DISCUSSION PAPER SERIES

No. 1823

EXTRACTING EXPECTATIONS ABOUT 1992 UK MONETARY POLICY FROM OPTION PRICES

Paul Söderlind

INTERNATIONAL MACROECONOMICS

Centre for Economic Policy Research

CEPR Discussion Paper No. 1823

March 1998

ABSTRACT

Extracting Expectations about 1992 UK Monetary Policy from Option Prices*

The UK pound left the ERM on 16 September 1992 after a period of turbulence. UK monetary policy soon shifted to lower short interest rates and an inflation target was announced. This paper uses daily option prices to estimate how the market's probability distribution of the future Deutsche mark/sterling exchange rate and UK and German interest rates changed over the summer and autumn of 1992. The results show, among other things, how various policy decisions affected the market's assessment of the probabilities of realignments and lending rate cuts.

JEL Classification: E43, E52, G13
Keywords: interest rates, exchange rates, futures, options, risk neutral distribution

Paul Söderlind
Stockholm School of Economics
PO Box 6513
SE–113 83 Stockholm
SWEDEN
Tel: (46 8) 736 9601
Fax: (46 8) 313 207
Email: nepso@hhs.se

*The author thanks Bhupinder Bahra, Neil Cooper, Magnus Dahlquist, and Lars E O Svensson for discussions; Citibank, Neil Cooper, Martin Edlund, Antti Koivisto and Alan Malz for generous help with data.

Submitted 16 January 1998

NON-TECHNICAL SUMMARY

Tight German monetary policy after reunification resulted in high interest rates and an appreciation of the ERM currencies against the US dollar. This had adverse effects on several ERM countries, which eventually undermined the credibility of the prevailing exchange rate parities. The UK pound was vulnerable because slow growth and low inflation in the United Kingdom created strong demands for a more expansive monetary policy. At the same time, a large number of the Conservative government's own supporters questioned the entire monetary policy framework, in particular the Maastricht Treaty.

The period between late August and mid-September 1992 was marked by a series of small crises for the pound: UK interest rates increased and the pound depreciated towards the lower ERM band limit. The UK monetary authorities eventually proved unwilling to accept very high interest rates in order to defend the exchange rate, and the pound was suspended from the ERM on 16 September 1992, 'Black Wednesday'.

Monetary policy soon shifted towards lower interest rates and a new monetary policy framework was put in place of the fixed exchange rate: short UK interest rates were lowered in a number of steps, a fairly ambitious inflation target was announced, and the Bank of England was granted more independence.

This paper uses data on futures and options on interest rates and exchange rates to give a detailed picture of how market expectations changed with these dramatic events.

An option gives the holder the right to buy an asset (for instance, a three-month bill) for a prespecified strike price at the expiry date of the option (for instance, two months ahead). The pay-off of the option is zero if the asset price at the expiry date is lower than the strike price, and positive otherwise. An option on a bond/bill is therefore a bet on the interest rate being lower than implied by the strike price. Similarly, an option on an exchange rate is a bet on a higher future exchange rate than implied by the strike price. The prices of these bets tell us something about the probability the market attaches to low interest rates/high exchange rates. By combining several options with different strike prices, we can trace out the market's probability distribution of the future rates.

This paper estimates time series of such distributions from daily option prices on the pound/Deutsche mark exchange rate, the ten-year sterling yield to maturity, the three-month sterling interest rate, and three-month Deutsche mark interest rates. The estimation is done for a sample of daily price quotes for the period between late-June to late-November 1992.

The estimated risk neutral distributions are mixtures of two normal distributions, where the parameters of the distributions are chosen to minimize the squared difference between actual and fitted option prices. This approach is flexible enough to capture the huge swings in market expectations over the summer and autumn of 1992, but still theoretical enough to rule out unreasonable results (like negative probabilities) and to provide a basis for a discussion about risk premia.

The estimates provide answers to questions like the following. In early September 1992, did the market assign a higher probability even to higher short interest rates than to lower interest rates, and what probability did the market assign to a realignment? How uncertain was the market about the long interest rate after Black Wednesday, and by how much was this uncertainty decreased by the announcement of the inflation target in early October 1992 and by the government's budget proposal in mid-November?

Several interesting results emerge. First, the path to Black Wednesday was marked by a series of small crises in late-August and early-September 1992. During each of these, the distributions of future UK interest rates and Deutsche mark/pound exchange rates widened because the market started to believe in the possibility of very high future interest rates and a moderate realignment. One possible interpretation is that the market believed in a small realignment; too small to ease the pressure on the pound. The actual outcome was, of course, a large devaluation and much lower interest rates. Second, the announcement of the UK inflation target on 8 October brought down long UK interest rates as well as uncertainty about future long interest rates. Third, the Autumn Statement by the UK Chancellor on 12 November put an end to the uncertainty about future monetary policy: the distribution of future UK interest rates narrowed dramatically immediately after the speech.

1 Introduction

The tight German monetary policy after the re-unification resulted in high interest rates and appreciation of the ERM currencies against the US dollar. The adverse effects on several of the ERM countries eventually undermined the credibility of the prevailing exchange rate parities. The British pound was vulnerable since the slow growth and low inflation in the UK created strong demands for lower interest rates, at the same time as a large number the government's own supporters questioned the entire monetary policy framework.

The UK monetary authorities eventually proved unwilling to accept very high interest rates in order to defend the exchange rate, and the pound was suspended from the ERM on 16 September 1992. Monetary policy soon shifted to significantly lower short interest rates. Somewhat later, a fairly ambitious inflation target was announced, and the Bank of England was granted a more independent status. The purpose of this paper is to give a detailed picture of the market expectations about these events.

Refined techniques for extracting market expectations from financial prices have recently been applied to this episode. For instance, Malz (1996) and Mizrach (1996) estimate "risk neutral" distributions of the pound exchange rate for the period up to the end of September 1992, and Campa and Chang (1996) calculates a minimum realignment intensity for the exchange rate using arbitrage arguments only.

