Did the Current International Financial Crisis Increase Central Bank Synchronization?

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Abstract

We investigate the synchronization hypothesis of leading central banks during the current global financial crisis. To this end, we employ several advanced econometric techniques which enable us to capture both linear and nonlinear links in target interest rates. We empirically study both the degree and the effectiveness of central bank coordinated-policy actions for three representative developed countries: the US, the UK, and France. As expected, we find strong evidence of causal interactions between monetary policies conducted by the US Federal Reserves (Fed), the Bank of England and the ECB. It is equally important to note that exogenous shifts in the Fed's monetary policy lead those in the UK and the ECB within a horizon of one to two days. The results also suggest that the US, European and UK central banks appear to have shown the same behavior in recent months, which explains the convergence toward a common equilibrium in the long run.

Keywords: Global financial crisis, monetary market relationships, central bank synchronization, VECMs and STECMs.

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1. Introduction

Financial stability is a key factor for a healthy and successful economy. In this context, depositors and investors have confidence that the financial system is safe and stable with a high degree of resilience to internal and external shocks. It is also important that failures in particular areas cannot spread to other sectors or to the whole economy.

Accordingly, preserving financial stability is widely viewed as a primary role for central banks. The underlying rationale for acting in accordance with this objective is that monetary policy and the stability of financial systems is interlinked. Indeed, a large number of past studies have found changes in target interest rates have had a significant impact on financial market conditions and stability by affecting equity prices and macroeconomic fundamentals such as inflation and exchange rate equilibriums (cf. Rigobon and Sack, 2003; Bernanke and Kuttner, 2005; Chen, 2007; Ioannidis and Kontonikas, 2007). To the extent that the financial system performs the function of efficiently allocating available funds to the most productive investments for individuals and corporations, the rise of financial instability can lead to stock market collapses and, as a result, provoke harmful repercussions on financial sector performance and economic growth as a whole. Inversely, if central banks fail to control the growing financial instability, their policies cannot be properly applied due to ineffective asset allocation and a pervasive lack of confidence by the investor community. It should be noted that the issue of financial stability and central bank missions has been examined by Healey (2001), Goodhart (2006) and Cihák (2006), among others.

More recently, the role of central banks in the regulation of global financial stability has come under close scrutiny in the aftermath of the financial crisis that originated with the massive failures of the subprime mortgage markets in the US and quickly spilled over to other countries. In addition to the efforts of other authorities such as governments and international regulatory institutions, it is generally believed that policy interventions by central banks are essential to regulate financial stability and to repair the negative impact of the financial crisis, but how can these actions be made most effective? In answer to this question, the majority of researchers and policymakers share a common view that more central bank coordination and cooperation would help the global economy to recover from the financial crisis.

Three factors underpin this notion. Firstly, policy coordination can help to remedy an operational asymmetry: that is, the current financial crisis is a global matter as a result of financial liberalization and globalization of capital markets, while policy coordination of central banks at international level is relatively weak. During the recent fifth ECB (European Central Bank) central banking conference, the Chairman of the Board of Governors of the US Fed (US Federal Reserve System), Ben Bernanke, pointed out that although the merits of coordinated monetary policies among central banks have been discussed by policymakers and academics for decades, such coordination has been quite rare in practice. A prime example concerns the joint announcement of interest rate cuts by the US Fed with five other leading central banks on October 8, 2008, in an effort to calm down the financial market turmoil and to combat the significant deterioration of the main economic performance indicators.

Secondly, the recent episode of financial instability and crisis indicates that the hypothesis of efficient capital markets, the purpose of self-regulated markets and the resilience of free markets appear implausible. More market discipline, developed in a coordinated framework by central banks, thus seems necessary to deal with global economic challenges.

Thirdly, as noted by many economists and banking experts, the current architecture of the global financial system is subject to much criticism due to the significant deficiencies and illegal actions carried out by major international financial institutions. Indeed, during the

2007-2009 crisis, the International Monetary Fund appeared to demonstrate major failures in fostering global monetary cooperation and securing global financial stability, while the Bank of International Settlement failed to provide a prudential framework for macroeconomic policies. Consequently, the central banks have been emerging as key actors in global regulation tasks by actively assuming their role as liquidity providers for the financial markets in crisis as a last resort lender. The principal aim is to restore investor confidence and to reduce the impact of the crisis on the real economy, and on financial and banking sectors. However, they are aware that they cannot monitor the financial crisis alone without effective coordination with other central banks elsewhere. For instance, the G20 summit of April 2, 2009, which met to address the financial crisis, gave hope that there would be more coordination, at least among the most important central bankers.

Table 1: Timelines of target interest rate changes by the US Fed, the Bank of England and the European Central Bank: Sep. 2007 – Apr. 2009 (*changes in basis points compared to previous rate level*)

US Federal Reserve System		**Bank of England**		**European Central Bank**	
Announcement dates	*Magnitude of change*	*Announcement dates*	*Magnitude of change*	*Announcement dates*	*Magnitude of change*
Sep. 18, 2007	-50				
Oct. 31, 2007	-25				
Dec. 11, 2007	-25	Dec. 6, 2007	-25		
Jan. 22, 2008	-75	Jan., 2008	-25		
Jan. 30, 2008	-50				
Mar. 18, 2008	-75				
Apr. 30, 2008	-25	Apr. 10, 2008	-25	Apr., 2008	
				Jul. 9, 2008	+25
Oct. 8, 2008	-50	Oct. 8, 2008	-50	Oct. 8, 2008	-50
Oct. 29, 2008	-50			Oct. 9, 2008	+50
		Nov. 6, 2008	-150	Nov. 12, 2008	-50
Dec. 16, 2008	-75	Dec. 4, 2008	-100	Dec. 10, 2008	-75
		Jan. 8, 2009	-50	Jan. 21, 2009	-100
		Feb. 5, 2009	-50		
		Mar. 5, 2009	-50	Mar. 11, 2009	-50
				Apr. 8, 2009	-50

Note: For the US, the changes in federal funds rate (*i.e.*, the interest rate at which depository institutions lend balances at the Federal Reserve to other depository institutions overnight) are specified and announced by the Federal Open Market Committee (FOMC) in its policy stance. For the UK, the official Bank Rate (*i.e.*, interest rate paid on commercial bank reserves) is voted by the Bank of England's Monetary Policy Committee. The ECB key interest rate is set by its Governing Council and refers to its deposit rate published in the monthly bulletin.

The context of today's global financial crisis and economic meltdown has created a natural framework for investigating the issue of central bank coordination. This paper aims to contribute to the debate by focusing on the effectiveness of monetary policy synchronization between the US Fed, the Bank of England and the Bank of France. Our motivation stems essentially from the importance of the policy decisions made by these central banks in the present global economy, and from their recent efforts to work together to manage the issues arising from the crisis as indicated in Table 1. Likewise, understanding the way each central bank conducts its monetary policy with its peers is of major interest since it gives us greater insight into the policy feedback rules.

We therefore attempted to empirically measure the degree of policy synchronization of certain central banks with respect to changes in their target interest rates during the current global financial crisis. These policy rates are important because they signal the monetary policy stance to the public, and have a considerable impact on financial market conditions and investment decisions. To this end, a nonlinear univariate and trivariate cointegration framework based on VECM (*Vector Error Correction Model*) and STECM (*Switching Transition Error Correction Model*) was developed to model the dynamics and the potential interest-rate interdependences between the three market zones. While the VECM is commonly known to be useful for modeling the nonlinear link between different nonstationary series, which is the case of interest rates, the STECM improves the nonlinear adjustment process of interest rates to their long-run equilibrium when interest rate deviations exceed a certain threshold. In other words, our combined econometric methodology is suitable for capturing any structural changes in the error-correction term.

Using three-month interbank offered interest rates, we find strong evidence of causal interactions between monetary policies conducted by the US Fed, the Bank of England and the ECB. Moreover, we show that exogenous shifts in the Fed's monetary policy lead those in the UK and the ECB within a horizon of one to two days. Our findings also suggest that the US, European and UK central banks appear to have had the same behavior in recent months, which explains the convergence of central bank target interest rates toward a common equilibrium in the long run. These findings are consistent with that of Scotti (2006) who investigated interest-rate feedback rules between the US Fed and ECB, using a combination of a bivariate autoregressive conditional hazard model and a conditional bivariate ordered probit model.

The remaining part of this work is organized as follows. Section 2 describes our econometric methodology and the data used. The main focus is on the specification, econometric implementation and estimation of the linear and nonlinear Error Correction Models. Section 3 reports and discusses the empirical results. Concluding remarks and policy implications are provided in Section 4.

2. Threshold Cointegration for Interest Rate Adjustment Dynamics

2.1 Linear Adjustment

The linear cointegration framework, introduced by Granger (1981) and developed by Engle and Granger (1987), and Johansen (1988), among others, indicates that two integrated series of order one, I(1), X_t and Y_t (e.g., two interest rate series) can evolve together in the long run if a linear combination between them is stationary. Two series are said to be cointegrated in this case and the theory suggests the existence of a long-run equilibrium to which the system converges over time. In addition, the following long-run relationship between X_t and Y_t must be verified:

$$Y_t = \alpha_0 + \alpha_1 X_t + z_t \tag{1}$$

In the above expression, z_t can be interpreted as the equilibrium error indicating the distance that the system of interest rates is from equilibrium at any point in time. Note too that z_t is an I(0) process and that (α_0, α_1) defines the cointegrated vector.

In the hypothesis of stationarity of z_t, the adjustment may be reproduced using a Linear Error Correction Model (LECM) and the dynamics of interest rate deviations from equilibrium can be modeled as:

$$\Delta z_t = \phi_0 + \lambda z_{t-1} + \sum_{i=1}^{p} \phi_i \Delta z_{t-i} + \varepsilon_t \tag{2}$$

where λ is the linear adjustment term ensuring the mean reversion to the equilibrium, ϕ_i are autoregressive parameters with $\forall\ i = 1,...,\ p$, ε_t is an error term and $\varepsilon_t \to N(0, \sigma_\varepsilon^2)$. Nevertheless, this specification has a drawback in that the adjustment to the long-run equilibrium is linear, symmetric and continuous, with a constant adjustment speed measured by the coefficient λ. It naturally becomes inefficient whenever the adjustment process is asymmetric, nonlinear and with a time-varying adjustment speed. We show, however, that the linear framework can be improved to capture these stylized facets in a cointegrating system when we extend it to a nonlinear framework.

