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A vast literature on the effects of sterilized intervention by the monetary authorities in the foreign exchange markets concludes that intervention systematically moves the spot exchange rate only if it is publicly announced, coordinated across countries, and consistent with the underlying stance of fiscal and monetary policy. Over the past fifteen years, researchers have also attempted to determine if intervention has any effects on the dispersion and directionality of market views concerning the future exchange rate. These studies usually focus on the variance around the expected future exchange rate – the second moment. In this paper we demonstrate how to use over-the-counter option prices to recover the risk-neutral probability density function (PDF) for the future exchange rate. Using the yen/dollar exchange rate as an example, we calculate measures of dispersion and directionality, such as variance and skewness, from estimated PDFs to test whether intervention by the Japanese Ministry of Finance had any impact on the higher moments of the exchange rate. We find little or no systematic effect, consistent with the findings of the literature on the spot rate as Japanese intervention during the period 1996-2004 was not publicly announced, rarely coordinated across countries and, in hindsight, probably inconsistent with the underlying stance of monetary policy.

Keywords: exchange rate intervention, monetary policy, risk-neutral probability density function
JEL code: F3, G15

Gabriele Galati is at the Bank for International Settlements and can be reached at gabriele.galati@bis.org; Patrick Higgins is at the Federal Reserve Bank of Cleveland and can be reached at patrick.c.higgins@clev.frb.org; Owen F. Humpage is at the Federal Reserve Bank of Cleveland and can be reached at owen.f.humpage@clev.frb.org; and William Melick is at Kenyon College and can be reached at melickw@kenyon.edu.

There is a clear consensus on the effect of sterilized intervention on the level of the exchange rate – a view that is shared both by academics and policymakers. Academics Sarno and Taylor (2001) state, ‘‘...official intervention can be effective if the intervention is publicly announced and concerted and provided that it is consistent with the underlying stance of monetary and fiscal policy.’’ Former Federal Reserve and United States Treasury official Truman (2003) concludes ‘‘The evidence on the short-run effectiveness of exchange market intervention is sufficient in my view to support the judicious use of intervention by the United States as a supplementary policy instrument as long as it generally is used in a manner consistent with other economic policies, but that same evidence falls substantially short of demonstrating that intervention is a separate policy instrument that can be used to manage exchange rates with any lasting effect.’’

Most studies find that intervention has at best a small impact on the level of the exchange rate, implying that quite often (most notably episodes outside the Plaza and Louvre periods) intervention is not publicly announced, is not coordinated, and is not consistent with the stance of monetary and fiscal policy (see for example Galati, Melick, and Micu (2005).) However, intervention that has no effect on the level of the exchange rate may influence market participants’ views on the uncertainty surrounding the future level of the exchange rate. More precisely, intervention may have no effect on the first moment of the density from which the future spot rate is expected to be drawn, but may still influence the higher moments of the density such as variance and skewness. For example, it is clearly possible for intervention to increase the uncertainty around market participant’s expectation for future values of the spot exchange rate without moving the current spot rate.

Studies that have examined whether or not intervention has an impact on the higher moments have tended to focus on the second moment (variance) or some other measure of dispersion. These studies have taken either a backward looking approach using a historical estimate of variance or volatility or a forward-looking approach using measures derived from options on foreign exchange. Dominguez (1998) and Sarno and Taylor (2001) provide good overviews of the literature on the use of both GARCH volatility and implied volatility to assess the impact of intervention. Consistent with the consensus view on level effects, empirical work on the second moment generally finds that the effect on dispersion depends on both the sample period and the intervention strategy.

Most studies devoted to the second moment have taken the backward-looking approach and examined conditional exchange rate volatility, usually estimated with GARCH models. Among the more influential early studies, Baillie and Humpage (1992) find a positive relationship between Federal Reserve, Bank of Japan and Bundesbank intervention and the conditional volatility of the mark/dollar and yen/dollar exchange rates for the period February 1987 to February 1990. Dominguez (1993) finds that officially announced intervention reduces volatility, while intervention that is not detected by the market increases volatility. Among more recent studies, Dominguez (2003b) finds evidence of a significant short-run impact of intervention on exchange rate volatility both at the intra-day and the daily frequency. Beine et al (2003) introduce regime-dependency and test whether intervention can explain volatility regime switches. They find that, depending on the prevailing volatility level, coordinated central bank interventions can either increase or decrease volatility. Using a sophisticated econometric approach, Beine et al (2006) estimate realized volatility by decomposing exchange rate volatility into a continuously varying component and jumps. They present evidence that in some cases, coordinated interventions affect the jump part of the volatility process, while most coordinated interventions are associated with an increase in the persistent part of exchange rate volatility. Kim and Sheen (2006) use an EGARCH procedure and find that Japanese intervention was effective after 1995, especially when coordinated with the United States.

Bonser-Neal and Tanner (1996) are the first to have studied the effect of intervention on implied volatility. They find that intervention had a different impact on volatility over different time periods. Between February 1987 and December 1989 (the ‘‘Louvre period’’), intervention increased implied volatility, while there is less evidence that intervention reduced exchange rate volatility between 1990 and 1991. Murray et al. (1997) investigate the effect of different intervention strategies by the Bank of Canada on implied volatility of the Canadian/US dollar exchange rate. They find that intervention that was expected or that was unexpectedly light had no effect on implied volatility, while intervention that was unexpected and heavy significantly reduced implied volatility. Dominguez (1998) finds that the impact of intervention on implied yen/dollar and mark/dollar volatility is sample dependent. Frenkel et al (2005) present evidence of a positive relationship between intervention in the yen/dollar market and implied volatility.

Few studies have looked at the impact of central bank intervention on higher moments of exchange rate expectations. Galati, Melick and Micu (2005) use risk-neutral PDFs derived from OTC options prices and find little impact of intervention on either the variance or the skewness of the yen/dollar exchange rate. Castren (2004) uses Malz's (1997) method to estimate risk-neutral PDFs for yen/dollar, yen/euro and dollar/euro exchange rates. He finds evidence of a systematic impact of intervention on all four moments of yen/dollar exchange rate expectations, as well as on some moments of the other two currency pairs. Fratzscher (2006) looks at the effect of communications on exchange rates and intervention by the Fed, the Bank of Japan and the ECB on different option contracts – implied volatilities, risk reversals and strangles – without however backing out PDFs. He finds that monetary authorities' communication tends to reduce implied volatility in most cases whereas actual interventions raise implied volatility. Disyatat and Galati (forthcoming) investigate the impact of intervention by the Czech National Bank on expectations of the koruna/euro exchange rate described by implied volatilities and risk reversals. They find little evidence that intervention had a significant impact.

In this paper we provide a tutorial on using options quotes from the over-the-counter (OTC) market to derive measures of the higher moments of the expected exchange rate probability density function (PDF). We then examine whether intervention has any effect on these higher moments. The next section of the paper discusses the peculiarities of the OTC market. The second section shows how to derive the risk-neutral PDF for the one-month ahead exchange rate from OTC option quotes and discusses the limitations involved in working with risk-neutral PDFs. The third section presents an estimation strategy to determine the impact of intervention on the higher moments of the PDF, with particular attention paid to the potential complication that intervention and the higher moments are simultaneously determined. The fourth section presents estimation results that indicate a very small, if any, effect of intervention on the higher moments. Conclusions are offered in the fifth section.

I. The OTC Options Market

Options on foreign exchange trade both over-the-counter (OTC) and on organized exchanges. The main difference between the two markets is that each day the OTC market introduces a new set of contracts at horizons of one week, one month, three months and so on, while the exchanges introduce contracts on a monthly or quarterly cycle so that each day the horizon covered by each contract declines. Thus, a time series of prices from the OTC contracts is a constant maturity series, while a time series of prices from the exchange contracts is not. Table 1 shows that the volume in the OTC market is at least an order of magnitude larger than that on the exchanges. For most currency pairs, price discovery takes place in the OTC market, however, arbitrage ensures that the prices across the two markets do not get too far out of line. The exchange-traded options may appear to provide the advantage of a wider range of strike prices, although these prices are often thinly traded, or not traded at all. Options traded in the OTC market are usually European, meaning that they can only be exercised at maturity. Exchanges trade both European and American options, where an American option can be exercised at any time between purchase and maturity.

In this paper we use OTC options prices in order to create a constant maturity density function for the expected future spot rate. Describing how the density functions are estimated requires an explanation of the quoting conventions followed in the OTC market. We offer only a brief description here, details can be found in Malz (1996) and Malz (1997).

A few definitions are in order. In the standard Black-Scholes model first applied to foreign exchange by Garman and Kohlhagen (1983) and Grabbe (1983), the price of a European, one-month, foreign exchange call option with strike price X, forward rate F, and domestic and foreign risk-free rates r and r^*, is written as

(1)

$$C(X,\sigma) = \frac{1}{1 + r^* \cdot (t'/360)} \cdot \left(F \cdot \Phi(d_1(X,\sigma)) \; - \; X \cdot \Phi(d_2(X,\sigma))\right)$$

$$d_1 = \frac{\ln\left(\frac{F}{X}\right) + \left(\frac{\sigma^2}{2}\right) \cdot \left(\frac{t}{365}\right)}{\sigma \cdot \sqrt{t/365}} \quad , \quad d_2 = d_1 - \sigma \cdot \sqrt{t/365}$$

where t is the number of calendar days between the day the option price is quoted and the same day in the next month, and t' is the number of calendar days between two business days after the date the option price is quoted and two business days after the day in the next month that is the same as that on which the option price is quoted. The symbol Φ represents the standard normal cumulative distribution function and σ is the annualized volatility of the spot exchange rate.

The first derivative of the call's price with respect to the exercise price is known as the call's delta, and this is given by

(2) $$\frac{\partial C(X,\sigma)}{\partial X} = \frac{1}{1 + r^* \cdot (t'/360)} \cdot \Phi(d_1(X,\sigma))$$

Notice that the call's delta will always fall between zero and one, and will be closer to zero (one) the further the strike price is above (below) the forward rate.

The OTC market quotes option prices (and prices of popular option combinations) in terms of delta and volatility. Once a deal is struck, the standard formulae given above are used to translate the quote from delta and volatility terms into a strike price and option price in units of foreign currency. As an example, consider a call option with a delta of 0.5 (referred to as at-the-money (ATM)) that is quoted at a price of 0.14 units of volatility (vols). Assume that the current forward rate is ¥115/$, that the one-month Japanese interest rate is 0.04 percent, and that both t and t' are equal to 30. The translation from the quote in (delta, volatility) space to one in (strike, option price) space involves two steps. First, the strike price is found by setting the equation for the call's delta equal to 0.5 and solving for X.

(3) $$\frac{\partial C(X,\sigma)}{\partial X} = \frac{1}{1+.0004\cdot(30/360)} \cdot \Phi(d_1(X,0.14)) = 0.5 \quad \Rightarrow \quad X \approx 115.09\,.$$

Once the strike price has been determined, the foreign currency price of the call is then calculated as

(4) $$C(115.09,0.14) = \frac{1}{1+.0004\cdot(30/360)} \cdot (115\cdot\Phi(d_1(115.09,0.14)) - 115.09\cdot\Phi(d_2(115.09,0.14)) = 1.7961$$

To reiterate, trades in the OTC market are initially made with strikes and option prices quoted in terms of delta and volatility. As above, these strikes and prices are then translated into units of foreign currency using the standard formulae given above in order to calculate the precise amount of money that must change hands when the option is sold and when the option matures.

