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A UNIFYING FRAMEWORK FOR ANALYSING OFFSETTING CAPITAL FLOWS AND STERILIZATION: GERMANY AND THE ERM

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ABSTRACT

This paper provides a unifying framework in which identified offset and sterilization equations can be derived and estimated. The theoretical model suggests that, in the case where the central bank cares about both external and internal goals and capital is less than perfectly mobile, there will be some offsetting capital flows and the central bank will sterilize. Several results from the literature are encompassed as special cases. The equations are estimated for the German experience of the 1980s and the results point to active sterilization by the Bundesbank during this period. Copyright © 2002 John Wiley & Sons, Ltd.

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1. INTRODUCTION

The extent to which monetary policy changes are neutralized by offsetting capital flows (which change the central bank's foreign exchange reserves) and the extent to which these flows can be sterilized are issues which have long been of interest to central banks and policy-makers concerned about their ability to conduct an independent monetary policy. Moreover, the problem has become potentially more acute with the removal of capital controls, growing financial integration and the adoption of exchange rate targets by a number of industrial (particularly European) and developing countries. Existing work on the offset and sterilization coefficients can be separated into two main groups. The first seeks to calculate the offset coefficient from structural estimates of asset demand functions and capital flow equations. The extent of sterilization is then established by estimating a central bank reaction function.[1] The second group takes an explicitly reduced-form approach; papers of this genre usually focus on estimating either the offset coefficient or the sterilization coefficient but not both.[2] Whatever the differences between these groups, both are characterized by the separate estimation of the two coefficients.[3] The contribution of this paper is to provide a unifying theoretical framework in which both the monetary policy reaction function and foreign exchange market intervention by the central bank can be jointly determined. Care is taken to ensure that the resulting semi-reduced-form equations are identified, thus enabling better estimates of the offset and sterilization coefficients to be derived.

The paper is organized as follows. In the following section, we provide a theoretical framework in which the issues of the paper can be discussed. We compare our approach with that of existing theoretical work in

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the area and suggest the advantages of our approach. We also show that the main theoretical results in the literature can be derived from our framework by simply placing restrictions on certain of the parameters. In Section 3, we provide an empirical implementation of the model examining the German experience in the Exchange Rate Mechanism (hereafter ERM) of the European Monetary System. We concentrate on Germany for two reasons. First, it has been the focus of much work in this area and we provide a comparison with our results. Second, throughout the period of the operation of the ERM, the Bundesbank has sought to maintain monetary independence in spite of its exchange rate target. Our results suggest that it has succeeded in its goal and sterilized in both the short and the long term.

2. OFFSET AND STERILIZATION: A UNIFYING FRAMEWORK

The essential problem faced by researchers in estimating offset and sterilization coefficients can be illustrated by considering the following example. Assume that the central bank wishes to tighten monetary policy while at the same time caring about the level of the exchange rate. Open-market operations to remove liquidity from the system cause the interest rate to rise and attract capital inflows. To prevent the exchange rate from appreciating away from its target, the central bank has to intervene in the foreign exchange market, selling the domestic currency. Such intervention undermines the initial tightening of monetary policy. To prevent this, the central bank can sterilize the foreign exchange intervention—at the same time as it sells domestic currency in the foreign exchange market, it soaks up the excess liquidity in the domestic money market.

These two operations can be summarized in the following equations (Argy and Kouri, 1974):

$$\Delta NDA_t = -a\Delta NFA_t + X \tag{1}$$

$$\Delta NFA_t = -b\Delta NDA_t + Z \tag{2}$$

ΔNDA is the change in net domestic assets (and is non-zero when the central bank intervenes in the domestic money market), ΔNFA is the change in net foreign assets (non-zero when foreign exchange market intervention is undertaken), and X and Z represent other factors which might affect domestic money market or foreign exchange market intervention respectively. The coefficients a and b are the ones of interest, representing the sterilization and offset coefficients respectively. The obvious problem in estimating these coefficients is that of simultaneous equation bias and hence from both a theoretical and an empirical point of view identification becomes crucial.

One way of partially getting around the problem is to calculate the offset coefficient from a structural model of asset demands and supplies. Herring and Marston (1977a,b), for example, derive an equation which relates the change in foreign exchange reserves to any given change in net domestic assets from a portfolio model which includes demand for both foreign and domestic bonds as well as the demand for and the supply of commercial bank reserves held at the central bank. The offset coefficient is a function of the interest sensitivity of capital flows, the interest sensitivity of the demand for deposits and the reserve requirement ratio. These parameters can then be estimated where necessary from the structural equations and the offset coefficient calculated. The disadvantages of this approach, of course, are, first, that any misspecification of the underlying structural equations will yield incorrect parameters (Obstfeld, 1982) and, second, that data on asset stocks and wealth (required to estimate the asset demand functions) often do not exist or are of poor quality.

The alternative is to estimate the offset coefficient directly from a reduced-form equation derived from a portfolio model. This is the approach taken, for example, by Kouri (1975; see also Fratianni, 1977; Neumann, 1978). The change in foreign exchange reserves (equated in these studies with capital flows) is derived as a function not only of the change in net domestic assets but also the current account and changes in domestic and foreign income, domestic and foreign interest rates, the risk premium, the expected exchange rate and domestic and foreign wealth. In the empirical estimation, however, the problem of the endogeneity of net domestic assets (equation (2)) remains and appropriate instruments have to be found.

Similar problems also affect the derivation and estimation of the authorities' reaction function (equation (1)). Herring and Marston (1977a) derive the sterilization coefficient from the loss function of the monetary authorities (that is, separately from the offset coefficient). The loss function includes changes in foreign exchange reserves, inflation and output. The central bank is assumed to suffer a loss if foreign exchange reserves alter, inflation differs from its target of zero and output deviates from its trend. The inclusion of foreign exchange reserves suggests that Herring and Marston assume that the target fixed exchange rate is always met and hence the loss can be measured by the change in foreign exchange reserves (rather than deviations from the exchange rate target) with the central bank experiencing greater losses the more it intervenes to meet the target. In the highly fixed exchange rate regime of Bretton Woods, this assumption is perhaps not so strong as it seems at first sight. In a target zone system where the actual rate may not always be at the central rate, it is better to include deviations from the central rate target directly in the loss function and we do this below. While the approach adopted by Herring and Marston is grounded in loss-minimizing behaviour by the central bank, it does not solve the problem of the endogeneity of net foreign assets in the reaction function. In econometric implementation, therefore, some form of instrumental variables or two-stage least squares is therefore usually employed where the instruments are chosen in a somewhat *ad hoc* fashion (see also Kearney and MacDonald, 1986; Hutchison, 1988).