2.2 The STECMs

We now focus on the introduction of the hypotheses of nonlinearity and switching regimes to the LECM specification. This yields a promising nonlinear framework given by the STECMs (*Switching Transition Error Correction Models*). The latter were initially introduced by Granger and Teräsvirta (1993), and applied for the first time by Van Dijk and Franses (2000), while their statistical properties and modeling approach were explicitly developed by Van Dijk *et al.* (2002). One of the main advantages of this nonlinear specification is to enable the adjustment of interest rate dynamics to be nonlinear and asymmetrical with time-varying adjustment speed. In particular, it takes the smoothness in adjustment into account, and specifies the dynamic process depending on both the magnitude and/or the sign of disequilibrium associated with exogenous shocks and financial crises.

STECMs have recently been used in several studies including, among others, Anderson (1997), Balke and Fomby (1997), and Liu (2001) for interest rates; Franses and Van Dijk (2000) and Jawadi and Prat (2009) for stock prices, Jawadi *et al*. (2009) for insurance premiums; Escribano (1997) for the money demands of the United Kingdom; and Rothman *et al.* (2001) for relationships between production and money demands. Overall, these studies suggest that STECMs are suitable for capturing nonlinearity and switching regimes, smoothness, persistence, discontinuities, structural breaks, inertia effects and asymmetry in the adjustment dynamics induced by market friction, by conditionally defining an on-off adjustment dynamic process on the sign and/or the size of the disequilibrium.

Formally, the STECM constitutes an extension of the LECM to the nonlinear framework. As a prime example, a two-regime STECM can be specified as a combination of two LECMs insofar as it integrates two adjustment terms reproducing respectively the degree of adjustment in the first regime and the intensity of error-correction in the second regime. In practice, the extension to the nonlinear framework is made through the introduction of a nonlinear component defined as the product of a transition function and the adjustment term of the second regime. More specifically, we can set up a two-regime STECM for interest rate deviations as follows:

$$\Delta z_t = \phi_0 + \lambda_1 z_{t-1} + \sum_{i=1}^{p} \phi_{1,i} \Delta z_{t-i} + \lambda_2 z_{t-1} \times F(z_{t-d}, \gamma, c) + \varepsilon_t \tag{3}$$

where λ_1 and λ_2 are the adjustment terms in the 1st and 2nd regimes respectively; z_{t-1} is the error-correction term; *F(.)* is the transition function; γ and *c* refer respectively to the transition speed ($\gamma > 0$) and the threshold parameters; *d* is the delay parameter; and z_{t-d} denotes the transition variable.

The STECM describes two regimes corresponding to the extreme values of *F(.)* and an intermediate state continuum. The first regime is obtained when the interest rate adjustment dynamic is close to equilibrium (i.e., *F = 0*) and corresponds to:

$$\Delta z_t = \phi_0 + \lambda_1 z_{t-1} + \sum_{i=1}^{p} \phi_{1,i} \Delta z_{t-i} + \varepsilon_t \tag{4}$$

The dynamics of the second extreme regime is written as:

$$\Delta z_t = \phi_0 + (\lambda_1 + \lambda_2) z_{t-1} + \sum_{i=1}^{p} \phi_{1,i} \Delta z_{t-i} + \varepsilon_t \tag{5}$$

In all cases, λ_1 and λ_2 constitute the most important parameters for this specification as their values and signs determine the adjustment dynamics of interest rates and their convergence speed toward equilibrium (Michael *et al.*, 1997). Indeed, even though λ_1 is positive, interest rates are nonlinearly mean-reverting and the STECM is stable only if λ_2 and ($\lambda_1 + \lambda_2$) are negative and statistically significant. This implies that for small deviations, interest rate movements may depart from the equilibrium and would be characterized by explosive behavior or a unit root, while for large deviations, the adjustment process would be mean-reverting.

According to Teräsvirta and Anderson (1992), Granger and Teräsvirta (1993), and Teräsvirta (1994), *F(.)* can be either an exponential or a logistical function. A first-order logistical transition function is thus defined as follows:

$$F(z_{t-d}, \gamma, c) = \left[1 + \exp\left(-\gamma \; (z_{t-d} - c)\right)\right]^{-1} \tag{6}$$

Note that a first-order exponential transition function corresponds to:

$$F(z_{t-d}, \; \gamma, \; c) = 1 - \exp\left[-\gamma \; (z_{t-d} - c)^2\right] \tag{7}$$

The system composed of Equations (3) and (6) defines a LSTECM, whereas the system combining Equations (3) and (7) results in an ESTECM. The latter captures the asymmetry inherent in the size of interest rate deviations while the LSTECM reproduces the asymmetry in the sign of interest rate deviations.[1] Two interest rate dynamics or regimes are distinguished in accordance with these specifications. In the first regime, interest rate deviations are small, and may be away from the equilibrium, uncorrected, near unit root and random. However, in the second regime, large interest rate deviations shall be nonlinearly mean-reverting to equilibrium when they exceed a certain threshold and then approach a white noise.

According to Van Dijk *et al.* (2002), the empirical modeling approach of STECMs is carried out in several steps. The specification first requires the definition of the explanatory variables, the determination of the lag number (p), linearity tests and the choice of transition function. Second, the ESTECM is estimated by the Nonlinear Least Squares (NLS) method based on a nonlinear optimization process.[2]

Before moving on to the analysis of the empirical results, we briefly present the linearity tests required for STECM modeling.

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[1] See Teräsvirta (1994) for more details regarding the statistical properties of these transition functions.
[2] See Jawadi and Prat (2009) for more details concerning the STECM modeling.

2.3 Nonlinear Adjustment Tests

These testing procedures aim to test the null hypothesis of linearity H_0 against its alternative of nonlinearity H_1. Under H_0, the interest rate adjustment deviation dynamic is reproduced using a LECM (e.g., Equation (2)), while a STECM given by Equation (3) is more appropriate under (H_1). However, the null hypothesis is defined differently and this can give rise to a problem of nuisance parameters, and the usual statistic inference is no longer available. To remedy this problem, Luukkonen *et al.* (1988) proposed replacing the transition function *F(.)* in Equation (3) by its Taylor development and applying Lagrange Multiplier (LM) tests to check for nonlinear adjustment. In the LM tests, their distribution is known under H_0 and follows a standard χ^2 distribution.

To apply these tests, we have to determine the number of lags in the LECM, noted p, based on usual information criteria (AIC and BIC), the Ljung-Box test for serial autocorrelation, and the partial autocorrelation function. Next, a grid search defines the possible value for the delay parameter (d). For example, plausible values that we consider for *d* include the following set [1,2,3,4,5] when using daily data. We then apply nonlinear adjustment tests for the possible values of d. The optimal value defining the transition in Equation (3) is the one for which linearity is most rejected.

As pointed out by Luukkonen and Saikkonen (1988), the LM test implementation (LM_3 test) can be described in three main steps:[3]

Step 1: We estimate the LECM and compute the Squared Sum of Residuals under H_0 (SSR_0).

Step 2: We estimate the following auxiliary regression for each possible value of d and we compute the Squared Sum of Residuals associated with this regression (SSR_1):

$$\Delta z_t = \phi_0 + \lambda_1 z_{t-1} + \sum_{i=1}^{p} \phi_{1,i} \Delta z_{t-i} + \lambda_2 z_{t-1} \times z_{t-d} + \lambda_2 z_{t-1} \times z^2_{t-d} + \lambda_2 z_{t-1} \times z^3_{t-d} + \nu_t \qquad (8)$$

Step 3: We compute the Lagrange Multiplier statistics of LM_3 test as follows:

$LM_3(d) = T \times \frac{SSR_0 - SSR_1}{SSR_0} \rightarrow_{H_0} \chi^2(3\,p)$, where p and T refer to the number of lags and the number of observations respectively.

In practice, the LM_3 statistics are computed for all possible values of d. The optimal value for d is the one whereby linearity is strongly rejected, or equivalently the value that should minimize the *p*-value of the LM_3 test.

3. Empirical Results

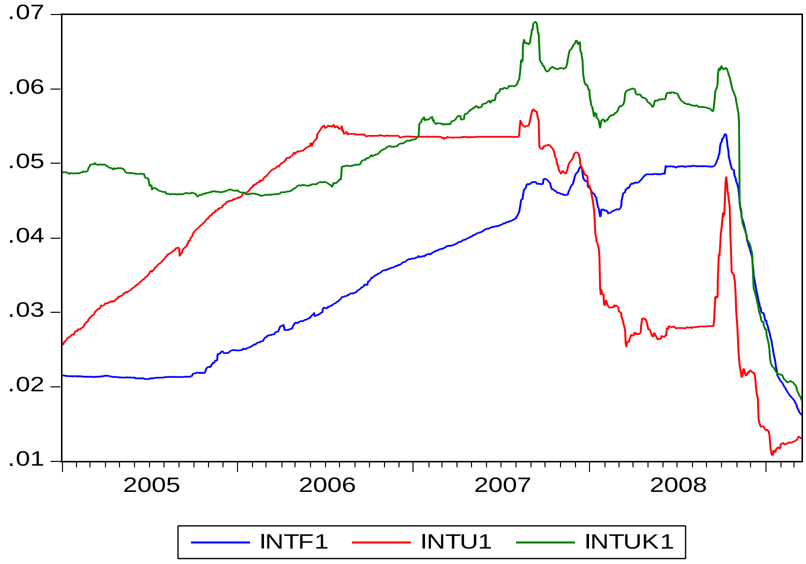
3.1 Data and Preliminary Results

This study aims to investigate how American, British and European central banks have managed the current international financial crisis. It also attempts to investigate whether the current financial crisis leads to greater synchronization between their monetary policies and decisions. To this end, we use data from three industrialized countries: the USA, the UK and France. The choice of the USA arises from the fact that the financial crisis originated in the USA due to massive failures in the housing markets. It also helps us to study the reaction of

[3] Several LM tests were developed (LM_1, LM_2, LM_3, LM_4). For more details of these tests, see Van Dijk *et al.* (2002).

the Federal Reserve and its decisions vis-à-vis this crisis. As the financial crisis was rapidly transmitted to other countries, we also decided to study the UK and France to explore the way the Bank of England and the ECB reacted to reduce the negative effects of the said crisis.

