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On the nonlinear influence of Reserve Bank of Australia interventions on exchange rates

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Abstract:

This paper applies nonlinear econometric models to empirically investigate the effectiveness of the Reserve Bank of Australia (RBA) exchange rate policy. First, results from a STARTZ model are provided revealing nonlinear mean reversion of the Australian dollar exchange rate in the sense that mean reversion increases with the degree of exchange rate misalignment. Second, a STR-GARCH model suggests that RBA interventions account for this result by strengthening foreign exchange traders' confidence in fundamental analysis. This in line with the so-called coordination channel of intervention effectiveness.

Keywords: foreign exchange intervention; market microstructure; smooth transition; nonlinear mean reversion

JEL Classification: C10; F31; F41

Non-technical summary

Although the Reserve Bank of Australia (RBA) adopted a flexible exchange rate regime in the early 1980s, it has not become indifferent to exchange rate movements as reflected in relatively frequent interventions in the Australian dollar (AUD)–US dollar (USD) market (RBA, 2008). Of course, there exists an extensive literature on the effectiveness of RBA operations applying linear econometric models. While Kim, Kortian and Sheen (2000) show that, over the period from 1986 to 1993, RBA interventions contemporaneously affected the exchange rate level, Edison, Cashin and Liang (2006) conclude, on the contrary, that RBA intervention can not be regarded as being effective. Regarding the motives of intervention Kearns and Rigobon (2005) identify the RBA strategy as primarily one of slowing down otherwise precipitous exchange rate movements or "leaning against the wind", as also suggested by a number of previous studies (Rogers and Siklos, 2003; Kim and Sheen, 2002; McKenzie, 2004). While the results of these studies are mixed, none of these studies takes into account a potential nonlinear impact of RBA intervention on the exchange rate.

To fill the gap, this paper applies nonlinear econometric modeling techniques to investigate the effectiveness of foreign exchange interventions conducted by the RBA in the AUD-USD market over the period 1984-2008. We first apply Lundberg and Teräsvirta's (2006) smooth transition autoregressive target zone (STARTZ) model to show that the AUD-USD exchange rate exhibits nonlinear dynamics in the sense that mean reversion increases with the current degree of misalignment. As the STARTZ model is a pure time series framework, it provides no reasoning for this type of nonlinearity. Thus, in a second step, we investigate whether official intervention may account for this finding.

Based on a heterogeneous expectations framework we argue that strong and persistent misalignments of the exchange rate are caused by a coordination failure of foreign exchange traders expectations (Frankel and Froot, 1990). Specifically, if the exchange rate deviates from its perceived fundamental value, stabilizing speculators accumulate losses and refrain from trading (Shleifer and Vishny, 1997). As a result the exchange rate is locked in an unstable regime and remains persistently misaligned. Sarno and Taylor (2001) suggest that in such circumstances, central banks intervention operations may encourage stabilizing speculators to re-enter the market thereby providing the otherwise lacking mean reversion of the exchange rate. Applying a Smooth Transition Regression General Autoregressive Conditional Heteroskedasticity (STR-GARCH) model reveals that RBA operations exert a stabilizing influence on the AUD-USD exchange rate via this coordination channel. More specifically, we show that RBA interventions are more effective the further the exchange rate deviates from its fundamental value. We also provide several robustness tests such as sub-sample estimations, testing linear vs. nonlinear influence and analyzing the persistency of intervention effectiveness. All tests indicate that our results are robust and the nonlinear influence is present in different sub-samples.

Our results provide an explanation for why the RBA continues to pursue sterilized intervention despite the prevailing skepticism in academia over its effectiveness. The nonlinear dynamics on foreign exchange markets allow interventions to be effective through the coordination of expectations. These effects are absent in standard linear time series approaches applied in previous contributions to the foreign exchange intervention literature. From a policy perspective, the results suggest a stabilizing influence of interventions by providing a long-run guidance of market expectations, which must not be interpreted as an incitement to an intensive exchange rate management. The reason is that intervention effectiveness tends to be low in the neighbourhood of ppp.

Nicht-technische Zusammenfassung

Trotz des Übergangs zu flexiblen Wechselkursen Anfang der 1980er Jahre hat die Reserve Bank of Australia (RBA) immer wieder in den Devisenmarkt mit sterilisierten Interventionen eingegriffen. Mittlerweile existiert eine umfangreiche Literatur über die Effektivität von RBA Interventionen auf der Basis linearer ökonometrischer Modelle. Während Kim, Kortian und Sheen (2000) für die Periode 1986 bis 1993 einen signifikanten Effekt der RBA-Interventionen nachweisen, finden Edison, Cashin und Liang (2006) dagegen keinerlei Einfluss auf den Wechselkurs. Hinsichtlich der Interventionsmotive interpretieren Kaerns und Rigobon (2005) die Politik der RBA als Abmilderung von ansonsten exzessiver Wechselkursbewegungen. Diese "Leaning against the wind"-Strategie findet sich auch in einer Reihe vorhergehender Beiträge (Rogers und Syklos, 2003; Kim und Sheen, 2002; McKenzie, 2004). Während die Studien also zu keinem einheitlichen Ergebnis hinsichtlich der Effektivität der Zentralbankinterventionen kommen, ist ihnen jedoch eine überwiegend lineare Untersuchungsmethode gemeinsam.

Um diese Lücke zu schliessen, untersucht das vorliegende Diskussionspapier die Wirksamkeit sterilisierter RBA-Interventionen im Zeitraum zwischen 1984 und 2008 mittels nichtlinearer Modelle. Zunächst kann mit Hilfe des von Lundberg und Teräsvirta (2006) entwickelten Smooth Transition Autoregression Target Zone (STARTZ)-Modell nachgewiesen werden, dass der AUD-USD Wechselkurs nichtlineare Eigenschaften in dem Sinne aufweist, dass die Rückkehr des Wechselkurses zum bedingten Erwartungswert (Mean Reversion) mit der aktuellen Fehlbewertung des Wechselkurses zunimmt. Da dieses Modell keinen Aufschluss darüber gibt, wie es zu den nichtlinearen Effekten kommt, wird in einem zweiten Schritt untersucht, ob die Interventionen der RBA zu den beobachteten nichtlinearen Zeitreiheneigenschaften geführt haben könnten.

In Anlehnung an den von Taylor und Reitz (2008) entwickelte Ansatz wird ein Modell mit heterogenen Erwartungen unterstellt, das anhaltende Fehlbewertungen des Wechselkurses auf die mangelnde Koordination von Wechselkurserwartungen zurückgeführt (Frankel und Froot, 1990). Mangelnde Koordination von Wechselkurserwartungen resultiert dann in einen zeitvariablen Einfluss stabilisierender Spekulation auf den Wechselkurs. In Phasen zunehmender Fehlbewertung verhindern aufgelaufene Verluste, dass stabilisierende Spekulanten sich auf den Devisenmärkten engagieren (Shleifer und Vishny, 1997). Der Wechselkurs kann deshalb in einem Zustand massiver Fehlbewertung verharren. Sarno und Taylor (2001) vermuten, dass unter diesen Umständen Zentralbankinterventionen stabilisierende Spekulanten zur Rückkehr in den Devisenmarkt ermutigen können und die anderweitig fehlende Mean Reversion des Wechselkurses bewirken.

