The Coordination Channel of Foreign Exchange Intervention: A Nonlinear Microstructural Analysis

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ABSTRACT

The coordination channel has been proposed as a means by which foreign exchange market intervention may be effective, in addition to the traditional portfolio balance and signaling channels. If strong and persistent misalignments of the exchange rate are caused by non-fundamental influences, such that a return to equilibrium is hampered by a coordination failure among fundamentals-based traders, then central bank intervention may act as a coordinating signal, encouraging stabilizing speculators to re-enter the market at the same time. We develop this idea in the framework of a simple microstructural model of exchange rate movements, which we then estimate using daily data on the dollar-mark exchange rate and on Federal Reserve and Bundesbank intervention operations. The results are supportive of the existence of a coordination channel of intervention effectiveness.

JEL classification: C10; F31, F41
Keywords: foreign exchange intervention; coordination channel; market microstructure; nonlinear mean reversion

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1 Introduction

When monetary authorities engage in active exchange rate management, they do so by conducting occasional foreign exchange market interventions, which can be defined as sales or purchases of foreign currency in order to influence the future path of the exchange rate (Neely, 2000; Schwartz, 2000). It is common practice among central banks to sterilize the impact of foreign exchange market interventions on the monetary base (Taylor, 1992; Dominguez and Frankel, 1993; Weber, 1994). Given that the impact of intervention on the domestic money supply is typically neutralized, the question arises as to how sterilized intervention can affect exchange rates. Since Mussa (1981), the academic literature has traditionally distinguished two channels through which sterilized intervention may be effective: the 'signaling channel' and the 'portfolio balance channel'. However, the poor empirical evidence on both of these channels, as on traditional economic models of foreign exchange rate behaviour more generally, suggests that there may be other forces at play (Taylor, 1994, 2004, 2005; Sarno and Taylor, 2001).

As a result, recent studies investigating the effectiveness of central bank intervention have increasingly made use of the market microstructure approach to exchange rates (Lyons, 2001), where market makers' adjustment of exchange rates depend on whether or not the order flow comes from informed traders (Mende et al., 2005). In these models, while order flow from informed traders is expected to change the exchange rate, uninformed traders' activity does not affect market makers' price-setting behavior. In addition, if the analysis is extended to a multiple dealer model, an informational asymmetry occurs between market makers (Lyons, 1997). Within this asymmetric information framework, central banks are perceived to be informed traders, implying that official intervention should alter exchange rates through a process of information dissemination. Empirical support for the market microstructure approach to intervention effectiveness is provided by Peiers (1997), who reports on the price leadership of Deutsche Bank, reputedly one of a small number of few market makers used for the Bundesbank's intervention operations. Given the available information technologies on financial markets, however, the dissemination of information through foreign exchange order flow may be a matter of just a few hours. From this point of view, it is not surprising that Dominguez (2003) finds the influence of Federal Reserve intervention to be concentrated in approximately the first three hours following the submission of the central bank's order, with the exchange rate subsequently reverting to the pre-intervention level. In line with the propositions of the market microstructure approach, trading volume and new information on fundamentals both affect the sustainability of intervention operations, but generally not permanently. Applying event study methodology, Fatum and Hutchison (2003) provide limited support for the effectiveness of intervention, concluding that intervention may signal central banks' views on the fundamental value of the exchange rate but cannot substitute for more fundamental policy actions.

Given that neither the traditional transmission channels nor more recent approaches to central bank intervention appear to account for prolonged effects on exchange rates (prolonged, that is, beyond a few hours), a further channel of influence, the coordination channel, has been proposed (Taylor, 1994 2004, 2005; Sarno and Taylor, 2001), whereby central bank intervention may be seen as resolving a coordination failure in the foreign exchange market. Given the prevalence of non-fundamental influences in the foreign exchange market such as technical analysis, as well as the general heterogeneity and diversity of opinion even among traders basing their analysis on economic fundamentals (Allen and Taylor, 1990; Taylor and Allen, 1992; Cheung and Chin, 2001), there may be periods in which the exchange rate moves strongly and persistently away from the fundamental equilibrium level. Kilian and Taylor (2003), for example, sketch a simple model whereby technical or chartist traders, who base their forecasts on extrapolations, tend to dominate so long as the exchange rate is within the broad range of estimates provided by fundamentalists, since the latter group will be characterized by disagreements concerning directional as well as point forecasts of the exchange rate while the exchange rate is within this range. Once the exchange rate moves outside the range of most fundamentalists' estimates of the fundamental equilibrium, however, a consensus develops among fundamentalists concerning directional forecasts (e.g. they mostly agree that the currency is overvalued, even if they disagree as to the extent of the overvaluation).[1] At this point, however, since fundamentalists' trades based on their own forecasts would have been extremely unprofitable in the immediate past, during which time the non-fundamentalist traders held sway, the fundamentalists will have lost either lost confidence, or lost credibility with their managers, or exhausted their liquidity, or all three (Shleifer and Vishny, 1997). This therefore deters fundamentalist traders from entering the market and trading on a fundamentals-based forecast, even though they know that if they were all to enter the market together, they would force a return of the exchange rate to a level consistent with fundamentals. In other words, the market suffers from a coordination failure (Howitt, 2003). The central bank, perceiving this situation, then enters the market and announces its intervention, effectively acting as a coordinating signal to the fundamentalists, who follow it into the market, returning the exchange rate to a level to a level consistent with the economic fundamentals.[2] This is the coordination channel of intervention effectiveness.

The course of the US dollar during the 1980s can be viewed as a case study for the role of publicly announced intervention as a coordinating signal. A traditional interpretation of the macroeconomic fundamentals clearly reveals a drastically overvalued US dollar by the end of 1984, yet it took a policy of concerted intervention, publicly announced at the Plaza Agreement of the G5 Finance Ministers in February 1985, to prick the irrational bubble

[1] In the model of De Grauwe and Grimaldi (2006), a similar effect is created by assuming that there is an exchange rate band, determined by transactions costs in goods arbitrage, outside of which informed traders assume that the exchange rate will revert to its fundamental equilibrium but within which they forecast no change in the exchange rate (i.e. they assume a random walk in the level).

[2] Although they do not emphasis the role of central bank intervention as a coordinating signal, similar models of interaction between fundamentalists and non-fundamentalists (or, more generally, between informed and uninformed traders) have been proposed by Frankel and Froot (1987, 1990), Goodhart (1988), Shleifer and Vishny (1997) and, more recently, De Grauwe and Grimaldi (2005, 2006).

(Frankel and Froot, 1986, 1990a, 1990b).