In this paper, we derive the offset and sterilization coefficients jointly from the loss function of the authorities, while at the same time providing a means of identifying the resulting semi-reduced-form equations. We assume that the central bank has an objective function (a loss function) which it seeks to minimize subject to a number of constraints that reflect the working of the economy.[4] The loss function takes the following form:

$$L_t = \alpha(s_t - s_t^T)^2 + \beta(p_t - p_t^T)^2 + \gamma(Y_t - Y_t^T)^2 + \delta(\sigma_{r,t})^2 + \varepsilon(\sigma_{s,t})^2 \tag{3}$$

where L_t is the loss at time t; $(s_t - s_t^T)^2$ is the squared deviation of the current exchange rate (s_t, the domestic price of a unit of foreign currency) from its target (s_t^T); $(p_t - p_t^T)^2$ is the squared deviation of the logarithm of the price level (p_t) from its target (p_t^T); $(Y_t - Y_t^T)^2$ is the squared deviation of real income (Y_t) from its trend (Y_t^T, that is, deviations of income from its trend are costly); $(\sigma_{r,t})^2$ is a measure of the volatility of interest rates; and $(\sigma_{s,t})^2$, is a measure of the volatility of exchange rates. The parameters α, β, γ, δ and ε are the weights assigned by the central bank to each of the objectives respectively. We assume here that they are all positive.[5]

The rationale for the existence of interest rate and exchange rate volatility in the loss function is simple. Central banks dislike interest rate volatility since it can send confusing signals to the markets about the direction of monetary policy. For this reason, they design mechanisms to limit interest rate volatility (standing facilities etc.) and intervene actively to prevent it (through fine-tuning operations).[6]

Avoiding exchange rate volatility can also be useful if the central bank believes that volatility can make its target exchange rate more difficult to achieve.[7] Thus the central bank experiences a loss not only if the exchange rate is away from its target ($(s_t - s_t^T)^2$), but, if the rate is away from its target, then greater volatility increases the chances of the target not being met (an additional cost captured by σ_{st}^2). The particular formulation of the objective function raises two issues with respect to foreign exchange market intervention. First, do central banks actually seek to influence both exchange rate level and its volatility? Second, are they successful? With respect to the first issue, concern over the exchange rate level is not in doubt especially in countries where there is an explicit target. But there is also evidence that central banks care about exchange rate volatility and maintaining 'orderly' market conditions. Wonnacott (1982) argues that research from earlier periods shows this to be true; Edison (1993) surveys the more recent literature and finds some support for the view that reducing volatility is an explicit aim of central banks. With respect to the second question, evidence on the success of intervention is more mixed, although some recent research on intervention by the G-3 finds that intervention has been successful in influencing both the level and volatility of the exchange rate.[8]

We can rewrite equation (3) in a slightly different form. Substituting cyclical income (Y_{ct}) for ($Y_t - Y_t^T$) and subtracting p_{t-1} from both p_t and p_t^T: [9]

$$L_t = \alpha(s_t - s_t^T)^2 + \beta(\Delta p_t - \Delta p_t^T)^2 + \gamma(Y_{ct})^2 + \delta(\sigma_{r,t})^2 + \varepsilon(\sigma_{s,t})^2 \tag{3a}$$

where Δp_t is inflation and Δp_t^T is target inflation, assumed to be zero for simplicity. We work with this version of the loss function in what follows.

This loss function (equation (3a)) is minimized by the central bank choosing foreign exchange market intervention (ΔNFA_t) and domestic money market intervention (ΔNDA_t), subject to a number of constraints. It seems appropriate in our context to allow the degree of intervention to be a choice variable. If the exchange rate were completely fixed, then a central bank has no choice—it must intervene by the amount of the capital flow and the current account to maintain the chosen rate.[10] In the context of the 1980 s and 1990 s, this seems an inappropriate assumption for European ERM members. They manage their exchange rates through a mixture of intervention, the use of bands of fluctuation and realignments. The constraints include the following:

(1) *Inflation*

$$\Delta p_t = \pi_1(\Delta NFA_t + \Delta NDA_t) + \pi_2 \Delta p_{t-1} \quad \pi_1 > 0,\ 0 < \pi_2 < 1 \tag{4}$$

Inflation depends on past inflation and the change in the current monetary base (both foreign, ΔNFA_t, and domestic, ΔNDA_t, components).

(2) *Cyclical income*

$$Y_{c,t} = \varphi_1(\Delta NFA_t + \Delta NDA_t) + \varphi_2 Y_{c,t-1} \quad \varphi_1 > 0,\ 0 < \varphi_2 < 1 \tag{5}$$

Cyclical income depends on the two components of the monetary base and the cyclical position of the economy in the previous period.

(3) *Balance of payments and the exchange rate*

$$\Delta NFA_t = CA + \Delta NK_t \tag{6}$$

where CA is the current account surplus and ΔNK_t is the net capital inflow in time t. The current account is assumed to be exogenous for simplicity.[11] The net capital inflow (resulting from changes in debt accumulated by domestic residents abroad, changes in holdings of foreign assets by residents and changes in holdings of domestic assets by foreigners) depends on the uncovered interest differential:

$$\Delta NK_t = (1/c)\Delta(s_t - E_t s_{t+1} + r_t - r_t^*) \tag{7}$$

where s_t is the current exchange rate (logarithm); $E_t s_{t+1}$ is the current expectation of the exchange rate at time $t+1$; r_t is the domestic interest rate; r_t^* is the foreign interest rate and c represents the degree of relative risk aversion between domestic and foreign assets. If $c = 0$, then domestic and foreign assets are perfect substitutes and capital is perfectly mobile: any deviation from uncovered interest parity will lead to an infinite capital flow. We assume for the present that $0 < c < \infty$, that is, capital is mobile but not perfectly so. We also assume that the domestic interest rate is negatively related to the level of the domestic component of the monetary base, NDA_t, and hence:

$$\Delta r_t = -\psi \Delta NDA_t \quad \psi > 0 \tag{8}$$

Using equations (7) and (8) in (6) and solving for the current exchange rate generates:

$$s_t = c\Delta NFA_t - cCA + s_{t-1} + \psi \Delta NDA_t + \Delta(E_t s_{t+1} + r_t^*) \tag{9}$$

This equation embodies a number of well-known propositions. First, an increase in foreign exchange reserves as a result of intervention to sell the domestic currency causes s_t to increase (the exchange rate to depreciate). Second, an increase in the current account surplus causes s_t to fall. Third, an increase in the domestic component of the monetary base causes s_t to increase. Finally, an increase in either the expected depreciation or the foreign interest rate will cause s_t to increase as capital flows out of domestic assets.

(4) *Interest rate volatility*

$$\sigma_{r,t} = \eta\sigma_{r,t-1} - \zeta(\Delta NDA_t - d_1\Delta NDA_t) \quad \eta, \zeta > 0 \tag{10}$$

This equation states that interest rate volatility depends positively on past levels of volatility and negatively on the *absolute* amount of intervention undertaken by the central bank in the domestic money market. When the money market is in deficit, NDA_t is rising as the central bank injects funds to prevent interest rate rises. When the money market is in surplus, the central bank is withdrawing funds to prevent interest rate falls. For estimation purposes we replace the absolute value by the term $(\Delta NDA_t - d_1\Delta NDA_t)$ which is equivalent to having the absolute value of intervention. d_1 is a dummy which takes a value of 0 when the money market is in deficit and a value of 2 when it is in surplus. The specific form of the dummy allows us to use the actual ΔNDA in equation (10) and not its absolute value.[12]

(5) *Exchange rate volatility*

$$\sigma_{s,t} = \kappa\sigma_{s,t-1} - \zeta(\Delta NFA_t - d_2\Delta NFA_t) \quad \kappa, \xi > 0 \tag{11}$$

Equation (11) for exchange rate volatility is similar to that for interest rate volatility. Volatility is positively related to past levels of volatility and negatively to the *absolute* amount of intervention in the foreign exchange market. d_2 is a dummy which takes a value of 2 when there is an excess demand for foreign currency (and the central bank is losing reserves) and a value of 0 when foreign currency is in excess supply (and the central bank is cumulating reserves). As with equation (10), the dummy allows us to write exchange rate volatility as a function of foreign exchange intervention rather than its absolute value.

