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EURO MONEY MARKET SPREADS DURING THE 2007-? FINANCIAL CRISIS

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In 2012 all ECB publications feature a motif taken from the €50 banknote.

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Abstract

In the paper we investigate the empirical features of euro area money market turbulence during the recent financial crisis. By means of a novel Fractionally Integrated Heteroskedastic Factor Vector Autoregressive model, we find evidence of a deterministic *level* factor in the EURIBOR-OIS (OIS) spreads term structure, associated with the two waves of stress in the interbank market, following the BNP Paribas (9 August 2007) and the Lehman Brothers (16 September 2008) "shocks", and two additional factors, of the long memory type, bearing the interpretation of *curvature* and *slope* factors. The unfolding of the crisis yielded a significant increase in the persistence and volatility of OIS spreads. We also find evidence of a declining trend in the level and volatility of OIS spreads since December 2008, associated with ECB interest rate cuts and full allotment policy.

Key words: money market interest rates, credit/liquidity risk, fractionally integrated heteroskedastic factor vector autoregressive model.

JEL classification: C32, E43, E58, G15.

NON-TECHNICAL SUMMARY

In this paper we carry out an econometric analysis of the term structure of euro EURIBOR-OIS interest rate spreads. The data set is composed of daily data covering fifteen EURIBOR-OIS spreads, ranging from the one-week maturity to the one-year maturity. The sample runs from 20 June 2005 to 7 April 2009 (992 days). The econometric analysis is done in several steps.

The first step consists in testing for structural breaks in the means and variances (volatility) of the EURIBOR-OIS spreads. We find three break-points in the mean levels of the EURIBOR-OIS spreads, with similar location across maturities. The first break-point is located between 9 August and 16 August 2007, the second in 16 September 2008, and the third in 5 December 2008. 9 August 2007 is the day the French bank BNP Paribas revealed its inability to value structured products for two of its investment funds exposed to U.S. sub-prime mortgage risk, which were then closed. 16 September 2008 is the day after the bankruptcy of the American investment bank Lehman Brothers. These two break-points are economically intuitive. The third break-point follows the announcement, on 4 December 2008, of a 75 basis points (b.p.) decrease in key ECB policy rates, implemented on 10 December 2008. The location of this break-point is less intuitive from an economic point of view given that the ECB implemented a sequence of reductions in its key policy rates during the period October 2008 - May 2009: 12/11/08 (-50 b.p.), 10/12/08 (-75 b.p.), 21/01/09 (-100b.p.), 11/03/09 (-50b.p.), 08/04/09 (-25b.p.), 13/05/09 (-25b.p.).

For the volatility component (variance) we find only a single break point located in 9 August 2007. In short we find four regimes for the mean levels and two regimes for the variances of the euro EURIBOR-OIS spreads.

Regimes in the mean	Before 9 August 2007	Between 9 August 2007 and 16 September 2008	Between 16 September 2008 and 5 December 2008	After 5 December 2008
Regimes in the variance	Before 9 August 2007	After 9 August 2007		

The second step consists in testing for long-memory in the means and variances (volatility) of the break-free EURIBOR-OIS spreads. Due to the breaks in the means and variances of the EURIBOR-OIS spreads, testing for long-memory is done for the break-free series, standardised according to the selected regimes for their variances. A cubic spline smoother is applied to the estimated break processes in order to yield smooth transitions across regimes. We find significant long-memory in the standardised break-free series which increases with maturity up to the three-week horizon, decreasing thereafter. However, similar persistence can be found for consecutive maturities. We find significant instability in the estimated persistence parameter when computed separately for the pre-crisis and crisis periods. These econometric results suggest that, after a shock, the EURIBOR-OIS spreads do not return to their (regime-changing) unconditional means as quickly as a mean-reverting process would.

The third step consists in estimating an econometric model for the term structure of EURIBOR-OIS spreads. Given the findings of the two previous steps the dynamics of the term structure of EURIBOR-OIS spreads is modelled using a fractionally integrated, heteroskedastic factor, vector autoregressive (FI-HF-VAR) model. Fractional integration is motivated by the long-memory analysis in the mean (i.e. slow and non-monotonic return of the series to the mean after a shock). Heteroskedasticity is justified by the long-memory analysis in the variance and is akin to GARCH-type modelling of the conditional variance. Structural breaks in mean and variance are allowed in line with the break-point tests. A modelling framework with factors is justified for statistical reasons, which is the need to reduce the dimensionality of the system (avoiding multicolinearity and loss of efficiency in the estimation); and for economic reasons because the dynamics of the EURIBOR-OIS spreads should reflect the evolution of only a few common determinants. A first order dynamic specification is estimated for the FI-HF-VAR model following a multi-stage iterative procedure akin to Stock-Watson (2005). The main conclusions from the estimation of the model are as follows.

First, the strong joint movement in the observed EURIBOR-OIS spreads can be related (at least partially) to a common break process. Changes in this component are closely associated with the two waves of increasing bank stress, after August 2007 and after September 2008. This component captures **the level of EURIBOR-OIS spreads**. An interesting conclusion is that towards the end of the sample period, while the level component of the EURIBOR-OIS spreads was on a declining trend, a measure of banks' credit risk (iTraxx Euro Financials) kept rising, thereby casting doubts about the existence of a reliable relationship between EURIBOR-OIS spreads and CDS-based measures of credit risk. Indeed, this gives strong support to the hypothesis that beyond credit risk considerations, liquidity risk and/or confidence factors are relevant in explaining the evolution of the EURIBOR-OIS spreads, also pointing to a role for ECB interventions in restoring confidence and liquidity conditions in the money market.

Second, we find that two common long memory factors jointly account for over 80% of total variance (65% and 18%, respectively) across the (break-free) term structure of EURIBOR-OIS spreads. The first common long memory factor is dominating for maturities between three and six-months reminiscent of a **curvature factor** capturing the medium-term evolution in the EURIBOR-OIS spreads. The second common long memory factor mainly explains dynamics at the shortest end of the term structure of the EURIBOR-OIS spreads; this feature is reminiscent of a **slope factor**, possibly capturing a "pure" liquidity risk component. The proposed interpretation for the two long memory factors is supported by the results of the forecast error variance decomposition.

Third, the estimation and testing of the FI-HF-VAR model using separate sub-samples (pre-August 07 and post-August 07) reveals a significant increase in persistence after the crisis. In fact, the dynamics of the term structure of EURIBOR-OIS spreads changes from stationarity (albeit with long memory) to non-stationarity (i.e. essentially unpredictable during the crisis).