Even if the role of the monetary authorities in providing a coordinating signal in the foreign exchange market seems clear, however, the question arises as to why a central bank should resort to interventions in the foreign exchange market rather than simply to a transparent communication and information policy in pursuing its coordinating strategy. There is, of course, nothing in the above reasoning that precludes central bankers using policy announcements *in addition* to intervention operations as a coordinating signal (as was the case, for example, with the 1985 Plaza Accord), but the question remains as to why intervention operations are necessary in addition to (or in place of) announcements. As with the signaling channel of intervention effectiveness, it has to be borne in mind that central banks may be beleaguered by credibility problems which can only be resolved by resorting to monetary policy actions such as interventions. Such actions underscore the fact that monetary authorities follow a policy of *"putting their money where their mouth is"* and stand ready to act on the intervention signal (Mussa, 1981). On the other hand, as central bank credibility and transparency increases, one would perhaps expect to see less reliance on intervention. From this perspective, given the Bank of England's shift to a transparent policy of inflation targeting in 1992 and full independence in 1997, it is perhaps, not surprising that the UK authorities have not intervened over the past decade. On the other hand, while the newly established European Central Bank was seeking to establish its credibility, it is not surprising that it not infrequently resorted to intervention operations.

Using a Markov regime-switching model of the real exchange rate and intervention data from the Federal Reserve, the Bundesbank and the Bank of Japan, Taylor (2004, 2005) provides some supporting evidence for the coordination channel of intervention effectiveness, showing that intervention operations increased the switching probability from the unstable to the stable state in the 1980s for dollar-mark and dollar-yen, and that the probability of an intervention switching the exchange rate into the stable state increased with the size of the deviation of the exchange rate from the fundamentals-based equilibrium (based on purchasing power parity). In this paper, we use a more direct testing strategy to investigate empirically the coordination channel. First, we explicitly use a simple theoretical market microstructure framework to model the (smooth) transition between stable and unstable regimes, from which we develop an empirical model in which we find that the speed of mean reversion of the exchange rate does indeed slow as the exchange rate deviates from its equilibrium value until, when misalignment is sufficiently large, the system becomes locked in an unstable regime. Second, within this empirical framework, we investigate the role of reported intervention as a driving variable in the transition between the stable and unstable regimes.[3] We find that reported intervention does indeed appear to govern the transition between regimes, although it does not appear to influence the level of the exchange rate directly, while secret intervention operations appear to have no discernible effects. Our empirical results are therefore supportive of the existence of a coordination channel of intervention effectiveness.

The remainder of the paper is organized as follows. In Section 2, we develop our microstructural model of the foreign exchange market and of the coordination channel of intervention effectiveness, focusing on the order submission behavior of stabilizing speculators. In Section 3 we develop an empirical model, informed by our theoretical analysis and recent empirical work on nonlinear exchange rate adjustment. In the following section, we describe our daily data set on German mark-US dollar exchange rates, intervention and fundamentals, while in Section 5 we present our main empirical results concerning intervention effectiveness. In Section 6 we report the results of robustness checks on the

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[3] In contrast to Taylor (2004, 2005), we model daily exchange rate dynamics and so avoid averaging the effectiveness by cumulating intervention operations to a monthly frequency. In addition, the *direction* of intervention is considered---Taylor (2004, 2005) only considers the amount of intervention, regardless of direction. Considering the direction of investment is important because, for instance, central bank purchases of an overvalued currency may puzzle traders and may lead to a loss in confidence in fundamental analysis. As a result, our estimation strategy allows for investigating the influence of intervention using original intervention

empirical model. In particular, we examine whether intervention effectiveness operates via its effect on informed traders' confidence in fundamentals (as the coordination channel suggests) or more directly, and whether only reported (as opposed to secret) interventions should affect exchange rates (as the coordination channel also suggests). In a final section, we make some concluding remarks and suggestions for future research.

2 A Microstructural Model of the Coordination Channel

To study the effectiveness of central bank intervention in the conceptual framework of the coordination channel, we assume that exchange rates are determined in an order-driven market populated by heterogeneous agents (Bacchetta and van Wincoop, 2006; De Grauwe and Grimaldi, 2005, 2006). Demand for currency is expressed in terms of market orders, i.e. traders ask for an immediate transaction at the best available price. All orders are filled by the market maker at an exchange rate that is shifted from the previous exchange rate by an amount that depends on the excess demand of traders (Kyle, 1985; Evans and Lyons, 2002). At first glance, the Kyle structure of the model may appear inappropriate because it posits a batched and centralized trading structure, whereas real-world foreign exchange markets are decentralized dealer markets (Sarno and Taylor, 2002). However, as Vitale (1999) points out, the batch structure may serve as a proxy for the prevailing lack of transparency.

Assuming a log-linear price-impact function, the change in the exchange rate at time t+1 may be expressed as a function of net order flow from informed and uninformed trades, plus a noise term:

$$s_{t+1} = s_t + a^M \left(D_t^I + D_t^U\right) + \varepsilon_{t+1}, \tag{1}$$

where s_t is the logarithm of the spot exchange rate at time t, defined as the price of home currency in units of foreign currency, and a^M is a positive reaction coefficient determined by

data without loss of information.

the market maker. D_t^I and D_t^U denote the net order flow from informed and uninformed speculators, respectively. The exchange rate depends on the *net* order flow from informed and uninformed speculators because the market maker does not observe them individually. Due to this trading protocol we may distinguish three sources of exchange rate variation. Firstly, the noise term ε_{t+1} captures publicly available information that directly affects the market maker´s price-setting decision. Secondly, public news may operate via induced order flow and thirdly, exchange rate variation may be caused by order flow that is unrelated to publicly available news. Evans and Lyons (2003) find that all three sources significantly account for observed exchange rate changes; in particular, they find at the daily frequency one third of the price variation from publicly available macro news seems to be directly and immediately incorporated, while two thirds are transmitted via order flow.[4]

Orders are submitted by risk-neutral speculators and depend on expected excess returns. Expected excess returns on foreign exchange markets consist of the expected change in the exchange rate and on the interest differential. When calculating expected exchange rate changes, however, speculators differ with respect to the information set upon which their expectations are conditioned.

