International links between the dollar, euro and yen interest rate swap markets: A new approach using the wavelet multiresolution method

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Abstract

We use the wavelet multiresolution method to examine the links between the world's largest interest rate swap markets, namely the US dollar, the euro and the Japanese yen, over various time horizons. In contrast to approaches used in previous studies, wavelet analysis allows us to decompose the data into various time scales. First we investigate the issue of causal relationships across the three major international swap markets using a wavelet multiscaling method. Using this technique, we find that the dynamic causal interactions intensified over time and are persistent after the d3 wavelet time scale, which corresponds to 8-16 trading days. We find that the variances of the dollar and the euro swap markets are high compared to the yen market. We also find that the correlation between swap markets varies over time but remains very high, especially between the dollar and the euro. However, it is much lower between the euro and the yen, and between the dollar and the yen, implying that even though there have been striking developments in international swap markets since 1999, the yen market remains relatively less integrated with the other major swap markets. Finally, there is a noticeable variability in the euro swap market, compared to the dollar and yen swap markets, regardless of the time scale.

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1. Introduction

Twenty years ago, interest rate swaps were an obscure and specialized transaction. Today, they are one of the most heavily traded financial contracts. In 1982 the notional amount of swaps outstanding was almost zero; ten years later it had reached $3 trillion; in June 2003, it reached $95 trillion. The swap market is now so important that some commentators have suggested it could take over the fundamental pricing role of the government bond market should that market disappear. Yet despite the obvious significance of swaps, the empirical research literature is at present very small compared to the literature on equity and conventional debt markets.

Most empirical studies of interest rate swaps have studied US dollar swaps. These studies include Brown, Harlow and Smith (1994), Collin-Dufresne and Solnik (2001), Duffie and Huang (1996), Duffie and Singleton (1997), Li and Mao (2003), In, Brown and Fang (2003b), Lang, Litzenberger and Liu (1998), and Sun, Sundaresan and Wang (1993). Despite the huge size of the global swap market, there is relatively little evidence on the pricing of interest rate swaps other than US dollar swaps. We know of only four published studies on other currencies: In, Brown and Fang (2004) on the Australian and US dollar; Brown, In and Fang (2002) on the Australian dollar; Eom, Subrahmanyam and Uno (2002) on the Japanese yen; and Lekkos and Milas (2001) on the British pound.

Recently, there has been a little-noted but potentially highly significant change in the structure of the world's swap market. In an historic shift, the size of the euro swap market now comfortably exceeds that of its US dollar counterpart.[1] Statistics available from the website of the Bank for International Settlements show that as at June 2003, the notional amount of euro interest rate swaps outstanding stood at the equivalent of $40.7 trillion, while the corresponding figure for US dollar swaps was $27.6 trillion. The notional amount of yen interest rate swaps outstanding was $13.5 trillion. The creation and expansion of the euro swap market has the potential to reshape the channels of influence between swap markets, rendering obsolete our current knowledge of the links between these markets.

During the period in which swap markets developed rapidly, international capital markets were becoming increasinly globalized. In this environment, economic and financial commentators frequently assume that changes in one country's interest rate market will directly and rapidly affect those in another. Although there are many studies of short-term links between international stock markets, much less has been written on short-term links between debt markets. In part, this lack of evidence is due to the focus of the interest rate literature on real rather than nominal interest rates. A partial exception is Al Awad and Goodwin (1998), whose study includes analysis of weekly changes in nominal interest rates.[2] Using impulse response analysis, they conclude that shocks in nominal US interest rates evoke significant responses in the UK, France and Germany but not *vice-versa.*

We have chosen to study the swap market because, unlike many other financial contracts, the interest rate swap contract is both internationally standardized and heavily traded.

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[1] Trichet mentions but does not discuss "the huge expansion of the euro interest-rate swap market" (Trichet, 2001, p. 8).

[2] Most of their analysis concerns real interest rates, calculated using weekly inflation rates that are interpolated from monthly data.

It is therefore an ideal vehicle for a study of the international links between interest rate markets. There are only three published studies of the short-run international links between interest rate swap markets, none of which includes the euro: Eom, Subrahmanyam, and Uno (2002) using weekly data on the US and Japanese markets, In, Brown and Fang (2003a) using daily data on the US, UK and Japanese markets and Lekkos and Milas (2001) using weekly data on the US and UK markets. It is an intriguing area of study because it provides insights into information transmission, and the pricing of swaps with different maturities.

The main purpose of this paper is to deepen our knowledge of the links between the three major international swap markets: the US dollar, the euro and the Japanese yen. Swap market participants are a diverse group and include intraday traders, hedge funds, portfolio managers, commercial banks, large corporations and central banks. These participants operate on very different time scales. Owing to the different decision-making time scales among traders, the true dynamic and causal relationships between international swap markets will vary over different time scales associated with these different horizons. As a result, low-frequency shocks and high-frequency shocks will affect the market differently. Thus, we need an econometric method that can capture the underlying dynamic structure at different time scales, which in turn involves the separation of local dynamics from global dynamics such as the market's long-term growth path, and transitory changes from permanent changes. Traditional methods are poorly equipped for this task because they use only two time scales (the long run and the short run). Our paper contributes to the literature on the causal relationships by using a wavelet mutliscaling method that decomposes a given time series on a scale-by-scale basis. The wavelet covariance decomposes the covariance between two stochastic processes over different time scales. A wavelet covariance in a particular time scale indicates the contribution to the covariance between two stochastic variables. This feature of wavelet analysis allows us to examine the covariance/correlation over different time scales.

The remainder of the paper is organized as follows. Section 2 discusses the data and provides descriptive statistics. Section 3 outlines the methodology used. Section 4 presents the empirical results and discusses the findings. Finally, section 5 provides a summary and conclusion.

2. Data and descriptive statistics

We use daily closing mid-rate data on swap maturities of three, five and ten years, for the US dollar, the euro and the Japanese yen in the period January 4, 1999 to January 31, 2003, giving a sample size of 1065 observations for each swap maturity. Data for each currency were collected from Datastream.

TABLE 1 ABOUT HERE

Descriptive statistics are reported in Panel A of Table 1. On average, the yield curves for swap rates are upward sloping in the three currencies during the sample period. The variances range from 0.832 to 2.133 for dollar swap rates, from 0.072 to 0.185 for yen swap rates and from 0.262 to 0.502 for euro swap rates. The measures for skewness and kurtosis are also reported to indicate whether swap rates are normally distributed. The sign of skewness varies between countries and maturities. In all cases, the Jarque-Bera statistic (denoted by JB) rejects normality at any conventional level of statistical significance. The Ljung-Box statistic for 15 lags (denoted by LB(15)) and squared term (denoted by $LB^2(15)$)

indicate that significant linear and nonlinear dependencies exist. Nonlinear dependencies can be captured satisfactorily by autoregressive conditional heteroskedasticity models.

Panel B of Table 1 presents cross-correlations for swap rates for the three different maturities in the three currencies. The correlation structure of these swap markets is perhaps the most important feature from the viewpoint of investors and portfolio managers because hedging and diversification strategies invariably involve some measure of correlation (In and Kim, 2004). Overall, the correlations between markets vary with maturity. The strongest correlation is observed between the dollar and the yen, regardless of the maturity, followed by the dollar and the euro, and finally the euro and the yen. The correlations range from 0.827 to 0.865 for the dollar-yen, from 0.600 to 0.729 for the dollar-euro, and from 0.366 to 0.400 for the yen-euro.