Fourth, conditional variance analysis reveals that long memory and structural change characterise the volatility of both common long memory factors. While long memory in variance is not strong the change in the level and range of variation of volatility, after the unfolding of the crisis, is remarkable. For both factors the increase in volatility is particularly strong at the outset of the crisis in August 2007 and following Lehman bankruptcy in mid September 2008; reversion to pre-Lehman volatility levels starting from mid December 2008 is visible possibly associated with the progressive ECB interest rate decreases, which reinforced the fixed rate full allotment liquidity policy.

In short, the non-stationarity in the EURIBOR-OIS spreads can be associated with the two waves of magnified stress in the interbank market which led to permanent changes in the levels, variances and persistence of the spreads, and are therefore due to the long lasting (permanent) effects of the financial market crisis on confidence, credit and liquidity risks.

An important question is whether, as a consequence of the crisis, wide and volatile EURIBOR-OIS spreads became a long-lasting feature of the money market going forward. Should this be the case, it would raise important challenges for the current generation of theoretical models of the yield curve and of the pricing of interest rate and credit derivatives.

1 Introduction

The evolution of the spreads between unsecured money market rates of various maturities and central banks' key policy rates has been subject to considerable debate and controversy in relation to the worldwide financial market turbulence that started in August 2007. Central to the controversy are the relative roles of *liquidity* and *counterparty (credit) risks* in explaining the size and dynamics of various money market spreads and their term structure.

One popular view regards the 2007-2008 financial crisis as mainly a *banking solvency* crisis from its inception (Taylor and Williams, 2009). These authors are critical of central banks' liquidity interventions during the crisis. They consider them as either being misguided or at best as having no effect. Conversely, other economists see the crisis as evolving in various stages which, starting as a *liquidity crisis* subsequently became also a solvency crisis. These authors tend to see central bank liquidity injections as successful (Christensen et al., 2009; McAndrews et al., 2008; Wu, 2008).

A peculiar feature of the pre-crisis euro area money market was the virtual absence of spreads between EURIBOR interest rates and overnight indexed swap rates of various maturities (OIS spreads). After the crisis, sizable and volatile OIS spreads became features of the euro money market. These raised important challenges for the transmission mechanism of monetary policy, and for setting the appropriate monetary policy stance and its smooth implementation. Moreover, the OIS spreads can be seen as *indicators of stress* in the financial markets, reflecting a combination of credit risk, liquidity risk, and swings in the risk appetite of investors. Hence, understanding the dynamics of OIS spreads is important also from the perspective of their use as financial stability indicators.

In this paper, we investigate the empirical features of turbulence in the euro money market during the recent financial crisis. For this purpose we propose and estimate a Fractionally Integrated Heteroskedastic Factor Vector Autoregressive (FI-HF-VAR) model of the term structure of OIS spreads. This provides a fairly general framework allowing for stochastic (stationary or non-stationary) and deterministic features (e.g. structural breaks), either common or idiosyncratic, and conditional and or unconditional heteroskedasticity. Fractional integration is motivated by the slow and non-monotonic return of the series to the mean after a shock. Heteroskedasticity is justified by the long-memory analysis in the variance and is akin to GARCH-type modelling of the conditional variance. Structural breaks in mean and variance are allowed in accordance with break-point tests. A modelling framework with factors is justified for statistical reasons, which is the need to reduce the dimensionality of the system (avoiding multicolinearity and loss of efficiency in the estimation); and for economic reasons because the dynamics of the OIS spreads should reflect the evolution of only a few common determinants.

It is found that most of the non stationarity in the OIS spreads is indeed common across their term structure and is associated with two waves of magnified stress in the interbank market; the first after 9 August 2007, following the day the French bank BNP Paribas closed two of its investment funds exposed to sub-prime mortgage risk; the second, after 16 September 2008, the day after the bankruptcy of Lehman Brothers. This led to permanent changes in the levels, variances and persistence of the spreads. Three common persistent factors, driving the OIS term structure, are uncovered. The first common factor is of a deterministic type and captures the *level* of OIS spreads, featuring a remarkable up to ten fold increase after 9 August 2007, and an additional two fold increase after 16 September 2008. The other two common factors are of the long memory type, and bear the interpretation of *curvature* and *slope* factors, respectively. After the crisis a significant increase in their persistence can be noticed, leading to a switch from stationary to non stationary long memory. A break in the level of their volatility is also noticeable featuring a remarkable four fold increase after the crisis.

Since December 2008, a declining trend in the level and volatility of the OIS spreads can be detected, matching the sequence of ECB policy rate cuts (250 basis points in total) that reinforced the *fixed rate - full allotment* liquidity policy that started in October 2008. This evidence suggests that the policies implemented by the ECB paved the way for a gradual reversal in investment sentiment, and mitigated liquidity risk in the euro area money market.

The remainder of the paper is structured as follows. In Section 2 the persistence properties of the OIS spreads are investigated; in Section 3 the FI-HF-VAR model is introduced, while in Section 4 the empirical results are reported; Section 5 presents some conclusions.

2 Statistical features of OIS spreads in crisis times

The data set is composed of fifteen OIS spreads, from one-week maturity (x_t^{1w}) to one-year maturity (x_t^{1y}), collected in the vector x_t. The data has daily frequency and is obtained from REUTERS. The sample runs from 20 June 2005 to 7 April 2009 (992 days).

Persistence analysis involves testing for structural breaks and long memory. Bai and Perron (1998) tests (BP) are used to estimate the number

(k) and location of break points ($s_\tau \in T$, $\tau = 1, ..., k$), while the Dolado et al. (2004) approach (DGM), modified to account for a general and unknown structural break process (Morana, 2009), is employed to validate the estimated break processes ($\hat{b}_t$). Moreover, the Moulines and Soulier (1999) broad band log periodogram estimator (BBLP) is used to assess the degree of fractional integration of the actual (x_t) and break-free ($\hat{l}_t = x_t - \hat{b}_t$) OIS spreads.

2.1 Deterministic persistence

The BP tests in Table 1, columns 1-2, indicate two break points in the OIS spread levels, with similar location across maturities. The first occurs between 9 August and 16 August 2007, and the second is located in 16 September 2008.

On 9 August 2007 the French bank BNP Paribas revealed its inability to value structured products for two of its investment funds exposed to U.S. sub-prime mortgage risk, which were then closed. Interbank market stress was indeed sizable, with the average spread moving from a range of 3 basis points (1-week) to 7 basis points (1-year), to a range of 15 basis points to 74 basis points until 15 September 2008. After 16 September 2008, the day after the bankruptcy of Lehman Brothers, OIS spreads climbed rapidly, reaching maximum values in the range of 100 basis points to 233 basis points.