The use of the Black-Scholes formulae by the OTC market to translate option quotes does not mean that market participants believe that all the assumptions of the Black-Scholes model are correct. This is clearly not the case, as the market almost always quotes options with different strike prices at different volatilities. This pattern is known as the volatility smile and is a violation of the constant volatility implied by the assumption of a normal distribution for the return to holding the underlying asset in the Black-Scholes model.

The OTC market readily quotes two popular option combinations, the strangle and the risk reversal. Both involve option pairs that are the same distance away from the 50-delta or ATM strike, which is roughly the forward rate. In a strangle, a dealer either sells or purchases a pair of call and put options where the call has a strike price above the ATM forward rate and the put has a strike price below the ATM forward rate. A 25-delta strangle has options with strikes at call deltas of 25 and 75, while a 10-delta strangle has options with strikes at call deltas of 10 and 90. In a risk-reversal, rather than either buying or selling both options, a dealer buys the call and sells the put or vice-versa. Risk reversals and strangles are quoted as follows in terms of volatilities, where $V_{50\delta}$ is the volatility for an ATM option, that is, an option with a call delta equal to 50.

(5)
$$\begin{aligned}
&\text{10 - Delta Strangle Price} = STRG_{10\delta} = \frac{V_{90\delta} + V_{10\delta}}{2} - V_{50\delta} \\
&\text{25 - Delta Strangle Price} = STRG_{25\delta} = \frac{V_{75\delta} + V_{25\delta}}{2} - V_{50\delta} \\
&\text{10 Delta Risk Reversal Price} = RR_{10\delta} = V_{10\delta} - V_{90\delta} \\
&\text{25 Delta Risk Reversal Price} = RR_{25\delta} = V_{25\delta} - V_{75\delta} \\
&\text{ATM Option Price} = ATM = V_{50\delta}
\end{aligned}$$

These quotes for strangles, risk reversals and an ATM option uniquely determine five volatilities at different call deltas, as shown below.

(6)
$$\begin{aligned}
V_{10\delta} &= ATM + STRG_{10\delta} + \frac{RR_{10\delta}}{2} \\
V_{25\delta} &= ATM + STRG_{25\delta} + \frac{RR_{25\delta}}{2} \\
V_{50\delta} &= ATM \\
V_{75\delta} &= ATM + STRG_{25\delta} - \frac{RR_{25\delta}}{2} \\
V_{90\delta} &= ATM + STRG_{10\delta} - \frac{RR_{10\delta}}{2}
\end{aligned}$$

Table 2 presents an example of all of the above calculations for a single day in our dataset. Quotes for risk reversals, strangles, and an ATM option are used to solve for five option prices expressed in terms of call delta and volatility. The bottom panel of Table 2 uses the Garman-Kohlhagen equations to translate the prices from call delta volatility terms into strike prices and option prices in terms of yen. Figure 1 plots the volatility smile for this example day and Figure 2 plots the smile translated into strike prices and option prices in units of Japanese yen.

II. Using Options to Recover the Risk-Neutral PDF and its Moments

Holding volatility constant, the price of a call option with strike price X can be written in terms of the probability density function (PDF) for the underlying asset, in this case the foreign exchange rate. Cox and Ross (1976) derive the following equation

$$(7) \qquad C(X) = e^{-r \cdot T} \cdot \int_X^{\infty} (S - X) \cdot f(S) dS$$

where $T = \dfrac{t}{365}$, S for our application is the spot exchange rate, and $f(S)$ is the risk-neutral density function from which S will be drawn at the option's expiration. Breeden and Litzenberger (1978) noted that the PDF could be recovered directly by differentiating the above equation twice.

$$(8) \qquad \frac{\partial^2 C(X)}{\partial X^2} = e^{-r \cdot T} \cdot f(S)$$

Differentiating equation (7) a single time would yield an expression involving the cumulative distribution function (CDF).

As discussed in Chang and Melick (1999), equation (7) or equation (8) is used in every recovery of the risk-neutral PDF.[1] A more recent survey of the various numerical methods used to implement the recovery can be found in Bliss and Panigirtzoglou (2002). One class of methods posits a particular functional form for the PDF and estimates the parameters of the PDF by minimizing the difference between actual and predicted option prices using equation (7). Melick and Thomas (1997) provide an example of this technique. Of late, however, the literature seems to be settling on methods that involve differentiating the function that relates a call's option price to its strike price, a la equation (8). In this approach, option prices across discrete

[1] Although not explicitly in recoveries of the stochastic process that governs tick by tick moves in the underlying asset price. See Bates (1996a) for an example of a recovery of the asset price's stochastic process rather than the density function from which the asset price will be drawn at expiration.

strike prices are used to construct a smooth curve that relates the option price to the strike price. This curve is then differentiated (usually numerically) once to recover the CDF and twice to recover the PDF. This technique was pioneered by Shimko (1993) in an application to options on equities and first applied to the OTC currency option markets by Malz (1996).

Implementations of this differentiation method vary in the ways in which the smooth call price function is generated. Most authors advocate first smoothing option prices in (delta, volatility) space and then converting to (strike price, option price) space to differentiate. Bliss and Panigirtzoglou (2004) extol the virtues of this approach.

In what follows, we smooth in both (delta, volatility) space and in (strike price, option price) space to recover two estimates of both the PDF and CDF. We then demonstrate that for the purposes of extracting moments or percentiles from the PDF or CDF, it makes remarkably little difference which smoothing technique is used. Our first technique follows what has become the standard approach and fits a cubic spline to the option prices in (delta, volatility) space.[2] We depart from the standard approach by not adding two pseudo-data points at a low and high delta to contain the extent of the volatility smile. (We will follow this strategy with our second technique.) The cubic spline gives us a smooth function that is then evaluated at 15,000 evenly spaced points and each point is converted from (delta, volatility) space to (strike price, option price) space using equations (1) and (2). The smooth curve in (strike price, option price) is then numerically differentiated using Richardson's method (Press et al (1992) page 183) to obtain the CDF and the PDF. The four panels of Figure 3 show the steps in the process using the example data found in Table 2. In each panel, the points corresponding to the observed option prices are plotted as squares.

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[2] The spline is fit using IMSL Fortran routine DCSDEC imposing the restriction that the second derivative of the spline equal zero at the end points. This is known as a "natural" spline. See de Boor (1978). Unlike Bliss and Panigirtzoglou (2004), we do not add pseudo data points to the volatility smile to force the smile to flatten out beyond the observed option prices, although we will follow this advice in our second technique.

Our second technique first adds two pseudo data points to the observed option prices. These data points are at deltas of 99 and 1 and have volatilities equal to the observed volatilities at 90 and 10 delta respectively. These seven data points in (delta, volatility) space are then converted into (strike price, option price) space where they are used to fit a cubic spline.[3] This is a departure from the standard approach that fits the spline in (delta, volatility) space. The first and second derivatives of the spline in (strike price, option price) space are then evaluated at 15,000 evenly spaced points to recover the CDF and PDF.[4] The four panels of Figure 4 show the steps in this second technique, again using the example data found in Table 2. As for Figure 3, in each panel the points corresponding to the observed and pseudo option prices are plotted as squares.

Despite the differences between the PDFs plotted in Figures 3 and 4, the two techniques for recovering the CDF and the PDF are essentially indistinguishable in terms of the percentiles and moments that are calculated from the CDF and PDF. This is demonstrated in Table 3, which compares correlations in the moments and percentiles across the two techniques. In short, for our purposes it does not matter which splining method is used to recover the CDF and PDF. In the work that follows, we use moments and percentiles derived from the spline in (strike price, option price) space.

It is worth remembering that the recovered CDFs and PDFs are risk-neutral so that they combine both the actuarial (often called subjective) assessments of market participants about future exchange-rate movements as well as preferences towards risk. A simple analogy with fire insurance helps to clarify the issue. If we observe an increase in the premium paid by a homeowner for fire insurance we do not know if this is due to the homeowner now viewing a fire

[3] For this spline we use IMSL Fortran routine DCSCON, which preserves the concavity of the data (Irvine (1986)). Concavity is an important consideration for option prices.

[4] Since the spline coefficients are known, the evaluation of the derivatives is done analytically and very rapidly. Thus, the second technique requires much less computing time than the first technique. Generating CDFs and PDFs for each of the 2536 days in our sample took 2 minutes and 38 seconds using the second technique. The first technique, which uses numerical derivatives and must first convert the 15,000 points from (delta, volatility) space to (strike price, option price) space took just over 35 minutes.

as a more likely event or due to the homeowner revising her view of the potential losses associated with a fire. In the same way, if we observe a rightward shift in a recovered PDF we do not know if this is due to market participants now viewing a dollar appreciation as a more likely event or due to market participants revising their views of the potential losses associated with a dollar appreciation.

The inability to disentangle actuarial probabilities from preferences toward risk opens the question of the usefulness of the recovered CDFs and PDFs. Especially in applications to foreign exchange, there are several reasons why the recovered risk-neutral CDFs and PDFs will be very useful and might even be quite close to the actuarial CDFs and PDFs. First, if markets are fairly competitive, then any premiums paid for risk are likely to be small. Continuing the fire insurance analogy, if there are many companies offering to underwrite fire insurance, the risk-premium paid by the homeowner may be bid down to almost zero. Assuming such a competitive market is clearly unrealistic for the oft-studied equity markets, where only a few large investment banks write index options, (see Bates (2006)), but may well be appropriate for the foreign exchange market. The dominant position in equities is a long position, with investors having to pay a substantial premium to hedge against a sharp decline in equity prices. However, in foreign exchange those that are exposed in the event of a sharp depreciation of the dollar are much more likely to be roughly equal in size to those exposed in the event of a sharp appreciation of the dollar. Thus it is likely that if neither side dominates the market then the risk premium will be small, especially with many investment banks willing to write options on foreign exchange. In terms of a CAPM framework, the risk premium will be small the closer the beta on foreign exchange is to zero.

Empirically, Craig and Keller (2004) find no evidence of a risk premium in the foreign exchange options market. The same is true for Sarwar (2001) in an investigation of foreign exchange options traded on the Philadelphia Stock Exchange. However, Low and Zhang (2005) find risk premia in OTC foreign exchange options. Based on calibrations, Bates (1996b) argues that it is "unlikely that the risk neutral and actual parameters would deviate substantially." (page 70.) In short, the empirical evidence is mixed.

