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Realignment risk in the exchange rate mechanism: Evidence from pound-mark cross-rate options.

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ABSTRACT

This paper uses a new data source, options on the pound-mark cross-rate, to examine the credibility of the exchange rate band between the German mark and the British pound in the Exchange Rate Mechanism from October 1990 through August 1992. Using two arbitrage-based tests, we provide clear evidence of imperfect credibility throughout this entire period and determine minimum bounds perceived by the market for the "intensity" of realignment, a measure incorporating both probability and magnitude of realignment. Finally, we identify a positive empirical relationship between implied volatility and the change rate's distance from the center of the band that proves useful for evaluating alternative theoretical models of target zones.

REALIGNMENT RISK IN THE EXCHANGE RATE MECHANISM: EVIDENCE FROM POUND-MARK CROSS-RATE OPTIONS

I. Introduction

The purpose of this paper is to examine the credibility of the target zone between the German mark and the British pound in the Exchange Rate Mechanism (ERM) from October 1990, when the pound first entered the ERM, to September 1992, when the pound left the ERM and dropped by about 10% against the mark over the course of a few days, as shown in Figure 1.[1] This paper departs from the wide body of earlier work based on interest rate differentials by using instead prices on mark-pound cross-rate[2] options to test whether financial markets perceived the target zone as credible during this period. We show empirically that financial markets did not perceive the pound-mark target zone to be credible for most of this period, and numerically determine minimum values for the "intensity" of realignment, a measure incorporating both the probability and magnitude of realignment.

Option prices on an exchange rate within a credible target zone must obey certain limitations based on arbitrage. First, the price of a call option on the mark should be no higher than the present value of the difference between the strike price (in pounds) and the upper limit of the exchange rate band (in pounds). Second, the convexity of the option premium with respect to the strike price defines a maximum value for all options with strike prices between the upper and lower bands. A violation of either of these conditions would constitute a rejection of full credibility.

We find that both these properties were violated by observed option prices,

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[1]During this period, the pound/mark exchange rate was permitted to fluctuate up to 6% (6% ERM limits for the pound were wider than the 2.25% band among other currencies) in either direction from a central rate of 0.339 pounds/mark (2.95 marks/pound), resulting in a floor of 0.3198 pounds/mark (3.125 marks/pound) and a ceiling of .3600 pounds/mark (2.78 marks/pound). By agreement, the central banks of the two countries were required to intervene to support the weaker currency when the exchange rate reached either edge of the band.

[2]The term cross-rate is used in foreign exchange markets to denote any exchange rate between two non-(U.S.)dollar currencies.

implying that the pound-mark exchange rate band in the ERM was not credible. Thus, a positive probability of a devaluation of the pound was perceived by financial markets for the entire period. We show that observed prices imply, for most of the period, a *minimum* intensity of realignment of approximately 3% over a forward-looking six-month horizon, a value consistent with a 30% probability of a 10% devaluation of the pound. By mid-summer 1992, this minimum intensity had risen to 5%, consistent with a 50% probability of a 10% devaluation.

The paper also shows that, for most of the October 1990-September 1992 period, the implied volatility in pound-mark option prices was highest near the edges of the band. This finding contradicts a standard theoretical result in the existing literature on credible target zones, in which the instantaneous volatility of the exchange rate is highest at the center of the band.[3] The paper also shows that this positive relationship between implied volatility and the distance from the central rate existed and was already clearly evident in the data up to six months before the pound left the ERM. This finding confirms that long before September 1992, financial markets did not believe that the ERM target zone was fully credible.

The rest of the paper is organized as follows. Section II briefly reviews how existing tests of credibility proposed in the target zone literature fail to demonstrate with sufficient conviction the market's skepticism on the credibility of the target zone. Section III describes the option data used for the rest of the analysis. Section IV shows that, counter to the implications of most existing target zone models, implied volatility was highest at the edges, rather than the center, of the pound-mark exchange rate band. Section V performs two arbitrage-based tests to show the lack of credibility of the exchange rate band and uses risk-neutrality to compute the minimum possible "intensity" of realignment financial markets perceived during this period. Section VI concludes.

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[3]See Svensson (1992a) or Dumas, Jennergren, and Näslund (1992) for a theoretical derivation of this relationship.

II. Assessing Target Zone Credibility Using Interest Rates

The literature on exchange rate target zones has long been concerned with estimating the credibility of ERM target zones.[4] Two tests commonly used to assess target zone credibility are the "simplest test" and the "drift adjustment" method.

The "simplest test" of target zone credibility (Svensson 1991b) is based on the relative level of interest rates in the two countries and thus the location of the forward rate with respect to the exchange rate band. The currency perceived as vulnerable will typically need to pay a higher interest rate and thus will trade at a forward discount. Therefore, even if the spot rate lies within the band, the forward rate may fall outside the band. In this "simplest test," a forward rate outside the ERM band signals that markets perceive such a band as not credible. One-, three-, and six-month forward rates for the period the pound participated in the ERM are plotted in Figures 2a to 2c. For this period, forward rates remained *within* the band until very late in August 1992. Therefore, this test is uninformative with regard to credibility problems in the pound-mark target zone regime until just before the realignment actually occurred.

A second approach to assessing credibility, the "drift adjustment" method, was suggested by Bertola and Svensson (1993) to provide numerical estimates of realignment expectations in a target zone model.[5] The "drift adjustment" method assumes uncovered interest rate parity, which implies that the interest rate differential equals the expected depreciation of the currency with the higher interest rate. This expected depreciation is decomposed into the sum of the expected rate of depreciation *within* the band and the expected rate of realignment *of* the band. Therefore, the expected rate of realignment will equal the difference between the interest rate differential and the expected rate of

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[4]For a survey of this literature on exchange rate target zones and the empirical performance of target zone models, see Svensson (1992b).

[5]Empirically, Svensson (1993) shows how this method provides much better forecasts of realignments in ERM history than do alternative tests.

depreciation within the band. This approach is called the "drift-adjustment" method because the interest rate differential has been corrected for the "drift" of the exchange rate within the band.

The empirical estimation of this method within the context of the ERM has been performed by Lindberg et al. (1991) and Rose and Svensson (1991). To obtain an estimate of the expected rate of depreciation within the band these papers use a number of estimation alternatives, including different sets of independent variables and functional forms. A summary of these results suggests that a regression of the realized rates of depreciation within the band on the current exchange rate consistently provides reasonable results of the expected rate of depreciation. Therefore, we use daily data to estimate the following equation

$$(x_T - x_t) = \beta_0 + \beta_1 x_t + \varepsilon_{t,T} \qquad (1)$$

where x_t is the natural logarithm of the deviation of the spot exchange rate at time t from its central parity, T represents the time at the end of the period, β_0 and β_1 are parameters to be estimated, and $\epsilon_{t,T}$ is a forecast error term occurring between t and T.

Table 1 shows the results of estimating equation (1) for the pound/mark exchange rate using daily data for the period to September 1992. The expected rate of depreciation within the band is estimated for three time horizons: 1, 3, and 6 months. Since the procedure estimates the expected rate of depreciation conditional on no realignment, we use daily data from November 1990, one month after the pound entered the ERM, up until 1, 3, and 6 months before 17 September 1992 when the pound left the ERM. For each maturity we present the results of two specifications. In the first column, the estimation of equation (1) is reported. In the second column, we report the results of adding to the right-hand side of the equation the domestic and foreign interest rates (i and i^*), since they have typically proven to be significant in this context (Svennson (1993)). In parentheses below the parameter estimates, we report the standard errors corrected for serial correlation due to overlapping observations using the method by Newey and West (1987).

The coefficient on the exchange rate is always negative, always significant (except for the first specification for one month), and ranges from -1.92 to -4.29. The significant negative values suggest a mean-reversion in the exchange rate within the band. The coefficients on the domestic interest rate are always significantly negative, suggesting that a higher domestic interest rate leads to a depreciation of the home currency, while the foreign interest rate is always insignificant. These estimates enable us to estimate the expected rate of depreciation within the band. The confidence intervals for these estimated rates of depreciation (not reported here) are too wide to provide statistically significant information on a possible depreciation or appreciation of the pound within the band during most of this period.[6]

We can now compute the expected rate of realignment of the exchange rate band by subtracting from the interest differential these estimates of the expected rate of depreciation within the band. Figures 3a and 3b show the estimated 95% confidence interval of the expected rate of devaluation of the exchange rate using the results for the 3- and 6-month horizon.[7] These graphs report the percentage/year expected rate of devaluation of the pound. Therefore, a value of 20% implies a 20% depreciation of the pound within a year or, equivalently, an expected 5% devaluation in the next three months. For both maturities, there existed a significantly positive expectation of a pound devaluation from November 1990 until approximately March 1991, but from that point on, despite positive point estimates, the hypothesis of a zero expected devaluation cannot be rejected.

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[6]This estimation method does not prevent the expected depreciation within the band from actually falling outside the edges of the band. Chen and Giovannini (1992) suggest an ad hoc alternative to prevent this from happening.

[7]These expected rates of realignment were computed using the predicted rates of depreciation from the specification that includes the domestic and the foreign interest rates as explanatory variables.

III. Description of the Over-the-Counter Options Data

This paper's tests of the credibility of the pound-mark band will be based on a different data source: prices of over-the-counter options between the pound and the mark. Options, whose price depends on the exchange rate's second moment rather than its first, could potentially prove more effective than interest rates. Our data, which were provided by a commercial bank in London, take the form of daily closing quotes[8] on pound-mark options, expressed as implied volatilities, which traders by agreement substitute into a Garman-Kohlhagen formula (Black-Scholes adjusted for the foreign interest rate) to determine the option premium. Since the volatility is the only unobservable parameter in the Black-Scholes formula, these volatilities--representing traders' subjective assessments of future movements in the underlying asset--uniquely determine the options' price.[9] By convention, these quotes are used in pricing the market's most commonly traded instrument: at-the-money forward European straddles, i.e., a European call option and a European put option with a common strike price equal to the forward exchange rate of the same maturity as the option.[10]

Summary statistics based on the average of daily bid and ask implied volatilities (percent per year) are presented in Table 2 for the pound/mark (GBP/DEM) exchange rate. As can be seen by comparing data for the one-, three-, and six-month options, the mean implied volatility is a declining function of maturity, as shown in Table 2. Difference-in-means tests (not reported) across different maturities, taking into account possible correlation over time and across maturities, reject for all maturity pairs the null hypothesis that the means of these series were the same. The lower unconditional means of implied volatilities (per unit time) for longer horizons are consistent with bounded

[8]We use the average of the bid and ask quote.

[9]Note that traders do not necessarily believe that the Black-Scholes conditions (such as geometric Brownian motion) hold. The Black-Scholes formula simply represents a convenient mapping between volatility quotes and the option premium paid in a given transaction.

[10]These quotes do not apply to other strike prices or instruments, which are less liquid and for which one must request quotes on a customized basis.

exchange rates as was true in the ERM.

Sample statistics for skewness (two-tailed) and kurtosis indicate the presence of significant skewness and kurtosis at the 5% level for a number of the implied volatility series. Positive skewness and significantly negative kurtosis, indicating "thinner tails" than would be expected under a normal distribution, were found for the one-, three-, and six-month options.

Autocorrelation functions and partial autocorrelation functions, shown at the bottom of Table 2, suggest that an AR(1) specification successfully characterizes the statistical behavior of these three time series.[11] The first-order autocorrelation coefficients are significant and fall in the range of 0.96 to 0.98, indicating mean-reversion in these series. These coefficients suggest a mean half-life of shocks to implied volatility of 17 to 34 trading days. The first-order autocorrelation coefficients increase as a function of the options' maturity, indicating a greater degree of persistence. The partial autocorrelations are typically near zero after the first lag, further suggesting that an AR(1) characterization is appropriate. The relatively brief period of data coverage (23 months), as well as the near unit-root characteristics of the AR(1) process, unfortunately preclude the meaningful interpretation of augmented Dickey-Fuller tests for unit roots.

While the implied volatility quotes in our data refer to bid and ask prices for straddles, we can easily decompose these into the price of a put and a call independently. Although traders use the Black-Scholes model in the mapping from implied volatility quotes to option prices, the decomposition into put and call follows simply from put-call parity and does not require any assumptions about the validity of the Black-Scholes model.

Suppose that rather than Black-Scholes, some "true" model holds for price determination at which trades are conducted, but traders continue to use Black-Scholes to quote prices. Then, Straddle (BS) = Straddle (True). By put-call

[11]Empirically, the first-order autocorrelations implied by our estimates of higher order autocorrelations never differ by more than 1% from the actual first-order autocorrelation.

parity[12] applied independently to each side of the equation:

2 Call (BS) + PV(Strike) - Underlying = 2 Call (True) + PV(Strike) - Underlying,

so,

Call (BS) = Call (True), and Put (BS) = Put (True).

In other words, we can obtain the value of the put and call by simply substituting into the Black-Scholes formula the implied utility quotes provided by option traders.[13]

IV. Model-Based Evidence of Imperfect Regime Credibility

Relatively little work on target zones has focused on option pricing: to our knowledge the existing literature on option-pricing within a target zone consists of Ball and Roma (1990), Dumas, Jennergren, and Näslund [hereafter, DJN] (1992, 1993), and Ingersoll (1993). Of these, DJN (1992) and Ingersoll (1993) assume perfect credibility, while Ball and Roma (1990) and DJN (1993) incorporate potential realignment.

DJN (1992) uses the well-known Krugman (1991) model as a starting theoretical framework. The Krugman model has two crucial assumptions: the target zone is credible, and interventions occur only when the exchange rate reaches the edges of the target zone. Under these assumptions, the model obtains some implications for the behavior of exchange rates and interest rates within the target zone.[14] DJN (1992) use this framework to obtain numerical solutions for the valuation of options in a target regime. Ingersoll (1993) also presents a model of credible target zones. In this model the exchange rate follows a

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[12]Call + PV (Strike) = Put + Underlying. Applying to a put and call with a common strike price and expiration date, put-call parity is an arbitrage relationship that is model-independent.