Orders from uninformed traders D_t^U are not derived from a mathematically well-defined econometric or economic model and are perceived to be largely uninformative regarding the equilibrium value of the exchange rate that is consistent with the underlying economic fundamentals. Since such traders' investment strategies are perceived to be a major source of systematic forecasting errors, the term "noise trader" has become a familiar description in the analysis of financial markets literature over the past two decades (Black, 1986). In the Kyle model, uninformed traders complicate the market maker's inference of the equilibrium value from the order flow, which, in contrast, allows informed traders to

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[4] Dominguez and Panthaki (2005) provide further supporting evidence on the relevance of all three sources of

camouflage their information-revealing orders. In real-world financial markets, uninformed traders may correspond to chartists or technical traders (Allen and Taylor, 1990; Sager and Taylor, 2006). Although there exists a remarkable number of different chartist or technical trading rules, these forecasting devices generally rely on historical exchange rates. Their practical importance is confirmed by the market survey studies of Allen and Taylor (1990), Taylor and Allen (1992) and Cheung and Chinn (2001), which reveal that up to 30% of traders are best characterized as technical traders. In addition, there is some evidence that technical traders may generate persistent risk-adjusted profits (Levich and Thomas, 1993; LeBaron, 1999; Qi and Wu, 2006). Given that an important element of technical trading relies on trend-following, extrapolative methods (Taylor and Allen, 1992), we model uninformed traders' orders as a positive function of the recent return, plus a term in the interest differential:

$$D_t^U = a^U \left(s_t - s_{t-1}\right) + b^U (i_t^* - i_t)\,, \tag{2}$$

where i_t^* and i_t represent the interest rates of foreign and home currency deposits, respectively. The parameter a^U is expected to be positive. The expected sign of b^U, however, is not immediately clear. According to uncovered interest rate parity (UIP), the interest differential $(i_t^* - i_t)$ should be an unbiased predictor of the percentage change in the exchange rate, $\left(s_{t+1} - s_t\right)$. Equivalently, given that covered interest rate parity (the condition that the interest differential is just equal to the forward premium) is known to hold closely, at least among eurodeposit interest rates (Taylor, 1987, 1989), UIP implies that the forward exchange rate should be an unbiased predictor of the spot rate. If uninformed traders believed in UIP, therefore, one would expect b^U to be positive. However, the failure of UIP (equivalently, the failure of forward rate unbiasedness) is so well documented as to have established itself as a stylized fact (Froot and Thaler, 1990; Taylor, 1995), and it seems that, if anything, there is a

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exchange rate changes.

tendency among traders to bet against UIP using various 'forward-rate bias' trading strategies (Fabozzi, 2001; Rosenberg, 2003), which would suggest a negative sign for b^U.[5] Overall, therefore, the sign of this coefficient is ambiguous.

Informed traders base their expectations about future exchange rate changes on an analysis of exchange rate fundamentals. In general, this boils down to the calculation of a time-varying long-run equilibrium value, f_t say, towards which the exchange rate is expected to revert over time, although the weight attached to the deviation from fundamentals in determining orders may vary over time. Thus, informed traders' orders may be expressed as

$$D_t^I = a^I w_t \left(f_t - s_t \right) + b^I (i_t^* - i_t) , \tag{3}$$

where a^I is a positive reaction coefficient and w_t determines the weight attached by informed speculators to deviations of the exchange rate from its fundamental equilibrium level, $0<w_t<1$. As before, the sign of the coefficient on the interest differential, b^I, is ambiguous.

According to equation (3), so long as $w_t>0$, the actions of informed traders amount to stabilizing speculation in the sense that it will tend to drive the exchange rate towards its equilibrium value. The finite speed of adjustment a^I (for given w_t) may be rationalized by the fact that informed traders are aware of the uniformed traders' destabilizing influence on exchange rates (DeLong et al., 1990). Alternatively, informed traders may recognize that closing their open positions moves the exchange rate in the opposite direction and so the adjustment has to be gradual (Osler, 1998).

Since the basis for the coordination channel of intervention effectiveness is the time-varying influence of stabilizing speculation on exchange rates through its effect on informed traders' confidence, the informed traders' reaction coefficient a^I has to be adjusted by a variable w_t ranging between zero and unity. In the following, we construct w_t as a measure of speculators' confidence in fundamental analysis as basis for their trades.

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[5] The act of buying high-interest rate currencies is also referred to in the markets as a 'carry trade'—see e.g.

The precise notion of confidence that w_t is designed to capture is worthy of further comment. Firstly, if the distance between the exchange rate and its equilibrium value increases, fundamental analysis wrongly predicts the sign of the exchange rate change. The gap $\left(f_t - s_t\right)$ may thus represent a temporary deviation exploitable for speculative purposes. However, if the exchange rate is trending away from the fundamental equilibrium, then traders face a fundamental risk (Figlewski, 1979) and betting against the trend may be associated with substantial losses. Informed traders thus become increasingly reluctant to submit orders (Shleifer and Vishny, 1997). Conversely, if misalignments decrease, fundamental analysis delivers correct predictions and regains its popularity. The ability of current misalignments to signal shifts in the equilibrium value is diminished by noise. Misalignments from high-volatility (high signal-to-noise ratio) periods are less informative than those from low-volatility (low signal-to-noise ratio) periods (De Grauwe and Grimaldi, 2006). It therefore seems reasonable to postulate that standardized absolute misalignment influences traders' confidence. Secondly—and crucially from the point of view of the coordination channel—we allow the trading activity of central banks in the foreign exchange market to influence informed traders' confidence in fundamental analysis. If a central bank sells a currency that is widely perceived to be overvalued, it reveals its commitment to a lower exchange rate. In the market microstructure literature, central banks are perceived to have superior information about the exchange rate's fundamental value, because they observe innovations in fundamental data series in advance and are able to assess their impact on future exchange rate returns (Sager and Taylor, 2006). Informed traders then become more confident that the exchange rate will revert to its fundamental value and engage in trading. The market increasingly focuses on fundamentals, so interventions may be viewed as a device with which to coordinate traders' expectations.

As argued by Taylor (2004, 2005), the influence of intervention operations on traders'

Galati and Melvin (2004).

confidence through the coordination channel should depend on the level of current misalignment. In the neighborhood of the fundamental value, the potential stabilizing gains of interventions should be negligible because informed traders will interpret small misalignments as temporary phenomena exploitable for speculative purposes and will trade intensively in the market. If the misalignment is large, however, intervention will tend to be more effective, because informed traders who have reduced their orders because of a loss in confidence in the fundamentals may by encouraged by the central bank intervention. Finally, it must be noted that buying an overvalued currency would puzzle informed traders and perhaps drive them out of the market. To capture these misleading signals, we set an indicator variable equal to –1 if the exchange rate is overvalued and equal to +1 if it is undervalued according to the measure of the fundamental equilibrium. Multiplying the indicator variable by the current sale or purchase provides us with an intervention measure (int_t) that is positive only if the central bank operates in the appropriate direction.

