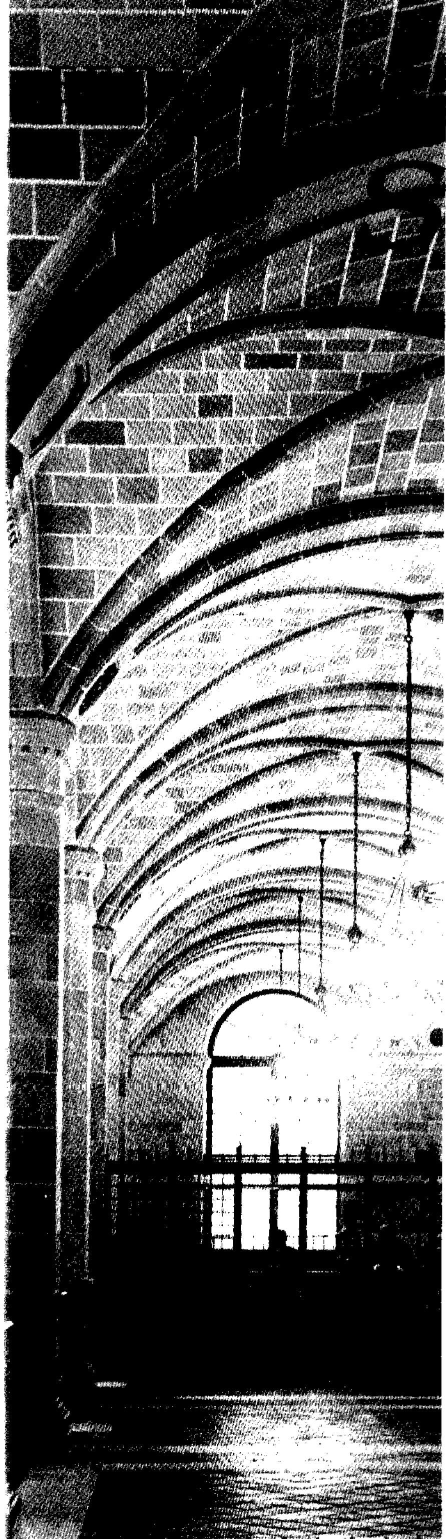

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Using Option Prices to Estimate Realignment Probabilities in the European Monetary System

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Abstract:

Risk reversals are a combination of options from which price information about market expectations of future exchange rates can be extracted. This paper describes a procedure for estimating the market's perceived probability distribution of future exchange rates from the prices of risk reversals and other currency options. This procedure is used to estimate the ex ante probability of a realignment of the French franc and pound sterling.

The procedure for estimating the realignment probabilities relies on the jump-diffusion model of exchange rate behavior and the resulting option pricing formula. By fitting this model to market option price data, the unobserved parameters of the jump-diffusion process are retrieved. These parameter estimates form the basis for estimating the ex ante probability distribution of exchange rates and thus the realignment probabilities.

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Introduction

The use of derivatives prices to draw conclusions about future asset prices is common. The forward exchange rate can be interpreted as the market's point estimate of the future spot exchange rate. Analogously, implied volatilities calculated from foreign currency options have been interpreted as the market's estimate of actual future volatility. In the same spirit, the prices of certain combinations of options can be interpreted as the market's best guess as to the skewness in the distribution of future exchange rates.

Options are frequently sold in combinations. Among the most common in the currency option markets is the *risk reversal,* consisting of an out-of-the-money call and out-of-the-money put. The exercise price of the call component is higher than the current forward exchange rate, and the exercise price of the put is lower. Risk reversals trade as a standard instrument in over-the-counter currency option markets, with prices expressed as the difference between the prices of the constituent put and call. This paper describes a procedure for estimating the market's perceived probability distribution of future exchange rates from the prices of risk reversals and other currency options. It then uses this procedure to estimate the probability of a realignment of the French franc and pound sterling in the European Monetary System (EMS).

In academic studies, option prices have been interpreted as the market's forecast of the second moment of daily changes in the underlying asset price over the life of the option; when combined with a point estimate of the future asset price, they provide a picture of the probability distribution of the asset price at maturity. Some researchers, however, have attempted to extract information about higher moments of asset price distributions from options prices. Bates (1988a, 1991, 1993) uses prices of exchange-traded options to extract information about the third and fourth moments of asset price changes to form a more exact picture of the terminal distribution. The model described here is similar, but uses a simpler procedure made possible with risk reversal data to estimate the realignment probability of the French franc and pound sterling. In contrast to previous studies of Exchange Rate Mechanism (ERM) exchange rates, it is possible with this procedure to identify both the ex ante probability *and* the magnitude of a realignment.[1]

I. Institutional Features of the EMS[2]

The ERM began operations on March 12, 1979; it consists of (a) a grid of bilateral central parities; (b) rates for compulsory intervention, or fluctuation limits, set until August 2, 1993, at 2.25 percent or 6 percent above and below the parities; and (c) the obligation of central banks on both sides of a currency pair to purchase or sell unlimited amounts of currency at the fluctuation limits. Bundesbank concerns about the potential for the ERM to undermine its control of the German money supply were addressed by a

[1] Malz (1995) presents a technique for extracting the risk-neutral probability density of the future exchange rate from option prices without assuming that the exchange rate follows a jump-diffusion, and applies it to flexible exchange rates.

[2] The history and institutions of the ERM are surveyed in Giavazzi and Giovannini (1989), Ungerer et al. (1990), and Gros and Thygesen (1992).

public commitment from the German government to shield it from a potential conflict between the intervention obligations and monetary stability either by means of a realignment or by a temporary suspension of the intervention obligations. The unilateral Bundesbank reservation has remained in effect throughout the existence of the ERM.[3]

Until 1987, realignments in the ERM were frequent, and the system relied heavily on capital controls to counter selling pressures on weak currencies. From 1987 until 1992, there were no realignments in the EMS.[4] This period also witnessed a burst of political activity aimed at establishing a full-fledged currency union, the European Monetary Union (EMU), by the end of the 1990s; several European countries outside the ERM pegged their currencies to the German mark or to the European Currency Unit. Investors began to pour funds into assets denominated in European currencies other than the mark with the conviction that further realignments were unlikely. The persistent, but diminishing, interest rate differentials vis-à-vis mark-denominated assets were seen as more than adequate compensation for the dwindling exchange rate risk.

In 1991 and early 1992, "convergence trading" was undermined by economic and political shocks.[5] German unification was financed by borrowing from the public. The Bundesbank tightened monetary policy to

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[3] See Emminger (1986, pp. 361f.).

[4] The January 7, 1990, realignment of the Italian lira was a technical step to ease its entry into narrow ±2.25 fluctuation bands around its central parities vis-à-vis the remaining narrow-band currencies.

[5] The crisis of the ERM through early 1993 is reviewed by Eichengreen and Wyplosz (1993), Group of Ten (1993), and Goldstein et al. (1993).

thwart the perceived threat to monetary stability. Two-thirds of the DM 108 billion swing in the 1991 current account was financed by short-term funds attracted to mark deposits by rising interest rates. The difficult Maastricht summit in December 1991 and the Danish public's rejection of the draft Treaty on European Union on June 2, 1992, highlighted the obstacles to EMU.

Investors saw that the costs to politicians of participating in EMU—enduring the Bundesbank's tight-money regime—were increasing, while the prospective benefits were becoming more uncertain. Interest rate differentials vis-à-vis the mark had diminished; as a result, the buffer which might have absorbed part of the Bundesbank's interest rate hikes was thinner, and the return for bearing realignment risk had fallen. By late August 1992, positions in nonmark European assets were being liquidated on a large scale.

The lira devaluation on September 13, 1992, brought no end to the run on the lira and sterling; on September 16, 1992, after an attempt to combat selling pressure through interest rate hikes, Italy and the United Kingdom withdrew from the ERM. Other currencies were devalued once or several times over the next eight months. By mid-1993, calm appeared to have returned. Abruptly, in July 1993, provoked by an aggressive attempt by the Banque de France to cut interest rates to sub-German levels, the crisis flared again. On August 1-2, 1993, the fluctuation margins for all currency pairs other than mark/Dutch guilder were widened to ±15 percent, but the parities were left unchanged.

II. Measuring the Credibility of ERM Parities

A. Inferences on Ex Ante Realignment Probabilities from Interest Rate Differentials

Empirical assessments of the credibility of ERM exchange rates have hitherto relied almost exclusively on interest rate differentials and the assumption of open interest parity. In the ERM context, realignment can be treated as a potential regime change that significantly affects the anticipated exchange rate. Forecasts of logarithmic changes in the exchange rate in n periods can be written as a probability-weighted average of forecasts conditioned on both current information and the occurrence of a realignment. Under open interest parity, the expected depreciation $E[s_{t+n} - s_t | \Theta_t]$ is equal to the forward premium of the mark vis-à-vis the domestic currency:

$$(1) \qquad E[s_{t+n} - s_t | \Theta_t] = \pi_t^n \, E[s_{t+n} - s_t | \Theta_t, \text{ realignment}] + (1 - \pi_t^n) E[s_{t+n} - s_t | \Theta_t, \text{ no realignment}]$$

where s_t is the logarithm of the exchange rate (domestic currency units per German mark), π_t^n is the subjective probability of a realignment, and Θ_t is the information set at time t.[6]

Equation 1 assumes that only zero or one realignment can occur between times t and $t+n$, corresponding to the infrequent changes in ERM parities prior to September 1992. The withdrawal of sterling and the lira

[6] This line of research is closely related to the "peso problem" explanation of the prediction bias in forward foreign exchange rates. Its application to the ERM is surveyed in Neely (1994) and Malz (1994). The latter paper reestimates some of these models for the French franc and the pound sterling during the 1992-93 ERM crisis.

from the ERM, the repeated devaluations of the peseta and escudo, and the widening of the bands were unprecedented. The zero-one realignment model is nonetheless a valid approximation for the one-month maturities I will focus on here, since these were discrete events resulting in immediate, large changes in exchange rates.