However, even if the risk premium in foreign exchange is substantial, the recovered risk-neutral CDFs and PDFs are still of great interest in a study of the effects of intervention or other variables. Understanding the impact of central bank intervention is of primary importance, at a first cut it may not be of great concern whether the intervention operates by changing market participants' views of likely future movements in exchange rate moments or by changing market participants'attitudes towards risk. Moreover, risk-aversion parameters are likely to change rather slowly over time, implying that comparisons of daily changes in risk-neutral CDFs and PDFs are quite likely to yield good measures of changes in the actuarial CDFs and PDFs.[5]

III. Data and Estimation Strategy

We obtained indicative quotes from J.P. Morgan on the one-month yen/dollar forward rate, a one-month at-the-money option, one-month 25-delta strangle and risk-reversal, and one-month 10-delta strangle and risk-reversal for every business day from January 24, 1996 through November 4, 2005. As mentioned above, an example of these quotes is shown in Table 2. These quotes are made at noon in Tokyo. Data on Japanese intervention is taken from the Ministry of Finance web site.[6] During the period of our study, U.S. monetary authorities intervened only once. We do not use this single episode in our analysis. From the BIS database we obtained daily data on rates paid on one-month dollar deposits in London and one-month yen deposits in Tokyo. From Money Market Services we obtained data from 1996 through 1999 on the surprise component of the data releases shown in Table 4 Data on the surprise component of these releases from 2000 through 2005 were collected from Bloomberg.

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[5] See Piazzesi and Swanson (2004) for a discussion of differencing as a means of eliminating the risk premium.

[6] www.mof.go.jp/english/e1c021.htm

Following the method described in Section II, we calculated a PDF for each of the 2536 days in our sample. From these PDFs we calculated the second and third moments - variance and skewness, where a positive value for skewness indicates an extended right tail for a PDF measured in yen per dollars. We also use the ATM implied volatility and the 25-delta risk reversal as alternate measures of dispersion and skewness. Although perhaps more difficult to interpret, these measures are immediately available; unlike variance and skewness which can only be calculated after the PDFs have been estimated.

Our goal of understanding the impact of intervention on the higher moments of the expected exchange rate distribution is complicated by the possibility that the moments and intervention are determined as part of a simultaneous system. More plainly, it is clearly possible that policy authorities respond to changes in the variance or skewness for the expected future exchange rate when they intervene. Moreover, the variance and skewness are also likely to respond to the intervention by the policy authorities. As emphasized by Neely (2005), this simultaneous determination makes it much more difficult for the econometrician to isolate the effect of intervention on the moments of the exchange rate distribution. The problem is illustrated by the simple two-equation system considered by Galati, Melick and Micu (2005).

(9) $$M_t = a_1 + a_2 \cdot I_t + a_3 \cdot X_t + \varepsilon_t$$

(10) $$I_t = b_1 + b_2 \cdot M_t + b_3 \cdot Y_t + \eta_t$$

In this system, M_t is the moment under consideration (for example the variance), I_t is the intervention undertaken by the monetary authority, and X_t and Y_t are exogenous variables such as macroeconomic data releases or interest differentials that affect the moment and the intervention decision. Equation (9) is of greatest interest for our paper as it captures the effect of intervention on the moment. Equation (10) is a reaction function that characterizes how the monetary authorities respond to the moment – for example intervening to calm disorderly markets. Estimating either equation (9) or (10) by OLS will lead to biased estimates of the coefficients of interest due to the fact that $\text{cov}(I_t, \varepsilon_t) \neq 0$ and $\text{cov}(M_t, \eta_t) \neq 0$.

Unfortunately, a simultaneous estimation of the two-equation system runs the risk that any misspecification in one of the equations will contaminate the estimates of the other equation. Various solutions to the problem have been proposed from estimating equations that only use lagged values of M_t and I_t on the right-hand side to GMM and SMM methods (Kearns and Rigobon (2005). We follow the lead of Galati, Melick and Micu (2005) and use OLS to estimate the modified reaction function

(11) $I_t = b_1 + b_2 \cdot M_{t-1} + b_3 \cdot Y_t + \gamma_t$

that uses only lagged values of the moments. We then estimate what is of greatest interest, equation (9), using two stage least squares (TSLS) to replace I_t on the right-hand side of equation (9) with its predicted value, $\hat{I}_t$ from the OLS estimation of equation (11). This procedure requires that the fit of equation (11) (the first stage regression) be sufficient so that $\text{cov}\left(I_t, \hat{I}_t\right)$ be far enough away from zero to ensure that the instrument is relevant. That is, we want to make sure that our TSLS estimates do not suffer from the problem known as weak instruments.

We estimate a reaction function that is more realistic than the simple specification of equation (11). Following the lead of Almekinders and Eijffinger (1996), we posit that the monetary authority intervenes to lean against the wind and to calm disorderly markets by attempting to counter sharp movements in the higher moments of the PDF. To implement the leaning against the wind strategy we construct the following variables that measure how far the yen/dollar forward rate is away from its 7-day moving average, both when the yen is appreciating and when the yen is depreciating.

$$devtara_t = \begin{cases} \ln(F_t) - \frac{1}{7}\cdot\sum_{i=1}^{7}\ln(F_{t-i}) & if \;\; F_t \le F_{t-1} \\ 0 & otherwise \end{cases}$$

$$devtard_t = \begin{cases} \ln(F_t) - \frac{1}{7}\cdot\sum_{i=1}^{7}\ln(F_{t-i}) & if \;\; F_t > F_{t-1} \\ 0 & otherwise \end{cases}$$

To measure disorderly markets, we construct several variables based on the variance and skewness of the PDF. In this construction, we also allow for an asymmetric response of the monetary authorities depending on whether the yen is appreciating or depreciating. For the variance we create

$$highva_t = \begin{cases} v_t - (\bar{v} + 1.5\cdot\sigma_v) & if \;\; v_t - (\bar{v} + 1.5\cdot\sigma_v) > 0 \;\; and \;\; F_t \le F_{t-1} \\ 0 & otherwise \end{cases}$$

$$highvd_t = \begin{cases} v_t - (\bar{v} + 1.5\cdot\sigma_v) & if \;\; v_t - (\bar{v} + 1.5\cdot\sigma_v) > 0 \;\; and \;\; F_t > F_{t-1} \\ 0 & otherwise \end{cases}$$

where $\bar{v}$ and σ_v are the mean and standard deviation for the variance over our entire sample. Note that implicit in these variables is the assumption that markets are judged to be disorderly if the variance is more than 1.5 standard deviations above the historical mean.

For skewness we calculate similar variables, although in this case markets can be judged to be disorderly if skewness is either high or low by historical standards.

$$highskwa_t = \begin{cases} skw_t - \left(\overline{skw} + 1.5 \cdot \sigma_{skw}\right) & if \;\; skw_t - \left(\overline{skw} + 1.5 \cdot \sigma_{skw}\right) > 0 \;\; and \;\; F_t \leq F_{t-1} \\ 0 & otherwise \end{cases}$$

$$highskwd_t = \begin{cases} skw_t - \left(\overline{skw} + 1.5 \cdot \sigma_{skw}\right) & if \;\; skw_t - \left(\overline{skw} + 1.5 \cdot \sigma_{skw}\right) > 0 \;\; and \;\; F_t > F_{t-1} \\ 0 & otherwise \end{cases}$$

$$lowskwa_t = \begin{cases} skw_t - \left(\overline{skw} - 1.5 \cdot \sigma_{skw}\right) & if \;\; skw_t - \left(\overline{skw} + 1.5 \cdot \sigma_{skw}\right) < 0 \;\; and \;\; F_t \leq F_{t-1} \\ 0 & otherwise \end{cases}$$

$$lowskwd_t = \begin{cases} skw_t - \left(\overline{skw} - 1.5 \cdot \sigma_{skw}\right) & if \;\; skw_t - \left(\overline{skw} + 1.5 \cdot \sigma_{skw}\right) < 0 \;\; and \;\; F_t > F_{t-1} \\ 0 & otherwise \end{cases}$$

Descriptive statistics for the variables used in the reaction function are found in Table 5. Separate statistics are provided for yen purchases $\left(Intb_t\right)$ and yen sales $\left(Ints_t\right)$. As can be seen in Table 5, over our sample the largest purchase of yen by the Ministry of Finance (MoF) amounted to ¥2.62 trillion (April 1998) while the largest sale amounted to ¥1.67 trillion (January 2004). The vast majority of interventions were yen sales (164 out of 170). Across the 164 sales, and not shown in Table 5, the average sale amounted to roughly ¥0.33 trillion and across the 6 purchases the average purchase amounting to roughly ¥0.68 trillion.

While the yen was appreciating, the largest deviation from its seven-day moving average was a bit more than 11 percent, while depreciating the largest deviation was more than 7 percent. The variance of the one-month PDF reached as high as 1.4 when the yen was appreciating and 0.4 when the yen was depreciating. The skewness of the one-month PDF reached as high as 1.8 when the yen was appreciating and 1.3 when the yen was depreciating. When the yen was appreciating, skewness fell as low as -1.1 and fell as low as -1.2 when the yen was depreciating.

The surprises in the macroeconomic data releases are measured in percentage points, with the exception of the trade releases and the Tankan survey. Thus, market expectations for the headline CPI were as much as 0.2 percentage points below the actual release and as much as 0.3 percentage points above the release. As it turns out, these variables were almost always insignificant in our subsequent regressions and in the end omitted from our final specifications.[7]

IV. Estimation Results

To arrive at a final specification for the reaction function, we used a general to simple estimation strategy, beginning with five lags of each of the variables shown in Table 5 and eliminated insignificant variables while making sure that the residuals remained well behaved. In order to allow for asymmetric behavior on the part of the MoF, we estimated a reaction function separately for yen purchases and yen sales, with final specifications displayed in Table 6. Several results are of interest. First, we have no success in explaining yen purchases against dollars by the MoF. The explanatory power for this reaction function, measured by an $\overline{R}^2$ of roughly 0.007, is extremely low. This is not surprising given that the MoF purchased yen on only 6 of the 2536 days in our sample. Aside from lagged purchases, the only statistically significant variable in the regression is $devtara_t$. Its coefficient of –0.47 implies that when the yen is appreciating, a one percentage point increase in the deviation of the 30-day forward rate from its 7-day moving average is associated with a MoF purchase of ¥5 billion. Thus, for yen purchases the MoF appears to be leaning with the wind.

[7] The only macroeconomic variable that elicited a statistically significant response by the MoF is a surprise move in the target federal funds rate by the FOMC. According to our preliminary specification, an unexpected 25 basis point decrease in the target rate is associated with an ¥82 billion sale of yen by the MoF, an attempt to counter any appreciation of the yen triggered by the decline in U.S. interest rates. However, the result is not of major economic importance, given the average sale of ¥328 billion during the period. In addition, the presence of macroeconomic variables in the reaction function would require that they be treated as instruments when estimating the effect of intervention on the moments (equation 11). We did not feel comfortable with the assumption that the fed funds surprise could be treated as exogenous.

Fortunately, results are much better for describing MoF sales of yen. An $\overline{R}^2$ of 19 percent is respectable, and several coefficients are statistically significant and economically reasonable. When the yen is appreciating, a one percentage point increase in the deviation of the 30-day forward rate from its 7-day moving average is associated with a MoF sale of ¥11 billion. – the MoF sells yen to offset the appreciation of the yen. However, the result is not very significant in an economic sense. A one percentage point move away from the 7-day moving average is quite large, yet this triggers an extremely modest amount of intervention. To put the ¥11 billion in context, when the MoF sold yen, the average sale was ¥328 billion.

