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US-euro area term structure spillovers, implications for central banks

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Abstract

Spillovers between the US and euro area term structures of interest rates are examined. Implications for monetary policy are investigated using term-structure metrics that proxy conventional and unconventional instruments, i.e. the short rate, the 10 year term premium, and the 10 year risk-free rate. A new discrete-time arbitrage-free term structure model is used to extract these variables, at a daily frequency during the period covering 2005 to 2016. Relying on forecast error variance decompositions, following Diebold and Yilmaz (2009), it is found that transatlantic spillovers have increased by approximately 11%-points during the examined period, making it more difficult for central banks to directly assess the impact of their policies.

Keywords: *Yield curve modelling, Monetary policy, international spillovers.*

JEL: *C32, E43, E58*

Non-technical summary

This paper measures the degree to which US and euro area yield curves have interacted during the period from January 2005 to January 2016. The methodology suggested by Diebold and Yilmaz (2009) is used to quantify such interactions, also termed ”spillovers”, and the variables that enter the analysis are estimated using a new arbitrage-free term-structure model.

A moving data window is used such that a time series of spillover observations is generated. A window-length of 250 observations is used, and the analysis is repeated for each data window spanned by the data set, by moving this window forward by one observation at the time, until the end of the data sample is reached.

The empirical results document that spillovers are present and vary over time. Spillovers from the US to the euro area, and from the euro area to the US, have increased by a total of 11%-points from 2005 to 2016, implying that it has become more difficult for the Fed and the ECB to obtain clean measures of the financial market impacts of the implemented policies.

1 Introduction

Monetary policy is transmitted to the economy through the yield curve. Conventional policy acts on the short-end of the term structure, where the central bank exerts control over the rate at which commercial banks obtain central bank funding. Unconventional policies, for example purchases of longer-term debt, impact medium and longer-term maturities primarily through the term structure of term premia (see, among others, Christensen and Rudebusch (2012) and D'Amico, English, López-Salido, and Nelson (2012), Vayanos and Vila (2009), and Joyce, Miles, Scott, and Vayanos (2012)). For central banks to achieve their objectives, it is naturally important that policy signals are calibrated correctly, and that that the impact of implemented policies can be assessed at a reasonable level of precision. If the transmission channels are perturbed, and if such perturbations vary in strength over time, it extra challenging for central banks to calibrate appropriate policies, as well as to, subsequently, obtain precise measurements on the market reaction to implemented policies.

Financial market spillovers, as measured and documented by e.g. Diebold and Yilmaz (2009), Diebold and Yilmaz (2012), and Diebold and Yilmaz (2016)), have the potential to mute or amplify monetary policy signals, and thereby to act as a disrupting force for the successful implementation and measurement of central bank policies. Interactions between systemically important fixed-income markets are naturally of particular importance in this context, especially in the light of the growing use of unconventional central bank policies. For example, after the the Fed and the ECB lowered policy rates successively towards zero from during 2008 and 2009, the Fed initiated large-scale asset purchase programmes (LSAPs) in 2008, 2010, and 2011, which grew the Fed balance sheet from just under 1 trillion USD in 2008, to approximately 4.5 trillion USD in 2015. Similarly, the ECB introduced the covered bond purchase programmes I, II, and III (in 2009, 2011, and 2014), the Outright Monetary Transactions programme[1] (in 2012), forward guidance in 2013, Targeted Longer-Term Refinance Operations (in 2014 and 2015), and the Public Sector Purchase Programme[2] (in 2015). While the ECB balance sheet has not displayed monotonic growth since the launch of these initiatives, it has increased from around 1.5 trillion EUR in 2008 to 2.8 trillion EUR at the end of 2015. From the perspective of central banks, it is important to assess the extent to which conventional and unconventional policies, targeted at local bond markets, are being perturbed by developments in systemically relevant fixed income markets that lie beyond

[1] This programme substituted the Securities Market Programme that was launched in 2010.