3. Research methodology: The wavelet multiresolution method[3]

3.1 Basic concept of wavelets

A major innovation of this paper is to introduce a new approach to study spillover effects in international interest rate markets. The approach is based on the wavelet multiresolution or multiscaling method (or 'wavelet analysis' for short). Wavelet analysis is a relatively new and powerful mathematical tool for signal processing. Like conventional Fourier time series analysis, it involves the projection of a signal onto an orthogonal set of components; sine and cosine functions in the case of Fourier analysis and wavelets in the case

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[3] This section draws heavily on In and Kim (2004).

of wavelet analysis. A critical difference is that wavelet transforms present the characteristics of the *local* behavior of the function whereas Fourier transforms present the characteristics of the *global* behavior of the function. Compared to Fourier analysis, wavelet analysis offers three advantages. First, it can handle non-stationary data. Second, it can handle localization in time. Third – and most importantly for this research – it permits resolution of the signal in terms of the time scale of analysis.

Basic wavelets are characterized into 'father' and 'mother' wavelets, $\phi(t)$ and $\psi(t)$, respectively. These wavelets are functions of time only. A father wavelet represents the smooth baseline trend components of a time series while the mother wavelets are used to describe all deviations from the trend. Through scaling and translation, any function $f(t)$ can be built up as a sequence of projections onto father and mother wavelets generated from $\phi(t)$ and $\psi(t)$.

The wavelet representation of the function $f(t)$ can now be given as:

$$f(t) \approx \sum_k s_{J,k}\phi_{J,k}(t) + \sum_k d_{J,k}\psi_{J,k}(t) + \sum_k d_{J-1,k}\psi_{J-1,k}(t) + \cdots + \sum_k d_{1,k}\psi_{1,k}(t) \qquad (1)$$

where J is the number of multiresolution components, and k ranges from 1 to the number of coefficients in the specified component. The coefficients $s_{J,k}$, $d_{J,k}$, …, $d_{1,k}$ are the wavelet transform coefficients. Note that the detail coefficients $d_{j,k}$, …, $d_{1,k}$ can capture the higher frequency oscillations and represent increasingly finer-scale deviations from the smooth trend, while $s_{J,k}$ represents the smooth coefficients that capture the trend.

To show the multiresolution decomposition method, we now describe the discrete wavelet transform (DWT). The DWT calculates the coefficients of the wavelet series approximation (see equation (1)) for a discrete signal $f_1, \ldots, f_n$ of finite extent. The DWT maps the vector f = $(f_1, f_2, \ldots, f_n)'$ to a vector of n wavelet coefficients w = $(w_1, w_2, \ldots, w_n)'$. The vector w contains the coefficients $s_{J,k}$, $d_{J,k}, \ldots, d_{1,k}$, j = 1, 2, …, J of the wavelet series approximation, Eq. (1). The DWT is mathematically equivalent to multiplication by an orthogonal matrix W:

$$\mathrm{w} = \mathrm{Wf} \tag{2}$$

where the coefficients are ordered from coarse scales to fine scales in the vector w. In the case where n is divisible by 2^J,

$$\mathbf{w} = \begin{pmatrix} \mathbf{s}_J \\ \mathbf{d}_J \\ \mathbf{d}_{J-1} \\ \vdots \\ \mathbf{d}_1 \end{pmatrix} \tag{3}$$

where $\mathbf{s}_J = (s_{J,1}, s_{J,2}, \ldots, s_{J,n/2^J})'$

$$\mathbf{d}_J = (d_{J,1}, d_{J,2}, \ldots, d_{J,n/2^J})'$$

$$\mathbf{d}_{J-1} = (d_{J-1,1}, d_{J-1,2}, \ldots, d_{J-1,n/2^J})'$$

$$\vdots \qquad\qquad \vdots$$

$$\mathbf{d}_1 = (d_{1,1}, d_{1,2}, \ldots, d_{1,n/2^J})'$$

Each set of coefficients $\mathbf{s}_J$, $\mathbf{d}_J$, $\mathbf{d}_{J-1}$, …, $\mathbf{d}_1$ is called a 'crystal', and the wavelet associated with each coefficient is referred to as an 'atom'. Using the product of the crystals and the corresponding wavelet atoms, the multiresolution decomposition of a signal or function can now be defined as:

$$S_{J,k} = \sum_k s_{J,k}\phi_{J,k}(t), \tag{4}$$

$$D_{J,k} = \sum_k d_{J,k}\psi_{J,k}(t) \quad \text{and} \tag{5}$$

$$D_{1,k} = \sum_k d_{1,k}\psi_{1,k}(t), \text{j} = 1, 2, \ldots, \text{J-1}$$

Eqs. (4) and (5) are called the 'smooth' and the 'detail' signals, respectively, and they constitute a decomposition of a signal into orthogonal components at different scales. Similar to the wavelet representation (1), a signal $f(t)$ can now be expressed in terms of these signals:

$$f(t) = S_{J,k} + D_{J,k} + D_{J-1,k} + \ldots + D_{1,k} \tag{6}$$

As each term in Eq. (6) represents components of the signal $f(t)$ at different resolutions, it is called a 'multiresolution decomposition'.

Our analysis adopts the MODWT (Maximal Overlap Discrete Wavelet Transform) instead of DWT. It provides basically all functions of the DWT, such as Multiresolution Analysis (MRA) decomposition and analysis of variance (for more detail, see In and Kim, 2004 and Percival and Walden, 2000).

3.2 Estimation of wavelet variance, covariance and correlation

The wavelet coefficients (MODWT) indicate the changes at a particular scale. Thus, applying the MODWT to a stochastic time series produces a scale-by-scale decomposition. The basic idea of the wavelet variance is to substitute the notion of variability over certain scales for the global measure of variability estimated by the sample variance (Percival and Walden, 2000). If we assume that the dependence structure of the first difference of each swap rate is independent of time, then we may define the wavelet variance of an asset. The wavelet variance[4] is estimated using the MODWT coefficients for scale $\lambda_j \equiv 2^{j-1}$ through:

$$\tilde{v}_l^2(\lambda_j) \equiv \frac{1}{\tilde{N}_j} \sum_{t=L_j-1}^{N-1} [\tilde{d}^{\,l}_{j,t}]^2 , \; l = X, Y \qquad (7)$$

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[4] We follow the derivation of Gençay, Selçuk, and Whitcher (2002, Chapter 7).

where $\tilde{d}^{l}_{j,t}$ is the MODWT wavelet coefficients of variables l at scale λ_j. $\tilde{N}_j = N - L_j + 1$ is the number of coefficients unaffected by the boundary, and $L_j = (2^j - 1)(L - 1) + 1$ is the length of the scale λ_j wavelet filter.[5]

To this point, we have examined how to derive wavelet variances. Note that as with the wavelet variance, the wavelet covariance can also decompose the sample covariance into different time scales. In other words, a wavelet covariance in a particular time scale indicates the contribution to the covariance between two stochastic variables (for more detail, see Lindsay, Percival and Rothrock, 1996). The wavelet covariance at scale λ_j can be expressed as follows:

$$Cov_{XY}(\lambda_j) \equiv \frac{1}{\tilde{N}_j} \sum_{t=L_j-1}^{N-1} \tilde{d}^{X}_{j,t} \tilde{d}^{Y}_{j,t} \tag{8}$$

Note that the estimator does not include any coefficients that make explicit use of the periodic boundary conditions. We can construct a biased estimator of the wavelet covariance by simply including the MODWT wavelet coefficients affected by the boundary and renormalizing. Given that covariance does not take into account the variation of the univariate time series, it is natural to introduce the concept of wavelet correlation.