Figure 1: Interest rate dynamics



The data consists of the daily three-month interest rates obtained from Datastream International. Working with daily data is supported by the fact that monetary policy adjustments tend to be immediate in the short term. As the main aim of this paper is to study the central banks' policies over recent years and to investigate their responses during the current international financial crisis, the data selected covers the period December 31, 2004 to March 19, 2009.

Before turning to the cointegration tests, we checked the integration order of the interest rate series. To do this, we used several traditional unit root tests such as the Augmented Dickey-Fuller (1981)'s test, and Phillips and Perron (1988)'s test. The null hypothesis of unit root is not rejected in any of the interest rate series studied, as suggested by Figure 1. However, since these tests may not be powerful when data is not generated by linear processes, we also applied another unit root test that is robust to structural breaks (i.e. test of Zivot and Andrew, 1992). The latter also confirms the previous results, indicating that the interest rate series are integrated of order one, noted I(1), for the three countries in our sample.[4]

In order to get an overview regarding the linkages between the American, European and British central bank policies and decisions, we estimated the bilateral correlations between their interest rates. In addition, to check whether the current financial crisis increased comovements between them, we computed these correlations over two subperiods: December 31, 2004 - July 31, 2007 and August 01, 2007 - March 19, 2009. The results are reported in Table 2. This choice approximately identifies different central bank policies before and after the subprime crisis.

[4] Results of unit root tests are not presented to save space but may be obtained upon request to the corresponding author.

Table 2: Correlation Matrix

	DIF	DIU	DIUK
First Subperiod : December, 31, 2004 - July, 31, 2007			
DIF	1.00	0.02	0.07
DIU		1.00	-0.02
DIUK			1.00
Second subperiod: August, 01, 2007– March, 19, 2009			
DIF	1.00	0.38	0.58
DIU		1.00	0.40
DIUK			1.00

Note: DIF, DIU and DIUK designate interest rate changes for respectively France, the USA and the UK.

Our findings show a significant increase in bilateral correlations after the subprime crisis. This is indicative that the crisis yielded greater synchronization between the monetary policies led by the American, European and British central banks, as central banks have a tendency to coordinate their policies to a larger extent in order to regulate and overcome the financial crisis. However, these findings need to be improved using more parsimonious, robust modeling techniques since the correlation techniques are based on static and linear modeling.

Furthermore, the descriptive statistics of interest rates give rise to a number of remarks. On the one hand, the negative sign of the interest rate highlights the large decrease in interest rates in recent months, notably after the current international financial crisis. On the other hand, the strong rejection of symmetry and normality as well as the leptokurtic character inherent to interest rate dynamics suggest some evidence of nonlinearity and asymmetry characterizing their dynamics.

Table 3: Descriptive Statistics

	DIF	DIU	DIUK
Mean	-4.93E-06	-1.15E-05	-2.80E-05
Std. Dev.	0.0002	0.0004	0.0004
Skewness	-1.11	-2.66	-16.13
Kurtosis	12.72	38.21	410.42
Jarque-Bera	4542.35	57982.8	7634819.0
Probability	0.00	0.00	0.00

Note: DIF, DIU and DIUK designate interest rate changes for respectively France, the USA and the UK.

Before moving to the investigation of the interest rate dynamics via nonlinear modeling, we propose reproducing the linkages between central bank policies in a linear framework using linear cointegration techniques (i.e., two-step procedure of Engle and Granger, 1987; and trace test procedure of Johansen, 1988).

3.2 Bivariate and Multivariate Linear Cointegration Modeling

3.2.1 The Engle and Granger (1987)'s Two-Step Procedure

We firstly estimate a long-run relationship between interest rates (i.e., Equation (9)) that is an extension of the first equation) and test for a cointegration relationship between interest rates by testing the stationarity of the residual of the cointegration relationship (z_t). The stationarity of the error disequilibrium (z_t) suggests that interest rates are cointegrated and that they may be linearly mean-reverting.

$$i_t^j = \alpha + \beta \, i_t^k + \delta \, i_t^l + z_t \qquad (9)$$

Where i_t denotes the interest rate, (α, β, δ) is the cointegrated vector and z_t measures the disequilibrium error. We study three cases: for j = France, k = USA and l = UK; for j = UK, k = USA and l = France; and finally for j = USA, k = France and l = UK.

Table 4: Linear Cointegration Tests

	France	UK	USA
α	-0.005 (-5.06)	0.01 (25.7)	0.003 (2.05)
β	-0.22 (-12.07)	0.30 (22.4)	-0.53 (-12.07)
δ	0.96 (39.9)	0.61 (39.9)	1.09 (22.39)
R^2	0.60	0.69	0.33
ADF	-3.54	-3.63	-3.49

From Table 4, American, European and British interest rates seem to be at least relatively cointegrated at the statistical level of 10%, and their policies recently synchronized. In this sense, while focusing on the interest rate deviations to the equilibrium defined through the cointegration relationship, we may specify their adjustment dynamics and mean reversion phenomenon while estimating an LECM, given in equation (2) and recalled in what follows:

$$\Delta z_t = \phi_0 + \lambda z_{t-1} + \sum_{i=1}^{p} \phi_i \Delta z_{t-i} + \varepsilon_t$$

This modelling may reproduce the comovements between interest rates, followed by central bank actions. It also indicates how one central bank adjusted its interest rates in accordance with that of the others. We carried out the estimation of this model using the Linear Least Square Method (LLSM) for the three series studied, and reported the results in Table 5. According to our findings, the linear adjustment term is negative, but it is statistically significant at only 10% level for France and the USA. This suggests that the linear error correction mechanism is *a priori* not fully and continually activated, or rather, is misspecified. Otherwise, the significant dependence of interest rate deviations on the previous deviations indicates some evidence of persistence in interest rates, probably because their decrease began several months earlier.

Thus, in order to investigate the linkages between interest rates and the possible synchronization between central banks using a more parsimonious model, we extend the study to the multivariate cointegration framework. Such multivariate cointegration tools, introduced by Johansen (1988), are more powerful than univarite cointegration techniques and have the advantage of testing simultaneously for several cointegration relationships.

Table 5: LECM Estimation

	France	UK	USA
ϕ_0	$1.69 *10^{-5}$ (1.62)	$-1.8 *10^{-5}$ (-1.67)	$1.2 *10^{-5}$ (0.82)
ϕ_1	0.14 (4.58)	0.16 (5.4)	-0.30 (9.66)
λ	-0.003 (-1.84)	-0.002 (-0.77)	-0.003 (-1.89)
R^2	0.02	0.03	0.08

3.2.2 The Johansen (1988)'s Cointegration Procedure

We firstly applied the trace test to check the null hypothesis of "no cointegration relationship" against its alternative of at most one cointegration relationship, and we reported the results in Table 6. Following our findings, we reject the null hypothesis at 5% statistical level (55.86 > 35.19), but we accept the hypothesis suggesting the presence of at most one cointegration relationship (12.06< 20.26).

Table 6: Johansen Tests

Hypothesized		Trace	0.05	
No. Of CE(s)	Eigenvalue	Statistic	Critical Value	Prob.**
None *	0.039	55.86	35.19	0.00
At most 1	0.007	12.06	20.26	0.44
At most 2	0.003	3.67	9.16	0.46

Note: (*): denotes rejection of the hypothesis at the 0.05 level

Table 7 reports the estimation of the cointegration relationship while normalizing the French interest rate, meaning that the latter defines the endogenous variable in the cointegration relationship.

Table 7: Cointegration Relationship Estimation

1 Cointegrating Equation(s)		Log likelihood	22798.18
Normalized cointegrating coefficients			
INTF	INTUK	INTU	C
1.00	-2.41	-0.73	0.12
t-ratios	(-6.7)	(-2.81)	(6.67)

Note: INTF, INTUK and INTU are respectively the French, British and American interest rates.

In order to apprehend the mean reversion in interest rates during the present financial crisis within a multivariate framework, we estimated the dynamics of interest rate deviations toward equilibrium (z_t), in a second step, using a VECM with three equations (France, the UK and the USA) and we reported the main results in Table 8. Our results show that the linear adjustment term is significant at 5% only for the USA, while they indicate that on the basis of this linear specification, ECB and British interest rates are not linearly mean-reverting. This means that the ECB and Bank of England may continue to decrease their interest rates in the future.

More interestingly, our results highlight strong evidence of synchronization between the US Fed, the Bank of England and the ECB. Indeed, for each country in our sample, the short-term interest rate deviations depend not only on their previous deviations but also on those of the other central banks. This dependence is more statistically significant until two days, reflecting the temporal shift between countries and the time required to decode and understand information transmitted from another market as well as the time needed to apprehend other central bank decisions and actions. The low dependence between France and the USA is supported by the difference between the Fed and the ECB in the ways they manage the financial crisis and with regard to the decrease in interest rates. Indeed, while the Fed immediately decreased the US interest rate, and in several stages, the ECB kept its interest rate constant, even increased it, and only decreased it very recently (see, Table 1).

Table 8: VECM Estimation

Error Correction:	D(ZF)	D(ZU)	D(ZUK)
CointEq1	0.0003	-0.003	0.001
	[0.29]	[-2.42]	[0.69]
D(ZF(-1))	-0.23	-0.43	0.75
	[-1.03]	[-1.4]	[3.21]
D(ZF(-2))	0.76	1.26	-0.68
	[3.35]	[4.05]	[-2.9]
D(ZU(-1))	-0.01	0.47	0.02
	[-0.29]	[7.04]	[0.4]
D(ZU(-2))	-0.06	-0.04	0.08
	[-1.30]	[-0.63]	[1.58]
D(ZUK(-1))	-0.37	-0.10	0.89
	[-1.59]	[-0.3]	[3.69]
D(ZUK(-2))	0.65	1.16	-0.55
	[2.76]	[3.6]	[-2.24]
C	1.6E-05	1.6E-05	-1.7E-05
	[1.6]	[1.12]	[-1.59]
Adj. R-squared	0.03	0.11	0.04
Log likelihood	7190.81	6839.36	7138.58

Note: Values between [] denote t-ratios of the estimators.