[2] The Public Sector Purchase Programme, the Asset Backed Purchase Programme and the Covered Bond Purchase Programme III, are collected under the heading of the Expanded Asset Purchase Programme.

the central bank's control. The analysis performed below contributes to this end by estimating spillovers between the US and euro area (EA) fixed income markets. These transatlantic spillovers are quantified to occur between term-structure metrics that are impacted by conventional and unconventional monetary policies: (i) the short rate; (ii) the 10 year term-premium; and (iii) the 10 year risk-free rate. A new discrete-time arbitrage-free yield curve model is developed to extract the term-structure metrics from daily US and EA zero-coupon data covering the period from 2005 to 2016. As a means to capture spillovers between these variables, I follow closely the methodology suggested by Diebold and Yilmaz (2009).

The rest of the paper is organised as follows. Section 2 develops, implements, and estimates a new arbitrage-free term-structure model that is close in spirit to the dynamic Nelson-Sigel set-up (Diebold and Li (2006), Christensen, Diebold, and Rudebusch (2011)), but which is set in discrete-time, and which explicitly includes the short rate as one of the modelled yield curve factors. Section 3 outlines and motivates the spillover analysis, Section 4 presents and discusses the empirical findings, and Section 5 concludes the paper.

2 The yield curve model

This section develops a new discrete-time arbitrage-free term structure model that is similar in its set-up to the dynamic Nelson-Siegel model (see, Christensen, Diebold, and Rudebusch (2011)). Contrary to previous arbitrage-free Nelson-Siegel type models, the one presented here is set in discrete-time, and it explicitly includes the short-rate as one of its factors, together with a slope and a curvature factor. This factor structure allows for the direct estimation of the time series dynamics of the short-rate, and it is therefore straight-forward to calculate term-premia and expectations to the risk-free rate at longer maturities. Were this to be done in a traditional Nelson-Siegel factor structure, it would be necessary to estimate and account for the time-varying correlation between the level, (minus) slope and curvature factors.

2.1 The well-known structure for arbitrage-free term-structure models

Using the standard affine arbitrage-free set-up, following, among many others, Duffie and Kan (1996), Dai and Singleton (2000), and Ang and Piazzesi (2003), let X_t denote the vector of the N modelled yield curve factors, at time t. Furthermore, let the dynamics of X_t be governed by vector autoregressive (VAR) processes under both the empirical measure, $\mathbb{P}$, and the risk neutral measure, $\mathbb{Q}$. Without loss of generality, due to the companion form, these are written as VAR(1) processes:

$$X_t = \mu^{\mathbb{P}} + \Phi^{\mathbb{P}} X_{t-1} + \Sigma\epsilon_t^{\mathbb{P}}, \qquad \epsilon_t^{\mathbb{P}} \sim N(0,1) \tag{1}$$

$$X_t = \mu^{\mathbb{Q}} + \Phi^{\mathbb{Q}} X_{t-1} + \Sigma\epsilon_t^{\mathbb{Q}}, \qquad \epsilon_t^{\mathbb{Q}} \sim N(0,1). \tag{2}$$

with $\Sigma\Sigma' = \Omega$ being the variance of the residuals, which is the same for both measures. The risk free one-period short rate is assumed to be a function of X_t, such that:

$$i_t = \rho_0 + \rho_1' X_t. \tag{3}$$

To facilitate a mapping between the empirical and risk neutral measures, the time-varying market prices of risk is specified in the following way:

$$\lambda_t = \lambda_0 + \lambda_1 X_t, \tag{4}$$

with λ_0 being of dimension $N - by - 1$, and λ_1 being of dimension $N - by - N$, and where the mapping between $\mathbb{P}$ and $\mathbb{Q}$ is assumed to result from:

$$\lambda_0 = \Sigma^{-1}\left(\mu^{\mathbb{P}} - \mu^{\mathbb{Q}}\right) \tag{5}$$

$$\lambda_1 = \Sigma^{-1}\left(\Phi^{\mathbb{P}} - \Phi^{\mathbb{Q}}\right). \tag{6}$$