This paper differs on several accounts. First, it studies a broader range of asset prices: the three month sterling and mark interest rates, a ten year sterling yield to maturity, and also the pounds/mark exchange rate. Second, it pays attention to both the ERM crisis in August and September 1992 and the announcement of the new UK monetary policy framework in October and November 1992. Third, it applies and extends the methods in Söderlind and Svensson (1997), which are flexible enough to capture the huge swings in market expectations over the summer and autumn of 1992, but still theoretical enough to rule out negative probabilities and to allow a meaningful discussion of risk premia. The results are presented in the form of a time series of 90% confidence intervals for each of the four assets.

2 Estimation of Risk Neutral Distributions from Option and Futures Prices

2.1 Option Pricing under Mixtures of Normal Distributions

A European call option gives the holder the right, but not the obligation, to buy an asset for the strike price, X, at the expiry date, τ. The price of the asset is then $Q(\tau)$, so the option's payoff is the maximum of zero and $Q(\tau) - X$. In a frictionless market, the law of one price (assets with the same payoff structure have the same price) implies that the call option price, C, at the trade date t is

$$C(t,\tau;X) = \mathrm{E}_t\left\{D(t,\tau)\max[0, Q(\tau) - X]\right\}, \tag{2.1}$$

where $D(t,\tau)$ is a nominal discount factor.[1] As an example, *Figure 2.1.a* shows a fairly typical relationship between the call price and the log strike price, in this case for trade on 16 September of options on the December 1992 short sterling interest rate (more about data later on). Call options with high strike prices are cheap since there is only a small chance that they will turn out to be profitable.

Söderlind and Svensson (1997) assume that the distribution of the logs of $D(t,\tau)$ and $Q(\tau)$, conditional on the information in t, is a mixture of n bivariate normal distributions.[2] Let $\phi(x;\mu^j,\Omega^j)$ denote a normal multivariate density function over x with mean vector μ^j and covariance matrix Ω^j. The weight of the j^{th} normal distribution is α^j, so the probability density function, pdf, of $\ln D(t,\tau)$ and $\ln Q(\tau)$ is

$$\mathrm{pdf}\left(\begin{bmatrix}\ln D(t,\tau)\\ \ln Q(\tau)\end{bmatrix}\right) = \sum_{j=1}^{n}\alpha^j\phi\left(\begin{bmatrix}\ln D(t,\tau)\\ \ln Q(\tau)\end{bmatrix};\begin{bmatrix}\bar{d}^j\\ \bar{q}^j\end{bmatrix},\begin{bmatrix}\sigma^j_{dd} & \sigma^j_{dq}\\ \sigma^j_{dq} & \sigma^j_{qq}\end{bmatrix}\right), \tag{2.2}$$

with $\sum_{j=1}^{n}\alpha^j = 1$ and $\alpha^j \geq 0$. *Figure 2.1.b* gives a univariate example; it illustrates how mixing two normal distributions (thin solid and dashed curves) produces a distribution (thick solid curve) with pronounced skewness. In fact, two normal distributions are enough to produce a wide range of different shapes (skewed, bi-modal, leptokurtic, and so forth).

[1] See, for instance, Duffie (1992).

[2] Ritchey (1990), Melick and Thomas (1997), and Bahra (1996) assume that the risk-neutral distribution is a mixture of *univariate* log-normals. This is implied by the assumption of *bivariate* log-normals in Söderlind and Svensson (1997). Mixtures of normals have recently been increasingly used in econometric studies (see, for instance, Hamilton (1989)).

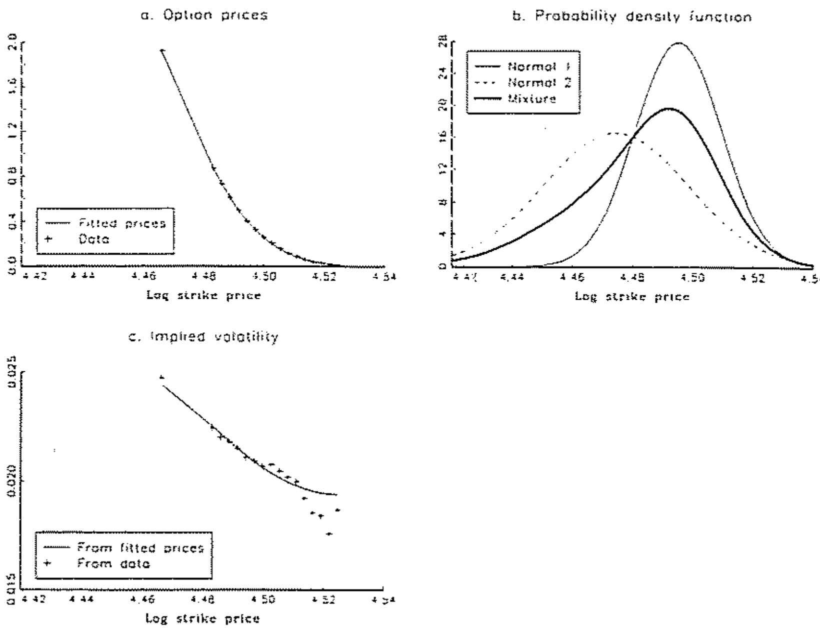

Figure 2.1: Data and results for short sterling interest rate option on 16 September 1992.

One interpretation of mixing normal distributions is that they represent different macro economic "states," where the weight, α^j, is interpreted as the probability of state j.

Let $i(t,\tau)$ be the spot interest rate on a bill with maturity date τ, and $\Phi(.)$ be the standardized normal distribution function. If $\bar{d}^j = \bar{d}$ and $\sigma_{dd}^j = \sigma_{dd}$ in (2.2), then the European call option price (2.1) has a closed form solution in terms of the spot interest rate, strike price, and the parameters of the bivariate distribution

$$C(X) = e^{-i(t,\tau)(\tau-t)} \sum_{j=1}^{n} \alpha^j \left[\exp\left(\bar{q}^j + \frac{1}{2}\sigma_{qq}^j + \sigma_{dq}^j\right) \Phi\left(\frac{\bar{q}^j + \sigma_{qq}^j + \sigma_{dq}^j - \ln X}{\sqrt{\sigma_{qq}^j}}\right) - X\Phi\left(\frac{\bar{q}^j + \sigma_{dq}^j - \ln X}{\sqrt{\sigma_{qq}^j}}\right)\right] \tag{2.3}$$

A forward contract written in t stipulates that, in period τ, the holder of the contract gets one asset (then worth $Q(\tau)$) and pays $F(t,\tau)$. This can be thought of as an option with a zero strike price and no discounting. The forward price then follows directly from (2.3) as

$$F(t,\tau) = \sum_{j=1}^{n} \alpha^j \exp\left(\bar{q}^j + \sigma_{dq}^j + \frac{\sigma_{qq}^j}{2}\right) \tag{2.4}$$

In the case with only one normal distribution ($n = 1$), (2.3) and (2.4) can be combined to give the Black-Scholes formula.