Overall, both bivariate and multivariate cointegration techniques, as well as correlation estimations, suggest some evidence of significant linkages between the recent interest rate series in France, the UK and the USA. This may support the hypothesis of synchronization between the Fed, the ECB and the Bank of England. This modeling also indicates that central bank actions and policies during periods of economic growth are similar to those conducted during financial crises, and that business cycles are relatively symmetric (e.g., central bank policies in normal periods before July 2007 are very similar to those with crises afterwards. However, this modeling is based on restrictive hypotheses of both linearity and symmetry. It therefore limits interest rate modeling to a linear, symmetric and continuous system, with constant adjustment over time, leading potentially to certain misspecifications in modeling interest rates.

In addition, as suggested in Figure 1, the interest rate dynamics seem to be neither linear nor symmetric and the empirical results associated with linear modeling need to be improved. Indeed, the current international financial crisis clearly shows that economic moderation and central bank actions and policies strongly depend on economic phases and circumstances. For example, the intensity of interest rate increases in 2005 was less marked than that associated with interest rate decreases following the subprime crisis. This suggests strong evidence of asymmetry in interest rate adjustment dynamics that may escape LECM represented by Equation (1). To capture this eventual asymmetry, it is useful to apply nonlinear modeling that is more robust and powerful than linear cointegration techniques.

Table 9: Descriptive Statistics for Interest Rate Deviations

	ZUK	***ZU***	***ZF***
Mean	-5.25E-18	-1.70E-18	-9.29E-19
Std. Dev.	0.005	0.010	0.007
Skewness	-0.431	-0.236432	-0.764792
Kurtosis	3.45	1.70	2.86
Jarque-Bera	43.49	87.6	107.8
Probability	0.00	0.00	0.00

Before turning to the interest rate estimation by extending the methodology to the nonlinear framework, we propose analyzing the statistical properties of interest rate deviations (z_t) that we reported in Table 9. Interest rate deviations are negative on average for all three countries, reproducing the intensity of interest rate decreases within the financial crisis. In addition, the skewness parameter is negative and normality and symmetry hypotheses are significantly rejected, indicating that interest rate adjustment dynamics may be relatively asymmetric and nonlinear. Lastly, we focus on interest rate modeling by nonlinear error correction models (NLECMs) that are robust to asymmetry, characterizing interest rate dynamics.

3.3 STECM Modeling

We study the adjustment dynamic of interest rate deviation for the USA, the UK and France using STECMs. In addition to interest rates in the long-run relationship (equation (9)), we also introduce interest rate deviations in the short-term nonlinear ECM in order to reproduce how far one interest rate deviates following a deviation in the other interest rates. Formally, we rewrite the STECM (equation (3)) as follows:

$$\Delta z_t = \phi_0 + \lambda_1 z_{t-1} + \sum_{i=1}^{p} \phi_{1,i} \Delta z_{t-i} + \sum_{j=0}^{p} \phi_{2,j} \Delta z^{U}{}_{t-j} + \sum_{k=0}^{p} \phi_{3,l} \Delta z^{UK}{}_{t-k} + \lambda_2 z_{t-1} \times F(z_{t-d}, \gamma, c) + \varepsilon_t \qquad (10)$$

This specification concerns the French case in which current and lagged US and UK interest rate deviations are introduced as explanatory variables in the nonlinear ECM. Similar STEC representations are also retained for the UK (respectively the USA), while current and lagged French and US (respectively UK) interest rate deviations are introduced as explanatory variables.

3.3.1 Specification

In practice, several tests (Ljung-Box tests, autocorrelation functions and Information Criteria) were used to determine the LECM lag number for interest rate deviations. In accordance with our results, we retained p = 3 for the USA and p = 4 for the UK and France, indicating the importance of persistence and inertia effects in characterizing interest rate adjustment dynamics. In addition, for each interest rate in the sample we studied, we found that the current and previous deviations of the other interest rates significantly affected the adjustment dynamic of the interest rate considered. This indicates significant linkages between central bank decisions over the last few years and notably strong dependence on Fed decisions.

Table 10 - LM Linearity Test (*p-values*)

Delay	**USA**	**France**	**UK**
p	3	4	4
$\hat{d}$ *p-value*	4 (0.00)	1 (0.00)	2 (0.00)
Teräsvirta test conclusion	ESTECM	ESTECM	ESTECM

Note: p is the number of lags in the change of deviation, $\hat{d}$ is the delay number defining the transition variable z_{t-d}.

We then applied the nonlinear adjustment tests and Teräsvirta (1994) tests to choose the type of transition function. We report the main results obtained in table 10.[5] Our findings highlight the rejection of the linear adjustment hypothesis for interest rates in all three coun-

[5] More details about these tests may be obtained upon request to the corresponding author.

tries, suggesting that the UK, US and French interest rates are nonlinearly mean reverting, while the Teräsvirta tests retained the exponential function to reproduce the transition between the interest rate regimes before and after the financial crisis.

These results are highly interesting for several reasons. Firstly, the rejection of linearity and the choice of a similar exponential transition function points to some common features between the US, UK and French interest rate dynamics. Secondly, the acceptation of switching regime hypothesis suggests that in the recent financial crisis and central bank actions, interest rates are characterized by at least two types of regimes. The activation of these regimes and the transition from one regime to another one depends on the intensity of one central bank intervention (in general the Fed's) on the monetary markets and consequently on the actions of the others.

3.2.2 Estimation and Validation

In practice, we estimated an ESTECM (3,4), ESTECM (4,1) and ESTECM (4,2) for the USA, France and the UK respectively and we report the results obtained in table 11. Our estimations indicate several important findings. Firstly, all the AR coefficients are statistically significant at either 5% or 10% statistical levels, confirming the persistence effects suggested by linear modeling, and suggesting continuity in interest rate decreases by central banks over the last few months. Secondly, for all interest rate series, both current and previous interest rate deviations significantly affect the dynamic of the interest rate considered, indicating some evidence of comovements between interest rates, at least in the most recent period as shown in Figure 1. It also suggests nonlinear dependence between interest rates by dynamic interaction in continuous time between the Fed and the European and British central banks. More interestingly, while the current interest rate deviation (for all estimations) significantly and negatively affects the interest rate adjustment dynamic, the latter is positively and nonlinearity correlated with the lagged interest rate deviations. This means that in periods of turbulence in an international financial crisis, each central bank decision immediately implies trouble for the other monetary policies, but after a certain time lag, once more information about this action has been extracted, the latter may insure the market and get positive feedback about the other central banks.

Thirdly, the parameters of the exponential function are statistically significant, confirming the Teräsvirta (1994) tests and suggesting the presence of two regimes characterizing the dynamic interest rate deviations. A central regime, in which the interest rate may deviate from the long-run equilibrium and be uncorrected until its deviations exceed a certain threshold, and an outsider regime describing the dynamics of the interest rate when it moves back to equilibrium thanks to the activation of the nonlinear adjustment terms $\hat{\lambda}_1$ and $\hat{\lambda}_2$. The latter, that are the most important parameters of the nonlinear adjustment model, are statistically significant at 5% level. The second adjustment term $\hat{\lambda}_2$ is negative in all three cases and the sum $(\hat{\lambda}_1 + \hat{\lambda}_2)$ is also negative. This means that even though the central bank interest rate may deviate in the first regime from the equilibrium $(\hat{\lambda}_1 \geq 0)$, interest rates are nonlinearly mean reverting and the estimated ESTECM are stable over the estimated period.

Fourthly, in order to check the robustness of these results, we check the statistical properties of the estimated residuals and we show that the latter are symmetrical, stationary, and are not autocorrelated but are characterized by an ARCH effect.

In order to illustrate the different regimes characterizing the interest rate adjustment dynamics more explicitly, we plotted the estimated transition function for the UK, the USA and

France respectively in figures (2A, 2B), (3A, 3B) and (4A, 4B). For Figures 2A, 3A and 4A, we plotted the estimated transition function with the transition variables, which were plotted according to the time factors in figures 2B, 3B and 4B. This leads to several interesting findings. Firstly, the most important observations are symmetrically distributed, confirming the choice of the exponential representation. Secondly, the estimated transition functions show the presence of variable adjustment speed that increases with the size of the interest rate deviations. Indeed, the more the latter increase, the more important the interest rate mean-reversion is. Thirdly, for all three countries, the estimated transition function values are very low and did not exceed 12% maximum for the UK. This reflects the importance of adjustment intensity of central bank actions in decreasing their interest rates in order to move them back to equilibrium. It also indicates that interest rate deviations are relatively near unit root and their dynamics may approach a random walk.

Finally, while the US monetary market is characterized by the more volatile transition function, perhaps because of the Fed's successive interventions, the UK market has a higher transition function, reflecting the highest interest rate decrease in 2009. More interestingly, both types of Figures show similar dynamics for the three-month interest rate for France, the UK and the USA, suggesting some evidence of synchronization between their central banks. In addition, these functions significantly and correctly reflect the interest deviations, decreases and adjustments mentioned in the first table.