Mit Hilfe eines Smooth Transition Regression General Autoregressive Conditional Heteroskedasticity (STR GARCH)-Modells kann gezeigt werden, dass die Devisenmarktoperationen der RBA einen stabilisierenden Einfluss auf den Wechselkurs entlang dieses Koordinationskanals ausübte. Dabei ist dieser Einfluss umso stärker, je grösser die aktuelle Fehlbewertung war. Eine Reihe von Robustheitstests wie z.B. Schätzungen des Modells in verschiedenen Teilperioden, Berücksichtigung verzögerter Interventionen und linearer Modellkomponenten unterstützen die Ergebnisse.

Die Ergebnisse bieten eine Erklärung dafür, warum die RBA trotz der allgemein vorherrschenden Skepsis in der Literatur auf Devisenmärkten interveniert. Die nichtlineare Wechselkursdynamik im Koordinationsmechanismus bietet insofern eine Basis für wirksame Devisenmarktinterventionen, als dass sie einen langfristig koordinierenden Einfluss auf Wechselkurserwartungen erlaubt. Sie kann jedoch keinesfalls zum Anlass für eine mechanistische Feinsteuerung von Wechselkursen genommen werden, weil Interventionen im Falle geringfügiger Fehlbewertungen auch hier nahezu wirkungslos sind.

Contents

On the Nonlinear Influence of Reserve Bank of Australia Interventions on Exchange Rates[1]

1 Introduction

While the Australian economy can be regarded as relatively small, the Australian dollar (AUD) is the sixth largest currency traded in the world market, and the AUD-USD exchange rate is the fourth heaviest traded currency pair (Bank for International Settlements, 2007). Since the AUD was floated in December 1983, it has moved in a wide range around an average of AUD 1.5 per USD. Although it adopted a flexible exchange rate regime in the early 1980s, the Reserve Bank of Australia (RBA) has not become indifferent to exchange rate movements, as reflected in RBA's view that "There is an extensive literature, for example, on speculative bubbles, herding, fads, and other behavior which can drive market prices away from their equilibrium values, even in a market which is deep and liquid. When such overshooting occurs, intervention may help in limiting the move or returning the exchange rate towards its equilibrium level, thus obviating the need for costly adjustment by the real economy to the incorrect signals which the exchange rate would otherwise give." (RBA, 2008).

This intervention policy can be regarded as publicly disclosed in most cases because RBA interventions are generally conducted by entering the broker market directly and announcing the intervention publicly (Edison, Cashin and Liang, 2006). Rogers and Siklos (2003) also note that the RBA regularly announces its intervention operations and communicates its foreign exchange purchases and sales directly to the foreign exchange market. Only occasionally does the RBA use an agent bank to conceal the RBA's presence in the market (Rankin, 1998). Jüttner and Tonkin (1992) emphasize that the Australian market is "well informed of intervention operations". Furthermore, the RBA (2003) itself publishes its intervention policy, which has always been one of sterilized intervention.

[1]We are grateful to Guy Debelle, Michael Dear, Mardi Dungey, Stefan Gerlach, Heinz Herrmann, Phil Lowe, the editor Jeffrey Sheen, and two anonymous referees for helpful comments and suggestions. We thank Suk-Joong Kim and the Reserve Bank of Australia for kindly providing the intervention data used in this study. The views expressed here are those of the authors and are not necessarily those of the Deutsche Bundesbank or its staff.

Hutcheson (2003) conducted a questionnaire among exchange rate dealers licensed by the RBA: interestingly, some three-quarters of survey participants reported that they believe that there was some degree of credibility in the RBA's intervention effectiveness.

Since the RBA publishes its intervention data it is readily available and, therefore, frequently used in order to examine the RBA's intervention policy. Applying Friedman's (1953) profitability test[2] for intervention effectiveness, Andrew and Broadbent (1994) estimate profits of AUD 3.4 billion for the RBA in the period from December 1983 to June 1994, suggesting that its foreign exchange operations were stabilizing for the AUD as the RBA bought foreign exchange when its price was low and sold it when its price was high. Using the same profitability measure, Becker and Sinclair (2004) lengthen the sample period and estimate profits of AUD 5.8 billion for the RBA for the period from December 1983 to June 2004. Hence, both of these studies conclude that RBA interventions exerted a stabilizing influence on the AUD-USD exchange rate. Compared to that, Edison (1993) argues that profitability is a questionable criterion for evaluating the success of intervention since profitable interventions are not always stabilizing and stabilizing interventions are not always profitable.[3]

Kearns and Rigobon (2005) support the view that, over the period from 1986 to 1993, RBA interventions contemporaneously affected the exchange rate level significantly.[4] Moreover, Kearns and Rigobon (2005) identify the intervention strategy as primarily one of slowing down otherwise precipitous exchange rate movements or "leaning against the wind", as also suggested by a number of previous studies (Rogers and Siklos, 2003; Kim and Sheen, 2002; McKenzie, 2004). Hopkins and Murphy (1997) undertake a case study approach covering the period of July to October 1993 where the AUD experienced a high depreciation. They find that interventions and associated statements by the RBA did

[2]The application of this test relies on the assumption that the central bank acts as a stabilizing speculator, buying (selling) the foreign currency when the price is low (high) and, therefore, realizing profits by contemporaneously mitigating the exchange rate volatility.

[3]For instance, Jacobson (1983) argues that, if the monetary authority successfully pegs the exchange rate this would yield zero profits. In contrast to that, Neely (2004) argues that, if interventions are explicitly designed to make profits, the reserve management authority would be likely to be successful. Therefore, major governments should actively manage their foreign exchange portfolios.

[4]This view is also supported by the evidence reported by Karunaratne (1996) and Kim, Kortian and Sheen (2000) and, more recently, by Kim and Pham (2006).

enhance the stability of the market. In contrast, Makin and Shaw (1997) conclude that neither the exchange rate level nor the exchange rate volatility was influenced by RBA interventions during 1983 and 1993. In recent work, Rogers and Siklos (2003) lengthen the sample period and end up finding little evidence that the RBA was successful in managing the AUD exchange rate during 1983 to 1997. In particular, their results suggest that, although the volatility and kurtosis of AUD-USD exchange rate movements were modestly affected, RBA interventions had virtually no effect on the level of the exchange rate.