Estimates of π_t^n based on this model agree in treating $E[s_{t+n} - s_t | \Theta_t, \text{realignment}]$, the anticipated exchange rate change in the event of a realignment, as a known constant. The procedure using option prices I present here, in contrast, identifies both π_t^n and $E[s_{t+n} - s_t | \Theta_t, \text{realignment}]$.

In this framework, Collins (1985, 1992) treats $E[s_{t+n} - s_t | \Theta_t, \text{no realignment}]$, the anticipated exchange rate change in the absence of a realignment, as an iid normal variate. The probability π_t^n is assumed to be determined by the stock of foreign exchange reserves held by the non-German central bank and the domestic interest rate.

More recent work has been done using target zone models incorporating realignment risk that interpret $E[s_{t+n} - s_t | \Theta_t, \text{no realignment}]$ as the exchange rate movement within the fluctuation limits. This component of expected exchange rate changes is mean-reverting and of significant magnitude relative to the interest rate differential.[7] Rose and Svensson (1991) and Rose (1993a, 1993b) estimate the probability of realignment for the French franc and pound sterling using a fixed realignment size. Chen and

[7] Krugman (1991) presents the credible target zone model. Bertola and Svensson (1993) present a model of target zones with Poisson-distributed realignment probabilities. Svensson (1993) surveys models and empirical research on target zones.

Giovannini (1992, 1993) estimate projections of the expected value of devaluation $\pi_t^n E[s_{t+n} - s_t | \Theta_t$, realignment] on fundamentals.

B. Inferences on Exchange Rate Credibility from Option Prices

Recently, attempts have been made to establish theoretical option values for exchange rates in a target zone. Dumas, Jennergren, and Näslund (1993b) present a model of option values in a credible target zone. One implication of the model, directly related to the finding that mean-reversion in a target zone is stronger the longer the time horizon, is that the term structure of implied volatilities is downward sloping. Campa and Chang (1994) test this feature of the model on sterling/dollar option prices and find evidence against credibility of the target zone.[8]

III. The Stochastic Behavior of Nominal Exchange Rates

The Black-Scholes model, the benchmark model for pricing and managing the risks of options, is based on the assumption that nominal exchange rate returns follow a random walk. To extract information about realignment expectations from option prices, I use an alternative model of option values based on an alternative specification of the stochastic behavior of exchange rate changes. Following is an outline of what is known about the statistical properties of exchange rates.[9]

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[8] Dumas, Jennergren, and Näslund (1993a) study option valuation in target zones with realignments.

[9] See Boothe and Glassman (1987), Hsieh (1988), Baillie and McMahon (1989), and de Vries (1994) for surveys.

A. Stylized Facts Concerning Flexible Exchange Rates

Floating exchange rates, it is generally agreed, are unit root processes. There is less agreement on the behavior of the log price relatives or nominal returns $s_t - s_{t-1}$. Most investigations find these to be stationary and serially uncorrelated, but beyond that the results are less conclusive, in part because of the wide range of hypotheses about the process the price relatives follow.

The hypothesis that the log price relatives are normal iid has been in doubt since the advent of floating exchange rates in the 1970s. The distribution of $s_t - s_{t-1}$ violates normality in three crucial respects. First, it is leptokurtotic or "fat-tailed," that is, large values occur too frequently to be consistent with normality. Second, the distribution appears to be skewed, so positive and negative returns of a given size are not equally likely. Finally, the variance of the price relatives appears to be time varying. The lack of autocorrelation in $s_t - s_{t-1}$ indicates that its variance rather than its mean varies; it has long been noted that the volatility of asset price relatives clusters, that is, large absolute values of $s_t - s_{t-1}$ tend to be followed by large values. Thus, nominal returns are not both iid and normally distributed, suggesting two approaches to characterizing nominal exchange rate returns: non-normal distributions and time-varying distribution parameters.

There is strong evidence that flexible exchange rate returns follow jump-diffusions, that is, a sum of iid normal and Poisson-distributed jump components, which can account both for the kurtosis and the skew in nominal returns.[10] If jumps in either direction are equally likely, then the frequency of large changes will be greater than is consistent with normality, but no skew will be apparent. If jumps in one direction are larger or more frequent, the distribution will be skewed.

Time-varying parameters can be represented by autoregressive conditional heteroscedasticity (ARCH) models, which can account for kurtosis as well as for the time variation of volatility.[11]

B. Stylized Facts Concerning Exchange Rates in a Target Zone

There are reasons to expect ERM currencies to display different stochastic properties. Models of credible target zones as well as target zones with realignment risk imply that the exchange rate is mean-reverting, tending to return to the central parity. Target zone models with realignment risk imply that exchange rates should show evidence of jumps.

Nieuwland, Verschoor, and Wolff (1991, 1993) find no evidence of mean reversion but cite strong evidence of jumps in ERM exchange rates. Ball and Roma (1993) find that processes incorporating both jumps and mean reversion fit ERM currencies well. They combine Poisson-distributed jumps with a diffusion component that is Ornstein-Uhlenbeck or geometric Brownian with reflecting barriers. The reflecting-barrier process, in which mean reversion is driven by proximity to the fluctuation margins, worked best in earlier years of the ERM, while the Ornstein-Uhlenbeck process, in which mean reversion is driven by distance from the central

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10 See Akgiray and Booth (1988), Tucker and Pond (1988), and Jorion (1988).

11 See Hsieh (1988, 1989) and Baillie and Bollerslev (1989) for applications to currencies.

parity, best describes the ERM in later years.

IV. The Black-Scholes Implied Volatility

Although option dealers are well aware that exchange rate behavior does not conform precisely to the assumptions of the Black-Scholes model, they use the model as a benchmark for option valuation and draw from it the terminology and metrics used by the option markets. The key assumption of the Black-Scholes foreign exchange option pricing model is that the logarithm of the forward exchange rate follows geometric Brownian motion, that is:

$$S_T = S_0 + (\alpha - r^*) \int_0^T S_t dt + \sigma \int_0^T S_t dW_t \ , \tag{2}$$

where W_t denotes a standard Brownian motion, S_t the level of the exchange rate, σ the variance rate or volatility, α the expected rate of return on the currency, and r^* the foreign risk-free interest rate; α, σ and r^* are assumed constant.[12] The model results in the Black-Scholes formulas for the values of options on foreign exchange. The value of a call is

$$v(S_t, \tau; X, \sigma, r, r^*) = S_t e^{-r^*\tau} \Phi(d + \sigma\sqrt{\tau}) - X e^{-r\tau} \Phi(d) \ , \tag{3}$$

[12] The original exposition of the Black-Scholes model is Black and Scholes (1973). An identical model was developed independently and presented in Merton (1976). The application of the model to foreign currency options is also called the Garman-Kohlhagen model, after its publication by Garman and Kohlhagen (1983). See also Grabbe (1983). Merton (1982) provides an introduction to the properties of the two stochastic processes, geometric Brownian motion and jump-diffusion, on which this paper focuses.

and the value of a put is

$$(4) \qquad w(S_t, \tau; X, \sigma, r, r^*) = Xe^{-r\tau}\Phi(d) - S_t e^{-r^*\tau}\Phi(-d+-\sigma\sqrt{\tau}) \ ,$$

where $\Phi(\cdot)$ represents the cumulative normal distribution, and

$$(5) \qquad d = \frac{\ln\left(\frac{S_t}{X}\right) + \left(r - r^* - \frac{\sigma^2}{2}\right)\tau}{\sigma\sqrt{\tau}} \ ,$$

where $\tau \equiv T - t$. The volatility σ is not observable and must be estimated to calculate the option value.

If S_t is measured in units of domestic currency per foreign currency units, the Black-Scholes formulas are also expressed in domestic currency units. Exchange-traded currency options are usually defined this way. Alternatively, one can replace the Black-Scholes option value on the left-hand side of equations (3) or (4) with an observed option price v_t and interpret the formula as returning the volatility as an implicit function of v_t, the variables S_t and τ, and the parameters, X, r and r^*. Treated this way, the volatility is called the Black-Scholes implied volatility. The Black-Scholes formula increases monotonically in σ, so the implied volatility is a unique inverse function of $v(S_t, \tau; X, \sigma, r, r^*)$.[13]

Although option dealers are well aware that exchange rates do not conform precisely to the assumptions of the Black-Scholes model, they use the

[13] The notion of implied volatility was formalized by Latané and Rendleman (1976) and Schmalensee and Trippi (1978).

model as a benchmark for option valuation and draw the option markets' terminology from it. Rather than quoting option prices, dealers quote implied volatilities, or "vols."[14] If a dealer is asked to quote a one-month call option on mark-Paris (value of the mark in French francs), he might answer "one-month at-the-money forward calls are three at four," meaning that he buys a one-month at-the-money mark-Paris call option with an exercise price equal to the current forward exchange rate for three volatility points (three vols) and sells them for four. The value in francs is then calculated from the Black-Scholes formula.[15]

V. Information Content of Risk Reversal Prices

A. Kurtosis, Skew, and Option Prices

The Black-Scholes model of option values has motivated two lines of empirical research. One examines how closely the market prices of options correspond to their theoretical values. The other seeks to extract information about the probability distribution of the underlying asset from option prices. These agendas are closely related, because to translate option prices into accurate information about the underlying distribution, a correct option valuation model is required. A correct option pricing model, in turn, can be derived only from a correct characterization of the statistical

[14] "Vol" refers to both implied volatility and its unit of measure (percent per annum).

