# Central Bank Intervention Under Target Zones: The Portuguese Escudo in the ERM

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**Abstract**

For Portugal, the transition to the Euro began in September 1989 and featured three successive institutional arrangements related to the Exchange Rate Mechanism of the European Monetary System: shadowing it, belonging to it with 6% and then with 15% fluctuation bands. Using daily data, we study how the degree of mean reversion of the exchange rate and central bank intervention reflect the change in economic regime towards stability and convertibility. Our Markov regime-switching framework with an EGARCH specification allows for deviations from central parity and intervention to affect the mean, the conditional variance and the state transition probabilities in the different policy regimes. Mean reversion is significant even when volatility is high in ERM-6, unlike central bank intervention, which almost disappears in ERM-15. Intervention affects the mean and the variance of the exchange rate when volatility is low, and the variance in ERM-S, even when volatility is high.

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# 1 Introduction

The Escudo was created on May 22, 1911 and served as Portugal's national currency until February 28, 2002. In September 1989, entry into the European Currency Unit basket uncannily introduced a long-run exchange rate objective and therefore the potential for mean reversion. Following entry into the Exchange Rate Mechanism (ERM) of the European Monetary System (EMS) in April 1992, full currency convertibility was established in December 1992. In May 1998, Portugal was found to fulfil the convergence criteria laid out in the Union Treaty and on January 1, 1999 became a founding member of the Euro. This completed a gradual and initially neglected change in economic regime towards stability oriented macroeconomic policies.

The present research seeks to better understand the process of earning credibility that accompanied moving the escudo into the Euro during nearly ten years. We use previously unavailable intervention data, kindly provided to us by the *Banco de Portugal*, in order to answer the following two inter-related questions. First, how did central bank intervention affect the mean and volatility of the change in the Portuguese Escudo-Deutsche Mark (PTE/DEM) exchange rate? Second, can changes in the effects of intervention be associated to the successive exchange rate regimes adopted during the transition?

Recent exchange rate research has focused on regime-switching models, as these are particularly well suited to deal with the dynamics of exchange rate in target-zones. In the case of the ERM, for example, periods of low volatility were interrupted by currency crises, speculative attacks and realignments. Our model allows for the possibility that the effects of intervention are not the same across different volatility states. In particular, central bank intervention is allowed to affect the mean, the conditional variance, and the state transition probabilities in each policy regime.

The proposed approach combines a Markov regime-switching framework with an Exponential Generalized Autoregressive Conditional Heteroscedasticity (MSGARCH) model and incorporates the stylised features of exchange rates dynamics. The change in economic regime towards exchange rate stability and convertibility is reflected in the degree of mean reversion of the exchange rate with respect to the numeraire. In the case of Portugal, mean

reversion applied to three successive regimes involving the ERM: shadowing (S) and observing a 6 and then a 15 per cent fluctuation band.

Our approach captures features such as volatility clustering, asymmetric response of volatility to positive and negative shocks, non-normality, time-varying transition probabilities and differences in the distributions across regimes. We also presume that GARCH effects are persistent and quite pronounced when using *daily* exchange rate data, compared to a weekly or a monthly frequency, though Bollen, Gray and Whaley (2000) and Beine, Laurent and Lecourt (2001) have argued that the need for GARCH-type models within regimes disappears once one accounts for the different volatility levels.

Mean reversion is significant in the low volatility state in ERM-S and ERM-15, and in the high volatility state in ERM-6, suggesting that the regime change was becoming credible. There was also active central bank intervention during ERM-S (mostly purchases) and ERM-6 (purchases and sales). Intervention was always effective under inconvertibility, and, with convertibility, it only had the expected effect in the mean and variance in the low volatility state. This result suggests that intervention is effective when there is no financial reputation. Since the result does not apply to ERM-15, intervention is effective when it is least needed, because credibility has already been acquired and volatility is low.

The rest of the paper is organised as follows. In Section 2, we briefly discuss economic regime change following research by Braga de Macedo (2001a) and Braga de Macedo, Nunes and Covas (2003) and introduce mean reversion through successive exchange rate regimes. Section 3 presents the results for the analysis using the MSGARCH model and section 4 concludes. A brief survey of theoretical and empirical analysis of target zones and central bank intervention is provided in Appendix 1, while Appendix 2 describes the SWARCH model used with weekly data, Appendix 3 the daily exchange rate and intervention data and Appendix 4 the single-regime exponential GARCH model.

# 2 Economic Regime Change & Mean Reversion

The Escudo became a fully convertible currency after the gradual implementation of economic policies geared towards price stability under successive exchange rate regimes culminating with the introduction of the Euro. The crawling peg policy, in place since August 1977, was gradually abandoned after the Escudo entered the ECU basket in September 1989. One year later, the central bank announced that the currency would be allowed to float within an unidentified band centred on some long-run exchange rate objective, which was not identified but probably was interpreted as the virtual ECU parity of 172 Escudos.

Moreover, intervention by the central bank would be motivated by the need to ensure a stable functioning of the foreign exchange market. In the months that followed, however, the Escudo was subject to strong appreciation pressures that forced frequent interventions.[1] While liberalisation measures required by membership of the European Community were implemented, controls on capital inflows were used to prevent a negative impact on the domestic monetary policy during this turbulent period.[2]

The main element of the EMS was the ERM, an adjustable peg system in which each currency had a central rate expressed in terms of the ECU. In turn, these central rates defined the bands within which the exchange rates could fluctuate freely. The ERM member countries were required to keep the bilateral rates within the established margins by actively intervening in the foreign exchange market if a currency approached the limits of its band. However, realignments of the central rates were also permitted, should the participants decide by mutual agreement that a particular parity could not be defended. The bands were originally set at ±2.25% but a ±6% band was later set for Italy and the new entrants into the ERM (Spain, Portugal and the United Kingdom). The last change took place in August 1993, following the months of currency turmoil, and broadened the bands to ±15% (except

[1] As a result, the official foreign reserves held by the *Banco de Portugal* increased significantly from 3462 million USD in 1990 to 6174 million USD in 1991, which represented about 9% of the gross domestic product.

[2] For a detailed description of the Portuguese Escudo's record during this period see Braga de Macedo (2001b).

for the DEM and the Dutch Guilder, which remained within the narrower band of ±2.25%).

The Escudo's joined the ERM in April 1992, became fully convertible in December and was subject to successive speculative crises until the widening of the bands in August 1993. During this period, the Escudo's central parity was realigned twice but always in the wake of the earlier devaluations of the Spanish Peseta. As for intervention policy, the central bank continued to purchase foreign currency during the first months of ERM membership. After September 1992 and during the EMS's crises, the central bank intervened by selling reserves in order to sustain the depreciating Escudo. The crisis stopped after the widening of the bands in August 1993.

Braga de Macedo, Nunes and Covas (2003) infer the change in economic regime from the stochastic properties of the weekly PTE/DEM exchange rate. Their sample period runs from January 7, 1987 until October 15, 1998 and encompasses six successive exchange rate regimes. The estimation technique employed, based on Hamilton and Susmel (1994), allows for different states depending on the volatility of the exchange rate. Markov switching autoregressive conditional heteroscedasticity (SWARCH) specifications with more than three states were found to adequately capture all regimes. The estimated conditional volatility of the exchange rate was lower and more stable in the ERM than when the Escudo was inconvertible and the central bank controlled the currency directly.[3] In the face of systemic turbulence, the Escudo's entry into the ERM and its return to convertibility were stabilising influences.

The final model specification used in the study had five states, as it was suggestive of the nature of the response of the central bank to speculative attacks during the ERM crisis regime. In particular, the analysis detected a short-lived period of very low volatility prior to the first realignment of the Escudo before reverting to a high volatility state. This episode of "false stability" lent itself to the interpretation that a strong market intervention by the central bank was able to maintain the rate at the top of the band before adjusting to the central rate.[4] This interpretation of the monetary

[3] The comparison excludes the sub-periods of crises before the widening of the bands and the one after volatility for prospective EMU qualifying currencies subsided.

[4] The subsequent re-estimation of the models using a larger data set that ends on

authorities' response to speculative attacks raises the issue of central bank intervention *per se* and motivates our first research question: how did central bank intervention affect the Escudo's level and volatility during its transition process? In attempting to answer this question, we used intervention data kindly provided to us by the *Banco de Portugal*.

One would expect *a priori* that the effect of intervention on the level of the exchange rate to be greater during the period of increased capital controls and when the currency was inconvertible. On the other hand, given the ambiguous nature of policy goals during ERM-S, central bank intervention could also have resulted in increased volatility. In fact, as discussed in Dominguez (1998), intervention can have a positive effect on volatility when policy ambiguity is coupled with exchange market inefficiencies. In addition, the central bank publicly announced its desire for increased volatility in order to discourage short-term speculative capital inflows. Finally, one would also expect that intervention becomes less effective following the restoration of full convertibility and as the credibility of greater financial integration process gradually took hold.

The fact that a long-run exchange rate objective has been present through the successive exchange rate regimes experienced since the end of the crawling peg is also important for our analysis. The Escudo's percentage deviation from its established (or virtual) central parity is used in order to capture the mean reversion effect that characterises credible target zone arrangements, as discussed in Appendix 1. The deviation from central parity is shown in Figure 1 and clearly reflects the turbulent behaviour of the exchange rate during the early part of the ERM 6 period and also the effects of the November 23, 1992 and May 14, 1993 realignments.[5] During this period, the PTE/DEM exchange rate oscillated within the range of -4.89% to 5.31% deviations from the established central parity. The ERM 15 period is characterised by positive deviations until September 1996, negative deviations during 1997 and

December 30, 1998 confirmed all of the previous analysis' results, with an increase in volatility in the last few weeks before the introduction of the Euro. Braga de Macedo (2001b) reports some of the differences relative to the earlier sample, which are available from the authors upon request.

[5]The first realignment occurred in the wake of the ERM crisis that took place in September 1992 while the second and the third (March 6, 1995) were the result of the PTE following the realignments of the Spanish Peseta.

a gradual convergence to zero during 1998. The deviations for this period range from -2.86% to 5.63%.

Taking mean reversion as a proxy for the regime change towards exchange rate stability, we estimated the SWARCH models used by Braga de Macedo, Nunes and Covas (2003) with three additional explanatory variables in the mean and conditional variance equations, namely, foreign currency purchases and sales and also the deviation from central parity. We found mean reversion to be always significant in explaining the rate of change of the PTE/DEM exchange rate. Intervention, however, only had effects on the mean exchange rate under currency convertibility.