2.2 Estimation of the Distributions

We are primarily interested in estimating the parameters in the true marginal distribution of the future asset price, $Q(\tau)$. The basic idea is to use data on option and futures prices (as a close approximation to the forward prices) to "back out" the parameters of the distribution from the asset pricing relations (2.3) and (2.4).

From (2.2) the true (marginal) distribution of the future log asset price is a mixture of univariate normal distributions

$$\text{pdf}[\ln Q(\tau)] = \sum_{j=1}^{n} \alpha^j \phi\left(\ln Q(\tau); \bar{q}^j, \sigma_{qq}^j\right). \tag{2.5}$$

Suppose we knew these parameters - would that be enough to determine the correct forward and options prices? No, both the forward contract and the option have uncertain payoffs and may therefore be affected by risk premia. In (2.3) and (2.4) the risk premia show up in the form of the covariance of the future asset price with the stochastic discount factor, σ_{dq}^j.

Conversely, data on forward and option prices can only help us to back out the parameters of the "risk neutral" distribution. The weights, α^j, and the variances, σ_{qq}^j, are the same as in the true distribution (2.5), but the means are $\bar{q}^j + \sigma_{dq}^j$ instead of $\bar{q}^j$ This is evident from (2.3) and (2.4), where $\bar{q}^j$ and σ_{dq}^j always show up as a sum, so there is no way to separate them.[3]

The risk neutral distribution will, of course, coincide with the true distribution if the covariance terms are zero. However, in general, both the mean and the variance of the

[3] See Cox and Ross (1976) for risk neutral valuation of contingent claims.

risk neutral distribution are different from those of the true distribution.[4]

In estimating the distributions of the three month sterling interest rate, ten year sterling yield to maturity, and the marks/pound exchange rate (more about data later on) I use a mixture of two lognormals. For each trade day, the parameters are estimated by minimizing the sum of squared price errors of options and futures. The probabilities of the two states (α^1 and $1 - \alpha^1$) are restricted to be the same for all three variables. In practice, this does not make much difference for the interest rate distributions, but it is necessary for estimating the exchange rate distribution since we have only three exchange rate options. The distribution of the three month mark interest rate is also a mixture of two lognormals, but is estimated separately since there is no strong reason to believe that Germany had the same "macro economic states" as the UK.

As an example, return to Figure 2.1, which shows some estimation results for 16 September (a particularly challenging day). Figure 2.1.a shows that the model fits the prices of the 17 available options of the December three month sterling interest rate fairly well, even if the prices of options with very high strike prices are overestimated. This is perhaps more easily seen in Figure 2.1.c, which shows the "implied volatilities," which are obtained by backing out the only unknown parameter in the Black-Scholes formula from in each option separately. If the assumption of only one normal distribution was correct, then the implied volatilities should be on a horizontal line. For this trade day they are clearly not, but the estimated model seems to capture most of the features of data (fitted values are marked by the solid curve). The estimated probability density function in Figure 2.1.b (thick solid curve) is indeed much more skewed than a normal distribution.

3 Data

This section describes the data and discusses how it relates to the assumptions in Section 2. More details are found in Appendix A. The main data are daily option quotes for four different type of contracts: three month sterling interest rate futures, three month mark

[4] The variance is unaffected by the risk adjustment in the special case where $\sigma^j_{dq} = \sigma_{dq}$ and $\bar{q}^j = \bar{q}$ for all j. This is, of course, always the case when $n = 1$.

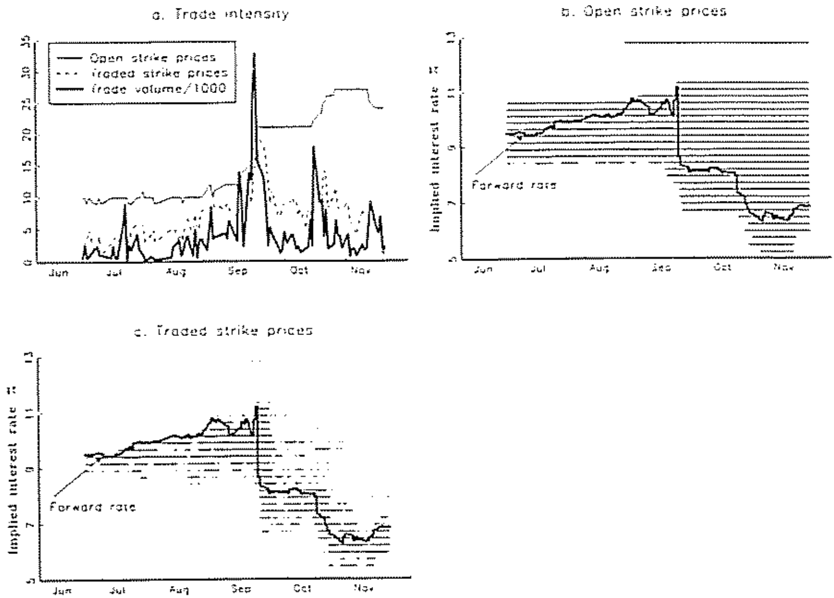

Figure 3.1: Trade statistics for the short sterling interest rate option.

interest rate futures, long UK government bond futures, and the marks/pound exchange rate. The sample covers each trade day between 23 June 1992 and 20 November 1992.