[15] For example, a one-month call struck at-the-money forward with a domestic interest rate of 15 percent and a volatility of 6 percent would cost 2.3 centimes per mark of underlying. With a volatility of 10 percent, it would cost 3.9 centimes.

properties of the underlying asset prices.

The Black-Scholes model implies that all options on the same asset have identical implied volatilities, regardless of time to maturity and moneyness. However, options with the same strike but different maturities, options with the same maturity but different strikes, and puts and calls with the same maturity and strike often have different implied volatilities. These biases offer tests of the Black-Scholes model and suggest alternative option pricing models.[16]

Out-of-the money options on currencies with flexible exchange rates often have higher implied volatilities than at-the-money options. This bias, called the volatility smile, is evidence that market participants view exchange rates as kurtotic. Out-of-the money call options on a currency often have implied volatilities that differ from those of equally out-of-the money puts. This bias, called skew, can be so strong as to offset or exceed the smile: the out-of-the-money put or call then has an implied volatility that is less than or equal to that of the at-the-money options. Option skew indicates that the market perceives directional bias in exchange rates.[17]

The Black-Scholes implied volatility has been interpreted as the market-adjusted certainty equivalent of the second moment of asset price

[16] Tests have usually been carried out in terms of option values, using price data from option exchanges, but they can be translated into the implied volatility terms of the over-the-counter option markets. The Black-Scholes model was tested by MacBeth and Merville (1979) and Rubinstein (1985) for equity options, and by Bodurtha and Courtadon (1987) and Hsieh and Manas-Anton (1988) for exchange-traded currency options.

[17] Cookson (1993, pp. 24ff.) discusses the option smile and skew.

returns over the life of the option.[18] The evidence from option prices on skew and kurtosis in expected future asset prices suggests that one might improve the Black-Scholes estimate of the perceived probability distribution using simultaneous observations of option prices with different strike prices. Breeden and Litzenberger (1978) showed that, given the probability distribution of the underlying asset price, the second derivative of the corresponding European call option formula with respect to the exercise price, evaluated at a particular level X^0, is the probability of the time T asset price being X^0 or higher. The Breeden-Litzenberger result has motivated attempts to numerically reconstruct a probability distribution consistent with a set of observed option prices.[19] Alternatively, one can postulate an alternative distribution to the normal iid. Bates (1988a, 1991) fits option prices with varying exercise prices to a jump-diffusion option pricing formula to estimate the parameters of the jump-diffusion. This is essentially the method I employ below.

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[18] This research on implied volatility is analogous to that on the relationship of the forward exchange rate to market estimates of the first moment of the future spot rate. Lyons (1988) uses implied volatilities to test whether the forward exchange rate prediction bias can be explained by time-varying risk premiums based on a portfolio balance model of the exchange rate.

[19] Shimko (1993) applies this finding to derive the implied probability distribution of the S&P 500 index. However, his method requires additional assumptions regarding the probability density above the highest and below the lowest exercise levels of traded option contracts. As shown in section VI, risk reversal data shed light primarily on these tail probabilities. Rubinstein (1994), Dupire (1994), and Derman and Kani (1994) also present numerical methods for recovering distributions from option prices.

B. Risk Reversal Price Quotes

The over-the-counter currency option market convention for quoting risk reversal prices, like those for standard option price quotes, are based on the Black-Scholes implied volatility. A risk reversal consists of an out-of-the-money put and call. The dealer exchanges one of the options for the other with the counterparty. Because the put and the call are generally not of equal value, the dealer pays or receives a premium for exchanging the options. This premium is expressed as the difference between the implied volatilities of the put and the call.

In order to quote risk reversal prices, dealers need a convention for expressing the degree to which the component put and call are out-of-the-money. Over-the-counter options markets have adopted the option delta, the rate of change of the Black-Scholes option value with respect to the spot rate, as a metric for moneyness. The delta of a currency call can be written

$$\delta_v(S_t, \tau; X, \sigma, r, r^*) \equiv \frac{\partial v(\cdot;\cdot)}{\partial S_t} = e^{-r^*\tau}\Phi(d+\sigma\sqrt{\tau}), \tag{6}$$

while that of currency put is

$$\delta_w(S_t, \tau; X, \sigma, r, r^*) \equiv \frac{\partial w(\ )}{\partial S_t} = 1-\delta_v(S_t, \tau; X, \sigma, r, r^*) . \tag{7}$$

This metric is closely related to the probability distribution of logarithmic changes in the exchange rate, given that geometric Brownian motion is the true process. The probability distribution of the logarithmic change in the spot rate is simply $\Phi(d)$. Since $N(d+\sigma\sqrt{\tau})$ is a probability, for any positive S_t, σ, and τ, $0 < \delta_v < 1$.

Risk reversals are usually standardized as a combination of a 25-delta call and a 25-delta put. The dealer quotes the implied volatility differential at which he is prepared to exchange a 25-delta call for a 25-delta put. For example, if the mark-Paris rate is strongly expected to rise (French franc depreciation), an options dealer might quote mark-Paris risk reversals as follows: "one-month 25-delta risk reversals are 1.5 at 3.0 mark calls over." This means he stands ready to pay a net premium of 1.5 volatility points to buy a 25-delta mark call and sell a 25-delta mark put against the French franc and charges a net premium of 3.0 volatility points to sell a 25-delta mark call and buy a 25-delta mark put.

C. A First Look at the Information Content of Risk Reversal Prices

The most direct way of accessing the information content of risk reversal prices is to recall the definition of an option: an option pays off if the exchange rate ends higher than the exercise price. The option price thus reflects the likelihood that it will end in-the-money. The constituent options in a risk reversal are equally out-of-the-money in delta terms. They would have the same price, and the risk reversal price would equal zero, if the market believed that the tails of the density function of percent changes in the forward rate were symmetrical, that is, increases or decreases in the forward rate of a given magnitude are equally likely. Directional biases are thus clearly revealed by the prices of risk reversals. If an out-of-the-money call on a currency is more valuable than an equally out-of-the-money put, this reflects a market consensus that, loosely speaking, the call is more likely to pay off, that is, the currency is more likely to appreciate than depreciate.[20]

Consider, for example, the mark-Paris risk reversal displayed in the top panel of Chart 1 as a long mark call/short mark put position. On September 16, 1992, mark calls were more expensive than puts. The strike price of the mark call component was FF3.4692 and that of the mark put FF3.3717. The risk reversal price indicates that the market considered the expected value of exchange rate realizations on October 16 in excess of FF3.4692 to be greater than that of realizations below FF3.3717. The data on market sentiment on future spot rates are independent of those contained in the current spot or forward exchange rates.

The risk reversal thus gives an indication of the relative likelihood, as perceived by the market, of a large appreciation or depreciation of the franc. In other words, it is a measure of the tail probabilities. The procedure outlined below for extracting the probability distribution of the exchange rate from risk reversal data can be thought of as a way of transforming, via the jump-diffusion model, the information on the expected values of currency moves embedded in option prices into a statement about probabilities.

Using volatilities as a metric for the option value and delta as a metric for moneyness leads to a reformulation of Bates' (1988a, 1991) option-based measure of asymmetry in the asset-price distribution, the crash premium. In the metrics here, the crash premium may be defined as the risk

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[20] Asymmetry in the tails is not, however, a sufficient condition for a non-zero risk reversal price. The expected value of exchange rate changes beyond the 25-delta points might be equal, even if the tails are not mirror images of one another.

reversal price itself. In the Black-Scholes model, the risk reversal price is zero. If risk reversal prices deviate from zero, there is ipso facto a crash premium.

VI. Currency Option Prices in the Presence of Realignment Risk

The prices of risk reversals indicate skew in the perceived distribution of the mark-Paris exchange rate. Following Bates (1988a, 1991), I explain the option price skew using an asymmetric jump-diffusion model of the stochastic process for the exchange rate, which can be written

$$S_T = S_0 + \int_0^T (\alpha - r^* - \lambda E[k]) S_t dt + \int_0^T \sigma_w S_t dW_t + \int_0^T S_t k dq_{t,T}, \qquad (8)$$

where σ_w denotes the diffusion volatility of the exchange rate, $q_{t,T}$ is a Poisson counter over the interval (t,T) with average rate of occurrence of jumps λ, and k is the possibly random jump size.

The option pricing formula is derived by Merton (1976) and Bates (1988b, 1991).[21] An important point in deriving the option price is that the risk to a seller of options of an increase in the option price following a jump in the asset price cannot be managed by a continuous-adjustment hedging strategy. The option might jump further in-the-money, in which case the writer will be underhedged. If he attempts to hedge in advance of jumps, he will be overhedged unless a jump occurs. Therefore, in contrast to the Black-Scholes model, the jump-diffusion model does not permit

[21] See also Ball and Torous (1983, 1985) and Jarrow and Rudd (1983, pp. 164ff.).

risk-neutral pricing techniques without additional assumptions. The estimated parameters are the risk-neutral parameters and are not in general equal to the true parameters.[22]

For the mark cross rates in the ERM, it seems more appropriate to employ a simpler version of the jump-diffusion model, in which k is nonstochastic and there is either zero or one jump in the exchange rate over the life of the option. Ball and Torous (1983, 1985) and Bates (1988a) refer to this as the Bernoulli distribution version of the model. The formula for a call becomes:

$$(9) \quad \begin{aligned} c(S_t,\tau;X,\sigma_w,r,r^*,\lambda,k) &= (1-\lambda\tau)\left[S_t e^{-(r^*+\lambda k)\tau}\Phi(d_0+\sigma_w\sqrt{\tau}) - Xe^{-rt}\Phi(d_0)\right] \\ &\quad + \lambda\tau\left[S_t e^{-(r^*+\lambda k)\tau}(1+k)\Phi(d_0+\sigma_w\sqrt{\tau}) - Xe^{-rt}\Phi(d_1)\right] \\ &= (1-\lambda\tau)\,v\left(S_t e^{\lambda k\tau},\tau;X,\sigma_w,r,r^*\right) + \lambda\tau v\left[S_t e^{\lambda k\tau}(1+k),\tau;X,\sigma_w,r,r^*\right] \end{aligned}$$

where

$$(10) \qquad d_0 = \frac{\ln(S_t/X) + \left(r - r^* - \lambda k - \sigma_w^2/2\right)\tau}{\sigma_w\sqrt{\tau}}$$

and

$$(11) \qquad d_1 = \frac{\ln(S_t/X) + \ln(1+k) + \left(r - r^* - \lambda k - \sigma_w^2/2\right)\tau}{\sigma_w\sqrt{\tau}} \quad .$$

[22] The risk-neutral parameter λ might be greater than the "true" subjective parameter if agents are risk-averse and are willing to pay a premium for, say, a mark-Paris call to protect themselves against a realignment. The risk-neutral parameter might be smaller, however, if agents can hedge partially by selling currency to the central bank, which then takes on part of the currency exposure.