According to Edison, Cashin and Liang (2006), who use an event-study technique, the foreign exchange operations of the RBA during 1984 to 2001 did not consistently influence the level of the AUD-USD. However, they find some indication of a "leaning against the wind" intervention strategy inasmuch as on days when RBA purchased AUD, the currency often strengthened either immediately or over time by reversing a previously depreciating trend. Additionally, the authors find that RBA interventions generally tended to increase exchange rate volatility, suggesting that they contributed to market uncertainty. Edison, Cashin and Liang (2006) therefore conclude that RBA intervention cannot be regarded as being effective in general. This conclusion is also supported by Ahdi, Ahmed and Abdelwahed (2003), who apply a fractionally integrated generalized autoregressive conditional heteroskedasticity model and conclude that RBA intervention usually increases exchange rate volatility. There are many explanations for the mixed results on the effectiveness of RBA interventions. For instance, the different policy regimes with quite distinct intervention policy are likely to cause different exchange rate response to RBA interventions. Hence, the analysis of RBA intervention effectiveness should be evaluated for different subperiods before conclusion or policy implications ca be provided.

In contrast to the mixed results concerning the effectiveness of intervention, a much clearer picture arises from the extensive research on the *motives* for central bank intervention. Kim and Sheen (2002), for example, provide evidence that the probability of RBA intervention is significantly higher in periods of deviations of the exchange rate from its trend level. Overall, we would argue that the mixed evidence on the effectiveness of foreign exchange market intervention by the RBA may be due to a common feature of previous analyses. Previous studies have used the traditional taxonomy of the portfolio balance and signaling channels of intervention effectiveness, whereas we believe that RBA intervention may have largely operated through a nonlinear law of motion that will not have been captured within the traditional linear framework.

In this paper, we apply nonlinear econometric modeling techniques in order to investigate the effectiveness of foreign exchange interventions conducted by the RBA in the AUD-USD market over the period 1984-2008. We first apply Lundberg and Teräsvirta's (2006) smooth transition autoregressive target zone (STARTZ) model to show that the AUD-USD exchange rate exhibits nonlinear mean reversion dynamics. As this model is a pure time series framework, it provides no reason why the mean reversion is positively correlated with the exchange rate's misalignment. Thus, in a second step, we argue that official intervention becomes increasingly effective the further away the nominal exchange rate deviates from its equilibrium value, in accordance with the predictions of the coordination channel of intervention effectiveness (Reitz and Taylor, 2008).

The remainder of the paper is organized as follows. In Section 2 we describe our data set on daily AUD-USD exchange rates, official intervention and fundamentals. In Section 3 we apply the Lundbergh/Teräsvirta (2006) STARTZ model. In Section 4 we present our microstructural model of intervention. In Section 5 an empirical model is developed informed by our theoretical analysis and recent empirical work on nonlinear exchange rate adjustment. The estimation results concerning intervention effectiveness are reported in Section 6, while Section 7 contains robustness checks. Section 8 concludes.

2 The data

Our data spans the period from the deregulation of the Australian dollar market in January 1984 to December 2008, and includes the temporary excess volatility due to the 1997-98 Asian economic crisis, the 1998-99 Russian financial crisis and the recent global financial crisis, all of which led to large-scale interventions by the RBA.[5] Over our sample period,

[5]Models of Australia's real effective exchange rate tend to discard data from 1984 to exclude the considerable adjustment processes in the first months of floating (Aruman and Dungey, 2003). The empirical results of this study are robust regarding the particular starting point of the sample.

RBA intervention operations took place on 2,879 out of a total of 6,537 trading days (44 percent). Thus, the RBA intervened heavily compared to other central banks (Kearns and Rigobon, 2005). Neely (2000, 2006) reports that, over nearly the same period, fourteen central banks intervened on average on only about 4-5 percent of all trading days. The average size of intervention was USD 50 million—compared to a daily traded turnover in the AUD of USD 72 billion (Rankin, 1998)—with the largest intervention being a dollar sale of USD 1,256 million in August 1992. The total amount of US dollars bought in intervention operations over our sample period exceeded USD 30 billion. During the entire period from 1983 to 2008 a reserves position of AUD 20 billion was built up, mostly originating from the period between 1988 and 1992. Interestingly, the intervention strategy of the RBA has changed several times over our sample period which makes an analysis of subperiods quite appealing. After a long period of frequent intervention operations until the early 1990s, the RBA refrained from intervening in the foreign exchange market between November 1993 and June 1995 and subsequently changed its intervention strategy, moving from generally small daily interventions with frequent changes in direction to less frequent but larger scale interventions. Between February 2000 and April 2002 the RBA rarely intervened while afterwards interventions took place on a regular basis. The intervention data was kindly provided by the RBA.

A potential drawback in any empirical analysis of Australian foreign exchange intervention is that the RBA frequently undertakes operations in both securities and foreign exchange markets on behalf of the Australian government. Each day, the government is required to make payments as part of its regular operations, reflecting payments for foreign goods and services or expenses involved in maintaining embassies. To ensure that these transactions do not affect the level of reserves in the RBA portfolio, the RBA purchases or sells foreign exchange. These operations are carried out at market prices. Over the period 1989 to 2005, total sales of foreign exchange to the government were around AUD 4 billion per financial year (RBA 2008, p. 11), while trades with other market participants were on average AUD 3 billion per financial year. The trades with the government are still quite substantial (Edison, Cashin and Liang, 2006). The transactions with the government can be to some extent regarded as intervention policy if the RBA regards these transactions when they are passed through as destabilizing to the market. In that case the government's needs are met from the RBA portfolio, and are passed through with a time lag to the market when market conditions are more favorable (RBA 2000, p. 12). However, we only include trades between the RBA and market dealers in our analysis. An advantage of analyzing the AUD-USD market in this context, however, arises from the fact that the US monetary authorities have refrained from intervening in the AUD-USD market (Federal Reserve Bank, 2006). Therefore, we can conclude that, inasmuch as there is a significant link between intervention and the exchange rate, it arises from RBA intervention.

The exchange rate data used in this study are daily interbank mid-rate quotations (10.00am Sydney) of the spot AUD exchange rates against the US dollar. The price of one US dollar is expressed in AUD. In terms of the preceding analysis, therefore, Australia represents the home economy while the US is taken as the foreign economy. The home interest rate is thus i^{AUS}, the overnight AUD deposit interest rate (10.00am Sydney), and the foreign interest rate is i^{USD}, the effective federal funds rate. The exchange and interest rates are taken from Datastream.