These results, described in Appendix 2, cannot capture the possible intra-week effects of central bank intervention nor do they reflect the fact that turbulence in the ERM would lead one to expect considerable intervention activity. This is why we emphasise the daily exchange rate and differences in intervention data as they allow for a closer look at the intermediate period during which the Escudo was in the ERM but the whole grid was under attack, i.e. between April 1992 and August 1993. In addition, we adopt an alternative modelling approach that allows for the analysis of *intra*-regime structural change.

# 3 Central Bank Intervention & Regime Switching

The daily bilateral PTE/DEM exchange rate, denoted by $S_t$, is used to study the effects of intervention.[6] The dependent variable is taken to be $\Delta s_t = 100 \cdot \ln[S_t/S_{t-1}]$, implying that a depreciation is then denoted by $\Delta s_t > 0$ under this convention. The time period considered runs from September 21, 1989, when the Escudo entered into the ECU currency basket, until December 31, 1998, the last day prior to the introduction of the Euro. This period was chosen since it encompasses the three policy regimes implemented during the transition process to the Euro. Three distinct sub-periods are considered based on the knowledge of policy regime change: the shadowing of the ERM before entry (September 1989 to April 1992), the ERM crises from April 1992 to July 1993 and the widened-bands period after August 1993.

[6]The data used here is presented and discussed in appendix 3.

The level of intervention undertaken by the central bank in period $t-1$, in millions of DEM, is denoted by $I_{t-1}$. We do not distinguish between purchases ($I_{t-1} > 0$) and sales ($I_{t-1} < 0$) since the periods under consideration are relatively homogenous with respect to the type of intervention pursued. The same criterion applies to the distinction between sterilised and unsterilised intervention given the lack of information concerning daily sterilisation procedures used to compensate for changes in foreign currency reserves. The volume of intervention is lagged one period in order to avoid the problem of contemporaneous simultaneity with the dependent variable. The mean reversion effect is captured by the inclusion of the term $D_{t-1} = 100.[S_{t-1}/\text{Central Parity}_{t-1} - 1]$, which measures the exchange rate's percentage deviation from its central parity in period $t-1$.

Following the considerations discussed in section 2 and Gray's (1996) methodology, this paper proposes an unified model that combines a Markov regime-switching formulation with an exponential GARCH-type specification for the conditional volatility. The resulting MSGARCH model explicitly allows for central bank interventions to affect both the mean, the conditional variance and the time-varying transition probabilities (TVTP).[7] It also allows for the possible asymmetric effect of positive and negative shocks on the volatility and for positive variances only. Moreover, the possibility that the higher moments of the distributions of the daily exchange rate's change might vary across regimes is taken into account. Considering Student t - distributions with regime dependent degrees of freedom incorporates this latter feature.[8]

The specification of the mean and conditional variance equations of the two-regime model is as follows:

$$
\begin{aligned}
\Delta s_{it} &= \alpha_{i0} + \alpha_{i1}\Delta s_{t-1} + \alpha_{i2}\Delta s_{t-2} + \alpha_{iI} I_{t-1} + \alpha_{iD} D_{t-1} + e_t \\
\ln v_{it} &= \beta_{i0} + \beta_{i|e|}\left|\frac{e_{t-1}}{\sqrt{v_{t-1}}}\right| + \beta_{ie}\frac{e_{t-1}}{\sqrt{v_{t-1}}} + \beta_{iv}\ln v_{t-1} + \beta_{i|I|}|I_{t-1}| + \beta_{i|D|}|D_{t-1}| \\
e_t &= \sqrt{v_{it}}\varepsilon_t \qquad \varepsilon_{it} \sim i.i.d\ t(d_i)
\end{aligned}
$$

where $t(d_i)$ denotes a standardised Student-$t$ distribution with $d_i$ degrees of freedom, a mean of zero and a unit variance. The subscript $i = 1, 2$

[7] In order to better appraise the importance of a regime-switching formulation, a single regime EGARCH model is estimated in appendix 4.

[8] On the issue of within regime departures from normality, see also Campbell (2001).

denotes each of the possible values taken by the unobserved regime variable $Z_t$ upon which the distribution of the exchange rate return depends. It is assumed that $Z_t$ evolves according to a first-order Markov chain where the probability that the process is in regime $i$ at time $t$, conditional on it having being in regime $j$ during $t-1$ is given by $\Pr(Z_t = i|\ Z_{t-1} = j, \Psi_{t-1})$, where $\Psi_{t-1} = \{Z_{t-1}, Z_{t-2}, ..., \Delta s_{t-1}, \Delta s_{t-2}, ...\}$ denotes the information set of period $t-1$. Although the regimes are not directly unobservable, it is nevertheless possible to infer the probability that the process is in regime $i$ at time $t$, which is given by $p_{it} = \Pr(Z_t = i|\Psi_{t-1})$.

Let $t(\mu, v, d)$ denote a generic Student $t$-distribution with mean $\mu$, variance $\nu$ and $d$ degrees of freedom whose density function is given by:

$$f(y) = \frac{\Gamma\left(\frac{d+1}{2}\right)}{\Gamma\left(\frac{d}{2}\right)\sqrt{\pi}\sqrt{d-2}\sqrt{v}}\left(1+\frac{(y-\mu)^2}{(d-2)v}\right)^{-\frac{d+1}{2}}$$

Under the above assumptions, the distribution of exchange rate returns is generated by a mixture of two distributions each weighted with probability $p_{it}\quad i = 1, 2$, i.e. $\Delta s_{it}|\Psi_{t-1} \sim t(\mu_{it}, v_{it}, d_i)$ with $\mu_{it} \equiv E[\Delta s_{it}|\Psi_{t-1}]$ and where $v_{it}$ is as defined above. The error term can therefore be calculated as

$$e_{t-1} = \Delta s_{t-1} - E(\Delta s_{t-1}|\Psi_{t-2}) = \Delta s_{t-1} - \sum_{i=1}^{2} p_{it-1}\mu_{it-1}$$

while the conditional volatility during period $t-1$ is calculated as

$$v_{t-1} = \sum_{i=1}^{2} p_{it-1}(\mu_{it-1}^2 + v_{it-1}) - \left(\sum_{i=1}^{2} p_{it-1}\mu_{it-1}\right)^2$$

Central bank interventions and deviations from central parity are assumed to affect the TVTP in the following manner:

$$\Pr(Z_t = i|Z_{t-1} = i, \Psi_{t-1}) = \Phi(\gamma_{i0} + \gamma_{i|I|}|I_{t-1}| + \gamma_{i|D|}|D_{t-1}|)$$

where $\Phi(\cdot)$ denotes the cumulative standard normal distribution function. This formulation allows one to study not only the impact of these two variables on the dynamics of the mean and conditional variance equation but

also their effect on the transition probabilities. Finally, note that each of the model's parameters will always depend on the unobserved regime $Z_t$.

Regarding the signs of the parameters, intervention is deemed effective when $\alpha_I > 0$ in the mean equation. For example, when the central bank sells foreign currency ($I_{t-1} < 0$), the domestic currency should appreciate ($\Delta s_t < 0$). To understand the effect of deviations from central parity, consider the case of $D_{t-1} > 0$: if the target-zone is credible, the exchange rate should revert back to its long-run level ($\Delta s_t < 0$) implying that $\alpha_D < 0$ in the mean equation. Note that this parameter is an elasticity and will therefore be extremely useful as a comparative measure of the importance of the mean reversion effect during different time periods.

The parameters $\beta_{|e|}$ and $\beta_v$ capture the effect of volatility clustering in the conditional variance equation. Possible asymmetric responses to shocks are measured by $\beta_e$ : negative shocks increase the subsequent period's conditional volatility more than positive shocks when $\beta_e < 0$. The parameter $\beta_v$ also captures the effect of persistence: a conditional variance that is stationary implies that $\beta_v < 1$. The absolute value of $D_{t-1}$ is also included in the conditional variance equation in order to determine the impact of deviations from parity on the volatility level of period $t$. Bilateral target-zone models predict that $\beta_{|D|} < 0$, reflecting the fact that the exchange rate becomes less sensitive to movements in the fundamentals the closer it approaches the boundaries. Finally, the parameters $\gamma_{i|I|}$ and $\gamma_{i|D|}$ respectively capture the effect of interventions and deviations from central parity on the TVTP.

Hamilton's filter was used to construct the filtered probabilities and the log-likelihood of the whole sample. In Table 1, we present the results obtained for the three sub-samples considered. The low-volatility regime is labelled as regime one and the high-volatility regime as regime two. Non-significant variables were excluded from each estimated equation, the most notable being the asymmetric exponential GARCH variable. Whenever a parameter did not significantly differ across regimes, that restriction was also imposed. In conformity with results of the single-regime model (refer to Appendix 4), the estimated $t$-distribution degrees of freedom in the first sub-sample do not differ much between the two regimes and it is possible to reject the null hypothesis of a Normal distribution. However, there is now evidence that the Normal distribution is more appropriate for the high-volatility regime of

the second sub-sample. Note also that the estimated degrees of freedom are rather low in the third sub-sample reflecting the presence of thick tails.

The issue of ascertaining the suitability of the two-regime models over the corresponding single-regime model presents several difficulties. First, it is well known that the usual likelihood-ratio test statistic has a non-standard distribution and the appropriate critical values require rather cumbersome computational procedures (see Hansen, 1992, 1994). Moreover, the single and two-regime models might not always be nested and so require alternative testing procedures. A possible solution is to resort to model-selection criteria. In our analysis, the AIC criterion always selects the two-regime models for the three samples considered. On the other hand, the SBC criterion selects the single-regime model for the first and third sub-period and the two-regime model for the second sub-period. We favour the AIC criterion, however, as it more successful in choosing the correct state dimension when compared to the SBC criterion, which tends to underestimate it (Psaradakis and Spagnolo, 2003).

Another possible check of the appropriateness of the two-regime model is obtained by looking at the graph of the estimated probabilities of being in each regime at time $t$. The smoothed probabilities of being in the high-volatility regime, presented in Figures 2 to 4, clearly delineate the different regimes present in the sample data. Our estimation identifies five periods as belonging to the high-volatility regime in the first sub-sample. The first period runs from September 1989 until mid-May 1990 and the second period from July 1990 until mid-January 1991. The third, lasting approximately four months, starts in mid-March 1991 while the fourth occurs mainly during September 1991. The beginning of the second and third periods coincides with two large sterilisation operations undertaken by the central bank and the treasury at about the same time. Large amounts of public debt bonds were issued in these operations in anticipation of pending external public debt repayments. The month of July 1991 also coincided with the imposition of additional controls on the mobility of capital. The final period of high volatility begins during November 1991 and extends itself until February 1992.