Following the above line of argument, informed traders' confidence in the fundamentals can be expressed as a function of the standardized absolute misalignment and the intervention of the central bank:

$$w_t = \frac{2\,exp(c_t)}{1 + exp(c_t)}, \tag{4}$$

where

$$c_t = -(\varphi_1 - \varphi_2\, int_t)\frac{|\, f_t - s_t \,|}{\sigma_t^S}, \tag{5}$$

and where σ_t^S denotes the conditional standard deviation of exchange rate movements. As central banks' intervention operations will not be able completely to eliminate informed traders' lack of confidence, we assume $\varphi_1 > \varphi_2\, int_t$, which means the value of c_t lies on the interval (–∞, 0). A logistic normalization transforms the value c_t into a confidence measure w_t

ranging between 0 and 1.[6]

Combining equations (1)–(5), the solution for the exchange rate emerges as

$$s_{t+1} = s_t + \alpha(s_t - s_{t-1}) + \delta w_t(f_t - s_t) + \gamma(i_t^* - i_t) + \varepsilon_{t+1}, \tag{6}$$

with $\alpha = a^M a^U > 0$, $\delta = a^M a^I > 0$, and $\gamma = a^M(b^U + b^I)$, the sign of γ being ambiguous.

From equation (6) we can see that, for a given value of δ, informed traders' stabilizing impact on the exchange rate increases nonlinearly with their confidence in fundamental analysis. If, for instance, the exchange rate is near its fundamental equilibrium value, informed traders provide maximum mean reversion, since w_t will be close to unity. However, as the exchange rate becomes increasingly misaligned, informed traders reduce their orders and mean reversion weakens. This creates a role for central bank intervention which, though its coordinating influence on informed traders, effectively raises their confidence in the fundamentals and generates an increase in the degree of mean reversion of the nominal exchange rate towards the fundamental equilibrium.

We now turn to empirical implementation of the model.

3 The Empirical Model

Our aim is to investigate empirically the role of central bank intervention through an investigation of the nonlinear theoretical exchange rate model outlined in the previous section. Our empirical model belongs to the STAR (Smooth Transition Autoregressive) family of models originally proposed by Ozaki (1985) and further developed and analyzed by Teräsvirta and Anderson (1992), Granger and Teräsvirta (1993) and Teräsvirta (1994). STAR models allow an economic variable to follow a given number of regimes, with switches between regimes achieved in a smooth and continuous fashion and governed by the value of a particular variable or group of variables. The STAR framework has previously proved

[6] The logistic form of (4) was suggested by the switching mechanism of Brock and Hommes (1997) and Lux (1998) and is in the spirit of recent work by De Grauwe and Grimaldi (2005, 2006), who develop a similar

successful in applications to exchange rate behavior (Taylor and Peel, 2000; Taylor et al., 2001; Kilian and Taylor, 2003).[7]

In order to examine the empirical evidence of the market microstructure model we shall use daily data, implying that the conditional variance of exchange rate returns cannot be treated as constant over time. To cope with the heteroskedastic properties of daily exchange rate returns, we therefore apply the STAR-GARCH procedure originally developed by Lundbergh and Teräsvirta (1998) and applied by Gallagher and Taylor (2001) and Reitz and Westerhoff (2003). The STAR-GARCH model consists of a mean equation containing a smooth transition function and a standard GARCH(1,1) volatility equation. In the present context, given the theoretical model outlined above, this suggests an empirical model of the form:

$$\Delta s_t = \alpha \Delta s_{t-1} + \delta\, w_t\left(\varphi; f_{t-d} - s_{t-d}; \mathrm{int}_{t-1}; h_{t-d}\right)\,\left(f_{t-1} - s_{t-1}\right) + \gamma(i^*_{t-1} - i_{t-1}) + \varepsilon_t \tag{7}$$

$$w_t\left(\varphi; f_{t-d} - s_{t-d}; \mathrm{int}_{t-1}; h_{t-d}\right) = \frac{2\exp\left(-\left(\varphi_1 - \varphi_2\,\mathrm{int}_{t-1}\right)\frac{|\,f_{t-d} - s_{t-d}\,|}{\sqrt{h_{t-d}}}\right)}{1 + \exp\left(-\left(\varphi_1 - \varphi_2\,\mathrm{int}_{t-1}\right)\frac{|\,f_{t-d} - s_{t-d}\,|}{\sqrt{h_{t-d}}}\right)} \tag{8}$$

$$h_t = \beta_0 + \beta_1 \varepsilon^2_{t-1} + \beta_2 h_{t-1}, \tag{9}$$

where Δ is the first-difference operator, $\varphi = (\varphi_1, \varphi_2)$, $\varepsilon_t = \nu_t \cdot \sqrt{h_t}$ and $\nu_t \overset{iid}{\sim} N(0,1)$. The major differences between the empirical model (7)-(9) and the theoretical model set out in the previous section thus lies in our introduction of a GARCH model to capture the conditional standard variance of the error term and in an allowance for a delay in the influence of standardized misalignment on the confidence measure $w_t(\varphi; f_{t-d} - s_{t-d}; int_{t-1}; h_{t-d})$. This

switching function in their model of chartist-fundamentalist interaction.

[7] De Grauwe and Grimaldi (2001) apply a quadratic specification to model deviations of the exchange rate from fundamental equilibrium, which can be interpreted as an approximation to a STAR specification.

confidence measure is itself bounded between zero and unity. It depends on the sign and magnitude of interventions (*int*$_t$) as well as on a standardized measure of the perceived deviation from the fundamental equilibrium, $\left|f_{t-d} - s_{t-d}\right| / \sqrt{h_{t-d}}$, where the conditional standard deviation in (5) is explicitly modeled in (9) as a GARCH(1,1) process, ie. $\sigma_t^S = \sqrt{h_t}$.

We allow in our empirical model for a value of the delay parameter, *d,* different from one since the importance of searching for an appropriate value of the delay parameter in empirical applications of STAR models has been stressed by Teräsvirta and others (e.g. Teräsvirta and Anderson, 1992; Granger and Teräsvirta, 1993; Teräsvirta, 1994). In our empirical implementation, it turns out, however, that a value of the delay parameter of unity was in fact selected, exactly consistent with our theoretical model.

4 Data

We use daily spot US dollar exchange rates against the Deutsche Mark (DM) to calculate percentage exchange rate returns as $100 \cdot \Delta s_t$. The price of one US dollar is expressed in German marks. In terms of the preceding discussion, therefore, the US is taken as the home economy and Germany as the foreign economy. The home interest rate is thus i_t^{US} , the overnight US dollar eurodeposit interest rate, and the foreign interest rate is i_t^{DM} , the overnight eurodeposit DM interest rate.

