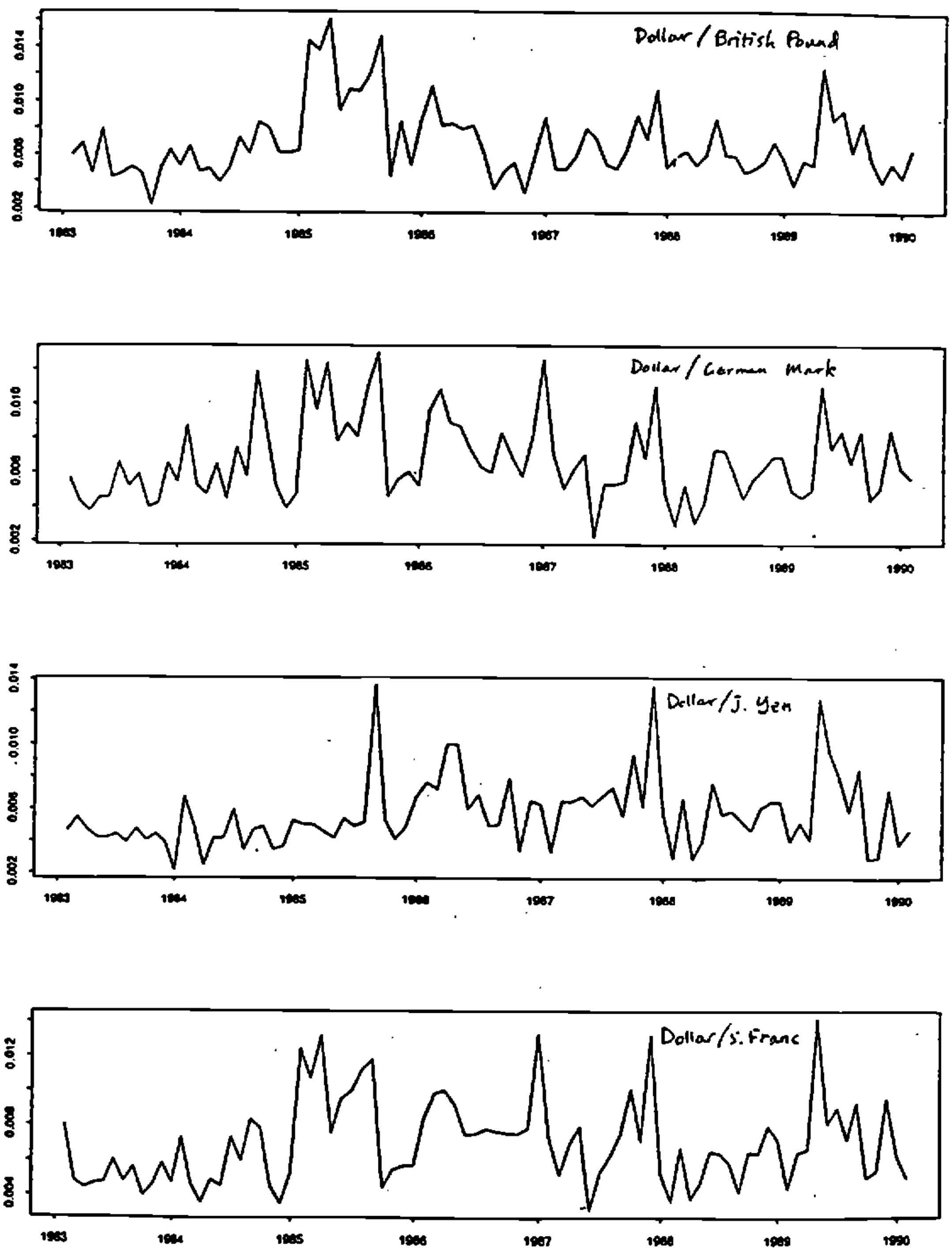


Figure 4: Percentage bid-ask spreads in the foreign exchange market (1983:2-1990:2)