Although the wavelet covariance decomposes the covariance between two stochastic processes on a scale-by-scale basis, in some situations it may be beneficial to normalize the wavelet covariance by the variability inherent in the observed wavelet coefficients. This leads us to calculate the wavelet correlation. The wavelet correlation is simply made up of the

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[5] Percival and Walden (2000, p. 309) provide the asymptotic relative efficiencies for the wavelet variance

wavelet covariance for $\{X_t, Y_t\}$ and wavelet variances for $\{X_t\}$ and $\{Y_t\}$. Using Eqs. (7) and (8), the MODWT estimator of the wavelet correlation can be expressed as follows:

$$\tilde{\rho}_{XY}(\lambda_j) \equiv \frac{Cov_{XY}(\lambda_j)}{\tilde{v}_X(\lambda_j)\tilde{v}_Y(\lambda_j)} \qquad (9)$$

As with the usual correlation coefficient between two random variables, $|\tilde{\rho}_{XY}(\lambda_j)|<1$. The wavelet correlation is analogous to its Fourier equivalent, the complex coherency (Gençay, Selçuk, and Whitcher, 2002, p. 258).

4. Empirical results

In order to test for Granger-causality between the three swap markets at different time scales, a MODWT multiresolution analysis was performed using the Daubechies LA(8) wavelet filter. Since we use daily data, the wavelet scales d1, d2, d3, d4, d5, d6, and d7 are associated with oscillation of periods 2-4, 4-8, 8-16, 16-32, 32-64, 64-128 and 128-256 days, respectively.

TABLES 2 AND 3 ABOUT HERE

Tables 2 and 3 report the Granger-causality test of swap rates and swap volatilities, respectively. Both tests are based on the wavelet domain for the three different maturities. The results reported in these tables show that there are causality effects between pairs of swap markets even in the first layer, which represents a period of 2 days. Overall, however, the

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estimator based on the orthogonal DWT compared to the estimator based on the MODWT.

causality effects show strongly beyond the third layer, which represents a data length of around 8 days. It follows that the three swap markets become more strongly related as the time-scale increases. For example, Table 2 shows that the Granger-causality of 3-year swap rates is strong, evidenced by the fact that four out of the six connections at the longest (d7) wavelet scale are statistically significant, while all six connections for both 5-year swap rates and 10-year swap rates are statistically significant. Similarly, the results in Table 3 show that the Granger-causality of swap volatilities is strongest at the longest (d7) wavelet scale, evidenced by the statistical significance of five out of the six connections for both 3-year and 5-year swap volatilities, and all six connections for 10-year swap volatilities . In short, the key common finding from Tables 2 and 3 is that, overall, the wavelet multiscale Granger-causality tests indicate that the connections among all three swap markets are stronger and more certain in the long term, regardless of swap maturity.

We analyze the relationships between pairs of swap markets using wavelet analysis. To be consistent with the Granger-causality tests, we use the MODWT based on the Daubechies least asymmetric family of wavelets (LA(8)). We investigate the swap market links in terms of wavelet covariances and correlations over the various time scales. To investigate the multiscale correlation, we report the variances of swap market rates for the three currencies, for the three different swap maturities.

FIGURE 1 ABOUT HERE

Figure 1 illustrates the MODWT-based wavelet variance of dollar swap rates, euro swap rates and yen swap rates. The wavelet variances show that the 3-year swap market is more volatile than the 5-year and 10-year swap markets regardless of the time scale. This pattern is consistent across the different currencies, supporting the conventional perception that shorter-term rates tend to be more volatile than longer-term rates.

In addition to examining the variances of currencies, a natural question is how different currency series are associated with one another. Note that a wavelet covariance in a particular time scale indicates the contribution to the covariance between two series. Figure 2 shows the MODWT-based wavelet covariances for 3-year, 5-year and 10-year swap rates and for pairs of swap markets (i.e., dollar *vs* euro, dollar *vs* yen, and euro *vs* yen) using the LA(8) wavelet filter.

FIGURE 2 ABOUT HERE

Overall, the movements of covariance decrease as the time scale increases. However, it is difficult to compare wavelet covariances between maturities or between currencies because of the different variability exhibited by them. Therefore, we examine the wavelet correlations.

FIGURE 3 ABOUT HERE

Figure 3 shows the correlation between pairs of swap markets (i.e., dollar *vs* euro, dollar *vs* yen, and euro *vs* yen) against the wavelet scales for 3-year, 5-year and 10-year swap rates. A distinctive feature of Figure 3 is the high and significantly positive relationship that can be observed in all time scales in the case of the dollar *vs* the euro. The correlation between these markets steadily increases over time and, at more than 0.6 on average, remains very high.

In contrast, the correlations between the dollar and the yen, and between the euro and the yen, show a low and (usually) positive relationship in all time scales. For the 3-year and 5-year swap rates, the correlations between the dollar and the yen, and between the euro and the yen increase slightly over time, up to the 4th layer, which represents a data period of around 16 days. After this point, the series falls into low and negative relationships. Similarly, for 10-year swap rates, the correlations between the dollar and the yen, and between the euro and the yen, remain very low and positive until the 5th layer, turning negative at the 6th layer. It is positive at the 7th layer for the dollar-yen pair but remains negative for the euro-yen pair. The low magnitude of the correlations involving the yen imply that the yen swap market is less tightly connected with the other major swap markets.

FIGURE 4 ABOUT HERE

Figures 4(a), 4(b) and 4(c) show the LA(8) MODWT MRA of 10-year swap rates for the dollar, the euro and the yen respectively, using various time scales (i.e., the seven different wavelet details, d1 to d7). In each plot, the topmost panel shows the original time series. Below it, from top to bottom, are the wavelet details d1, d2, … , d7. One of the distinctive features of the MRA of the three swap markets is that there are many peaks in the original series for the euro swap market, compared to the dollar and yen swap markets. This feature is captured in the d1 and d2 components. At the highest time scale, d7, representing the deviation from the long-term trend, overall there is relatively smooth movement in each currency. However, the long-term movement of the euro swap market is different from that of the dollar and yen swap markets. The deviation from the long-term movement of the euro swap market has more pronounced peaks and troughs, reflecting the less stable nature of the market, even in the long-term scales. For those market participants who are operating in the international swap markets on longer time horizons, such as central banks, this empirical finding may lead to better informed views on the behavior of swap rates.

Overall, as the time scale increases from the finest time scale (d1) to the coarsest time scale (d7), the wavelet coefficients show a progressively smoother movement, implying that short-term noise in the market is eliminated and consequently there emerges the "true" underlying economic relationship between swap markets. These wavelet MRA figures indicate that the wavelet decomposition provides information that cannot be captured by conventional analysis. In other words, the decomposition of data into several time scales is important in economics and finance, since it detects the frequency burst in various time scales.

5. Concluding remarks

This paper examines the links between the major international interest rate swap markets, namely the US dollar, the euro and the Japanese yen over various time horizons. We propose a new approach – the wavelet multiscaling method – to undertake this investigation. The approach focuses on the relationship in four ways: (1) the lead-lag causal relationship, (2) variance (covariance), (3) correlations and (4) multiresolution analysis.

To examine the lead-lag relationship between the two markets, we employ the Granger-causality test for various time scales across the three major international swap markets using a wavelet multiscaling method. Using this technique, we find that the dynamic causal interactions intensify over time. It is found that beyond the third-level time scale, the three major swap markets show more active feedback relationships regardless of swap maturity.