The interest rate and bond options are from London International Futures and Options Exchange (LIFFE) and are paid at exercise, not at purchase. The daily settlement prices, fixed by an administrative decision at the close of business, are used for the "marking to market." This ensures that investors each day receive their gains (and pay their losses) due to price changes. These institutional features ("futures style margining") have three important consequences. First, the interest rate term in (2.3) drops out. Second, there is essentially no opportunity cost of holding the option, so the LIFFE options, which are American (can be exercised before or on expiry date), are actually priced as European options (can only be exercised on expiry date).[5] This is of great help since it is hard to arrive at closed form expressions for prices of American options. Third, the settlement prices of options with open positions affect the daily cash flow of at least two investors (issuer and holder). This should provide incentives to the members of the exchange (some of which hold positions, others act as brokers) to "battle out" settlement prices close to the equilibrium prices.

The three month sterling interest rate, called *short sterling* below, futures option expired on 16 December 1992, and delivery into the futures contract was on the following day. *Figure 3.1.a* illustrates the trade intensity by showing the number of different strike prices with open positions and trade on each day. It also shows the number of contracts (à 500,000 pounds) traded. According to all three series, the trade intensity was fairly high after mid August, with marked peaks in mid September and mid October. The average number of options with open positions and trade were 17 and 7, respectively, and the average number of traded contracts was 4365.

Figure 3.1.b shows which short sterling options that had open positions on each day; *Figure 3.1.c* does the same for trade. The strike prices (vertical axis) have been transformed into interest rates in order to facilitate the comparison with the estimation results presented later. The thick solid curve is the forward interest rate. Until late August, most trade was in options with strike (interest) rates at or below the forward rate, so the data contains relatively little information about the shape of the distribution above the forward rate. However, there were sizeable open positions (several thousand contracts) for strike rates above the forward rate, and the prices on those options should contain useful information (see the previous discussion). In most of the paper, I will therefore use all options with open positions. As a robustness check, I will study if the estimation results are markedly different when the non-traded options are excluded. (The answer turns out to be no.) After mid September there were generally open positions and trade for a wide range around the forward rate.

The three month mark interest rate, called *Euromark* below, futures option expired on 14 December 1992, with delivery into the futures contract the following day. The trade

[5] See Chen and Scott (1993) for a theoretical argument.

intensity was similar to that of the short sterling option with an average number of 13 and 6 options with open positions and trade, respectively, and an average of 3669 traded contracts (à 1,000,000 marks).

The LIFFE interest rate options are not options on a bill/bond, but on futures on a bill/bond. This distinction does not matter if three conditions are satisfied: *(i)* the option is European; *(ii)* the option and the futures have the same maturity; and *(iii)* only one unique bond/bill can be delivered into the futures contract. The options on the short sterling and Euromark satisfy all three conditions, but the option on the *long gilt* (UK government bond) futures does not. This option expired on 23 November 1992, but the seller of the underlying futures could deliver any of a number of different bonds at any time during December 1992.

In practice, only two different bonds were actually delivered (in significant amounts) into LIFFE's long gilt futures at any time between September 1991 and March 1993. Moreover, most futures positions were typically closed within two weeks of the expiry date of the option. We may therefore assume that either of these two specific bonds would be delivered, and that both the option and futures expired on 1 December 1992. This allows me to present the results in terms of the yield to maturity, which may be more informative than the bond price. It turns out that the results are very similar for the two bonds, so we may as well look at only one of them: the 13.5% coupon bond maturing in 2004.

The evolution of the trade intensity of the long bond option was similar to that of the short sterling option, even if the long bond option was, on average, less traded. The average number of strike prices with open positions and trade were 11 and 5, respectively, and the average number of traded contracts (à 50,000 pounds) was 2430

The marks/pound *exchange rate* options are over-the-counter European options on the exchange rate one month from the trade date. The quotes, recorded by Citibank at noon London time, are for three different combinations of call and put options (at-the-money forward, 25-delta "risk reversals" and "strangles"). They allow us to calculate implied call option prices at three different strike prices: below, at, and above the current forward rate, respectively, with the exact location depending on the uncertainty of the market.

These data are described in detail by Malz (1996), who notes that liquidity was generally good, with the notable exceptions of 15 and 16 September.

In addition to the option and futures data described above, I also use interest and exchange rate data from Bank of International Settlements (one, three, and six month sterling eurodeposits, one month mark eurodeposits, and the marks/pound exchange rate).

4 Results

4.1 Inside the ERM

Figures 4.1.a-d illustrates the estimation results for each of the four assets by showing the risk neutral expected values (forward rates) and the 90% confidence bands. In general, we would expect the confidence interval to decrease if the trade date gets closer to the expiry date of the option, as it does for the interest rate and bond options, but not for the exchange rate option.[6]

The period from early July to mid August was characterized by a slowly depreciating expected exchange rate and increasing expected sterling interest rates. The figures show that uncertainty - the width of the confidence intervals - increased steadily over this period. The 90% confidence band for the exchange rate crossed the lower ERM band limit (2.778 marks/pound) for the first time on 14 July.

In late August, the US dollar depreciated rapidly and a series of concerted central bank interventions failed to strengthen the dollar.[7] This seems to have increased tensions within the ERM (the effect on the ERM currencies was asymmetric). A few days later, French opinion polls showed, for the first time, a small majority for "no" in EMU in referendum (to be held on 20 September). Over a couple of days, the expected short sterling and long gilt increased by 0.5%, the expected pound exchange rate depreciated

[6] In the Black-Scholes model, the variance is decreasing linearly to zero.

[7] The following is a lists of commonly cited events. July 16: Italian and German discount rates raised. July 30: rumours about French polls in favour of "no." August 11, 21, and 24: fall of dollar in spite of concerted inventions. September 3: UK government announces Ecu 10 billion borrowing programme to support the pound. September 5: meeting of EU finance ministers and central bankers. September 8: FIM abandons Ecu peg. September 13: ITL devalued. September 14: reduction in German discount rate. September 16: the pound is suspended from ERM. September 20: small majority in favour of EMU in French referendum. October 8: UK chancellor announces inflation target. October 16: Bank of England cuts the lending rate. October 29: Mansion House speech by UK chancellor. November 12: Autumn Statement in Parliament by UK chancellor. Announcement of lending rate cut the next day. See, for instance, Bank of England (1992) and Stephens (1996) dicussions of these events.