The most difficult variable to define in this context is the fundamental equilibrium value of the exchange rate, f_t. We assume that the fundamental value can be adequately described by 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 the long-run exchange rate equilibrium. Edison, Cash and Liang (2006) emphasize that the RBA has intervened whenever it believes that the exchange rate has moved away from its equilibrium. Of course, it is difficult to quantify the equilibrium exchange rate and to identify when the exchange rate overshoots. However, the RBA "has come to regard overshooting as unlikely to be occurring unless the exchange rate has moved a long way and the move does not appear to be supported by economic and financial factors" (RBA, 2008). In this situation in which the exchange rate is misjudged with regard to its fundamentals, the RBA "intervened to try to move the exchange rate towards what it judged to be a more sustainable level" (RBA, 1992). Since Cuestas and

Regis (2008) provide evidence that the ppp holds in Australia for the time period 1977 – 2004, it is not hard to believe that the ppp is such a sustainable level. Indeed, Karunaratne (1996) emphasizes that one major aim of RBA interventions is to achieve ppp.[6]

In this context, it is worth noting, that the RBA officially adopted an inflation target in 1993 with the stated objective of keeping underlying inflation between 2 and 3 percent. Recent papers have focused on the implications of exchange rate fluctuations for inflation targeting countries. For instance, Ball (1998), Svensson (2000), and Bharucha and Kent (1998) analyzed whether inflation targeting central banks in small open economies pay too much attention to these fluctuations. They argue that exchange rate fluctuations have only temporary effects on inflation and monetary policy attempts to offset these effects could cause undue variability in output. Hence, the link between inflation targeting and the exchange rate deserves special attention.

Quarterly observations of the consumer price indices (CPIs) were taken from the International Monetary Fund's International Financial Statistics database to construct a measure of the ppp fundamental as $f_t = log(CPI_t^{AUD}) - log(CPI_t^{USD})$. In line with Cuestas and Regis (2008) we normalized the ppp fundamental to be equal to the nominal exchange rate at the beginning of January 1994. Given that the RBA stopped intervening for the following 18 month, this seems to be a reasonable choice.[7] Daily exchange rates, the ppp fundamental and the RBA intervention record are presented in Figure 1.

3 Does the Australian Dollar exhibit time series nonlinearities?

In this section we apply Lundberg and Teräsvirta's (2006) Smooth Transition Autoregression Target Zone (STARTZ) model, which has originally been developed to investigate and adequately characterize the dynamic behavior of an exchange rate fluctuating within a Krugman (1991) target zone framework. Of course, we do not consider the RBA's ex-

[6]This is supported by Kim and Sheen (2002), who provide evidence that the RBA is more likely to intervene if the AUD-USD exchange rate deviates from its medium-term level.

[7]We effectively relaxed this normalization by allowing for a shift parameter in preliminary estimations. The estimated value was, however, in no case significantly different from zero at the five percent level, and so we omitted it in our final estimations.

change rate policy as anything like an explicit Krugman-type target zone arrangement. However, we make use of the fact that the STARTZ model is able to detect nonlinearities in exchange rate dynamics, i.e. the patterns of misalignment autocorrelation depends nonlinearly on the exchange rate's deviation from its fundamental value. Since such nonlinear dynamics can also be attributed to commodity price cycles, we interpret their existence only as a prerequisite for the subsequent nonlinear analysis of RBA interventions.

The STARTZ model identifies potential transition dynamics of both the conditional mean and the conditional variance when the exchange rate moves between the central parity and the boundaries of an exchange rate range. In particular, it tests whether the time series properties of the exchange rate depend nonlinearly on its current position within this range. Without further investigating what mechanism introduces this nonlinearity, the conditional mean is assumed to behave like a random walk process in the neighborhood of the fundamental value, whereas close to the boundaries the exchange rate tends to follow a white noise process. Thus, the different regimes are identified by the persistence of exchange rate shocks. Our application of the STARTZ model parameterizes the first and second moments of $z_t = s_t - f_t$, i.e. the deviation of the exchange rate from purchasing power parity:

$$z_t = \sum_{i=1}^{k} \alpha_i z_{t-i} + (z^L - \sum_{i=1}^{k} \alpha_i z_{t-i})G^L + (z^U - \sum_{i=1}^{k} \alpha_i z_{t-i})G^U + \epsilon_t \tag{1}$$

$$G^L(z_{t-1}, \psi, \theta, z^L) = (1 + exp(-\psi(z^L - z_{t-1})))^{-\theta} \tag{2}$$

$$G^U(z_{t-1}, \psi, \theta, z^U) = (1 + exp(-\psi(z_{t-1} - z^U)))^{-\theta} \tag{3}$$

$$\epsilon_t = \nu_t^{iid} \sqrt{h_t} \tag{4}$$

where ν_t^{iid} is N(0,1). Moreover, z^L and z^U denote the lower and upper edges of the range. Equations (2) and (3) are generalized logistic functions and ψ and θ are slope and asymmetry parameters, respectively. The interpretation of the mean dynamics defined in equations (1) to (4) is that, in the neighborhood of the fundamental value, the behavior of the exchange rate is mostly driven by a linear combination of its lags, since the transition functions G^U and G^L remain small. Close to the boundaries of the range, however, the exchange rate depends nonlinearly on lagged values of the misalignment. For example, when the exchange rate approaches the upper bound, G^U becomes larger, imposing a smooth transition from the autoregressive behavior towards white noise-like dynamics around $f_t + z^U$.

As is well known from the literature, the exchange rate volatility will shrink substantially at the edges of the band if the target zone is suitably defined and works properly. In order to control for this hump-shaped distribution of the conditional variance, Lundberg and Teräsvirta (2006) parameterize the volatility process similar to the mean dynamics:

$$h_t = \beta_0 + \beta_1\epsilon_{t-1}^2 + \beta_2 h_{t-1} + (\xi - (\beta_0 + \beta_1\epsilon_{t-1}^2 + \beta_2 h_{t-1}))G^L + (\xi - (\beta_0 + \beta_1\epsilon_{t-1}^2 + \beta_2 h_{t-1}))G^U, \tag{5}$$

where $\xi > 0$ ensures positivity of the conditional variance.[8] The process defined in equation (5) allows for a smooth transition from a GARCH-like behavior around the fundamental value and a close-to-constant conditional variance at the edges of the band.

The parameter estimates represented in Table 1 are obtained by recursively maximizing the (quasi) log-likelihood function by means of the BFGS (Broyden, Fletcher, Goldfarb, and Shanno) algorithm.