[13]In our case, since the strike price equals the forward rate, we know the put and call are equal in value, so the decomposition becomes still simpler: Put(True)=Call(True)=½ Straddle(True) = ½ Straddle (BS).

[14]There exist numerous empirical studies that have tested some of the implications derived from the Krugman model. A common conclusion of these studies is that the observed behavior of exchange rates within the ERM is not consistent with the predictions of this model. See Svensson (1992b) for a summary of this research.

Brownian motion in which the volatility parameter is zero at the edges of the band and is a maximum at the (geometric) mean of the band. This characterization of implied volatility, at a maximum near the center and a minimum at the edges, also appears in DJN (1992) and is consistent with the behavior of *instantaneous* volatility in the underlying exchange rate in most models of credible target zones.[15]

DJN (1993) expand the framework in DJN (1992) to obtain option prices when the target zone is not fully credible and the possibility of realignment exists. In their model the realignment mechanism is driven by a Poisson jump process with endogenous realignment size. Despite this possibility of realignment, implied volatility from option prices will still be at a maximum at the central rate and lower at the edges of the band. As the probability of realignment increases, this hump-shaped pattern becomes increasingly flat but the pattern remains.

Ball and Roma (1990) propose an option-pricing model in an ERM framework with potential realignment. They describe a stable ERM regime in which the distance from the central exchange rate follows an Ornstein-Uhlenbeck process, then superimpose upon this mean-reverting process a constant probability of jump in the central parity. The magnitude of this jump increases with the distance from the central rate, thereby offsetting the mean-reversion of the exchange rate in the absence of realignment, and thus keeping expected returns on the currency constant. In this model, in contrast to DJN (1992, 1993) and Ingersoll (1993), they find implied volatility is greatest at the edges of the band, where both mean-reversion and the expected magnitude of possible realignment are greatest.

We focus on the relationship between implied volatility and the location of the exchange rate within the band as a means of evaluating alternative models and assessing credibility. Empirical results from a regression of implied volatility from each option price on the corresponding spot rate indicate a statistically significant increase in implied volatility as the spot rate moves away from its central parity. These results, shown in Table 3, reflect financial markets' emphasis on potential realignment *of* the band. This observed positive

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[15]See Svensson (1991a).

relationship between implied volatility and distance from the central rate demonstrates the lack of full credibility of the band in the context of the models discussed above.

Since the mark never closed below its central rate after 20 August 1991, proximity to the ceiling of the band and distance from the central rate become equivalent measures. Moreover, anecdotal evidence suggests that only the mark's ceiling, and not its floor, was subject to credibility problems. Results of a regression of implied volatility on the distance from the mark's upper bound are reported in the second panel of Table 3. Implied volatility was a significantly negative function of distance from the ceiling for all maturities. We also included a time trend to allow for the possibility that the observed negative correlation between spot and implied volatility is due solely to a time effect. The results show the time trend to be insignificant, while the coefficients on the distance from the ceiling remain significantly negative.

The relationship between implied volatilities and the spot exchange rate is also evident in scatterplots for one-, three-, and six-month options in the year prior to the pound's September 1992 devaluation. As shown in Figures 4a to 4c, a very clear positive correlation can be found between implied volatilities and the mark's value against the pound from October 1991 to September 1992.

A rejection of the credibility of the target zone might not seem so surprising given our knowledge today of the events of September 1992. More interesting is the fact that the implied volatility-exchange rate relationship, even prior to the summer of 1992, indicated that the target zone lacked credibility well before its collapse. In a regression over the six months from 01 September 1991 to 01 March 1992, the relationship between implied volatilities and the distance from the mark's upper bound is always significantly negative. These results, shown in Table 4, are not affected by the inclusion of a time trend.

Our results indicate a rejection of certain implications of credible target zone models, suggesting that, at least for the pound-mark target zone, emphasis should be placed on the possibility of realignments. Furthermore, among the existing models discussed above, the Ball and Roma (1990) model is most likely to provide a useful theoretical framework. In the next section we will use two arbitrage-based tests to test the credibility of this target zone and to obtain a measure of the perceived intensity of realignment. The advantage of these arbitrage-based tests is that they are model-independent and thus not vulnerable to specification error.

V. Arbitrage-Based Evidence of Imperfect Regime Credibility

We now conduct two tests based on arbitrage principles of option pricing in order to: (1) provide further evidence of imperfect credibility in the pound-mark target zone, and (2) estimate, under the assumption of risk neutrality, a lower bound on the intensity of realignment embedded in market prices during the pre-September 1992 period.[16] The first test is based on the maximum value of a call option in a credible target zone, while the second is based on the convexity of the value of a put option with respect to its strike price. Both tests are based on arbitrage relationships, and thus not dependent on any particular model governing either option prices or the dynamics of the exchange rate.

A. Maximum Value of the Call

Our first test compares the observed market value of a call option on the mark with its maximum possible value conditional on full credibility. By definition, the value (in pounds) of a call option on the mark with a strike price K (in pounds), at its time of expiration, T, is

$$Call_{t,T} = Max[0, S_T - K] \tag{2}$$

where S_t is the pound value of one mark at time t.

If the target zone is fully credible, then the call's highest possible value at expiration is $\bar{S}-K$, where $\bar{S}$ is the upper bound on the exchange rate band,

[16]Examples of previous studies that use option prices to infer certain distributional properties of the underlying asset are Bates (1991) and Grundy (1991).

which occurs only when the exchange rate is at its upper bound. Therefore, under credibility, the call today must be worth no more than the present value of $\bar{S}$-K, i.e., $(\bar{S}-K)/(1+i_{t,T})$. Any violation of this condition constitutes evidence of imperfect credibility.[17] Figure 5 depicts these relationships graphically.

The results of this comparison, shown in Figures 6a to 6c, provide strong evidence of imperfect credibility in the pound-mark target zone. These figures show the observed value of a call option with one, three, and six months to expiration, and the maximum value for each of these options that is consistent with a credible exchange rate target zone. Whenever the observed value is above the computed maximum value, credibility is violated. While the one-month and three-month call options exceeded their maximum value under credibility only occasionally before the late summer of 1992, six-month call options indicate the mark's upper bound against the pound lacked credibility throughout much of the pound's participation in the ERM.

The overpricing of the call, relative to its maximum possible value under full credibility, is most prominent for six-month options. If a target zone is fully credible, implied volatility in option prices should normally decline as a function of the time to expiration, reflecting the mean-reversion in the spot rate necessitated by the constraints of the target zone. As we saw above, the unconditional mean implied volatility of the six-month option is lower than that of shorter options, but this dropoff in implied volatility was not sufficient in the six-month pound-mark options. The call options became overpriced, thereby violating their maximum possible value consistent with credibility.

A similar test on the put option would be a test of the credibility of the **floor** of the mark's value against the pound. Under credibility, the value of a put option cannot exceed the present value of the difference between the strike price and the lower bound. Figure 6d shows the value of a put option and its

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[17]Note that any strike price outside the band will immediately cause a rejection of credibility, provided that the value of the option is negative. Since in our data the strike price equals the forward rate, whenever the "simplest" test rejects credibility, so will this test. This test, however, can reject credibility even when the forward rate is within the band, as shown below.

maximum value under credibility at the six-month horizon. Even at this horizon, where the value of the put is the highest, the value of the put did not exceed its maximum value under the null hypothesis of credibility.[18] Thus, option prices indicate that the mark's upper bound on the exchange rate band lacked credibility, but do not suggest imperfect credibility of the lower bound. This result is consistent with macroeconomic conditions at the time and the pattern of previous ERM realignments, which indicated that in potential realignments the pound would be more likely to be devalued than the mark.

Given that the upper bound of the exchange rate band is not credible, we can estimate the minimum upper bound, $\bar{S}'$, that would be consistent with the observed call prices. We define $\bar{S}'$ as the lowest possible S_t that satisfies: $Call_{t,T} = (S_t-K)/(1+i_{t,T})$. Figures 7a to 7c show the value of this minimum upper bound for one-, three-, and six-month options. For the one-month and three-month options, the minimum upper bound consistent with credibility remains below or just slightly above the actual upper bound of 0.360 GBP/DEM until the summer of 1992. In the case of the six-month option, however, this minimum upper bound was frequently above 0.360 GBP/DEM. It was in the neighborhood of 0.370 GBP/DEM from November 1990 to February 1991 and November 1991 to April 1992 and rose steadily above 0.360 GBP/DEM in July and August of 1992, ultimately approaching 0.380 GBP/DEM. Note that these minimum upper bounds do not indicate the market's perceived probability of realignment; they are simply minimum upper bounds consistent with credibility, given observed option prices. Having established the lack of credibility of the pound-mark target zone, we now turn to estimating the market's perceived intensity of realignment of the ERM band, rather than simply identifying the minimum upper bound.

The observed value of the call options enable us to identify a minimum intensity of realignment as perceived by financial markets prior to September 1992. Under risk neutrality,[19] the expected value at time t of a call option is:

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[18]A similar result occurs when using the one- and three-month options.

[19]That is, if all investors were risk-neutral or if exchange rate risk was not priced.

$$Call_{t,T}=\frac{1}{1+i_{t,T}}E_t\int_K^{\infty}(S_T-K)f(S_T)dS_T \tag{3}$$

where f(S) is the density function of the distribution of the exchange rate.[20] The intensity of realignment at time t between t and T, $G_{t,T}$ is defined as:

$$G_{t,T} = \int_{\bar{S}}^{\infty}(S_T-\bar{S})f(S_T)dS_T \tag{4}$$

By definition, $G_{t,T}$ sums over all possible realignments the size of the realignment times the probability that such a realignment will take place.[21] Adjusting the lower limit of integration and introducing $\bar{S}$, we can re-write the right-hand side of equation (3) as follows:

$$Call_{t,T} = \frac{1}{1+i_{t,T}}E_t\left[\int_{\bar{S}}^{\infty}(S_T-\bar{S})f(S_T)dS_T+\int_{\bar{S}}^{\infty}(\bar{S}-K)f(S_T)dS_T+\int_K^{\bar{S}}(S_T-K)f(S_T)dS_T\right] \tag{5}$$

The intensity of realignment, G(t,T), appears as the first term on the right-hand side of this equation. The third term represents the expected value of the call option if the exchange rate remains within the band between K and $\bar{S}$. This expected value is not observable, but it is bounded by its value under the scenario in which the exchange rate at time t+T always equals $\bar{S}$.

$$\int_K^{\bar{S}}(S_T-K)f(S_T)dS_T \leq \int_K^{\bar{S}}(\bar{S}-K)f(S_T)dS_T \tag{6}$$

Therefore, substituting equation (6) back into equation (5) and solving for the

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[20]Without the assumption of risk neutrality, f(S) would represent the "risk neutral" distribution of the exchange rate. In such a world the measure of intensity computed below would represent a "risk neutral" intensity of realignment and could be interpreted as the market price of a security that pays $(S_T-\bar{S})$ whenever $S_T > \bar{S}$.

[21]We are implicitly assuming that realignments occur only when the spot rate moves outside the current band.

intensity of realignment $G_{t,T}$ we get

$$G_{t+T} \geq Call_{t,T}(1+i_{t,T}) - \int_{K}^{\infty} (\bar{S}-K) f(S_T)\, dS_T = Call_{t,T}(1+i_{t,T}) - (\bar{S}-K)(1-F(K)) \qquad (7)$$

where F(K) is the cumulative distribution function of S_T at point K.

All terms on the right-hand side of this equation are observable at time t except for [1-F(K)], the probability that the call option will finish in the money at expiration. We know that the maximum value of this term is 1.[22] Hence the minimum intensity of realignment, over the horizon of the option, can be expressed as:

$$G_{t+T} \geq Call_{t,T}(1+i_{t,T}) + K - \bar{S} \qquad (8)$$

Figures 8a to 8c show the value of the right-hand side of equation (8) for one-, three-, and six-month options. Using the one-month option does not permit rejection of the hypothesis of a zero intensity of realignment through most of the period. For the six-month option, however, there is a positive probability of realignment for most of this period. The minimum intensity of realignment is above zero at all times except the periods from March to October 1991 and from April to June 1992. For comparison with the 11% rise in the mark (from 0.36 to 0.40 pounds) that occurred in mid-September 1992 when the pound left the ERM, note that an intensity of 2% observed during much of this period can be interpreted as a 20% probability of a one-time 10% appreciation of the mark within the six-month time period covered by these options.

B. Convexity of a Put Option

The second arbitrage-based test of target zone credibility relies on the

[22]Below we will provide a closer estimate using information from observed prices for put options.

convexity[23] of the put option with respect to the strike price, as outlined in Grundy (1991).[24] Under perfect credibility of the exchange rate band, we know the theoretical value of a put option on the mark when the strike price (in pounds) is equal to either the upper bound or the lower bound of the exchange rate band. When the strike equals the upper bound, the option will always be exercised and must therefore be worth its intrinsic value. When the strike is set to the lower bound of the band, the option will never be exercised and must be worthless. The convexity of the put option with respect to its strike price permits us to use interpolation to determine a maximum value of the put, conditional on credibility, for any strike price between the floor and ceiling.