The date of 5 December 2008 could also be selected as break point, which coincided with the 75 basis points cut announced on 4 December 2008 by the ECB and implemented on 10 December 2008. A sizeable contraction (-16% on average) and a reversal in the OIS spreads trend can be observed since 5 December 2008, the OIS spreads having steadily decreased thereafter, converging towards first stress wave levels; yet, by the end of our sample, i.e. 7 April 2009, only the one-, two- and three-week OIS spreads had actually achieved pre-Lehman Brothers bankruptcy levels. As the minimum regime length is fixed at 15% of the sample size, the significance of the suggested additional break point could not be tested by means of the BP tests.

Also the volatility component has been assessed for structural breaks by means of the BP tests, using $|\Delta x_t|$, i.e. the absolute first difference of the spreads as volatility proxy (Table 1, column 3). While the increase in long-term volatility triggered by the unfolding of the crisis and the spreading of the first stress wave is indisputable (from 1 basis points up to 19 basis points over the first stress wave period), less clear-cut is whether a further increase in long-term volatility occurred following the spreading of the second stress wave. The BP tests point to a single break in variance in 9 August 2007. The modelling of the conditional variance processes is undertaken within the multi-stage estimation strategy proposed for the FI-HF-VAR model (see Section 3).

2.2 Stochastic persistence

In order to account for deterministic persistence when testing for long memory[1], estimation of the break processes has been performed by means of OLS regressions of each OIS spread ($x_{i,t}$: $x_t^{1w}, ..., x_t^{1y}$) on dummies (D_j, $j = 1, .., 4$), computed according to the outcome of the structural break analysis

$$\begin{aligned} x_{i,t} &= b_{i,t} + e_{i,t} \qquad i = 1, ..., 15 \\ b_{i,t} &= \alpha_{i,0} + \alpha_{i,1} D_{1,t} + \alpha_{i,2} D_{2,t} + \alpha_{i,3} D_{3,t} + \alpha_{i,4} D_{4,t}, \end{aligned}$$

where D_1 is a (first stress wave) step dummy variable with unity value over the period 9 August 2007 to 7 April 2009 inclusive, D_2 is a (second stress wave) step dummy variable with unity value over the period 16 September 2008 to 7 April 2009 inclusive, D_3 is a (second stress wave) broken linear trend variable, with non-zero values over the period 16 September 2008 to 4 December 2008 inclusive, and D_4 is a (stress resolution) broken linear trend variable, with non-zero values over the period 5 December 2008 to 7 April 2009 inclusive.

A cubic spline smoother has been applied to the estimated break processes

$$\hat{b}_{i,t} = \hat{\alpha}_{i,0} + \hat{\alpha}_{i,1} D_{i,1,t} + \hat{\alpha}_{i,2} D_{i,2,t} + \hat{\alpha}_{i,3} D_{3,t} + \hat{\alpha}_{i,4} D_{4,t},$$

in order to yield a smooth transition across regimes; knowing the position of the knots (s_τ), the smoothing parameter p for spline computation is obtained from the minimization of the objective function

$$S(p) = p \sum_\tau \left(\hat{b}_\tau^* - f(s_\tau) \right)^2 + (1-p) \int f''(s)^2,$$

where $\int f''(s)^2$ is the integrated squared second derivative of the cubic spline function $f(s) = a_\tau + b_\tau s + c_\tau s^2 + d_\tau s^3$ (see Silverman (1985) for details). The procedure yields the *cubic spline dummy break process* $\hat{b}_{i,t}$; implementation within the DGM testing framework, suggests that the estimated cubic spline dummy break processes are appropriate for the data investigated (Table 1, column 4).

[1] See Baillie (1996) for an introduction to long memory processes.

Due to the breaks in the mean and variance of the OIS spreads, the fractional differencing parameter has been estimated for the break-free series ($\hat{l}_t = x_t - \hat{b}_t$), standardized according to the selected regimes for their unconditional variance (Table 1, column 6). Results show that sizable long memory can be found in the standardized break-free series, in the range 0.24 to 0.64 (0.40 on average). A statistically significant hump-shaped profile can be noted in the cross-section of persistence, which increases with maturity up to the three-week horizon and decreases thereafter. Yet, similar persistence can be found for consecutive maturities.

According to the BBLP estimator, strong (non stationary) long memory, not statistically different across maturities, can also be found in the actual OIS spreads (x_t), with an average estimated fractional differencing parameter of about 0.94 (Table 1, column 5).

The finding of significant long memory in both the actual and standardized break-free specifications points to non spurious structural change in the OIS spreads, as, otherwise, evidence of overdifferencing, i.e. a negative estimate for the fractional differencing parameter, would be expected (Granger and Hyung, 2004). The DGM test supports the latter conclusion, pointing to significant break processes, of the estimated type, for all the (actual) OIS spreads, as the null of pure long memory process is rejected in all cases, at the 5% significance level.[2]

Evidence of significant instability can also be detected in the estimated persistence parameter, when computed separately for the pre-crisis and crisis periods. The null of temporal stability is in fact strongly rejected both using a Bonferroni bounds joint test and a maturity by maturity pairwise comparison (the p-values are virtually zero in all cases).

3 The FI-HF-VAR model

Given the evidence of both long memory and structural breaks, the dynamics of the OIS interest rate spreads (x_t) term structure are modelled according to the following fractionally integrated heteroskedastic factor vector autoregressive (FI-HF-VAR) model (Morana, 2011)

[2] Critical values for the test have been computed by simulation, also allowing for unconditional heteroskedasticity under the null. Details are available upon request from the authors.

$$
\begin{aligned}
C(L)\left(x_t - \Lambda_\mu \mu_t - \Lambda_f f_t\right) &= v_t \qquad (1)\\
v_t &\sim iid(0, \Sigma_v)\\
D(L) f_t &= \eta_t = H_t^{1/2} \psi_t, \qquad (2)\\
\psi_t &\sim iid(0, I_r).
\end{aligned}
$$

According to the above specification, the n-variate OIS spreads vector x_t, at time period t, $t = 1, ..., T$, is a real valued fractionally integrated process subject to structural breaks.

Then, μ_t is a m-variate vector of common deterministic break processes, $m \leq n$, with $n \times m$ matrix of loadings Λ_μ; f_t is a r-variate vector of heteroskedastic fractionally integrated common factors, $r \leq n$, of order d_i in mean and b_i in variance, with $0 < d_i < 1$, $0 < b_i < 1$, $i = 1, ..., r$, and $n \times r$ matrix of loadings Λ_f, $D(L) \equiv diag\left\{(1-L)^{d_1}, (1-L)^{d_2}, ..., (1-L)^{d_r}\right\}$; ψ_t is a r-variate vector of common zero mean i.i.d. innovations, with identity covariance matrix, and $E\left[\psi_{it} v_{js}\right] = 0$ all i, j, t, s.