Second, it is found that there is an approximate linear relationship between the wavelet variance and the wavelet scale, indicating the potential for long memory in the swap volatility series. Wavelet variances and covariances decrease as the wavelet time scale increases. Overall, the wavelet variances show that the dollar and the euro swap markets are more volatile than their yen counterparts, regardless of the time scale.

Third, we also find that the correlation between the swap markets varies over time but remains very high, especially for the euro and dollar swap markets but is much lower between the euro and yen swap markets, and between the dollar and yen swap markets. This finding implies that the yen swap market is relatively less integrated with the other major swap markets.

Fourth, according to the MODWT multiresolution analysis, we also find that there is a noticeable variability in the euro swap market, compared to the dollar and yen swap markets, regardless of the different time scales. The analysis shows that introduction of the euro swap market provides an insight for central banks, in particular, which operate on larger time horizons in the international swap markets.

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Table 1

Preliminary statistics

Panel A. Descriptive statistics

	US Dollar			Euro			Japanese Yen		
	3-year	5-year	10-year	3-year	5-year	10-year	3-year	5-year	10-year
Mean	5.311	5.683	6.127	4.365	4.701	5.230	0.485	0.860	1.674
Variance	2.133	1.445	0.832	0.502	0.402	0.262	0.072	0.155	0.185
Skewness	-0.281	-0.297	-0.195	-0.220	-0.408	-0.540	0.247	0.077	-0.105
Kurtosis	-1.019	-0.815	-0.785	-0.845	-0.734	-0.649	-1.561	-1.622	-1.281
JB	60.103	45.124	34.113	40.313	53.445	70.475	118.886	117.786	74.769
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
LB(15)	15424.404	20080.098	19659.073	19277.968	18942.066	18511.819	19300.468	19797.507	19385.871
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
LB^2(15)	20532.641	20227.587	19752.334	19471.121	19098.794	18627.753	18062.089	19173.404	19310.049
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)

The statistics refer to swap rates (% pa) using daily closing mid-rate data for the period January 4, 1999 to January 31, 2003 for US dollars, euros and Japanese yen. Data were collected from Datastream. Significance levels are in parentheses. LB(n) is the Ljung-Box statistic for up to n lags, distributed as χ^2 with n degrees of freedom. Skewness and kurtosis are defined as $E[(R_t - \mu)]^3$ and $E[(R_t - \mu)]^4$, where μ is the sample mean. JB indicates the Jarque-Bera statistic.

Panel B. Cross-correlations between swap rates

3-year swap rates

	Dollar	Dollar (*t*-1)	Euro	Euro (*t*-1)	Yen	Yen (*t*-1)
Dollar	1.000	0.999	0.600	0.594	0.858	0.856
Dollar (*t*-1)		1.000	0.602	0.598	0.858	0.856
Euro			1.000	0.998	0.406	0.404
Euro (*t*-1)				1.000	0.402	0.400
Yen					1.000	0.997
Yen (*t*-1)						1.000

5-year swap rates

	Dollar	Dollar (*t*-1)	Euro	Euro (*t*-1)	Yen	Yen (*t*-1)
Dollar	1.000	0.998	0.638	0.631	0.865	0.864
Dollar (*t*-1)		1.000	0.640	0.636	0.865	0.863
Euro			1.000	0.997	0.367	0.367
Euro (*t*-1)				1.000	0.362	0.362
Yen					1.000	0.997
Yen (*t*-1)						1.000

10-year swap rates

	Dollar	Dollar (*t*-1)	Euro	Euro (*t*-1)	Yen	Yen (*t*-1)
Dollar	1.000	0.997	0.729	0.722	0.827	0.825
Dollar (*t*-1)		1.000	0.731	0.728	0.825	0.824
Euro			1.000	0.997	0.366	0.365
Euro (*t*-1)				1.000	0.359	0.359
Yen					1.000	0.997
Yen (*t*-1)						1.000

The correlations are calculated using daily closing mid-rate swap rates (% pa) data for the period January 4, 1999 to January 31, 2003 for US dollars, Euros and Japanese yen. Data were collected from Datastream.

TABLE 2
Granger-causality test of swap rates on the wavelet domain
Panel A. 3-year swap rates

	d1	d2	d3	d4	d5	d6	d7
EUR → USD	0.034	3.903*	4.839*	4.000*	3.383*	20.987*	1.599
	(0.853)	(0.020)	(0.028)	(0.046)	(0.034)	(0.000)	(0.206)
USD → EUR	1.296	0.756	4.442*	1.993	6.924*	21.339*	1.793
	(0.255)	(0.470)	(0.035)	(0.158)	(0.001)	(0.000)	(0.181)
JPY → USD	1.505	0.001	0.786	8.594*	3.308*	0.429	95.165*
	(0.220)	(0.973)	(0.502)	(0.003)	(0.037)	(0.513)	(0.000)
USD → JPY	1.859	0.852	6.600*	8.594*	1.954	0.375	84.400*
	(0.173)	(0.356)	(0.000)	(0.003)	(0.142)	(0.540)	(0.000)
JPY → EUR	0.001	1.166	4.894*	0.011	1.402	2.893*	8.424*
	(0.975)	(0.322)	(0.027)	(0.917)	(0.201)	(0.003)	(0.004)
EUR → JPY	1.220	2.565*	4.084*	0.002	6.265*	4.836*	6.530*
	(0.270)	(0.018)	(0.044)	(0.962)	(0.000)	(0.000)	(0.011)

The significance levels are in parentheses and * indicates significance at 5% level.

Panel B. 5-year swap rates

	d1	d2	d3	d4	d5	d6	d7
EUR → USD	0.360	2.378	0.851	1.796	0.549	35.913*	11.713*
	(0.549)	(0.093)	(0.493)	(0.097)	(0.459)	(0.000)	(0.001)
USD → EUR	4.552*	2.805	1.262	2.150*	0.446	36.005*	12.561*
	(0.033)	(0.061)	(0.283)	(0.046)	(0.504)	(0.000)	(0.000)
JPY → USD	2.823	1.696	16.537*	4.440*	8.667*	3.951*	127.260*
	(0.093)	(0.184)	(0.000)	(0.035)	(0.000)	(0.047)	(0.000)
USD → JPY	0.001	5.116*	18.949*	5.686*	3.816*	3.108	105.212*
	(0.976)	(0.006)	(0.000)	(0.017)	(0.022)	(0.078)	(0.000)
JPY → EUR	0.739	1.707	0.010	0.006	1.959	0.409	25.319*
	(0.390)	(0.116)	(0.921)	(0.939)	(0.058)	(0.523)	(0.000)
EUR → JPY	0.634	2.467*	0.001	0.101	3.914*	0.113	20.052*
	(0.426)	(0.022)	(0.980)	(0.750)	(0.000)	(0.737)	(0.000)

The significance levels are in parentheses and * indicates significance at 5% level.