The value of a European put option under jump-diffusion can be derived by invoking put-call parity:

$$(12)\quad p(S_t,\tau;X,\sigma_w,r,r^*,\lambda,k) = (1-\lambda\tau)\left[Xe^{-r\tau}\Phi(-d_0) - S_t e^{-(r^*+\lambda k)\tau}\Phi(-d_0-\sigma_w\sqrt{\tau})\right]$$
$$+\lambda\tau\left[Xe^{-r\tau}(1+k)\Phi(-d_1) - S_t e^{-(r^*+\lambda k)\tau}\Phi(-d_1-\sigma_w\sqrt{\tau})\right]$$
$$= (1-\lambda\tau)\,w\left(S_t e^{\lambda k\tau},\tau;X,\sigma_w,r,r^*\right) + \lambda\tau w\left[S_t e^{\lambda k\tau}(1+k),\tau;X,\sigma_w,r,r^*\right],$$

where d_0 and d_1 are as defined in equations (11) and (12).

The Bernoulli version of the jump-diffusion model captures the widespread, but not unanimous, market view that the risk for sterling or the franc was that a realignment or a collapse of the system would bring about a single sharp change in the currency's value, but that repeated realignments within a month's time were unlikely. Each formula is an average of the Black-Scholes option value given a jump, weighted by the probability of a jump, and the Black-Scholes value absent a jump, weighted by the probability of no jump.

The expected value of a jump, λk, is added to the return on a foreign currency deposit r^* in the formulas. Intuitively, the current exchange rate must already have depreciated by, say, 5 percent, to reflect a jump with an expected value of 5 percent. Otherwise, the weighted average of the zero-jump and one-jump future spot rates would not equal the current forward rate. The λk term implies that if there is no jump, the exchange rate will appreciate by λk; if there is a jump, the exchange rate will depreciate by approximately $1+k-\lambda k$, not including the forward points $S_t\left[e^{(r-r^*)\tau}-1\right]$.

VII. Estimates of Realignment Probabilities Using Option Prices

A. Normalized Black-Scholes and Jump-diffusion Option Price Formulas

Over-the-counter options and risk reversals are quoted in implied volatilities for options of a specified delta. This permits a simplification of the price formulas needed in estimating the jump-diffusion parameters from Black-Scholes prices. Data on the spot exchange rate, the foreign and domestic interest rates, and the exercise prices of the options are not needed.[23]

The data pertain to one-month options, so τ can be set to unity throughout. The volatilities are then converted from the standard annual basis on which they are quoted to a monthly basis by dividing by $\sqrt{12}$. To avoid clutter, I do not incorporate this change of units in the notation, but take it into account in estimation. The jump parameter λ, however, is a monthly rate.

Dividing equation 3 through by $X_t e^{-r}$ yields

$$v(R_t, \sigma) \equiv e^r v(R_t, 1;1,\sigma,0,0) = R_t \Phi(d+\sigma) - \Phi(d) , \tag{13}$$

where $R_t \equiv F_{t,t+1}/X$, $F_{t,t+1} = S_t e^{r-r^*}$, and

[23] The dimension reduction is similar to that of Merton (1973, p.166). We both divide the current asset price by the exercise price to eliminate it as an argument and express the option price as a future value to eliminate the domestic interest rate. However, where Merton eliminates the volatility by combining it with the time to maturity, I set the time to maturity to unity. I also substitute the forward exchange rate for the spot rate in order to eliminate the foreign interest rate.

$$(14) \qquad d = \frac{\ln(R_t)}{\sigma} - \frac{\sigma}{2} \ .$$

The simplified Black-Scholes formula for a currency put is

$$(15) \qquad w(R_t,\sigma) \equiv e^r w(R_t,1;1,\sigma,0,0) = \Phi(-d) - R_t \Phi(-d-\sigma) \ .$$

The jump-diffusion formulas can be similarly normalized. The formula for a call is

$$(16) \qquad \begin{aligned} c(R_t,\sigma_w,\lambda,k) &\equiv e^r c(R_t,1;1,\sigma_w,0,0,\lambda,k) \\ &= e^r\left[(1-\lambda)\, v(R_t e^{-\lambda k},1;1,\sigma_w,0,0) + \lambda v\,(R_t(1+k)\, e^{-\lambda k},1;1,\sigma_w,0,0)\right] \\ &= (1-\lambda)\, v\,(R_t e^{-\lambda k},\sigma_w) + \lambda v\,[R_t(1+k)\, e^{-\lambda k},\sigma_w] \ , \end{aligned}$$

and for a put

$$(17) \qquad \begin{aligned} p(R_t,\sigma_w,\lambda,k) &\equiv e^r p(R_t,1;1,\sigma_w,0,0,\lambda,k) \\ &= (1-\lambda)\, w\,(R_t e^{-\lambda k},\sigma_w) + \lambda w\,[R_t(1+k)\, e^{-\lambda k},\sigma_w] \ . \end{aligned}$$

B. Estimation Procedure

The task is to estimate the three parameters σ_w, λ and k in the jump-diffusion formula. The data are the prices, in volatilities, of at-the-money forward one-month options and one-month 25-delta risk reversals. The jump-diffusion model, like the Black-Scholes model, postulates that the parameters are constants. In extracting the parameters from daily option prices for evidence on the market view of the future exchange rate distribution on that day, I implicitly permitted them to vary over time.

It is difficult to estimate all three parameters from daily data. If σ_w in the jump-diffusion formula is set at a value close to σ in the Black-Scholes formula, the option values the two formulas grind out will be so close to one another that it is hard to estimate the parameters λ and k reliably. In order for the jump parameters to have a role in explaining observed option prices, σ_w must have a value well below the observed at-the-money forward volatility. I assume that σ_w is constant over long periods and is equal to the implied volatility of mark-Paris options during periods when λ can be assumed close to zero. Increases in implied volatility are then due to increases in λ and k. The assumed values of 0.01 and 0.03 per annum are approximately equal to the observed implied volatility of mark-Paris and sterling-mark options, respectively, prior to the 1992 ERM crisis. Some experimentation indicates that the results are not sensitive to the assumed value for σ_w, as long as it is a small number. At somewhat higher values of σ_w, the estimated values of λ are somewhat lower.

The assumption that the Brownian component of the exchange rate's motion will not change in the event of a realignment implies that the alternative to no realignment is a realignment plus preservation of the previous band width. However, the experience of the ERM crisis shows that the alternative may be suspension of participation in the target zone or no realignment plus widening of the band. To the extent that the public believes in these latter alternatives, the assumption that the Brownian motion volatility is constant is implausible.

As a check on robustness, I estimate the parameters of the model for the French franc on the alternative assumption that, in the event of a realignment, the Brownian motion volatility, too, jumps, from 0.01 to 0.03 percent. The effect is limited: the estimated realignment probability increases slightly compared with the constant-volatility estimates.

As a further check of robustness, I estimated both λ and k jointly, and λ alone, with k set to an assumed value. The assumed values of k are 0.03 for the franc and 0.10 for sterling, approximately equal to the maximum depreciation these currencies experienced in the month after the widening of the ERM bands or the suspension of participation in the ERM. The French franc closed at a low of FF 3.5453 against the mark on August 16, 1993, 3.2 percent below its floor of FF 3.4305. The pound closed at a low of DM 2.4301 on October 5, 1992, or about 12.5 percent below its floor of DM 2.7780.

The mechanical estimation procedure is as follows. I first calculate the option prices in francs or sterling from the at-the-money volatilities and risk reversal prices expressed in vols. To do so:

- I transform the risk reversal prices into levels of implied volatility for the one-month 25-delta puts and calls. The 25-delta mark call volatility is set equal to the at-the-money volatility plus 0.75 times the risk reversal price. The 25-delta mark put volatility is set equal to the at-the-money volatility minus 0.25 times the risk reversal price. This assignment, based on the suggestions of market participants in ERM, produces a lopsided smile, that is, the volatility of the put is lower than that of at-the-money volatilities.[24]
- Next, I use these volatilities and equation 6 or 7 to solve for the for-

[24] I estimated the parameters using other assignments, for example, by assigning all the risk reversal spread to the put or to the call, or splitting it evenly between the put and call. The parameter estimates were not sensitive to these changes.

ward rate/exercise price ratio at which the option delta is 25, 50, or 75 percent.

- With both the implied volatility and the forward rate/exercise price ratio, I can transform the volatilities into option prices using the normalized Black-Scholes formula. These prices are expressed in percent of the exercise price, exponentiated up to time T values. The differences between the spot exchange rates and the exercise prices are small and the maturity short, so the prices are also expressed, approximately, as a percent of the spot rate.