In quiescent times, when variance or skewness is not particularly high, the MoF responds to an increase in variance (Δv_t) or an increase in skewness (Δskw_t) by selling yen. Although statistically significant, the response is economically insignificant. A one standard deviation increase in variance (skewness) triggers a ¥6 (¥8) billion sale. Calculating the response of the MoF to changes in the higher moments during unsettled times requires combining the coefficients on Δv_t and $highva_t$ as well as the coefficients on Δskw_t and $highskwa_t$. A one standard deviation increase in the variance of the PDF when the variance is already high and when the yen is appreciating is associated with a miniscule ¥0.04 billion sale. A one standard deviation increase in the skewness of the PDF when the skewness is already high and when the yen is appreciating ($highskwa_t$) is associated with a ¥17 billion sale.

Estimation of the reaction functions like those in Table 6, involving only lagged values of the exchange rate and lagged values of the higher moments, allows us to turn to the question of greatest interest – the effect of intervention on the exchange rate moments. However, it is not possible to proceed with an estimation of the effect of yen purchases on the moments, given that our instruments for yen sales (the right hand side variables in Table 6) are so weak. Stock, Wright and Yogo (2002) provide threshold values for the F test of overall significance for a first stage regression necessary to avoid weak instrument problems. We have 15 instruments for both yen purchases and sales and the threshold F statistic according to Stock, Wright and Yogo is 26.80 in such a situation. As can be seen at the bottom of Table 6, the F statistic for purchases is only 2.2, while for sales it is a healthy 44.1. Thus, we can only proceed with an analysis of the effect of yen sales on the higher moments.

As for the reaction function, we followed a general to simple estimation strategy, arriving at the specification displayed in Table 7 for the variance and the specification displayed in Table 8 for the skewness. Both tables compare OLS estimation with TSLS estimation that replaces actual sales with their predicted values generated with the coefficients in Table 6. Interestingly, Hausman tests were unable to reject the null that intervention is exogenous with respect to both the variance and skewness, suggesting that the OLS estimates are preferred to the less efficient IV estimates.

With regard to the effect of intervention on the variance of the PDF, the coefficient estimates in Table 7 present a relatively benign view. The OLS estimates indicate that a ¥1 trillion sale decreases Δv_t by roughly 1/4th of a standard deviation. The IV estimates for yen sales imply a larger effect, both statistically and economically. The IV estimates indicate that a ¥1 trillion sale decreases the change in variance (Δv_t) by roughly 2/3rd of a standard deviation. In short, the evidence on intervention's effect on the variance of the PDF is less than compelling, either in a statistical or economic sense. This finding of little or no effect can be reconciled with the previous literature quite easily, as earlier findings of a significant association between intervention and volatility were time and currency pair dependent. Over our period, the MoF was almost always operating unilaterally and often attempting to counteract a relatively restrictive stance for monetary policy. These are not the preconditions for a successful intervention.

The same benign view holds for skewness. The OLS results presented in Table 8 indicate that MoF sales decrease skewness (heighten the view that the yen will appreciate). Thus, the market appears to treat intervention as a confirmation of the prevailing view. Rather than reversing market views, intervention appears to strengthen market views. While the OLS estimates are only borderline statistically significant, they imply that a ¥1 trillion sale leads to a 1/3rd of a standard deviation decrease in skewness. IV estimates of the effect of intervention on skewness are statistically insignificant.

Given the unique quoting conventions of the OTC market, Tables 9-11 answer the question of whether or not it is necessary to first recover the PDFs from the OTC option prices in order to assess the impact of intervention on market expectations. The short answer is no. Figures 5 and 6 demonstrate that there is a very close connection between the variance of the PDF and the readily available ATM implied volatility and an equally close connection between the skewness of the PDF and the readily available 25-delta risk-reversal price. In this light, Tables 9-11 re-estimate the MoF reaction function (Table 9) and the impact of intervention on dispersion and skew (Tables 10 and 11) using ATM implied volatility instead of the variance of the PDF and the 25-delta risk reversal instead of the skewness of the PDF.

Not surprisingly, the results are almost identical after adjusting for the units in which the different variables are measured. As in Table 6, we have no ability to characterize yen purchases in Table 9. Explanatory power is again incredibly low and aside from lagged intervention the only statistically significant variable in the regression is $devtara_t$. Its coefficient of –0.48 again implies a leaning with the wind behavior for yen purchases. More specifically, when the yen is appreciating, a one percentage point increase in the deviation of the 30-day forward rate from its 7-day moving average is associated with a MoF purchase of ¥5 billion.

As before, results are much better for describing MoF sales of yen. As in Table 6, the $\overline{R}^2$ is much higher for sales and several coefficients are statistically significant and economically reasonable. When the yen is appreciating, a one percentage point increase in the deviation of the 30-day forward rate from its 7-day moving average is associated with a MoF sale of ¥10 billion, compared to an estimate of ¥11 billion in Table 6. Again, the result is not very significant in an economic sense.

When dispersion or directionality is not particularly high, the MoF responds to an increase in dispersion (Δiv_t) or an increase in directionality ($\Delta rr25_t$) by selling yen. Although statistically significant, the response is economically insignificant. A one standard deviation increase in ATM implied volatility triggers a ¥7 billion sale, as does a one standard deviation increase in the 25-delta risk reversal. Both results are remarkably close to the estimates in Table 6. A one standard deviation increase in implied volatility when volatility is already high and when the yen is appreciating is associated with a small ¥1 billion sale, a bit larger than the miniscule sale from Table 6. A one standard deviation increase in the risk reversal when the risk reversal is already high and when the yen is appreciating ($highrr25a_t$) is associated with a ¥17 billion sale, almost identical to the effect from Table 6.

With regard to the effect of intervention on dispersion, the coefficient estimates in Table 10 present a view that is in line with the findings from Table 7 – intervention has little effect. The OLS estimates indicate that a ¥1 trillion sale decreases Δiv_t by roughly $1/4^{th}$ of a standard deviation. As before, the evidence on intervention's effect on dispersion is less than compelling, with large interventions having a fairly modest effect both in a statistical or economic sense.

The OLS results presented in Table 11 indicate that MoF sales heighten the view that the yen will appreciate. Thus, as in Table 8, the market appears to treat intervention as a confirmation of the prevailing view. Even so, the OLS estimates are only borderline statistically significant and they imply that a ¥1 trillion sale leads to a $1/3^{rd}$ of a standard deviation decrease in the risk reversal.

All told, the evidence presented in Tables 6-11 suggests that intervention has a marginal effect on the higher moments of the expected exchange rate. Statistical significance is borderline, and economic effects tend to be small. This finding may be the result of the combination of a few episodes in which intervention had a meaningful effect coupled with a majority of episodes in which it did not. That is, it could be the case that almost all of the time, intervention has no discernable effect on the higher moments, however, in a few instances intervention and the higher moments move together – generating both the borderline statistical significance and the economically small impact.

IV.1 Event Counts

An alternative econometric approach that may be less sensitive to a handful of influential observations is to follow the lead of Humpage (1999, 2000) and use nonparametric techniques that rely on event counts.[8] To do so, we define four specific success criteria and count the number of corresponding successes in our sample. Then, following Henriksson and Merton (1981) and Merton (1981), we model success as a hypergeometric random variable and test whether the observed the number of successes exceeds the expected number under that distribution.[9] The hypergeometric distribution fits our success counts because it does not require individual events to be independent, nor does the distribution depend on a presumed probability of an individual success. Moreover, the moments of the hypergeometric distribution are defined in a manner that compares days of intervention against the entire sample, rather than against days of no intervention.

We conceptualize the MoF as trading on private information and revealing that information to the market through its trades. If this information is useful to price discovery, knowledge that the MoF is buying or selling dollars will induce traders to alter the probabilities that they attach to future exchange-rate changes. MoF interventions then will successfully predict changes in the distribution of future exchange rates, and we conclude—*ala* Henriksson and Merton—that MoF intervention has forecast value. If, on the other hand, the observed success

[8] Chaboud and Humpage (2005) use this technique to investigate the effects of Japanese intervention on spot exchange rates
[9] Leahy (1995) first applied this technique to an analysis of profits from U.S. intervention.

count does not exceed the expected value, we conclude that MoF intervention lacks forecast value.

We specify three success criteria, each in terms of the higher moments of the expected future exchange-rate distribution. Our first criterion counts a MoF intervention as successful if it reduces the variance of the distribution of future exchange-rate changes. That is:

$$(12)\qquad SC1_t = \begin{cases} 1 \text{ if } \left|I_t\right| \neq 0 \text{ and } \sigma_t < \sigma_{t-1}, \text{ and} \\ 0, \text{ otherwise.} \end{cases}$$

In equation 12, I_t refers to Japanese intervention day t with positive (negative) values indicating sales (purchases) of U.S. dollars, and σ_t refers to the variance of the expected distribution of the yen per dollar exchange rate in one month.

Our second success criterion is similar to the first, except that we express success in terms of the implied volatility (IV) of the expected future exchange-rate process.

$$(13)\qquad SC2_t = \begin{cases} 1 \text{ if } \left|I_t\right| \neq 0 \text{ and } IV_t < IV_{t-1}, \text{ and} \\ 0, \text{ otherwise.} \end{cases}$$

Our third success criterion counts a success if official MoF dollar sales skew the distribution of future expected exchange rate to the left, implying a higher probability of a dollar depreciation or a smaller probability of a dollar appreciation.

$$(14)\qquad SC3_{(sell),t} = \begin{cases} 1 \text{ if } \mathrm{I_t} > 0 \text{ and } Sk_t < Sk_{t-1}, \text{ and} \\ 0, \text{ otherwise.} \end{cases}$$

Our last criterion counts a success if official MoF dollar purchases skew the distribution to the right, implying a higher probability of a dollar appreciation or a smaller probability of a dollar depreciation.

$$(15)\qquad SC3_{(buy),t} = \begin{cases} 1 \text{ if } \mathrm{I_t} < 0 \text{ and } Sk_t > Sk_{t-1}, \text{ and} \\ 0, \text{ otherwise.} \end{cases}$$

We keep our event window limited to a single day. In doing so, the chance that we might fail to count an intervention as successful if it induces a change in expectations beyond day *t* seems remote.[10] Chang and Taylor (1998), Cheung and Chinn (2001), and Dominguez (2003a), among others, find that exchange markets begin to respond to intervention within minutes or hours, not days. So, our success criteria should capture this movement even if complete adjustment extends beyond a single day. Alternatively, we may count an intervention successful even though the exchange-rate movement that led to that conclusion subsequently disappears. This occurrence is more problematic. Opening the event window, however, quickly causes overlap among interventions, making inferences about individual successes impossible. Consequently, we keep the event window narrow.

IV.2 Count Results

We find that the Japanese MoF lacked forecast value with respect to all of our success criteria. Table 12 presents our results. The first column indicates specific success criteria. The next column shows the number of interventions. During our sample period, the Japanese MoF intervened on 170 days, of which 164 were dollar purchases and 6 were dollar sales. The next two columns in table 12, respectively, count successes for each corresponding criterion and express that number as a percent of the total interventions. Under success criteria SC1, for example, 84 (or 49.4%) of the 170 interventions were successful.