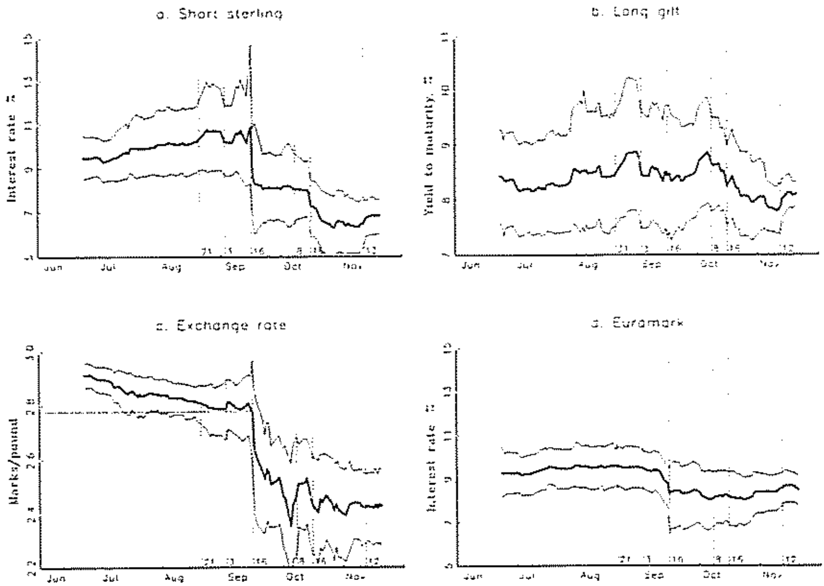

Figure 4.1: Risk neutral expected values and 90% confidence intervals.

1%, and the uncertainty grew significantly. In contrast, the distribution of the Euromark was almost unaffected.

The widening of the confidence bands was mostly due to the emergence of elongated upper tails of the interest rate distributions and an elongated lower tail of the exchange rate distribution. The market clearly believed that UK monetary policy was in big trouble. For instance, the risk neutral probability of an exchange rate below the band limit (2.778) was only 16% on 20 August but increased to 38% on 26 August.[8] Similarly, the risk neutral probability of a short sterling above 10.7% increased from 26% on August 20 to 46% on 26 August.

[8] This is similar to the findings by Malz (1996), who estimates realignment probabilities of up to 40% in late August. Mizrach (1996) estimates the risk neutral probability that the pound should depreciate more than 3% against the US dollar (using a different method). He finds that this probability increases from early September, but reaches a significant level only on 15 September.

This pattern of market expectations of a cheaper pound and higher sterling interest rates was to repeat itself on several occasions before the pound finally left the ERM on 16 September. Afterwards, we know that the direct result of leaving the ERM was a cheaper pound, and *lower* interest rates, so the market got it only half right. So what kind of scenario did the market consider? Probably a small realignment - too small to ease the pressure on the pound, so the interest rate differential towards the mark would have to remain high. The market did certainly not expect the pound to fall as it did - to 2.642 on 17 September (and then even further). On August 26 this event had only a 1% probability.

The crisis in late August appears to have been brought to an end by the announcement of the Ecu borrowing programme to support the pound (on 3 September). The expected sterling interest rate and exchange rate, as well as the uncertainty, then returned to their mid August values.

The respite was short, and a second crises developed a couple of days later, possibly prompted by the further easening of US monetary policy, and worsened by the failed meeting of the European finance ministers and central bankers over the weekend 5 and 6 September. The expected exchange rate depreciated rapidly the following Monday, and the probability of an exchange rate below the band limit increased from 20% to 30%. The European exchange rate market was now very turbulent, and on 8 September the Finnish markka had abandon the unilateral Ecu peg. On the same day, the expected short sterling rose to the same levels as in late August, and the uncertainty about both the exchange rate and the short sterling increased. One difference to the crisis in late August, however, was that the expected long gilt remained unchanged this time.

This second crisis was temporarily checked around the next weekend (12-13 September): the Italian lira was realigned on 13 September, and the German discount and Lombard rates cut the next day. This generated the first significant change in the expected Euromark since the start of the sample - it decreased by 0.6% to 8.8%, but the uncertainty remained small. This change was within the 90% confidence interval, but a larger change would not have been. For instance, a December Euromark of 8.3% (the expected value on 16 September) had only a 5% probability on 11 September. This gives some perspective on the common claim that "the reductions of 50 basis points in the German discount rate ...were smaller than had been *hoped* for" (Bank of England (1992), page 392, emphasis added). Maybe, but not smaller than *expected*.

In any case, the expected short sterling returned to its mid August value, and the expected exchange rate appreciated somewhat. This is similar to what happened after the Ecu borrowing programme (3 September). However, there is one important difference: the uncertainty did not fall back this time.

4.2 Out of the ERM

On 16 September, the "Black Wednesday," the ERM was in a state of chaos: several currencies were forced below the band limits and central banks intervened heavily. At the close of business (London), the expected Euromark had fallen by 0.5% to 8.3%. The shape of the Euromark distribution had also changed significantly - for the first time since the start of the sample. It was now much wider than before and had an elongated lower tail; the market did not rule out further cuts in the mark interest rate. The expected short sterling, in contrast, had increased to roughly the same levels as in late August, and the uncertainty was extremely large. The uncertainty about the long gilt had also increased somewhat, but the expected value was actually somewhat lower than the day before.

Trade in all three interest rate options was brisk on 16 September. In contrast, there was little trade in the over-the-counter exchange rate option (see Malz (1996)), so we should probably treat the results for it with some caution. In any case, the expected exchange rate was (by noon London time) essentially the same as the day before, but the width of the confidence band almost twice as large - mostly because of an elongated lower tail.