In the second sub-sample, the high-volatility regime coincides almost perfectly with the periods of EMS instability, namely September 1992, November

1992 and July 1993. The high-volatility regime persists at the beginning of the third sub-sample and lasts until January 1996. This period encompasses the last realignment of the PTE in March-April 1995 and uncertainty surrounding the local elections in the last trimester of 1995. The final period of high-volatility prior to the introduction of the Euro lasts from August 1996 until March-April 1997.

The estimated results of the model are very different across the three sub-samples considered. Turning first to the mean equation, there is strong evidence of autocorrelation in the dependent variable for both regimes during ERM S and ERM 15 and almost none in the remaining period. The intervention variable's coefficient is significant in the low-volatility regime during the ERM S and ERM 6 periods, and so confirms the results obtained with the single-regime exponential GARCH models. However, in contrast with the single-regime results, there is now evidence of mean reversion in the low-volatility regime of the ERM S and ERM 15 periods.

This result confirms the picture that emerges from Figures 1 and 4: the convergence of the PTE to the central parity, prior to the decision regarding the Euro start-up member countries, occurred in the stable low-volatility regime that began around March-April 1997. Surprisingly, there is also evidence of very strong mean reversion during the *high-volatility* regime of ERM 6 (-0.5325 in Table 1). In fact, the mean reversion effect for this period is seventeen times larger than the result obtained in the preceding period, and ten times as large when compared to that of the ERM 15 period.

The equations describing conditional volatility present differences across the two regimes but also have some common features. For example, the parameters $\beta_{1|e|}$ and $\beta_{2|e|}$ are significant in all cases excepting one for the three periods. Moreover, interventions seem to have no direct effect on the conditional variance. The persistence of shocks to volatility implied by the estimates of $\beta_{1v}$ and $\beta_{2v}$ is moderate in the low-volatility regime of the ERM S and ERM 15 periods while it is fairly high in the high-volatility regime of the former. Note that the estimated parameter $\beta_{1|D|}$ is significant and correctly signed in the low-volatility regime of ERM 6. This suggests that the low-volatility regime of ERM 6 is also characterised by a credible target-zone despite the absence of a significant mean reversion effect.

Interventions seem to have had no direct effect on the conditional variance

in any of the periods. Upon consideration of the estimated values of $\gamma_{1|I|}$ and $\gamma_{2|I|}$ in the TVTP equations, it appears that interventions have an *indirect* effect on volatility, a result that is not apparent using the single-regime exponential GARCH model. During the ERM S period, interventions not only strongly increase the probability of moving from the low to the high-volatility regime, they also appear to have the *opposite* effect. Moreover, judging from the estimated parameters values, this effect is equally pronounced in both regimes. There is also evidence that central bank interventions increase the probability of leaving the low-volatility during the ERM 6 period. Comparing the magnitude of the estimated parameter with that of ERM S reveals that this effect is very slight, however.

# 4 Conclusion

Based on the Escudo's transition to the Euro, this paper suggests that there must be a change in economic regime towards exchange rate stability and convertibility in order for a target zone regime to be credible. We attempt to capture this feature by the degree of mean reversion of the exchange rate with respect to the numeraire under different institutional arrangements. In the case of Portugal, these include shadowing the ERM (ERM-S) and ERM membership with 6% (ERM-6) and, subsequently, 15% (ERM-15) fluctuation bands. The paper looks at the effects of central bank intervention on the mean and volatility of the change in the exchange rate. One would expect, *a priori*, that the effect of central bank intervention on the level of the exchange rate to be greater when the currency was inconvertible and capital controls were being tightened. However, central bank intervention could well have resulted in increased volatility, given the ambiguous exchange rate regime of ERM shadowing. Finally, one would also expect intervention to become less effective as the credibility of greater financial integration process gradually takes hold.

The present study incorporates the effects of central bank intervention and the fact that a long-run exchange rate objective has been present through out the Escudo's successive three exchange rate regimes. The percentage deviation from the established (or virtual) central parity is thus included as a measure of the mean reversion effect that characterises a credible target zone. We then re-estimate the SWARCH models of Braga de Macedo, Nunes and

Covas (1999). While results obtained do not reflect the fact that turbulence in the ERM would lead one to expect considerable intervention activity, they provide strong evidence of mean reversion.

The use of daily exchange rate and intervention data does allow for a closer look at the intermediate period during which the Escudo was in the ERM while the whole grid was under attack (ERM-6). The analysis relies on a MSGARCH model, characterised by a regime-switching exponential GARCH specification with time-varying transition probabilities, instead of the single-regime models commonly used in the literature. This alternative modelling approach allows for the analysis of intra-regime structural change as well as incorporating many of the exchange rate's stylised features. Evidence for ERM-S suggests that foreign currency purchases increased the probability of leaving the low-volatility regime and indirectly reduced exchange rate variability, via the transition probability, in the high-volatility regime. The first effect is perverse but it is partly offset by the fact that intervention is effective in depreciating the currency.

In the ERM-6 period, central bank intervention (now both purchases and sales) is slightly less effective in the low-volatility regime but it is much less likely to induce a move to the high volatility regime as a result, so that the perverse offset of ERM-S disappears. There is good evidence that the target-zone arrangements are credible for both regimes during this period. There is also evidence of a stabilising effect of the target-zone on volatility, confirming the earlier finding based on weekly data for the convertibility period. Significantly, the high-volatility regime is characterised by a very strong mean reversion effect, even though central bank interventions have no impact on the mean, the conditional variance and the transition probability.

The ERM-15 period shows much weaker evidence of mean reversion and the absence of significant intervention effects. The fact that no discernible impact of intervention can be found is perhaps partially explained by the relatively low frequency of intervention during this period.

There is no evidence of a direct effect of intervention on conditional volatility for any of the periods considered. Instead, our analysis detects what appears to be an indirect channel, via the regime transition probabilities, through which interventions affect the exchange rate. Intervention seemingly increases the probability of regime change. This effect is stabilising

when volatility is low provided it is simultaneously effective in depreciating the exchange rate, as is the case in ERM S. On the other hand, under ERM-S, mean reversion is very weak as depreciation takes more than one month to work itself out.

We note, however, that the effect of mean reversion is not always significant across different volatility states. In ERM-S and ERM-15, it is significant only in the low volatility state while the converse is true for ERM-6. This last finding can be rationalised by noting that volatility was much higher in ERM-6 than in the other two periods. The positive and very strong mean reversion effect (-0.5325 in Table 1) confirms the credibility of the regime change that took place during ERM membership and the restoration of full convertibility.

The mean reversion variable is not capable of fully capturing the regime change because central bank intervention is taking place at the same time. According to the model with daily data, intervention is always effective under inconvertibility, and with convertibility it only has an effect in the mean in the low volatility state. This does not apply to ERM-15 largely because intervention is much less frequent. This result is also consistent with the episodes of false stability identified in Braga de Macedo et al. (2003) when the exchange rate was very stable during the speculative attack of late 1992. Therefore intervention is effective either when there is no credibility or when credibility has already been acquired and volatility is low: intervention is most effective when it is least needed. The robustness of this result is being investigated by Brites-Pereira (2003) as it will further reinforce our understanding of the interaction between volatility and credibility in the transition between exchange rate regimes.

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## Table 1: MSEGARCH Estimation Results

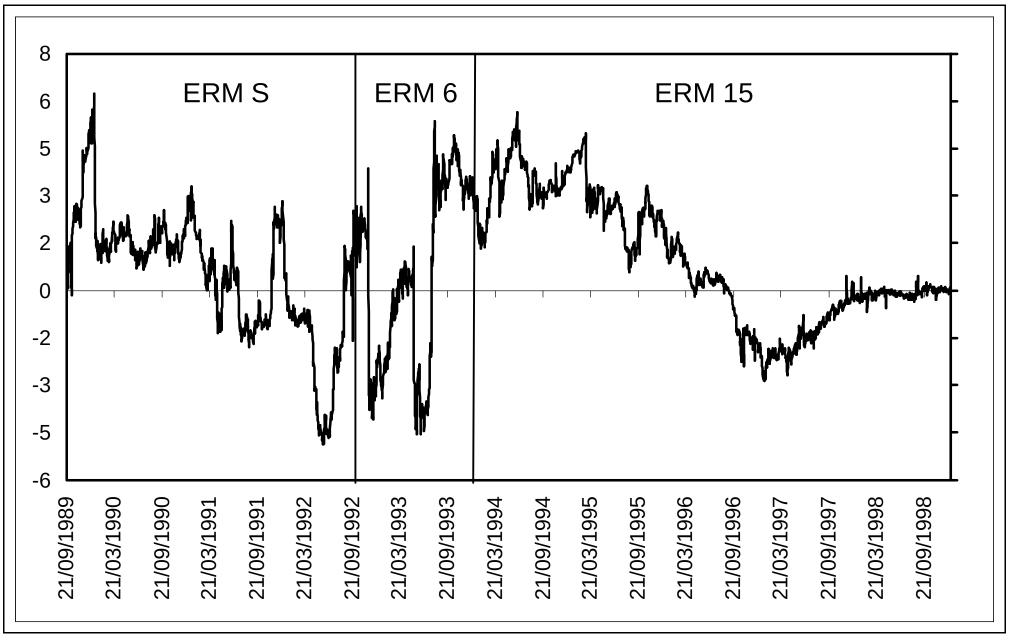
| | ERM S | | ERM 6 | | ERM 15 | |
|---|---|---|---|---|---|---|
| **Parameter** | Estimate | Std. Error | Estimate | Std. Error | Estimate | Std. Error |
| **Mean** | | | | | | |
| $\alpha_{10}$ | -0.0440 | 0.0188** | 0.0206 | 0.0171 | -0.0083 | 0.0042** |
| $\alpha_{20}$ | 0.0210 | 0.0147* | 1.3694 | 0.2212** | 0.0048 | 0.0064 |
| $\alpha_{11}$ | -0.3480 | 0.0798** | — | — | -0.4052 | 0.0407** |
| $\alpha_{21}$ | -0.1727 | 0.0570** | — | — | -0.1589 | 0.0364** |
| $\alpha_{12}$ | — | — | — | — | -0.1027 | 0.0358** |
| $\alpha_{22}$ | — | — | — | — | -0.0701 | 0.0281** |
| $\alpha_{1I}$ | 0.5672 | 0.1656** | 0.2905 | 0.1022** | — | — |
| $\alpha_{2I}$ | — | — | — | — | — | — |
| $\alpha_{1D}$ | -0.0307 | 0.0129** | — | — | -0.0533 | 0.0080** |
| $\alpha_{2D}$ | — | — | -0.5325 | 0.0772** | — | — |
| **Variance** | | | | | | |
| $\beta_0^1$ | -1.7865 | 0.8673** | -2.1055 | 0.3182** | -2.2358 | 0.3925** |
| $\beta_0^2$ | -1.0468 | 0.2913** | -1.7153 | 0.3972** | -2.2631 | 0.4180** |
| $\beta_{1\|e\|}$ | — | — | 0.4158 | 0.2090** | 0.4958 | 0.1304** |
| $\beta_{2\|e\|}$ | 0.4953 | 0.1241** | 0.9561 | 0.3209** | 0.5988 | 0.1222** |
| $\beta_{1v}$ | 0.5220 | 0.2660** | — | — | 0.5107 | 0.0918** |
| $\beta_{2v}$ | 0.7057 | 0.1062** | — | — | 0.3216 | 0.1406** |
| $\beta_{1\|D\|}$ | — | — | -0.1270 | 0.0745** | — | — |
| $\beta_{2\|D\|}$ | — | — | — | — | — | — |
| **TVTP** | | | | | | |
| $\gamma_{10}$ | 2.3742 | 0.7286** | 2.3259 | 0.2335** | 2.9530 | 0.3943** |
| $\gamma_{20}$ | 2.8603 | 0.7856** | 1.3861 | 0.4145** | 2.8992 | 0.1963** |
| $\gamma_{1\|I\|}$ | -1.1028 | 0.5678** | -0.0389 | 0.0249* | — | — |
| $\gamma_{2\|I\|}$ | -1.1384 | 0.5098** | — | — | — | — |
| $d_1$ | 5.1138 | 0.8600** | 5.0783 | 1.7604** | 2.8172 | 0.3066** |
| $d_2$ | | | | $\infty$ | 3.1712 | 0.4141** |
| N. Obs. | 633 | | 438 | | 1358 | |