We assume that the fundamental equilibrium value of the exchange rate, f_t, can be adequately described by a measure of the purchasing power parity (PPP) level, based on relative consumer prices. Takagi (1991) provides evidence from survey data that foreign exchange market participants accept PPP as a valid relationship in the long run and that estimates of the PPP level are frequently taken as an indication of “fair value” (Rosenberg, 2003). This view is also supported by recent research that suggests that the exchange rate reverts to the PPP level, but only in the long run (Rogoff, 1996).[8] Furthermore, PPP as a measure of the fundamental exchange rate f_t seems to be suited to investigate central bank intervention, because monetary authorities have in the past used it as a target level (Dominguez and Frankel, 1993; Neely, 2002, 2005a). Monthly observations of consumer price indices (CPIs) for the US and Germany were taken from the International Monetary Fund's International Financial Statistics database to construct a measure of the PPP fundamental as $\log\left(CPI_t^{DM}\right) - \log\left(CPI_t^{US}\right)$. A problem in applying this measure to an empirical model involving daily data is that observations on the consumer price indices are only available at the monthly frequency. Accordingly, we transformed the PPP fundamental series to daily frequency by taking the latest published value of the CPI indices as valid for the entire following month, which seems to be compatible with the information environment of a market participant in a daily trading context.[9] The PPP fundamental was normalized to be equal to the nominal exchange rate at the beginning of January 1990, although we effectively relaxed this normalization by allowing a shift parameter θ in our estimations, such that $f_t = ppp_t - \theta$. The estimated value of θ was, however, in no case significantly different from zero at the five percent level, and so we omitted it in our final estimations.

Daily log exchange rates and our measure of the PPP fundamental are represented in the upper panel of Figure 1.

[Figure 1]

[8] There is strong evidence, moreover, that this mean reversion may be nonlinear (Taylor and Peel, 2000; Taylor et al., 2001; Kilian and Taylor, 2003).

[9] To check whether or not the estimation results are driven by this simplifying assumption we experimented with linearly interpolated data. However, the estimation results do not change significantly.

With the monetary tightening under the Federal Reserve Chairman Paul Volcker, the rise in US interest rates increased the relative attractiveness of dollar assets from the perspective of global investors in the early part of our sample. Subsequently, the US dollar experienced a real appreciation that was accompanied by growing current account imbalances. From mid-1984 to early 1985, the US dollar gained another 20 percent, even though the interest differential started to decline. This prompted the widespread conclusion that the US dollar was following a bubble-path and policy makers started to rethink the merits of flexible exchange rates. The upward trend of was effectively reversed when finance ministers and central bank governors decided at the Plaza Hotel in September 1985 to bring down the dollar.

We use Federal Reserve and Bundesbank intervention data in order empirically to investigate the coordination channel. As can be seen in the lower panels of Figure 1, interventions by both the Federal Reserve and the Bundesbank were sporadic and clustered over the sample period. The percentage of trading days in which intervention occurred is 0.134 for the Federal Reserve and 0.249 for the Bundesbank, respectively. The average Federal Reserve intervention was –2.1 million dollars, indicating a near balance between purchases and sales. In contrast, the Bundesbank sold dollars in this period, the average intervention being DM – 26.56 million. Conditional on the occurrence of intervention, the mean absolute value of purchases or sales is US$ 112.1 million of the Federal Reserve and DM 158.3 million of the Bundesbank. Our sample ends at December 1992, because there was little intervention activity during the Clinton administration.

5 Estimation Results

The modeling procedure for building STAR models was carried out as suggested by Granger and Teräsvirta (1993) and Teräsvirta (1994). First, linear autoregressive models were estimated in order to choose the lag order of the autoregressive term on the basis of the Bayes Information Criterion criterion. We found that first-order autocorrelation seemed to be appropriate for exchange rate returns in our data. Second, we tested linearity against the STAR model for different values of the delay parameter d, using the linear model ($w_t = 1$, for all t) as the null hypothesis and choosing the value of d that gives the smallest marginal significance level (Granger and Teräsvirta, 1993).[10] The transition parameters φ_1 and φ_2 are slope parameters that determine the speed of transition between the two extreme regimes, with low absolute values resulting in slower transition. Since (8) is a linear transformation of the standard logistic transition function as proposed by Teräsvirta and Anderson (1992), robust standard errors may be derived. This is important because conditional normality cannot be maintained. Under fairly weak regularity conditions, however, the resulting robust estimates are consistent even when the conditional distribution of the residuals is non-normal (Bollerslev and Wooldridge, 1992). Teräsvirta (1994) points out that estimating the transition parameters φ_i may cause particular problems such as slow convergence of the estimation routine or overestimation, and suggest setting the initial value of the transition parameter equal to the reciprocal of the sample variance of the transition variable in the iterative estimation procedure. However, the recommended rescaling of the transition variable by means of the conditional standard deviation has already been introduced for theoretical reasons. On the basis of this standardization, we therefore set $\varphi_1 = 1$ and $\varphi_2 = 0$ as the starting values for the estimation routine. Table 1 contains our final estimation results.

[Table 1]

The estimation results are pleasing in the sense that the point estimates of the coefficients are significantly different from zero and appropriately signed and the estimated

[10] Checking the standardized residuals of the model reveals that setting $d = 1$ passes the test for no remaining nonlinearity up to ten lags using the specification test of Eitrheim and Teräsvirta (1996).

model passes a number of diagnostic checks for remaining serial correlation, nonlinearity or conditional heteroscedasticity in the standardized residuals.

We also tested the model against a restricted model in which $\delta = \gamma = \varphi_1 = \varphi_2 = 0$, so that the constrained model became a simple AR(1)-GARCH(1,1) model. The resulting test statistic, *LRT*, is reported in Table 1, and reveals that the simple AR(1)-GARCH(1,1) model is rejected against our STAR-GARCH model at the one percent significance level.

Although, the point estimates of the uninformed trader and informed trader coefficients accord with our theoretical priors, the significantly negative point estimate of the interest rate differential coefficient implies—on average—an appreciation of the dollar if US interest rates are higher than German interest rates. Given our discussion of the likely sign of the coefficients b^U and b^I in Section 2, however, this is not surprising.

Statistically significant point estimates of φ_1 indicate moderate transition between regimes with respect to the standardized misalignment. The interpretation in terms of our model is straightforward. If the exchange rate converges towards the PPP value—as predicted by fundamental analysis—informed traders gain confidence in fundamental analysis and trade more heavily in the market. But, the more the exchange rate deviates from PPP, the more reluctant informed traders are to submit speculative orders. These related dynamics are represented in Figure 2, where the percentage deviation of the exchange rate from the PPP fundamental and the implied simulated mean reversion parameter are plotted from January 1980 to December 1992.[11]

[Figure 2]

[11] The simulated mean reversion parameter is calculated as $\rho = \delta w_t \cdot 100$.