The relationships in equations (10) and (11) are those which, as we shall see below, provide identification of the system. The relationship between interest rate volatility and ΔNDA_t identifies the equation for domestic money market intervention and the relationship between exchange rate volatility and ΔNFA_t identifies the equation for foreign exchange market intervention.

The model's long-run properties can be derived by assuming a steady state where all growth rates are zero (for simplicity). This generates the following familiar results. First, from equation (5), income is on trend and the cyclical component is zero. Second, the balance of payments equation (6) generates either a flow equilibrium (a current account surplus equal to the capital outflow) or a full stock equilibrium, where the current account is zero and there are no capital flows. From equation (9), this implies that the exchange rate is fixed for a given foreign interest rate.

Solving equations (3a) to (11) above, we derive two identified semi-reduced-form equations which represent optimal rules according to which the central bank should conduct its intervention in both the money and foreign exchange markets. We assume that the central bank minimizes equation (3) with respect to the policy instruments available to it (ΔNDA_t and ΔNFA_t) subject to the constraints which describe the workings of the economy and are given in equations (4), (5), (9), (10) and (11):

$$\begin{aligned}\partial L_t/\partial\Delta NDA_t = 0 = {}&(\partial L_t/\partial s_t)(\partial s_t/\partial\Delta NDA_t) + (\partial L_t/\partial\Delta p_t)(\partial\Delta p_t/\partial\Delta NDA_t)\\&+ (\partial L_t/\partial Y_{c,t})(\partial Y_{c,t}/\partial\Delta NDA_t) + (\partial L_t/\partial\sigma_{r,t})(\partial\sigma_{r,t}/\partial\Delta NDA_t)\\&+ (\partial L_t/\partial\sigma_{s,t})(\partial\sigma_{s,t}/\partial\Delta NDA_t)\end{aligned} \tag{12}$$

$$\begin{aligned}\partial L_t/\partial\Delta NFA_t = 0 = {}&(\partial L_t/\partial s_t)(\partial s_t/\partial\Delta NFA_t) + (\partial L_t/\partial\Delta p_t)(\partial\Delta p_t/\partial\Delta NFA_t)\\&+ (\partial L_t/\partial Y_{c,t})(\partial Y_{c,t}/\partial\Delta NFA_t) + (\partial L_t/\partial\sigma_{r,t})(\partial\sigma_{r,t}/\partial\Delta NFA_t)\\&+ (\partial L_t/\partial\sigma_{s,t})(\partial\sigma_{s,t}/\partial\Delta NFA_t)\end{aligned} \tag{13}$$

where from the constraints we have:

$$\partial L_t/\partial s_t = \alpha(s_t - s_t^T)$$

$$\partial L_t/\partial \Delta p_t = \beta \Delta p_t$$

$$\partial L_t/\partial Y_{c,t} = \gamma Y_{c,t}$$

$$\partial L_t/\partial \sigma_{r,t} = \delta \sigma_{r,t}$$

$$\partial L_t/\partial \sigma_{s,t} = \varepsilon \sigma_{s,t}$$

$$\partial s_t/\partial \Delta NDA_t = \psi$$

$$\partial s_t/\partial \Delta NFA_t = c$$

$$\partial p_t/\partial \Delta NDA_t = \pi_1 = \partial p_t/\partial \Delta NFA_t$$

$$\partial Y_{c,t}/\partial \Delta NDA_t = \varphi_1 = \partial Y_{c,t}/\partial \Delta NFA_t$$

$$\partial \sigma_{r,t}/\partial \Delta NDA_t = \zeta(d_1 - 1)$$

$$\partial \sigma_{s,t}/\partial \Delta NFA_t = \xi(d_2 - 1)$$

$$\partial \sigma_{r,t}/\partial \Delta NFA_t = 0 = \partial \sigma_{s,t}/\partial \Delta NDA_t$$

Substituting the partial derivatives into equations (12) and (13) and then substituting for s_t, p_t, $Y_{c,t}$, $\sigma_{r,t}$ and $\sigma_{s,t}$ from equations (4), (5), (9), (10) and (11) and solving for semi-reduced-form equations for ΔNDA_t and ΔNFA_t respectively gives us:

$$\begin{aligned}\Delta NDA_t = &-[(\alpha\psi c + \beta\pi_1^2 + \gamma\varphi_1^2)/\theta_1]\Delta NFA_t + [\alpha c\psi/\theta_1]CA \\ &- [\alpha\psi/\theta_1](s_{t-1} - s_t^T) - [\alpha\psi/\theta_1]\Delta(E_t s_{t+1} + r_t^*) - [\beta\pi_1\pi_2/\theta_1]\Delta p_{t-1} \\ &- [\gamma\varphi_1\varphi_2/\theta_1]Y_{c,t-1} - [\eta\delta\zeta/\theta_1](d_1 - 1)\sigma_{r,t-1} \end{aligned} \quad (14)$$

where $\theta_1 = [\alpha\psi^2 + \beta\pi_1^2 + \gamma\varphi_1^2 + \delta\zeta^2] > 0$

$$\begin{aligned}\Delta NFA_t = &-[(\alpha\psi c + \beta\pi_1^2 + \gamma\varphi_1^2)/\theta_2]\Delta NDA_t + [\alpha c^2/\theta_2]CA - [\alpha c/\theta_2](s_{t-1} - s_t^T) \\ &- [\alpha c/\theta_2]\Delta(E_t s_{t+1} + r_t^*) - [\beta\pi_1\pi_2/\theta_2]\Delta p_{t-1} - [\gamma\varphi_1\varphi_2/\theta_2]Y_{c,t-1} \\ &- [\kappa\varepsilon\xi/\theta_2](d_2 - 1)\sigma_{s,t-1} \end{aligned} \quad (15)$$

where $\theta_2 = [\alpha c^2 + \beta\pi_1^2 + \gamma\varphi_1^2 + \varepsilon\xi^2] > 0.$

The coefficient on ΔNFA_t in equation (14) is the sterilization coefficient and that on ΔNDA_t in equation (15) is the offset coefficient. Both will be negative. However, they could be greater than or less than -1. The other coefficients in the equations indicate how the central bank should react to changes in the exogenous variables. Thus, to take some examples from equation (15), an increase in the current account surplus should lead the central bank to increase its foreign exchange reserves as it sells domestic currency to prevent appreciation of the exchange rate away from its target. If the target exchange rate depreciates (S_t^T increases) and hence a negative gap opens up between it and last period's exchange rate, then again foreign exchange reserves should be cumulated as the bank intervenes to sell domestic currency.