## Table 1 (continued): MSEGARCH Estimation Results

| | ERM S | | ERM 6 | | ERM 15 | |
|---|---|---|---|---|---|---|
| Log-Likelihood | -20.3 | | -142.6 | | 484.5. | |
| AIC | -36.3 | | -155.4 | | 467.5 | |
| SBC | -71.9 | | -180.4 | | 423.2 | |
| Diagnostics | | | | | | |
| $LB_1$ | 0.1609 | (0.6883) | 0.0309 | (0.8606) | 1.6842 | (0.1944) |
| $LB_2$ | 1.6936 | (0.4288) | 0.4600 | (0.7945) | 2.5075 | (0.2854) |
| $LB_3$ | 1.8364 | (0.6070) | 1.3105 | (0.7266) | 3.6172 | (0.3059) |
| $LB_5$ | 6.5247 | (0.2585) | 1.5975 | (0.9016) | 7.3356 | (0.1969) |
| $LB_{10}$ | 15.5343 | (0.1138) | 6.6423 | (0.7587) | 10.0977 | (0.4320) |
| $LB_{15}$ | 18.9789 | (0.2147) | 13.6070 | (0.5555) | 20.0782 | (0.1690) |
| $LM_1$ | 0.0398 | (0.8418) | 0.0262 | (0.8713) | 0.0947 | (0.7583) |
| $LM_2$ | 0.3407 | (0.8434) | 0.0365 | (0.9819) | 0.1758 | (0.9159) |
| $LM_3$ | 1.0791 | (0.7821) | 0.0370 | (0.9981) | 0.2965 | (0.9607) |
| $LM_5$ | 1.7351 | (0.8844) | 0.1049 | (0.9998) | 0.2988 | (0.9977) |
| $LM_{10}$ | 2.9764 | (0.9820) | 0.2412 | (1.0000) | 0.5173 | (1.0000) |
| $LM_{15}$ | 4.6686 | (0.9946) | 0.4484 | (1.0000) | 3.9165 | (0.9980) |

*Notes*: The variables are defined as in the text. A double (single) asterisk means that the estimated parameter is significantly different from zero at a 5% (10%) level. A degree of freedom $d_i = +\infty$ denotes a Normal distribution in the *i-th* regime. $LB_t$ denotes the Ljung-Box statistic for serial correlation in the standardised residuals up to lag *t*. $LM_t$ denotes the ARCH-LM statistic for the squared standardised residuals up to lag *t*. The p-values corresponding to these statistics are in given parenthesis.

**Figure 1: Daily Percentage Deviation of PTE/DEM from Central Parity**




*Note:* The Portuguese Escudo was realigned on the following dates: November 23, 1992; May 14, 1993; and March 6, 1995. The first realignment occurred in the wake of the 1992 ERM crisis whilst the others were the result of the PTE following the realignments of the Spanish Peseta.

**Figure 2: Smoothed Probabilities of the High-Volatility Regime**
**ERM S**

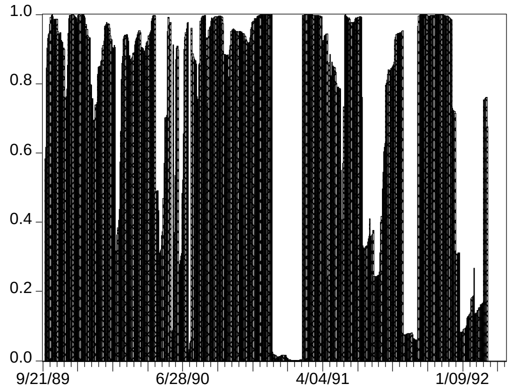



**Figure 3: Smoothed Probabilities of the High-Volatility Regime**
**ERM 6**

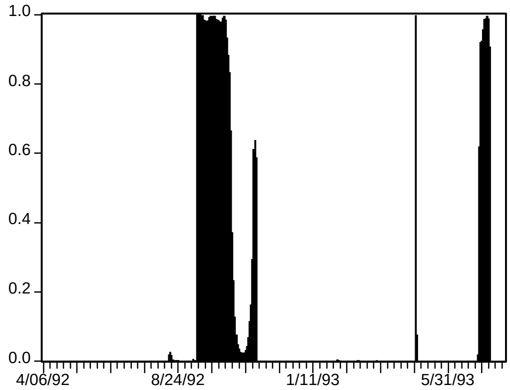
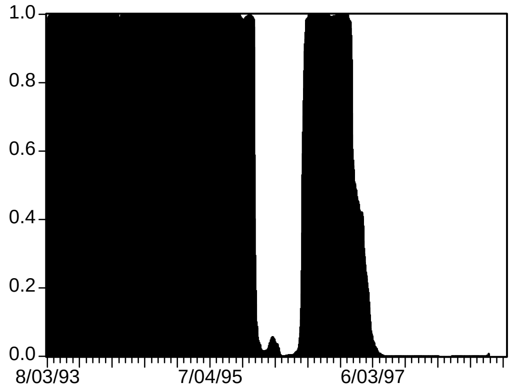



**Figure 4: Smoothed Probabilities of the High-Volatility Regime**
**ERM 15**



## Appendix 1. Brief Overview of Theoretical and Empirical Studies on Target-Zones and Central Bank Intervention.

The ERM is the most well known example of a target-zone exchange rate system. This type of exchange rate arrangement has been extensively studied in the literature following Krugman's (1991) seminal contribution, which highlights the peculiar dynamics of the target-zones' participating currencies. Krugman's main result is that there is a stabilising effect on the exchange rate when the target-zone is credible. In particular, the exchange rate is less volatile (i.e. reacts less to changes in fundamentals) than under a pure float in the interior of the zone. This stabilising influence is known as the honeymoon effect. Moreover, this effect is more pronounced the closer the exchange rate gets to its boundaries, so that it is totally unaffected by the fundamentals when it reaches its floor or ceiling. The honeymoon effect is caused by the market's expectations that the monetary authorities will intervene whenever the exchange rate reaches the edges of the band. These *infra*-marginal interventions suggest a non-linear S-shaped relationship between the exchange rate and its fundamentals that differs from the linear relationship typical of a free-floating regime.

Empirical studies based on Krugman's model have consistently rejected some of its more important implications, such as the negative relationship between the interest rate differentials and the exchange rate (e.g. Svensson, 1991). It also predicts that the exchange rate will be at or near its limits most of the time. The facts about target-zones suggest the exact opposite: exchange rates tend to be in or around their central parity most of the time. Moreover, the model is predicated on the absence of both realignments and *intra*-marginal (within-band) interventions, a situation that is often unrealistic. Consequently, a "second-generation" of models was developed that extended Krugman's specification to include these alternatives. Prominent examples of these models are those of Bertola and Caballero (1992), Bertola and Svensson (1993), Froot and Rogoff (1991) and Lindberg and Söderlind (1994). The newer models have highlighted the fact that a time-varying credibility of the target zone can significantly affect exchange rate behaviour. As such, they can easily accommodate the notion of credibility as the perception of economic agents with respect to the commitment to maintain the exchange rate around its central parity. In this context, a credible target-zone regime implies that the exchange rate is always mean-reverting.

The effectiveness of central bank intervention on the foreign exchange market has also been the subject of several recent studies.[9] In general, the empirical evidence that emerges is mixed.[10] It is clear from this literature, however, that the impact of intervention on the level and the volatility of exchange rates might not be uniform over time and across policy regimes. In the context of a target-zone, intervention is thought to affect the exchange rate mostly through the signalling or expectations channel: a change of agents' expectations regarding *future* movements in the variables that impact upon the exchange rate will affect the *current* exchange rate. Intervention affects these expectations by signalling the future stance of policy. For example, in target-zones the monetary authorities face the choice of allowing relatively small variations of the exchange rate within its band, or that of having it move within the whole official band. When this happens, two different signals are possible. The central bank may want to signal its intent of pursuing a narrower implicit band than the official one in order to reduce volatility. By intervening frequently inside the band, it is able to achieve this objective. Alternatively, it could signal its desire for some degree of monetary independence by only intervening when the exchange rate is close to or at the edges of the currency band (Svensson, 1994). In this case, intervention could have a stabilising effect if the policy is known and credible. Conversely, if the signal results in agents perceiving an uncertain or non-credible policy then intervention could result in increasing volatility. In sum, the effect of intervention on exchange rates depends on market conditions, agents' expectations and the credibility of policy regimes.