Finally, the yield at time t for maturity n is assumed to be an affine function of the factors, with a set of loading factors that depend on maturity:

$$y_{t,n} = -\frac{A_n}{n} - \frac{B_n'}{n} X_t. \tag{7}$$

It turns out that A_n and B_n can be found using the following set of recursive equations:

$$A_{n+1} = A_n + B_n'\mu^Q + \frac{1}{2} B_n' \Sigma\Sigma' B_n - \rho_0, \tag{8}$$

$$B_n = -\left[\sum_{k=0}^{n-1} \left(\Phi^Q\right)^k\right]' \rho_1. \tag{9}$$

2.2 The Discrete-Time Short-Rate AFTSM

In order to derive a model with the following factor structure:

$$X_t = \begin{bmatrix} \text{short rate} \\ \text{slope} \\ \text{curvature} \end{bmatrix}, \tag{10}$$

it follows from (3) that $\rho_0 = 0$ and $\rho_1' = [1, 0, 0]$, the latter being a row vector. In order to obtain factor loadings that corresponds to (10), I choose the $\mathbb{Q}$-measure autoregressive matrix to be:[3]

$$\Phi^Q = \begin{bmatrix} 1 & 1-\gamma & 1-\gamma \\ 0 & \gamma & \gamma-1 \\ 0 & 0 & \gamma \end{bmatrix}, \tag{11}$$

Inserting this expression for Φ^Q in (9) gives:

$$B_n = -\begin{bmatrix} n \\ n-1-\sum_{k=1}^{n-1}\gamma^k \\ -(n-1)\gamma^{n-1}+\sum_{k=0}^{n-2}\gamma^k \end{bmatrix}. \tag{12}$$

Using the convergence results for geometric series and simplifying terms, a tidy expression is obtained:

$$B_n = -\begin{bmatrix} n \\ n-\frac{1-\gamma^n}{1-\gamma} \\ -\gamma^{n-1}n+\frac{1-\gamma^n}{1-\gamma} \end{bmatrix}. \tag{13}$$

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[3] In the case of the continuous-time DNS model Christensen, Diebold, and Rudebusch (2011) show that

$$\Phi^Q = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1-\lambda & 1-\lambda \\ 0 & 0 & 1-\lambda \end{bmatrix}.$$

In a discrete-time DNS set-up Niu and Zeng (2012) show that

$$\Phi^Q = \begin{bmatrix} 1 & 0 & 0 \\ 0 & e^{-\lambda} & e^{-\lambda} \\ 0 & 0 & e^{-\lambda} \end{bmatrix}.$$

with $\rho_1 = \left[1 \, \frac{1-e^{-\lambda}}{\lambda} \, \frac{1-e^{-\lambda}}{\lambda} - e^{-\lambda}\right]$.

For convenience the expression for A_n is repeated here, and the model assumption of $\rho_0 = 0$ is applied:

$$A_{n+1} \quad = A_n + B_n'\mu^Q + \tfrac{1}{2}B_n'\Sigma\Sigma'B_n. \tag{14}$$

An expression for the yield curve at time t is then obtained if Y_t collects $y_{t,n}$ $\forall n$ by increasing maturity, and if $A = -A_n/n$ and $B = -B_n'/n$ are defined similarly. Finally, let ν collect the individual n_i maturities at which yields are observed. The expression for the yield curve observed at time t is then:

$$Y_t = A + BX_t + \eta_t. \tag{15}$$

2.3 Comparison with the DNS model

Before the discrete-time short-rate arbitrage-free term-structure model is estimated, it may be helpful to illustrate how it compares to the DNS model. The factor structure of the DNS model is defined by the (a) the yield curve level, (b) minus the slope, and (c) the curvature, while the model I propose is defined in terms of factors for (a^*) the short rate, (b^*) the slope, and (c^*) the curvature. In order to facilitate a comparison between these two models with different factor structures, it is necessary to adapt the DNS model slightly. This can be done by rotating its factors (Nyholm (2015)).