The important point to note about the two equations is that the volatility of the domestic interest rate and the exchange rate identify the domestic money market intervention rule and the foreign exchange market intervention rule respectively. Thus the two equations are independent of each other and it is possible to solve for reduced-form equations for both ΔNFA_t and ΔNDA_t (although we do not do that here).

Equations (14) and (15) represent the general case where the central bank cares about all the arguments in its loss function and capital is less than perfectly mobile. It is interesting, however, to derive some theoretical results for special cases and compare these with the results from the existing literature. We consider three special cases here.

(1) *The central bank cares only about the exchange rate target* ($\beta = \gamma = \delta = 0$)—In this case, equations (14) and (15) collapse to:

$$\Delta NDA_t = -[c/\psi]\Delta NFA_t + [c/\psi]CA - [1/\psi](s_{t-1} - s_t^T) - [1/\psi]\Delta(E_t s_{t+1} + r_t^*) \quad (14a)$$

$$\Delta NFA_t = -[\alpha\psi c/(\alpha c^2 + \varepsilon\xi^2)]\Delta NDA_t + [\alpha c^2/(\alpha c^2 + \varepsilon\xi^2)]CA - [\alpha c/(\alpha c^2 + \varepsilon\xi^2)](s_{t-1} - s_t^T) - [\alpha c/(\alpha c^2 + \varepsilon\xi^2)]\Delta(E_t s_{t+1} + r_t^*) - [\kappa\varepsilon\xi/(\alpha c^2 + \varepsilon\xi^2)](d_2 - 1)\sigma_{s,t-1} \quad (15a)$$

and the intervention rules, not surprisingly, are dependent neither on the stage of the business cycle, nor on inflation nor on the volatility of the domestic interest rate. This is similar to the result derived by Herring and Marston (1977a, pp. 51–2) where the inflation and income terms drop out of the reaction function if the central bank cares only about external balance. From equation (14a) we can see that the amount of sterilization depends only on the relationship between c and ψ, the degree of risk aversion and the sensitivity of interest rates to money market intervention respectively. If the degree of risk aversion is small and interest rates are very sensitive to money market intervention, then only a small amount of sterilization is optimal.

(2) *The central bank cares only about inflation and income* ($\alpha = \delta = \varepsilon = 0$)—In this case, the central bank will sterilize completely—the coefficient is -1 as is clear from equations (14b) and (15b).

$$\Delta NDA_t = -\Delta NFA_t - [\beta\pi_1\pi_2/(\beta\pi_1^2 + \gamma\varphi_1^2)]\Delta p_{t-1} - [\gamma\varphi_1\varphi_2/(\beta\pi_1^2 + \gamma\varphi_1^2)]Y_{c,t-1} \quad (14b)$$

$$\Delta NFA_t = -\Delta NDA_t - [\beta\pi_1\pi_2/(\beta\pi_1^2 + \gamma\varphi_1^2)]\Delta p_{t-1} - [\gamma\varphi_1\varphi_2/(\beta\pi_1^2 + \gamma\varphi_1^2)]Y_{c,t-1} \quad (15b)$$

Again this result is similar to that derived by Herring and Marston (1977a, p.51) when the central bank cares only about internal balance. Moreover, the two equations are no longer independent of one another. In other words, both foreign exchange market intervention and domestic money market intervention are equivalent in their effect on inflation and cyclical income (as is clear from equations (4) and (5)) and the authorities are indifferent between using foreign exchange market intervention and money market intervention.

(3) *Capital is perfectly mobile and the exchange rate is completely fixed* ($c = 0, \sigma_s, \sigma_r = 0$)—Under perfect capital mobility, domestic and foreign assets are perfect substitutes for each other and hence relative risk aversion is zero, $c = 0$. With a completely fixed exchange, there is no exchange rate volatility and, given the exogenously fixed foreign interest rate and uncovered interest parity, there can be no interest rate volatility. Thus both the volatility terms drop out of the loss function. Finally, $\psi = 0$ since the domestic interest rate cannot be altered (the foreign interest rate is given and the expected change in the exchange rate is zero). In this case, the intervention rules again collapse to one (equations 14(b) and 15(b)) and both types of intervention become equivalent.
This result is merely the well-known conclusion that with full capital mobility and completely fixed exchange rates, a central bank cannot have a domestic intervention policy which is independent of its foreign intervention policy. Hence the model includes this result as a special case.

In conclusion, the model presented here seeks to provide a framework in which both money market and foreign exchange market intervention can be determined jointly. In the general case, there will be offsetting changes in foreign exchange reserves. Additionally, it will be optimal for the central bank to undertake some sterilization, although exactly how much is unknown. Indeed, the bank could engage in 'oversterilization' (that is, the sterilization coefficient could be greater than -1). The equations are both identified through the volatility terms and this allows estimation of the two equations as a system. In this way, we overcome the main problem faced by the previous literature, namely that each equation is estimated individually and instruments for the endogenous variables are chosen in a rather *ad hoc* fashion.

3. EMPIRICAL IMPLEMENTATION: GERMANY IN THE ERM

The question of the degree of monetary autonomy experienced by Germany (from the 1960s' experience of fixed exchange rates under Bretton Woods, through the managed float of the 1970s to the ERM experience since 1979) has been a rich source of empirical research on the sterilization and offset coefficients. Early work undertaken by Kouri (1975) estimates the offset coefficient (using a reduced-form capital flow model) at −0.73 for the period 1960 to 1972. This figure is challenged by Neumann (1978) who argues that the figure for net domestic assets used by Kouri is not properly measured. Re-estimation over the same period yields significantly smaller offset coefficients of −0.39 to −0.47 (depending on the exact sub-period chosen). Herring and Marston's (1977a) structural estimate of the offset coefficient for the 1960s produces a figure of −0.78, much closer to that of Kouri's. Estimates of the extent to which the Bundesbank sterilizes over the same period suggest a high figure of around 90% (Herring and Marston, 1977a,b).[13]

Mastropasqua *et al.* (1988) and Von Hagen (1989) examine the extent to which Germany has sterilized during the ERM years. This is an interesting question since if Germany has successfully sterilized, then this would provide support for the view that the ERM has worked in an asymmetric fashion with Germany adopting its preferred monetary policy and other countries following that lead. Mastropasqua *et al.* estimate a simple reaction function, which includes inflation and growth along with the change in the net foreign assets of the Bundesbank, using instrumental variables to deal with the problem of endogeneity. For the period 1979 to 1984, they derive an estimate for the sterilization coefficient of −0.64 from the two-stage least squares results and −0.82 from ordinary least squares. Output growth is not significant and inflation is only just significant.

Von Hagen (1989) confirms this result of less than perfect sterilization. His contribution is twofold. First, he distinguishes between intervention in European currencies and in the dollar. This is important for a period during which Germany was not only a member of the ERM but was also involved at various times in intervention to influence the level of the dollar (following the Plaza Agreement and the Louvre Accord of 1985 and 1987 respectively).[14] As will become clear below, we incorporate these ideas by including target exchange rates *vis-à-vis* European currencies and the dollar and more than one foreign rate of return.