Table 11 - ESTECM Estimations

	USA	France	UK
p	3	4	4
$\hat{d}$	4	1	2
$\hat{\gamma}$	11.42 (3.01)*	13.28 (2.22)*	100.47 (1.79)**
c	-0.0004 (-1.94)**	0.0011 (1.73)**	0.0008 (10.55)*
$\hat{\phi}_0$	$-7.6*10^{-6}$ (-1.06)	$-5.2*10^{-6}$ (-2.5)*	$2.0*10^{-6}$ (-1.16)
$\hat{\lambda}_1$	-0.04 (-3.36)	0.007 (2.44)*	0.03 (3.65)*
$\hat{\lambda}_2$	-0.05 (-3.55)	-0.01 (-2.69)*	-0.04 (-3.8)*
$\hat{\phi}^{UK}_{1,0}$	-2.06 (-16.2)*	-0.99 (-11.7)*	-
$\hat{\phi}^{UK}_{1,1}$	1.34 (8.6)*	0.52 (16.8)*	0.52 (17.2)*
$\hat{\phi}^{UK}_{1,2}$	0.61 (4.2)*	0.07 (2.2)*	0.09 (2.53)*
$\hat{\phi}^{UK}_{1,3}$	0.12 (3.3)*	0.06 (2.1)*	0.11 (3.44)*
$\hat{\phi}^{UK}_{1,4}$	-	0.09 (3.3)*	0.09 (3.3)*
$\hat{\phi}^{USA}_{2,0}$	-	-0.05 (-7.03)*	-0.09 (-16.3)*
$\hat{\phi}^{USA}_{2,1}$	0.52 (17.1)*	0.03 (5.1)*	0.05 (6.84)*
$\hat{\phi}^{USA}_{2,2}$	0.04 (1.13)	-	0.006 (0.87)
$\hat{\phi}^{USA}_{2,3}$	0.12 (4.6)*	-	0.02 (3.3)*

$\hat{\phi}^{F}{}_{3,0}$	-0.94 (-7.03)*	-	-0.93 (-117.2)*
$\hat{\phi}^{F}{}_{3,1}$	0.83 (5.6)*	0.49 (16.3)	0.51 (16.4)*
$\hat{\phi}^{F}{}_{3,2}$	0.61 (4.32)*	0.07 (2.2) *	0.08 (2.51) *
$\hat{\phi}^{F}{}_{3,3}$	-	0.07 (2.04) *	0.09 (2.81) *
$\hat{\phi}^{F}{}_{3,4}$	-	0.01 (3.31)	0.09 (3.22) *
$\overline{R}^2$	0.82	0.96	0.92
DW	2.04	2.02	1.99
ADF	-17.66	-15.25	-15.2
Q(12)' p-value	0.00	0.00	0.00
ARCH (q)	62.6* (q =2)	49.3* (q =1)	79.2* (q =1)
Nb. of iterations	9	32	20

Note: The values under the estimates are the t-ratios. Q(12) is the Ljung-Box statistics. (*) and (**) indicate respectively the significativity at 5% and 10%. DW, ADF and ARCH are the statistics of the Durbin Watson, ADF and ARCH tests. $\overline{R}^2$ denotes the determination coefficient. F, UK and USA denotes the initials of France, the UK and the USA respectively.

