

# IMPLIED VOLATILITY LINKAGES AMONG MAJOR EUROPEAN CURRENCIES

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## Abstract

This paper examines linkages in expected future volatilities among major European currencies. For that purpose, volatility expectations implied by currency options on the euro, British pound, and Swiss franc quoted against the U.S. dollar are analysed. Vector autoregressive modelling is applied to ascertain the dynamics of the implied volatilities across currencies. The results show that the market expectations of future exchange rate volatilities are closely linked among major European currencies. Furthermore, it is found that the implied volatility of the euro significantly affects the volatility expectations of the British pound and the Swiss franc.

*JEL classification:* F31; G13; G15

*Keywords:* exchange rates, volatility linkages, implied volatility

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This paper examines linkages in expected future volatilities among major European currencies. For that purpose, volatility expectations implied by currency options on the euro, British pound, and Swiss franc quoted against the U.S. dollar are analysed. Vector autoregressive modelling is applied to ascertain the dynamics of the implied volatilities across currencies. The results show that the market expectations of future exchange rate volatilities are closely linked among major European currencies. Furthermore, it is found that the implied volatility of the euro significantly affects the volatility expectations of the British pound and the Swiss franc.

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## 1. INTRODUCTION

Over the last two decades, considerable attention has been devoted to the volatility of exchange rates. Given that the foreign exchange market is by far the largest financial market in the world, understanding the dynamics of exchange rate volatility is of high importance. Undisputedly, exchange rate volatility has important implications for the economy. Exchange rate volatility, for instance, creates uncertainty for the prices of exports and imports, and thereby significantly affects international trade flows (see e.g., Caporale and Doroodian, 1994; Rose, 2000). Several studies have shown that exchange rate volatility has a major impact on the profitability of multinational firms, and consequently, also on stock prices (see e.g., Jorion, 1990; Bailey and Chung, 1995; Dumas and Solnik, 1995; Baum et al., 2001). Moreover, since increasing exchange rate volatility tends to discourage investment decisions, it may also have an adverse effect on industrial production and employment (see e.g., Belke and Gros, 2002).

Exchange rate volatility may be a major concern for global financial stability, as Robert Mundell noted in his Nobel Lecture (Mundell, 2000). The ERM crisis of 1992 and the Asian currency crisis in the autumn of 1997 are recent notorious examples of the potential impact of exchange rate volatility on the economy. Especially the Asian currency crisis demonstrated how uncertainty in one currency may first spread to other currencies and finally cause a chain reaction of contagion throughout the global financial markets (see e.g., Tuluca and Zwick, 2001; Cartapanis et al., 2002; Baur, 2003). These currency crises clearly indicate that exchange rate volatilities are affected not only by country specific economic fundamentals and monetary policy but also by common uncertainty factors. In other words, volatilities tend to be linked across

currencies in the sense that movements in one currency may affect other currencies beyond the impact of macroeconomic fundamentals. These volatility linkages across exchange rates have important practical implications for international investors, multinational firms, risk managers, bank supervision authorities, and monetary policy makers. International investors, for instance, need to consider the impact of exchange rate volatility linkages on portfolio diversification. From the viewpoint of monetary policy makers, volatility linkages may be disquieting, as they imply that exchange rates are affected by global uncertainty factors which are beyond the control of local monetary policy.

This paper focuses on volatility linkages among major European currencies. In particular, the purpose of this paper is to examine linkages in market expectations of future exchange rate volatility. Although not directly observable, these volatility expectations are implicit in the market prices of currency options, and can thus be estimated given an option pricing model. In this paper, volatilities implied by currency options on the euro, British pound, and Swiss franc quoted against the U.S. dollar are used to investigate linkages in expected exchange rate volatilities. Implied volatility may be regarded as market participants' forecast of the average future volatility of the underlying asset over the remaining life of the option contract. Provided that market participants are rational, implied volatility should incorporate all the available information that is relevant for forming expectations about the future volatility. Therefore, implied volatility may be considered as the best available estimate of market uncertainty. By focusing on linkages in expected exchange rate volatilities as implied by option prices, this paper provides new evidence on the exchange rate volatility dynamics.

Although exchange rate volatility has been a focus of extensive research over recent years, surprisingly little is known about volatility linkages across exchange rates.<sup>1</sup> The literature on volatility transmission in the foreign exchange markets was pioneered by Engle et al. (1990). They examined exchange rate volatility linkages across market segments and noted that volatility tends to spill over from one marketplace to another.<sup>2</sup> Volatility linkages across exchange rates have previously been examined in Najand et al. (1992), Alexander (1995), Laopodis (1998), Kearney and Patton (2000), and Speight and McMillan (2001). A common feature of these papers is the use of autoregressive conditional heteroskedasticity (ARCH) modelling to assess volatility linkages across exchange rates. In brief, these previous studies demonstrate that volatilities tend to be linked across currencies.

Najand et al. (1992) use data on the British pound, Canadian dollar, Japanese yen, German mark, and Swiss franc futures quoted against the U.S. dollar to show that volatility in one currency is transmitted to other currencies. In particular, they show that the German mark significantly influences the other four currencies. Regarding the European currencies, Najand et al. (1992) show that the volatility of the British pound is significantly affected both by the German mark and the Swiss franc. Alexander (1995) documents that the volatilities of the European Monetary System (EMS) currencies, including the German mark, are considerably affected by the British pound and the Japanese yen. These results are contradicted by Kearney et al. (2000), who show that

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<sup>1</sup> Considerable literature has examined volatility linkages in stock markets (see e.g., Lin et al., 1994; Koutmos and Booth, 1995; Booth et al., 1997; Kearney, 2000) and among interest rates (see e.g., Laopodis, 2002; Zhou, 2003).