Von Hagen's second innovation is to distinguish between short- and long-run sterilization. He notes that the Bundesbank divides the domestic component of the money supply into two parts—a transitory part which is controlled in the short term and a permanent part which is controlled over the medium to long term. He argues that foreign exchange market intervention is sterilized through changes in the transitory component, changes which are reversed after a short period of time.[15] Thus, unless the permanent component is altered or sterilization through the transitory component is permanently renewed, sterilization will only be temporary. Von Hagen distinguishes between these two parts of the domestic component of the monetary base in his empirical estimation and concludes that while sterilization is indeed perfect in the short run, in the long run the monetary base is not independent of foreign exchange intervention. An alternative method of incorporating differences between long- and short-run sterilization which we adopt here is to include a number of lags in the estimation of the reaction function. If sterilization is indeed reversed over time, then we anticipate that the coefficients on the lagged values of changes in both components of the monetary base will cause the long-run sterilization coefficient to be lower than the short-run.

We jointly estimate modified versions of equations (14) and (15) over the period 1979 to 1992 (that is, before the first crisis in the ERM). The modification is the inclusion of more than one foreign country. This affects the terms including the exchange rate, the volatility of the exchange rate and the foreign interest rate. In particular, we choose to include France and Italy (as representative of Germany's ERM commitment) and the USA (to capture any effect from intervention in the DMN-dollar market in the mid-1980 s). The rationale for this modification is simple. We model the total change in net foreign assets of the Bundesbank and this could arise from intervention in a number of foreign exchange markets.

Quarterly data is taken from IMF, *International Financial Statistics*, for the period 1979:2 to 1992:2 (a detailed list of definitions is found in the Appendix). In addition to the variables in equations (14) and (15), a dummy was included to capture the effect of German monetary unification on the domestic money supply (it takes the value of 1 in the third quarter of 1990 and a value of zero otherwise). Exchange rate volatility is measured as the standard deviation of the within quarter change in the logarithm of the daily exchange rate.[16] We also experiment with a centred, five-quarter, moving-average deviation from the five-quarter mean calculated according to the following formula:

$$\sigma_{s,t} = (1/5)\left\{\sqrt{\sum_{i=-2}^{2}(\Delta s_{t+i} - \Delta\hat{s})^2}\right\} \quad \text{where } \Delta\hat{s} = (1/5)\sum_{i=-2}^{2}\Delta s_{t+i}$$

This captures the idea that intervention may be greater in periods where volatility is higher for more than one quarter (Klein, 1977). In the absence of daily data on exchange rates, the latter measure is used for interest rate volatility.[17]

The dummy variables d_1 and d_2 indicating whether the money and foreign exchange markets are in surplus or deficit are calculated from the sign of the change in net domestic assets and net foreign assets respectively. Thus if the change in net domestic assets at time t is negative, then this implies a surplus on the domestic money market and d_1 takes the value of 2. A positive change in net domestic assets implies a deficit and d_1 takes the value of 0. The value of d_2 is calculated in the same way (when ΔNFA_t is negative, $d_2 = 2$; when it is positive, $d_2 = 0$). The expected spot rate at time t is taken to be the actual spot rate (that is, we assume perfect foresight). Finally, the exchange rate target is the ERM average central rate of the DM *vis-à-vis* the French franc and the Italian lira over the quarter (for the European currencies) and the purchasing power parity rate for the DM–dollar target (see Appendix for more details).

The time series properties of the variables were explored using ADF tests and the results are presented in the Appendix. *A priori*, it is anticipated that all the variables are I(0). In practice, however, for the time period considered here, this is not entirely true. A few of the variables are not I(0), although such a conclusion is sensitive to the number of lags included and the time period considered. It is important to note that both dependent variables, ΔNDA and ΔNFA, are I(0).[18] In view of these results, we proceed on the assumption that all the variables are I(0).

To derive asymptotically efficient estimates of the coefficients, we estimate the equations by three-stage least squares. However, we begin with two-stage least squares estimates for comparative purposes and to allow the presentation of some test statistics.[19] The results are shown in Table 1.[20] Up to two lags of each variable are included initially since theory does not give us clear guidance on this issue. Insignificant variables are deleted from the equations. The results are discussed in detail below when we consider the three-stage estimates. For the present, we can mention that the long-run offset coefficient is -0.28 and the long-run sterilization coefficient is -0.98. Tests for autocorrelation, ARCH and heteroscedasticity for each equation are also presented in Table 1. They do not indicate any significant problems.

Correlation between the residuals of the two equations of 0.82 justifies our moving to three-stage least squares and gives asymptotically efficient estimates. The results are presented in Table 2. The move from 2SLS to 3SLS has, as expected, reduced the coefficient standard errors. The results indicate that a number of the hypothesized variables are significant. As in other work, there is little evidence that inflation or income are significant. The insignificance of income over the period considered may be explained by the fact that during the 1980s, central banks were far more concerned with inflation than with income deviations from trend. The insignificance of inflation is more difficult to understand. It probably stems from the fact that whereas ΔNDA_t and ΔNFA_t are rather volatile series, inflation is not.[21] The current account is significant only in the ΔNDA_t equation and the effect as expected is positive.

The volatility terms interacted with the dummy variables (d_1 and d_2) are significant in both equations[22] and there is strong support for the influence of deviations of the actual DM exchange rate from its target. This is confirmed in Table 3 where the results of Wald tests for the joint significance of variables are presented. The volatility measures which are used to identify the equations are jointly significant in both equations. Additionally deviations of the DM–French franc exchange rate from its target, the composite French variable and the volatility of the DM–French franc exchange rate (the French variables, Table 3) are significant as are the equivalent Italian and US variables.

Table 1. Offset and sterilization equations: Germany, 1979–92
Estimation Method: two-stage least squares (2SLS)
Sample: 1980:2–1992:2

Offset equation: dependent variable ΔNFA_t

Variable	Coefficient	Standard error (t-stat)
1 Constant	−1.252	1.120 (−1.12)
2 ΔNDA_t	−0.222	0.100 (−2.21)
3 ΔNDA_{t-1}	−0.170	0.083 (−2.05)
4 ΔNFA_{t-1}	−0.402	0.159 (−2.53)
5 $(s_{t-1,\mathrm{FF}} - s^T_{t,\mathrm{FF}})_{t-1}$	−98.14	46.25 (−2.12)
6 $\Delta(E_t s_{t+1,LI} + r^*_{t,LI})_{t-1}$	−92.08	41.07 (−2.24)
7 $(s_{t-1,LI} - s^T_{t,LI})_{t-1}$	136.35	44.12 (3.09)
8 $(s_{t-1,\$} - s^T_{t,\$})_t$	−8.722	4.934 (−1.77)
9 $[(d_2 - 1)\sigma_{s,LI,t-1}]_t$	−1329	356.0 (−3.73)
10 $[d_2 - 1)\sigma_{s,\$,t-1}]_{t-1}$	−142.2	109.3 (−1.30)
11 Unification dummy	5.941	5.342 (1.11)