As shown in Figure 9a, with the horizontal axis now denoting the strike price of the put option, we know with certainty the value of the put when the strike price equals either the floor or the ceiling. Clearly, provided that the floor is credible, a put is worth zero when its strike price is set to the floor of the band. When the strike equals the ceiling, under perfect credibility, the option will always be exercised. By arbitrage, the put option with strike price $\bar{S}$ must be worth its intrinsic value, i.e., the present value of the strike price minus the underlying (a foreign zero coupon bond), or $\bar{S}/(1+i_{t,T})-S_t/(1+i^*_{t,T})$, where S_t is today's spot rate.[25]

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[23]To see that the put option is convex with respect to its strike price notice that: a one dollar increase in the strike price increases the value of the put by (the present value of) a full one dollar for options that will definitely finish in the money and by zero for options that will definitely finish out of the money. The higher the strike price, the more likely the put will finish in the money, and therefore, the bigger the increase in the put value per one dollar increase in strike price. Thus, $\partial^2 Put/\partial K^2 > 0$.

[24]Grundy (1991) uses this convexity to show that given option prices (on the same underlying security) at n different strike prices, relatively tight bounds can be placed on option prices at other strike prices.

[25]To show this, suppose the put sells for less than $\bar{S}/(1+i_{t,T})-S_t/(1+i^*_{t,T})$. Then, buy the underpriced put and also buy the underlying (a foreign zero coupon bond) for $S_t/(1+i^*_{t,T})$. By assumption, the cash outlay will be less than $\bar{S}/(1+i_{t,T})$, which accrues interest between now and expiration at rate i. At expiration date T, under the assumption of perfect credibility, the put finishes in-the-money and is worth $\bar{S} - S_T$, and the long position in the maturing foreign bond will be worth S_T, for a net value of $\bar{S}$, which more than covers the initial outlay plus interest. Reverse all these transactions if the put is overpriced.

We know that the put is a convex function of its strike price, but we cannot ascertain the degree of the put's convexity. We can, however, use linearity as a limiting case. Interpolating between the value of the put options with strike prices at either end of the target zone, we can set an upper limit on the value of a put option in a credible exchange rate band with a strike price between these two extremes. Thus, if credibility holds, the value of the put must lie below the line joining the two extreme strike prices in Figure 9a (line A).

Note that if the ceiling is not credible, the put may finish out-of-the-money and be worth zero, while the offsetting long position (in the arbitrage used to determine the price) in the underlying is still worth S_{t+T}, which is by assumption more than the cash outlay, plus interest, of $\bar{S}$. When this outcome is possible, the put option must therefore be worth more than $\bar{S}/(1+i)-S_t/(1+i^*)$, reflecting the asymmetry (and thus "time value") in the put, which does not obligate the holder to sell the underlying at $\bar{S}$. The higher value of this put under imperfect credibility is represented by the end of line B in Figure 9a.

Empirical results of this convexity test for pound-mark options with time-to-expiration of one, three, and six months are shown in Figures 10a to 10c. One-month puts indicate imperfect credibility only toward the end of the summer of 1992, but three-month and six-month puts, which violate the convexity condition for much of the sample, demonstrate that the market doubted the credibility of the ceiling on the pound-mark rate long before the summer of 1992. As was true for the six-month calls, the implied volatilities of six-month puts are too high to be consistent with a credible target zone.

We can estimate the minimum post-realignment ceiling that is consistent with full credibility, $\bar{S}''$, given the current prices of the put options, as done earlier with the call options. As illustrated in Figure 9b, we extrapolate from the put with strike equal to $\underline{S}$ through the observed put with strike price K (equal to the forward rate), extending the line until the value on the vertical axis equals $\bar{S}''/(1+i_{t,T})- S_t/(1+i^*_{t,T})$. This will be the value of a put option with a strike price of $\bar{S}''$, which by definition is the upper bound of a credible exchange rate band. Algebraically, we can show that this will occur when

$$[\frac{\bar{S}''}{1+i_{t,T}}-\frac{S_t}{1+i^*_{t,T}}] = \frac{\bar{S}''-\underline{S}}{K-\underline{S}} Put_{t,T} \qquad (9)$$

The values of $\bar{S}''$ based on one-, three-, and six-month options are depicted in Figures 11a to 11c.

The put options can help us obtain more strict values of the minimum value of the intensity of realignment reported above in Figures 8a to 8c. Returning to equation (7) above, we can now use the put options to obtain a better estimate of the probability that a call option will finish in the money, [1-F(K)], which we had previously set equal to one.

Assuming risk neutrality again, the value at time t of a put option expiring at T is

$$Put_{t,T}=\frac{1}{1+i_{t,T}}E_t \int_{-\infty}^{K} (K-S_T) f(S_T) dS_T \qquad (10)$$

Under the assumption of full credibility of the lower bound of the exchange rate band (an assumption that could not be rejected in the previous tests), we know that the put option attains its maximum value when S_T equals $\underline{S}$. It follows that

$$Put_{t,T} \leq \frac{(K-\underline{S})}{1+i_{t,T}} \int_{\underline{S}}^{K} f(S_T) dS_T = \frac{(K-\underline{S})}{1+i_{t,T}} F(K) \qquad (11)$$

Therefore we know that an upper limit for [1-F(K)], which we previously had approximated as 1, must be

$$1-F(K) \leq 1-\frac{Put_{t,T}(1+i_{t,T})}{(K-\underline{S})} \qquad (12)$$

We can now use this term to re-estimate the intensity of realignment using one-, three-, and six-month call options. Figures 12a to 12c show the new estimated intensities of realignment, which (necessarily) are always higher than those estimated in 8a to 8c.[26] The intensity of realignment continues to be positive for most of the period, based on the six-month call option. The intensity of realignment estimated from this option has remained surprisingly constant throughout most of the period around a value of 3%. This value can be interpreted as the market's perception of a 30% probability of a 10% devaluation of the pound from its floor against the mark, to take place within six months. Starting in June 1992 the value of this intensity starts to rise steadily to a maximum in late August around 5%, a value consistent with a 50% probability of a 10% devaluation of the pound.

VI. Conclusion

This paper has used options prices on the exchange rate between the pound and the mark to test the credibility of the ERM target zone between these currencies during the period of the pound's participation in the ERM from October 1990 through August 1992. The paper develops two arbitrage-based methods for testing this credibility: one based on the maximum value of a call option and the second based on the convexity of the put option with respect to its strike price. Unlike earlier tests based only on interest rates, these arbitrage-based tests using options clearly reject the hypothesis of credibility of the pound/mark target zone for the entire period. The estimated intensity of realignment from six-month call options was positive during the pound's participation in the ERM and is estimated to be surprisingly constant near 3% over a six-month horizon.

The paper also documents empirically the positive relationship between the implied volatility in option prices and the spot exchange rate's distance from the central rate. This stylized fact can be used to distinguish among alternative theoretical models of options prices in target zones and reject those models based on full credibility, in which (implied) volatility declines with the spot distance from the central rate.

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[26] These new estimates, $Call_{t,T}(1+i_{t,T})+(K-\bar{S})[1-Put_{t,T}(1+i_{t,T})/(K-\underline{S})]$, are also less variable over time because of offsetting effects of changes in K, the strike price. In equation (8), the term $K-\bar{S}$, which declines in magnitude as K rises, is multiplied by $1-Put_{t,T}(1+i_{t,T})/(K-\underline{S})$, which increases with K.

The methodology developed here could be easily applied to analyze the behavior of other exchange rates, both in and out of the ERM. Obvious episodes in recent history include the Italian lira's departure from the ERM in September 1992 and the problems of the French franc in late July 1993, ultimately leading to a widening of the ERM bands. Other applications might include non-ERM target zones such as the Swedish krone vs. the ECU or perceived target zones as may characterize the dollar-yen exchange rate.

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Table 1

Expected Rate of Depreciation Within the Band

$$(x_{t+T}-x_t) = \beta_0+\beta_1 x_t+\beta_2 i^*_{t,T}+\beta_3 i_{t,T}+\varepsilon_{t+T}$$

	1 Month		3 Month		6 Month	
	(1)	(2)	(1)	(2)	(1)	(2)
β_0	0.064* 0.026	0.989 0.587	0.059* 0.027	0.074 0.353	0.036* 0.011	0.158 0.127
β_1	-2.824 1.769	-3.095* 1.573	-3.474* 0.873	-4.286* 1.011	-1.915* 0.503	-2.250* 0.266
β_2		-5.192 6.524		3.859 4.218		1.084 1.328
β_3		-4.028* 1.296		-3.163* 0.732		-1.949* 0.316
N. Obs.	464	464	422	422	356	356
R^2	0.07	0.18	0.32	0.66	0.38	0.68

* Significant at the 5% level.

Table 2

Descriptive Statistics of Implied Volatility of GBP/DEM Options

Daily Observations from October 1, 1990 to August 31, 1992 (N=478)

	Time to Maturity of the Options		
	1 Month	3 Months	6 Months
Mean	4.3234	4.1667	3.9623
Std. Dev.	0.9706	0.8280	0.7504
Skewness	0.2290	0.2480	0.2960
Kurtosis	2.4580	2.4490	2.5110
Minimum	2.5	2.7	2.7
Maximum	7.9	6.7	6.2
Lags	Autocorrelation Functions		
1	0.9712	0.9844	0.9745
2	0.9436	0.9659	0.9512
3	0.9138	0.9450	0.9349
4	0.8819	0.9258	0.9205
5	0.8495	0.9049	0.9056
6	0.8147	0.8825	0.892
7	0.7752	0.8604	0.8700
8	0.7433	0.8415	0.8508
9	0.7163	0.8248	0.8307
10	0.6944	0.8048	0.8080
Lags	Partial Autocorrelation Functions		
1	0.9712	0.9844	0.9745
2	0.0091	-0.0940	0.0404
3	-0.0861	-0.0680	0.1335
4	-0.0239	-0.0072	0.0350
5	-0.0236	-0.0658	0.0074
6	-0.0755	-0.0550	-0.0213
7	-0.1314	0.0178	-0.0618
8	0.1623	0.0935	-0.0306
9	0.0855	0.0472	-0.0450
10	-0.0478	-0.1294	-0.0564

Table 3

A. REGRESSION OF THE IMPLIED VOLATILITY OF OPTION PRICES ON THE DISTANCE BETWEEN SPOT AND CENTRAL GBP/DEM RATE (0.339 GBP/DEM)[a]

October 1, 1990 to September 1, 1992

Options Maturity:	Distance Between Spot Rate and Central Rate		
	β Coef.	R^2	D-W
1 Month	0.521* (0.969)	.19	2.07
3 Month	0.316* (0.069)	.21	1.90
6 Month	0.187* (0.082)	.15	2.09
12 Month	0.266* (0.056)	.11	2.09

B. REGRESSION OF THE IMPLIED VOLATILITY OF OPTION PRICES ON THE DISTANCE BETWEEN SPOT RATE AND LOWER GBP/DEM BOUND (0.360 GBP/DEM)[a]

September 1, 1991 to September 1, 1992

Options Maturity	Distance Between Spot Rate and Lower Bound:			Distance Between Spot Rate and Lower Bound, plus Time Trend:			
	β Coef.	R^2	D-W	β Coef.	Time[b]	R^2	D-W
1 Month	-1.300* (0.170)	.73	2.16	-1.778* (0.176)	0.200 (0.535)	.74	2.16
3 Month	-0.722* (0.118)	.80	1.93	-0.692* (0.120)	0.898 (0.748)	.80	1.94
6 Month	-0.496* (0.100)	.70	1.88	-0.478* (0.102)	0.813 (0.913)	.71	1.89
12 Month	-0.577* (0.103)	.62	2.05	-0.554* (0.105)	0.635 (0.764)	.63	2.07

Standard errors are reported below the coefficient.

* Significant at the 1 percent level.

a All specifications include a constant (not reported) and have been corrected for autocorrelation of the residuals.

b This coefficient indicates annual estimated change in implied volatility.

Table 4

REGRESSION OF THE IMPLIED VOLATILITY OF OPTION PRICES ON THE DISTANCE BETWEEN SPOT RATE AND LOWER GBP/DEM BOUND (0.360 GBP/DEM)[a]

September 1, 1991 to March 2, 1992

Options Maturity	Distance Between Spot Rate and Lower Bound:			Distance Between Spot Rate and Lower Bound, Plus Time Trend:			
	β Coef.	R^2	D-W	β Coef.	Time[b]	R^2	D-W
1 Month	-1.194* (0.207)	.77	2.03	-1.199* (0.214)	-0.427 (1.719)	.78	2.04
3 Month	-0.741* (0.167)	.68	2.15	-0.734* (0.172)	0.789 (1.206)	.71	2.14
6 Month	-0.443* (0.113)	.53	1.96	-0.437* (0.116)	0.546 (1.175)	.69	1.96
12 Month	-0.372* (0.080)	.31	1.98	-0.363* (0.082)	0.631 (0.956)	.61	1.97

Standard errors are reported below the coefficient.