$H_t = Var(f_t|\Omega_{t-1}) \equiv diag\left\{h_{1,t}, h_{2,t}, ..., h_{r,t}\right\}$ is the $r \times r$ conditional variance matrix for the unconditionally and conditionally orthogonal common factors f_t. Consistent with the constant conditional correlation $FIGARCH$ model of Brunetti and Gilbert (2000), the ith generic element along the main diagonal of H_t is the $FIGARCH(1, d, 1)$ model (Baillie et al., 1996)

$$
(1 - \beta_i L)\, h_{i,t} = w_{i,t} + \left(1 - \beta_i L - (1 - \phi_i L)(1 - L)^{b_i}\right) \eta_{i,t}^2, \qquad i = 1, ..., r, \qquad (3)
$$

augmented by a time-varying intercept $w_{i,t}$ in the conditional variance equation, specified as

$$
w_{i,t} = \vartheta_{i,0} + \vartheta_{i,1} D_{1,t}, \qquad (4)
$$

where D_1 is a step dummy variable with unity value over the period 9 August 2007 to 7 April 2009 inclusive, consistent with the results of the structural breaks analysis. As for the break processes in mean, gradual transition across regimes is allowed for by means of cubic spline smoothing.

The following $ARCH(\infty)$ representation can be obtained from the above model

$$
\begin{aligned}
h_{i,t} &= \frac{w_{i,t}}{(1 - \beta_i)} - \frac{(1 - \phi_i L)(1 - L)^{b_i}}{(1 - \beta_i L)} \eta_{i,t}^2, \qquad i = 1, ..., r, \qquad (5)\\
&= w_{i,t}^* + \psi_i(L) \eta_{i,t}^2, \qquad (6)
\end{aligned}
$$

where $w^*_{i,t} = \dfrac{w_{i,t}}{(1-\beta_i L)}$ and $\psi_i(L) = \dfrac{(1-\phi_i L)(1-L)^{b_i}}{(1-\beta_i L)} = \psi_{1,i}L + \psi_{2,i}L^2 + \ldots$.

The term $w^*_{i,t}$ bears the interpretation of break in variance process or long-term conditional variance level. To guarantee the non negativity of the conditional variance process at each point in time all the coefficients in the $ARCH(\infty)$ representation must be non-negative, i.e. $\psi_{j,i} \geq 0$ for all $j \geq 1$ and $w^*_{i,t} > 0$ for any t. Sufficient conditions can be found in Baillie et al. (1996). The use of the double long memory model is motivated by the finding of long memory in variance, as well as in the mean component of the OIS spreads, as discussed in Section 4.

Finally, v_t is a n-variate vector of zero mean idiosyncratic i.i.d. shocks, with diagonal contemporaneous covariance matrix Σ_v, assumed to be consistent with the condition of weak cross-sectional correlation of the idiosyncratic components (Assumption E) stated in Bai (2003, p.143), and $C(L) \equiv I_n - C_1 L - C_2 L^2 - \ldots - C_s L^s$, is a finite order stationary matrix of polynomials in the lag operator, where C_j, $j = 1, .., s$ is a square matrix of coefficients of order n.

3.1 Estimation

Having decomposed each OIS spread ($x_{i,t}$, $i = 1, ..., n$) in the break-process ($\hat{b}_{i,t}$) and break-free (pure long memory) ($\hat{l}_{i,t} = x_{i,t} - \hat{b}_{i,t}$) components, estimation of the FI-HF-VAR model is implemented following a multi-stage iterative procedure, similar to Stock and Watson (2005), consisting of the following steps:

• **Step 1: initialization.** An initial estimate of the equation system in (1) is obtained as follows.

•• Firstly, the initial estimate of the $m \leq n$ common break processes and their factor loading matrix is obtained by means of Principal Components Analysis (PCA), implemented using the estimated break process $\hat{b}_{i,t}$, $i = 1, ..., n$, collected in the vector $\hat{b}_t$. This yields $\hat{\mu}_t = \hat{\Lambda}_b^{-1/2} \hat{A}' \hat{b}_t$ and $\hat{\Lambda}_\mu = \hat{A} \hat{\Lambda}_b^{1/2}$, where $\hat{\Lambda}_b$ is the $m \times m$ diagonal matrix of the non zero eigenvalues of the estimated reduced rank $n \times n$ variance-covariance matrix of the (estimated) break processes $\hat{\Sigma}_{\hat{b}}$ (rank $m < n$), and $\hat{A}$ is the $n \times m$ matrix of the associated orthogonal eigenvectors.

•• Next, the initial estimate of the $r \leq n$ common long memory factors and their factor loading matrix is obtained by means of PCA implemented using the estimated break-free series $\hat{l}_{i,t}$, $i = 1, ..., n$, collected in the vector $\hat{l}_t$. This yields $\hat{f}_t = \hat{\Lambda}_l^{-1/2} \hat{B}' \hat{l}_t$ and $\hat{\Lambda}_f = \hat{B} \hat{\Lambda}_l^{1/2}$, where $\hat{\Lambda}_l$ is the $r \times r$ diagonal matrix of the non zero eigenvalues of the estimated reduced rank $n \times n$

variance-covariance matrix of the (estimated) break-free processes $\hat{\Sigma}_{\hat{l}}$ (rank $r < n$), and $\hat{B}$ is the $n \times r$ matrix of the associated orthogonal eigenvectors.

•• Finally, conditional on the estimated common deterministic and stochastic factors, $x_t - \hat{\Lambda}_\mu \hat{\mu}_t - \hat{\Lambda}_f \hat{f}_t$ is computed, and the initial estimate $\hat{C}(L)$ is obtained by means of OLS estimation of the VAR model in (1).

• **Step 2: the iterative procedure.** An updated estimate of the equation system in (1) is obtained as follows.

•• First, a new estimate of the m common deterministic factors and their factor loading matrix can be obtained by the application of PCA to the (new) long memory-free series $x_t - \left[I - \hat{C}(L)L\right] \hat{\Lambda}_f \hat{f}_t$, yielding $\hat{\Lambda}_\mu^{(new)}$ and $\hat{\mu}_t^{(new)}$.

•• Next, conditional on the new common break processes, the new estimate of the common long memory factors and their factor loading matrix is obtained from the application of PCA to the (new) break-free processes $\hat{l}_t^{(new)} = x_t - \hat{\Lambda}_\mu^{(new)} \hat{\mu}_t^{(new)}$, yielding $\hat{\Lambda}_f^{(new)}$ and $\hat{f}_t^{(new)}$.

•• Then, $x_t - \hat{\Lambda}_\mu^{(new)} \hat{\mu}_t^{(new)} - \hat{\Lambda}_f^{(new)} \hat{f}_t^{(new)}$ is computed, and the new estimate $\hat{C}(L)^{(new)}$ is obtained by means of OLS estimation of the VAR model in (1).