$R^2 = 0.683$ SE = 4.02	Mean dependent variable = −0.455 $n = 47$	
Fourth order autocorrelation	$\chi^2(4) = 0.63$ probability = 0.959	
(Breusch–Godfrey LM test) ARCH (LM test)	$\chi^2(1) = 0.008$ probability = 0.928	
White heteroscedasticity test	$\chi^2(20) = 13.93$ probability = 0.788	

Sterilization equation: dependent variable ΔNDA_t

Variable	Coefficient	Standard error (t-stat)
12 Constant	−0.517	1.982 (−0.27)
13 ΔNFA_t	−0.735	0.261 (−2.82)
14 ΔNFA_{t-1}	−0.664	0.179 (−3.70)
15 ΔNDA_{t-1}	−0.417	0.102 (−4.09)
16 CA_{t-2}	0.133	0.074 (1.80)
17 $(s_{t-1,\mathrm{FF}} - s^T_{t,\mathrm{FF}})_{t-1}$	−179.9	66.63 (−2.70)
18 $(s_{t-1,LI} - s^T_{t,LI})_{t-1}$	141.2	74.90 (1.89)
19 $\Delta(E_t s_{t+1,\mathrm{LI}} + r^*_{t,\mathrm{LI}})_{t-1}$	−103.3	65.02 (−1.59)
20 $(s_{t-1,\$} - s^T_{t,\$})_{t-1}$	−13.05	7.257 (−1.80)
21 $(d_1 - 1)\sigma_{r,t-1}$	−16.47	5.031 (−3.27)
22 Unification dummy	27.28	6.680 (4.08)

$R^2 = 0.754$ SE = 6.008	Mean dependent variable = 3.482 $n = 49$	
Fourth order autocorrelation	$\chi^2(4) = 6.50$ probability = 0.16	
(Breusch–Godfrey LM Test) ARCH (LM test)	$\chi^2(1) = 2.53$ probability = 0.11	
White heteroscedasticity test	$\chi^2(20) = 15.97$ probability = 0.65	

Notes:
ΔNDA_t = change in German net domestic assets
ΔNFA_t = change in German net foreign assets
$(s_{t-1,\mathrm{FF}} - s^T_{t,\mathrm{FF}})_{t-1}$ = deviation of DM/French franc exchange rate from its target
$\Delta(E_t s_{t+1,\mathrm{LI}} + r^*_{t,\mathrm{LI}})_{t-1}$ = expected change in the Italian composite variable
$(s_{t-1,\mathrm{LI}} - s^T_{t,\mathrm{LI}})_{t-1}$ = deviation of DM/lira exchange rate from its target
$(s_{t-1,\$} - s^T_{t,\$})_t$ = deviation of DM/dollar exchange rate from its target
$[(d_2 - 1)\sigma_{s,\mathrm{LI},t-1}]_t$ = volatility of the DM/lira exchange rate (interacted with the dummy)
$[(d_2 - 1)\sigma_{s,\$,t-1}]_{t-1}$ = volatility of the DM/dollar exchange rate (interacted with the dummy)
CA_{t-1} = German current account of the balance of payments (in DM)
$(d_1 - 1)\sigma_{r,t-1}$ = volatility of German domestic interest rate (interacted with the dummy) 1987, quarter 4 dummy: see note 17.

Table 2. Offset and sterilization equations: Germany, 1979–92
Estimation method: three-stage least squares (3SLS)
Sample: 1980:2–1992:2

Offset equation: dependent variable ΔNFA_t

Variable	Coefficient	Standard error (t-stat)
1 Constant	−0.362	0.953 (−0.38)
2 ΔNDA_t	−0.399	0.076 (−5.24)
3 ΔNDA_{t-1}	−0.236	0.068 (−3.49)
4 ΔNFA_{t-1}	−0.457	0.122 (−3.74)
5 $(s_{t-1,\mathrm{FF}} - s^T_{t,\mathrm{FF}})_{t-1}$	−114.1	39.24 (−2.91)
6 $\Delta(E_t s_{t+1,\mathrm{LI}} + r^*_{t,\mathrm{LI}})_{t-1}$	−82.46	35.02 (−2.35)
7 $(s_{t-1,\mathrm{LI}} - s^T_{t,\mathrm{LI}})_{t-1}$	129.43	37.67 (3.44)
8 $(s_{t-1,\$} - s^T_{t,\$})_t$	−8.633	4.055 (−2.13)
9 $[(d_2 - 1)\sigma_{s,\mathrm{LI},t-1}]_t$	−984.9	274.2 (−3.59)
10 $[(d_2 - 1)\sigma_{s,\$,t-1}]_{t-1}$	−142.0	84.15 (−1.69)
11 Unification dummy	11.62	4.466 (2.60)
$R^2 = 0.6282$ SE = 4.359	Mean dependent variable = −0.455 $n = 47$	

Sterilization equation: dependent variable ΔNDA_t

Variable	Coefficient	Standard error (t-stat)
12 Constant	−0.547	1.641 (−0.33)
13 ΔNFA_t	−0.961	0.210 (−4.57)
14 ΔNFA_{t-1}	−0.684	0.157 (−4.36)
15 ΔNDA_{t-1}	−0.455	0.088 (−5.16)
16 CA_{t-2}	−0.109	0.057 (1.92)
17 $(s_{t-1,\mathrm{FF}} - s^T_{t,\mathrm{FF}})_{t-1}$	−194.9	58.15 (−3.35)
18 $(s_{t-1,\mathrm{LI}} - s^T_{t,\mathrm{LI}})_{t-1}$	162.6	64.29 (2.53)
19 $\Delta(E_t s_{t+1,\mathrm{LI}} + r^*_{t,\mathrm{LI}})_{t-1}$	−117.4	55.70 (−2.11)
20 $(s_{t-1,\$} - s^T_{t,\$})_{t-1}$	−14.33	6.134 (−2.34)
21 $(d_1 - 1)\sigma_{r,t-1}$	−12.11	3.989 (−3.04)
22 Unification dummy	27.79	5.834 (4.76)
$R^2 = 0.7347$ SE = 6.310	Mean dependent variable = 3.482 $n = 49$	

Augmented Dickey–Fuller tests for order of integration of the residuals (dependent variable is the first difference of the residual, 4 lags included):

residuals from ΔNFA equation: ADF test statistic = −4.01
residuals from ΔNDA equation: ADF test statistic = −3.54

1% critical value = −3.585 Hence we can reject the null hypothesis that the residuals are I(1).
Normality of the residuals: from ΔNFA equation: Jarque–Bera = 0.36 (probability = 0.83)
(H_0: normality) from ΔNDA equation: Jarque–Bera = 0.03 (probability = 0.98)

The coefficient on ΔNDA_t in the offset equation (coefficient 2) gives us a measure of the short-term offset. It indicates that capital flows offset 40% of any change in monetary policy. The short-term sterilization coefficient (coefficient 13) is −0.96, which indicates that the authorities fully sterilize any foreign exchange intervention. Not surprisingly, the coefficient is not significantly different from −1 (t-statistic = −0.19). The long-run offset and sterilization coefficients are −0.44 and −1.13 respectively. At the bottom of Table 2 the results of a test of whether these are significantly different from −1 are presented. In the case of the offset coefficient, it is, not surprisingly, significantly different from −1, indicating that, in the long run, capital flows offset only 44% of any monetary policy change. This rather low figure reflects the fact that the DM