Figure 2A – Transition Function for the UK

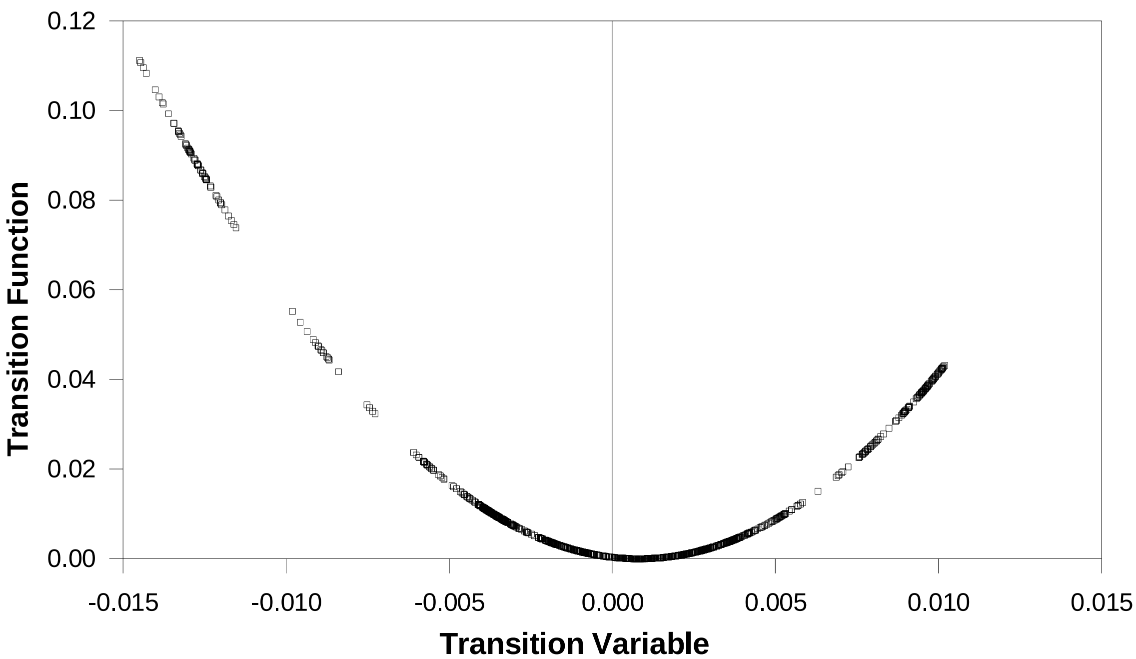


Figure 2B – "Intertemporel" Transition Function for the UK

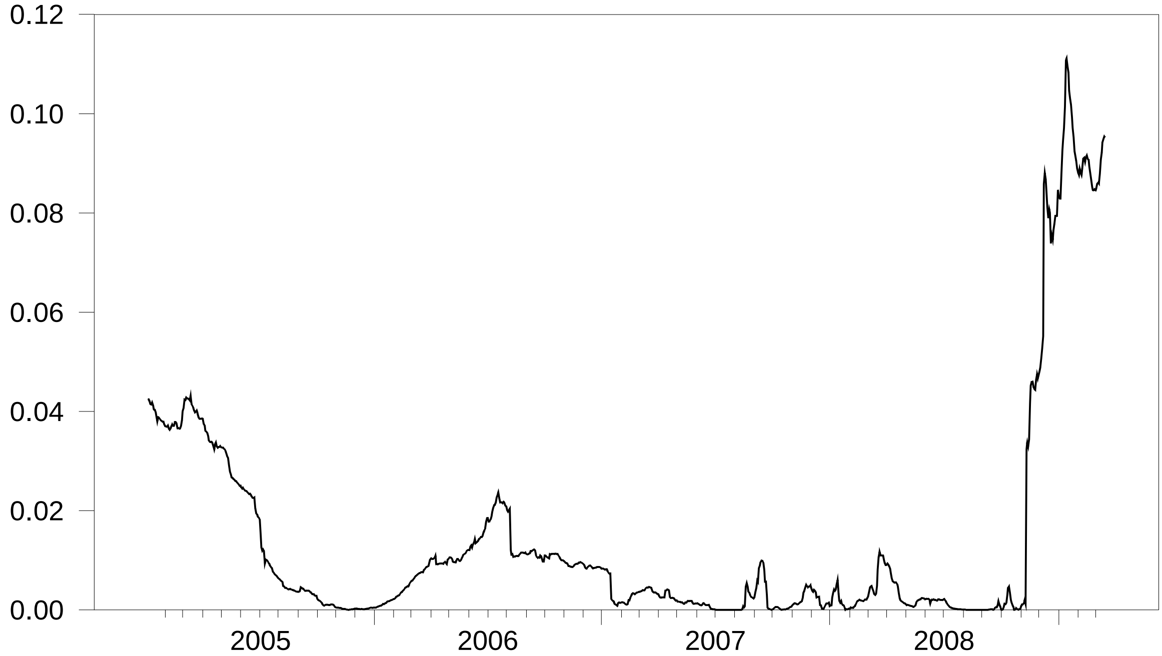


Figure 3A – Transition Function for the USA

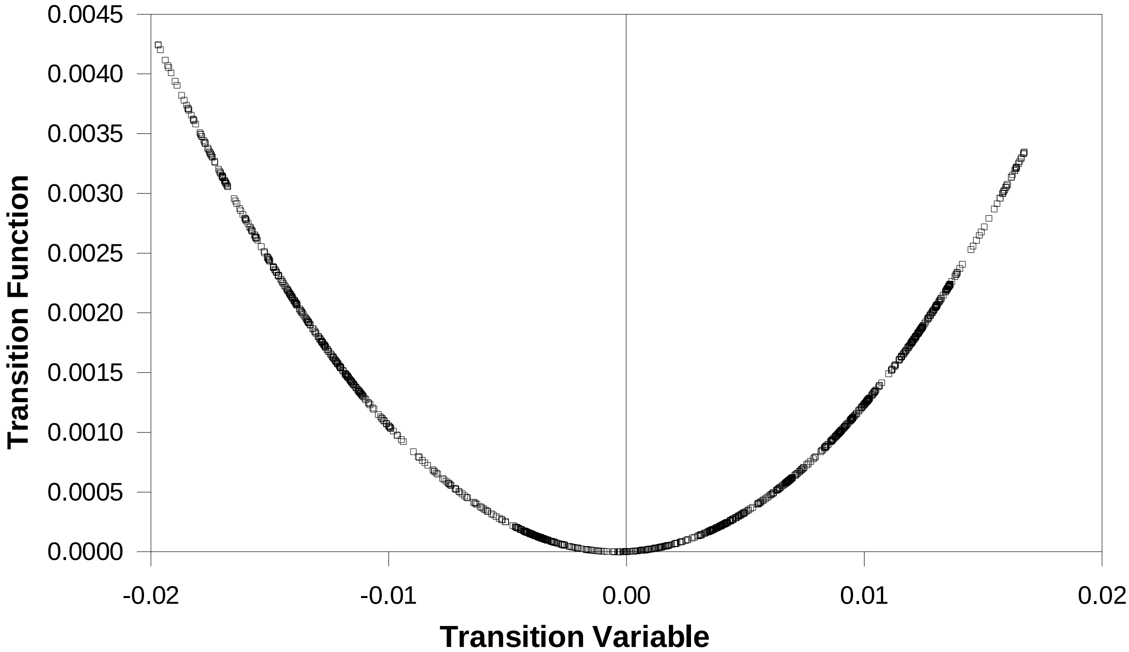


Figure 3B – “Intertemporel” Transition Function for the USA

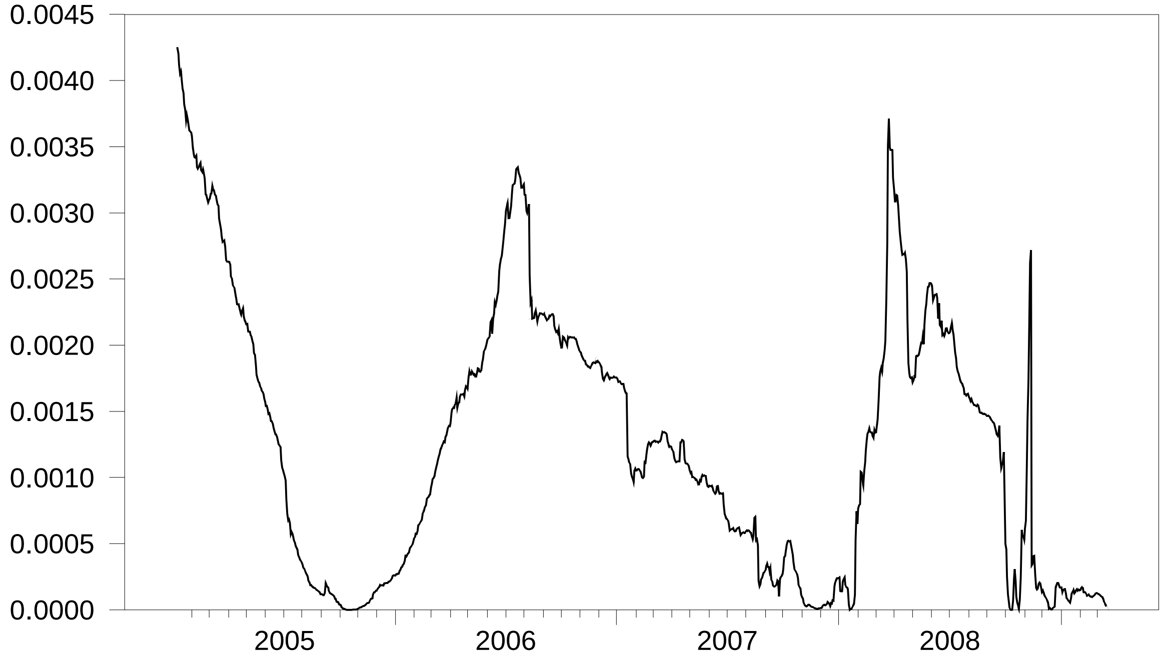


Figure 4A –Transition Function for France

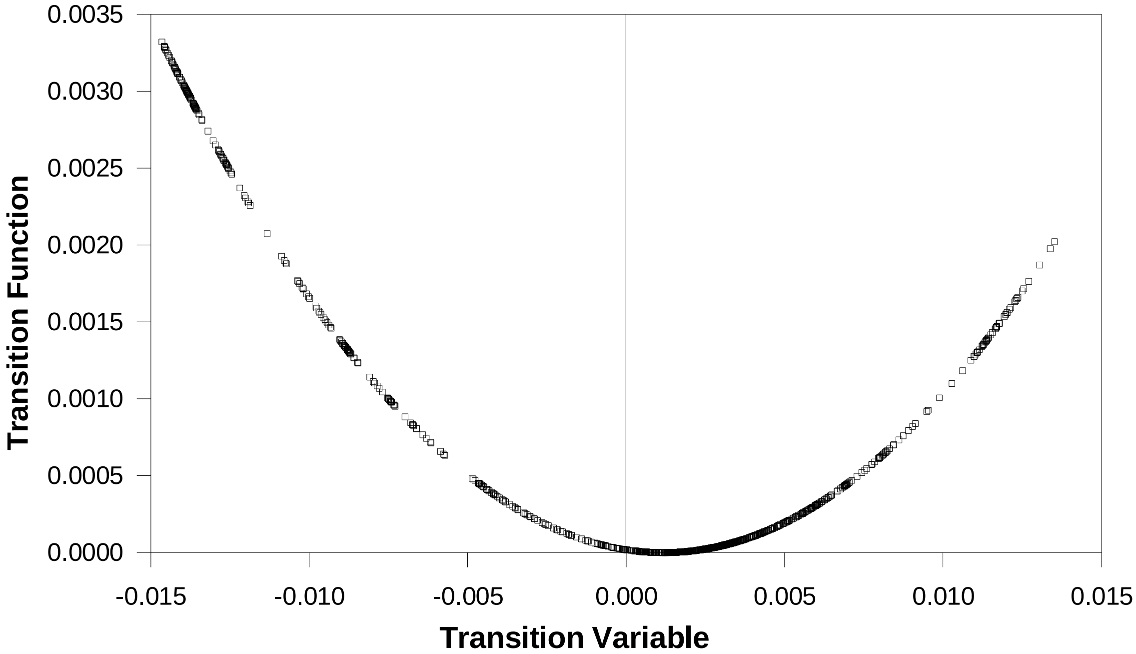
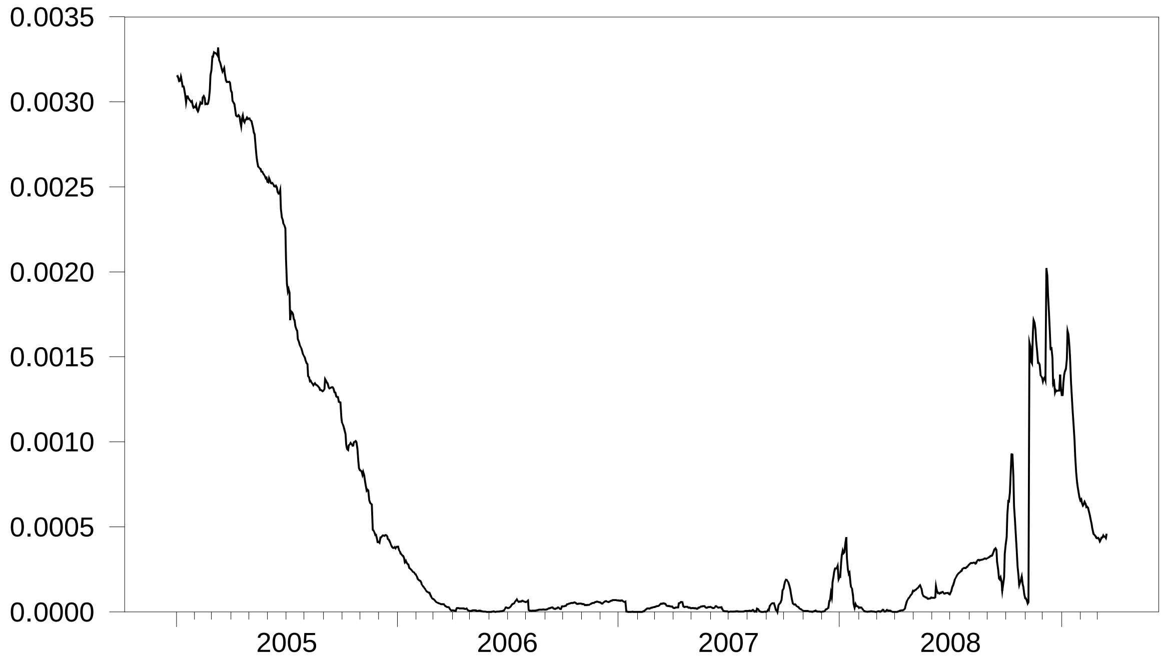


Figure 4B – "Intertemporel" Transition Function for France



Finally, in order to show the problematic of interest rate adjustment and central bank synchronization more explicitly, we gauge the interest rate under- and overvaluation phases and try to reproduce the intensity of interest rate mean reversion using the two indicators developed by Peel and Taylor (2000) to investigate the exchange rate adjustment toward purchasing power parity (PPP), but never applied to interest rates.[6]

3.3.1 Interest Rate Under and Overvaluation Periods

The main contribution and originality of this exercise is twofold. On the one hand, we determine the phases of under- and overvaluation of interest rates and we implicitly investigate the effects of the current international financial crisis on monetary markets. On the other hand, we specify the speed of mean reversion on interest rates and the rhythm of correction of interest rate misalignments. To do this, we use the two indicators developed by Peel and Taylor (2000). The first indicator corresponds to:

$$\Omega(z_t) = 100 \times F(z_t) \times sign\,(z_t), \quad sign(z_t) \equiv \frac{z_t}{|z_t|}, \quad -100 \leq \Omega(z_t) \leq 100 \tag{11}$$

This indicator reproduces the magnitude of the interest rate deviation from equilibrium. According to Peel and Taylor (2000), a positive indicator (respectively negative) implies that interest rates are over-evaluated (respectively under-evaluated), while interest rates are in equilibrium when this indicator converges toward zero.

The second indicator is given by:

$$\Gamma(z_t) = 1 - F(z_{t-d}), \quad 0 \leq \Gamma(z_t) \leq 1 \tag{12}$$

[6] These indicators were estimated by Jawadi and Prat (2009) to investigate the under- and overvaluation of stock prices to their fundamentals.

This indicator evaluates the interest rate adjustment speed. Indeed, the more $\Gamma(z_t)$ tends toward 1, the more the interest rate deviations (z_t) approach a random walk, while the more $\Gamma(z_t)$ convergence toward the speed of adjustment increases and z_t converges toward a white noise (Jawadi and Prat,2009).

In practice, we compute these two indicators for the three countries in our sample and report the results through the graphs in Figures (5A, 5B), (6A, 6B) and (7A, 7B) for the UK, the USA and France respectively. Analysis of these Figures gives rise to a number of interesting remarks. Firstly, the graphs for the second indicator highlight a higher adjustment speed, indicating that interest adjustment is highly activated for all three central banks since it is close to the unity at all times. This also confirms the low estimated value for the transition functions. Secondly, we observe clear phases of interest rate overvaluation for the USA and the UK (respectively an undervaluation phase for the ECB) in 2005. This phase is followed by an interest rate deviation correction phase. The last phase is more agitated, probably because of the effect of the financial crisis. But it is worth noting that the last phase shows several similarities in interest rate adjustment dynamics for the USA, the UK and France, suggesting some indication of synchronization between central banks in the last period.