Figure 2 shows that the strong appreciation of the dollar starting in the early 1980s is associated with a significant decline of the mean reversion parameter. The upward trend of the exchange rate is reversed in 1985 when the mean reversion parameter reaches its lowest level.

The statistically significant parameter φ_2 indicates that an intervention operation compensated for the lack of confidence caused by exchange rate misalignments. The numbers suggest that at the average level of exchange rate volatility, a 20% misalignment results in a daily mean reversion towards fundamentals of 0.24%, or well in excess of 1% on a weekly basis. Under these circumstances an intervention operation of US$ 200 million increases the mean reversion parameter to 0.5%. The doubling of mean reversion by a slightly larger than average intervention operation indicates an economically significant contribution by the Federal Reserve. From the model's perspective, Federal Reserve interventions encouraged agents to engage in fundamental speculation, thereby helping to bring the exchange rate back to the PPP level. In line with the analysis of Taylor (2004, 2005) the stabilizing influence of intervention increases as the real exchange rate moves away from its equilibrium level and misalignment grows. Using the above numbers, a US$ 200 million intervention increases mean reversion from 0.76% to 0.86% if the misalignment is 5% and from 0.04% to 0.19% if the misalignment is 40%.

Although this degree of reversion of the exchange rate towards fundamentals may seem small, put into the context of the empirical literature on exchange rate adjustment it is, in fact, very high, especially when one notes that they are expressed on a daily basis. Rogoff (1996), for example, notes that linear estimates of the speed of adjustment of the real exchange rate towards its mean imply half-lives of three to five years, or 21% to 13% *per annum*. The differences in the estimated speeds of adjustment in the studies surveyed by Rogoff (1996) and the present estimates may be reconciled by noting that mean reversion in our model is time-varying and nonlinear, and also that the model predicts substantial periods of misalignment.

Overall, therefore, our estimation results therefore provide strong support for the idea that intervention operations may stabilize exchange rates by coordinating stabilizing speculation based on exchange rate fundamentals.

6 Robustness Checks

6.1 Is the nonlinear effect of intervention on informed traders' confidence in the fundamentals crucial?

The logic of the coordination channel emphasizes the role of central bank intervention as a coordinating device for stabilizing speculation, which we have detected via its influence on the confidence that informed traders place in the economic fundamentals as a guide to their trades. However, via the more traditional signaling or portfolio balance channels, interventions may have a more direct impact on exchange rates. In order to distinguish between these two routes of effectiveness, and as a robustness check on our model of the coordination channel, we tried re-estimating the model with the impact of intervention on speculators' confidence removed (i.e. setting φ_2=0) and introducing the intervention variable directly as an explanatory variable into the mean equation. The exact specification of the model and the estimation results were as follows:

$$\Delta s_t = \underset{(1.82)}{0.03}\,\Delta s_{t-1} + \underset{(4.21)}{0.01}\, w_t\,\left(f_{t-1} - s_{t-1}\right) - \underset{(2.87)}{3.77}\,(i^*_{t-1} - i_{t-1}) - \underset{(0.16)}{0.04}\, INT_{t-1} + \varepsilon_t \tag{10}$$

$$w_t(\varphi;\, f_{t-1} - s_{t-1};\, h_{t-1}) = \frac{2\,exp\left(-\underset{(2.56)}{0.04}\,\dfrac{|\, f_{t-1} - s_{t-1}\,|}{\sqrt{h_{t-1}}}\right)}{1 + exp\left(-\underset{(2.56)}{0.04}\,\dfrac{|\, f_{t-1} - s_{t-1}\,|}{\sqrt{h_{t-1}}}\right)} \tag{11}$$

$$h_t = \underset{(4.61)}{0.014} + \underset{(8.08)}{0.075}\,\varepsilon_{t-1}^2 + \underset{(75.29)}{0.900}\,h_{t-1} \tag{12}$$

where figures in parentheses indicate asymptotic t-ratios. These results reveal that the estimated coefficients as well as their significance levels do not change substantially when interventions are introduced in the mean equation instead of driving informed traders' confidence. More importantly, estimation of this model reveals no statistically significant impact of exchange rate interventions on exchange rates. This suggests that chief impact of intervention on exchange rate movements was via the coordination channel, and also accords with Neely's (2005b) conjecture that explicitly allowing for the nonlinearity of intervention may be crucial in identifying its effects.

6.2 Reported versus secret intervention

The fact that the coordination channel of intervention effectiveness requires operations to be publicly available information provides us with a second robustness check. Officially, both Federal Reserve and Bundesbank intervention operations were conducted anonymously over the sample period. However, as Dominguez (2003) points out, central banks maintain relationships with traders allowing them to inform the entire market of their operations within minutes of the original call. Smith and Madigan (1988) quote Federal Reserve officials thus:

> "Most operations are conducted in the brokers' market, though at the beginning of a major intervention episode we have sometimes chosen to deal directly with several banks simultaneously to achieve maximum visibility."

While the dissemination of intervention information via interdealer traders comes close to an official announcement, monetary authorities can also intervene secretly by placing orders on the broker market. To what extent central banks allowed operations to be publicly available information is an empirical issue. Investigating the empirical evidence on the accuracy of press reports of foreign exchange intervention, Klein (1993) finds that in the case of the Federal Reserve the likelihood of intervention actually occurring given that it was reported by the press was 88 percent. Moreover, the likelihood of intervention being reported increased with the size of the operation. Thus, Federal Reserve interventions may be regarded as largely publicly available information in the foreign exchange market. In contrast, the number of reported interventions is significantly smaller in case of the Bundesbank. Only 46 out of 286 operations conducted in the period between November 1982 and December 1984 were reported by the press (Dominguez and Frankel, 1993). Thus, Bundesbank intervention operations may be regarded largely as secret.