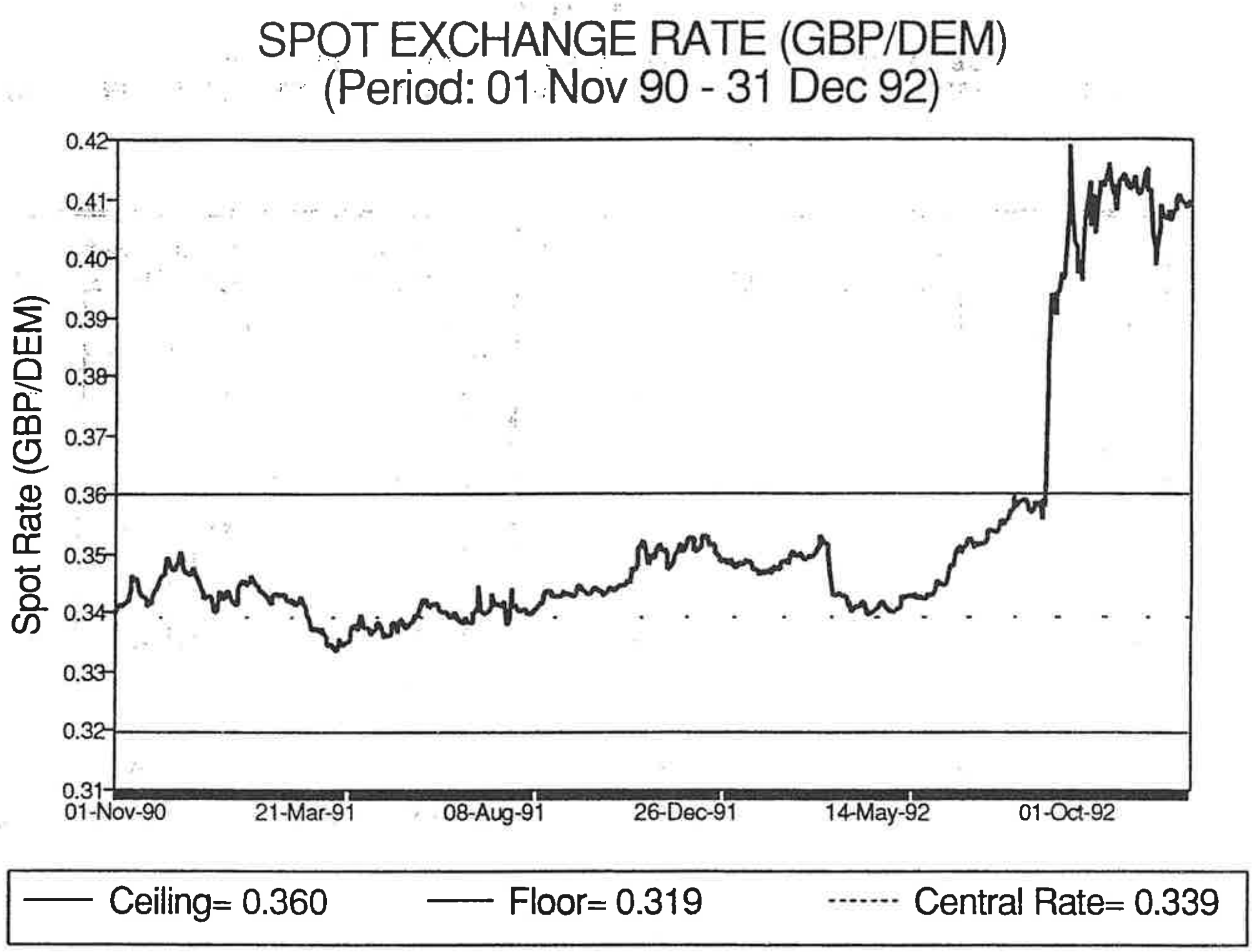
* Significant at the 5 percent level.

** Significant at the 10 percent level.

a All specifications include a constant (not reported) and have been corrected for autocorrelation of the residuals.

b This coefficient indicates annual estimated change in implied volatility.

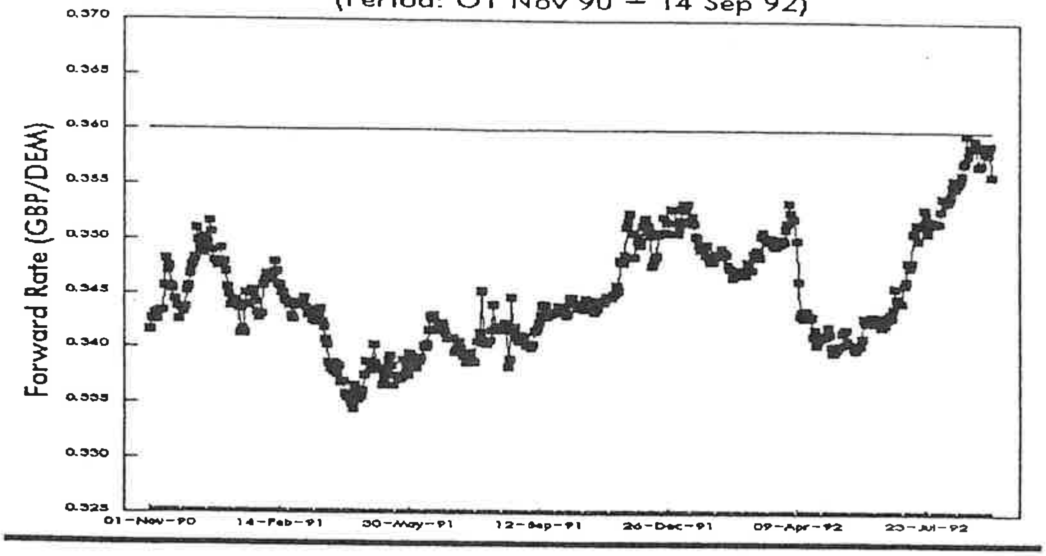
Figure 1



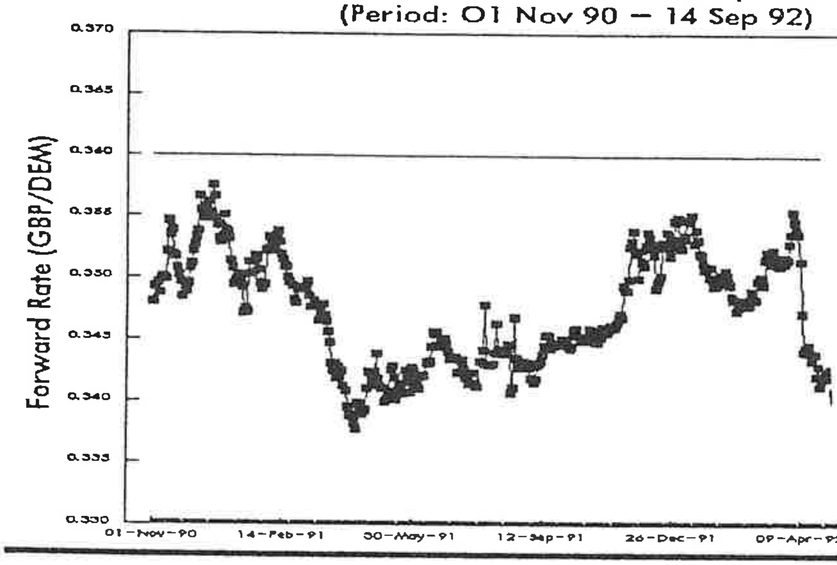
SPOT EXCHANGE RATE (GBP/DEM)
(Period: 01 Nov 90 - 31 Dec 92)
Spot Rate (GBP/DEM)
0.42
0.41
0.40
0.39
0.38
0.37
0.36
0.35
0.34
0.33
0.32
0.31
01-Nov-90
21-Mar-91
08-Aug-91
26-Dec-91
14-May-92
01-Oct-92
Ceiling= 0.360
Floor= 0.319
Central Rate= 0.339

Figures 2a - 2c

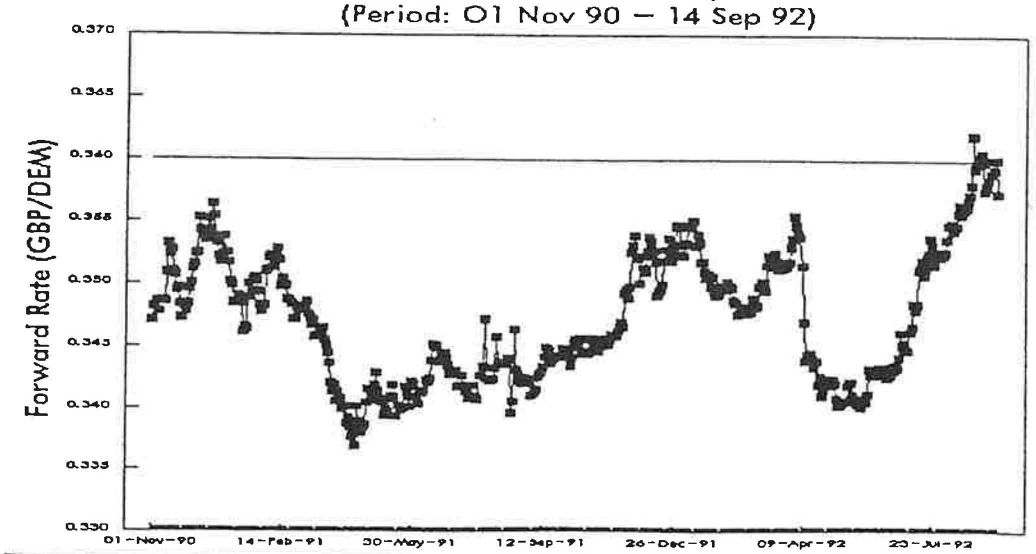
ONE-MONTH FORWARD RATE (GBP/DEM)
(Period: 01 Nov 90 — 14 Sep 92)



THREE-MONTH FORWARD RATE (GBP/DEM)
(Period: 01 Nov 90 — 14 Sep 92)



SIX-MONTH FORWARD RATE (GBP/DEM
(Period: 01 Nov 90 — 14 Sep 92)