The STARTZ model passes a number of diagnostic checks for remaining serial correlation and conditional heteroskedasticity in the standardized residuals. We also tested the model against remaining nonlinearities in both conditional mean and variance. Because only the p-value of fourth-order nonlinearity in the volatility process indicates some remaining nonlinearities we accept the model as adequately specified (Lundberg and Teräsvirta, 2006). The point estimates of the coefficients are appropriately signed and exhibit, in general, low standard errors. Regarding the transition function in the volatil-

[8] Of course, the respective parameters of the transition function are estimated separately from those in the mean equation.

ity equation, the relatively large parameter estimates of ψ_v and θ_v account for very low values of G^U and G^L. Apparently, the volatility dynamics do not reveal any hump-shaped distribution and are sufficiently described by a standard GARCH process. In contrast, the transition function in the mean equation behaves as expected. The value of G^U and G^L increase as the misalignment becomes stronger, implying a switch from autoregressive to more white-noise behavior of z_t. Additional evidence in favor of nonlinearities in the Australian dollar is provided by statistically significant estimates of z^L and z^U, which reveal a bandwidth of approximately 59 percent around the ppp value.[9] The comparatively wide range is plausible as the RBA did not maintain an target zone framework, but reportedly tried to limit overshooting or even helped the exchange rate to move back towards its equilibrium value in an environment of the considerable uncertainty surrounding the concept of the equilibrium value (RBA, 2008). Our conclusion from the presented STARTZ model is that there are nonlinear dynamics in the AUD-USD exchange rate around a central parity approximated by ppp. The important question we address in the next section is whether or not the intervention policy of the RBA has been a major driving force of these time series properties.

4 A microstructural model of the coordination channel of intervention effectiveness

There is a substantial literature on the effectiveness of foreign exchange intervention (Sarno and Taylor, 2001). While traditional studies focus on the portfolio or signaling channel as outlined in the introduction, more recently market microstructural approaches have become popular in examining the effect of foreign exchange market intervention (Dominguez, 2003; Vitale, 1999). Our model belongs to the latter group and follows the framework developed by Reitz and Taylor (2008).

Assuming that exchange rates are determined in an order-driven market governed by heterogeneous agents (De Grauwe and Grimaldi 2005, 2006), the exchange rate change at time $t+1$ can be expressed as a function of net order flows from informed and uninformed

[9] The symmetry of the exchange rate band is also in line with ppp as a proxy for the target rate.

trades plus a noise term:

$$s_{t+1} = s_t + a^M(D_t^I + D_t^U) + \epsilon_{t+1}, \tag{6}$$

where s_t is the logarithm of the spot exchange rate at time t, defined as AUD per US dollar, and a^M is a positive reaction coefficient determined by the market maker. D_t^I and D_t^U denote the net order flow from informed and uninformed speculators, respectively. The exchange rate change depends on the net order flow from both informed and uninformed speculators, because the market maker does not observe them individually.[10]

Orders are submitted by risk-neutral speculators and depend on expected excess returns, which consist of the expected change in the exchange rate and the interest differential. Assuming that uninformed traders correspond to chartists or technical traders (Menkhoff and Taylor, 2007), we follow Reitz and Taylor (2008) and model the uninformed trader's order as a positive function of the recent return, plus an interest differential component:

$$D_t^U = a^U(s_t - s_{t-1}) + b^U(i_t^* - i_t), \tag{7}$$

where i_t^* and i_t represent the interest rate of foreign and home currency deposits, respectively. While the parameter a^U is expected to be positive, the expected sign of b^U is not immediately clear. According to the uncovered interest rate parity (UIP) condition, the interest differential $(i_t^* - i_t)$ should be an unbiased predictor of the percentage change in the exchange rate. Equivalently, given that the covered interest rate parity is known to hold closely, at least among eurodeposit interest rates (Taylor, 1987, 1989), the UIP implies that the forward exchange rate should be an unbiased predictor of the spot rate. If uninformed traders believe in the UIP, therefore, one would expect b^U to be positive. However, the failure of the UIP (equivalently, the failure of the 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 tendency among traders to

[10] Popper and Montgomery (2001) provide a rationale for interventions by developing a model of heterogeneously informed traders. In this theoretical model, the central bank can affect the exchange rate by aggregating and disseminating agents' information.

bet against the UIP using various "forward-rate bias" or "carry trade" strategies (Fabozzi, 2001; Rosenberg, 2003; Galati, Heath and McGuire, 2007), which would suggest a negative sign for b^U.[11] Overall, therefore, the sign of this coefficient is ambiguous.

Compared to uninformed traders, informed traders base their expectations regarding future exchange rate developments on an analysis of exchange rate fundamentals, based on their view of a time-varying long-run fundamental equilibrium value, denoted f_t. While the exchange rate is expected to revert towards f_t over time, the weight attached to the deviation from fundamentals in determining orders may vary over time. Thus, informed traders' orders may be expressed as

$$D_t^I = a^I w_t(f_t - s_t) + b^I(i_t^* - i_t), \tag{8}$$

where a^I is a positive reaction function coefficient and w_t determines the confidence of informed speculators in fundamental analysis. Again, following similar reasoning as in the case of the uninformed speculator parameter b^U, the sign of the coefficient on the interest differential in equation (8), b^I, is ambiguous.

According to equation (8), as long as $w_t > 0$, orders of informed traders contribute to stabilizing speculation in the sense that they will tend to drive the exchange rate toward its equilibrium value. The confidence measure w_t is at the center of our analysis, because it reflects the time-varying impact of stabilizing speculation on exchange rates, thereby providing the basis for the coordination channel of intervention effectiveness. We assume that informed traders' confidence in the fundamentals can be expressed as a function of the standardized absolute misalignment and the intervention of the central bank:

$$c_t = -(\rho - \phi D_t INT_t)\frac{|f_t - s_t|}{\sigma_t^s} \tag{9}$$

and

$$w_t = \frac{2exp(c_t)}{1 + exp(c_t)} \tag{10}$$

[11] The act of buying high-interest rate currencies is also referred to as a "carry trade" (Galati and Melvin 2004).

and where σ_t^s denotes the conditional standard deviation of exchange rate movements. If the distance between the actual exchange rate and its fundamental value increases, fundamental analysis wrongly predicts the sign of the exchange rate change, causing informed traders to refrain from submitting orders. The reason is that the fundamental value is an unobservable variable and traders try to infer information from actual realizations of the exchange rate. In such a state space framework, a perceived permanent appreciation of the currency is interpreted as an increase of the fundamental value. Relative to an observable proxy such as ppp, it is optimal to attach a lower weight to the prior. Put differently, fundamentalists lose confidence in their trading strategy when misalignments grow. On the other hand, if the degree of misalignments falls, causing their fundamental analysis to correctly predict exchange rate movements, informed traders are encouraged to submit orders. Hence, it seems reasonable to postulate that a standardized measure of absolute misalignment should negatively influence traders' confidence in fundamentals. Moreover—and crucial to the framework of the coordination channel—we allow the trading activity of central banks in the foreign exchange market to positively influence informed traders' confidence in fundamental analysis. If the monetary authority sells an overvalued currency, it reveals its commitment to a lower exchange rate. In the market microstructure literature, central banks are regarded as having superior information about the exchange rate, 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). Even if central banks observe the same information as other market participants, they have more resources to study and critically being able to take a longer run perspective than most market participants. Hence, informed traders 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 regarded as a device with which to coordinate traders' expectations.