Panel C. 10-year swap rates

	d1	d2	d3	d4	d5	d6	d7
EUR → USD	1.057	3.758*	0.174	9.375*	7.623*	65.069*	99.982*
	(0.304)	(0.024)	(0.677)	(0.002)	(0.006)	(0.000)	(0.000)
USD → EUR	5.223*	3.064*	0.000	8.562*	7.644*	66.463*	102.677*
	(0.022)	(0.047)	(0.995)	(0.004)	(0.006)	(0.000)	(0.000)
JPY → USD	0.689	2.808	1.877	8.508*	3.649	9.220*	184.412*
	(0.407)	(0.094)	(0.171)	(0.004)	(0.056)	(0.002)	(0.000)
USD → JPY	0.088	3.189	0.323	6.119*	3.759	8.421*	146.127*
	(0.767)	(0.074)	(0.570)	(0.014)	(0.053)	(0.004)	(0.000)
JPY → EUR	1.022	2.811	1.687	14.661*	7.437*	2.226	42.680*
	(0.312)	(0.061)	(0.186)	(0.000)	(0.006)	(0.108)	(0.000)
EUR → JPY	0.478	2.198	6.506*	10.321*	8.744*	1.815	35.867*
	(0.489)	(0.112)	(0.002)	(0.001)	(0.003)	(0.163)	(0.000)

The significance levels are in parentheses and * indicates significance at 5% level.

Data used are daily closing mid-rate swap rates (% pa) for the period January 4, 1999 to January 31, 2003 for the US dollar, the euro and the Japanese yen. Data were collected from Datastream. Column headings (d1 to d7) refer to wavelet scales for oscillations of periods 2-4, 4-8, 8-16, 16-32, 32-64, 64-128 and 128-256 days. For example, the original data has been transformed by the wavelet filter (LA(8)) up to time scale 7 and the first detail (wavelet coefficient) d1 captures oscillation with a period length of 2 to 4 days. The last detail d7 captures oscillation with a period length of 128 to 256 days. EUR → USD indicates the Granger-causality test in the wavelet domain for the contemporaneous spillover effects of daily swap rates from the euro to the US dollar, USD → EUR from the US dollar to the euro, JPY → USD from the Japanese yen to the US dollar, USD → JPY from the US dollar to the Japanese yen, JPY → EUR from the Japanese yen to the euro, and EUR → JPY from the euro to the Japanese yen, respectively.

TABLE 3
Granger-causality test of swap volatilities on the wavelet domain
Panel A. 3-year swap volatilities

	d1	d2	d3	d4	d5	d6	d7
EUR → USD	0.004	1.234	4.903*	11.097*	7.899*	5.942*	1.521
	(0.952)	(0.267)	(0.000)	(0.001)	(0.000)	(0.015)	(0.145)
USD → EUR	0.285	0.087	3.113*	10.315*	0.898	8.010*	6.293*
	(0.594)	(0.768)	(0.009)	(0.001)	(0.408)	(0.005)	(0.000)
JPY → USD	1.269	1.194	43.546*	5.891*	24.091*	1.360	188.050*
	(0.260)	(0.303)	(0.000)	(0.015)	(0.000)	(0.254)	(0.000)
USD → JPY	1.340	2.357	28.071*	3.343	22.547*	3.536*	94.282*
	(0.247)	(0.095)	(0.000)	(0.068)	(0.000)	(0.014)	(0.000)
JPY → EUR	0.604	0.073	0.902	0.592	26.566*	15.847*	3.545*
	(0.437)	(0.788)	(0.462)	(0.737)	(0.000)	(0.000)	(0.014)
EUR → JPY	1.723	0.271	1.615	2.057	23.495*	21.234*	3.584*
	(0.190)	(0.603)	(0.168)	(0.056)	(0.000)	(0.000)	(0.013)

The significance levels are in parentheses and * indicates significance at 5% level.

Panel B. 5-year swap volatilities

	d1	d2	d3	d4	d5	d6	d7
EUR → USD	0.049	0.750	0.142	10.061*	17.686*	1.031	2.397
	(0.825)	(0.387)	(0.706)	(0.002)	(0.000)	(0.378)	(0.091)
USD → EUR	0.197	0.290	0.004	6.032*	13.484*	8.937*	18.577*
	(0.657)	(0.591)	(0.947)	(0.014)	(0.000)	(0.000)	(0.000)
JPY → USD	0.287	4.398*	34.615*	2.427	71.497*	7.749*	6.789*
	(0.751)	(0.013)	(0.000)	(0.089)	(0.000)	(0.000)	(0.000)
USD → JPY	1.084	2.018	23.584*	8.736*	56.131*	4.084*	4.846*
	(0.339)	(0.133)	(0.000)	(0.000)	(0.000)	(0.000)	(0.002)
JPY → EUR	4.544*	2.916*	2.548*	34.443*	107.460*	96.990*	9.540*
	(0.033)	(0.033)	(0.027)	(0.000)	(0.000)	(0.000)	(0.002)
EUR → JPY	6.356*	3.627*	2.603*	44.723*	91.437*	140.045*	5.303*
	(0.012)	(0.013)	(0.024)	(0.000)	(0.000)	(0.000)	(0.021)

The significance levels are in parentheses and * indicates significance at 5% level.

Panel C. 10-year swap volatilities

	d1	d2	d3	d4	d5	d6	d7
EUR → USD	0.483	1.975	0.000	35.581*	12.077*	0.421	162.778*
	(0.487)	(0.160)	(0.997)	(0.000)	(0.001)	(0.517)	(0.000)
USD → EUR	0.318	3.205	0.204	26.783*	8.785*	0.213	131.133*
	(0.573)	(0.074)	(0.652)	(0.000)	(0.003)	(0.644)	(0.000)
JPY → USD	0.591	1.105	3.915*	3.488*	6.361*	11.475*	6.209*
	(0.554)	(0.293)	(0.004)	(0.001)	(0.012)	(0.000)	(0.000)
USD → JPY	1.453	4.748*	1.068	5.128*	5.273*	9.892*	3.149*
	(0.234)	(0.030)	(0.371)	(0.000)	(0.022)	(0.000)	(0.002)
JPY → EUR	1.223	1.138	1.329	1.464	7.440*	235.625*	24.149*
	(0.296)	(0.333)	(0.257)	(0.176)	(0.006)	(0.000)	(0.000)
EUR → JPY	2.513*	2.940*	1.427	0.729	6.999*	275.184*	18.620*
	(0.028)	(0.032)	(0.223)	(0.647)	(0.008)	(0.000)	(0.000)

The significance levels are in parentheses and * indicates significance at 5% level.

Data used are daily closing mid-rate swap rate volatilities (% pa) for the period January 4, 1999 to January 31, 2003 for the US dollar, the euro and the Japanese yen. Data were collected from Datastream. Column headings (d1 to d7) refer to wavelet scales for oscillations of periods 2-4, 4-8, 8-16, 16-32, 32-64, 64-128 and 128-256 days. For example, the original data has been transformed by the wavelet filter (LA(8)) up to time scale 7 and the first detail (wavelet coefficient) d1 captures oscillation with a period length of 2 to 4 days. The last detail d7 captures oscillation with a period length of 128 to 256 days. EUR → USD indicates the Granger-causality test in the wavelet domain for the contemporaneous spillover effects of daily swap rate volatilities from the euro to the US dollar, USD → EUR from the US dollar to the euro, JPY → USD from the Japanese yen to the US dollar, USD → JPY from the US dollar to the Japanese yen, JPY → EUR from the Japanese yen to the euro, and EUR → JPY from the euro to the Japanese yen, respectively. Volatility is measured as the absolute value of the first difference of each swap rate.

Fig.1. Wavelet variances of US dollar, euro and Japanese yen swap rates

Note: Estimated wavelet variances of US dollar, euro and Japanese yen swap rates plotted on different wavelet time-scales on the horizontal axis. The vertical axis indicates the wavelet variance. The MODWT-based wavelet variances of US dollar, euro and Japanese yen swap rates have been constructed using the Daubechies least asymmetric wavelet filter of length 8 (LA(8)).