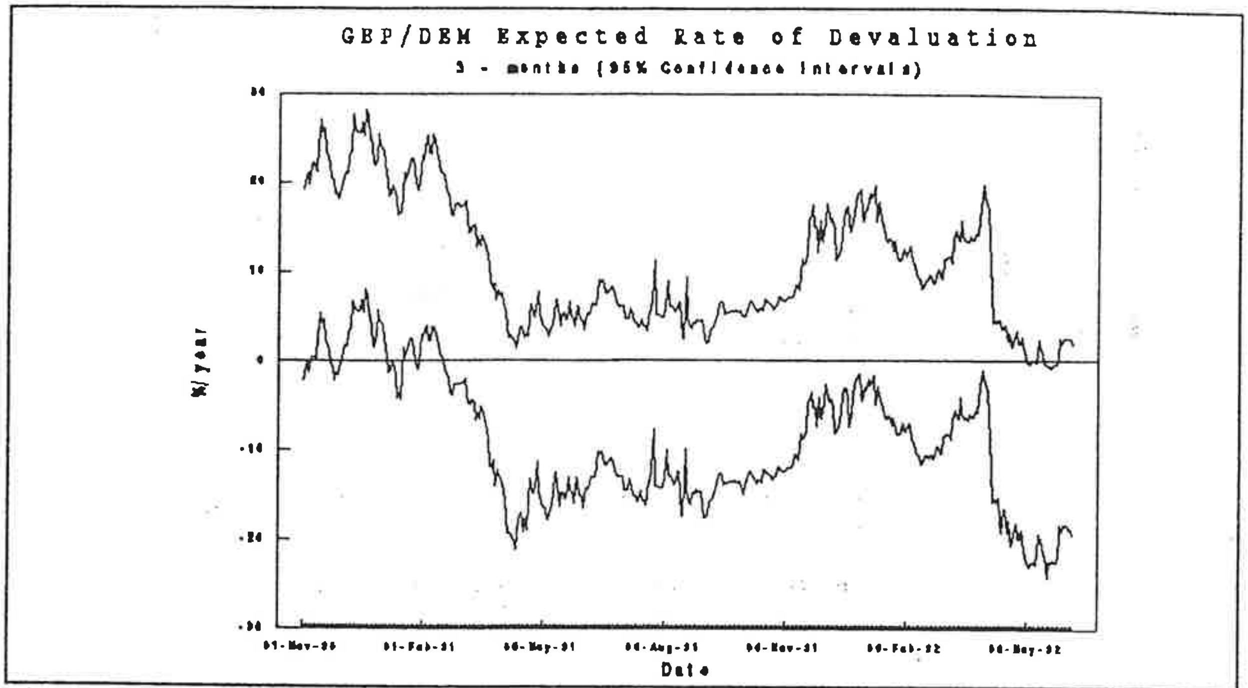


Figure 3a

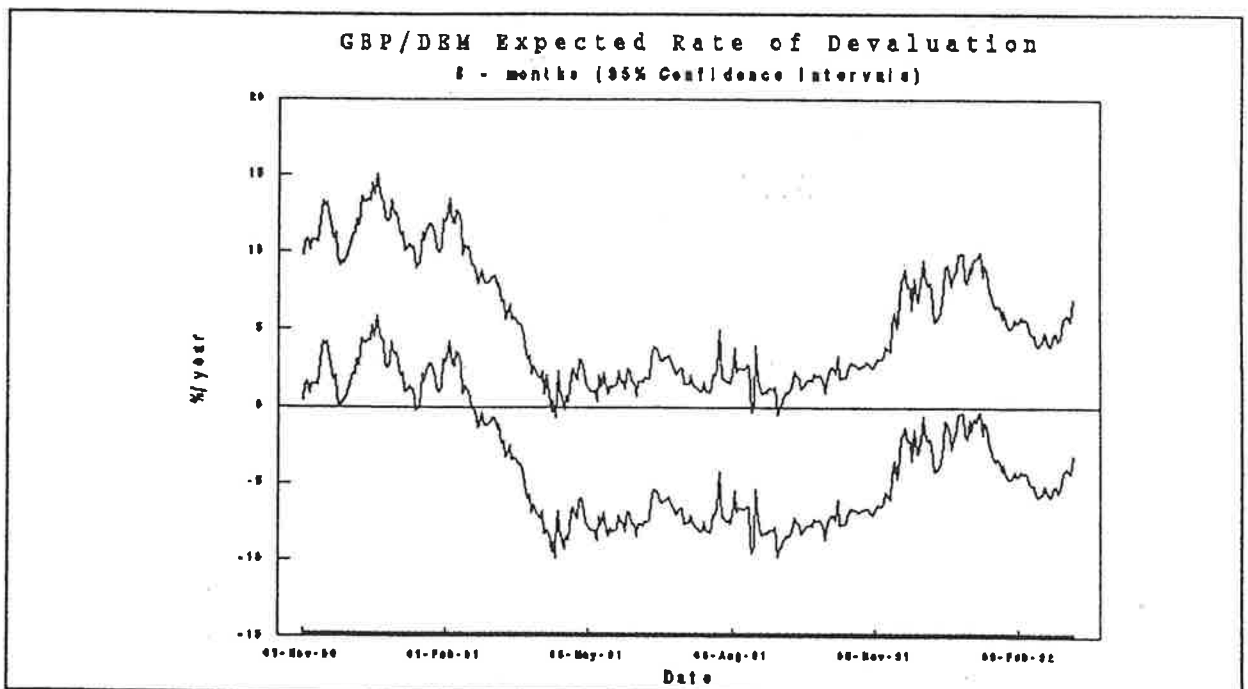


Figure 3b

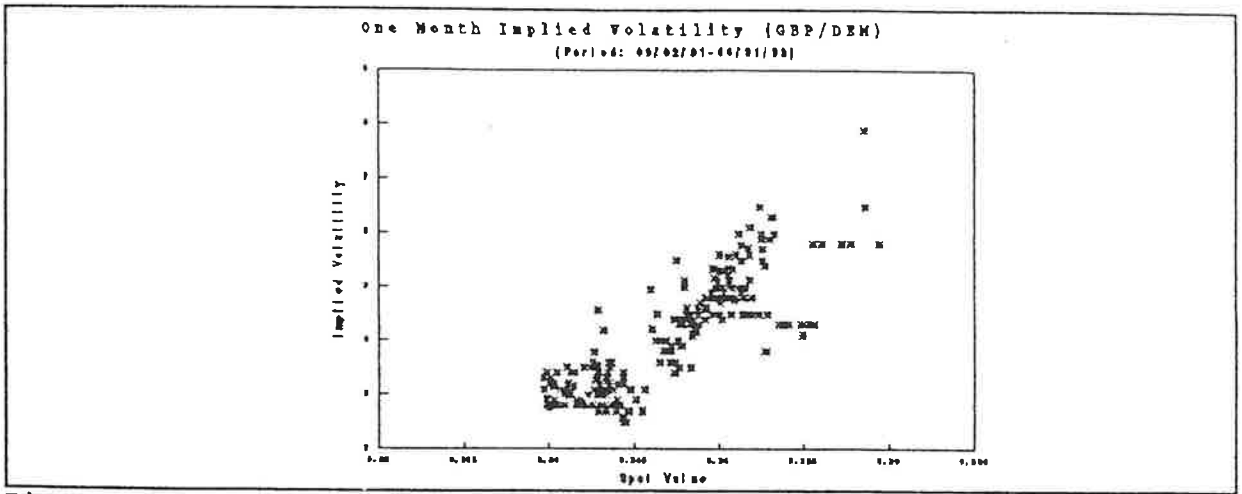


Figure 4a

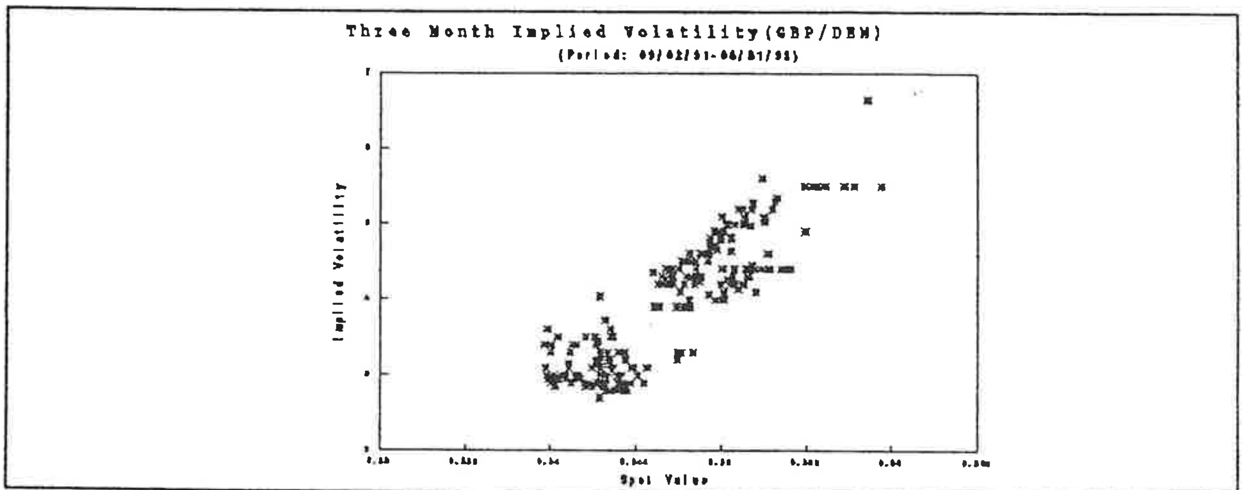


Figure 4b

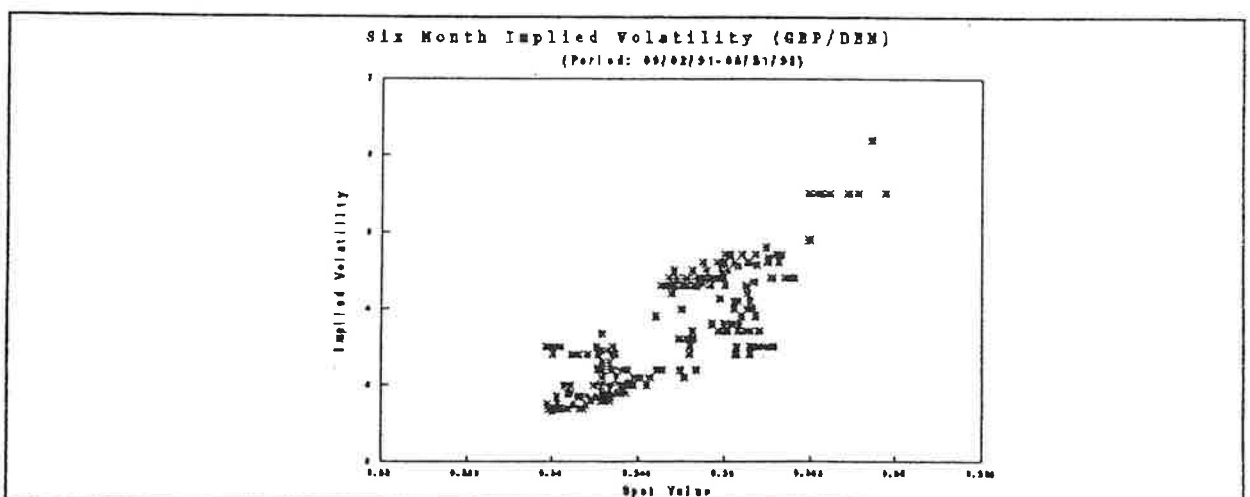


Figure 4c

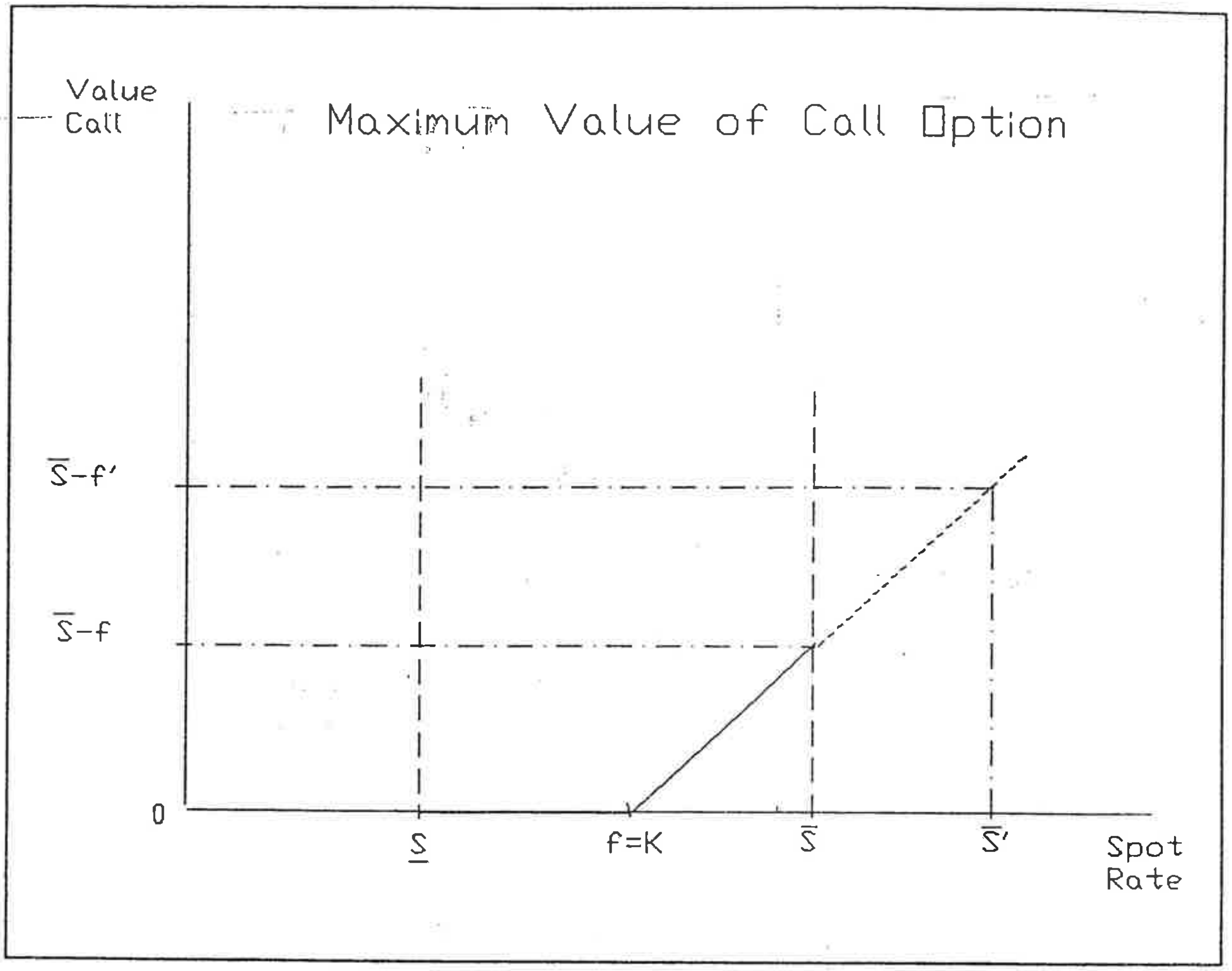
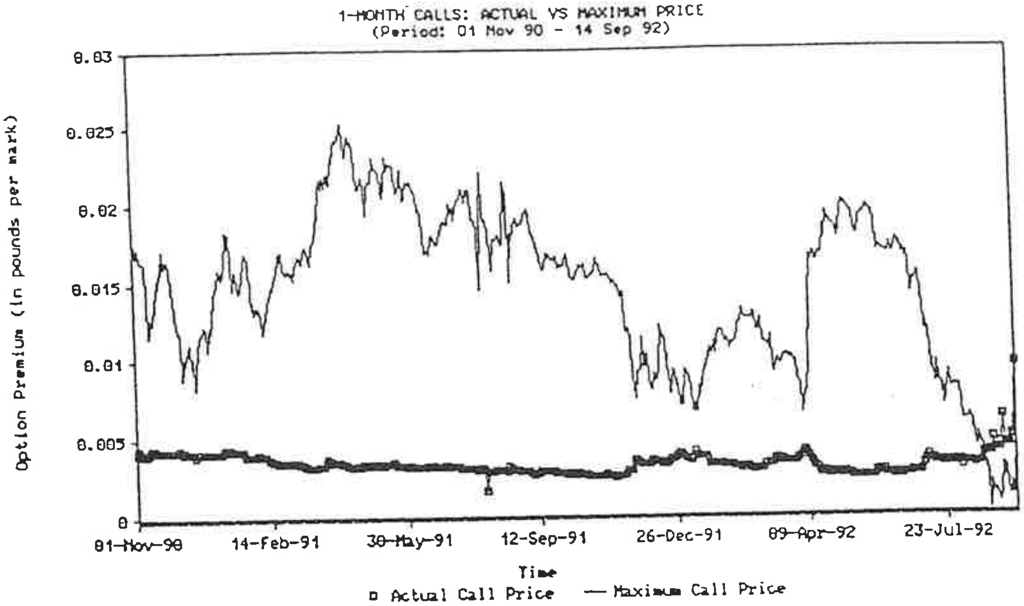
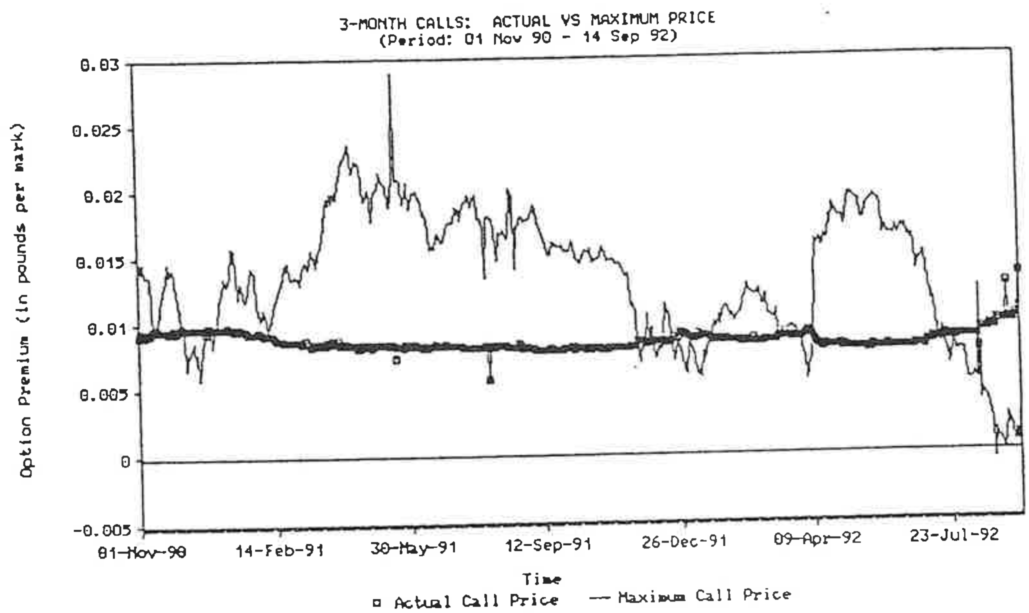
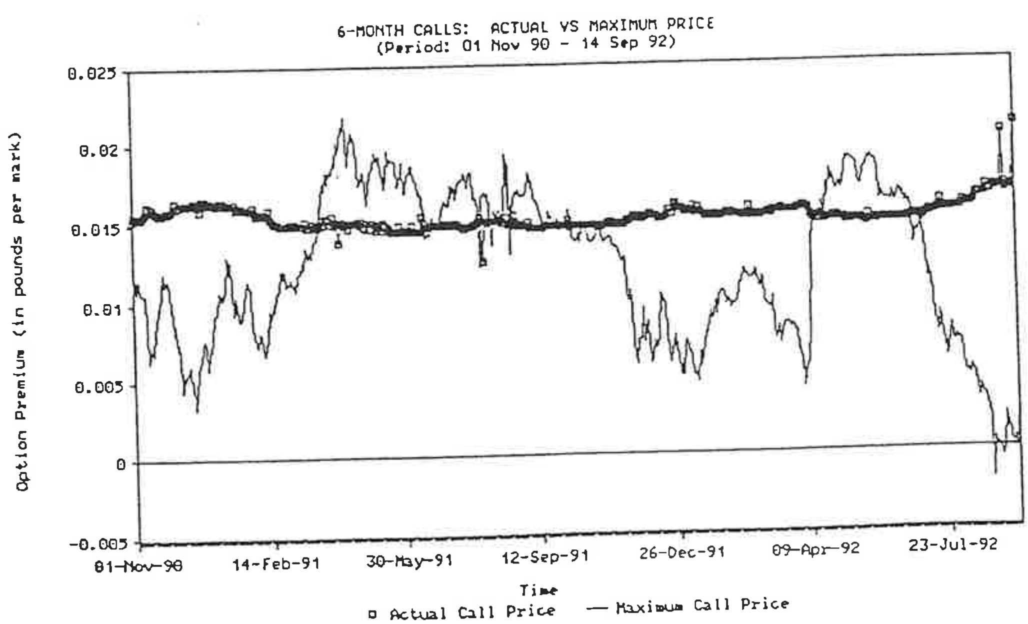