<sup>2</sup> Similar findings have been subsequently documented e.g. in Baillie and Bollerslev (1991), Ito et al. (1992), Kanas and Kouretas (2001, 2002), and Melvin and Peiers Melvin (2003).

the volatility of the German mark tends to be transmitted to the other EMS currencies, thereby suggesting that the German mark is the dominant currency within the EMS.

This paper contributes to the literature on exchange rate volatility in several respects. The main novelty of this paper is the focus on linkages in expected exchange rate volatilities. Whereas the previous studies by Najand et al. (1992), Alexander (1995), Laopodis (1998), Kearney et al. (2000), and Speight et al. (2001) use *ex post* volatility estimates to examine volatility linkages across exchange rates, this paper uses *ex ante* volatility estimates extracted from option prices. This approach has several advantages. Most importantly, implied volatility may be considered as the best available estimate of market uncertainty. It is well known that market uncertainty may change considerably from day to day. Such changes in uncertainty should be immediately reflected in option prices, and hence, also in implied volatilities. On the contrary, volatility estimates obtained via ARCH modelling are based on past observations, and hence, are by construction constrained to reflect only past market reactions rather than current or expected future market uncertainty. For most practical purposes, linkages in future exchange rate volatilities are of interest. As a considerable body of literature has confirmed the superiority of implied volatility to other volatility estimates in forecasting future volatility, these linkages in expected future volatilities across exchange rates may be most appropriately assessed using implied volatilities.

By examining implied volatility linkages across exchange rates, this paper extends the literature on implied volatility dynamics in the foreign exchange markets. Although several studies have examined implied volatilities in stock markets (see Mayhew, 1995 for a review), only little is known about the dynamics of implied volatilities derived from currency options. Previously, properties of implied volatilities

in the foreign exchange markets have been examined in Xu and Taylor (1994), Campa and Chang (1995), Bonser-Neal and Tanner (1996), Ederington and Lee (1996), Kim and Kim (2003), and Sarwar (2003). This paper extends the above literature by focusing on the cross-dynamics of implied volatilities. Regarding the predictive power of implied volatilities, Shastri and Tandon (1986), Jorion (1995), and Xu and Taylor (1995) show that implied volatility is superior to other volatility estimates in forecasting future exchange rate volatility. Since knowledge of potential causal relationships may improve volatility forecasts (Najand et al., 1992), this paper also contributes to the volatility prediction literature by providing information regarding the lead-lag relationships between implied volatilities.

Finally, this paper provides new evidence regarding the role of the euro among European currencies by focusing on the implied volatility linkages. Indisputably, the introduction of the euro is one of the most important events in the financial markets over recent years. Before the introduction of the euro, Mundell (1998) prophesied that the dollar-euro exchange rate is likely to become the most important price in the world. Detken and Hartmann (2000) and Frisch (2003) have later concluded that the euro became the second most widely used currency in international financial markets immediately after its introduction. Given the importance of the euro to the international monetary system, understanding the dynamics of the euro is certainly a high priority task.

The remainder of this paper is organized as follows. Section 2 describes the implied volatility data used in the empirical analysis. Section 3 presents the methodology used to examine linkages in expected exchange rate volatilities. The

empirical findings on the implied volatility linkages among major European currencies are reported in Section 4. Finally, concluding remarks are provided in Section 5.

## 2. DATA

The empirical analysis in this paper is performed using daily data on implied volatilities of the major three European currencies, the euro (EUR), the British pound (GBP), and the Swiss franc (CHF), quoted against the U.S. dollar. The sample period used in the analysis extends from January 2, 2001 to September 29, 2003. The euro, British pound, and Swiss franc are selected for the analysis since they are by far the most important European currencies, as measured both by the daily trading volume and the size of the economy. The euro accounts for about 35.4 % of the global foreign exchange market turnover against the U.S. dollar while the British pound and Swiss franc account for 8.5 % and 5.4 % respectively (see Bank for International Settlements, 2002).<sup>3</sup> Furthermore, the importance of these currencies is also reflected in the derivatives trading volumes. For instance, as measured by the number of contracts traded and premiums paid, options on the euro are distinctly the most actively traded currency options on the Philadelphia Stock Exchange (PHLX), which is widely considered as the world's leading marketplace for exchange-traded currency options.

The implied volatilities used in this paper are derived from the prices of currency options traded on the Philadelphia Stock Exchange. The PHLX currency options are quoted in U.S. cents per unit of the underlying foreign currency. Exercised currency

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<sup>3</sup> For comparison, the Japanese yen accounts for about 24.8 % and the Canadian dollar for about 4.6 % of the global turnover against the U.S. dollar.



options are settled by the delivery of the spot currency. In this paper, the European-style mid-month options are used to compute the implied volatilities. The expiration months for the mid-month currency options are March, June, September, and December as well as the two additional near-term months, so that six contract maturities are always available for trading. The mid-month currency options expire on the Friday before the third Wednesday of the contract month.