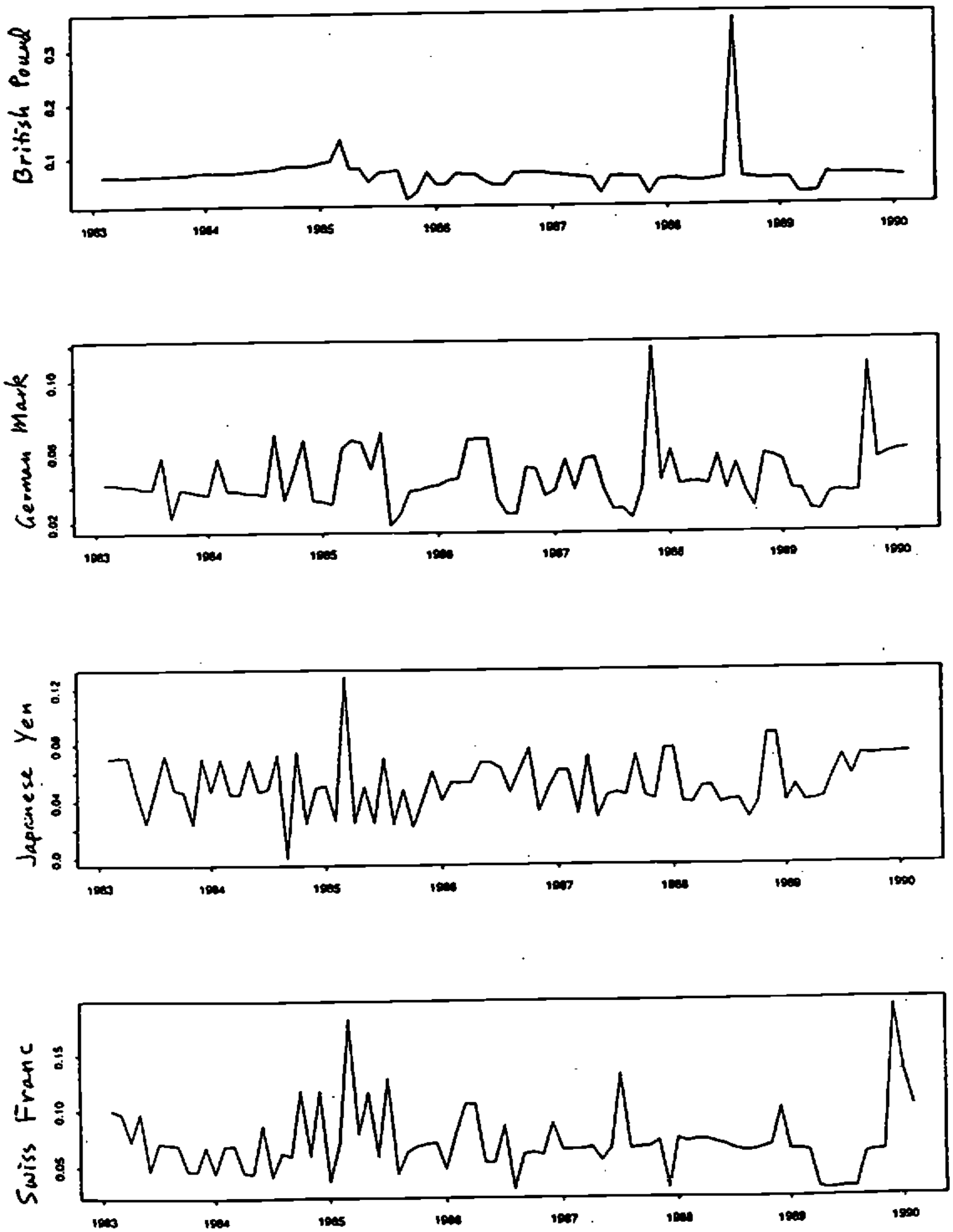
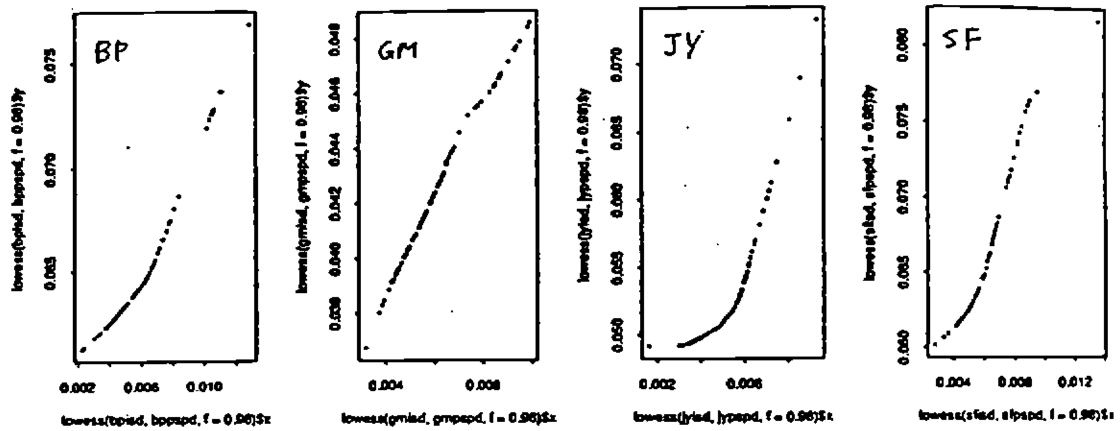
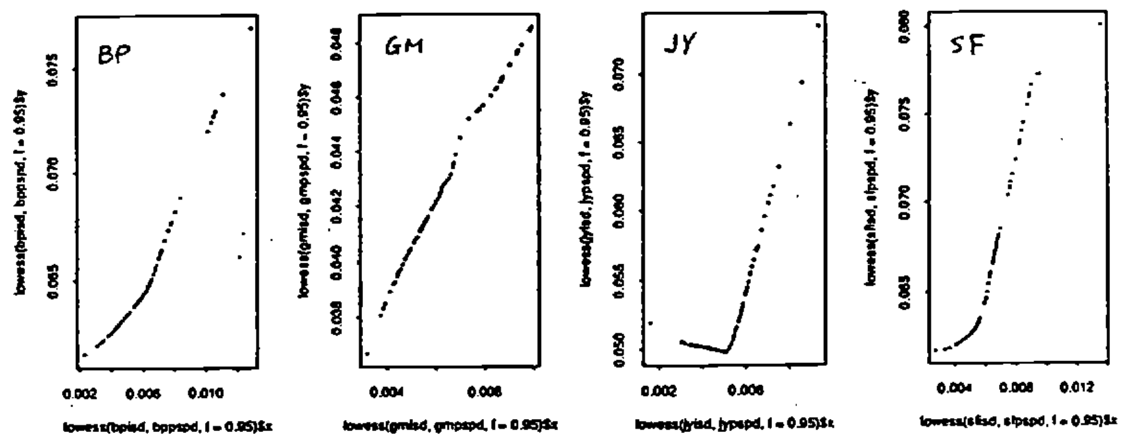


Figure 5: Smoothed scatter plots

by locally weighted regressions



(f = 0.98)



f = 0.95