The two columns headed "virtual successes" count the number of times that we observed the data corresponding to the success criteria whether or not the MoF intervened. Using success criteria SC1, for example, the volatility of the option price data fell between day *t-1* and day *t* on 1344, or 53.0% of the 2535 days in the sample, whether or not intervention took place.

The last three columns of table 12 refer to the hypergeometric distribution. Columns 7 and 8 show the expected numbers of successes and their standard deviations assuming that success is a hypergeometric random variable. In our sample, for example, we expect to observe 90.1 successes with a standard deviation of 6.3 under success criterion SC1. Our null hypothesis compares actual and expected successes. The last column of table 12 shows the p-value

[10] Goodhart and Hessse (1993) and Fatum and Hutchison (2002, 2006) allow for wider event windows.

associated with the probability of observing a greater number of successes than we actually observed. A low p-value indicates positive forecast value. Similarly, a very high p-value indicates “negative” forecast value and implies that the market could profit on average from taking a position opposite that of the monetary authority. Under success criterion SC1, for example, the p-value of 0.815 indicates that the MoF lacked forecast value with respect to declines in the variance of the expected future exchange-rate distribution.

Under all of our other criteria, the Japanese MoF lacked forecast value. The number of official Japanese dollar sales (6) is too small to make reasonable inferences, so we concentrate on official dollar purchases. With respect to all of the criteria—except $SC3_{(sell)}$—the observed number of successes always falls within one standard deviation of the expected value.

IV.3 Conditioning Success

The frequencies in table 12 correspond to unconditional probabilities. Success, however, may depend on specific attributes of the intervention process or environment. To test this conjecture, we run three probit regressions each using one of the success criteria as the bivariate dependent variable. We condition each success count on eight independent variables (see table 13). We include the amount of an intervention on the assumption that larger interventions affect market expectations more forcefully. We also expect that infrequent operations—those with a longer lapse of time since the previous intervention—will have a stronger expectations effect. In contrast, consecutive interventions may not convey new information to the market. A shift in the type of intervention—from purchases to sales—might contain new information, as might knowledge that the intervention is coordinated with the United States. Finally, we consider a dummy variable for 1999, 2000, and 2003 as a test for a differential impact from secret intervention. According to Beine and Lecourt (2004), the MoF conducted a substantially higher proportion of its interventions secretly in 1999, 2000 and 2003 than in all other years.

Table 13 presents the results of our probit regressions. With respect to the success criteria based on the variance (SC1) and on the implied volatility (SC2), the set of regressors jointly and individually lack explanatory power. With respect to the success criteria based on the skewness measure (SC3), where we combine purchases and sales of dollars, the regressors have explanatory power. This stems primarily from the size of an intervention, which is weakly significant. The signs on the coefficients associated with the amount of intervention and the lapse of time between interventions, however, are negative, indicating that large infrequent interventions reduce the likelihood of a success according to criterion SC3. This suggests that large interventions may induce the market to sell dollars when the MoF buys dollars, or that large interventions have negative forecast value.

V. Conclusion

Option prices are extremely useful when studying the effect of sterilized intervention in the foreign exchange market, as they allow for the estimation of the risk-neutral PDF from which market participants expect the future exchange rate to be drawn. This paper demonstrates how to recover the risk-neutral PDF from OTC options prices and argues that any differences between the risk-neutral and subjective (or actuarial) PDF are likely to be small and, even if not small, unimportant for studying the effects of intervention. In an application to intervention by the MoF from 1996 through 2005, we find little or no systematic impact of intervention on the higher moments of the PDF. This result is probably not surprising, given that the intervention was almost never coordinated, never publicly announced, and often at odds with the relatively tight monetary policy in place in Japan over the period. The MoF almost always sold yen in an effort to resist an appreciation of the yen against the dollar, an exercise unlikely to succeed given the extraordinarily low inflation rate in Japan over this period. Thus, our findings are consistent with the previous literature, where significant effects for intervention on the higher moments are conditional upon coordinated, publicly announced purchases or sales that are consistent with the stance of monetary policy.

References

Almekinders, Geert J., and Sylvester C.W. Eijffinger (1996) "A Friction Model of Daily Bundesbank and Federal Reserve Intervention", *Journal of Banking and Finance* 20(8), pp. 1365-1380.

Baillie, Richard and Owen Humpage (1992) "Post-Louvre intervention: did target zones stabilise the dollar?", *Federal Reserve Bank of Cleveland Working Paper* No. 9203

Bates, David S. (1996a) "Jumps and Stochastic Volatility: Exchange Rate Processes Implicit in Deutsche Mark Options". *Review of Financial Studies* 9(1), pp. 69-107.

Bates, David S. (1996b) "Dollar Jump Fears, 1984-1992: Distributional Abnormalities Implicit in Currency Futures Options", Journal of International Money and Finance 15(1), pp. 65-93.

Bates, David S. (2006) "The Market for Crash Risk". Mimeo, University of Iowa (earlier version available as NBER Working Paper 8557, (2001)).

Beine, Michel, Jérôme Lahaye, Sébastien Laurent, Christopher J. Neely, and Franz C. Palm (2006) "Central Bank Intervention and Exchange Rate Volatility, Its Continuous and Jump Components", *Federal Reserve Bank of St. Louis Working Paper* 2006-031B

Beine, Michel, Sébastien Laurent and Christelle Lecourt (2003) "Central Bank Intervention and Exchange Rate Volatility: Evidence from a Switching Regime Analysis, *European Economic Review*, 47(5), 891-911.

Beine, Michel, Christelle Lecourt (2004) "Reported and Secret Interventions in the Foreign Exchange Market." *Finance Research Letters*, 1(4), 215-225.

Bliss, Robert R. and Nikolaos Panigirtzoglou (2002) "Testing the Stability of Implied Probability Density Functions" *Journal of Banking and Finance* 26(2-3), pp. 381-422.

Bliss, Robert R. and Nikolaos Panigirtzoglou (2004) "Option-Implied Risk Aversion Estimates" *Journal of Finance* 59(1), pp. 407-446.

Breeden, Douglas T. and Robert H. Litzenberger (1978) "Prices of State Contingent Claims Implicit in Option Prices". *Journal of Business*, 51(4) pp. 621-651.

Bonser-Neal, C., Tanner, G. (1996) "Central bank intervention and the volatility of foreign exchange rates: evidence from the options market", *Journal of International Money and Finance* 15(6) pp. 853-878.

Castren, Olli (2004) "Do options-implied RND functions on G3 currencies move around the times of interventions on the JPY/USD exchange rate?", ECB Working Paper No. 410, November 2004

Chaboud, A. and Humpage, O. (2005) "An Assessment of the Impact of Japanese Foreign Exchange Interventions: 1991 – 2004", Board of Governors of the Federal Reserve System *International Finance Discussion Papers*, No. 824 (January).

Chang, P. H. Kevin and William R. Melick (1999) "Background Note", *Estimating and Interpreting Probability Density Functions*, Proceedings of a Workshop held at the Bank for International Settlements, pp. 1-10.

Chang Y. and Taylor, S. J. (1998) "Intraday Effects of Foreign Exchange Intervention by the Bank of Japan", *Journal of International Money and Finance*. 17(1) pp. 191-210.

Cheung, Y. and Chinn, M. D. (2001) "Currency Traders and Exchange Rate Dynamics: A Survey of the US Market", *Journal of International Money and Finance*. 20(4) pp. 439-471.

Cox, John C. and Stephen A. Ross (1976) "The Valuation of Options for Alternative Stochastic Processes". *Journal of Financial Economics* 3(1) pp. 145-166.

Craig, Ben R. and Joachim G. Keller (2004) "The forecast ability of risk-neutral densities of foreign exchange", *Federal Reserve Bank of Cleveland Working Paper* 0409.

de Boor, Carl (1978), *A Practical Guide to Splines*, Springer-Verlag, New York.

Disyatat, Piti and Gabriele Galati (forthcoming) "The effectiveness of foreign exchange intervention in emerging market countries: evidence from the Czech koruna", *Journal of International Money and Finance*.

Dominguez, Kathryn M. (1993) "Does central bank intervention increase the volatility of foreign exchange rates?", *NBER Working Paper* No. 4532.

Dominguez, Kathryn M, (1998) "Central bank intervention and exchange rate volatility", *Journal of International Money and Finance* 17(1) pp. 161-190.

Dominguez, Kathryn. M. (2003a) "The Market Microstructure of Central Bank Intervention", *Journal of International Economics*, 59(1) pp. 25-45.

Dominguez, Kathryn M. (2003b) "When do central bank interventions influence intra-daily and longer-term exchange rate movements" *NBER Working Paper* No. 9875, July.

Fatum, R., and Hutchison, M. (2002) "ECB Foreign-Exchange Intervention and the EURO: Institutional Framework, News and Intervention", *Open Economies Review*, 13(4) pp. 413-425.

Fatum, R., and Hutchison, M. (2006) "Effectiveness of Official Daily Foreign Exchange Market Intervention Operations in Japan", *Journal of International Money and Finance* 25(2) pp. 199-219.

Frenkel, Michael, Christian Pierdzioch and Georg Stadtmann (2005) "The Effects of Japanese Foreign Exchange Market Interventions on the Yen/U.S. Dollar Exchange Rate Volatility", *International Review of Economics and Finance*, 14 (1), pp. 27-39.

Fratzscher, Marcel (2006) "On the Long-Term Effectiveness of Exchange Rate Communication and Interventions", *Journal of International Money and Finance*, 25 (1), pp. 146-67.

Galati, Gabriele, William Melick and Marian Micu (2005) “Foreign Exchange Market Intervention and Expectations: The Yen/Dollar Exchange Rate”, *Journal of International Money and Finance*, 24(6), pp. 982-1011.

Garman, Mark B. and Steven W. Kohlhagen (1983) “Foreign Currency Option Values”, *Journal of International Money and Finance* 2(3), pp. 231-237.

Goodhart, C. A. E., and Hesse, T. (1993) “Central Bank Forex Intervention Assessed in Continuous Time”, *Journal of International Money and Finance* 12(4) pp. 368-89.

Grabbe, J. Orlin (1983) “The Pricing of Call and Put Options on Foreign Exchange”, *Journal of International Money and Finance* 2(3), pp. 239-253.

Henriksson, R. D., and Merton, R. C. (1981) “On Market Timing and Investment Performance. II. Statistical Procedures for Evaluating Forecasting Skills”, *Journal of Business* 54(4) pp. 513-533.

Humpage, Owen (1999) “U.S. Intervention: Assessing the Probability of Success”, *Journal of Money, Credit, and Banking*, 31(4), pp. 731-747.

Humpage, O. F. (2000) “The United States as an Informed Foreign-Exchange Speculator”, *Journal of International Financial Markets, Institutions, and Money* 10(3-4) pp. 287-302.

Irvine, Larry D., Samuel P. Marin, and Philip W. Smith (1986) “Constrained Interpolation and Smoothing”, *Constructive Approximation*, 2(1) pp. 129-151.

Kearns, Jonathan and Roberto Rigobon (2005) “Identifying the Efficacy of Central Bank Interventions: Evidence from Australia and Japan”, *Journal of International Economics*, 66(1), pp. 31-48.