The implied volatilities are extracted from the observed currency option prices using the Garman-Kohlhagen (1983) version of the Black-Scholes (1973) / Merton (1973) model. In the Black-Scholes framework, volatility of the underlying asset price is the only unobservable determinant of option price. Consequently, given the other variables, the price of an option,  $c_t$ , at time  $t$  can be expressed as a function of volatility,  $c_t = f(\sigma)$ , where  $\sigma$  denotes the volatility of the underlying asset price. Provided that option prices are observable on the market, volatility implied by option prices,  $\sigma_{iv}$ , can be obtained by inverting the pricing function,  $\sigma_{iv} = f^{-1}(c_t)$ , where  $f^{-1}$  is the inverse function of  $f$ . This implied volatility estimate is the market's assessment of the future volatility over the remaining life of the option.

Since implied volatilities tend to vary across strike prices and maturities (see e.g., Taylor and Xu, 1994; Xu and Taylor, 1994), constant maturity at-the-money implied volatility time-series of the euro, British pound, and Swiss franc against the U.S. dollar are constructed. First, implied volatilities are estimated for each trading day in the data set, for the two closest-to-money call and put options, and for two near-term expiration months. These call and put implied volatilities are then interpolated in order to obtain at-the-money implied volatilities. Subsequently, the at-the-money call and put implied volatilities are averaged, and then finally interpolated between the two adjacent maturity

volatility estimates. As a result, at-the-money implied volatility time-series with a constant maturity of one month are obtained.<sup>4</sup> These constant maturity implied volatilities on a given day reflect market expectations of future exchange rate volatility over the next month.

By using one-month at-the-money implied volatility time-series to examine volatility linkages, the well-known Black-Scholes biases can be minimized. While the Black-Scholes model systematically misprices in-the-money and out-of-the-money options, broad evidence suggests that it prices short-term at-the-money options correctly. For instance, Corrado and Miller (1996) show that for short maturity at-the-money options the implied volatilities derived from the Black-Scholes model are virtually identical with the volatilities based on stochastic volatility models. In addition, since short-term at-the-money and near-the-money options are the most actively traded option contracts, the implied volatilities derived from these options should most accurately reflect market expectations about the future volatility of the underlying asset.

(insert Figure 1 about here)

Figure 1 plots the developments in the one-month at-the-money implied volatility time-series of the euro, British pound, and Swiss franc over the period from January 2001 to September 2003. Figure 1 demonstrates that the implied volatilities are varying considerably over time. All exchange rates have been particularly volatile in the

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<sup>4</sup> These implied volatility series are essentially similar to the U.S. and German stock market volatility indices, VIX and VDAX, respectively.

aftermath of the September 11<sup>th</sup> terrorist attack. The substantial increase in exchange rate volatility expectations in the summer of 2002 is concurrent with the beginning of the dollar depreciation after the long dollar surge. Furthermore, turning the focus to the volatility linkages, Figure 1 indicates that the three implied volatility series tend to move together rather closely.

(insert Table 1 about here)

Table 1 reports descriptive statistics of the implied volatility time-series. It can be noted that the implied volatilities have ranged from about 5 % to almost 16 % during the sample period. Interestingly, the mean implied volatility estimates show that the British pound tends to be less volatile than the euro and the Swiss franc. The considerable correlations reported in Panel B of Table 1 confirm that market expectations of future volatility are closely linked across currencies.

### **3. FRAMEWORK OF ANALYSIS**

The choice of econometric methodology depends on the time-series properties of the implied volatilities. Depending on the stationarity of the implied volatility time-series, vector autoregressive (VAR) modelling with levels or first differences, or vector error correction (VEC) modelling are the applicable methodological candidates for examining implied volatility linkages. In order to determine the stationarity of the implied volatilities time-series, the augmented Dickey-Fuller and Phillips-Perron unit

root tests are performed.<sup>5</sup> The results of the unit root tests are reported in Table 2. The lag length used in the tests is decided based on the Schwartz information criterion. The test results in Table 2 indicate that the implied volatility time-series are stationary, as the null hypothesis of a unit root can be soundly rejected for all three implied volatility series.

(insert Table 2 about here)

Given that the unit root tests indicate stationarity of the implied volatility time-series, vector autoregressive (VAR) modelling may be applied to ascertain the causal dynamics of the implied volatilities. Hence, it is assumed that the implied volatility dynamics of the euro, British pound, and Swiss franc exchange rates against the U.S. dollar are described by the following unrestricted trivariate VAR( $p$ ) model

$$\boldsymbol{\sigma}_t = \boldsymbol{\alpha} + \sum_{i=1}^p \boldsymbol{\Phi}_i \boldsymbol{\sigma}_{t-i} + \boldsymbol{\varepsilon}_t \quad (1)$$

where  $\boldsymbol{\sigma}_t = (\sigma_{EUR,t}, \sigma_{GBP,t}, \sigma_{CHF,t})'$  is a covariance stationary  $3 \times 1$  vector of implied volatility time-series containing  $3 \times 711$  observations,  $\boldsymbol{\alpha}$  is a  $3 \times 1$  vector of intercepts,  $\{\boldsymbol{\Phi}_i, i=1, 2, \dots, p\}$  is a  $3 \times 3$  matrix of autoregressive coefficients,  $\boldsymbol{\varepsilon}_t$  is a  $3 \times 1$  vector of

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<sup>5</sup> Due to the nature of volatility, it is assumed that there is no time trend in the implied volatility series in the long run. However, the unit root tests were also performed with a time trend and the results remain unchanged. Moreover, the test results are not sensitive to the number of lags used.

white noise with zero mean and positive definite covariance matrix, and  $p$  denotes the lag order of the system.