Table 3. Wald Tests for joint significance of coefficients

Equation	Coefficients H_0: they are not jointly significant (numbers given in Table 1)	χ^2 (probability)
ΔNFA	Italian variables: 6, 7, 9	30.0(0.000)
	US variables: 8, 10	8.31(0.016)
	volatility measures: 9,10	14.2(0.001)
ΔNDA	Italian variables: 18, 19	8.01(0.018)
Both	French variables: 5, 17	13.5(0.001)
	Italian variables: 6, 7, 18, 19	35.48(0.000)
	US variables: 8, 10, 20	10.36(0.016)
	Volatility measures: 9, 10, 21	20.23(0.000)
	Test: H_0	χ^2(probability)
Long-run offset coefficient	$\frac{(\text{coeff } 2 + \text{coeff } 3)}{(1 - \text{coeff } 4)} = -1$	49.43(0.00)
Long-run sterilization coefficient	$\frac{(\text{coeff } 13 + \text{coeff } 14)}{(1 - \text{coeff } 15)} = -1$ where coeff = coefficient	0.59(0.44)

exchange rate has not been as fixed as it was during the Bretton Woods era. Within the ERM the width of the fluctuations bands has been used. Moreover, realignments have not been uncommon especially during the early years and, of course, agreements about the DM–dollar exchange rate have been even looser. The sterilization coefficient is, however, not significantly different from -1. Thus our results do not concur with Von Hagen's conclusion that, in the longrun, the Bundesbank is not able to sterilize the effect of its foreign exchange intervention. Instead the results here suggest that the Bundesbank completely sterilizes its foreign exchange intervention in the long run.

4. CONCLUSION

In this paper we have sought to provide a unified framework in which fully identified semi-reduced-form offset and sterilization equations can be derived and estimated. We develop a general model where it is assumed that the central bank cares about both external and internal goals and capital is less than perfectly mobile. The theoretical results suggest that there will be some offsetting capital flows (causing foreign exchange reserves to change following a change in domestic monetary policy) and that the central bank will sterilize. The model also encompasses several results from the literature as special cases. Thus we can derive the well-known result that with completely fixed exchange rates and perfect capital mobility, sterilization is impossible and the equations for foreign exchange intervention and domestic money market intervention collapse to one.

The derived equations were then estimated as a system for the German experience with the ERM and with intervention in the DM–dollar foreign exchange market during the 1980s. The results suggest that the amount of offset is rather low and lower than previous estimates for the Bretton Woods era. However, it must be remembered that exchange rates during the Bretton Woods regime were almost completely fixed. By contrast, during the period under consideration here, the Bundesbank was able to use the width of the bands in the ERM and benefited from a number of realignments. Thus the low offset is not surprising when viewed in this light. With respect to sterilization, the results point to active sterilization by the Bundesbank—the sterilization coefficient is not significantly different from -1. This suggests that the

Bundesbank had considerable monetary independence during the period considered and provides further evidence that the ERM has worked in an asymmetric manner.

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APPENDIX: DATA SOURCES AND DEFINITIONS

1. **Quarterly exchange** rates are period averages from *International Financial Statistics* (*IFS*, series rf) and Eurostat (for ERM central rates).
2. **Daily exchange rates** are from the Deutsche Bundesbank *Statistisches Beiheft zum Monatsberich*, no. 5, Devisenkursstatistik (Table 5)
3. **Interest rates** are Treasury Bill rates (Source: *IFS*, series 60c) for the USA, Germany and Italy and the call rate for France (source: *IFS*, series 60b).
4. **Inflation** is calculated from the consumer price index (source: *IFS*, series 64).
5. **Net foreign assets** are foreign assets minus foreign liabilities (Source: *IFS*, series 11 minus series 16c). Net domestic assets are calculated by subtracting net foreign assets from reserve money (source: *IFS*, series 14).
6. **Cyclical income** is calculated from the index of industrial production (Source: *IFS*, series 66c). The trend is filtered using the Hodrick–Prescott method with $\ddot{e} = 1600$.
7. **Purchasing power parity exchange rate series** is derived from the 1990 PPP exchange rate between Germany and the USA as calculated by the OECD. The series is extended backwards and forwards using relative prices as the OECD suggest. Hence the purchasing power parity exchange rate at any point in time between the DM and the dollar, PPP_t, is given by:

   $$PPP_t = PPP_{1990}(gecpi_t/uscpi_t)$$

   where PPP_{1990} is the OECD DM/dollar purchasing power parity exchange rate for 1990, $gecpi_t$ is the German consumer price index and $uscpi_t$ is the US consumer price index for each quarter.
8. The current account is from *IFS*, series 77a.d

Time series properties of the variables (ADF Tests)
Sample: 1980:4 to 1992:2

Test equation: $\Delta x_t = \alpha + \beta x_{t-1} + \sum_{i=1}^{4} \gamma_i \Delta x_{t-i}$
(That is, four lags and constant included unless otherwise stated).

x	t-statistic	Alternative results
ΔNFA_t	−3.27 **	
ΔNDA_t	−2.94 **	
$(d_2 - 1)\sigma_{s,FF,t-1}$	−5.04***	
$(d_2 - 1)\sigma_{s,\mathrm{LI},t-1}$	−3.84***	
$(d_2 - 1)\sigma_{s,\mathrm{US},t-1}$	−2.86 *	3 lags−3.47**
$s_{t-1,\mathrm{FF}} - s^T_{t,\mathrm{FF},}$	−1.42	no lags, sample 1981:1–1992:2 −4.34***
$s_{t-1,\mathrm{FF}} - s^T_{t,\mathrm{FF},}$	−2.63 *	
$s_{t-1,\mathrm{FF}} - s^T_{t,\mathrm{FF},}$	−2.52	
$\Delta(E_t s_{t+1,\mathrm{FF}} + r^*_{t,\mathrm{FF}})$	−2.60 *	3 lags−4.43***

$\Delta(E_t s_{t+1,\mathrm{LI}} + r^*_{t,\mathrm{LI}})$	−2.68 *	2 lags−3.58**
$\Delta(E_t s_{t+1,\mathrm{US}} + r^*_{t,\mathrm{US}})$	−2.42	3 lags−4.47***
$(d_1 - 1)\sigma_{r,t}$	−4.13***	
CA_t	−1.97	
Δp_t	−1.23	
$Y_{c,t}$	−4.48***	(no intercept since mean is zero by construction)

*Significant at the 10% level; ** significant at the 5% level; *** significant at the 1% level.