The fact that Federal Reserve interventions appeared to have been publicly available information (qualitatively if not quantitatively), while the Bundesbank appeared to have intervened in secret, allows us to conduct an interesting robustness check on our model of the coordination channel. Clearly, for intervention to be effective through the coordiantion channel, it must be publicly announced. Thus, substituting Bundesbank for Federal Reserve intervention data in our empirical model should result in an insignificant estimate of the influence of the intervention on informed traders' confidence in fundamentals. We therefore re-estimated the model using Bundesbank intervention data, and obtained the following results:

$$\Delta s_t = \underset{(1.72)}{0.02}\Delta s_{t-1} + \underset{(3.90)}{0.01}\, w_t\, \left(f_{t-1} - s_{t-1}\right) - \underset{(2.80)}{3.62}(i_{t-1}^{*} - i_{t-1}) + \varepsilon_t \tag{13}$$

$$w_t\left(\varphi; f_{t-1} - s_{t-1}; \mathrm{int}_{t-1}; h_{t-1}\right) = \frac{2\exp\left(-\left(\underset{(1.56)}{0.03} + \underset{(1.27)}{0.51}\mathrm{int}_{t-1}\right)\dfrac{|\, f_{t-1} - s_{t-1}\,|}{\sqrt{h_{t-1}}}\right)}{1 + \exp\left(-\left(\underset{(1.56)}{0.03} + \underset{(1.27)}{0.51}\mathrm{int}_{t-1}\right)\dfrac{|\, f_{t-1} - s_{t-1}\,|}{\sqrt{h_{t-1}}}\right)} \tag{14}$$

$$h_t = \underset{(4.32)}{0.014} + \underset{(7.92)}{0.075}\varepsilon_{t-1}^2 + \underset{(74.95)}{0.900} h_{t-1} \tag{15}$$

Interestingly, the parameter estimates as well as the significance levels of the mean equation generally remain in the same range as before. The introduction of the Bundesbank intervention data slightly distorts the estimation of the transition variable, however. Even though the parameter φ_1 is still correctly signed and of reasonable magnitude, it is no longer statistically significant. More importantly, however, we find that the parameter of the intervention measure is statistically insignificant. Bundesbank operations are obviously unable to improve traders' confidence in fundamental analysis, exactly as predicted by the coordination channel.

7 Conclusion

In this paper, we have developed and estimated a microstructural model of daily exchange rate behavior in order to study the effectiveness of Federal Reserve interventions in the German mark-US dollar foreign exchange market, and in particular to examine the relevance of the coordination channel of intervention effectiveness. Within our model, mean reversion of the exchange rate is provided by stabilizing speculation of informed trader traders, yet their foreign exchange market activity depends on their confidence in fundamental analysis. Parameter estimates reveal that the further removed the exchange rate is from the fundamental value, the weaker becomes informed traders' trading activity. This nonlinearity provides the basis for the coordinating role of central bank intervention. According to the coordination channel, intervention operations may stabilize exchange rates by coordinating stabilizing speculation of informed traders, reflected as a sudden rise in confidence of the informed traders in fundamental analysis. Here, the fundamental value of the exchange rate is approximated by purchasing power parity, implying that intervention effectiveness is assessed by testing whether intervention operations tend to induce stability in the real exchange rate. In line with the results of Taylor (2004, 2005), our empirical analysis provide evidence in favor of this route of intervention effectiveness. In particular, it was shown that the Federal Reserve's intervention policy tended to reduce misalignments of the mark-dollar exchange rate in a manner consistent with the coordination channel. In addition, the ability of intervention operations to stabilize exchange rates improved as exchange rate distortions grew, while in the neighborhood of purchasing power parity intervention appeared to be less effective.

Reestimating the model with the intervention variable directly affecting the exchange rate, rather than view its influence on traders' confidence in the fundamentals, or using data on secret Bundesbank interventions, yielded statistically insignificant parameter estimates, as predicted by the coordination channel of intervention effectiveness.

Our results may be interpreted as an explanation of why central banks continue to pursue sterilized intervention despite the prevailing skepticism in academia concerning its effectiveness.[12] The nonlinear dynamics on foreign exchange markets seem to allow for intervention effectiveness via a coordination of stabilizing speculation. These effects are likely to be absent from the standard linear time-series approaches applied in previous contributions. From a policy perspective, the results suggest a stabilizing role for intervention, but do not provide a basis for an intensive exchange rate management.

[12] Indeed, an implicit belief in the coordination channel appears to form an important part of policy makers' views on intervention—see, e.g. Wadhwani (2000).

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Table 1

Parameter estimates of the STAR model
(in percent) 1980.01.02 – 1992.12.31

γ	– 3.75 (3.07)***
α	0.03 (1.97)**
δ	0.01 (4.36)***
φ_1	0.05 (2.69)***
φ_2	0.11 (2.03)**
β_0	0.014 (4.34)***
β_1	0.075 (7.19)***
β_2	0.899 (72.20)***
LLh	– 374.78
LRT	14.12***
AR(1)	0.53
AR(5)	0.15
ARCH(1)	0.46
ARCH(5)	0.61
NRNL	0.16

Notes: The sample contains daily observations of the dollar spot exchange rate against the DM from January 1980 to December 1992. α, δ, γ, φ indicate the estimated parameters of the mean equations, β_0, β_1, and β_2 are the estimated GARCH(1,1) parameters, LLh is the log likelihood value and LRT the likelihood ratio test statistic with restrictions $\alpha = \delta = \varphi = 0$. AR(p) denotes the p-value for the Ljung-Box statistic for serial correlation of the residuals up to p lags. ARCH(q) denotes the p-value for the Ljung-Box statistic for serial correlation of the standardized squared residuals up to q lags. NRNL is the lowest p-value for no remaining nonlinearity up to ten lags. t-statistics in parentheses are based on robust estimates of the covariance matrices of the parameter estimates. * (**, ***) denotes significance at the 10% (5%, 1%) level.