In this paper, the VAR( $p$ ) system given by Equation (1) is used to ascertain possible lead-lag relationships between the implied volatility series and, additionally, to examine the transmission of shocks in the implied volatility of one exchange rate on the other implied volatilities in the system. The unrestricted trivariate VAR( $p$ ) model allows for unbiased testing of Granger causality and for reliable analysis of the shock transmission mechanism between the variables in the system. Therefore, the VAR modelling provides a suitable framework for analysing implied volatility linkages among European currencies.

Granger causality tests, impulse response analysis and variance decompositions are applied to interpret the estimated VAR( $p$ ) system. Granger causality tests are used to identify potential lead-lag relationships between the implied volatilities and the direction of causalities. The Granger causality tests are conducted based on the unrestricted trivariate VAR( $p$ ) system, and hence, the causality results should be more general and reliable than in a standard bivariate setting. Impulse response analysis is used to trace the impact of a shock in implied volatility of one exchange rate on the future values of itself and the other implied volatilities in the system. Moreover, impulse response analysis reveals the persistence of shocks in the system, and hence, enables the assessment of the time structure of volatility transmission. In order to avoid problems with the ordering of the variables in the system, the generalized impulses proposed by Pesaran and Shin (1998) are applied in the impulse response analysis. Finally, variance decomposition analysis is used to assess the fraction of variation in implied volatility of one exchange rate caused by innovations in the other implied volatilities in the system.

Hence, variance decompositions provide information about the relative importance of one implied volatility in affecting the other implied volatilities in the VAR.

(insert Table 3 about here)

Determination of an appropriate lag order,  $p$ , for the VAR system is an empirical issue. In this paper, the order of the VAR is defined based on the standard lag length criteria and likelihood ratio tests. In addition, given that the residuals of the VAR should exhibit no serial correlation if there are enough lags in the model, the residual serial correlations are analysed to confirm the adequacy of the lag order. Table 3 reports Akaike's, Schwartz's and Hannan-Quinn information criteria and Lütkepohl's (1993) modified likelihood ratio test for the lag order selection. All the information criteria reported in Table 3 suggest setting  $p=2$  while the likelihood ratio test suggests  $p=3$ . In addition, the Breusch-Godfrey LM test indicates significant serial correlation in the residuals of the VAR(2) model. Therefore, the VAR(2) system is augmented with one additional lag. Model diagnostics suggest that this specification is adequate. Consequently, the empirical analysis in this paper is based on the VAR system given by Equation (1) with  $p=3$ .

#### **4. RESULTS**

Table 4 reports summary statistics of the VAR(3) estimation results. The  $F$ -statistics indicate that the estimated VAR(3) model is statistically highly significant. Moreover, the  $R^2$  is relatively high for all equations, ranging from 0.847 for the Swiss

franc to 0.927 for the euro. The Ljung-Box statistic for 12 lags shows no sign of residual serial correlation in the model, thereby suggesting that the selected lag order is adequate.

(insert Table 4 about here)

The contemporaneous residual correlations of the estimated VAR(3) model are shown in Table 5. The reported residual correlations between the implied volatility series indicate instantaneous relationships between the volatility expectations of the major European currencies. All residual correlations in Table 5 are positive and statistically highly significant. The highest residual correlation is found between the euro and the Swiss franc, with the correlation coefficient of 0.40. The residual correlations are somewhat lower between the euro and the British pound and between the Swiss franc and the British pound, correlation coefficients being 0.23 in both cases. These residual correlations indicate that the market expectations of future exchange rate volatilities are contemporaneously and positively linked among the major European currencies.

(insert Table 5 about here)

Granger causality tests are performed in order to ascertain potential lead-lag relationships between the implied volatility series. Table 6 presents the Granger causality test results based on the trivariate VAR(3) specification. The results indicate that the euro is the dominant European currency, as the implied volatility of the euro is

found to Granger cause the volatility expectations of both the British pound and the Swiss franc. In contrast, the Granger causality test results suggest that the volatility expectations of the euro are not affected by the other major currencies. In addition, the results show weak volatility transmission ( $p$ -value of 0.079) from the pound to the franc. In general, the Granger causality test results in Table 6 clearly show that the euro is the leading source of volatility expectations among the major European currencies.

(insert Table 6 about here)

In order to trace the impact of a shock in implied volatility of one exchange rate on the future values of itself and the other implied volatilities in the VAR system, impulse response analysis is accomplished. Given the Granger causality test results, the main focus in the analysis is on the dynamics of responses of the British pound and Swiss franc volatility expectations to shocks in the volatility expectations of the euro. The impulse response analysis is performed using generalized one standard deviation shocks on the implied volatilities (see Pesaran and Shin 1998). The impulse response functions and the Monte Carlo simulated 95 percent confidence bounds (dashed lines) are presented in Figure 2. The impulse response function of the implied volatility of the pound to a shock in the implied volatility of the euro indicates that after the contemporaneous (day one) effect, the implied volatility of the pound still increases on the next day (day two), and afterwards, the effect seems to settle down. A similar pattern can also be observed for the impulse response function of the implied volatility of the franc to a shock in the implied volatility of the euro. In brief, the impulse



response functions shown in Figure 2 indicate that a shock in the volatility expectations of the euro significantly affects volatility expectations of the pound and the franc. The impact of a shock in the implied volatility of the euro seems to be incorporated into the volatility expectations of the British pound and the Swiss franc during the first two days.