Then I solve $\min_{\{\lambda_t, k_t\}} \sum_{i=1}^{3} (u_t^i)^2$ or $\min_{\{\lambda_t\}} \sum_{i=1}^{3} (u_t^i)^2$, with the u_t^i defined by

$$
\begin{aligned}
v(R_t^{25\delta}, \sigma_t^{25\delta}) &= c(R_t^{25\delta}, \sigma_w, \lambda_t, k_t) + u_t^1 \\
v(R_t^{50\delta}, \sigma_t^{50\delta}) &= c(R_t^{50\delta}, \sigma_w, \lambda_t, k_t) + u_t^2 \\
w(R_t^{75\delta}, \sigma_t^{75\delta}) &= p(R_t^{75\delta}, \sigma_w, \lambda_t, k_t) + u_t^3
\end{aligned}
\tag{18}
$$

where $R_t^{25\delta}$, $R_t^{50\delta}$ and $R_t^{75\delta}$ refer to the forward rate/exercise price ratio corresponding to the delta in the superscript, and $\sigma_t^{25\delta}$, $\sigma_t^{50\delta}$ and $\sigma_t^{75\delta}$ refer to the observed implied volatilities on the 25 delta call, the 50 delta call, and the 25 delta put, respectively. This step is carried out by nonlinear least squares.[25]

[25] This step is similar to the procedure outlined in Manaster and Rendleman (1982). I carried out the estimation procedure using both Mathcad 5.0 and TSP 4.2. The numerical results were generally identical except for rounding errors.

C. Data

While options on currencies and currency futures are traded on several exchanges, liquidity in currency option trading is centered in the over-the-counter market. The most important differences between over-the-counter and public currency option markets for the purposes of this paper are:

- Only American options are traded on the exchanges, while primarily European options are traded over-the-counter. Closed form solutions exist only for European options, making them simpler to evaluate.
- Contract maturities on exchanges are fixed dates, so that option prices on successive days pertain to options of different maturities. In over-the-counter markets, a fresh option for standard maturities (one week and one, two, three, six and twelve months) can be purchased each day, so that a series of prices for options of like maturity can be constructed.
- Data on exchange-traded European cross-rate options are largely unavailable. The only European cross-rate option contract currently trading is the Philadelphia Stock Exchange's mark/sterling contract, which was introduced on September 25, 1992.

Data on European cross-rate options is difficult to obtain. The difficulty is compounded by the illiquidity of the options markets during the crises of September 1992 and July 1993. Price data for the same instrument from different sources were therefore occasionally quite different. No dealers have systematic records of European cross-currency risk reversal prices during 1992 and 1993. Risk reversal price data for mark-Paris and sterling-mark for particular days was assembled by interviewing traders at several firms. Some traders had personal notes made at the time, including data on risk reversal prices, while others drew on memory. Two sources appeared particularly reliable and were able to provide risk reversal price data for the same dates for mark-Paris. I identify these as data sets I and II. Only one of these sources had data on sterling-mark risk reversals. The data should be considered indicative; it is not drawn from any firm's internal record of prices quoted at the time.[26]

D. The Implied Distribution of Future Exchange Rates and Realignment Probabilities

If the exchange rate follows the geometric Brownian process represented in equation 2, as assumed by the Black-Scholes model, the logarithm of its time T value is distributed normally:

$$\ln(S_T) \sim \Phi\left[\ln(S_t) + \left(r - r^* - \frac{\sigma^2}{2}\right)\tau, \sigma^2\tau\right], \tag{19}$$

where r replaces α in the risk-neutral distribution. In consequence, the variable

$$z' = \frac{\ln(S_T) - \ln(S_t) + r - r^* + \frac{\sigma^2}{2}(T-t)}{\sigma(T-t)} \tag{20}$$

is a standard normal variate.

If the exchange rate follows the jump-diffusion process represented in equation 9, the risk-neutral distribution of the logarithm of the terminal

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[26] The sources are Swiss Bank Corporation and Goldman Sachs.

exchange rate is

$$(21)\quad \ln(S_T) \sim \Phi\left[\ln(S_t) + \left(r - r^* - \lambda k - \frac{\sigma_w^2}{2}\right)\tau + q_{t,T}\ln(1+k), \sigma_w^2\tau\right].$$

and the variate

$$(22)\qquad z = \frac{\ln\left(\frac{S_T}{S_t}\right) - q_{t,T}\ln(1+k) - \left(r - r^* - \lambda k - \frac{\sigma_w^2}{2}\right)\tau}{\sigma_w\sqrt{\tau}}$$

is standard normal. In the Bernoulli distribution model, the Poisson counter $q_{t,T}$ takes on the value zero with probability (1-λ) and the value unity with probability λ. The terminal distribution function is thus a mixture of two normal distributions.

I use the parameter estimates, together with the forward rate, to calculate the probability distribution of the future exchange rate. The realignment probability is the likelihood that $S_T \leq \bar{S}$, where $\bar{S}$ denotes the upper fluctuation limit (francs or pounds per mark). Setting τ=1 and substituting $F_{t,t+1} = S_t e^{r-r^*}$, I calculate the probability as

(23)

$$\pi_t \equiv \text{prob}\{S_T \leq \bar{S}\} = (1-\lambda)\Phi\left[\frac{\ln\left(\frac{\bar{S}}{F_{t,t+1}}\right) + \lambda k + \frac{\sigma_w^2}{2}}{\sigma_w}\right] + \lambda\Phi\left[\frac{\ln\left(\frac{\bar{S}}{F_{t,t+1}}\right) - \ln(1+k) + \lambda k + \frac{\sigma_w^2}{2}}{\sigma_w}\right].$$

The probability that the exchange rate will exceed the weak intervention limit is displayed in Tables 2 and 3 and Chart 2 for the French franc and Table 5 and Chart 3 for sterling.

The implied density function for mark-Paris September 16, 1992, is displayed in the lower panel of Chart 1 and compared with the density implied by the Black-Scholes model, with the skew and kurtosis ignored. The jump-diffusion model may be thought of as a vehicle for transforming the expected values contained in risk reversal prices into probabilities.

The implied density function is bimodal because σ_w is small. It can be interpreted as saying that the franc will follow a low-volatility random walk with the starting point either at its no-realignment rate or its post-realignment rate. The forward rate on September 16 was FF 3.4135. If there is no realignment, the exchange rate strengthens by λk (1.23 percent) to FF 3.3720 and drifts with a volatility of 1 percent per annum. If there is a realignment, the exchange rate jumps to FF 3.4730 and drifts with a volatility of 1 percent. With a higher σ_w, say, above 5 percent, and λ and k still equal to 0.41 and 0.03, the distribution would be unimodal, centered at FF 3.4135 but skewed to the right.

This approach employs the current forward rate as the market's point estimate of the future spot exchange rate, as dictated by the law of motion 9. However, one could also substitute for F_{t+1} any other point estimate of the future spot rate since the option prices inform us only about the shape of the distribution. The location of the distribution could be based, for example, on survey data.

E. Results

The data are displayed for the franc in Table 1 and for sterling in Table 4. The option price data are the output of the first step of the procedure and are shown in percent of the forward rate/exercise price ratio. I also report the estimated option values using the jump-diffusion formula, evaluated at the estimated values parameters. Comparison with the data indicates closeness of fit.

The results are displayed for the franc in Tables 2 and 3 and for sterling in Table 5. The estimates of λ_t are plausible, quite low before the onset of the crisis and during the period of quiescence for mark-Paris in spring of 1993 but rising at times of greater pressure. The estimates in which k is permitted to vary result for most days in a value not far from 0.03 for the franc. For sterling, the estimated values of k are about 3 to 5 percent on the days of acute selling pressure, quite different from the assumed value of 0.10. These results suggest that the market was surprised by the extent, if not by the timing, of sterling's depreciation.

The estimated realignment probabilities conform closely to narrative versions of the ERM's unraveling. The probabilities were low at the beginning of 1992 for both sterling and the franc. By late August, they rose slightly for the franc but more sharply for sterling, consistent with sterling's role as the prime target of the speculative attack. The realignment probabilities continued to rise toward mid-September 1992 and peaked on September 16 or 17 for both currencies. Realignment probabilities for the franc remained high for the rest of 1992 and into early 1993 but declined as the ERM enjoyed a respite from pressure in the spring of 1993. In the last few days of the narrow-band ERM, the probability again returned to very high levels.

VIII. Conclusions

As shown in this paper, option prices can be used to estimate the market's subjective probability distribution of future asset prices. Previous work on expectations of realignments in the ERM have focused on interest rate differentials as a raw indicator of these expectations. Chart 4 compares several such estimates for the French franc with those based on option prices.[27] Two generalizations emerge from a comparison of the option-based estimates with those based on the forward premium:

- The option-based approach confirms the finding that the exchange markets did not price in a high probability of realignment until late August 1992.
- During the periods of acutest pressure, the estimated probabilities of realignment using option prices are high compared with most estimates using forward premiums.

The option-based estimates confirm the conclusion of other researchers that expectations were highly unstable during the ERM crisis: within a short space of time, the market consensus on the probability of a sharp depreciation of the franc changed dramatically.[28]

At the same time, there are significant differences between the probability estimates derived from forward premia and those derived from option prices. During early September, the options markets clearly reflect the intensity of the market's doubts about the French franc parity against the mark, while French interest rates do not. If we assume that the option prices provide the more accurate indicator of market sentiment, to what may we attribute the lag in the forward premium?

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[27] The interest rate-based estimates are drawn from Malz (1994). The option-based estimates are the ones from data set I for which λ_t and k_t were estimated jointly.

[28] See, for example, Goldstein et al. (1993) and Eichengreen and Wyplosz (1993).