Define a rotation matrix such that (i) the DNS level is rotated into a short rate; (ii) the DNS minus slope is rotated into (plus) slope; and (iii) the curvature is left unchanged. This can be achieved by the following matrix (where $A^{-1}A = I$):

$$A = \begin{bmatrix} 1 & 1 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & 1 \end{bmatrix}, \tag{16}$$

such that the DNS equation becomes:

$$Y_t = HA^{-1} \cdot A\beta_t + \epsilon_t. \tag{17}$$

Here, $H_n = \left[1 \;\; \left(1 - e^{-\theta n}\right)/\theta n \;\; \left(1 - e^{-\theta n}\right)/\theta n - e^{-\theta n}\right]$ is the DNS loading matrix, with θ being the so-called time-decay parameter. The rotated factors, with an economic interpretation similar to the one I propose in Section (2.2) is given by $A\beta_t$, where β_t hold the factor observations from the DNS model. Finally, HA^{-1} is the matrix of rotated DNS factor loadings.

It is noted that the loading structure of the discrete-time arbitrage-free model is based on power functions, while the rotated DNS model relies on exponential functions:

$$B = \begin{bmatrix} 1 & 1 - \frac{1-\gamma^{\nu(1)}}{(1-\gamma)\nu(1)} & \frac{1-\gamma^{\nu(1)}}{(1-\gamma)\nu(1)} - \gamma^{\nu(1)-1} \\ 1 & 1 - \frac{1-\gamma^{\nu(2)}}{(1-\gamma)\nu(2)} & \frac{1-\gamma^{\nu(2)}}{(1-\gamma)\nu(2)} - \gamma^{\nu(2)-1} \\ \vdots & \vdots & \vdots \\ 1 & 1 - \frac{1-\gamma^{\nu(N)}}{(1-\gamma)\nu(N)} & \frac{1-\gamma^{\nu(N)}}{(1-\gamma)\nu(N)} - \gamma^{\nu(N)-1} \end{bmatrix} \tag{18}$$

where $\nu(j)$ for $j = \{1, 2, \ldots, N\}$ refers to the individual components in the vector of maturities.

$$HA^{-1} = \begin{bmatrix} 1 & 1 - \frac{1-e^{-\theta\nu(1)}}{\theta\nu(1)} & \frac{1-e^{-\theta\nu(1)}}{\theta\nu(1)} - e^{-\theta\nu(1)} \\ 1 & 1 - \frac{1-e^{-\theta\nu(2)})}{\theta\nu(2)} & \frac{1-e^{-\theta\nu(2)}}{\theta\nu(2)} - e^{-\theta\nu(2)} \\ \vdots & \vdots & \vdots \\ 1 & 1 - \frac{1-e^{-\theta\nu(N)}}{\theta\nu(N)} & \frac{1-e^{-\theta\nu(N)}}{\theta\nu(N)} - e^{-\theta\nu(N)} \end{bmatrix} \tag{19}$$

Figure 1 draws a comparison between the loading structures contained in B and HA^{-1}, i.e between (18) and (19). In order to perform this comparison the free parameters γ and θ must be fixed at some reasonable value. Looking at the models autoregressive structure under $\mathbb{Q}$, the following relationship exists: $\gamma = 1 - \theta$. While it is necessary to estimate these parameters, for the current comparison I set $\theta = 0.05$ and thus $\gamma = 0.95$. The displayed loading patterns are very similar and deviations between the loading patterns for the slope and curvature factors are minute, ranging from -0.03 to 0.005.