As argued by Taylor (2004, 2005) and Reitz and Taylor (2008), the influence of intervention operations on traders' 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 intervention will 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 due to a loss in confidence in the fundamentals—may now be encouraged by the central bank's intervention to re-enter the market. Finally, it must be noted that the purchase of an overvalued currency by the monetary authority would puzzle informed traders and perhaps drive them out of the market. To capture these misleading signals, we set an indicator variable D_t 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 ($D_t INT_t$) that is positive only if the central bank operates in the appropriate direction. Negative values of $D_t INT_t$ may result from a temporary leaning-against-the-wind strategy and must not interpreted as irrational intervention behavior. As long as this is not communicated by the central bank, however, this type of intervention reflects other intervention targets and should lead to losses in traders' confidence according to the model. A logistic normalization transforms the value c_t into a confidence measure w_t.[12] Combining equations (6) – (10), the solution for the exchange rates can then be derived as

$$s_{t+1} = s_t + \alpha(s_t - s_{t-1}) + \delta w_t(f_t - s_t) + \gamma(i_t^* - i_t) + \epsilon_{t+1}, \tag{11}$$

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 (11) we can see that, for a given value of δ, informed traders' stabilizing impact on the exchange rate increases nonlinearly with their confidence in the 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. How-

[12]With the logistic form of equation (10) we follow the switching mechanism of Brock and Hommes (1997) and Lux (1998) and are in the spirit of recent work by De Grauwe and Grimaldi (2005, 2006), who develop a similar switching function in their model of chartist-fundamentalist interaction.

ever, as the exchange rate becomes increasingly misaligned, informed traders reduce their orders and mean reversion weakens. This creates a role for central bank intervention that, through 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 the empirical implementation of the model.

5 The empirical model

To empirically investigate the coordination channel of RBA intervention operations, we apply a Smooth Transition Regression (STR) model originally proposed by Ozaki (1985) and further developed and analyzed by Teräsvirta and Anderson (1992), Granger and Teräsvirta (1993) and Teräsvirta (1994). STR 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 STR framework has previously proved successful in applications to exchange rate behavior (Taylor and Peel, 2000; Taylor, Peel and Sarno, 2001; Kilian and Taylor, 2003).[13]

Since the data frequency is daily, 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 STR-GARCH procedure originally developed by Lundbergh and Teräsvirta (1998) and applied by Gallagher and Taylor (2001) and Reitz and Westerhoff (2003). The STR-GARCH model consists of a mean equation containing a smooth transition function and a standard GARCH(1,1) volatility equation. To assess the persistence of intervention effectiveness, we estimate the nonlinear influence of RBA operations for the period up to four lags. In the present context, given the theoretical model outlined above, this suggests an empirical model of the form:

$$\Delta s_t = \alpha \Delta s_{t-1} + \delta w_t (f_{t-1} - s_{t-1}) + \gamma (i^*_{t-1} - i_{t-1}) + \epsilon_t \tag{12}$$

[13]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 STR specification.

$$w_t(\rho, \phi, f_{t-d}, int_{t-d}, h_{t-d}) = \frac{2exp(-(\rho - \sum_{i=1}^{4} \phi_i D_{t-i} INT_{t-i})\frac{|f_{t-d}-s_{t-d}|}{\sqrt{h_{t-d}}})}{1 + exp(-(\rho - \sum_{i=1}^{4} \phi_i D_{t-i} INT_{t-i})\frac{|f_{t-d}-s_{t-d}|}{\sqrt{h_{t-d}}})} \quad (13)$$

$$h_t = \beta_0 + \beta_1 \epsilon_{t-1}^2 + \beta_2 h_{t-1}, \quad (14)$$

where Δ is the first-difference operator and $\epsilon = \nu_t \sqrt{h_t}$ and ν_t^{iid} is N(0,1). There are two major differences between the empirical model (12) – (14) and the theoretical model set out in the previous section. First, we introduce a GARCH model to capture the conditional variance of the error term, which is important given that we apply our model to daily exchange rate movements. Second, 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 STR models has been stressed by Teräsvirta and others (e.g., Teräsvirta and Anderson, 1992; Granger and Teräsvirta, 1993: Teräsvirta, 1994).

6 Estimation results

The modeling procedure for building STR 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. We found that first-order autocorrelation seemed to be appropriate for exchange rate returns in our data. Second, we tested linearity against the STR 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. The transition parameters ρ and ϕ_i are slope parameters that determine the speed of transition between the two extreme regimes, with low absolute values resulting in slower transition. Since equation (13) 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 may cause particular problems such as slow convergence of the estimation routine or overestimation, and suggests setting the initial value of the transition parameters 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 $\rho = 1$ and $\phi_i = 0$ as the starting values for the estimation routine. Table 2 contains our estimation results.

The estimation results are pleasing in the sense that the point estimates of the coefficients are significantly different from zero (except for α) and appropriately signed and the estimated model passes a number of diagnostic checks for remaining serial correlation, nonlinearity or conditional heteroskedasticity in the standardized residuals. We also tested the model against a restricted model in which $\delta = \gamma = \rho = \phi_i = 0$; the constrained model thus 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 STR-GARCH model at the one percent significance level.

While the positive signs of the point estimates of the trader coefficients, i.e., α and δ respectively, accord with our theoretical priors, only the estimate of the informed trader δ coefficient is statistically significant. The fact that the estimate of the uninformed trader coefficient α is statistically insignificant reveals that assuming a simple trend-following trading strategy may not be sufficient in order to model the average influence of chartist behavior (Menkhoff and Taylor, 2007). On the other hand, a negative and statistically significant estimate of the interest rate differential coefficient γ implies, on average, an appreciation of the AUD when Australian interest rates are higher than US interest rates. Given our discussion of the likely sign of the coefficients b^U and b^I in Section 4, however, this is not surprising and is consistent with evidence on the prevalence of so-called "carry trades" (Galati, Heath and McGuire, 2007).

The statistically significant and positively signed parameter ρ indicates that 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 stabilizing orders. However, the statistically significant and positive point estimate of the intervention parameter ϕ_1 indicates that an RBA intervention operation was able to compensate for the lack of confidence caused by exchange rate misalignment.