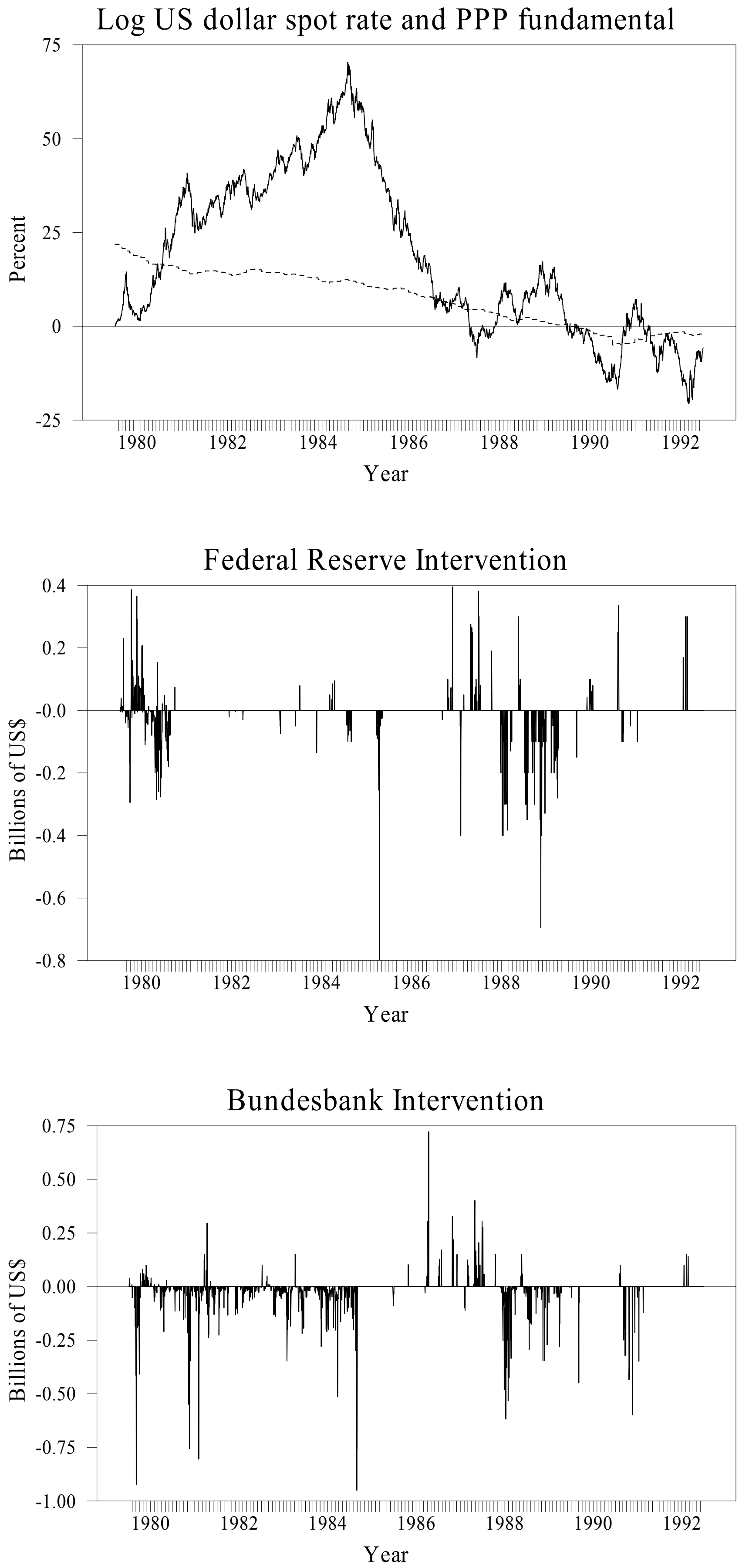

Fig. 1. *Log US dollar spot rate, PPP fundamental, and central bank intervention*

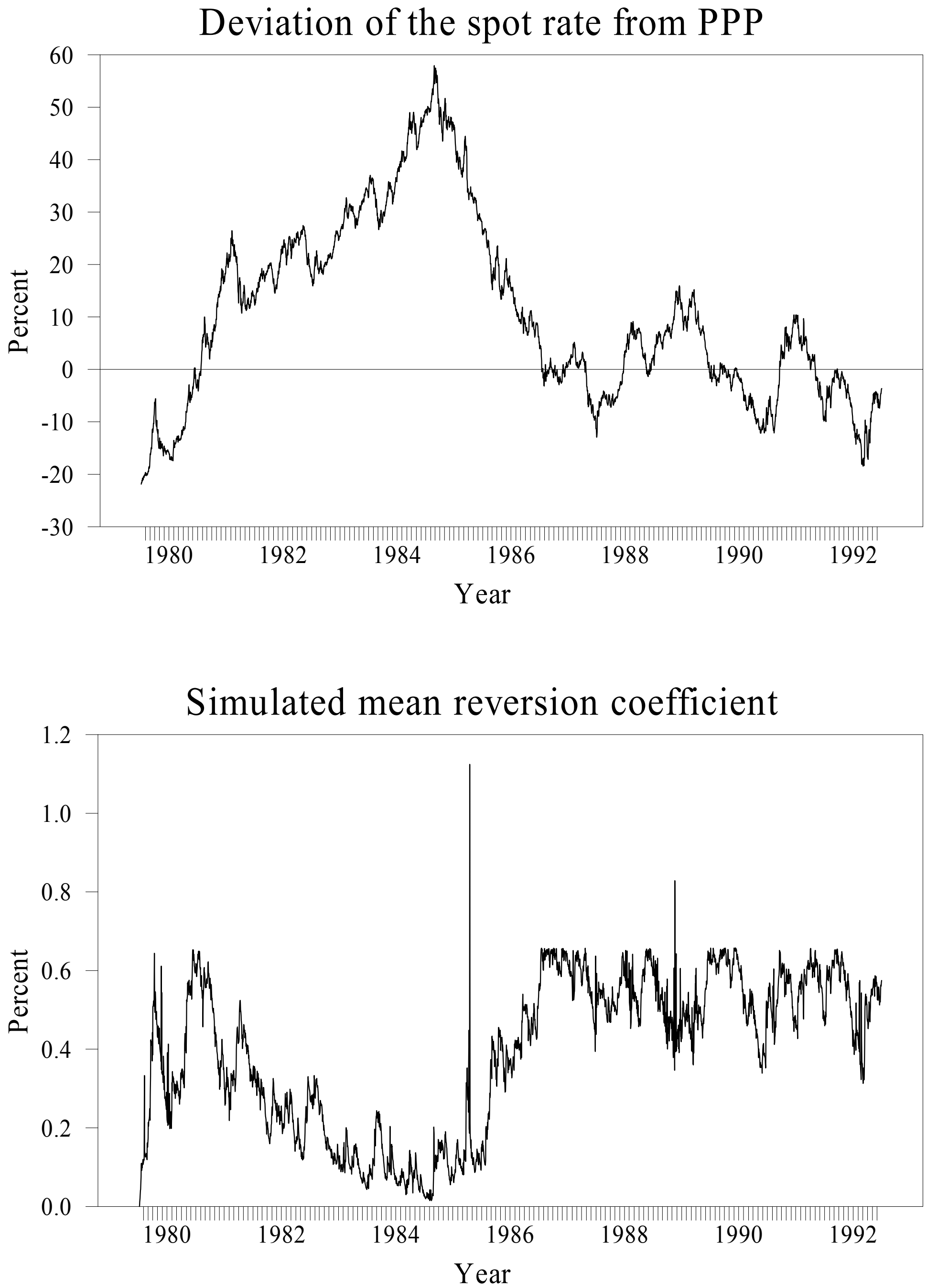

Fig. 2. *Deviation of the spot rate from PPP and simulated mean reversion coefficient*