•• The above procedure is iterated until convergence, yielding the final estimates $\hat{\Lambda}_\mu^{(fin)}$, $\hat{\mu}_t^{(fin)}$, $\hat{\Lambda}_f^{(fin)}$, $\hat{f}_t^{(fin)}$, and $\hat{C}(L)^{(fin)}$.

Then, the fractional differencing parameter is consistently estimated for each common long memory factor by means of the BBLP estimator, yielding $\hat{D}(L)$ and, by means of the (truncated) binomial expansion, a VAR representation for the common long memory factors in (2) can be obtained.

Impulse responses and forecast error variance decomposition can also be computed; see Morana (2011) for details, on the identification of the common and idiosyncratic structural shocks as well.

• **Step 3: conditional variance analysis.** QML estimation of the conditional variance processes in (3) is finally performed equation by equation, exploiting the unconditional and conditional orthogonality of the factors.

3.2 Asymptotic properties

The proposed multi-stage procedure may be conjectured to yield consistent and asymptotically Normal estimation. In fact, the iterative estimation of (1) bears the interpretation of QML estimation, performed via the EM algorithm (Dempster et al., 1977); consistent and asymptotically Normal estimation is also attained by means of BBLP estimation of (2) and QML estimation of (3).

The EM algorithm yields ML estimation in the presence of missing or unobserved data; in the Expectation (E) step the unobserved data (common deterministic and stochastic factors) are estimated (by PCA), given the observed data and the current estimate of model parameters; in the Maximization (M) step the likelihood function is maximized under the assumption that the unobserved data are known, conditioning on their E-step estimate (OLS estimation of model's parameters is performed). Convergence to the one-step ML estimate is ensured, as the value of the likelihood function is increased at each step.

Note that the E-step relies on consistent estimation of the unobserved components, which is actually delivered by PCA.

In fact, under some general conditions, Bai (2003), given the invertible matrix Ξ, established $\sqrt{n}$ consistency and asymptotic normality of PCA for Ξf_t, at each point in time, for $n, T \rightarrow \infty$ and $\sqrt{n}/T \rightarrow 0$, when both the unobserved factors and the idiosyncratic components show limited serial correlation, and the latter also display limited heteroskedasticity in both their time-series and cross-sectional dimensions.

In Bai (2004) the above results have been extended to the case of I(1) (non cointegrated) unobserved factors and I(0) idiosyncratic components, also featuring limited heteroskedasticity in both the time-series and cross-sectional dimensions for the latter components, for $n, T \rightarrow \infty$ and $n/T^3 \rightarrow 0$.

While there are no asymptotic results for the application of PCA to the intermediate case of fractionally integrated processes or to trend stationary processes, supporting Monte Carlo evidence is provided in Morana (2007, 2011). In particular, the proposed methodology is shown being accurate under several scenarios, featuring either short or long memory, both covariance and non covariance stationary, observational noise, relatively small cross-sectional and temporal dimensions, persistent/non persistent conditional heteroskedasticity and structural breaks.

4 Empirical results

On the basis of the BIC information criterion, a first order dynamic specification for (1) has been selected; moreover, 1000 replications have been employed for the simulation of the model and the computation of the median estimates of the parameters and confidence intervals. Also, consistent with the finding of structural instability in the unconditional variance for the OIS spreads, the unconditional variance-covariance matrix employed for policy analysis has been allowed to change according to the sub period (pre-crisis/crisis) investigated.[3]

As a preliminary result, and to further motivate the common factor analysis, in Table 2, Panel A (column 1) the results of PCA implemented on the actual OIS spreads (x_t) are reported; as is shown in the Table, PCA singles out a single factor accounting for about 99% of total variance, and over 95% of the variance for each OIS spread, from the 2-week maturity onwards. The latter finding is fully consistent with the evidence of common breaks for the OIS spreads, provided by the structural break analysis; yet it could also be indicative of common stochastic features, as it is actually revealed by the common long memory factor analysis (see below).

4.1 Level factor of OIS spreads

As shown in Table 2, Panel A (column 2), consistent with the structural break analysis, the strong comovement detected in the actual OIS spreads, can indeed be related (at least partially) to a common break process component. In fact, PCA carried out on the estimated break processes ($\hat{b}_t$) singles out a single common factor (break process), accounting for over 99% of total variance and no less than 90% of the variance for each break process (Figure 1, bottom plot). The latter component, being related to the two waves of increasing bank stress, captures the *level* of OIS spreads in the crisis period, reflecting, among other factors, the state of *investor confidence (risk appetite).*

Of particular interest is the break point detected following the announcement of the 75 basis points rate cut by the ECB on 5 December 2008. Then a declining trend in the levels of the OIS spreads started matching the timing of four further rate cuts carried out by the ECB in 2009, which reinforced the *fixed rate full allotment* liquidity policy that started in October 2008.[4]

Finally, note that towards the end of the sample period (after observation 900), while the common spreads level was on a declining trend, a measure of banks' credit risk (iTraxx Euro Financials) kept on rising, thereby casting some doubts about a reliable relationship between OIS spreads and CDS-based measures of credit risk (bottom plot); indeed this evidence gives strong support to the hypothesis that beyond credit risk considerations, liquidity

[3]For reasons of space only a selection of the results are reported in Table 2 and 3; a whole set of results is avalaible upon request from the authors.

[4]The ECB implemented a sequence of reductions of the main refinancing rate to a historical low of 1% over the period October 2008 – May 2009: 12/11/08 (-50b.p.), 10/12/08 (-75b.p.), 21/01/09 (-100b.p.), 11/03/09 (-50b.p.), 08/04/09 (-25b.p.), 13/05/09 (-25b.p.). Morover, unlimited access to central bank liquidity, against a wide range of collateral and at a broader spectrum of maturities, of up to 12 months, were granted to banks.

risk and/or investor confidence factors are also relevant for explaining the evolution of OIS spreads, pointing therefore to a role for ECB interventions in order to restore confidence and foster smooth money market conditions.

4.2 Curvature and slope factors of OIS spreads

Turning to the long memory (break-free) components ($\hat{l}_t = x_t - \hat{b}_t$), PCA also finds two common long memory factors (Figure 1, top plots), jointly accounting for over 80% of total variance (65% and 18%, respectively) across the term structure.

As shown in Table 2, Panel A (columns 3 and 4), although the first common long memory factor accounts for dynamics common to all the OIS spreads, it is dominating for maturities above one-month and, in particular, for maturities between three and six-months; this feature is reminiscent of a *curvature factor* capturing the medium-term evolution in the OIS spreads during the crisis period.