Empirically, the recent exchange rate research has focussed on regime-switching models, as these are particularly well suited to deal with the dynamics of exchange rates in target-zones.[11] For example, Engel and Hamilton

[9] For comprehensive surveys of this literature, refer to Edison (1993), Dominguez and Frankel (1993a), Almekinders (1995), Schwartz (2000) and Sarno and Taylor (2001).

[10] For example, Baillie and Humpage (1992) find that the impact of intervention on the USD/DEM exchange rate volatility was not constant over time. Bonser-Neal and Tanner (1996) consider the effect of intervention in *ex-ante* volatility of the USD/DEM and USD/YEN exchange rates during the period 1985-1991. They obtain mixed results over three different sub-samples and over the two exchange rates considered. Hung (1997) finds that intervention reduces both YEN/USD and DEM/USD exchange rate volatilities during 1985-1986, but increase them during 1987-1989.

[11] Well-known examples of regime-switching models include the Markov Switching Autoregressive Conditional Heteroscedasticity (SWARCH), pioneered by Hamilton and Sus-

(1990), Bekaert and Hodrick (1993) and Engel and Hakkio (1996) have documented regime shifts in major foreign exchange rates. The latter study shows, for example, that exchange rates in the ERM of the EMS are characterised by long periods of stability interrupted by periods of extreme volatility. Under these circumstances, regime-switching specifications provide better descriptions of the exchange rate data than either single-regime GARCH or exponential GARCH models. Indeed, several authors have shown that the high estimated persistence levels obtained using these models may in fact be a symptom of the presence of several regimes characterised by different volatility levels (e.g. Lamoreux and Lastrapes, 1990).[12]

Moreover, the appropriateness of regime-switching models is especially pertinent when studying the effectiveness of intervention. Most of the previous studies that tested for the effectiveness of intervention neglect the issue of *intra*-regime structural change. Typically, the data is divided into sub-samples based on exogenous knowledge about the timing of changes in international exchange rate arrangements or monetary policy, and a single-regime formulation is adopted for each of these sub-samples. For example, Bonser-Neal and Tanner (1996) and Hung (1997) consider the Plaza and the Louvre Accords as relevant events in terms of changes in regime. Rogers and Siklos (2001) take into account in their estimations a change in the Bank of Canada's intervention practice in 1995 and several intervention periods by the Australian central bank. In the case of the ERM, the effects of intervention may well be different under alternating volatility periods *within* the same policy regime.

mel (1994) and the Generalised Regime-Switching Model (GRS) due to Gray (1996). The latter contribution extended the former model's ARCH-type specification of each regime's conditional volatility to include GARCH effects.

[12]For some recent applications of regime-switching models to exchange rates see Brandner, Grech and Stix (2001) Bollen, Gray and Whaley (2000) and Beine, Laurent and LeCourt (2001).

## Appendix 2. Description of the SWARCH Model

Let $Y_t$ denote the weekly average value of the PTE/DEM exchange rate. The dependent variable is given by $y_t = 100 \cdot \ln[Y_t/Y_{t-1}]$. The amount of intervention purchases and sales undertaken by the central bank in period $t-1$, in millions of DEM, is respectively denoted by $I^P_{t-1}$ and $I^S_{t-1}$. The mean reversion effect of the ERM-S period and of the ERM target-zone proper is captured by the inclusion of the variable $Dev_{t-1} = 100.[Y_{t-1}/\text{Central Parity}_{t-1} - 1]$, which measures the exchange rate's deviation from its weekly central parity in period $t-1$. The full SWARCH model, augmented by the explanatory variables referred to in the text, is given by

$$\begin{aligned} y_t &= \alpha + \phi y_{t-1} + \alpha_P I^P_{t-1} + \alpha_S I^S_{t-1} + \alpha_D Dev_{t-1} + u_t \\ u_t &= \sqrt{g_{s_t}} e_t \\ e_t &= h_t v_t \qquad v_t \; i.i.d. \; N(0,1) \\ h_t^2 &= \beta_0 + \beta_1 e^2_{t-1} + \beta_2 e^2_{t-2} + \beta_P |I^P_{t-1}| + \beta_S |I^S_{t-1}| + \beta_D |Dev_{t-1}| \end{aligned}$$

where the residual $u_t$ follows a $K$-state Markov switching ARCH(2) process augmented by the additional explanatory variables. The variable $s_t$ takes a value in $\{1, 2, 3, ..., K\}$ and denotes the state that the process is in at date $t$. It is assumed that $s_t$ follows a Markov switching process with transition probabilities given by $p_{ij} = \Pr(s_{t+1} = j | s_t = i)$ for $i, j = 1, 2, ..., K$. The parameters $g_{s_t}$ denote how the scale of the process differs across the different states. The variance factor for the first state is normalised at unity ($g_1 = 1$) with $g_j > 1$ for $j = 2, 3, ..., K$.

The comparative results of the estimated models using weekly data are presented in Tables A.2.1 and A.2.2. The first table covers the whole sample period and is therefore closest to the earlier research in Braga de Macedo, Nunes and Covas (2003). It also includes the results of two single-regime models in order to facilitate comparisons. The second table focuses on the period after the Escudo's entry into the ECU basket. In both cases, the first three panels correspond to the following cases: no additional explanatory variables in the mean and variance equations; intervention and central parity variables in both equations; and, intervention variables in mean only and the central parity variable included in both.[13] The following information is

[13]The specification of the third model was motivated by the observation that the esti-

presented for each model: the number of estimated parameters; the value of the log-likelihood function; the MSE and MAE loss functions measuring one-step ahead forecast performance (described in Hamilton and Susmel, 1994); and, the AIC and SBC model selection criteria. The remaining two panels summarise qualitatively the significance of the estimated parameters.[14]

The results consistently establish that a three state specification is adequate when the SBC model selection criterion is used.[15] Moreover, the significance of the intervention variables is most evident when the number of states is low while the effect of deviation from central parity appears to be more pervasive across states. Braga de Macedo, Nunes and Covas (1999) identify six policy regimes during the sample period, making the interpretation of results across the whole sample difficult. In order to assess the consequences of this problem, the sample was truncated from September 1989 and further split into two sub-samples based on the date in which the Escudo became fully convertible. Braga de Macedo, Nunes and Covas (1999) argue that currency convertibility reflects the underlying policy credibility associated with the change in economic regime but they do not make use of the criterion.

Tables A.2.3 and A.2.4 present the results of the models when the date in which the Escudo became convertible is used to split the sample. They are striking in that the SBC criterion now favours a two state specification in both sub-samples. The results also firmly establish the importance of the deviation from central parity in explaining the observed exchange rate changes, as there is strong evidence of mean reversion in almost all cases. The smoothed probability of the high volatility state for the selected models in these two sub-samples are depicted in Figures A.2.1 and A.2.2, where the latter shows very clearly the effects of band-widening and of realignments.[16] Turning to central bank intervention, it seems to be ineffective

mated parameters of the intervention variables in the conditional variance equation were always insignificant across models.

[14]In some models, certain transition probabilities were insignificant and so were set to zero in subsequent estimations. Moreover, we were twice unable to obtain convergence of the maximum-likelihood procedure in the case of the five state models. Full details of the estimation results are available from the authors upon request.

[15]Although we have favoured the AIC criterion elsewhere in the paper, we regard the SBC criterion as being more appropriate in the present context as it is not biased towards selecting an over-parameterised model.

[16]The smoothed probabilities are the probabilities that the exchange rate return is in regime $i$ at time $t$ conditioned on the information of the whole sample.

when the Escudo was inconvertible while the opposite appears to be true when it was convertible. Moreover, the intervention effect is now associated with an insignificant mean reversion effect although the variance equation is still affected by the deviations from central parity.

These results are tantalising, especially when one recognises that exchange rate controls were gradually removed during the Escudo's transition process and especially after ERM entry. We therefore estimated both two and three state specifications with the convertibility period starting in April 1992 and August 1992. Both dates were subsequently discarded, especially the first, as the model without explanatory variables was preferable even though mean reversion effects were present. Starting the convertibility period in August 1992, when the *Banco de Portugal* announced the removal of the remaining exchange rate controls before the year-end, favours the two state specification with additional explanatory variables but the effect of intervention remains insignificant in both periods.

**Table A.2.1:**

**Whole Sample Period: January, 7 1987 – December, 31 1998**

| **Model 1 without Intervention or Central Parity** | **k** | **log-lik** | **MSE** | **MAE** | **AIC** | **SBC** |
|---|---|---|---|---|---|---|
| Single Regime ARCH – constant variance | 3 | -1682.94 | 1432.41 | 15.99 | -1685.94 | -1692.59 |
| Single Regime ARCH – arch terms | 5 | -1601.87 | 2037.89 | 18.06 | -1606.87 | -1617.95 |
| SWARCH (2,2) | 8 | -1527.11 | 1599.19 | 15.96 | -1535.11 | -1552.84 |
| SWARCH (3,2) | 11 | -1502.12 | 1458.20 | 14.56 | -1513.12 | **-1537.51** |
| SWARCH (4,2) | 15 | -1491.46 | 1423.61 | 14.66 | -1506.46 | -1539.71 |
| SWARCH (5,1) | 18 | -1488.53 | 1298.66 | 14.08 | -1506.53 | -1546.42 |

| **Model 2 with Intervention and Central Parity** | **k** | **log-lik** | **MSE** | **MAE** | **AIC** | **SBC** |
|---|---|---|---|---|---|---|
| Single Regime ARCH – constant variance | 9 | -1655.49 | 1284.93 | 15.01 | -1687.20 | -1702.71 |
| Single Regime ARCH – 2 arch terms | 11 | -1579.74 | 1878.86 | 17.50 | -1590.74 | -1675.44 |
| SWARCH (2,2) | 14 | -1511.74 | 1361.98 | 14.55 | -1525.74 | -1556.77 |
| SWARCH (3,2) | 17 | -1492.84 | 1334.20 | 14.17 | -1509.84 | **-1547.52** |
| SWARCH (4,2) | 22 | -1487.42 | 1385.37 | 14.19 | -1509.42 | -1558.18 |
| SWARCH (5,1) – no convergence | - | - | - | - | - | - |

| **Model 3 with Intervention and Central Parity** | **k** | **log-lik** | **MSE** | **MAE** | **AIC** | **SBC** |
|---|---|---|---|---|---|---|
| Single Regime ARCH – constant variance | 7 | -1647.01 | 1282.93 | 15.01 | -1654.01 | -1669.52 |
| Single Regime ARCH – 2 arch terms | 9 | -1579.75 | 1879.11 | 17.50 | -1588.75 | -1608.70 |
| SWARCH (2,2) | 12 | -1511.78 | 1362.25 | 14.55 | -1523.78 | -1550.36 |
| SWARCH (3,2) | 15 | -1494.78 | 1333.85 | 14.22 | -1509.78 | **-1543.02** |
| SWARCH (4,2) | 20 | -1487.46 | 1391.80 | 14.20 | -1507.46 | -1551.77 |
| SWARCH (5,1) – no convergence | - | - | - | - | - | - |

*Note: k* denotes the number of estimated parameters and *log-lik* the value of the log-likelihood function. All other designations have the usual interpretations.