Kim, Suk Joong and Jeffrey Sheen (2006) “Interventions in the Yen-Dollar Spot Market: A Story of Price, Volatility and Volume”, *Journal of Banking and Finance*, 30(11) pp. 3191-3214.

Leahy, M. P. (1995) “The Profitability of U.S. Intervention in the Foreign Exchange Markets”, *Journal of International Money and Finance* 14(6) pp. 823-844.

Low, Buen Sin and Shojun Zhang (2005) “The Volatility Risk Premium Embedded in Currecny Options”, *Journal of Financial and Quantitative Analysis* 40(4) pp. 803-832.

Malz, Allan M. (1996) “Using Option Prices to Estimate Realignment Probabilities in the European Monetary System: The Case of Sterling-Mark”, *Journal of International Money and Finance* , 15(5), pp. 717-748.

Malz, Allan M. (1997) “Estimating the Probability Distribution of the Future Exchange Rate from Option Prices”, *The Journal of Derivatives* , Winter, pp. 18-36.

Melick, William R. and Charles P. Thomas (1997) “Recovering an Asset’s Implied PDF from Option Prices: An Application to Crude Oil During the Gulf Crisis”. *Journal of Financial and Quantitative Analysis* 32(1), pp. 91-115.

Merton, R. C., (1981) “On Market Timing and Investment Performance. I. An Equilibrium Theory of Value for Market Forecasts”, *Journal of Business* 54(4) pp. 363-406.

Murray, John, Mark Zelmer and Des McManus (1997) “The effect of intervention on Canadian dollar volatility”, in Fenton, P., Murray, J. (Eds.), *Exchange Rates and Monetary Policy*. Proceedings of a Conference Hosted by the Bank of Canada, Ottawa, pp. 311-357.

Neely, Christopher (2005) "An Analysis of Recent Studies of the Effect of Foreign Exchange Intervention" *Federal Reserve Bank of St. Louis Review*, November/December 2005, 87(6), pp. 685-717.

Piazzesi, Monika, and Eric Swanson (2004) “Futures Prices as Risk-Adjusted Forecasts of Monetary Policy”, *National Bureau of Economic Research Working Paper* No. 10547.

Press, William H., Saul A. Teukolsky, William T. Vettering, and Brian P. Flannery (1992) *Numerical Recipes in Fortran: The Art of Scientific Computing*, 2nd Edition, Cambridge University Press, Cambridge.

Sarno, Lucio and Mark P. Taylor (2001) “Official intervention in the foreign exchange market: is it effective and, if so,how does it work?”, *Journal of Economic Literature* 39(3), pp. 839-868.

Sarwar, Ghulam (2001) “Is Volatility Risk for the British Pound Priced in U.S. Options Markets?” *Financial Review* 36(1), pp. 55-70.

Shimko, David (1993) “Bounds of Probability”, *Risk* 6(4), pp. 33-37.

Stock, James H., Jonathan H. Wright, and Motohiro Yogo (2002) “A Survey of Weak Instruments and Weak Identification in Generalized Method of Moments”, *Journal of Business and Economic Statstics* 20(4), pp. 518-529.

Truman, Edwin (2003) “The limits of exchange market intervention” in Bergsten, F.C., Williamson, J. (Eds.), *Dollar Overvaluation and the World Economy*. Institute for International Economics, Washington DC.

Table 1 Turnover in Foreign Exchange Options (Daily Average for the Month of April, Billions of U.S. Dollars)				
	1995	1998	2001	2004
OTC Market	41	87	60	117
Exchanges	4	2	1	2
Source: BIS Triennial Central Bank Survey, March 2005, Table C.2, additional detail provided by BIS				

Table 2 Example OTC Option Quotes and Calculations (JP Morgan, March 12, 1997)				
ATM	$RR_{25\delta}$	$RR_{10\delta}$	$STRG_{25\delta}$	$STRG_{10\delta}$
9.3003	0.0053	0.0151	0.3048	0.7658
Recovered Volatilities				
10 Delta ($V_{10\delta}$)	25 Delta ($V_{25\delta}$)	50 Delta ($V_{50\delta}$)	75 Delta ($V_{75\delta}$)	90 Delta ($V_{90\delta}$)
10.0736	9.6077	9.3003	9.6024	10.0585
Option Prices in terms of Japanese Yen ($F = 122.1009 \quad r^* = 0.5793\, percent \quad t = t' = 30$)				
Strike Price				
126.7566	124.4365	122.1424	119.8963	117.7115
Option Price				
0.1650	0.4949	1.2777	2.7107	4.5551

Table 3 Correlations Between Moments and Percentiles Derived from Splining in (Delta, Volatility) Space and Splining in (Strike Price, Call Price) Space	
Mean	0.9999
Variance	0.9939
Skewness	0.9957
Kurtosis	0.9988
1st Percentile	0.9998
5th Percentile	0.9999+
10th Percentile	0.9999+
25th Percentile	0.9999+
50th Percentile	0.9999+
75th Percentile	0.9999+
90th Percentile	0.9999+
95th Percentile	0.9998
99th Percentile	0.9998

Table 4 Macroeconomic Control Variables	
United States	Japan
Consumer Price Index	Trade Balance
Producer Price Index	Retail Sales
Industrial Production	Tankan Survey
Trade in Goods and Services	
Employment Situation (Unemployment Rate)	
FOMC Target Rate Changes	

Table 5 Descriptive Statistics for Variables Used in Estimating the Reaction Function						
Variable	Obs.	Units	Mean	Std. Error	Minimum	Maximum
$Intb_t$	2536	Trillions of Yen	0.00162	0.05449	0.00000	2.62010
$Ints_t$	2536	Trillions of Yen	-0.02122	0.11619	-1.66640	0.00000
$devtara_t$	2529	Log difference	-0.0022	0.0085	-0.1114	0.0295
$devtard_t$	2529	Log difference	0.0024	0.0076	-0.0747	0.0472
$highva_t$	2536	Yen squared	0.0081	0.0555	0.0000	1.4227
$highvd_t$	2536	Yen squared	0.0066	0.0410	0.0000	0.4394
$highskwa_t$	2536	Yen cubed	0.0281	0.1527	0.0000	1.7993
$highskwd_t$	2536	Yen cubed	0.0198	0.1223	0.0000	1.2630
$lowskwa_t$	2536	Yen cubed	-0.0056	0.0595	-1.1151	0.0000
$lowskwd_t$	2536	Yen cubed	-0.0110	0.0870	-1.2104	0.0000
Δv_t	2535	Yen squared	0.0000	0.0367	-0.5615	0.6603
Δskw_t	2535	Yen cubed	0.0000	0.2166	-1.2588	1.6011
CPIUS	2536	Percentage Points	-0.0004	0.0124	-0.2000	0.3000
PPIUS	2536	Percentage Points	-0.0010	0.0354	-0.6000	0.6000
IPUS	2536	Percentage Points	0.0012	0.0366	-0.5000	0.9000
TRDUS	2536	Billions of U.S. $	-0.0124	0.4975	-8.8000	6.9000
UNUS	2536	Percentage Points	-0.0007	0.0182	-0.3000	0.2000
FEDUS	2536	Percentage Points	-0.00039	0.01570	-0.50000	0.25000
TRDJP	2536	Billions of Yen	1.0797	39.7144	-368.0000	858.9400
RETLJP	2536	Percentage Points	-0.0114	0.2168	-3.4000	2.9000
TANKAN	2536	Index Number	-0.0121	0.6059	-15.0000	9.0000
MON	2536	Monday Dummy	0.1991	0.3994	0.0000	1.0000
TUE	2536	Tuesday Dummy	0.1999	0.4000	0.0000	1.0000
WED	2536	Wednesday Dummy	0.2015	0.4012	0.0000	1.0000
THU	2536	Thursday Dummy	0.2007	0.4006	0.0000	1.0000
Alternative Measures of Dispersion and Skew Based on Observable Option Prices						
$highiva_t$	2536	Volatility (Annual)	0.14599	0.97611	0.00000	24.47931
$highivd_t$	2536	Volatility (Annual)	0.09926	0.58362	0.00000	9.17920
$highrr25a_t$	2536	Volatility (Annual)	0.03307	0.17641	0.00000	1.80296
$highrr25d_t$	2536	Volatility (Annual)	0.02360	0.14550	0.00000	1.56200
$lowrr25a_t$	2536	Volatility (Annual)	-0.00572	0.06421	-1.20812	0.00000
$lowrr25d_t$	2536	Volatility (Annual)	-0.01090	0.09360	-1.46342	0.00000
Δiv_t	2535	Volatility (Annual)	-0.00102	0.65924	-8.49977	11.50048
$\Delta rr25_t$	2535	Volatility (Annual)	0.00010	0.22747	-1.53691	1.75116

Table 6
Japanese Reaction Function

	Purchases Dependent Variable $Intb_t$		Sales Dependent Variable $Ints_t$	
Variable	Coefficient	T-Statistic	Coefficient	T-Statistic
Constant	0.00575	2.33	-0.01198	-2.51
$Intb_{t-1}$	0.07136	3.57		
$Intb_{t-2}$	0.02038	1.02		
$Intb_{t-3}$	-0.00687	-0.34		
$Intb_{t-4}$	0.00046	0.02		
$Intb_{t-5}$	-0.00267	-0.13		
$Ints_{t-1}$			0.20209	10.35
$Ints_{t-2}$			0.19466	9.80
$Ints_{t-3}$			0.00681	0.34
$Ints_{t-4}$			0.07845	3.95
$Ints_{t-5}$			0.12900	6.61
$devtara_{t-1}$	-0.47170	-3.00	1.06502	3.54
$highva_{t-1}$	-0.01660	-0.76	0.15223	3.63
$highskwa_{t-1}$	-0.00747	-0.97	-0.03926	-2.64
Δv_{t-1}	-0.02460	-0.78	-0.15338	-2.52
Δskw_{t-1}	-0.00476	-0.89	-0.03874	-3.76
MON	-0.00709	-2.06	0.00150	0.23
TUE	-0.00643	-1.86	0.00586	0.88
WED	-0.00528	-1.54	0.00847	1.28
THU	-0.00600	-1.74	0.01381	2.09
Observations	2528		2528	
$\bar{R}^2$	0.006698		0.192624	
F-Test of Overall Significance	2.2171		44.0638	

Table 7
OLS and IV Estimates of the Impact of Intervention on Variance
Dependent Variable - Δv_t

	OLS		IV	
	Coefficient	T-Statistic	Coefficient	T-Statistic
Constant	-0.00357	-2.18	-0.00311	-1.86
Δv_{t-1}	0.01976	0.99	0.02330	1.15
$Ints_t$	0.00804	1.29	0.02414	1.69
MON	0.01008	4.39	0.01003	4.35
TUE	0.00165	0.72	0.00153	0.66
WED	0.00651	2.84	0.00638	2.77
THU	0.00039	0.17	0.00016	0.07
Observations	2534		2528	
$\overline{R}^2$	0.009866			

Hausman Test: F(1,2520) = 1.568, Significance Level 0.21
Fail to reject null that $Ints_t$ is exogenous

Table 8
OLS and IV Estimates of the Impact of Intervention on Skewness
Dependent Variable - Δskw_t