One explanation may be that in the short run, permitting money market rates to rise is only one possible central bank response to exchange rate pressures. Alternative and complementary responses include intervention in exchange markets, public declarations of resolve, and formal and informal attempts to curb speculative techniques. These responses may transitorily depress the money-market interest rates of currencies falling under selling pressure.

This paper has shown the usefulness of drawing inferences on the perceived probability distribution of future exchange rates from other asset prices, such as options, rather than relying exclusively on interest rate differentials. Future research in this area should examine how the information contained in option prices relates to that contained in forward exchange rates, and whether indicators of skewness in the distribution of exchange rates can improve the forecasting ability of forward rates.

References

Akgiray, Vedat, and G. Geoffrey Booth. 1988. "Mixed Diffusion-Jump Process Modeling of Exchange Rate Movements." *Review of Economics and Statistics* 70 (November): 631-37.

Baillie, Richard T., and Tim Bollerslev. 1989. "The Message in Daily Exchange Rates: A Conditional-Variance Tale." *Journal of Business and Economic Statistics* 7 (July): 297-305.

Baillie, Richard, and Patrick McMahon. 1989. *The Foreign Exchange Market: Theory and Econometric Evidence*. Cambridge: Cambridge University Press.

Ball, Clifford A., and Antonio Roma. 1993. "A Jump Diffusion Model for the European Monetary System." *Journal of International Money and Finance* 12 (October): 475-92.

Ball, Clifford A., and Walter N. Torous. 1983. "A Simplified Jump Process for Common Stock Returns." *Journal of Financial and Quantitative Analysis* 18 (March): 53-65.

__________. 1985. "On Jumps in Common Stock Prices and Their Impact on Call Option Pricing." *Journal of Finance* 40 (March): 155-73.

Bates, David S. 1988a. "The Crash Premium: Option Pricing under Asymmetric Processes, with Applications to Options on Deutschemark Futures." University of Pennsylvania, Rodney L. White Center for Financial Research Working Paper no. 36-88, October.

__________. 1988b. "Pricing Options on Jump-Diffusion Processes." University of Pennsylvania, Rodney L. White Center for Financial Research Working Paper no. 37-88, October.

__________. 1991. "The Crash of '87: Was it Expected? The Evidence from Options Markets." *Journal of Finance* 46 (July): 1009-1044.

_________. 1993. "Jumps and Stochastic Volatility: Exchange Rate Processes Implicit in PHLX Deutschemark Options." National Bureau of Economic Research Working Paper no. 4596, December.

Bertola, Giuseppe, and Lars E.O. Svensson. July. "Stochastic Devaluation Risk and the Empirical Fit of Target Zone Models." *Review of Economic Studies* 60 (July): 689-712.

Black, Fischer, and Myron Scholes. 1973. "The Pricing of Options and Corporate Liabilities." *Journal of Political Economy* 81 (May-June): 637-654.

Bodurtha, James N., Jr., and Georges R. Courtadon. 1987. "Tests of an American Option Pricing Model on the Foreign Currency Options Market." *Journal of Financial and Quantitative Analysis* 22 (June): 153-67.

Boothe, Paul, and Debra Glassman. 1987. "The Statistical Distribution of Exchange Rates: Empirical Evidence and Economic Implications." *Journal of International Economics*, 22 (May): 297-319.

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

Campa, José M., and P.H. Kevin Chang. 1994. "Assessing Realignment Risk in the Exchange Rate Mechanism Through Pound-Mark Cross-Rate Options." March. Mimeo.

Chen, Zhaohui, and Alberto Giovannini. 1992. "Target Zones and the Distribution of Exchange Rates: An Estimation Method." *Economics Letters* 40 (September): 83-89.

_________. 1993. "The Determinants of Realignment Expectations under the EMS: Some Empirical Regularities." NBER Working Paper no. 4291, March.

Collins, Susan M. 1985. "The Expected Timing of Devaluation: A Model of Realignments in the European Monetary System." Harvard University, October. Mimeo.

_________. 1992. "The Expected Timing of EMS Realignments: 1973-83." NBER Working Paper no. 4068, May.

Cookson, Richard. 1993. "Moving in the Right Direction." *Risk* 6 (October): 22-26.

Derman, Emanuel, and Iraj Kani. 1994. "Riding on a Smile." *Risk* 7 (February): 32-39.

Dumas, Bernard, L. Peter Jennergren, and Bertil Näslund. 1993a. "Realignment Risk and Currency Option Pricing in Target Zones." NBER Working Paper no. 4458, September.

__________. 1993b. "Currency Option Pricing in Credible Target Zones." NBER Working Paper no. 4522, November.

Dupire, Bruno. 1994. "Pricing with a Smile." *Risk* 7 (January): 18-20.

Eichengreen, Barry, and Charles Wyplosz. 1993. "The Unstable EMS." *Brookings Papers on Economic Activity* 1: 51-143.

Emminger, Otmar. 1986. *D-mark, Dollar, Währungskrisen: Erinnerungen eines Ehemaligen Bundesbankpräsidenten.* Stuttgart: Deutsche Verlags-Anstalt.

Garman, Mark B., and Steven W. Kohlhagen. 1983. "Foreign Currency Option Values." *Journal of International Money and Finance* 2 (December): 231-37.

Giavazzi, Francesco, and Alberto Giovannini. 1989. *Limiting Exchange Rate Flexibility: the European Monetary System.* Cambridge: MIT Press.

Goldstein, Morris, David Folkerts-Landau, Peter Garber, Liliana Rojas-Suárez, and Michael Spencer. 1993. *International Capital Markets: Part I. Exchange Rate Management and International Capital Flows*, Washington: International Monetary Fund.

Grabbe, J. Orlin. 1983. "The Pricing of Call and Put Options on Foreign Exchange." *Journal of International Money and Finance* 2 (December): 239-253.

Gros, Daniel, and Niels Thygesen. 1992. *European Monetary Integration.* London: Longman.

Group of Ten. 1993. *International Capital Movements and Foreign Exchange Markets* [Dini Report].

Hsieh, David A. 1988. "The Statistical Properties of Daily Foreign Exchange Rates: 1974-1983." *Journal of International Economics* 24 (February): 129-145.

_________. 1989. "Modeling Heteroscedasticity in Daily Foreign Exchange Rates: 1974-1983." *Journal of Business and Economic Statistics* 7 (July): 307-317.

Hsieh, David A., and Luis Manas-Anton. 1988. "Empirical Regularities in the Deutsche Mark Futures Options." *Advances in Futures and Options Research* 3: 183-208.

Jarrow, Robert A., and Andrew Rudd. 1983. *Option Pricing*, Homewood, Il: Richard D. Irwin, Inc.

Jorion, Philipe. 1988. "On Jump Processes in the Foreign Exchange and Stock Markets." *Review of Financial Studies* 1 (Winter): 427-445.

Krugman, Paul R. 1991. "Target Zones and Exchange Rate Dynamics." *Quarterly Journal of Economics* 106 (August): 669-682.

Latané, Henry A., and Richard J. Rendleman, Jr. 1976. "Standard Deviations of Stock Price Relatives Implied in Option Prices." *Journal of Finance* 31 (May): 369-381.

Lyons, Richard K. 1988. "Tests of the Foreign Exchange Risk Premium Using the Expected Second Moments Implied by Option Pricing." *Journal of International Money and Finance* 7 (March): 91-108.

Macbeth, James D., and Larry J. Merville. 1979. "An Empirical Examination of the Black-Scholes Call Option Pricing Model." *Journal of Finance* 34 (December): 1173-1186.

Malz, Allan M. 1994. "Forward Premia and the Probability of Realignment: The Case of the ERM Crisis 1992-1993." Federal Reserve Bank of New York, October. Mimeo.

_________. 1995. "Recovering the Probability Distribution of Future Exchange Rates from Option Prices." Federal Reserve Bank of New York, July. Mimeo.

Manaster, Steven, and Richard J. Rendleman, Jr. 1982. "Option Prices as Predictors of Equilibrium Stock Prices." *Journal of Finance* 37 (September): 1043-57.

Merton, Robert C. 1973. "The Theory of Rational Option Pricing." *Bell Journal of Economics and Management Science* 4 (Spring): 141-183.

__________. 1976. "Option Pricing When Underlying Stock Returns Are Discontinuous." *Journal of Financial Economics* 3 (January-March): 125-144.

__________. 1982. "On the Mathematics and Economics Assumptions of Continuous-Time Models." In William F. Sharpe and Cathryn M. Cootner, eds., *Financial Economics: Essays in Honor of Paul Cootner.* Englewood Cliffs, NJ: Prentice-Hall.

Neely, Christopher J. 1994. "Realignments of Target Zone Exchange Rate Systems: What Do We Know?" *Federal Reserve Bank of St. Louis Review* 76 (September/October): 23-34.

Nieuwland, Fred G.M.C., Willem F.C. Verschoor, and Christian C.P. Wolff. 1991. "EMS Exchange Rates." *Journal of International Financial Markets, Institutions and Money* 1: 21-42.

__________. 1993. "Stochastic Trends and Jumps in EMS Exchange Rates." July. Mimeo.

Rose, Andrew K. 1993a. "European Exchange Rate Credibility Before the Fall: The Case of Sterling." *Federal Reserve Bank of San Francisco Weekly Letter,* no. 93-18 (May 7).

__________. 1993b. Sterling's ERM Credibility: Did the Dog Bark in the Night?" *Economics Letters* 41: 419-27.

Rose, Andrew K., and Lars E.O. Svensson. 1991. "Expected and Predicted Realignments: The FF/DM Exchange Rate During the EMS." Board of Governors of the Federal Reserve System, International Finance Discussion Papers, no. 395, April.