Value
Call
Maximum Value of Call Option
$\bar{S}$-f′
$\bar{S}$-f
0
$\underline{S}$
f=K
$\bar{S}$
$\bar{S}$′
Spot
Rate

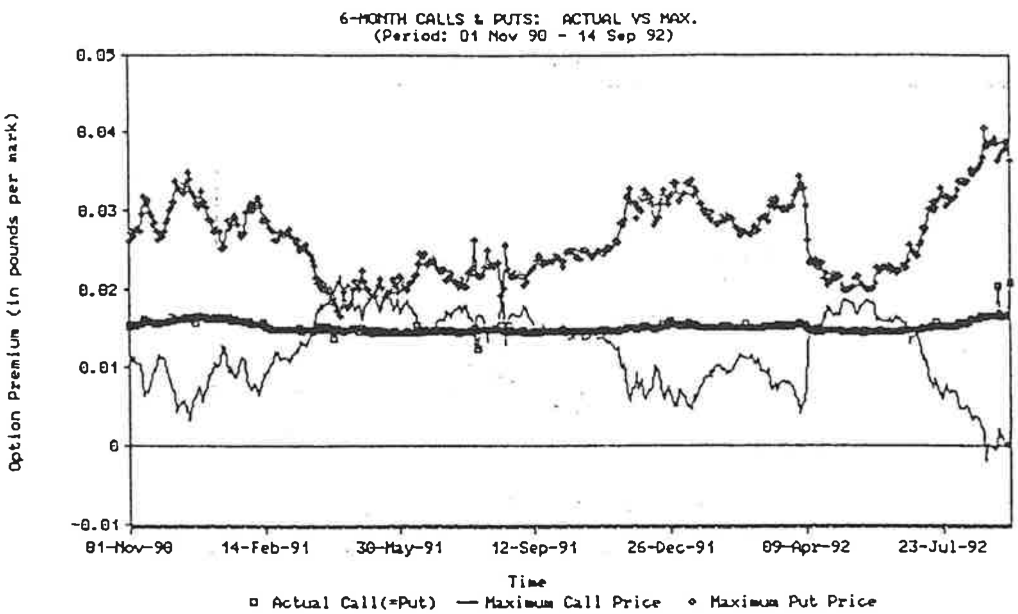
Figure 5

Figures 6a - 6d



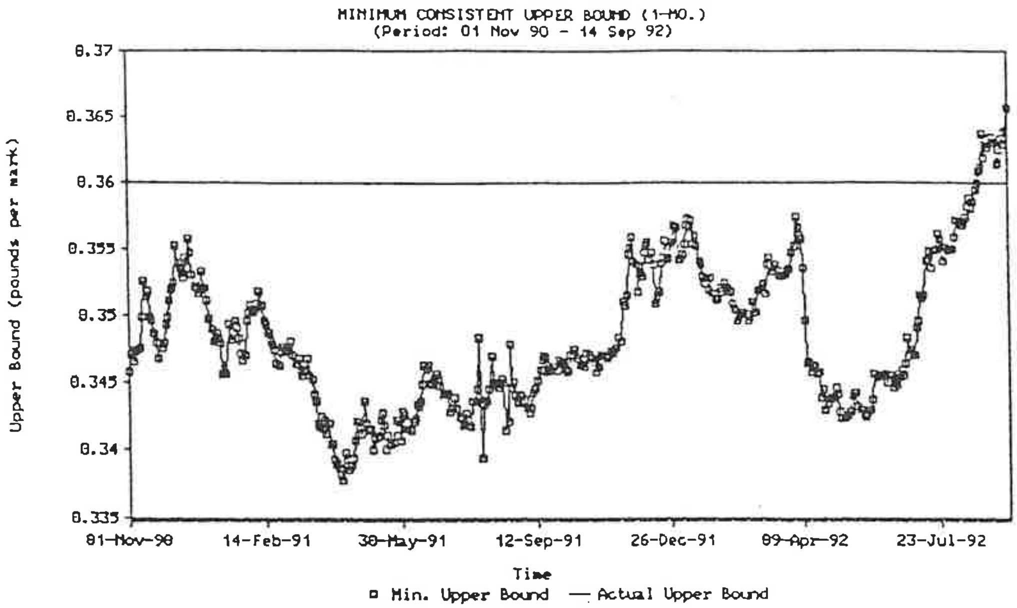


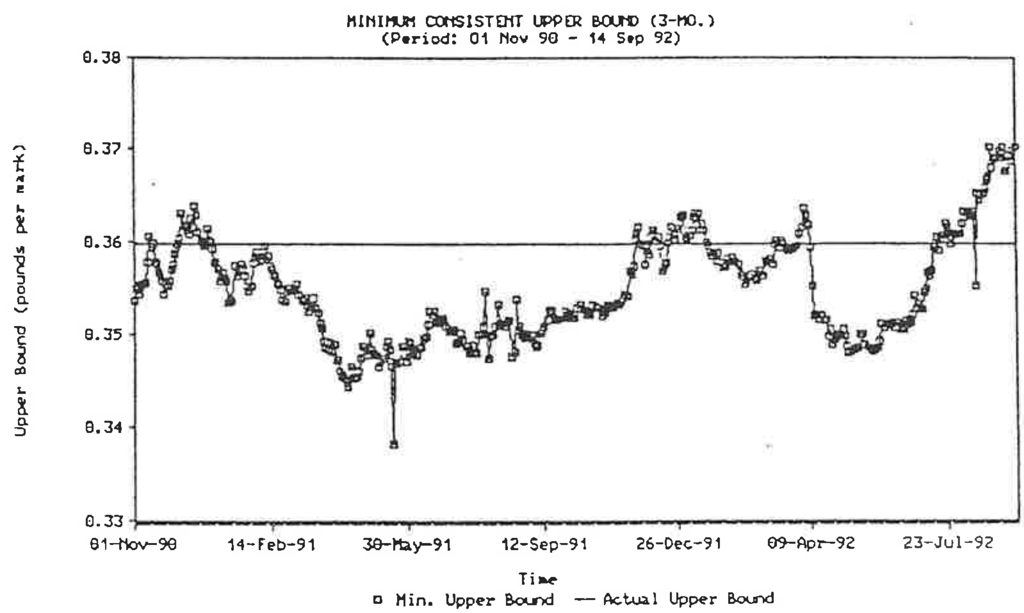


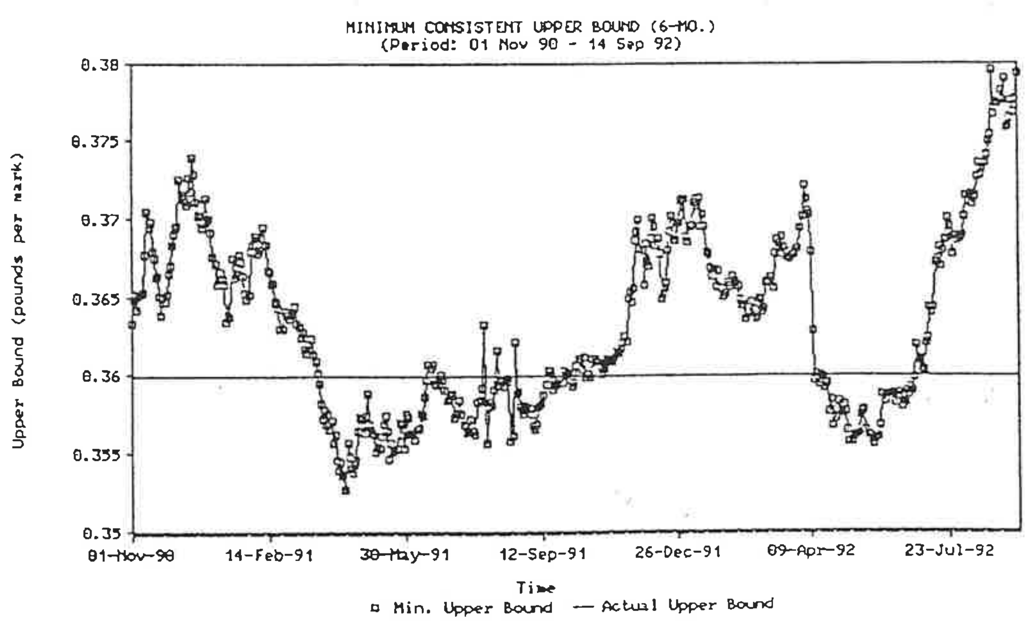


6-MONTH CALLS & PUTS: ACTUAL VS MAX.
(Period: 01 Nov 90 - 14 Sep 92)
Option Premium (in pounds per mark)
0.05
0.04
0.03
0.02
0.01
0
-0.01
01-Nov-90
14-Feb-91
30-May-91
12-Sep-91
26-Dec-91
09-Apr-92
23-Jul-92
Time
Actual Call(=Put)
Maximum Call Price
Maximum Put Price