**Are the Estimated Parameters Significant?**

| **Model 2 with Intervention and Central Parity** | **Mean** | | | **Variance** | | |
|---|---|---|---|---|---|---|
| | **Purchases** | **Sales** | **C. Parity** | **Purchases** | **Sales** | **C. Parity** |
| Single Regime ARCH - constant variance | Yes** | No | Yes** | No | No | Yes** |
| Single Regime ARCH – 2 arch terms | No | No | Yes** | No | No | Yes** |
| SWARCH (2,2) | Yes* | No | No | No | No | Yes** |
| SWARCH (3,2) | Yes** | No | Yes** | No | No | No |
| SWARCH (4,2) | No | No | Yes* | No | No | No |
| SWARCH (5,1) - no convergence | - | - | - | - | - | - |

| **Model 3 with Intervention and Central Parity** | **Mean** | | | **Variance** |
|---|---|---|---|---|
| | **Purchases** | **Sales** | **C. Parity** | **C. Parity** |
| Single Regime ARCH - constant variance | Yes** | No | Yes** | Yes** |
| Single Regime ARCH – 2 arch terms | No | No | Yes** | Yes** |
| SWARCH (2,2) | Yes* | No | No | Yes** |
| SWARCH (3,2) | No | Yes** | Yes** | No |
| SWARCH (4,2) | No | No | Yes* | Yes* |
| SWARCH (5,1) - no convergence | - | - | - | - |

*Note*: * (**) denotes parameter significance at the 10% (5%) level.

## Table A.2.2:
## Truncated Sample: September 21, 1989 - December 31, 1998

| Model 1 without Intervention or Central Parity | k | log-lik | MSE | MAE | AIC | SBC |
|---|---|---|---|---|---|---|
| SWARCH (2,2) | 8 | -1188.01 | 2091.81 | 18.91 | -1196.01 | -1212.70 |
| SWARCH (3,2) | 11 | -1167.54 | 1783.63 | 16.76 | -1178.54 | **-1201.50** |
| SWARCH (4,2) | 16 | -1158.17 | 1789.16 | 16.14 | -1174.17 | -1207.56 |

| Model 2 with Intervention and Central Parity | k | log-lik | MSE | MAE | AIC | SBC |
|---|---|---|---|---|---|---|
| SWARCH (2,2) | 14 | -1180.65 | 1869.10 | 17.96 | -1194.65 | -1223.86 |
| SWARCH (3,2) | 17 | -1166.04 | 1723.88 | 16.22 | -1183.04 | **-1218.52** |
| SWARCH (4,2) | 22 | -1156.46 | 1743.09 | 16.17 | -1178.46 | -1224.37 |

| Model 3 with Intervention and Central Parity | k | log-lik | MSE | MAE | AIC | SBC |
|---|---|---|---|---|---|---|
| SWARCH (2,2) | 12 | -1182.06 | 1665.75 | 16.90 | -1194.06 | -1219.11 |
| SWARCH (3,2) | 15 | -1166.65 | 1720.96 | 16.20 | -1181.65 | **-1212.96** |
| SWARCH (4,2) | 20 | -1156.56 | 1743.54 | 16.19 | -1176.56 | -1218.30 |

*Note: k* denotes the number of estimated parameters and *log-lik* the value of the log-likelihood function. All other designations have the usual interpretations.

### Are the Estimated Parameters Significant?

| Model 2 with Intervention and Central Parity | Mean | | | Variance | | |
|---|---|---|---|---|---|---|
| | Purchases | Sales | C. Parity | Purchases | Sales | C. Parity |
| SWARCH (2,2) | No | Yes* | No | No | No | Yes** |
| SWARCH (3,2) | No | No | Yes** | No | No | No |
| SWARCH (4,2) | No | No | Yes** | No | No | No |

| Model 3 with Intervention and Central Parity | Mean | | | Variance |
|---|---|---|---|---|
| | Purchases | Sales | C. Parity | C. Parity |
| SWARCH (2,2) | Yes* | No | No | Yes** |
| SWARCH (3,2) | No | No | Yes** | No |
| SWARCH (4,2) | No | No | Yes** | No |

*Note*: * (**) denotes parameter significance at the 10% (5%) level.

**Table A.2.3:**
**Inconvertible Escudo: September 21, 1989 – December, 9 1992**

| **Model 1 without Intervention or Central Parity** | **k** | **log-lik** | **MSE** | **MAE** | **AIC** | **SBC** |
|---|---|---|---|---|---|---|
| SWARCH (2,2) | 8 | -464.41 | 1235.12 | 21.55 | -472.41 | **-484.84** |
| SWARCH (3,1) | 10 | -459.95 | 1059.04 | 20.63 | -469.95 | -485.48 |

| **Model 2 with Intervention and Central Parity** | **k** | **log-lik** | **MSE** | **MAE** | **AIC** | **SBC** |
|---|---|---|---|---|---|---|
| SWARCH (2,2) | 14 | -461.58 | 1015.89 | 19.21 | -475.58 | **-497.32** |
| SWARCH (3,1) | 16 | -457.28 | 953.60 | 19.28 | -473.28 | -498.12 |

| **Model 3 with Intervention and Central Parity** | **k** | **log-lik** | **MSE** | **MAE** | **AIC** | **SBC** |
|---|---|---|---|---|---|---|
| SWARCH (2,2) | 12 | -461.56 | 1014.00 | 19.23 | -473.56 | **-492.19** |
| SWARCH (3,1) | 14 | -458.27 | 985.34 | 19.80 | -472.27 | -494.01 |

*Note:* *k* denotes the number of estimated parameters and *log-lik* the value of the log-likelihood function. All other designations have the usual interpretations.

**Are the Estimated Parameters Significant?**

| **Model 2 with Intervention and Central Parity** | **Mean** | | | **Variance** | | |
|---|---|---|---|---|---|---|
| | **Purchases** | **Sales** | **C. Parity** | **Purchases** | **Sales** | **C. Parity** |
| SWARCH (2,2) | No | No | No | No | No | No |
| SWARCH (3,1) | No | No | Yes** | No | No | Yes* |

| **Model 3 with Intervention and Central Parity** | **Mean** | | | **Variance** |
|---|---|---|---|---|
| | **Purchases** | **Sales** | **C. Parity** | **C. Parity** |
| SWARCH (2,2) | No | No | Yes* | No |
| SWARCH (3,1) | No | No | Yes* | No |

*Note*: * (**) denotes parameter significance at the 10% (5%) level.

## Table A.2.4:
## Convertible Escudo: December, 16 1992 – December, 31 1998

| Model 1 without Intervention or Central Parity | k | log-lik | MSE | MAE | AIC | SBC |
|---|---|---|---|---|---|---|
| SWARCH (2,2) | 8 | -702.83 | 3048.91 | 17.65 | -710.83 | -725.80 |
| SWARCH (3,2) | 12 | -690.38 | 2377.05 | 15.34 | -702.38 | **-724.84** |

| Model 2 with Intervention and Central Parity | k | log-lik | MSE | MAE | AIC | SBC |
|---|---|---|---|---|---|---|
| SWARCH (2,2) | 14 | -683.94 | 2469.30 | 17.05 | -697.94 | **-724.14** |
| SWARCH (3,2) | 18 | -681.84 | 2408.57 | 15.69 | -699.84 | -733.52 |

| Model 3 with Intervention and Central Parity | k | log-lik | MSE | MAE | AIC | SBC |
|---|---|---|---|---|---|---|
| SWARCH (2,2) | 12 | -684.67 | 2409.46 | 16.96 | -696.67 | **-719.12** |
| SWARCH (3,2) | 16 | -681.90 | 2385.10 | 15.60 | -697.90 | -727.85 |

*Note: k* denotes the number of estimated parameters and *log-lik* the value of the log-likelihood function. All other designations have the usual interpretations.

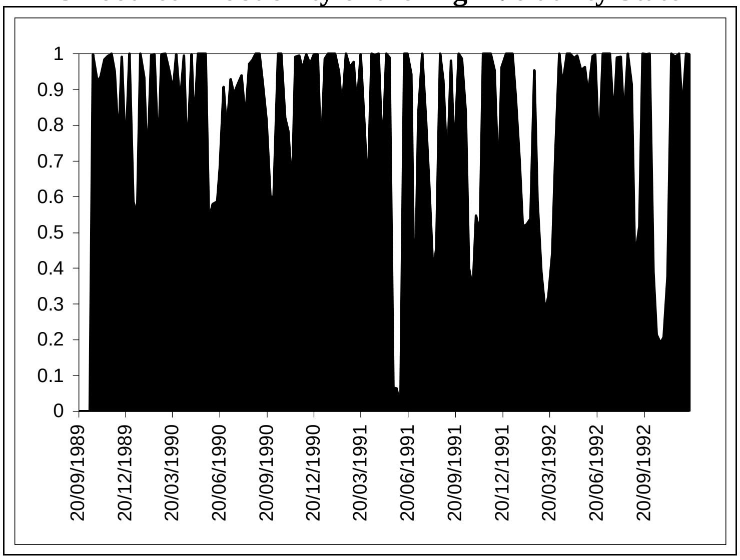
### Are the Estimated Parameters Significant?

| Model 2 with Intervention and Central Parity | Mean | | | Variance | | |
|---|---|---|---|---|---|---|
| | **Purchases** | **Sales** | **C. Parity** | **Purchases** | **Sales** | **C. Parity** |
| SWARCH (2,2) | No | Yes** | No | No | No | Yes** |
| SWARCH (3,2) | No | No | Yes* | No | No | Yes* |

| Model 3 with Intervention and Central Parity | Mean | | | Variance |
|---|---|---|---|---|
| | **Purchases** | **Sales** | **C. Parity** | **C. Parity** |
| SWARCH (2,2) | No | Yes** | No | Yes* |
| SWARCH (3,2) | No | No | Yes** | Yes* |

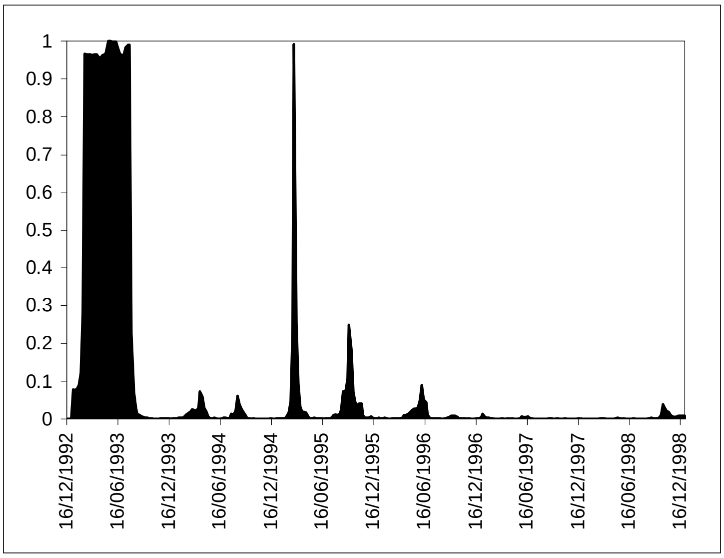
*Note*: * (**) denotes parameter significance at the 10% (5%) level.