The pound was suspended from the ERM after 7.30 pm (GMT). The next day, the expected exchange rate depreciated more than 5% against the mark, but the exchange rate distribution still had an elongated lower tail; the market was very uncertain about where the floating pound would go, and did not rule out further depreciation. On the same day, the expected short sterling fell more than 2%. The elongated upper tail of its

Figure 4.2: UK yield curve.

distribution was cut off, but the uncertainty remained large.

We have already noted that these dramatic changes were big surprises for the market, at least compared to what it believed in late August. The same is true for the market beliefs just before Black Wednesday. On 14 September, the probability of an exchange rate below 2.64 (the expected value as of 17 September) was only 1%. Similarly, the probability of a short sterling below 8.6% (the expected value as of 17 September) was just 10%.

The distribution of the Euromark and the long gilt did not change much on 17 September. The latter might appear surprising, but it seems as if the 13.5% coupon bond maturing in 2004 (with a duration of approximately six years) was located at a point where the effects of lower expected short interest rates and higher expected very long rates cancelled each other. This is illustrated in *Figure 4.2*, which shows estimated UK yield curves on 14 and 18 September.[9]

To illustrate how these dramatic changes map into changes in option prices, *Figure 4.3.a* shows the option prices against the strike (interest) rates on 14, 16, and 18 September 1992, and *Figure 4.3.b* shows the risk neutral distributions for the same days. The estimated distribution shifted to higher interest rates between 14 and 16 September, which meant a lower probability of a positive option payoff (actual interest rate below the

[9] Estimated extended Nelson and Siegel yield curve model (see Svensson (1995) or Söderlind and Svensson (1997)). Estimation by Sveriges Riksbank.

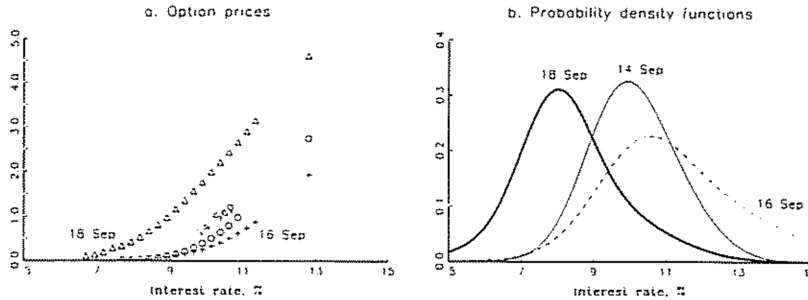

Figure 4.3: Data and results for short sterling interest rate.

strike rate). The options were therefore less valuable. Exactly the opposite holds for the change between 16 and 18 September. It is also interesting to note that the price changes are magnitudes larger than the estimation errors in Figure 2.1.a.[10]

4.3 Outside the ERM

The first two weeks outside the ERM brought an ongoing depreciation of the expected exchange rate, but fairly stable expected interest rates. There are no clear signs of any effects of the French voters' approval of the Maastricht treaty on 20 September, and the UK lending rate cut on 22 September (from 10% to 9%) seems to have been anticipated.

The uncertainty remained very large throughout September, probably because it was unclear what kind of monetary policy framework the UK government would put in place of the fixed exchange rate. Expectations about policy announcements around the Conservative Party conference possibly played a role in the turbulence in early October: the

[10] One could possibly suspect that the lonely option with a strike rate of approximately 13% is very important for the results. That would be problematic, since this option was traded infrequently (see Figure 3.1). Fortunately, this is not the case. For instance, on 16 September, estimation based on only traded options (excluding the 13% option) gives essentially the same distribution as in Figure 4.3.b (based on all options with open positions). The reason is that the 13% strike rate is so high that this option was almost certain to be exercised, and therefore contained essentially the same information as the forward rate. This is particularly clear on 18 September when an investor could either enter a foward contract which forced him to pay 91.6 in December 1992 to get a three month bill, or an option contract which forced him to pay 4.6 in December 1992 in return for the right to aquire the same bill for the strike price 87. Since 87+4.6=91.6, the market did not value the right to not exercise the option (if the bond price would be below 87, that is, the interest rate above 13%).

expected long gilt increased rapidly, the expected exchange rate depreciated, and the uncertainty grew. The expected short sterling was not affected, but the uncertainty around it increased. The pound recovered already the next day (6 September), but the problems were not over. The exchange rate uncertainty stayed large, and the expected long gilt increased even further. Calm was restored only on 8 October, probably because of the announcement of a UK inflation target.

The expected short sterling dropped 0.6% (to 7.3%) on 16 October as the Bank of England cut the lending rate (from 9% to 8%). This took the market by some surprise; two days earlier, the risk neutral probability of a December short sterling less than 7.3% was only 13%. Both the expected short sterling and the expected long gilt continued to decrease for several weeks thereafter, possibly driven by the Prime Minister's new "strategy for growth," announced on 20 October which aimed at "early and strong recovery" (see Stephens (1996)). There were signs of market expectations about even further interest rate cuts: the lower tail of the short sterling distribution was elongated.

The chancellor delivered his Autumn statement in Parliament on 12 November and announced a lending rate cut (from 8% to 7%) to take place the next day. The market responded by *increases* in the expected short sterling and long gilt, but the uncertainty decreased dramatically. It seems as if the speech surprised the market by strongly (and credibly, it appears) signalling that no further cuts should be expected.

5 Robustness of Results

5.1 Precision of the Estimates

Figure 5.1.a illustrates the precision of the estimator. The average price error is very close to zero for most days and the average absolute price errors fluctuate around 0.0026. Compared with the mean absolute price changes of 0.075, it appears as if the estimation errors are small. The price errors are somewhat larger in mid September, but still small compared with the large daily prices changes during that period (see, for instance, Figure 4.3.a).