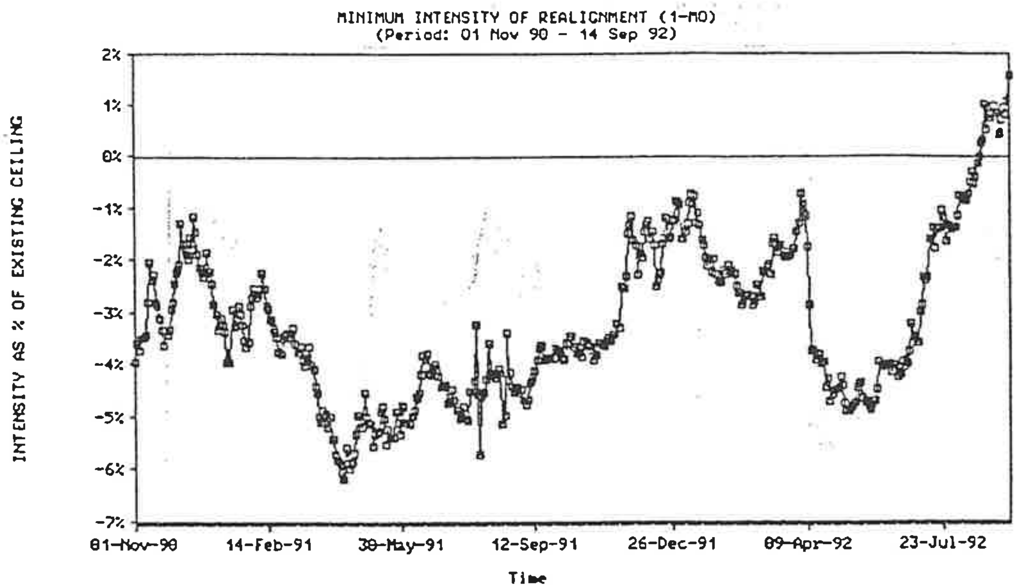
Figures 7a - 7c

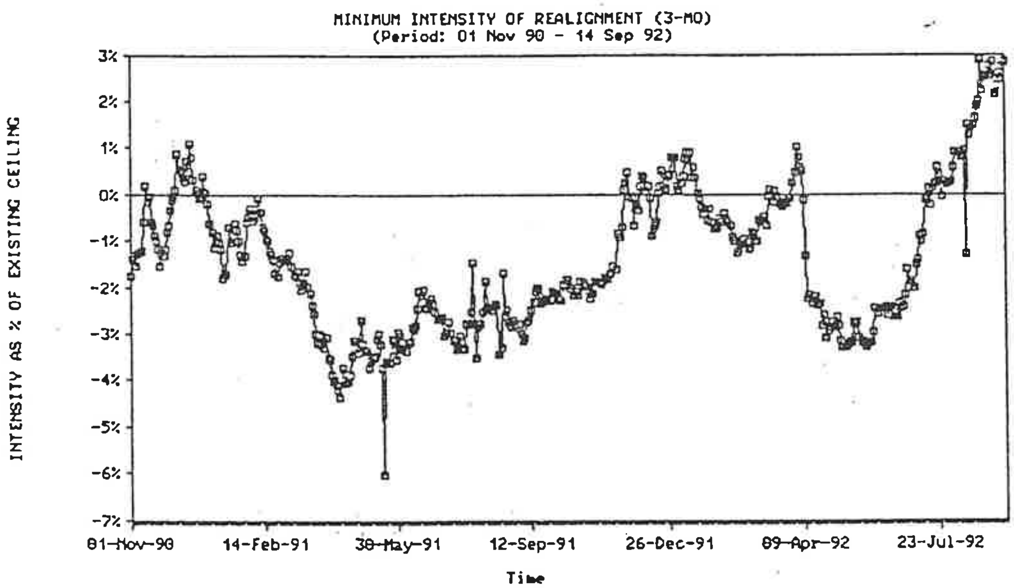


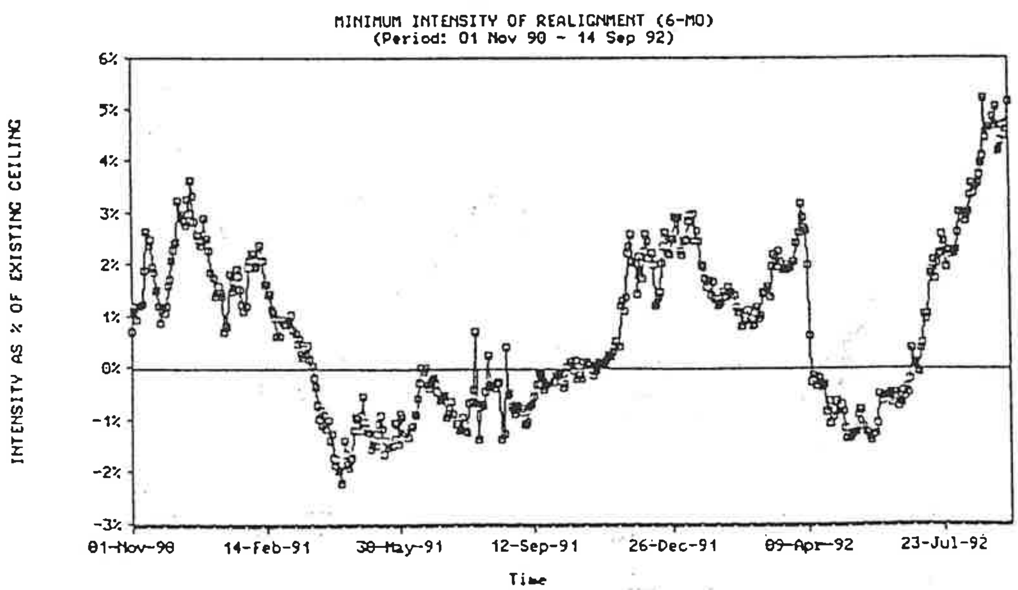




Figures 8a - 8c







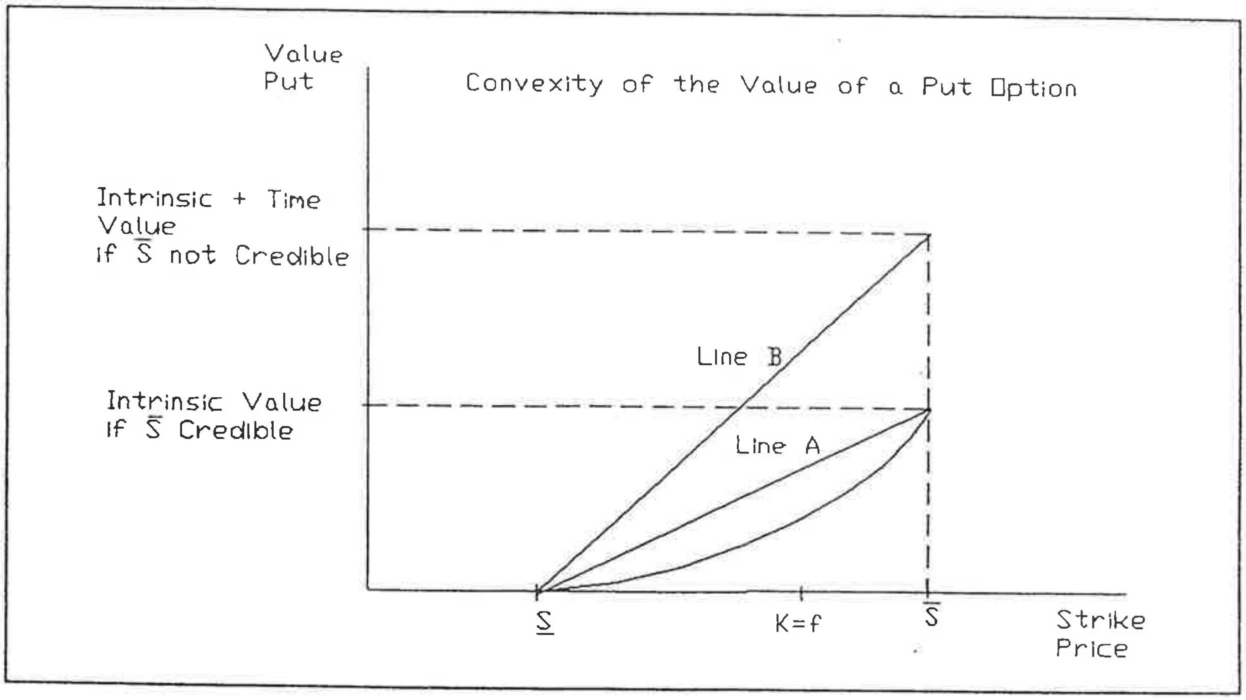


Figure 9a

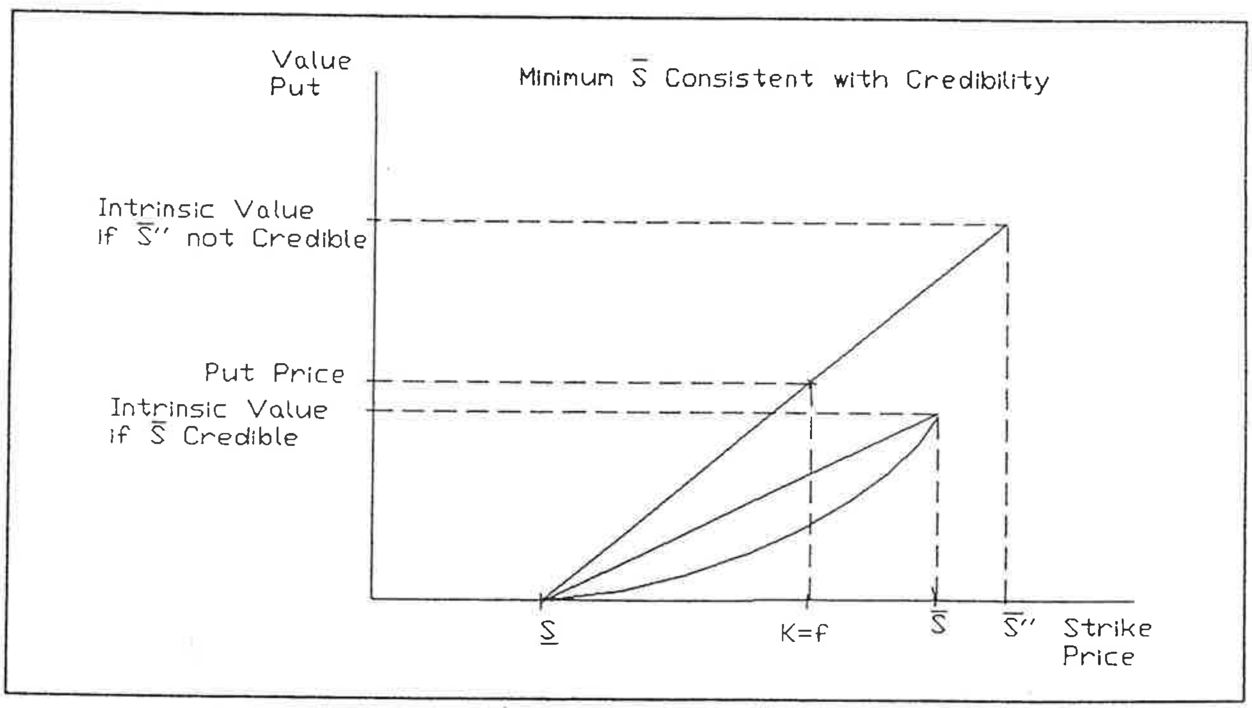
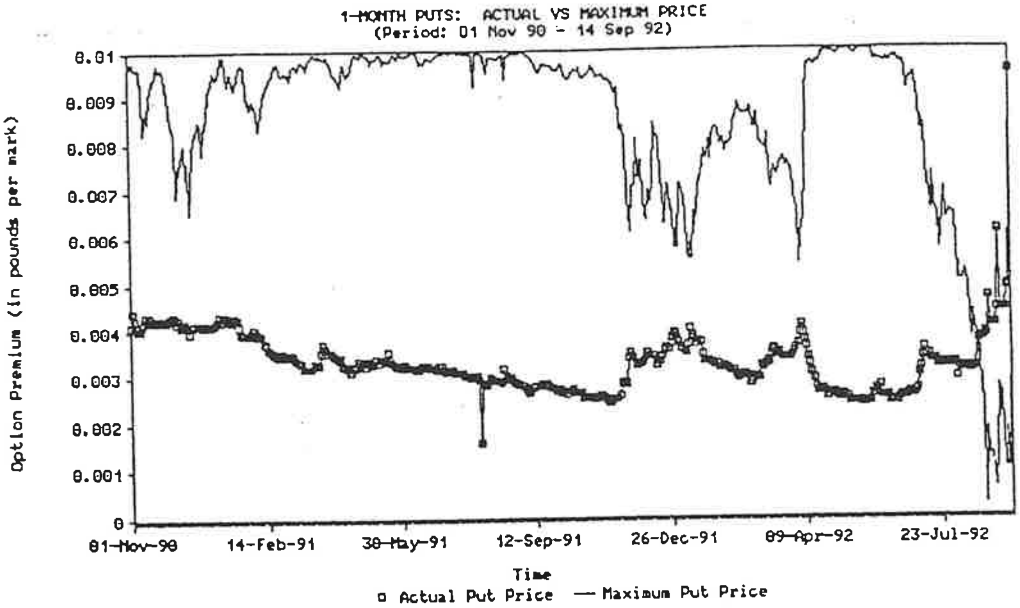
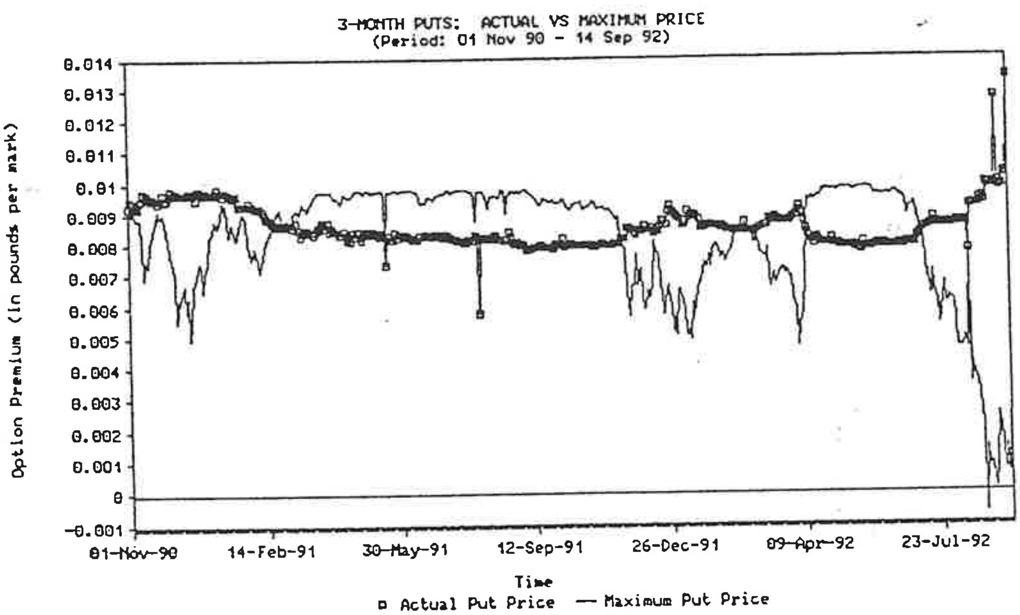
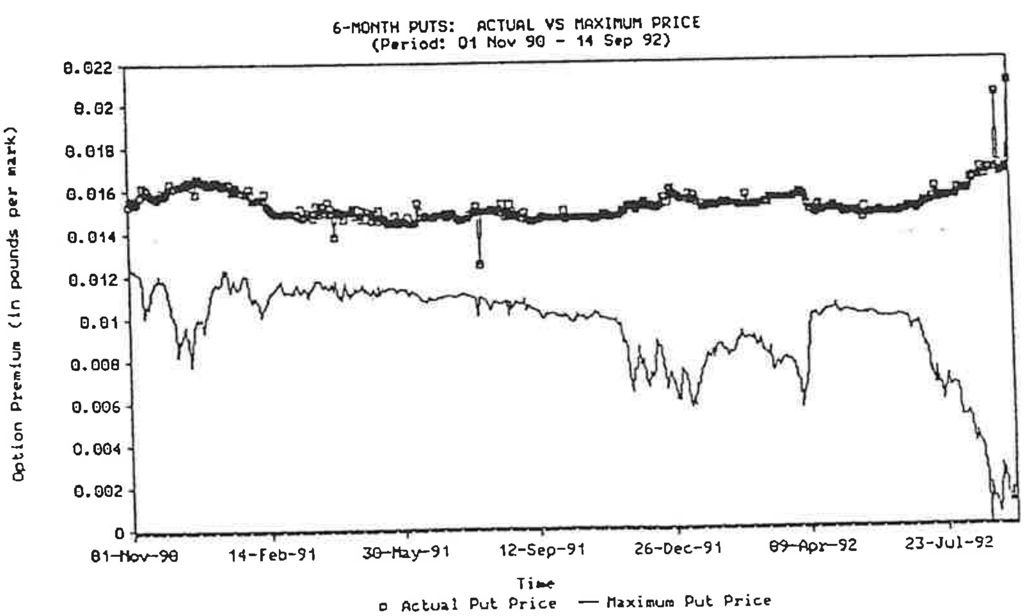