**Figure A.2.1: Inconvertible Escudo– SWARCH (2,2) model**
**Smoothed Probability of the High Volatility State**




*Note:* The SWARCH (2,2) model is chosen using the SBC criterion when considering the top three panels of Table A.2.3.

**Figure A.2.2: Convertible Escudo – SWARCH (2,2) model**
**Smoothed Probability of the High Volatility State**




*Note:* The SWARCH (2,2) model is chosen using the SBC criterion when considering the top three panels of Table A.2.4.

## Appendix 3. Analysis of Daily Data
## Exchange Rate Data

Exchange rate series were obtained from the H.10 release published by the Board of Governors of the Federal Reserve. The daily series for the PTE/DEM exchange rate ($S_t$) was constructed by taking the ratio of the PTE/USD and DEM/USD rates, assuming that the no-triangular-arbitrage condition holds. The data are the 12:00 buying rates in New York for cable transfers payable in PTE and DEM. The corresponding time in Portugal is 17:00, which corresponds to the end of the business day for most local banks and agencies.

The first difference of the logarithm of the PTE/DEM exchange rate, depicted in Figure A.3.1, easily identifies the volatility clusters typical of exchange rate returns in target-zones, i.e. periods of high volatility followed by periods of low volatility and conversely.

The descriptive statistics of the exchange rate return for each of the periods are given in Table A.3.1. The test results confirm that the distribution of the exchange rate is leptokurtic, i.e. it is more peaked and also has fatter tails when compared to the Normal distribution. A formal test, based on the Jarque-Bera statistic, clearly rejects the null hypothesis of normality. The kurtosis test statistic confirms the fat-tail property of the distribution for all periods. This problem seems to be more pronounced during ERM 6 period.[17] Not unexpectedly, the distributions are skewed reflecting the fact that the exchange rate usually drifts predominantly in one direction for prolonged periods of time before changing course. The Ljung-Box $Q$-statistics detect the presence of significant serial autocorrelation and the ARCH-LM statistics suggest that the ARCH effects are significant. These stylised features are taken into account by the modelling framework chosen for our analysis.

[17] In the case of a target zone, theoretical models establish that the exchange rate is more inelastic with respect to changes in the fundamentals at the boundaries since interventions inhibit it from moving outside the bands. By implication, one should expect its distribution to have fatter tails than freely floating rates.

**Table A.3.1: Descriptive Statistics for the Daily Exchange Rate Returns**

**ERM S**
(1989/09/21 – 1992/04/03)

| Variable | Statistic | Value | Null Hypothesis | p-value |
|---|---|---|---|---|
| $\Delta s_t$ | Minimum | -1.517 | | |
| | Maximum | 1.840 | | |
| | Median | 0.005 | | |
| | Mean | 0.005 | H0: Mean=0 | 0.652 |
| | Std Deviation | 0.295 | | |
| | Skewness | 0.709 | H0: Sk=0 | 0.000 |
| | Kurtosis | 8.998 | H0: K=0 | 0.000 |
| | Jarque-Bera | 1003.691 | H0: Normality | 0.000 |
| | $\rho(1)$ | -0.179 | | |
| | $Q(20)$ | 41.875 | H0: No Autocorrelation | 0.003 |
| | $LM(20)$ | 37.733 | H0: No ARCH | 0.000 |
| $\log S_t$ | ADF | -3.145 | H0: Unit Root | -2.867* |
| | Phillips-Perron | -3.438 | H0: Unit Root | -2.867* |

**ERM 6**
(1992/04/04 – 1993/08/02)

| Variable | Statistic | Value | Null Hypothesis | p-value |
|---|---|---|---|---|
| $\Delta s_t$ | Minimum | -2.881 | | |
| | Maximum | 4.696 | | |
| | Median | 0.012 | | |
| | Mean | 0.044 | H0: Mean=0 | 0.182 |
| | Std Deviation | 0.626 | | |
| | Skewness | 1.388 | H0: Sk=0 | 0.000 |
| | Kurtosis | 24.017 | H0: K=0 | 0.000 |
| | Jarque-Bera | 6797.496 | H0: Normality | 0.000 |
| | $\rho(1)$ | -0.282 | | |
| | $Q(20)$ | 40.358 | H0: No Autocorrelation | 0.003 |
| | $LM(20)$ | 56.658 | H0: No ARCH | 0.000 |
| $\log S_t$ | ADF | 0.559 | H0: Unit Root | -2.870* |
| | Phillips-Perron | 0.402 | H0: Unit Root | -2.867* |

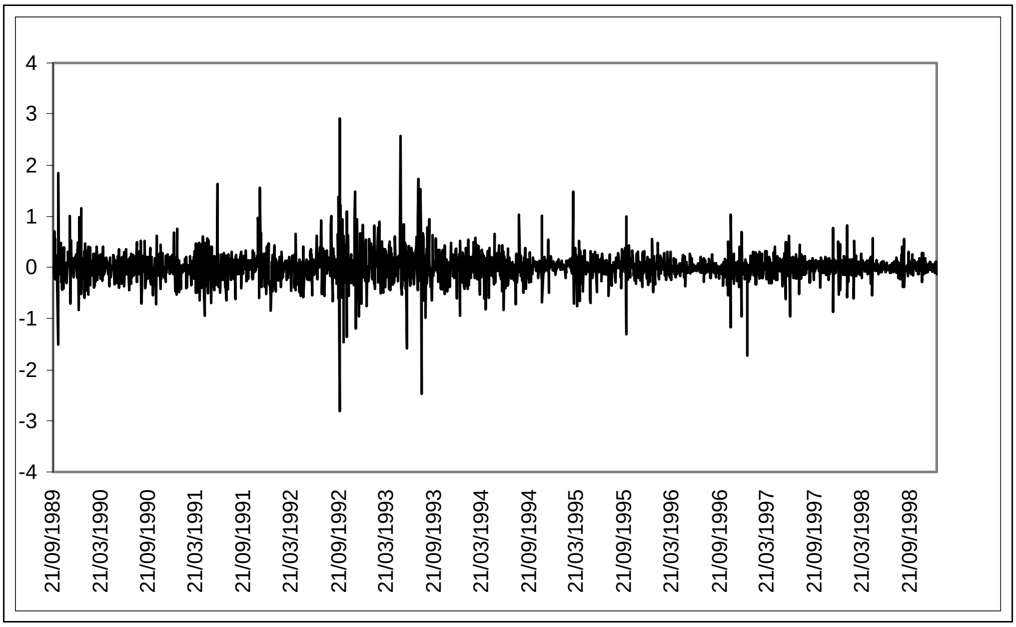
**Table A.3.1 (continued):**

**ERM 15**
(1993/08/03 – 1998/12/31)

| Variable | Statistic | Value | Null Hypothesis | p-value |
|---|---|---|---|---|
| $\Delta s_t$ | Minimum | -1.313 | | |
| | Maximum | 1.478 | | |
| | Median | 0.0008 | | |
| | Mean | -0.001 | H0: Mean=0 | 0.849 |
| | Std Deviation | 0.207 | | |
| | Skewness | -0.152 | H0: Sk=0 | 0.027 |
| | Kurtosis | 10.507 | H0: K=0 | 0.000 |
| | Jarque-Bera | 2982.689 | H0: Normality | 0.000 |
| | $\rho(1)$ | -0.237 | | |
| | $Q(20)$ | 106.83 | H0: No Autocorrelation | 0.000 |
| | $LM(20)$ | 83.732 | H0: No ARCH | 0.000 |
| $\log S_t$ | ADF | -1.871 | H0: Unit Root | -2.865* |
| | Phillips-Perron | -2.489 | H0: Unit Root | -2.864* |

***Note:* $S_t$ is the PTE/DEM exchange rate while $\Delta s_t$ denotes 100 times the log difference of the exchange rate. $\rho(1)$ denotes the value of the autocorrelation function at the first lag and $Q(20)$ is the Ljung-Box Q-statistic with a lag-length of 20 periods. $LM(20)$ denotes the ARCH-LM statistic for the squared standardised residuals with a lag-length of 20 periods. The fourth column gives the null hypotheses of the tests that were conducted. For example, the Jarque-Bera statistic tests for Normality while the ADF/Phillips-Perron procedures test for the presence of unit roots. The last column contains the corresponding p-values, except for the case of the unit root tests where an asterisk denotes the test's 5% critical value.**

**Figure A.3.1: Daily Percentage Change in PTE/DEM**



## Intervention Data

Intervention is defined as either a purchase or a sale of foreign currency by the monetary authorities that is specifically directed towards influencing the PTE's exchange rate. The *Banco de Portugal* provided the daily intervention data, given in United States Dollars (USD). The original data were subsequently converted into DEM using the daily DEM/USD exchange rate series. A positive (negative) volume of intervention corresponds to a purchase (sale) of foreign currency. Unfortunately, it was not possible to obtain detailed information about the sterilisation procedures undertaken to compensate for the intervention-induced changes in the reserves of foreign exchange. Like other studies undertaken in this field, we do not distinguish between sterilised and unsterilised intervention.

The results of the intervention data's analysis, presented in Table A.3.2, distinguishes between purchases and sales for each of the sub-periods. Given that the intervention data are not publicly available, only limited statistics are provided.[18] Overall, the frequency of intervention is defined as the percentage of intervention days relative to the total number of trading days in each sub-period. Intervention frequency is highest during the ERM S period (51.05%), followed by that of the ERM 6 period (35.07%) and is lowest in the ERM 15 period (24.19%).