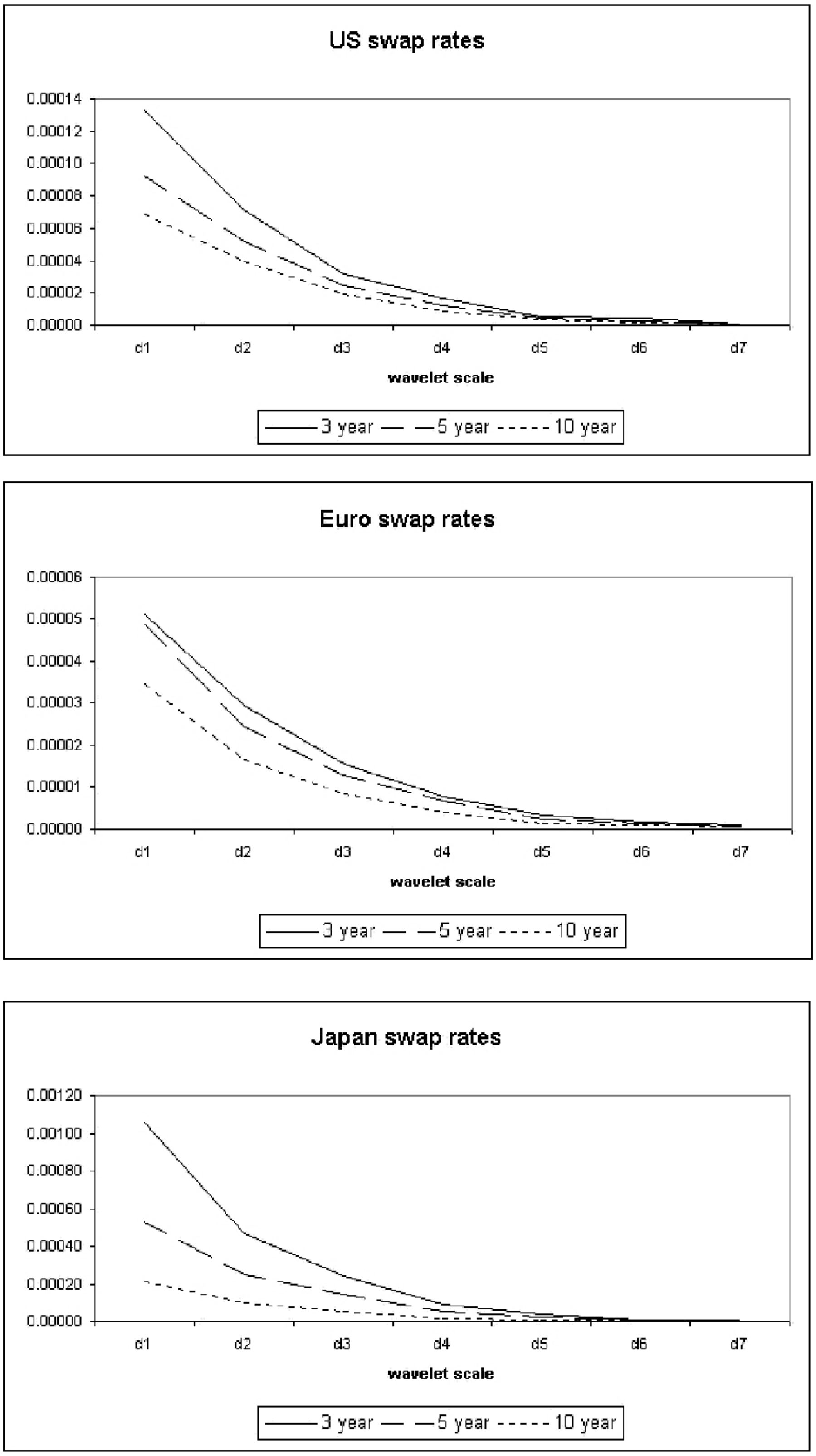
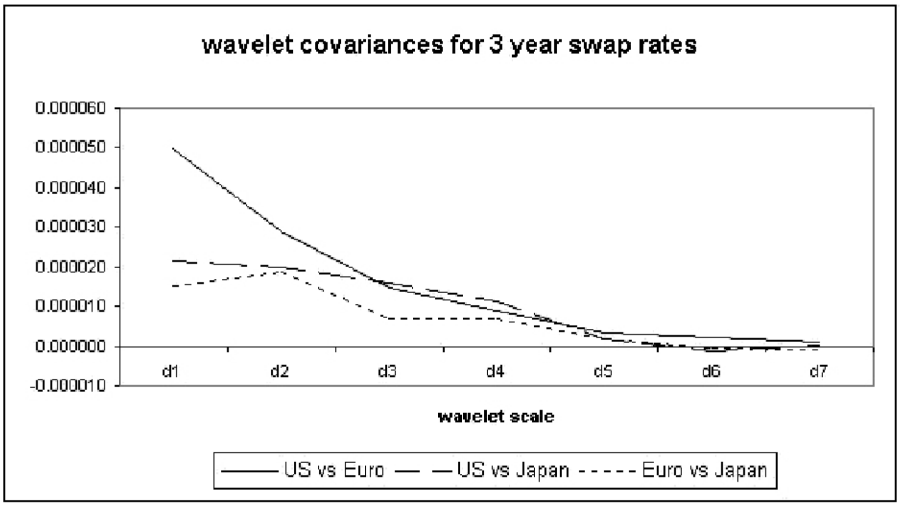
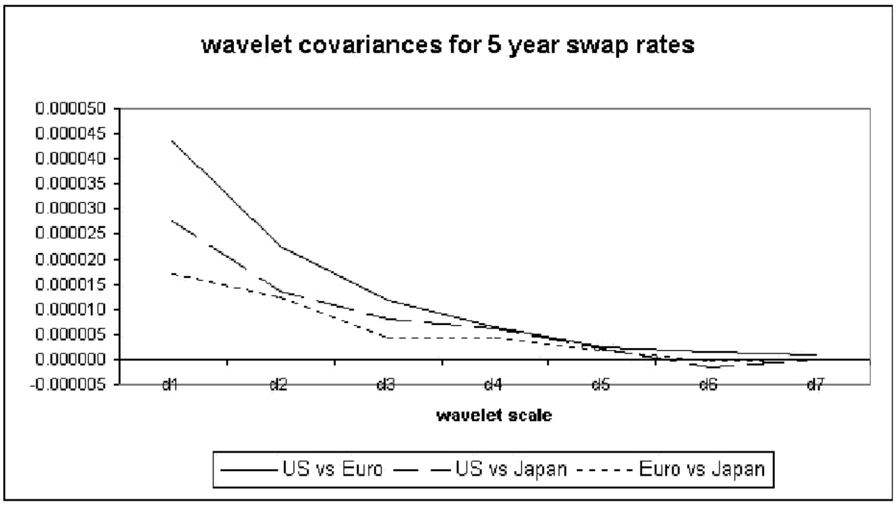


Fig.2. Wavelet covariances of US dollar, euro and Japanese yen swap rates

Note: Estimated wavelet covariances of US dollar, euro and Japanese yen swap rates plotted on different wavelet time-scales on the horizontal axis. The vertical axis indicates the wavelet covariance. The MODWT-based wavelet covariances of US dollar, euro and Japanese yen swap rates have been constructed using the Daubechies least asymmetric wavelet filter of length 8 (LA(8)).