Figure 5A – Undervaluation and Overvaluation Interest Rate Phases for the UK

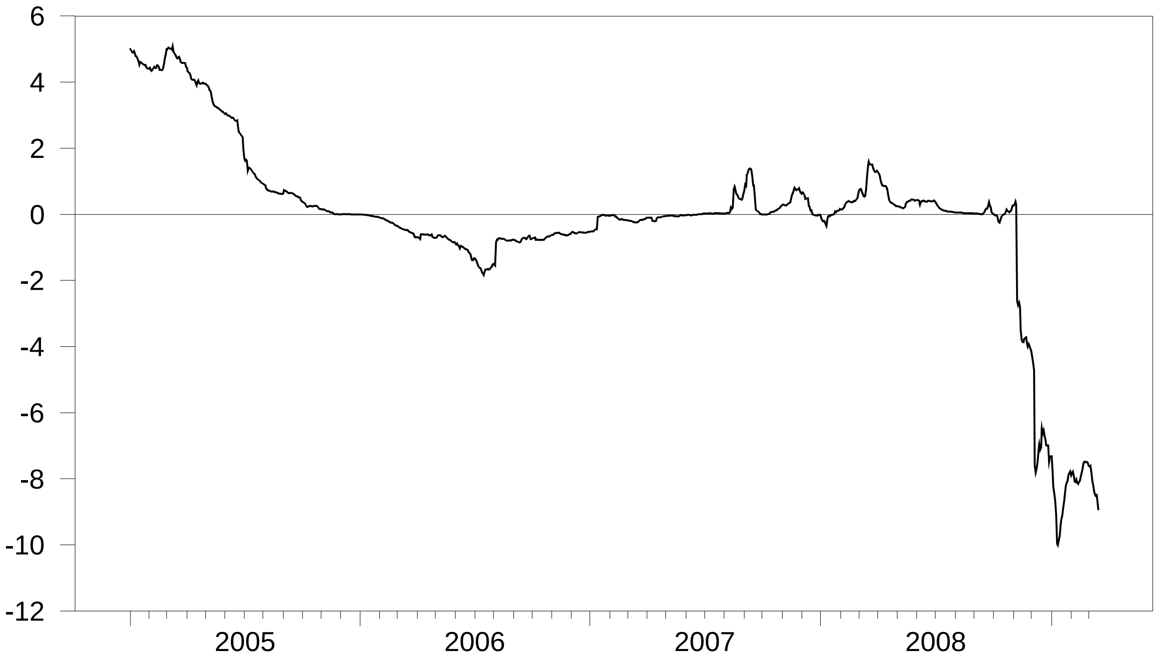


Figure 5B – Mean Reversion in Interest Rates for the UK

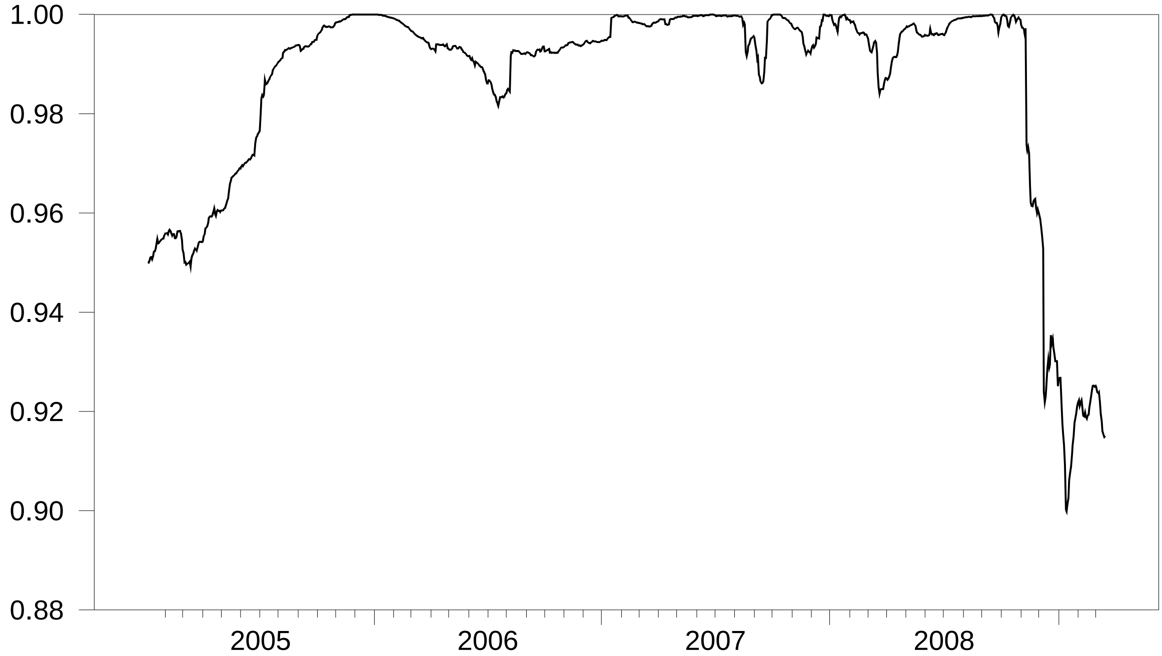


Figure 6A – Undervaluation and Overvaluation interest rate phases for the USA

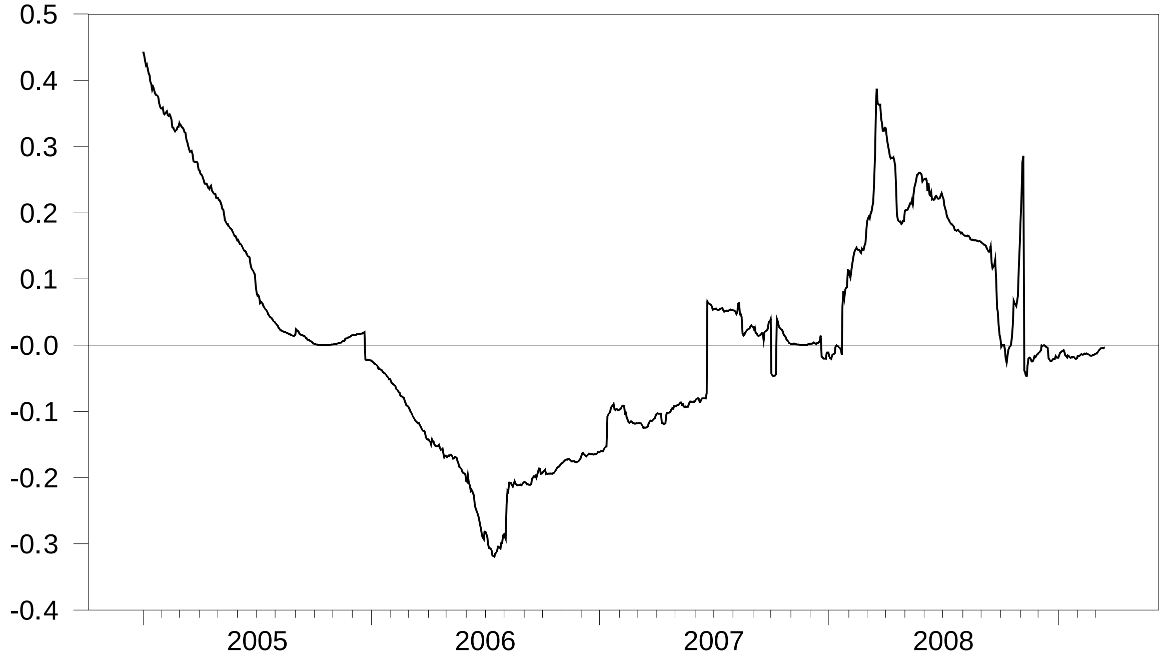


Figure 6B – Mean Reversion in Interest Rates for the USA

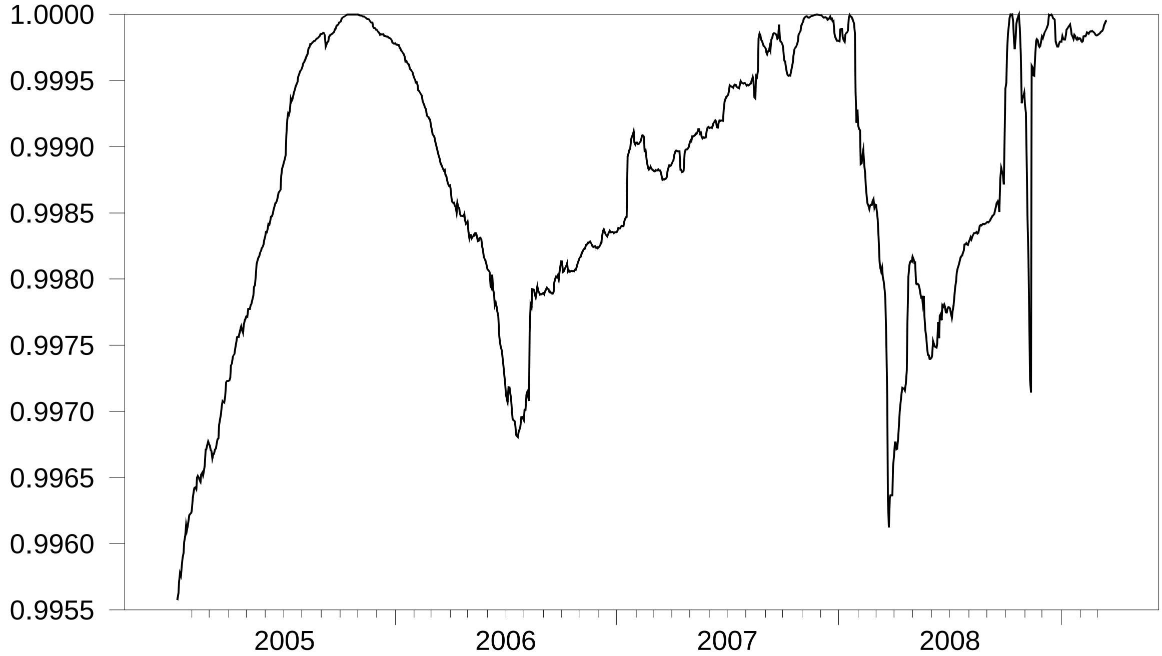


Figure 7A – Undervaluation and Overvaluation Interest Rate Phases for France

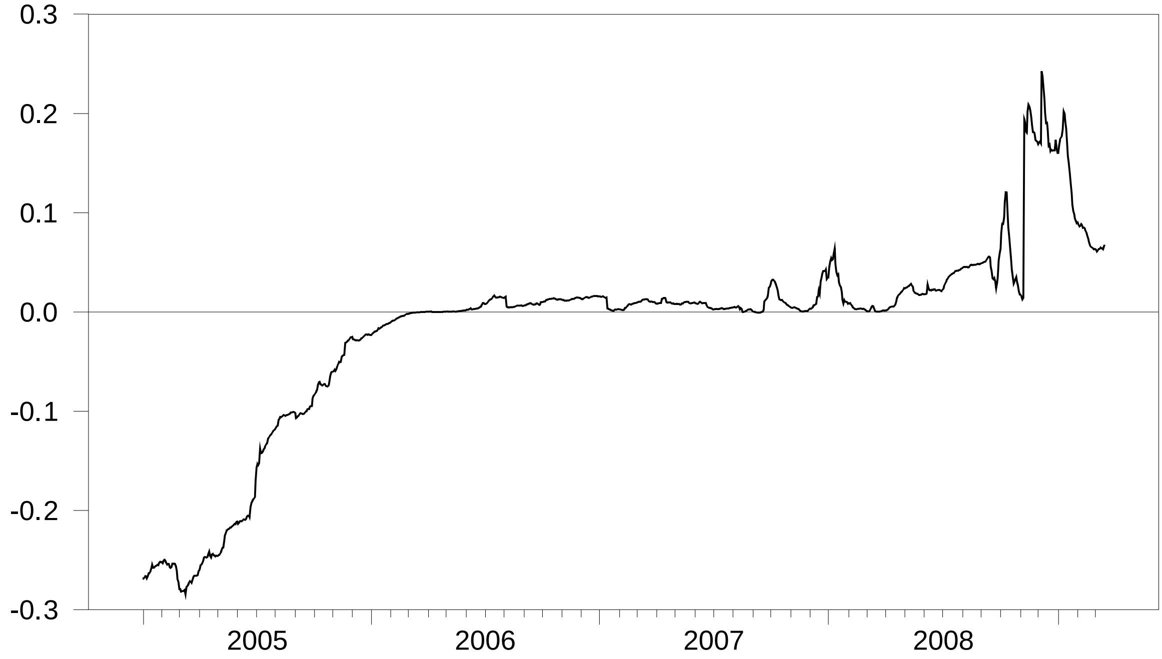
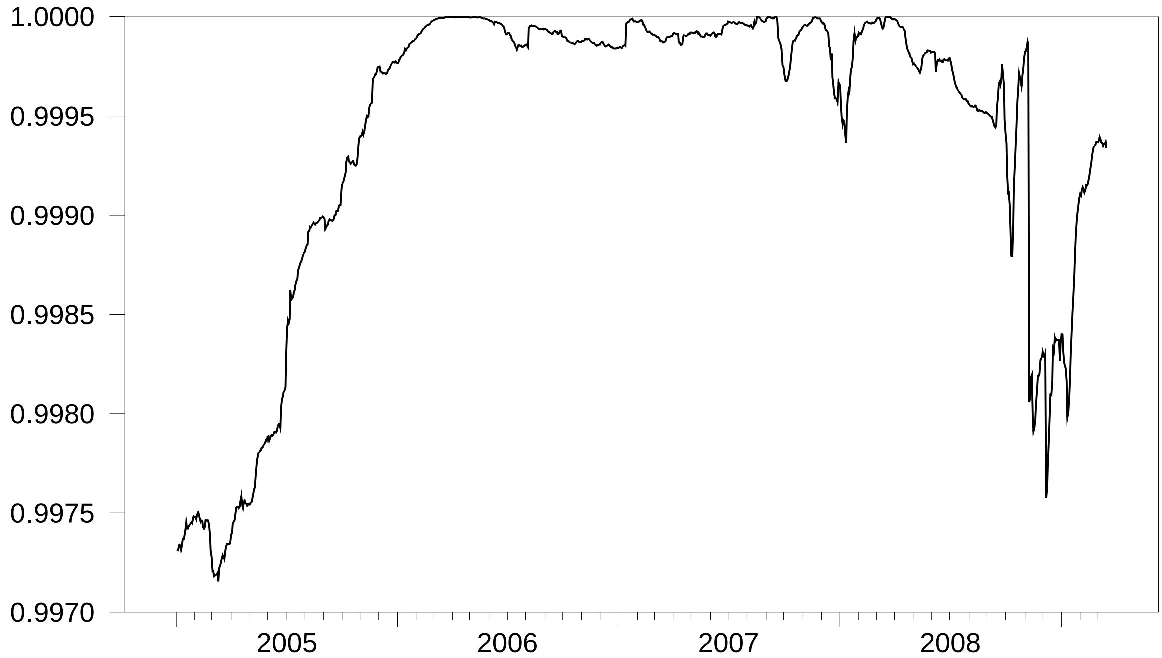


Figure 7B – Mean Reversion in Interest Rates for France



4. Concluding Remarks

In the context of today's international financial crisis and economic meltdown, this paper investigated the effectiveness of monetary policy synchronization between the US Fed, the Bank of England and the European Central Bank. It is claimed that these central banks must have attempted to work together to manage the crisis issues, and ultimately to make policy decisions that would reduce financial instability and restore investors' confidence. Methodologically, we used different linear and nonlinear bivariate and trivariate econometric techniques to address this problem: cointegration, VECMs and STECMs. These techniques enabled us in particular to examine short and long-run links between different central bank actions on their target interest rates. Moreover, our econometric methodology is suitable for capturing all forms of asymmetry, nonlinearity and structural changes in interest rate dynamics.

Our main findings support the synchronization hypothesis and a non-trivial relationship between the three central banks in terms of monetary policy. Furthermore, we establish that exogenous shifts in the Fed's monetary policy lead those in the UK and the ECB within a horizon of one to two days. The results also suggest that the US, European and UK central banks appear to have shown the same behavior in recent months, which explains the convergence toward a common equilibrium.

References

Anderson, H. M. (1997), "Transaction costs and nonlinear adjustment towards equilibrium in the US Treasury bill market", *Oxford Bulletin of Economics and Statistics*, 59, 465-484.

Balke, N.S. and Fomby, T. (1997), "Threshold cointegration", *International Economic Review*, 38, 627-645.

Bernanke, B. and Kuttner, K.N. (2005), "What explains the stock market's reaction to Federal Reserve policy", *Journal of Finance*, 60(3), 1221-1257.

Chen, S.S. (2007), "Does monetary policy have asymmetric effects on stock returns?", *Journal of Money*, 39(2-3), 667-668.

Cihák, M. (2006), "How do central banks write on financial stability?" IMF Working Paper No. 06/163 (Washington: International Monetary Fund).

Dickey, D.A. and Fuller, W.A. (1981), "Likelihood ratio statistics for autoregressive time series with a unit root", *Econometrica*, 49, 1057-1072.

Engle, R.F. and Granger, C.W.J. (1987), "Cointegration and error correction: representation, estimation and testing", *Econometrica*, 55(2), 251-276.

Escribano, A. (1997), "Nonlinear error-correction: The case of money demand in the UK (1878-1970)", Working Paper, No. 96-55, Universidad Carlos III De Madrid.

Franses, P.H. and Van Dijk, D. (2000). Non-linear time series models in empirical finance. Cambridge: Cambridge University Press.

Goodhart, C.A.E., 2006, "A framework for assessing financial stability?", *Journal of Banking and Finance*, 30(12), 3415-22.