	OLS		IV	
	Coefficient	T-Statistic	Coefficient	T-Statistic
Constant	-0.00696	-0.72	-0.00832	-0.84
Δskw_{t-1}	0.04497	2.25	0.04311	2.12
$Ints_t$	0.07400	1.99	0.03659	0.43
MON	-0.00525	-0.39	-0.00502	-0.37
TUE	0.00178	0.13	0.00215	0.16
WED	0.02421	1.78	0.02491	1.83
THU	0.02206	1.62	0.02294	1.68
Observations	2534		2528	
$\overline{R}^2$	0.004290			

Hausman Test: F(1,2520) = 0.232, Significance Level 0.63
Fail to reject null that $Ints_t$ is exogenous

Table 9
Japanese Reaction Function
Using ATM Implied Volatility and 25-delta Risk Reversal

	Purchases Dependent Variable $Intb_t$		Sales Dependent Variable $Ints_t$	
Variable	Coefficient	T-Statistic	Coefficient	T-Statistic
Constant	0.00569	2.30	-0.01246	-2.61
$Intb_{t-1}$	0.07104	3.55		
$Intb_{t-2}$	0.02040	1.02		
$Intb_{t-3}$	-0.00694	-0.35		
$Intb_{t-4}$	0.00040	0.02		
$Intb_{t-5}$	-0.00273	-0.14		
$Ints_{t-1}$			0.20167	10.34
$Ints_{t-2}$			0.19592	9.86
$Ints_{t-3}$			0.00858	0.43
$Ints_{t-4}$			0.07789	3.93
$Ints_{t-5}$			0.12826	6.58
$devtara_{t-1}$	-0.47759	-3.02	0.99578	3.29
$highiva_{t-1}$	-0.00150	-1.11	0.00918	3.53
$highrr25a_{t-1}$	-0.00298	-0.43	-0.04333	-3.23
Δiv_{t-1}	-0.00133	-0.72	-0.01139	-3.19
$\Delta rr25_{t-1}$	-0.00367	-0.71	-0.03280	-3.32
MON	-0.00704	-2.05	0.00210	0.32
TUE	-0.00642	-1.86	0.00679	1.02
WED	-0.00529	-1.54	0.00933	1.42
THU	-0.00596	-1.74	0.01426	2.16
Observations	2528		2528	
$\overline{R}^2$	0.006727		0.193448	
F-Test of Overall Significance	2.2224		44.2922	

Table 10

OLS and IV Estimates of the Impact of Intervention on Implied Volatility

Dependent Variable - Δiv_t

	OLS		IV	
	Coefficient	T-Statistic	Coefficient	T-Statistic
Constant	-0.06145	-2.09	-0.05571	-1.85
Δiv_{t-1}	0.04587	2.30	0.04880	2.40
$Ints_t$	0.18501	1.64	0.37441	1.45
MON	0.17414	4.22	0.17339	4.19
TUE	0.02426	0.59	0.02221	0.53
WED	0.11821	2.87	0.11618	2.81
THU	0.00575	0.14	0.00285	0.07
Observations	2534		2528	
$\overline{R}^2$	0.011065			

Hausman Test: F(2,2509) = 0.661, Significance Level 0.42

Fail to reject null that $Ints_t$ is exogenous

Table 11
OLS and IV Estimates of the Impact of Intervention on Risk Reversal
Dependent Variable - $\Delta rr25_t$

	OLS		IV	
	Coefficient	T-Statistic	Coefficient	T-Statistic
Constant	-0.00190	-0.19	-0.00248	-0.24
$\Delta rr25_{t-1}$	0.07285	3.66	0.07272	3.58
$Ints_t$	0.06890	1.77	0.06690	0.75
MON	-0.01104	-0.77	-0.01072	-0.75
TUE	-0.00210	-0.15	-0.00156	-0.11
WED	0.01875	1.32	0.01933	1.35
THU	0.01164	0.82	0.01214	0.85
Observations	2534		2528	
$\overline{R}^2$	0.006033			

Hausman Test: F(2,2509) = 0.00045, Significance Level 0.98
Fail to reject null that $Ints_t$ is exogenous

Table 12 Success Counts								
	Interventions					HyperGeometric		
	Total	Successes		Virtual Successes		Expected Successes	Std. Dev.	p-value
	#	#	%	#	%	#	#	
Dispersion								
SC1	170	84	49.4	1344	53.0	90.1	6.3	0.815
SC2	170	90	52.9	1285	50.7	86.2	6.3	0.246
Direction								
SC3(sell)	6	1	16.7	1302	51.4	3.1	1.2	0.903
SC3(buy)	164	84	51.2	1230	48.5	79.6	6.2	0.213

Table 13 Probit Regressions Dependent Variables SC1, SC2, and SC3						
	SC1		SC2		SC3	
Independent Variables	Coeff.	T-Stat	Coeff.	T-Stat.	Coeff.	T-Stat.
Constant	0.20948	0.81	0.09223	0.35	0.27629	1.04
Abs. Value Intervention	-0.00036	-1.21	-0.00038	-1.25	-0.00059	-1.88
Days since last intervention	-0.00201	-0.74	-0.00194	-0.70	-0.01039	-1.60
Consecutive interventions	-0.04596	-1.30	-0.01892	-0.53	0.00363	0.10
Shift to/from purchase/sale	0.58257	0.47	0.61271	0.49	-4.87490	0.00
Coordinated with USA	-5.91690	0.00	-5.81660	0.00	-5.90820	0.00
1999 Dummy	0.06825	0.16	0.16336	0.39	0.42172	0.92
2000 Dummy	0.81632	1.13	6.24230	0.00	-6.00090	0.00
2003 Dummy	0.12624	0.58	0.31779	1.46	-0.00529	-0.02
Total observations:	170		170		170	
Successful interventions:	84		90		85	
Unsuccessful interventions:	86		80		85	
Log Likelihood:	-114.23		-111.12		-108.31	
Likelihood Ratio Test	7.20		12.83		19.05	
5 Percent Critical Value	15.51		15.51		15.51	

Figure 1

Volatility Smile

(JP Morgan Quotes on March 12, 1997)

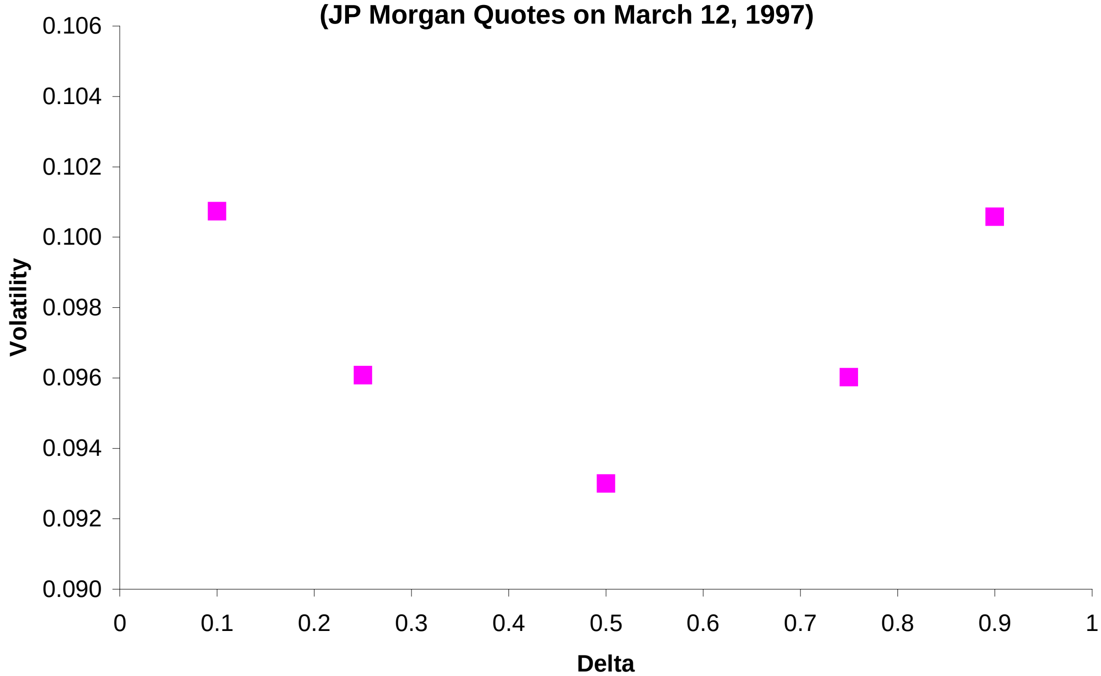

Figure 2
Option Prices
(Translated from JP Morgan Quotes from March 12, 1997)