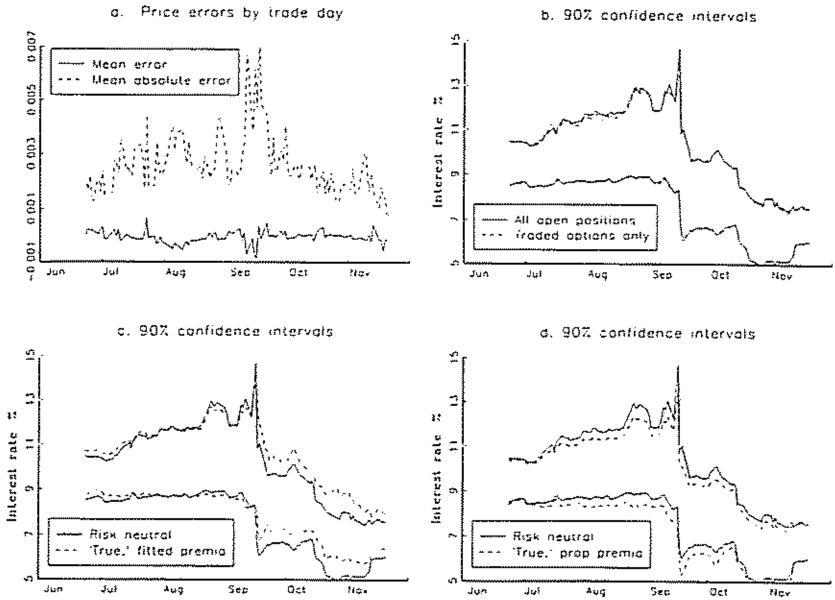

Figure 5.1: Robustness of results for short sterling interest rate.

5.2 Traded Options versus Options with Open Positions

Figure 5.1.b compares the 90% confidence intervals (for the short sterling) based on two different estimations: one using all options with open positions (the main approach) and the other using only options with trade. We noted earlier (in Figure 3.1) that there was relatively little trade in options with strike (interest) rates above the forward rate, at least before mid September. This shows up here in the form of a small difference between the upper confidence intervals until late August and occasionally in September. Otherwise, the differences are small. For instance, the largest difference for the lower boundary is 9 basis points (0.09%).

5.3 Risk Premia

The risk neutral distribution, which is what has been discussed so far, is a mixture of two normal distributions with means $\bar{q}^1 + \sigma^1_{dq}$ and $\bar{q}^2 + \sigma^2_{dq}$, respectively. The true distribution differs by setting σ^1_{dq} and σ^2_{dq} to zero. Unfortunately, we have no direct information about these covariance terms, but the effect of them can be illustrated by making assumptions about the (forward) term premium and the ratio $\sigma^2_{dq}/\sigma^1_{dq}$.

To see how, note that the forward price is given by (2.4) and that $\mathrm{E}_t \ln Q(\tau)$ equals $\sum_{j=1}^{n} \alpha^j \bar{q}^j$. If the term premium and the ratios $\sigma^j_{dq}/\sigma^1_{dq}$ ($j = 2, ..n$) are known, then σ^1_{dq} is the only unknown in the equation for the forward term premium[11], $\ln F(t,\tau) - \mathrm{E}_t \ln Q(\tau)$, so we can solve for it.

I use this approach to illustrate how different risk premia could affect the confidence intervals for the short sterling. To do this, $\sigma^2_{dq}/\sigma^1_{dq}$ is set equal to the ratio of the standard deviations of the two normal distributions[12], and two different assumptions about the term premium are explored.

In *Figure 5.1.c*, the term premium is predicted from a regression of ex post term premia on the lagged forward rate and three month interest rate, using a daily sample for 28 November 1979 to 31 August 1997 (excluding 1992). In this sample, the average ex post term premium is virtually zero, and the regression coefficients are 0.59 and -0.55, respectively..[13] Interestingly, these coefficients are very similar to what MacDonald and Macmillan (1994) found on a monthly 1989:10-1992:10 sample of survey data of interest rate expectations, but somewhat larger (in magnitude) than Gerlach and Smets (1995) found on monthly ex post data for 1968:4-1993:12.

The regression predict very small term premia for the period before the pound left the ERM, but term premia of -0.5% to -1% for the period out of ERM.[14] The "true" confidence intervals are then 0.5% to 1% above the risk neutral intervals for the period

[11] If $Q(t)$ is a price on a zero coupon bond, then this premium is proportional to the term premium on the continuously compounded forward interest rate.

[12] With only one state, the risk premium equals σ_{dq}, which in a mean-variance setting would be proportional to the standard deviation of the asset price.

[13] The data are daily three and six month Euro deposits rates from BIS. Some observations with obviously incorrect records have been excluded.

[14] The forward rate was approximately equal to the spot rate before 17 September, and clearly lower than the spot rate afterwards.

after 16 September. This makes the downward shift between 16 and 17 September less dramatic.

In Figure 5.1.d, the term premium is, entirely ad hoc, set to be proportional to the standard deviation of the risk neutral distribution, in such a way that the term premium is 1% on 16 September and essentially zero at the end of the sample. The main effect of this is to shift the distribution down between late August and mid October, but it changes few of the previous conclusions about how the distribution changed over time - except for the days around 16 September. The high uncertainty, and therefore high risk premium, on 16 September, means that both the increase in the forward rate between 15 and 16 September and the subsequent decrease between 16 and 17 September exaggerate the movements in the expected value.

6 Summary

This paper studies how market expectations about future UK monetary policy changed over the summer and autumn of 1992. The period before "Black Wednesday" (16 September) was marked by a series of small crises when the UK interest rates increased and the pound depreciated towards the lower ERM band limit. After the pound left the ERM, short UK interest rates were lowered in number of steps and a new framework for monetary policy (including inflation targets) was put in place of the fixed exchange rate.

This paper estimates a time series of risk neutral distributions from daily option prices on the pounds/mark exchange rate, a ten year sterling yield to maturity, the three month sterling interest rate, and the three month mark interest rates. The estimation is done for a sample of daily price quotes for the period between late June to late November 1992.

The estimated risk neutral distribution is a mixture of lognormal distributions. It is derived from a theoretical asset pricing framework where the conditional distribution of the asset price and the stochastic discount factor is a mixture of bivariate lognormal distributions. This theoretical framework gives a closed form solution for the option price and provides a useful basis for discussing the effects of risk premia. The estimation procedure picks parameters of the distribution in order to minimize the squared difference between predicted and actual option prices.