Granger, C.W.J. (1981), "Cointegrating Variables and Error Correcting Models", Working Paper, University of California, San Diego, Calafornia.

Granger, C.W.J. and Teräsvirta, T. (1993), "Modeling nonlinear economic relationships", Oxford University Press.

Granger, C.W.J. and Teräsvirta, T. (1993), "Modelling nonlinear economic relationships", Oxford: Oxford University Press.

Healey, J. (2001), "Financial instability and the central bank – international evidence." In R. A. Brealey , A. Clark, C. Goodhart, J. Healey, G. Hoggarth, D. T. Llewellyn, C. Shu, P. Sinclair and F. Soussa, *Financial Instability and Central Banks – A Global Perspective,* Centre for Central Bank Studies (London: Bank of England).

Ioannidis, C. and Kontonikas, A. (2007), "The impact of monetary policy on stock prices", *Journal of Policy Modeling*, 30, 33-53.

Jawadi, F. and Prat, G. (2009), "Nonlinear stock price adjustment in the G7 countries", Working Paper, University of Paris Ouest La Defense Nanterre.

Jawadi, F., Bruneau, C. and Sghaier, N. (2009), "Nonlinear cointegration relationships between non-life insurance premium and financial markets", *Journal of Risk and Insurance, forthcoming*.

Johansen, S. (1988), "Statistical analysis of cointegration vectors", *Journal of Economic Dynamics and Control*, 12(2-3), 231-254.

Liu, Y. (2001), "Modelling mortgage rate changes with a smooth transition error correction model", Working Paper, No. 23, Bank of Canada.

Luukkonen, R. and Saïkkonen, P. (1988), “Lagrange multiplier tests for testing nonlinearity in time series models”, *Scandinavian Journal of Statistic*, 15, 65-68.

Luukkonen, R., Saïkkonen, P. and Teräsvirta, T. (1988), “Testing linearity against smooth transition autoregressive models”, *Biometrika*, 75(3), 491-499.

Michael, P., Nobay, A.R. and Peel, D.A. (1997), “Transactions costs and nonlinear adjustment in the real exchange rates: an empirical investigation”, *Journal of Political Economy,* 105, 862-879.

Peel, D.A. and Taylor, M.P. (2000), “Nonlinear adjustment, long-run equilibrium and exchange rates fundamentals”, *Journal of International Money and Finance*, 19, 33-53.

Phillips, P.C.B. and Perron, P. (1988), “Testing for unit root in a time series regression”, *Biometrika*, 75, 335-346.

Rigobon, R. and Sack, B. (2003), “Measuring the reaction of monetary policy to the stock market”, *Quarterly Journal of Economics*, 118(2), 639-669.

Rothman, P., Van Dijk, D. and Franses, P.H. (2001), “A multivariate STAR analysis of the relationships between money and output”, *Macroeconomic Dynamics*, 5(4), 506-532.

Scotti, C. (2006), “A bivariate model of Fed and ECB main policy rates”, International Finance Discussions Paper (Board of Governors of the Federal Reserve System).

Teräsvirta, T. (1994), “Specification, estimation and evaluation of smooth transition autoregressive models”, *Journal of the American Statistical Association*, 89, 208-218.

Teräsvirta, T., and Anderson, H.M. (1992), “Characterizing nonlinearities in business cycles using smooth transition autoregressive models”, *Journal of Applied Econometrics*, 7, 119-136.

Van Dijk, D., Teräsvirta, T. and Franses, P.H. (2002), “Smooth transition autoregressive models - a survey of recent developments”, *Econometric Reviews,* 21, 1-47.

Zivot, E. and Andrews, D.W.K. (1992), “Further evidence on the great crash, the oil price shock and the unit root hypothesis”, *Journal of Business and Economic Statistics*, 10, 251-270.