(insert Figure 2 about here)

Finally, variance decomposition analysis is applied to ascertain the relative importance of one implied volatility in affecting the other implied volatilities in the VAR system. The variance decompositions are presented in Figure 3. The dashed lines around each variance decomposition present 95 percent confidence bounds obtained via Monte Carlo simulation. Figure 3 clearly demonstrates that the forecast variance of the implied volatility of the euro is solely caused by innovations in itself. Hence, also the variance decomposition analysis implies that the volatility expectations of the euro are not affected by the British pound and the Swiss franc. However, volatility expectations of the euro appear to have a considerable impact on the volatility expectations of the pound and the franc. About 13 % of two days ahead and about 26 percent of ten days ahead variance forecasts of the pound is attributable to innovations in the volatility expectations of the euro. For the volatility expectations of the Swiss franc, the corresponding figures are 20 % and 31 %, respectively. Therefore, the variance decompositions suggest that the expected future volatilities of the British pound and the Swiss franc are significantly affected by the expected volatility of the euro.

(insert Figure 3 about here)

## 5. CONCLUSIONS

This paper examines linkages in expected future volatilities among major European currencies. The main novelty of this paper is the focus on linkages in expected exchange rate volatilities. Whereas the previous studies (see Najand et al., 1992; Alexander, 1995; Laopodis, 1998; Kearney et al., 2000; Speight et al., 2001) use *ex post* volatility estimates to examine volatility linkages across exchange rates, this paper uses *ex ante* volatility estimates extracted from option prices. Provided that market participants are rational, option-implied volatility estimates should incorporate all the available information that is relevant for forming expectations about the future volatility. Therefore, implied volatilities provide a suitable framework for assessing linkages in expected exchange rate volatilities.

The empirical analysis in this paper is performed using daily data on volatilities implied by currency options on the euro, British pound, and Swiss franc quoted against the U.S. dollar. Vector autoregressive (VAR) modelling is applied to ascertain the causal dynamics of the implied volatilities across currencies. Granger causality tests, impulse response analysis and variance decompositions are used to interpret the VAR estimation results.

In brief, the results of this paper indicate that the market expectations of future exchange rate volatilities are closely linked among the major European currencies. In particular, the results show that the euro is the dominant European currency, as the implied volatility of the euro is found to significantly affect the volatility expectations

of the British pound and the Swiss franc. Moreover, the results suggest that the volatility expectations of the euro are not affected by the other currencies.

The results of this paper have important practical implications, for instance, to financial market practitioners and monetary policy makers. Knowledge of the causal relationships between exchange rate volatilities may be useful e.g. for asset pricing, portfolio selection, and risk management purposes. In particular, the leading role of the euro may be utilized for constructing better volatility forecasts which are needed in numerous financial applications. From the viewpoint of monetary policy makers, the documented volatility linkages may be disquieting, as they imply that the exchange rates are affected by common uncertainty factors which are beyond the control of local monetary policy. Considering that the U.K. and Switzerland are relatively large economies, but still the volatility expectations of the euro significantly affect uncertainty in the British pound and Swiss franc, smaller European currencies such as the Danish and Swedish kronas are likely to be even more vulnerable to the impact of the euro.