Within the coordination channel, intervention operations alter the composition of the foreign exchange market, implying that the effect of intervention on exchange rates is presumed to be persistent. However, it might be argued that the record of frequent RBA operations introduced some habit persistence and may have led informed traders to return to the foreign exchange market only if the central bank persistently intervenes. Put differently, stopping operations may be interpreted as an adverse signal, thereby thwarting the stabilizing effect of recent intervention. On the other hand, Neely (2005) points out that there is good reason to assume that the overall effect of intervention on exchange rates "takes at least a few days". To assess the persistence of intervention effectiveness, we therefore allow for additional lags in the transition function. The estimation routine reveals that lag orders higher than four are statistically insignificant at the ten percent level, implying that the inclusion of the last four operations seems to be sufficient. The coefficients reveal that the cumulative influence of intervention on traders' confidence drops slightly at the next trading day and then recovers. In line with Neely's (2005) conjecture, the inclusion of additional lags confirms the persistence of intervention effectiveness via the coordination channel.

From the model's perspective, the implication is that RBA interventions encouraged agents to engage in fundamental speculation, thereby helping to bring the exchange rate back towards the ppp level. Overall, our estimation results provide evidence for the idea that RBA interventions exhibit a stabilizing influence on the AUD-USD exchange rate by coordinating speculation based on exchange rate fundamentals.

7 Robustness checks

Linear influence of intervention operations

Although, as outlined in the introduction, the literature on Australian intervention effectiveness has been inconclusive, the microstructural model generally interprets intervention operations as order flow from informed sources. To this end, the nonlinear influence of central bank intervention via the coordination channel may be accompanied – or even substituted – by more standard routes of effectiveness. In order to test for a direct (linear) impact we introduce contemporaneous operations in equation (12)

$$\Delta s_t = \alpha \Delta s_{t-1} + \delta w_t (f_{t-1} - s_{t-1}) + \gamma (i^*_{t-1} - i_{t-1}) + \eta RBA_t + \epsilon_t, \tag{15}$$

where RBA_t denote the RBA's purchases of US dollars. The re-estimation of the model revealed an adversely signed coefficient, which is most likely due to a simultaneity problem, quite common in central bank intervention studies (Dominguez and Frankel, 1993). Against this background, we interpret this result as a consequence of the RBA's leaning-against-the-wind-strategy implying US dollar purchases if returns were negative and vice versa (Neely, 2004). Thus, the negative parameter of intervention operations most likely measures a combination of the central banks reaction to exchange rate changes and the influence of intervention on exchange rates. Consequently, a linear impact of intervention on exchange rate is ambiguous, as the literature on RBA intervention effectiveness suggests.[14]

Sub-sample estimation

As briefly outlined in the introduction, the RBA changed its intervention strategy in the early 1990s. Of course, abandoning a policy of generally small daily interventions with frequent changes in direction in favor of less frequent but larger scale interventions may influence the working of the coordination channel. As a further robustness check we split up the sample according to Kim et al. (2000) into five subperiods: (i) January 1984 – June 1986; (ii) July 1986 – September 1991; (iii) October 1991 – November 1993; (iv)

[14] Lagged values of RBA operations do not change this result.

July 1995 – December 1997; (v) January 1998 – December 2008.[15] Of course, most of these subperiods are too short to obtain reliable estimates of the full set of parameters due to the recursive structure of the nonlinear model. To reduce complexity we assume that the structural coefficients α, δ, γ, ρ, β_0, β_1, and β_2 equal their values of the full-sample estimation. The results of the sub-sample estimations based on these parameter restrictions are reported in Table 3.

While observing remarkable differences in the sign and absolute value of the parameters ϕ_i, the cumulative impact of intervention is positive in every single subperiod. In subperiod (iv) the primary impact is negative indicating a rise in traders' confidence while the RBA operated in the opposite direction. This is consistent with Kim et al. (2000) reporting that during that subperiod 'the RBA interventions were motivated to take advantage of the strong AUD to retire the bulk of existing swap positions at favorable prices, rather than motivated by the aim to achieving specific goals.' Moreover, Kim et al. (2000) report that compared to the other subperiods, the RBA has not released official statements along their intervention strategy. Since the perception of RBA intervention is a prerequisite for interventions to work through the coordination channel it is most likely that the market needed a trading day to learn RBA's foreign exchange operations. In fact, intervention effectiveness strongly recovers the next day as indicated by the coefficient ϕ_2.

Regarding the economic significance coefficients the results suggest that, at the average level of exchange volatility (0.6%), a 10% misalignment results in a daily mean reversion towards the fundamentals of 0.07%, or of 17.5% on an annualized basis. Under these circumstances a parameter value of 0.004 means that an average intervention of USD 40 million increases the mean reversion parameter to 0.79%. The degree of mean reversion induced by a slightly larger than average intervention operation is therefore some ten times higher with the intervention than without it, indicating an economically significant contribution to market stability from the RBA.

[15] Since the RBA rarely intervened between December 1993 and June 1995 we skipped this subperiod.

8 Conclusion

In contrast to standard linear time-series approaches employed by a number of previous contributions on RBA intervention effectiveness, this paper focuses on the RBA's potential to influence exchange rates in a nonlinear fashion. We first apply a STARTZ model to show that the AUD-USD exchange rate in fact exhibits nonlinearities in the sense that mean reversion increases with the degree of exchange rate misalignment. In a second step, we estimate a microstructural model of daily exchange rate behavior to study the effectiveness of RBA interventions within the framework of the so-called coordination channel of intervention effectiveness. According to the coordination channel, mean reversion of the exchange rate is provided by stabilizing speculation of informed traders, yet their market activity depends on their confidence in fundamental analysis. In this market setup, intervention operations may stabilize exchange rates by coordinating the actions of informed traders. In our analysis, the fundamental value of the exchange rate was approximated by the purchasing power parity, implying that intervention effectiveness is assessed by testing whether intervention operations tend to induce stability in the real exchange rate. Our empirical analysis provides evidence in favor of this route of intervention effectiveness. We find that the RBA's intervention policy tended to reduce misalignments in a nonlinear fashion, which, in turn, may explain why the Australian authorities continued to intervene in the foreign exchange market.

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Table 1: Parameter estimates of the STARTZ model

	January 2, 1984 - December 30, 2008
z^L	$-0.59(105.65)^{***}$
z^U	$0.59(108.17)^{***}$
α_1	$0.64(41.54)^{***}$
α_2	$-1.76(1.37)^{*}$
ψ_m	$-17.85(45.16)^{***}$
θ_m	$-0.18(75.16)^{***}$
ξ	$0.01(42.62)^{***}$
β_0	$0.000001(3.86)^{***}$
β_1	$0.07(9.80)^{***}$
β_2	$0.92(119.10)^{***}$
ψ_v	$-21.75(49.20)^{***}$
θ_v	$-64.10(41.14)^{***}$
LLh	29,877.8
$AR(1)$	0.50
$AR(5)$	0.57
$ARCH(1)$	0.32
$ARCH(5)$	0.62
$NRNL(mean)$	0.37
$NRNL(vol)$	0.04

Notes: The sample contains daily observations of the dollar spot exchange rate against the Australian dollar from January 1984 to March 2005. α_i, z^L, z^U, ψ_m, θ_m indicate the estimated parameters of the mean equations; β_0, β_1, β_2, ξ, ψ_v, and θ_v are the estimated parameters of the volatility equation; LLh is the log likelihood value; $AR(p)$ 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.