[** Insert Figure 1 around here **]

2.4 Data

Zero coupon yield curve data from the US and EA are used to extract the yield curve metrics relevant for the spillover analysis, i.e. the short rates, the 10 year term premia, and the model-expectation to the risk-free 10 year rates. Daily data covering the period from January 2005 to February 2016, for maturities $\{3, 12, 24, \ldots, 120\}$ months, are sampled. US data are from Gurkaynak, Sack, and Wright (2006)[4], and the EA data are the AAA-rated sovereign yield curves

[4] Yield curve factors are downloaded from http://www.federalreserve.gov/pubs/feds/2006/200628/200628abs.html and converted into yields for the desired maturities using Svensson (1994)

produced by the European Central Bank[5]. Plots of the data are shown in Figures 2 and 3, for selected maturities.

[** Insert Figure 2 around here **]

[** Insert Figure 3 around here **]

2.5 Yield curve calibration

The discrete-time arbitrage-free model is calibrated to data following a step-wise approach:

1. Conditional on $\hat{\gamma}$, the risk-neutral factor dynamics, $\hat{\Phi}^{\mathbb{Q}}$, and the loading structure of the model, $\hat{B}$, are known in close form, given equations (13) and (11), respectively.

2. With the factor interpretation in (10), I treat the factors as observed without error, and find them as $\hat{X} = \hat{B}^{-1}Y'$, where $\hat{B}^{-1}$ is the pseudo-inverse of $\hat{B}$.

3. With $\hat{X}$ and $\hat{B}$ known, equations (14) and (15) are used to find $\hat{\Sigma}$ and $\hat{\mu}^{\mathbb{Q}}$ as the solution to $\min_{\Sigma,\mu^{\mathbb{Q}}} \sum_n \sum_t [Y_t - (\hat{A} + \hat{B}\hat{X}_t)]^2$.

4. The dynamics under the $\mathbb{P}$-measure can now be found using (1) and constrained likelihood optimisation, imposing the value for $\hat{\Sigma}$, found in the previous step. This amounts to estimating a VAR model using maximum likelihood with a known error-term covariance matrix.

5. Steps 1-4 are performed over a grid of values for γ, and the optimal $\hat{\gamma}$ found as the one that minimises $\sum_n \sum_t \eta^2$.

Following the above calibration steps provides a close fit between fitted and observed yields.[6] The root-mean-squared error (RMSE) for US and EA yields are shown in Table 1, for each included maturity. Equally good fits are seen for the US and EA data, with RMSEs all falling in a narrow range from 0.01 to 0.06 percentage points (i.e. between 1-6 basis points). Figures 4 and 5 show observed and fitted $10Y$ yields for each market. These plots confirm that the model fit data well.

[** Insert Table 1 around here **]

[** Insert Figure 4 around here **]

[** Insert Figure 5 around here **]

[5] These data are Downloaded from https://www.ecb.europa.eu/stats/money/yc/html/index.en.html.

[6] The used calibration method can be seen as a special case of Andreasen and Christensen (2015).

2.6 Extracted factors and risk premia

On the basis of the calibrated model parameters, it is possible to extract from data, the variables needed for the spillover analysis. The short rate series are readily available from $\hat{X}$ as the first entry/factor (see, (10)), while the 10 year term premia and risk-free rates must be found using the calibrated model parameters.

Following, e.g. Gürkaynak and Wright (2012), the risk-free term structure can be calculated in the following way:

$$Y^{rf}_{t,n_i} = \frac{1}{n_i} \cdot E_t \left(\sum_{j=0}^{n_i - 1} i_{t,t+j} \right). \tag{20}$$

where $Y^{rf}_{n_i}$ denotes the risk-free yield at a given maturity n_i. Hence, the risk-free yield is defined as the average of the cumulated short rate in (3), over a given investment horizon, for each observation point, t, covered by the sample. For the application in this paper, I use $n_i = 10$ years. Further, following Gürkaynak and Wright (2012), the term-premium is defined as the difference between the model yield curve and the risk-free curve, i.e.

$$TP_{t,n_i} = \hat{Y}_{t,n_i} - Y^{rf}_{t,n_i}. \tag{21}$$

Here, $\hat{Y}_{t,n}$ refers to the model-fitted yield curve at time t for maturities n: $\hat{Y}_{t,n} = \hat{A} + \hat{B}\hat{X}_t$.