Differently, the second common long memory factor mainly explains dynamics at the shortest end of the OIS spreads term structure; this feature is reminiscent of a *slope factor*, possibly capturing a "pure" liquidity risk component. The proposed interpretation for these two factors is further supported by the results of the forecast error variance decomposition (see below).

As shown in Table 2, Panel B, in terms of their persistence properties, both stochastic factors show the long memory feature, with estimated fractional differencing parameters consistent with the findings of persistence analysis: the estimated parameters are 0.32 and 0.52, for the first and second principal component, respectively.

Subsample (pre-crisis and crisis) estimation and testing, point to a significant increase in persistence following the unfolding of the crisis (doubling for the first factor and a three fold increase for the second factor), moving from stationary long memory (0.24 and 0.44 for the first and second factor, respectively) for the pre-crisis sample to non stationary long memory (0.87 for both factors) for the crisis sample. The discontinuity in persistence can be appreciated in Figure 1 (top plots), showing a sizable increase in persistence following 9 August 2007 (observation 559), as the (standardized) common long memory factors appear to be much smoother than before.

Conditional variance analysis (step 3) also reveals that long memory and structural change affect the volatility of both common long memory factors; while long memory in variance is not strong, as the estimated persistence parameters are about 0.10 and 0.23, for the first and second common long memory factor, respectively, the change in the level and range of variation of volatility, after the unfolding of the crisis, is remarkable (a four fold increase) (Figure 1, centre plots). For both factors the increase in volatility was particularly strong at the outset of the crisis in August 2007 and following Lehman bankruptcy in mid September 2008; reversion to pre-Lehman volatility levels is already evident starting from mid December 2008, and possibly associated with the progression of ECB interest rate cuts, reinforcing the ample liquidity situation of the banking system, which resulted from the full allotment liquidity policy.

4.3 Forecast error variance decomposition and impulse response analysis

The results of the forecast error variance decomposition are reported in Table 3; two horizons, one-day and twenty-day, have been considered in the analysis.

As shown in Table 3, as a consequence of the crisis, at the short end of the term structure (up to the three-month maturity), fluctuations have become more idiosyncratic at short horizons (one-day), but more coordinated at longer horizons (twenty-day): the contribution of the own idiosyncratic shock is in fact dominating at the one-day horizon (70% on average; 25% in the pre-crisis period), while common shocks are dominating at the twenty-day horizon (95% on average; 70% in the pre-crisis period).

The contribution of the *curvature* factor shock is also increased at longer horizons (97% during the crisis; 68% before the crisis), still featuring a larger impact on medium- (3- to 9-month) than shorter- or longer-term maturities.

Differently, the contribution of the *slope* factor shock is decreased at both the one-day and twenty-day horizons (30% during the crisis; 65% before the crisis), only dominating at the short end of the term structure (50%), rather than at both the short and long end, as before the crisis (between 55% and 75%).

Interesting differences between the pre-crisis and crisis periods are also revealed by the impulse response functions (Figure 2). The crisis has in fact lead to an increase in the magnitude and persistence of both the *curvature* (top four plots) and *slope* (bottom four plots) shocks, as well as to a change in their response profiles, from monotonic to hump-shaped; in particular, during the crisis, full dissipation of shocks occurs well beyond the twenty days required before the crisis.

5 Conclusions

In this paper the consequences of the recent financial turmoil for the euro area money market have been assessed by investigating the persistence properties of the mean and the variance of OIS spreads in the framework of a FI-HF-VAR model.

It is found that most of the non stationarity in the OIS spreads can be associated with the two waves of magnified stress in the interbank market, the first after 9 August 2007 and the second after 16 September 2008, which led to permanent changes in the levels, variances and persistence of the spreads, therefore illustrating the long lasting (permanent) effects of the financial market crisis on confidence, credit and liquidity risks.

Deviations of the OIS spreads from long-term (time-varying) values tend to be corrected slowly due to their long memory feature. Also, the increasing trend in the OIS spreads was broken and reversed after the ECB cut its key policy rate by 75 basis points on December 2008; then, the sequence of interest rate cuts, together with other policy measures, like the policy of full allotment at a fixed rate in all refinancing operations, may have paved the way for a gradual reversal in market sentiment and reduction in liquidity risk.

Interestingly, despite of the trend reversal in the OIS spreads, the iTraxx Euro Financials, a measure of banks' credit risk, kept on rising, thereby supporting the view that, beyond credit risk, liquidity risk and/or confidence factors were also relevant during the crisis.

An important question that is left open is the permanent consequences of the crisis for the functioning of the euro area money market, which may not necessarily return to pre-crisis features. While a reduction in persistence to stationary long memory could be expected, i.e. to mean reverting spreads, as well as a sizable reduction in volatility, the level of OIS spreads might not come back to their pre-crisis values. Surely, a peculiar feature of the pre-crisis euro area money market was the virtual absence of OIS spreads. Should wide and volatile OIS spreads become a long-lasting feature of the money market going forward it would raise important challenges for theoretical models of the yield curve and for the pricing of interest rate and credit derivatives.

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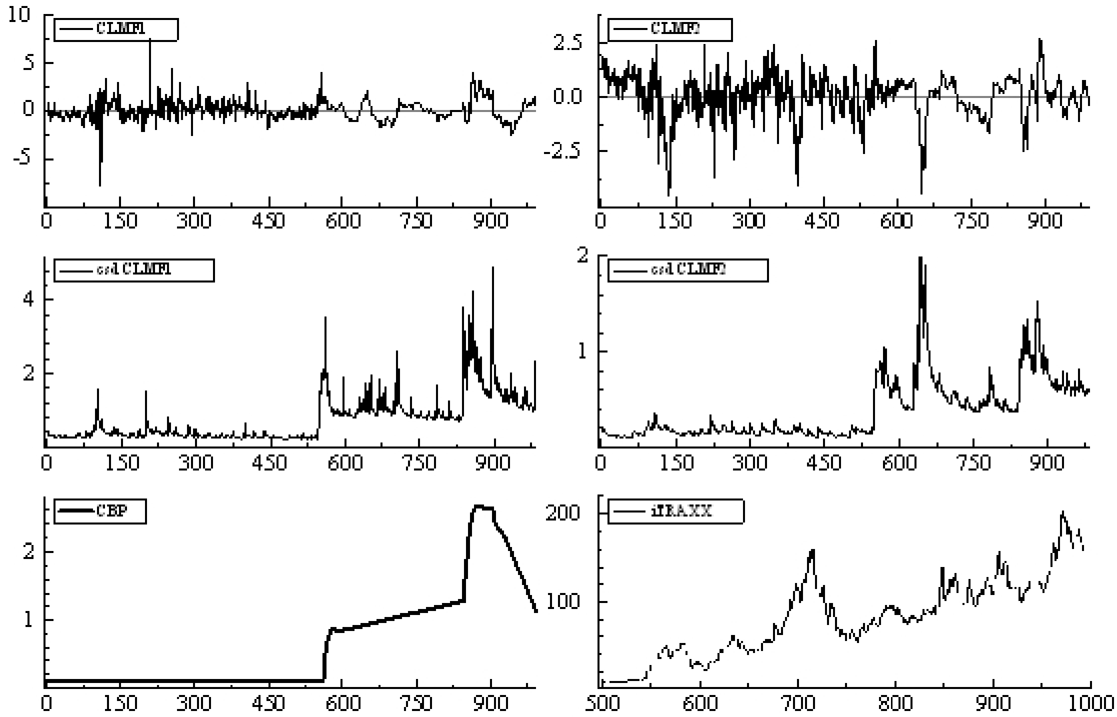