Table 2: Parameter estimates of the STR GARCH model

	January 2, 1984 - December 30, 2008
γ	$-1.26(2.26)^{**}$
α	0.01 (0.83)
δ	$0.02(4.78)^{***}$
ρ	$0.227(2.67)^{***}$
ϕ_1	$0.006(2.98)^{***}$
ϕ_2	$-0.001(3.15)^{***}$
ϕ_3	$0.001(1.97)^{**}$
ϕ_4	$-0.001(1.72)^{*}$
β_0	$0.005(4.70)^{***}$
β_1	$0.069(10.74)^{***}$
β_2	$0.922(137.34)^{***}$
LLh	-7.55
LRT	50.67^{***}
$AR(1)$	0.32
$AR(5)$	0.24
$ARCH(1)$	0.21
$ARCH(5)$	0.55
$NRNL$	0.17

Notes: The sample contains daily observations of the dollar spot exchange rate against the Australian dollar from January 1984 to March 2005. 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; LRT is the likelihood ratio test statistic with restrictions $\alpha = \delta = \gamma = \phi = 0$. $AR(p)$ 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.

Table 3: Sub-sample estimates of the STR GARCH model

Sub-periods	01/02/84 – 06/30/86	07/01/86 – 09/30/91	01/10/91 – 11/30/93	01/07/95 – 12/30/97	01/01/98 – 12/30/08
ϕ_1	0.020***	0.004***	0.015***	−0.003***	0.007***
	(5.69)	(7.43)	(10.14)	(8.77)	(3.18)
ϕ_2	−0.010***	−0.002***	−0.005***	0.010***	0.002**
	(6.78)	(11.09)	(5.87)	(8.77)	(1.99)
ϕ_3	0.004**	0.0002	−0.010***	0.000	−0.001***
	(2.21)	(0.42)	(5.68)	(0.01)	(5.70)
ϕ_4	−0.008***	−0.0006***	0.002***	−0.0015***	0.001***
	(3.20)	(3.87)	(5.11)	(4.43)	(4.82)
Intervention					
Frequency	84.6	68.9	23.5	43.7	42.0
Average Volume	13.4	62.5	138.0	39.4	43.5
Maximum	90	1025	1256	286	1189

Notes: The sample contains daily observations of the dollar spot exchange rate against the Australian dollar for different subperiods. the non-intervention period between 11/30/93 – 06/30/95 is skipped. The parameter values of α, δ, γ, ρ, β_0, β_1, and β_2 are taken from the full-sample estimation. 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. The lower panel reports the frequency, i.e. the number of interventions to total days, the average intervention volume and the highest intervention.

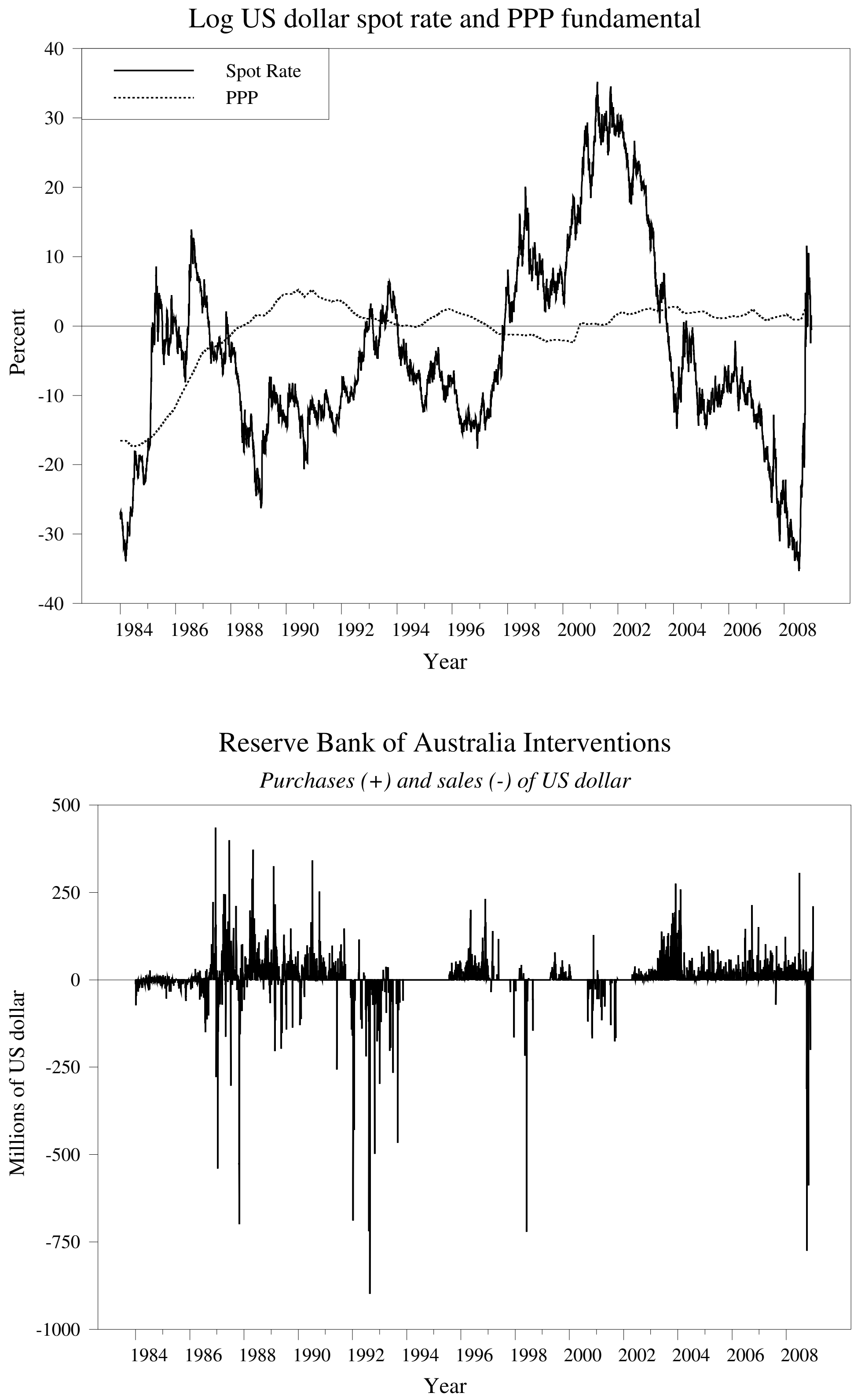

Figure 1: Log US dollar spot rate, PPP fundamental, and RBA intervention

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