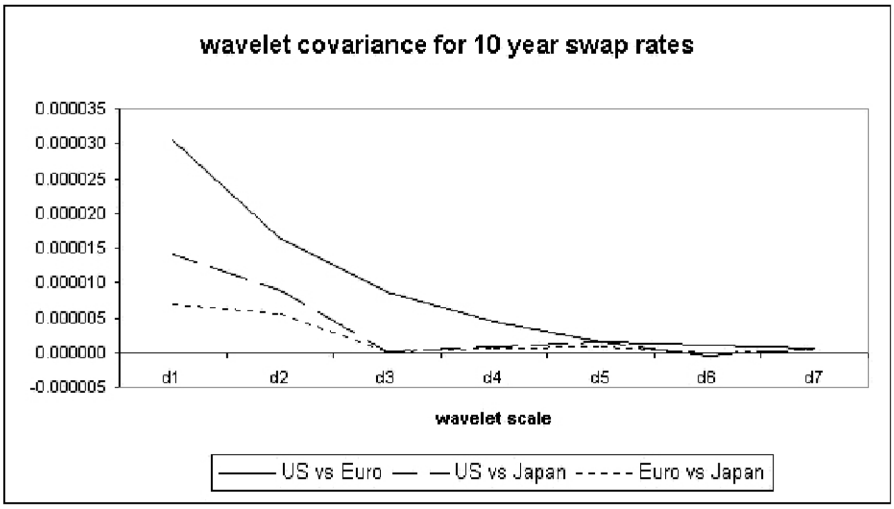
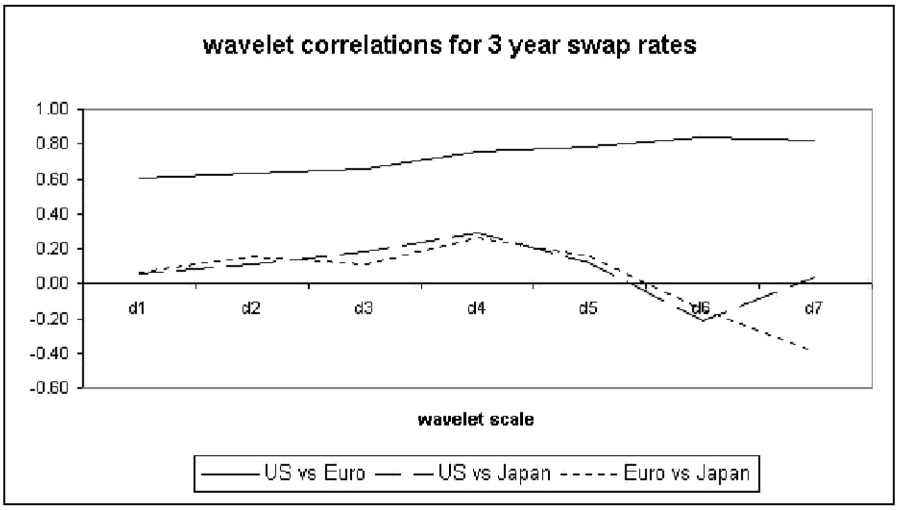
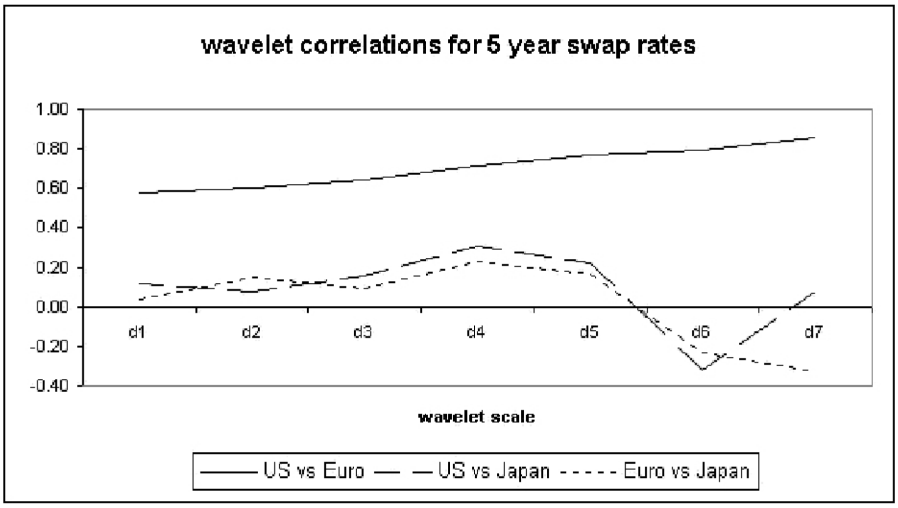


Fig.3. Wavelet correlations of US dollar, euro and Japanese yen swap rates

Note: The MODWT-based wavelet correlations have been constructed using the Daubechies LA(8) wavelet filter. Overall, the estimated wavelet correlation between US dollar and euro swap rates shows a steadily increasing pattern throughout the scales d1 to d7, regardless of the swap term. In contrast, estimated wavelet correlations between US dollars and yen, and between euros and yen, increase very slowly until the d4 scale (peaking at a correlation of about 0.2), then plunge down until around the d6 scale, beyond which it increases or decreases depending on the currency pair and the term.





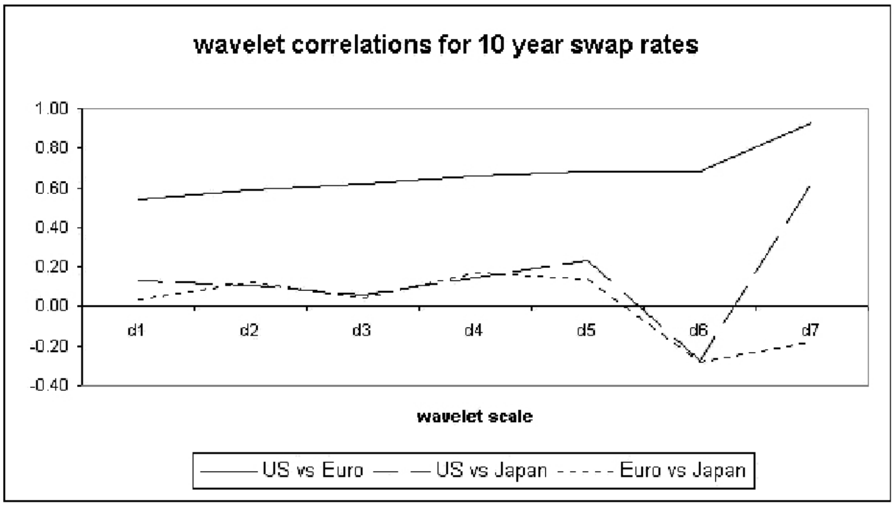


Fig.4.(a) Multiresolution analysis for US dollar 10-year swap rate

Note: LA (8) MODWT MRA of the US dollar 10-year swap rates. In each plot, the upper row is the original time series. Below it – from top to bottom – are the wavelet details d1, …, d8.