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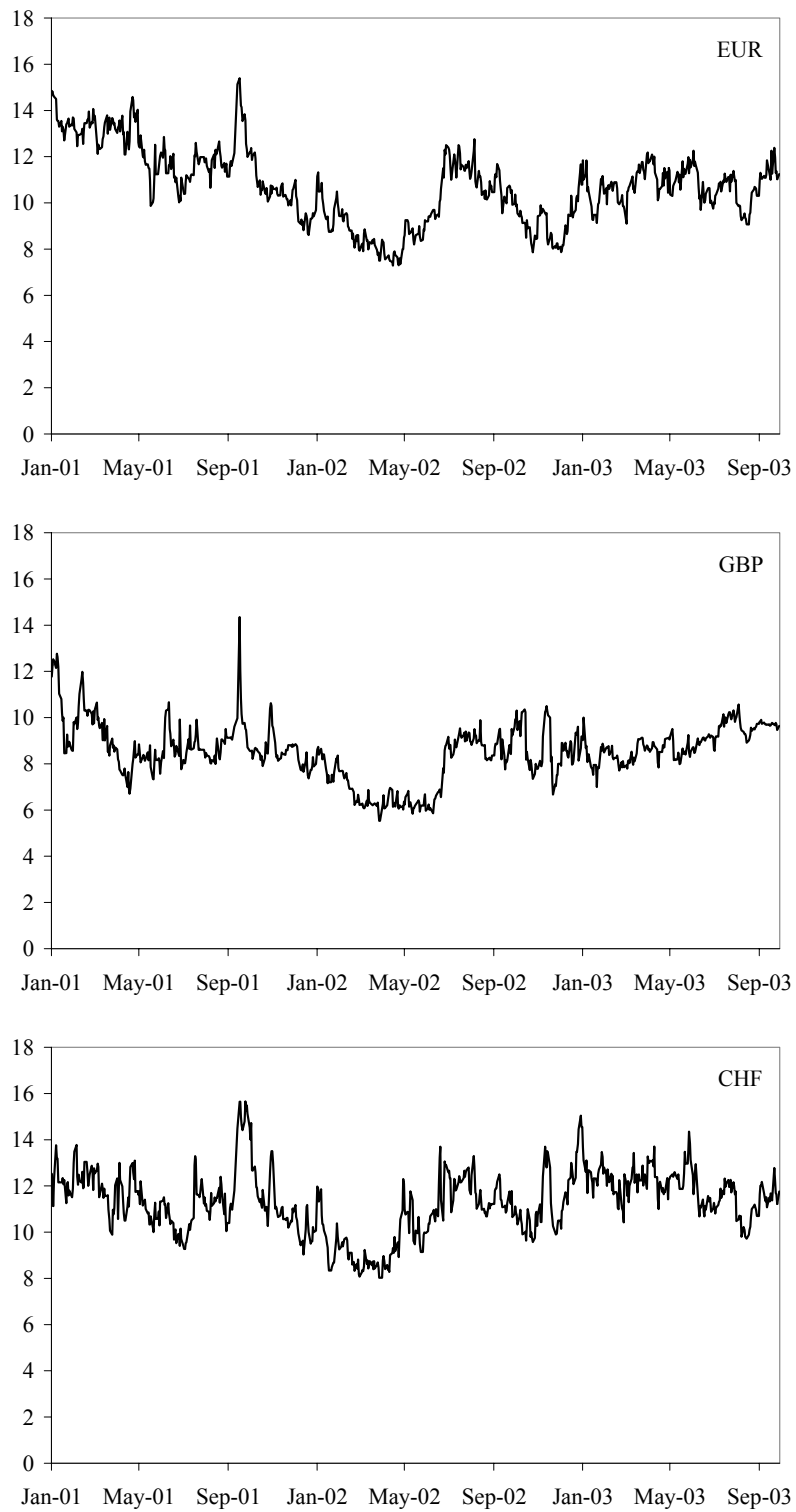
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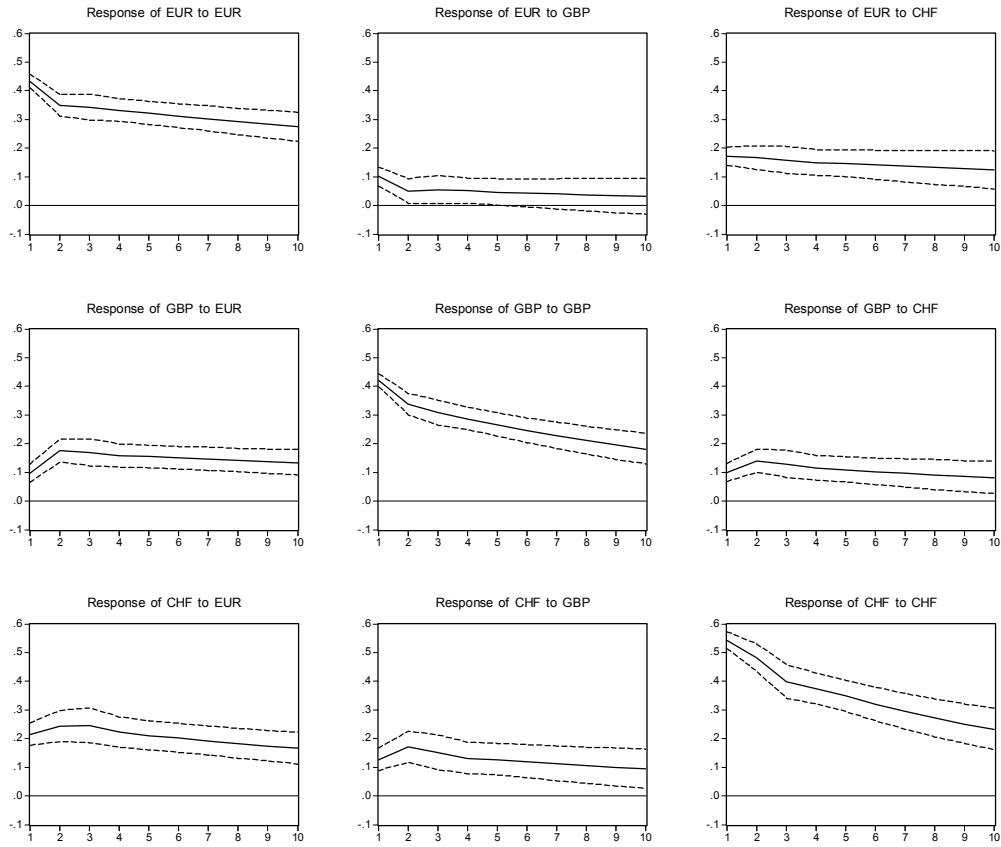
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**Figure 1.** Implied volatilities.