The frequency statistics presented in Table A.3.2, imply a given purchase (sale) intensity, calculated as the proportion of days during which purchases (sales) took place relative to the total number of intervention days. The two ERM sub-periods are overwhelmingly characterised by the sale of foreign currency, accounting for 64.47% of all intervention activity during ERM 6 and for 95.82% during ERM 15. The opposite is true for the ERM S period, where the intensity of foreign currency purchases is 80.71%. The ranking of the average value of the intervention volume confirms this picture: the average purchase volume is highest during the ERM S period while the average sales volume peak is highest during ERM 15.

The number and duration of intervention runs give a final feature of the central bank's intervention activity. An intervention run is defined by at least

[18] In conformity with the agreement made with the *Banco de Portugal,* both the analysis and the data must be presented in such a manner so as to ensure the confidentiality of the daily intervention operations.

three consecutive days during which the central bank always intervened in the same direction. The largest number of purchase runs occurred during the ERM S period (30), which also had the longest duration of all purchase runs (11 days). On the other hand, the ERM 15 period had the largest number of sales runs (42) and as well as one of the longest duration of sales runs (8 days).

**Table A.3.2: Foreign Exchange Market Intervention Data in DEM (1989/09/21– 1998/12/31)**

**PURCHASES**

| | Ranking of Average Value | Intervention Frequency | Number of Runs | Duration of Longest Run |
|---|---|---|---|---|
| **ERM S** | 1 | 41.20% | 30 | 11 |
| **ERM 6** | 2 | 12.46% | 4 | 6 |
| **ERM 15** | 3 | 1.01% | 1 | 3 |

**SALES**

| | Ranking of Average Value | Intervention Frequency | Number of Runs | Duration of Longest Run |
|---|---|---|---|---|
| **ERM S** | 3 | 9.85% | 4 | 6 |
| **ERM 6** | 2 | 22.61% | 17 | 8 |
| **ERM 15** | 1 | 23.18% | 42 | 8 |

*Note:* The ranking of the average value of intervention volume is from the larger (1) to the smaller (3) value. The intervention frequency is defined as the percentage of intervention days relative to the total number of *trading* days in each period. A run is defined by at least three consecutive days during which the central bank always intervened in the same direction

## Appendix 4. single-regime Models

The single-regime exponential GARCH model is estimated by way of comparison with the adopted regime-switching approach. Moreover, it is well known that this type of model is able to capture several stylised features of exchanges rate dynamics, such as volatility clustering, asymmetry responses to shocks and non-normality, which are also important for our analysis. The dependent variable of the analysis is given by $\Delta s_t = 100 \cdot \ln[S_t/S_{t-1}]$. Under this convention, a depreciation is then given by $\Delta s_t > 0$. The specification of the mean and variance equations is as follows:

$$\begin{aligned}
\Delta s_t &= \alpha_0 + \alpha_1 \Delta s_{t-1} + \alpha_2 \Delta s_{t-2} + \alpha_I I_{t-1} + \alpha_D D_{t-1} + e_t \\
\ln v_t &= \beta_0 + \beta_{|e|} \left| \frac{e_{t-1}}{\sqrt{v_{t-1}}} \right| + \beta_e \frac{e_{t-1}}{\sqrt{v_{t-1}}} + \beta_v \ln v_{t-1} + \beta_{|I|} |I_{t-1}| + \beta_{|D|} |D_{t-1}| \\
e_t &= \sqrt{v_t} \varepsilon_t \qquad \varepsilon_t \sim i.i.d\ t(d)
\end{aligned}$$

where $t(d)$ denotes a standardised Student-$t$ distribution with $d$ degrees of freedom, a mean of zero and a unit variance and whose density is given by

$$f(\varepsilon) = \frac{\Gamma\left(\frac{d+1}{2}\right)}{\Gamma\left(\frac{d}{2}\right)\sqrt{\pi}\sqrt{d-2}} \left(1 + \frac{\varepsilon^2}{(d-2)}\right)^{-\frac{d+1}{2}}$$

The density of the Student-$t$ distribution will approach that of the standard Normal distribution as the number of degrees of freedom increases. The log specification of the conditional variance is advantageous since it does not impose constraints on the parameters in order to ensure a strictly positive value.

Turning to the interpretation the mean equation's parameter values, intervention is seen to be effective when $\alpha_I > 0$. For example, when the central bank sells foreign currency ($I_{t-1} < 0$), the domestic currency should appreciate ($\Delta s_t < 0$). To understand the effect of deviations from central parity, consider the case of $D_{t-1} > 0$: if the target-zone is credible, the exchange rate should revert back to its long-run level ($\Delta s_t < 0$) implying that $\alpha_D < 0$. Note also that this parameter is an elasticity and will therefore be extremely useful as a comparative measure of the importance of the mean reversion effect during different time periods.

The parameters $\beta_{|e|}$ and $\beta_v$ capture the effect of volatility clustering in the conditional variance equation. Possible asymmetric responses to shocks are measured by $\beta_e$ : negative shocks increase the subsequent period's conditional volatility more than positive shocks when $\beta_e < 0$. The parameter $\beta_v$ also captures the effect of persistence: a conditional variance that is stationary implies that $\beta_v < 1$. Finally, the absolute value of $D_{t-1}$ is also included in the conditional variance equation in order to determine the impact of deviations from parity on the volatility level of period $t$. Bilateral target-zone models predict that $\beta_{|D|} < 0$, reflecting the fact that the exchange rate becomes less sensitive to movements in the fundamentals the closer it approaches the boundaries.

The maximum likelihood estimation results are presented in Table A.4. In general, autocorrelation effects in the log changes of the PTE/DEM exchange rate are important except during the ERM 6 period. The coefficient $\beta_e$ turned out to be insignificant in all periods and so was excluded from the final model. As such, there is no evidence of an asymmetrical response of volatility to positive versus negative shocks. The estimated coefficient on lagged volatility, $\beta_v$, is significant in all cases but is not particularly large, suggesting a moderate persistence of shocks to volatility. All the estimated degrees of freedom of the $t$-distributions are relatively small and, upon testing, the null hypothesis of a Normal distribution is rejected.

Turning to the effects of intervention on the mean, it appears to have been effective as the coefficient $\alpha_I$ is correctly signed and significant in the first and second sub-samples. This suggests that the purchases of foreign currency are associated with the depreciation of the domestic currency during the ERM S period. The same is true for the ERM 6 period where foreign currency sales contributed to the appreciation of the PTE. This effect decreases over time and is no longer significant during ERM 15. In all cases, there is no evidence of mean reversion. With regards to conditional variance, intervention had no effect on volatility in any of the periods. Finally, the estimated parameter $\beta_{|D|}$ is significant but wrongly signed in the conditional variance equation during ERM 15.[19]

[19] Brandner, Grech and Stix (2001) make a similar finding and highlight that this variable is often found to be positive in empirical work.

## Table A.4: EGARCH Estimation Results

| | ERM S | | ERM 6 | | ERM 15 | |
|---|---|---|---|---|---|---|
| **Parameter** | Estimate | Std. Error | Estimate | Std. Error | Estimate | Std. Error |
| **Mean** | | | | | | |
| $\alpha_0$ | -0.0037 | 0.0112 | 0.0265 | 0.0246 | 0.0009 | 0.0037 |
| $\alpha_1$ | -0.2055 | 0.0426** | — | — | -0.2459 | 0.0278** |
| $\alpha_2$ | — | — | — | — | -0.0569 | 0.0225** |
| $\alpha_I$ | 0.2322 | 0.0856** | 0.2173 | 0.1300** | 0.0302 | 0.0686 |
| $\alpha_D$ | -0.0034 | 0.0063 | 0.0008 | 0.0072 | -0.0006 | 0.0022 |
| **Variance** | | | | | | |
| $\beta_0$ | -1.3540 | 0.3131** | -0.9955 | 0.4013** | -2.3750 | 0.3755** |
| $\beta_{\lvert e \rvert}$ | 0.5213 | 0.1079** | 0.5957 | 0.1511** | 0.5585 | 0.0838** |
| $\beta_v$ | 0.6429 | 0.1000** | 0.4360 | 0.1748** | 0.4742 | 0.0923** |
| $\beta_{\lvert I \rvert}$ | -0.5136 | 0.6037 | 0.3058 | 0.5373 | 0.3778 | 0.5820 |
| $\beta_{\lvert D \rvert}$ | 0.0298 | 0.0398 | -0.0663 | 0.0645 | 0.1903 | 0.0417** |
| $d$ | 4.9829 | 0.7733** | 2.8373 | 0.4915** | 3.0509 | 0.2643** |
| N. Obs. | 633 | | 332 | | 1358 | |
| Log-Likelihood | -33.6587 | | -163.6910 | | 459.0580 | |
| AIC | -43.6587 | | -169.6910 | | 451.0580 | |
| SBC | -65.9111 | | -181.1064 | | 430.2029 | |
| Diagnostics | | | | | | |
| $LB_1$ | 0.0138 | (0.9064) | 0.2406 | (0.6238) | 2.1395 | (0.1436) |
| $LB_2$ | 0.9700 | (0.6157) | 0.4925 | (0.7817) | 2.5737 | (0.2761) |
| $LB_3$ | 0.9702 | (0.8085) | 1.0977 | (0.7776) | 3.2055 | (0.3610) |
| $LB_5$ | 5.6400 | (0.3428) | 1.4300 | (0.9210) | 8.0496 | (0.1535) |
| $LB_{10}$ | 12.2294 | (0.2700) | 5.7262 | (0.8377) | 11.9761 | (0.2867) |
| $LB_{15}$ | 16.0177 | (0.3809) | 13.6415 | (0.5529) | 19.8133 | (0.1792) |
| $LM_1$ | 0.1375 | (0.7108) | 0.0064 | (0.9360) | 0.0899 | (0.7643) |
| $LM_2$ | 0.2311 | (0.8909) | 0.0463 | (0.9771) | 0.2993 | (0.8610) |
| $LM_3$ | 0.8785 | (0.8306) | 0.0667 | (0.9955) | 0.4499 | (0.9297) |
| $LM_5$ | 3.5750 | (0.6121) | 0.0899 | (0.9999) | 0.4551 | (0.9937) |
| $LM_{10}$ | 6.5959 | (0.7630) | 0.1371 | (1.0000) | 0.6857 | (1.0000) |
| $LM_{15}$ | 9.0223 | (0.8763) | 0.2144 | (1.0000) | 4.0168 | (0.9977) |