Notes:

ΔNDA_t = change in German net domestic assets
ΔNFA_t = change in German net foreign assets
$(d_2 - 1)\sigma_{s,\mathrm{FF},t-1}$ = volatility of DM/French franc exchange rate (interacted with the dummy)
$(d_2 - 1)\sigma_{s,\mathrm{LI},t-1}$ = volatility of DM/lira exchange rate (interacted with the dummy)
$(d_2 - 1)\sigma_{s,\mathrm{US},t-1}$ = volatility of DM/US dollar exchange rate (interacted with the dummy)
$s_{t-1,\mathrm{FF}} - s^T_{t,\mathrm{FF}}$ = deviation of DM/French franc exchange rate from its target
$s_{t-1,\mathrm{LI}} - s^T_{t,\mathrm{LI}}$ = deviation of DM/lira exchange rate from its target
$s_{t-1,\$} - s^T_{t,\$}$ = deviation of DM/dollar exchange rate from its target
$\Delta(E_t s_{t+1,\mathrm{FF}} + r^*_{t,\mathrm{FF}})$ = expected change in the French composite variable
$\Delta(E_t s_{t+1,\mathrm{LI}} + r^*_{t,\mathrm{LI}})$ = expected change in the Italian composite variable
$\Delta(E_t s_{t+1,\mathrm{US}} + r^*_{t,\mathrm{US}})$ = expected change in the US composite variable
$(d_1 - 1)\sigma_{r,t}$ = volatility of German domestic interest rate (interacted with the dummy)
CA = German current account of the balance of payments (in DM)
Δp_t = German consumer price inflation
$Y_{c,t}$ = German cyclical income

NOTES

1. See, for example, Herring and Marston (1977a,b) and Obstfeld (1982,1983).
2. See, for example, Kouri (1975), Neumann (1978), Neumann (1984), Kamas (1986) and Pasula (1994) on the offset equation; and Kearney and MacDonald (1986), Hutchison (1988), Mastropasqua *et al.* (1988) and von Hagen (1989) on the estimation of reaction functions and the degree to which central banks sterilize.
3. The only exception to our knowledge is Argy and Kouri (1974) who estimate a capital flow equation and a sterilization equation jointly as a system using two-stage least squares.
4. Roubini (1988) also examines the authorities' decision within a loss-minimizing framework. His framework, however, differs significantly from ours in that, *inter alia*, the authorities have only one policy instrument at their disposal, domestic credit. Foreign exchange reserves enter as an argument in the loss function and hence only a reaction function specifying optimal sterilization can be derived.
5. Should the central bank want to encourage exchange rate volatility in order to introduce uncertainty into the minds of speculators, then ε would be negative. Such a situation might arise if a tight monetary policy and a stable exchange rate are causing large capital inflows as domestic residents find it cheaper to borrow abroad. In this case, increased exchange rate volatility can help to reduce the inflows since it introduces uncertainty about the actual cost of the funds borrowed from abroad. We do not constrain ε to be positive in the empirical work.
6. See EMI (1997) for a very clear and comprehensive account of central bank objectives with respect to monetary policy and the means by which they are achieved in EU countries.
7. Volatility can also be undesirable because of the effects it has on investment flows and trade or because of the potential spillover effects on domestic financial markets (Bonser-Neal, 1996).
8. Dominguez and Frankel (1993) examine in some detail intervention by the Fed in the period 1985–88, distinguishing sterilized from non-sterilized intervention, coordinated from uncoordinated, frequent from rare, announced from unannounced and initial interventions from subsequent. Overall, they conclude that intervention does seem to work especially initial and coordinated interventions. Likewise, Edison (1993) and Humpage (1991) conclude their reviews of the literature by arguing that the evidence does provide support for a short-term effect from intervention. More specifically, with respect to volatility, Dominguez (1993) finds that overall Fed intervention in the dollar–DM and dollar–Yen markets reduced volatility in the period 1985–91 as a whole while the results for Bundesbank intervention are more mixed. These results contrast with those of Bonser-Neal (1996).
9. $\beta(p_t - p^T_t)$ becomes $\beta[(p_t - p_{t-1}) - (p^T_t - p_{t-1})] = \beta(\Delta p_t - \Delta p^T_t)$.
10. Previous authors examining the Bretton Woods period assume that exchange rates were completely fixed even though there was a band around dollar rates. This assumption allows them to estimate the offset coefficient using a private capital flow equation (see above). The current account is often ignored for simplicity. If the exchange rate is completely fixed, then any private capital inflow is identical to the degree of offset because the inflow leads to an equal and opposite change in central bank foreign exchange reserves. If the central bank, by contrast, allows the exchange rate to move within a band (or realigns) as well as intervening, then the capital inflow following the monetary tightening will not be identical to the change in foreign exchange reserves. In this case, the

offset coefficient (which is the change in foreign exchange reserves following a change in the domestic component of the money supply) cannot simply be measured by substituting capital flows for the change in foreign exchange reserves.

11. This assumption simplifies the algebra and does not alter the general results derived below.
12. Thus when the money market is in deficit, the central bank is injecting funds and ΔNDA_t is positive. With d_1 equal to 0, $(\Delta NDA_t - d_1 \Delta NDA_t)$ is positive and hence intervention is negatively related to volatility by virtue of the negative sign in front of ζ. When the money market is in surplus, the central bank is withdrawing funds and ΔNDA_t is negative. With d_1 equal to 2, $(\Delta NDA_t - d_1 \Delta NDA_t)$ is again positive and intervention once more is negatively related to volatility.
13. Attempts to determine whether the extent to which the degree of sterilization differed (a) over the period or (b) between large and small changes in foreign exchange reserves or (c) between outflows and inflows does not produce significant results.
14. It has to be noted that Von Hagen's division of the change in foreign exchange reserves into interventions in dollars and other currencies is a somewhat imprecise since he does not use actual intervention data. He derives estimates of intervention in European currencies from European Monetary Cooperation Fund data. Dollar interventions are then calculated as the residual (the total change in reserves minus intervention in European currencies).
15. These changes are reversed automatically because the transitory component includes instruments such as repos.
16. Since the logarithm of the exchange rate is I(1), we use the change to get a better measure of volatility.
17. Interest rates are I(0) over the period and hence it is valid to calculate volatility from the level of the interest rate rather than its change. The results are unaffected by this.
18. There is therefore no danger of deriving spurious regression results owing to both dependent and independent variables being highly trended.
19. It is not possible to perform the usual tests on the three-stage least squares estimates. The presentation of test statistics on the two-stage least squares estimates is intended to be indicative.
20. It should be noted that these results represent a re-estimation of the three-stage results presented below. For that reason, some variables are included which are not significant here.
21. The coefficients of variation on ΔNDA and ΔNFA are 3.11 and 14.88 respectively. For inflation, the figure is lower at 0.67. The insignificance of income and inflation could be evidence that the central bank cares only about the exchange rate target, exchange rate volatility and interest rate volatility. However, in the absence of estimates of the structural parameters and especially the weights in the loss function, we cannot be sure of such a conclusion.
22. We present in Tables 1 and 2 the results using the intra-quarter standard deviation calculated from the daily exchange rate data. The results using the moving average measure were very similar (the volatility of the DM–French franc exchange rate was significant instead of the DM–lira rate as in Tables 1 and 2). It should be noted that the correlation between the various volatility measures is high, making it difficult to get all measures significant in the same equation.

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