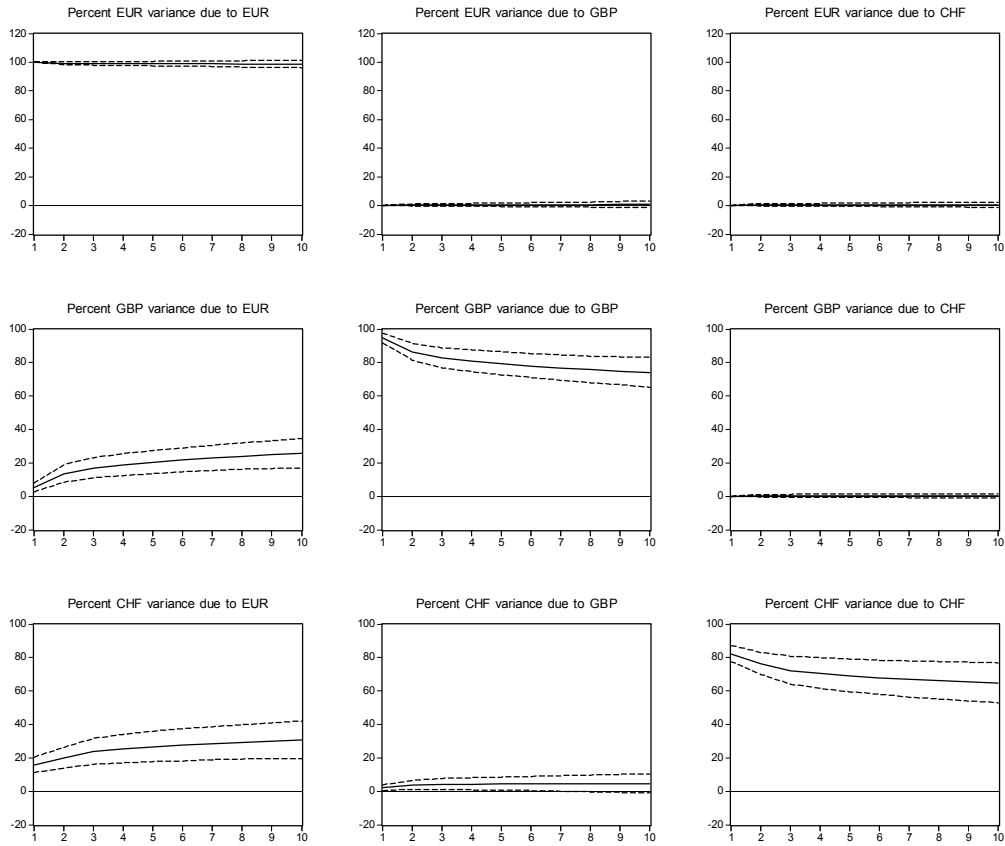
**Figure 2.** Impulse response functions.

The graphs present the impact of a generalized one standard deviation innovation in implied volatility of one exchange rate on itself and on the other implied volatilities in the system. Two standard error confidence bounds are presented around each impulse response function.



**Figure 3.** Variance decompositions.

The graphs present the percentage of forecast variance of implied volatility of one exchange rate caused by innovations in itself and in the other implied volatilities in the system. Two standard error confidence bounds are presented around each variance decomposition.



**Table 1.** Descriptive statistics and contemporaneous correlations of implied volatilities.

Panel A: Descriptive statistics			
	EUR	GBP	CHF
Mean	10.72	8.52	11.30
Median	10.73	8.57	11.31
Minimum	7.29	5.53	8.03
Maximum	15.40	14.35	15.66
Standard Deviation	1.61	1.22	1.38
Skewness	0.15	0.14	0.04
Kurtosis	2.65	4.21	3.26
No. of Observations	711	711	711

Panel B: Correlations			
	EUR	GBP	CHF
EUR	1.00		
GBP	0.63 <sup>†</sup>	1.00	
CHF	0.64 <sup>†</sup>	0.57 <sup>†</sup>	1.00

<sup>†</sup> significant at the 0.01 level

**Table 2.** Unit root tests.

The table reports Augmented Dickey-Fuller (ADF) and Phillips-Perron (PP) unit root tests without a time trend for the implied volatility series. The lag length for the unit root tests is decided based on the Schwarz information criterion. The critical value for the tests at the 1 % significance level is  $-3.44$ .

	ADF	p-value	PP	p-value
EUR	-3.672	0.005	-3.724	0.004
GBP	-4.856	0.000	-4.815	0.000
CHF	-5.575	0.000	-5.575	0.000

**Table 3.** Lag order selection for the VAR( $p$ ) model.

The table reports Akaike's (AIC), Schwarz's (SIC), and Hannan-Quinn (HQ) information criteria and Lütkepohl's (1993) modified likelihood ratio (LR) test for the lag order selection.

Lag	AIC	SIC	HQ	LR
0	9.282	9.302	9.290	
1	3.760	3.838	3.790	3877.960
2	3.654	3.790	3.706	91.840
3	3.659	3.853	3.734	14.362
4	3.667	3.920	3.765	11.723
5	3.670	3.981	3.790	15.492
6	3.672	4.041	3.815	16.318
7	3.682	4.110	3.848	10.342
8	3.690	4.176	3.878	12.241
9	3.689	4.234	3.900	16.746
10	3.697	4.301	3.930	11.823