Rubinstein, Mark. 1985. "Nonparametric Tests of Alternative Option Pricing Models Using All Reported Trades and Quotes on the 30 Most Active CBOE Option Classes from August 23, 1976 Through August 31, 1978." *Journal of Finance* 40 (June): 455-80.

__________. 1994. "Implied Binomial Trees." *Journal of Finance* 49 (July): 771-818.

Schmalensee, Richard, and Robert A. Trippi. 1978. "Common Stock Volatility Expectations Implied by Option Premia." *Journal of Finance* 33 (March): 129-47.

Shimko, David. 1993. "Bounds of Probability." *Risk* 6 (April): 33-37.

Svensson, Lars E.O. 1993. "An Interpretation of Recent Research on Exchange Rate Target Zones." *Journal of Economic Perspectives* 6 (Fall): 119-144.

Tucker, Alan L., and Lallon Pond. 1988. "The Probability Distribution of Foreign Exchange Price Changes: Tests of Candidate Processes." *Review of Economics and Statistics* 70 (November): 638-47.

Ungerer, Horst, Jouko J. Hauvonen, Augusto Lopez-Claros, and Thomas Mayer. 1990. "The European Monetary System: Developments and Perspectives." *Occasional Paper* 73. Washington, D.C.: International Monetary Fund.

Vries, Caspar G. de. 1994. "Stylized Facts of Nominal Exchange Rate Returns." In Frederick van der Ploeg, ed., *The Handbook of International Macroeconomics*. Oxford and Cambridge, U.S.: Blackwell.

Table 1

Market Data Used in Estimating Realignment Probabilities: French Franc

	Exchange Rates *		Option Prices **					
			Data Set I			Data Set II		
Date	S_t	$F_{t,t+1}$	25δ *call*	50δ *call*	25δ *put*	25δ *call*	50δ *call*	25δ *put*
31-Jan-92	3.4075	3.4087	0.0547	0.1379	0.0509	0.0846	0.2009	0.0726
19-May-92	3.3617	3.3619	0.0723	0.1551	0.0536	0.0920	0.2295	0.0846
27-Jul-92	3.3761	3.3773	0.0723	0.1551	0.0536	0.1058	0.2581	0.0945
21-Aug-92	3.3943	3.3949	0.0893	0.2009	0.0710	0.1132	0.2866	0.1065
11-Sep-92	3.4040	3.4054	0.2223	0.4290	0.1417	0.1690	0.4290	0.1604
14-Sep-92	3.3912	3.3930	0.2223	0.4290	0.1417	0.2145	0.5140	0.1887
15-Sep-92	3.3945	3.3963	0.3431	0.7398	0.2612	0.2160	0.5140	0.1881
16-Sep-92	3.4112	3.4134	0.3431	0.7398	0.2612	0.3048	0.7398	0.2752
17-Sep-92	3.4206	3.4271	0.3151	0.6835	0.2416	0.3919	0.9638	0.3629
25-Sep-92	3.3856	3.3952	0.3151	0.6835	0.2416	0.4211	1.0195	0.3823
30-Sep-92	3.3794	3.4045	0.2946	0.6271	0.2193	0.4411	1.0751	0.4051
06-Jan-93	3.4065	3.4181	0.2869	0.6271	0.2220	0.1889	0.4574	0.1682
19-May-93	3.3722	3.3725	0.1069	0.2866	0.1087	0.0952	0.2295	0.0835
28-Jul-93	3.4098	3.4187	0.2894	0.6553	0.2360	0.2352	0.5706	0.2109
30-Jul-93	3.4299	3.4441	0.4710	1.0751	0.3937	0.2368	0.5706	0.2103

* Spot rates are from official fixings against the dollar. Forward rates are calculated from spot rates and one-month Eurocurrency deposit rates.

** The options are defined as puts and calls on the German mark in terms of the French franc. The prices are calculated from market implied volatilities using the Black-Scholes formula by a method described in the text and are expressed, approximately, in percent of the value, in francs, of the mark.

Table 2

Realignment Probability Estimates: French Franc

Data Set I

	Both λ and *k* estimated						Only λ estimated; *k*=0.03				
	Option Prices *			Parameters			Option Prices *			Parameters	
Date	25δ *call*	50δ *call*	25δ *put*	λ_t	k_t	π_t	25δ *call*	50δ *call*	25δ *put*	λ_t	π_t
31-Jan-92	0.0543	0.1391	0.0497	0.1786	0.0052	0.0467	0.0596	0.1341	0.0442	0.0133	0.0227
19-May-92	0.0722	0.1558	0.0526	0.0702	0.0133	0.0002	0.0754	0.1526	0.0499	0.0252	0.0252
27-Jul-92	0.0722	0.1558	0.0526	0.0702	0.0133	0.0088	0.0754	0.1526	0.0499	0.0252	0.0252
21-Aug-92	0.0875	0.2077	0.0625	0.2501	0.0099	0.0358	0.1111	0.1840	0.0436	0.0441	0.0441
11-Sep-92	0.2110	0.4683	0.0863	0.2462	0.0254	0.2462	0.2549	0.4510	0.0673	0.1851	0.1851
14-Sep-92	0.2110	0.4683	0.0863	0.2462	0.0254	0.2454	0.2549	0.4510	0.0673	0.1851	0.1851
15-Sep-92	0.2938	0.8630	0.1668	0.3493	0.0389	0.3493	0.0724	0.7061	0.0970	0.4092	0.4068
16-Sep-92	0.2938	0.8630	0.1668	0.3493	0.0389	0.3493	0.0724	0.7061	0.0970	0.4092	0.4092
17-Sep-92	0.2712	0.7936	0.1536	0.3508	0.0356	0.3508	0.1278	0.6961	0.1088	0.3888	0.3888
25-Sep-92	0.2712	0.7936	0.1536	0.3508	0.0356	0.3508	0.1278	0.6961	0.1088	0.3888	0.3871
30-Sep-92	0.2582	0.7224	0.1342	0.3341	0.0331	0.3341	0.1775	0.6806	0.1225	0.3646	0.3646
06-Jan-93	0.2485	0.7238	0.1407	0.3522	0.0324	0.3522	0.1846	0.6883	0.1292	0.3754	0.3754
19-May-93	0.0928	0.3053	0.0958	0.4974	0.0123	0.0000	0.1701	0.2396	0.0269	0.0747	0.0747
28-Jul-93	0.2457	0.7594	0.1578	0.3777	0.0331	0.3777	0.1639	0.7032	0.1308	0.4005	0.4005
30-Jul-93	0.3867	1.2672	0.2827	0.3864	0.0556	0.3864	0.0000	0.7084	0.0024	0.4907	0.4907

* Option values are fitted using the jump-diffusion option pricing formula and the estimated parameter values.

Table 3

Realignment Probability Estimates: French Franc

Data set II

	Both λ and k estimated						Only λ estimated; k=0.03				
	Option Prices*			Parameters			Option Prices*			Parameters	
Date	*25δ call*	*50δ call*	*25δ put*	λ_t	k_t	π_t	*25δ call*	*50δ call*	*25 put*	λ_t	π_t
31-Jan-92	0.0819	0.2087	0.0645	0.3133	0.0089	0.1444	0.1092	0.1812	0.0407	0.0425	0.0464
19-May-92	0.0857	0.2410	0.0736	0.4018	0.0098	0.0000	0.1300	0.1999	0.0355	0.0531	0.0529
27-Jul-92	0.0977	0.2745	0.0775	0.3856	0.0115	0.0005	0.1533	0.2239	0.0342	0.0663	0.0663
21-Aug-92	0.1011	0.3077	0.0878	0.5683	0.0125	0.0530	0.1732	0.2449	0.0300	0.0775	0.0775
11-Sep-92	0.1416	0.4797	0.1230	0.4473	0.0190	0.3931	0.2680	0.3961	0.0273	0.1554	0.1554
14-Sep-92	0.1819	0.5851	0.1329	0.4081	0.0247	0.3569	0.3034	0.5526	0.0577	0.2478	0.2478
15-Sep-92	0.1840	0.5852	0.1312	0.4027	0.0248	0.3787	0.3023	0.5549	0.0597	0.2494	0.2494
16-Sep-92	0.2498	0.8578	0.2038	0.4249	0.0362	0.4249	0.0992	0.7207	0.1142	0.4511	0.4511
17-Sep-92	0.3180	1.1210	0.2756	0.4301	0.0476	0.4301	0.0005	0.6857	0.0996	0.5902	0.5902
25-Sep-92	0.3416	1.1908	0.2895	0.4212	0.0509	0.4212	0.0001	0.6902	0.0695	0.5792	0.4281
30-Sep-92	0.3572	1.2548	0.3091	0.4239	0.0537	0.4239	0.0001	0.6986	0.0373	0.5581	0.5383
06-Jan-93	0.1611	0.5160	0.1208	0.4120	0.0217	0.4116	0.2821	0.4460	0.0351	0.1824	0.1831
19-May-93	0.0897	0.2412	0.0711	0.3593	0.0101	0.0000	0.1314	0.2020	0.0373	0.0543	0.0543
28-Jul-93	0.1960	0.6541	0.1527	0.4208	0.0274	0.4208	0.2769	0.6894	0.1512	0.3757	0.3757
30-Jul-93	0.1979	0.6544	0.1509	0.4162	0.0275	0.4189	0.2751	0.6877	0.1494	0.3732	0.3770

* Option values are fitted using the jump-diffusion option pricing formula and the estimated parameter values.