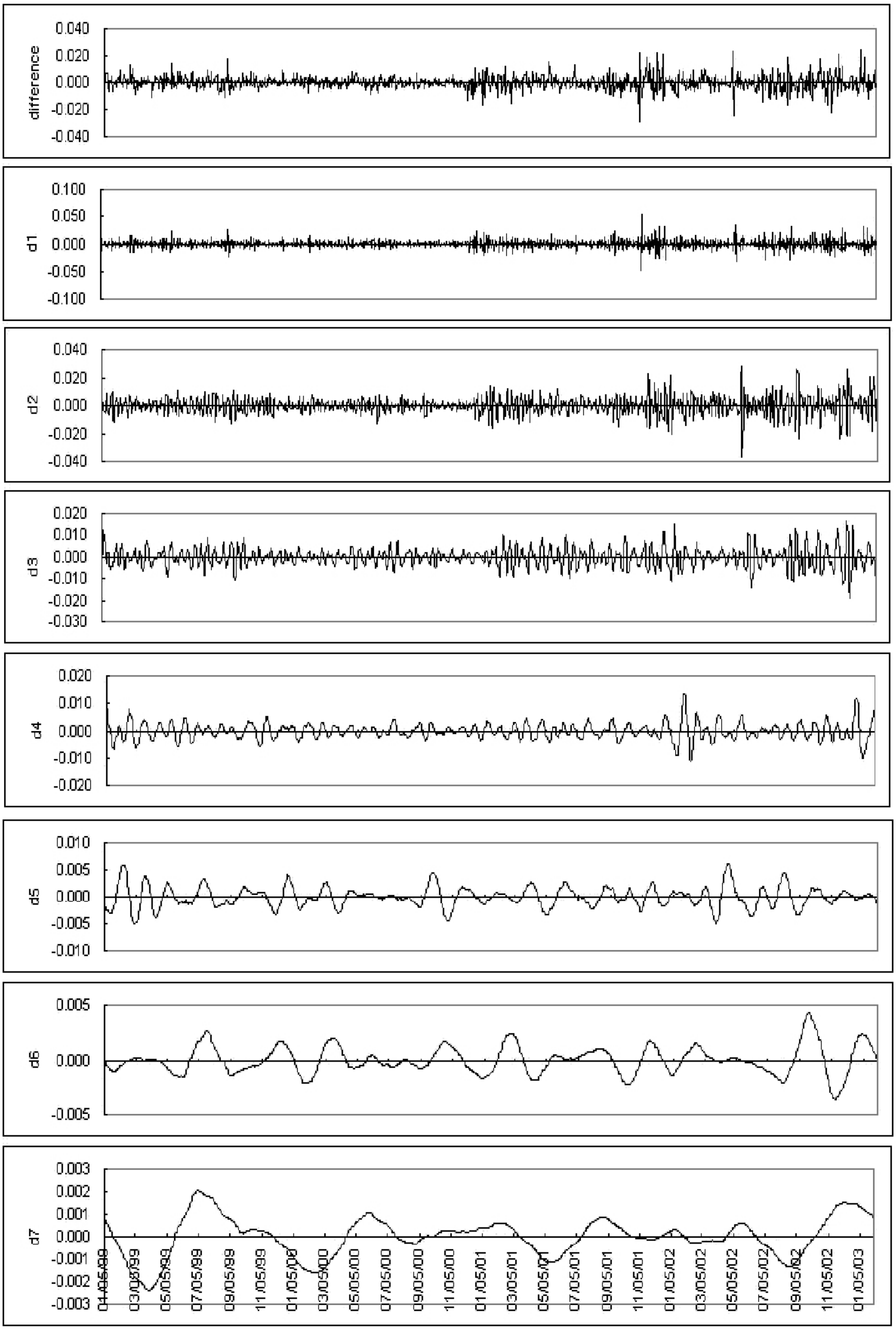


Fig.4.(b) Multiresolution analysis for euro 10-year swap rate

Note: LA (8) MODWT MRA of the euro10-year swap rates. In each plot, the upper row is the original time series. Below it – from top to bottom – are the wavelet details d1, …, d8

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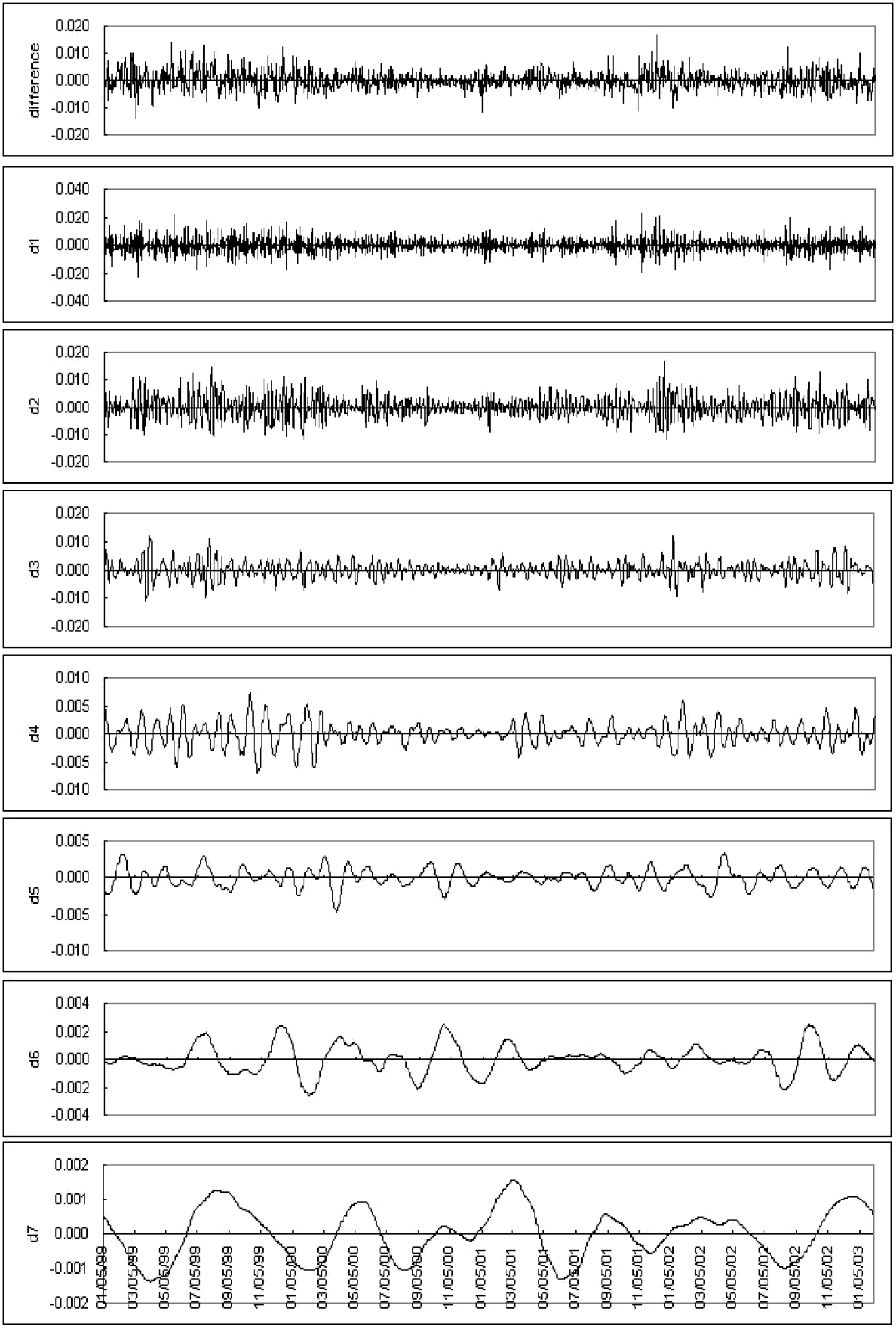

Fig.4.(c) Multiresolution analysis for Japanese yen 10-year swap rate

Note: LA (8) MODWT MRA of the Japanese Yen 10-year swap rates. In each plot, the upper row is the original time series. Below it – from top to bottom – are the wavelet details d1, …, d8.