Figure 9b

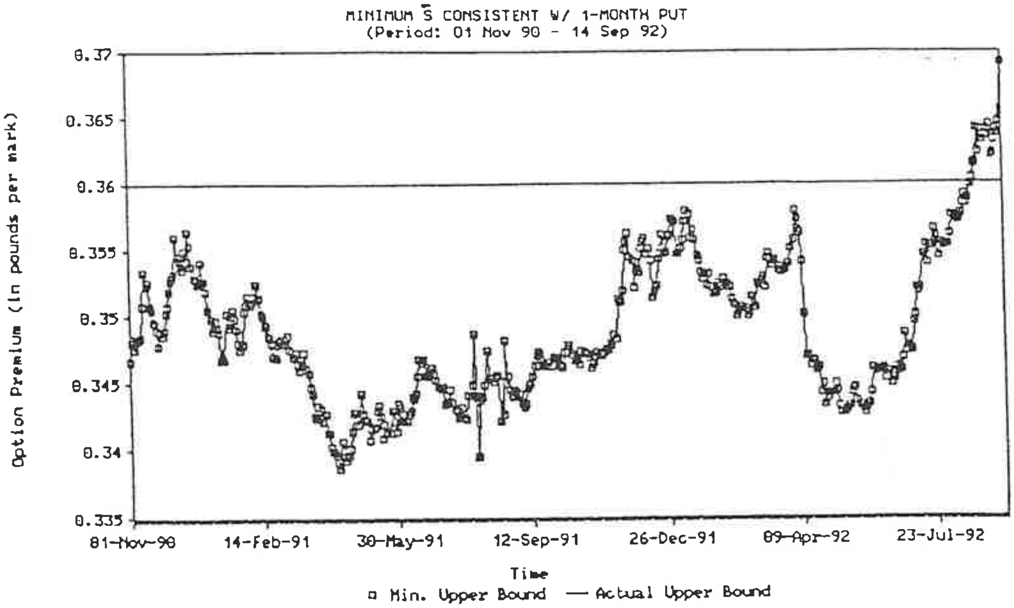
Figures 10a - 10c

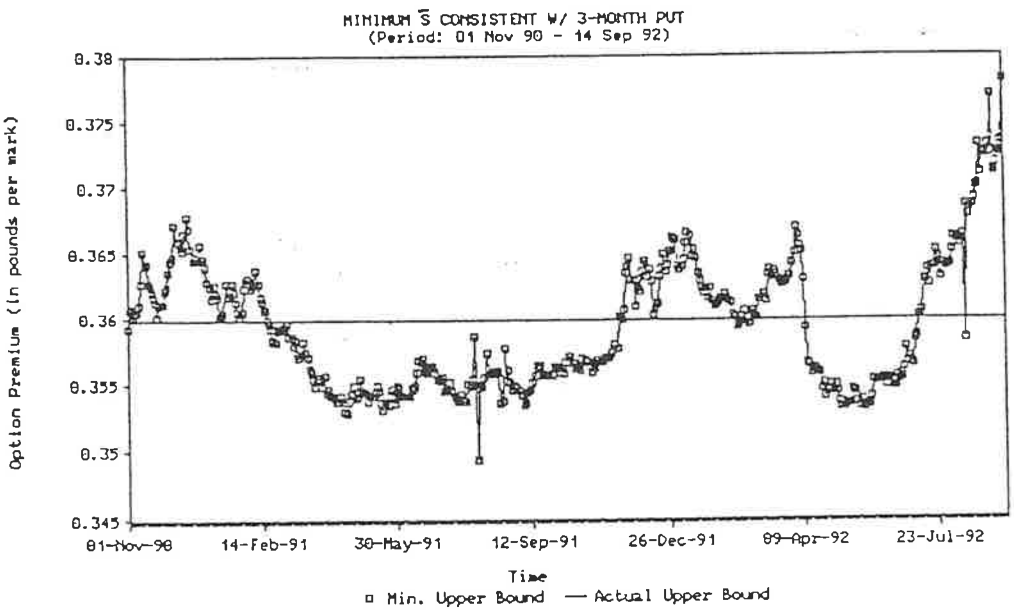


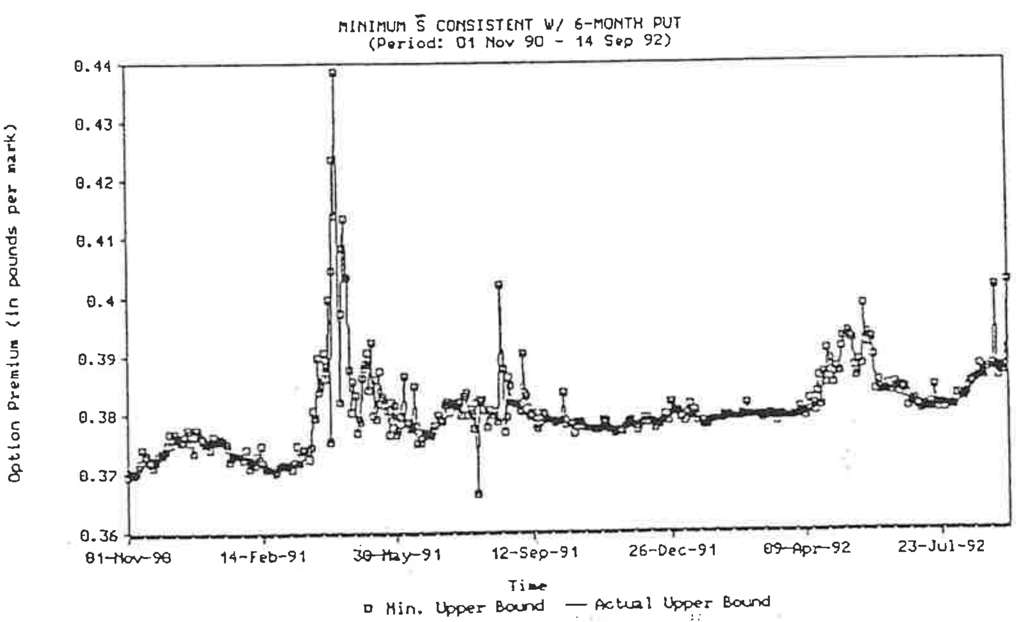




Figures 11a - 11c







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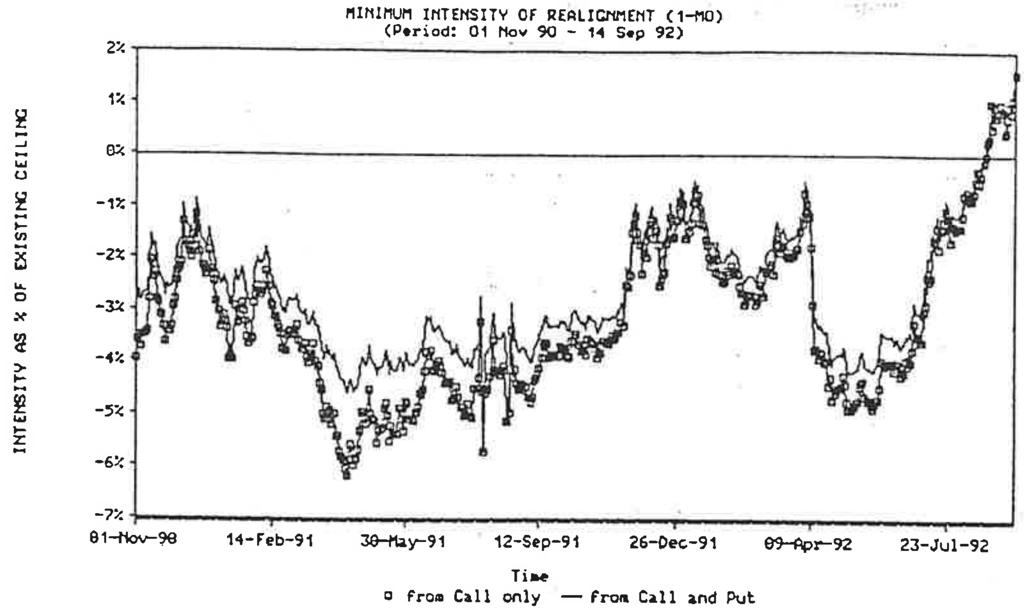

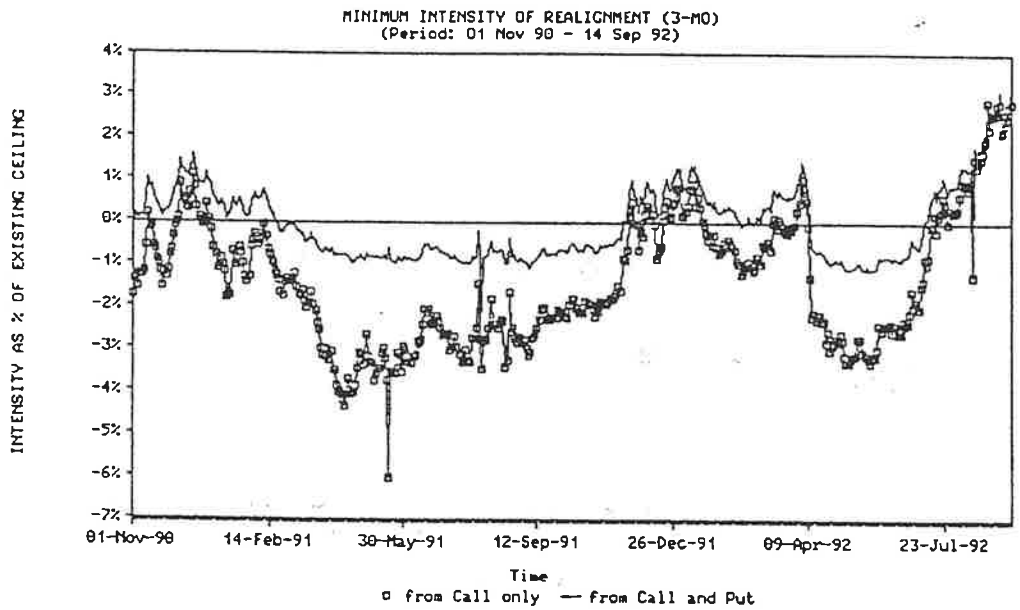

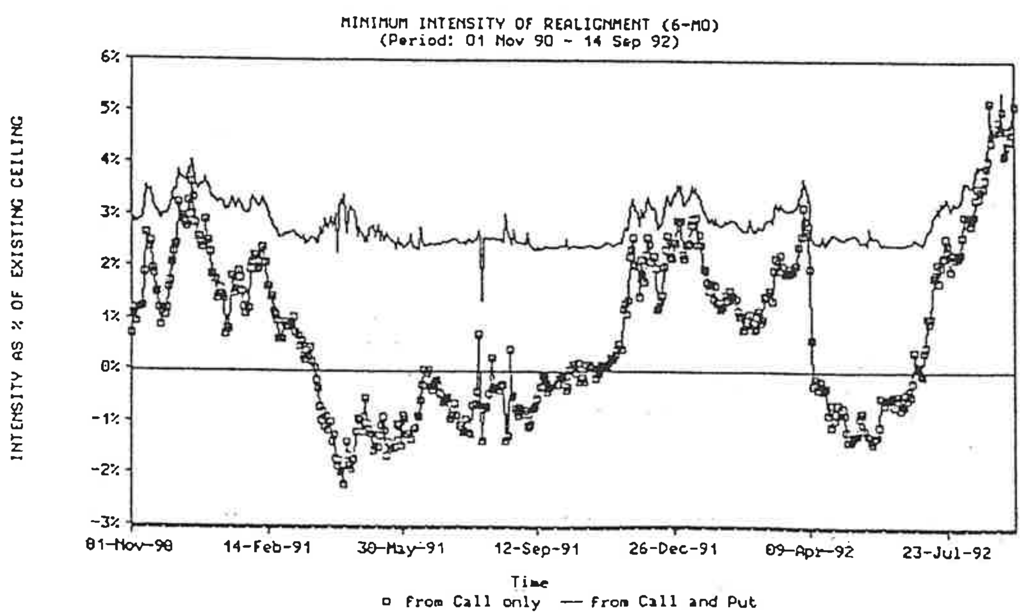

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