Table 4

Market Data Used in Estimating Realignment Probabilities: Pound Sterling

Date	Exchange Rates *		Option Prices **		
	S_t	$F_{t,t+1}$	25δ call	50δ call	25δ put
31-Jan-92	2.8718	2.8745	0.1947	0.5027	0.1898
19-May-92	2.9264	2.9269	0.1386	0.3550	0.1329
27-Jul-92	2.8523	2.8535	0.1889	0.4914	0.1859
21-Aug-92	2.8072	2.8077	0.2171	0.5593	0.2115
11-Sep-92	2.7884	2.7894	0.3048	0.7735	0.2932
14-Sep-92	2.8110	2.8132	0.2987	0.7735	0.2955
15-Sep-92	2.7900	2.7920	0.3048	0.7735	0.2932
16-Sep-92	2.7781	2.7835	0.4461	1.1307	0.4338

* Spot rates are from official fixings against the dollar. Forward rates are calculated from spot rates and one-month Eurocurrency deposit rates.

** The options are defined as puts and calls on the German mark in terms of the pound sterling. The prices are calculated from market implied volatilities using the Black-Scholes formula by a method described in the text and are expressed, approximately, in percent of the value, in sterling, of the mark.

Table 5

Realignment Probability Estimates: Pound Sterling

Both λ and *k* estimated

Date	Option Prices *			Parameters		
Date	25δ *call*	50δ *call*	25δ *put*	λ_t	k_t	π_t
31-Jan-92	0.1920	0.5240	0.1860	0.4010	0.0194	0.0007
19-May-92	0.1348	0.3561	0.1347	0.0210	0.0210	0.0000
27-Jul-92	0.1841	0.4992	0.1798	0.4033	0.0178	0.0119
21-Aug-92	0.2079	0.5745	0:1989	0.4107	0.0222	0.2521
11-Sep-92	0.2763	0.8222	0.2505	0.4169	0.0344	0.4105
14-Sep-92	0.2687	0.8204	0.2575	0.4406	0.0339	0.3300
15-Sep-92	0.2763	0.8222	0.2505	0.4169	0.0344	0.4041
16-Sep-92	0.3796	1.2524	0.3405	0.4239	0.0537	0.4248

Only λ estimated; *k*=0.03

Date	Option Prices *			Parameters	
Date	25δ *call*	50δ *call*	25δ *put*	λ_t	π_t
31-Jan-92	0.2445	0.4613	0.1229	0.0237	0.0237
19-May-92	0.1362	0.3572	0.1352	0.0029	0.0029
27-Jul-92	0.2356	0.4527	0.1232	0.0221	0.0224
21-Aug-92	0.2877	0.5004	0.1171	0.0309	0.0852
11-Sep-92	0.4565	0.6604	0.0982	0.0581	0.1762
14-Sep-92	0.4535	0.6558	0.0950	0.0574	0.0734
15-Sep-92	0.4565	0.6604	0.0982	0.0581	0.1566
16-Sep-92	0.7169	0.9997	0.0820	0.1105	0.1690

* Option values are fitted using the jump-diffusion option pricing formula and the estimated parameter values.

Chart 1
Risk Reversals and the Probability Density Function

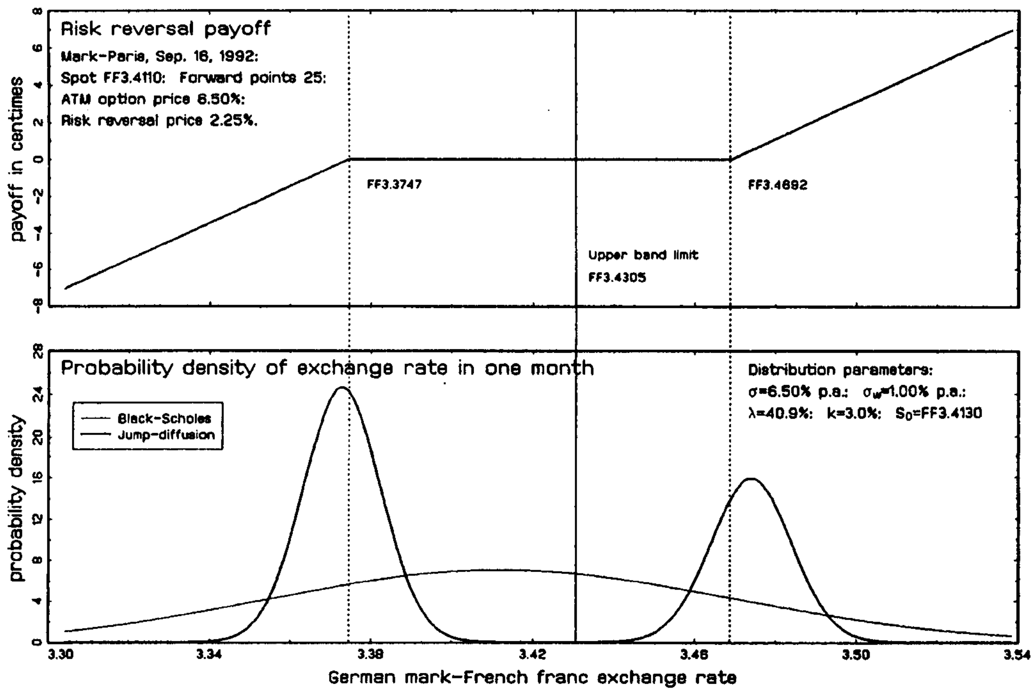

Chart 2
Probability of Realignment of French Franc:
Estimates from Option Prices

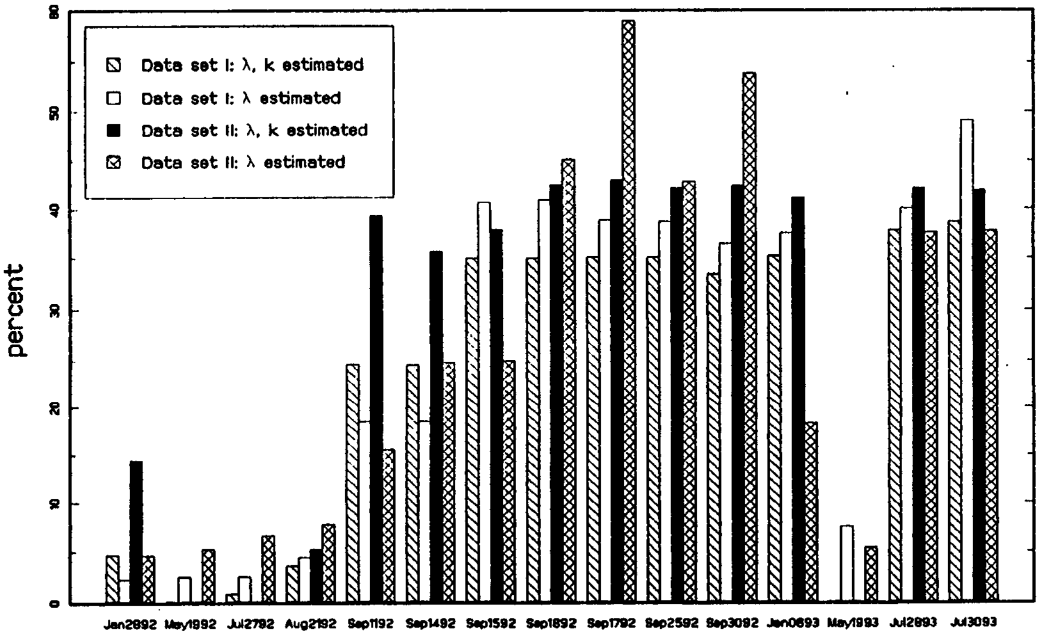

Chart 3
Probability of Realignment of Pound Sterling:
Estimates from Option Prices

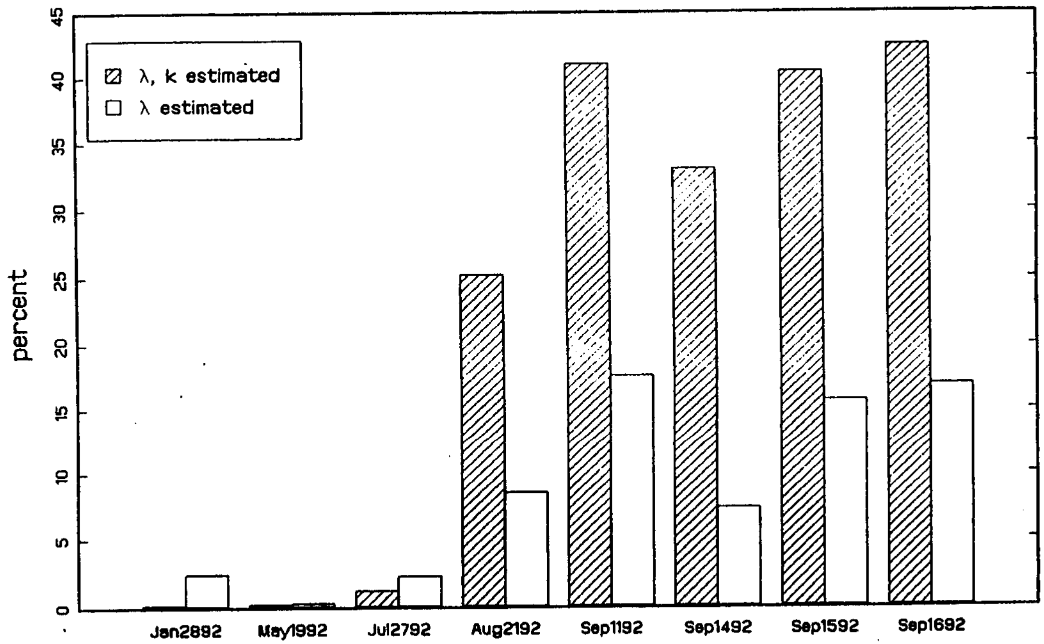

Chart 4
Probability of Realignment of French Franc in Next Month