Figure 1: level factor (CBP); (standardized) curvature (CLMF1) and slope (CLMF2) factors and their volatility (csd CLMF1, csd CLMF2); iTRAXX Financials Index (iTRAXX).

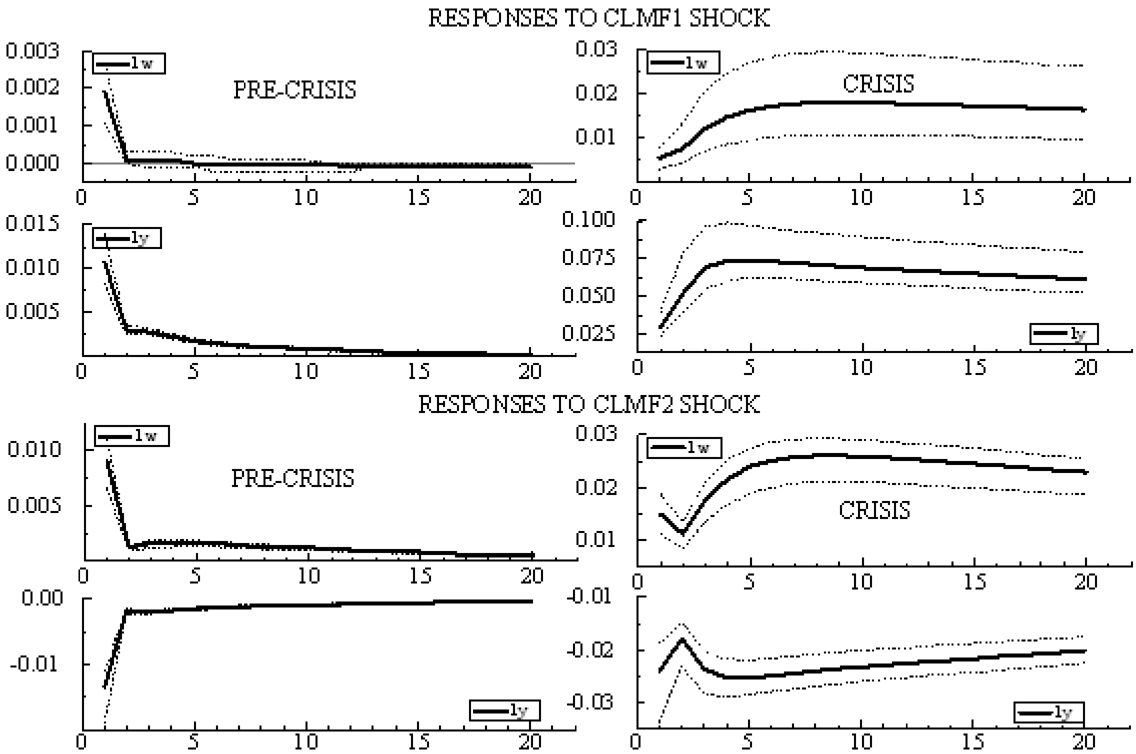

Figure 2: impulse responses, with 95% confidence interval, to a unitary curvature factor (CLMF1) shock and slope factor (CLMF2) shock, for the pre-crisis (left hand side plots) and crisis (right hand side plots) periods, for the 1-week (1w) and 1-year (1y) maturities.

Table 1: OIS spreads, persistence analysis: structural breaks tests and long memory analysis

Structural break tests					***Long memory analysis***	
	Bai-Perron			***DGM***	***BBLP***	
	Level		***Volatility***		***Level***	
	Break 1	***Break 2***	***Break 1***		***OIS spreads***	***l***
x^{1w}	558	844	557	0.005	0.857	0.455
x^{2w}	560	844	558	0.005	0.899	0.600
x^{3w}	560	844	557	0.005	0.980	0.644
x^{1m}	561	844	558	0.010	1.029	0.567
x^{2m}	561	844	553	0.025	1.035	0.472
x^{3m}	562	844	553	0.050	0.996	0.459
x^{4m}	562	844	554	0.030	0.962	0.386
x^{5m}	563	844	554	0.010	0.939	0.370
x^{6m}	563	844	554	0.005	0.934	0.344
x^{7m}	563	844	558	0.005	0.934	0.327
x^{8m}	563	844	558	0.005	0.919	0.307
x^{9m}	563	844	558	0.005	0.918	0.275
x^{10m}	563	844	554	0.005	0.912	0.260
x^{11m}	563	844	548	0.005	0.904	0.244
x^{1y}	563	844	548	0.005	0.890	0.277

In the Table the results of the Bai-Perron (BP, columns 1 to 4) and Dolado-Gonzalo-Mayoral (DGM, column 5) structural break tests are reported. The BP tests have been carried out on both the actual OIS spreads x_t (*level*) and on a volatility proxy obtained from their absolute first differences $|\Delta x_t|$ (*volatility*). In the table, the estimated location of the selected break points is reported. The dates of 9 August and 16 August 2007 correspond to observation 558 and 563, respectively; the date of 16 September 2008 corresponds to observation 844. The DGM test has been carried out assuming a time-varying unconditional variance. The latter takes two values according to the estimated values for the period 20/06/05 to 8/08/07 and 9/08/07 to 7/04/09. The estimated fractional differencing parameters, for the actual OIS spreads and their break-free (*l*) components, obtained using the Moulines-Soulier broad band log periodogram estimator (BBLP), are also reported (columns 5 and 6). The asymptotic standard error is 0.041 for all cases. The results are reported for the various OIS spreads maturities available, i.e. from 1-week (x^{1w}) to one-year (x^{1y}).