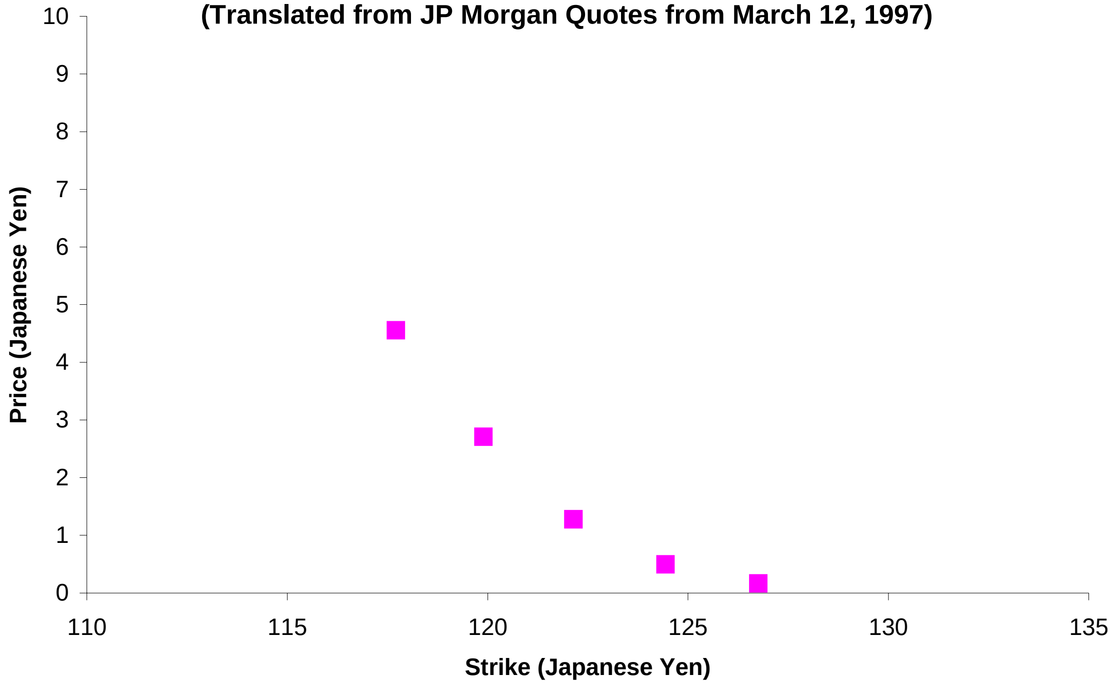

Figure 3

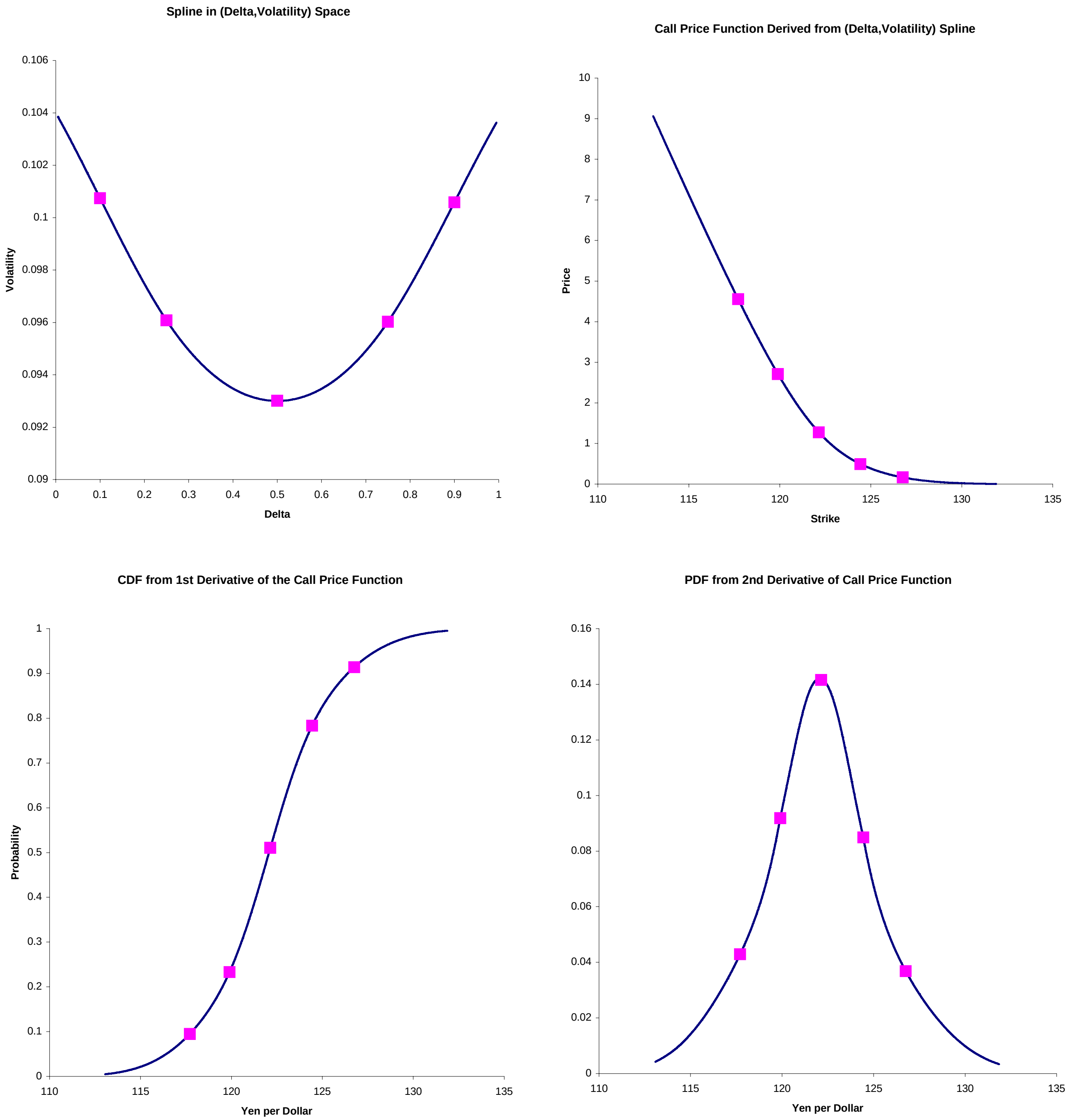
Spline in (Delta,Volatility) Space
Volatility
Delta
0.106
0.104
0.102
0.1
0.098
0.096
0.094
0.092
0.09
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Call Price Function Derived from (Delta,Volatility) Spline
Price
Strike
10
9
8
7
6
5
4
3
2
1
0
110
115
120
125
130
135
CDF from 1st Derivative of the Call Price Function
Probability
Yen per Dollar
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
110
115
120
125
130
135
PDF from 2nd Derivative of Call Price Function
Yen per Dollar
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
110
115
120
125
130
135

Figure 4

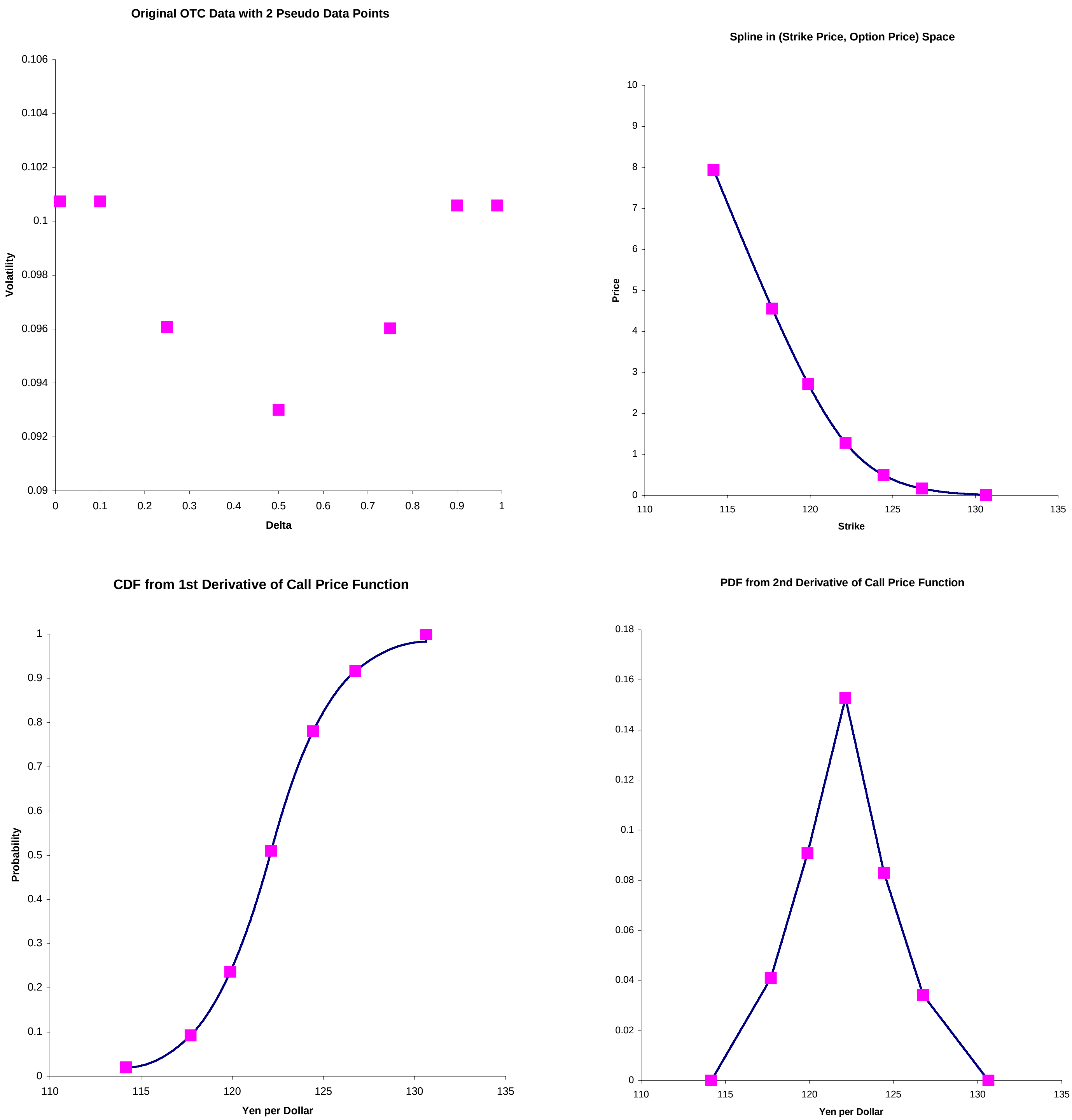
Original OTC Data with 2 Pseudo Data Points
Volatility
0.106
0.104
0.102
0.1
0.098
0.096
0.094
0.092
0.09
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1
Delta
Spline in (Strike Price, Option Price) Space
Price
10 9 8 7 6 5 4 3 2 1 0
110 115 120 125 130 135
Strike
CDF from 1st Derivative of Call Price Function
Probability
1 0.9 0.8 0.7 0.6 0.5 0.4 0.3 0.2 0.1 0
110 115 120 125 130 135
Yen per Dollar
PDF from 2nd Derivative of Call Price Function
0.18 0.16 0.14 0.12 0.1 0.08 0.06 0.04 0.02 0
110 115 120 125 130 135
Yen per Dollar

Figure 5

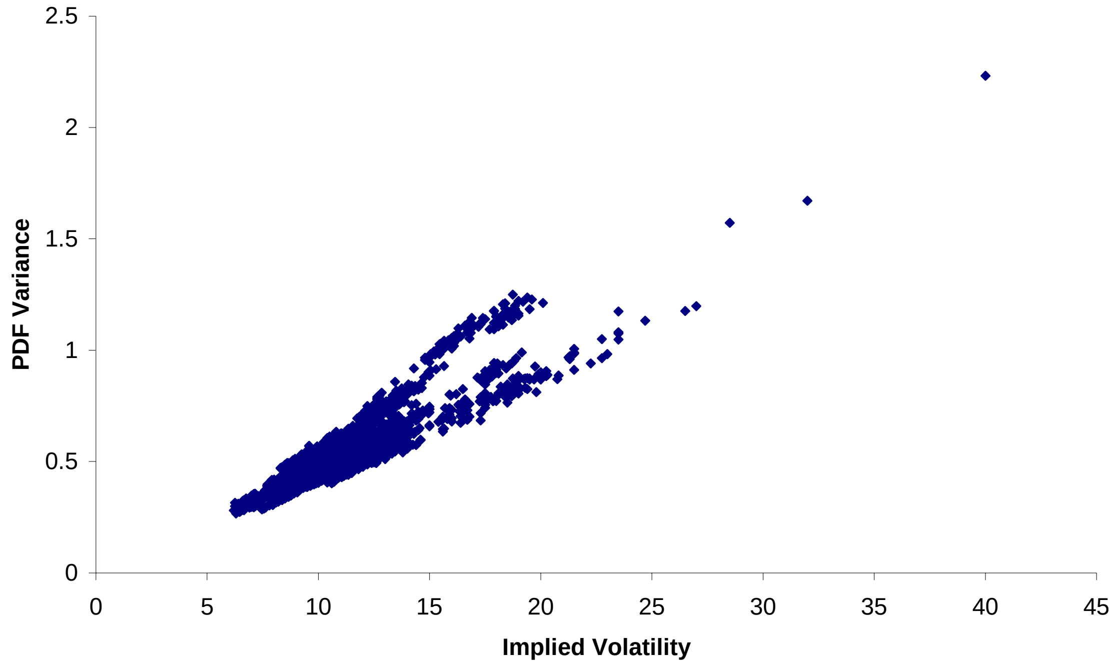

Figure 6