**Table 4.** Summary statistics of the VAR(3) model.

The table reports the summary statistics of the following trivariate VAR(3) specification:

$$\begin{aligned}\sigma_{EUR,t} &= \alpha_{EUR} + \sum_{i=1}^3 \beta_{EUR,i}^{EUR} \sigma_{EUR,t-i} + \sum_{i=1}^3 \beta_{EUR,i}^{GBP} \sigma_{GBP,t-i} + \sum_{i=1}^3 \beta_{EUR,i}^{CHF} \sigma_{CHF,t-i} + \varepsilon_{EUR,t} \\ \sigma_{GBP,t} &= \alpha_{GBP} + \sum_{i=1}^3 \beta_{GBP,i}^{EUR} \sigma_{EUR,t-i} + \sum_{i=1}^3 \beta_{GBP,i}^{GBP} \sigma_{GBP,t-i} + \sum_{i=1}^3 \beta_{GBP,i}^{CHF} \sigma_{CHF,t-i} + \varepsilon_{GBP,t} \\ \sigma_{CHF,t} &= \alpha_{CHF} + \sum_{i=1}^3 \beta_{CHF,i}^{EUR} \sigma_{EUR,t-i} + \sum_{i=1}^3 \beta_{CHF,i}^{GBP} \sigma_{GBP,t-i} + \sum_{i=1}^3 \beta_{CHF,i}^{CHF} \sigma_{CHF,t-i} + \varepsilon_{CHF,t}\end{aligned}$$

where  $\sigma_{j,t}$  denotes implied volatility of currency  $j$  quoted against the U.S. dollar at time  $t$ .  $Q(n)$  is the Ljung-Box statistic for  $n$  lags.

Dependent Variable	Adj. $R^2$	$F$ -Stat.	p-value	$Q(12)$	p-value
EUR	0.927	977.911	0.000	15.863	0.198
GBP	0.879	563.905	0.000	9.629	0.648
CHF	0.847	430.618	0.000	12.194	0.430

**Table 5.** Residual correlations of the VAR(3) model.

The table reports the residual correlations of the following trivariate VAR(3) specification:

$$\begin{aligned}\sigma_{EUR,t} &= \alpha_{EUR} + \sum_{i=1}^3 \beta_{EUR,i}^{EUR} \sigma_{EUR,t-i} + \sum_{i=1}^3 \beta_{EUR,i}^{GBP} \sigma_{GBP,t-i} + \sum_{i=1}^3 \beta_{EUR,i}^{CHF} \sigma_{CHF,t-i} + \varepsilon_{EUR,t} \\ \sigma_{GBP,t} &= \alpha_{GBP} + \sum_{i=1}^3 \beta_{GBP,i}^{EUR} \sigma_{EUR,t-i} + \sum_{i=1}^3 \beta_{GBP,i}^{GBP} \sigma_{GBP,t-i} + \sum_{i=1}^3 \beta_{GBP,i}^{CHF} \sigma_{CHF,t-i} + \varepsilon_{GBP,t} \\ \sigma_{CHF,t} &= \alpha_{CHF} + \sum_{i=1}^3 \beta_{CHF,i}^{EUR} \sigma_{EUR,t-i} + \sum_{i=1}^3 \beta_{CHF,i}^{GBP} \sigma_{GBP,t-i} + \sum_{i=1}^3 \beta_{CHF,i}^{CHF} \sigma_{CHF,t-i} + \varepsilon_{CHF,t}\end{aligned}$$

where  $\sigma_{j,t}$  denotes implied volatility of currency  $j$  quoted against the U.S. dollar at time  $t$ .

	EUR	GBP	CHF
EUR	1.00		
GBP	0.23 <sup>†</sup>	1.00	
CHF	0.40 <sup>†</sup>	0.23 <sup>†</sup>	1.00

<sup>†</sup> significant at the 0.01 level



**Table 6.** Granger causality tests.

The table reports the Granger causality test results based on the following trivariate VAR(3) specification:

$$\begin{aligned}\sigma_{EUR,t} &= \alpha_{EUR} + \sum_{i=1}^3 \beta_{EUR,t}^{EUR} \sigma_{EUR,t-i} + \sum_{i=1}^3 \beta_{EUR,t}^{GBP} \sigma_{GBP,t-i} + \sum_{i=1}^3 \beta_{EUR,t}^{CHF} \sigma_{CHF,t-i} + \varepsilon_{EUR,t} \\ \sigma_{GBP,t} &= \alpha_{GBP} + \sum_{i=1}^3 \beta_{GBP,t}^{EUR} \sigma_{EUR,t-i} + \sum_{i=1}^3 \beta_{GBP,t}^{GBP} \sigma_{GBP,t-i} + \sum_{i=1}^3 \beta_{GBP,t}^{CHF} \sigma_{CHF,t-i} + \varepsilon_{GBP,t} \\ \sigma_{CHF,t} &= \alpha_{CHF} + \sum_{i=1}^3 \beta_{CHF,t}^{EUR} \sigma_{EUR,t-i} + \sum_{i=1}^3 \beta_{CHF,t}^{GBP} \sigma_{GBP,t-i} + \sum_{i=1}^3 \beta_{CHF,t}^{CHF} \sigma_{CHF,t-i} + \varepsilon_{CHF,t}\end{aligned}$$

where  $\sigma_{j,t}$  denotes implied volatility of currency  $j$  quoted against the U.S. dollar at time  $t$ . The reported Wald statistic is for the joint significance of the coefficients of lagged implied volatilities of currency  $k$  in the implied volatility equation of currency  $j$ .

	Wald-stat.	p-value
Dependent: EUR		
GBP	5.567	0.135
CHF	4.934	0.177
Dependent: GBP		
EUR	31.876	0.000
CHF	3.875	0.275
Dependent: CHF		
EUR	9.344	0.025
GBP	6.796	0.079