Table 2: OIS spreads, co-persistence (principal components) analysis

Panel A: Principal components analysis implemented on				
	actual OIS spreads	*break processes (b)*	*break-free OIS spreads (l)*	
	pc_1	μ_1	f_1	f_2
tot	**0.997**	**0.997**	**0.651**	**0.175**
x^{1w}	0.907	0.897	0.086	0.410
x^{2w}	0.975	0.959	0.152	0.583
x^{3w}	0.983	0.969	0.227	0.553
x^{1m}	0.968	0.953	0.341	0.437
x^{2m}	0.982	0.990	0.559	0.112
x^{3m}	0.988	0.992	0.717	0.031
x^{4m}	0.995	0.997	0.826	0.005
x^{5m}	0.998	0.999	0.878	0.002
x^{6m}	0.999	0.999	0.935	0.017
x^{7m}	0.999	0.999	0.924	0.044
x^{8m}	0.999	0.999	0.896	0.069
x^{9m}	0.999	0.999	0.863	0.080
x^{10m}	0.998	0.998	0.816	0.083
x^{11m}	0.996	0.997	0.785	0.094
x^{1y}	0.994	0.996	0.764	0.102

Panel B: Long memory analysis of common stochastic factors			
	***d* (se)**	**d_{pc} (se)**	**d_c (se)**
f_1	0.320 (0.041)	0.243 (0.054)	0.886 (0.062)
f_2	0.516 (0.041)	0.441 (0.054)	0.874 (0.062)

Panel A reports the results of principal components analysis implemented on the actual OIS spreads (first column), their estimated break processes (*b*, second column) and (normalized) break-free (*l*) components (third and fourth columns). The first row (*tot*) shows the fraction of total variance explained by the first principal component extracted from the actual OIS spreads (pc_1), the first principal component extracted from their estimated break processes (μ_1), and the first two principal components extracted from their break-free components (f_1 and f_2); the subsequent fifteen rows display the fraction of the variance of the individual series attributable to the extracted principal components for each set of series (actual, break, and break-free processes). Results are for the various OIS spreads maturities available, i.e. from 1-week (x^{1w}) to one-year (x^{1y}).

Panel B reports the results of the long memory analysis carried out on the first two principal components (f_1 and f_2) extracted from the break-free OIS spreads (*l*). In the Table the estimated fractional differencing parameter (*d*), obtained using the Moulines-Soulier broad band log periodogram estimator, with standard error in brackets, is reported. Estimates for the full sample and for the pre-crisis (20/06/05 to 8/08/07; d_{pc}) and crisis (9/08/07 to 7/04/09; d_c) sub samples are reported.

Table 3: forecast error variance decomposition

		pre-crisis				Crisis			
	Horizon (days)	***f*₁**	***f*₂**	***all***	***Own***	***f*₁**	***f*₂**	***All***	***Own***
x^{1w}	**1**	2.7	57.1	**59.8**	**40.2**	1.5	12.0	**13.5**	**86.5**
	20	1.8	50.3	**52.1**	**47.9**	27.2	57.8	**85.0**	**15.0**
x^{2w}	**1**	4.5	83.5	**88.0**	**12.0**	4.6	31.2	**35.8**	**64.2**
	20	4.0	83.1	**87.1**	**12.9**	33.9	58.6	**92.4**	**7.6**
x^{3w}	**1**	5.7	82.3	**88.0**	**12.0**	5.9	31.7	**37.7**	**62.3**
	20	4.9	81.1	**86.0**	**14.0**	41.9	52.8	**94.7**	**5.3**
x^{1m}	**1**	10.2	74.0	**84.2**	**15.8**	6.3	15.2	**21.5**	**78.5**
	20	7.8	70.6	**78.4**	**21.6**	63.6	31.2	**94.8**	**5.2**
x^{2m}	**1**	27.6	29.3	**56.9**	**43.1**	14.4	5.9	**20.3**	**79.7**
	20	23.1	25.0	**48.1**	**51.9**	90.0	6.9	**96.9**	**3.1**
x^{3m}	**1**	69.7	3.2	**72.9**	**27.1**	39.9	2.0	**41.9**	**58.1**
	20	67.7	2.9	**70.6**	**29.4**	97.8	0.9	**98.7**	**1.3**
x^{4m}	**1**	86.6	2.6	**89.2**	**10.8**	77.1	0.3	**77.4**	**22.6**
	20	87.1	2.4	**89.5**	**10.5**	99.5	0.1	**99.6**	**0.4**
x^{5m}	**1**	79.1	15.6	**94.7**	**5.3**	89.6	5.8	**95.4**	**4.6**
	20	80.4	14.8	**95.2**	**4.8**	98.7	1.2	**99.9**	**0.1**
x^{6m}	**1**	67.0	29.8	**96.8**	**3.2**	80.2	13.7	**93.9**	**6.1**
	20	68.6	28.5	**97.1**	**2.9**	96.7	3.1	**99.8**	**0.2**
x^{7m}	**1**	61.6	36.5	**98.0**	**2.0**	79.7	19.0	**98.7**	**1.3**
	20	63.3	34.9	**98.2**	**1.8**	95.6	4.4	**100.0**	**0.0**
x^{8m}	**1**	56.4	42.3	**98.7**	**1.3**	75.3	23.7	**99.1**	**0.9**
	20	58.2	40.6	**98.9**	**1.1**	94.2	5.7	**100.0**	**0.0**
x^{9m}	**1**	51.5	47.0	**98.5**	**1.5**	71.6	27.6	**99.2**	**0.8**
	20	53.6	45.1	**98.6**	**1.4**	93.0	6.9	**99.9**	**0.1**
x^{10m}	**1**	45.3	50.2	**95.5**	**4.5**	67.3	31.9	**99.2**	**0.8**
	20	47.8	48.0	**95.8**	**4.2**	91.8	8.2	**100.0**	**0.0**
x^{11m}	**1**	42.3	55.9	**98.2**	**1.8**	63.5	35.9	**99.3**	**0.7**
	20	45.2	53.0	**98.2**	**1.8**	90.6	9.4	**100.0**	**0.0**
x^{1y}	**1**	37.6	58.5	**96.1**	**3.9**	58.8	39.2	**98.0**	**2.0**
	20	41.0	55.1	**96.1**	**3.9**	89.3	10.6	**100.0**	**0.0**

The Table reports for each OIS spread the median forecast error variance decomposition at the one-day and twenty-day horizons, obtained from the structural VMA representation of the FI-HFVAR model. For each OIS spread series the Table shows the percentage of forecast error variance attributable to each common factor shock (f_1 and f_2), together with their sum (*all*). The last column reports the percentage of the forecast error variance attributable to the own idiosyncratic shock (*own*). The results are reported for the various OIS spreads maturities available, i.e. from 1-week (x^{1w}) to one-year (x^{1y}), for the pre-crisis (20/06/05 to 8/08/07) and crisis (9/08/07 to 7/04/09) periods.