While forward rates measure the market's (risk neutral) mean of a future asset price, option data can give an estimate of the entire (risk neutral) distribution. This allows us to give quantitative answers to questions like the following. How uncertain was the market? What probability did the market assign to a realignment? Did the market attach a higher probability to an increase in the short interest rate than to a decrease?

Several interesting results emerge from the estimates. First, the path to the "Black Wednesday" was marked by a series of small crises in late August and early September 1992. During each of these, the distributions of the future UK interest rates and marks/pound exchange rate widened because the market started to believe in the possibility of fairly high interest rates and a moderate realignment. (The actual outcome was a large devaluation and much lower interest rates.) Second, the announcement of the UK inflation target on 8 October, brought down the long UK interest rates as well as the uncertainty about the future long interest rates. Third, the Autumn Statement by the UK chancellor on 12 November, put an end to the uncertainty about the future monetary policy: the distribution of future UK interest rates narrowed dramatically immediately after the speech.

A Data

The data on the *three month euromark* and *sterling interest rate futures* from LIFFE is described in LIFFE (1997b). I use prices on the interest rate futures with last trading day 14 and 16 December 1992, respectively, as well as prices (daily settlement price) and strike prices on effectively European calls and puts on the futures (with expiry on 14 and 16 December 1992, respectively). The futures price and the strike prices are quoted as 100 minus the three month simple annual interest rate in percent (day count is "actual/360"). For a given strike price, X, the implied LIBOR rate (in percent) is $100 - X$, and the price of the bill is 1/(1+days/360*LIBOR/100). The continuously compounded interest rate is therefore $360/\text{days} * \ln[1+\text{days}/360\,(1 - X/100)]$. There were 90 days between 14 (16) December 1992 and 14 (16) March 1993. The option price is not paid at the trade date, but at the expiry date. This means that the discount rate $e^{-i(t,\tau)(\tau-t)}$ in (2.3) is effectively zero.

The data on the *long gilt futures* from LIFFE is described in LIFFE (1997a). I use prices on the bond futures with delivery on any day in December 1992, as well as prices (daily settlement price) and strike prices on (effectively) European calls and puts on the futures (with expiry 23 November 1992). Delivery can be made of any bond on the "List of Deliverable Gilts," and the actual payment from the holder of a futures is the futures price times the price factor plus accrued interest. LIFFE's price factor for a bond is, in this case, defined as

$$\text{price factor} = \frac{1}{1.045^{x/182.5}}\left[c + \frac{c}{0.09}\left(1 - \frac{1}{1.045^n}\right) + \frac{1}{1.045^n}\right] - \frac{c}{2}\left(\frac{182.5 - x}{182.5}\right),$$

where x is the number of days from 1 December to the next coupon date, c the annual coupon (for instance, 0.135), and n is the number of half years from the next coupon date to the maturity date. The accrued interest is the last term. The annual continuously compounded yield to maturity, y, solves the equation

$$\begin{matrix}\text{Actual} \\ \text{payment}\end{matrix} = \sum_{i=0}^{n} \frac{c/2}{e^{y(x/182.5+i)/2}} + \frac{1}{e^{y(x/182.5+n)/2}}.$$

Only two bonds were actually delivered in significant amounts into the futures during the period September 1991 to March 1993 (source: LIFFE), in spite of changing yield curves which could alter the "cheapest to deliver bond." The 13.5% August 2004 bond had $\{x, c, n\} = \{62, 0.135, 23\}$, and the 12.5% May 2003 bond had $\{x, c, n\} = \{150, 0.125, 21\}$, as of 1 December 1992. The option price is not paid up front.

References

BAHRA, B. (1996): "Probability Distributions of Future Asset Prices Implied by Option Prices," *Bank of England Quarterly Bulletin*, August 1996, 299–311.

BANK OF ENGLAND (1992): *Quarterly Bulletin*, November.

CAMPA, J. M., AND P H. K. CHANG (1996): "Arbitrage-Based Testsof Target-Zone Credibility: Evidence from ERM Cross-Rate Options," *American Economic Review*, 86, 726–740.

CHEN, R.-R., AND L. SCOTT (1993): "Pricing Interest Rate Futures Options with Futures-Style Margining," *Journal of Futures Markets*, 13, 15–22.

COX, J. C., AND S. A. ROSS (1976): "The Valuation of Options for Alternative Stochastic Processes," *Journal of Financial Economics*, 3, 145–166.

DUFFIE, D. (1992): *Dynamic Asset Pricing Theory*. Princeton University Press, Princeton.

GERLACH, S., AND F. SMETS (1995): "The Term Structure of Euro-Rates: Some Evidence in Support of the Expectations Hypothesis," Working Paper No. 28, Bank of International Settlements.

HAMILTON, J. D. (1989): "A New Approach to the Economic Analysis of Nonstationary Time Series and the Business Cycle," *Econometrica*, 57, 357–384.

LIFFE (1997a): *Government Bond Futures*.

——— (1997b): *Short Term Interest Rates: Futures and Options*.

MACDONALD, R., AND P. MACMILLAN (1994): "On the Expectations View of the Term Structure, Term Premia and Survey-Based Expectations," *Economic Journal*, 104, 1070–1086.

MALZ, A. 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, 717–748.

MELICK, W. R., AND C. P. THOMAS (1997): "Recovering an Asset's Implied PDF from Options Prices: An Application to Crude Oil During the Gulf Crisis," *Journal of Financial and Quantitative Analysis*, 32, 91–115.

MIZRACH, B. (1996): "Did Option Prices Predict the ERM Crises?," Working Paper 96-10, Rutgers University.

RITCHEY, R. J. (1990): "Call Option Valuation for Discrete Normal Mixtures," *Journal of Financial Research*, 13, 285–296.

Söderlind, P., and L. E. O. Svensson (1997): "New Techniques to Extract Market Expectations from Financial Instruments," *Journal of Monetary Economics, forthcoming.*

Stephens, P. (1996): *Politics and the Pound: The Conservatives' Struggle with Sterling.* Macmillan.

Svensson, L. E. O. (1995): "Estimating Forward Interest Rates with the Extended Nelson Siegel Method," *Sveriges Riksbank Quarterly Review*, (3), 13–26.