The generated variables are shown in figures 6, 7, and 8.

[** Insert Figure 6 around here **]

[** Insert Figure 7 around here **]

[** Insert Figure 8 around here **]

As a control variable, and because monetary policy spillovers may be carried by the exchange rate, the spot EUR/USD is included as well:

[** Insert Figure 9 around here **]

3 Measuring Term-Structure Spillovers

I follow closely Diebold and Yilmaz (2009), and derive spillovers from the VAR model's forecast-error variance decomposition. To circumvent concerns about the ordering of variables in the VAR, I rely on generalised decompositions, see Koop, Pesaran, and Potter (1996), Pesaran and Shin (1998), and Lanne and Nyberg (2016, forthcoming), as also implemented in the context of spillover analysis by e.g. Diebold and Yilmaz (2012) and Diebold and Yilmaz (2016).

Let Z collect the variables that are included in the analysis:

$$Z = \begin{bmatrix} \text{Short rate}_{US} \\ \text{Short rate}_{EA} \\ \text{Term Premium 10Y}_{US} \\ \text{Term Premium 10Y}_{EA} \\ \text{Long-term risk-free rate}_{US} \\ \text{Long-term risk-free rate}_{EA} \\ \text{EUR/USD} \end{bmatrix}. \tag{22}$$

The following companion-form VAR(1) model is then estimated:

$$Z_t = k + F \cdot Z_{t-1} + u_t, \qquad u \sim N(0, \Upsilon). \tag{23}$$

Generalised impulse response functions (GIRFs) are calculated from the moving average representation of the VAR model, as the difference between a conditional and an unconditional forecast, where the conditioning information set is the shock to the i'th variable (Koop, Pesaran, and Potter (1996)). Let D_{t-1} represent the data available at time $t-1$, and let $h = \{1, 2, \ldots\}$ be the forecast horizon, let $i = \{1, 2, \ldots, 7\}$ count the variables in Z such that Z^i refers to the i'th variable, and denote by δ_j the shock to variable j, $j = \{1, 2, \ldots, 7\}$. The GIRF is then defined in the following way:

$$GIRF(i, t+h, \delta_{j,t}, D_{t-1}) = E\left(Z^i_{t+h} | u_{j,t} = \delta_{j,t}, D_{t-1}\right) - E\left(Z^j_{t+h} | D_{t-1}\right). \tag{24}$$

As noted by Pesaran and Shin (1998), using (24) for the purpose of forecast error variance decomposition can make the results difficult to interpret, since contributions from each shock to one variable will not necessarily sum to unity, if Υ is not diagonal. To mitigate this problem, a normalisation is implemented (see, e.g., Diebold and Yilmaz (2016) and Lanne and Nyberg (2016, forthcoming)) such that each row of the variance decomposition matrix sums to unity. The generalised forecast error variance decomposition for variable i at horizon h is then given by:

$$\theta_{i,j}(t+h) = \frac{\sum_{l=0}^{h} GIRF(i, t+l, \delta_{j,t}, D_{t-1})^2}{\sum_{j=1}^{7}\sum_{l=0}^{h} GIRF(i, t+l, \delta_{j,t}, D_{t-1})^2}. \tag{25}$$

In the context of spillover analysis, as suggested by Diebold and Yilmaz (2012), it is relevant to highlight two aspects of $\theta_{i,j}(t+h)$: (a) row i holds the variance contributions from a shock to each of the variables included in the VAR model, to the error-variance of variable i, and the row-sum equals unity; and (b) column j holds the contributions from variable j to the error variance of each of the other variables in the VAR model, and the column-sum does therefore (typically) not sum to unity. Consequently, analysis of the row entries of $\theta_{i,j}(t+h)$, provides information about how much spillover there is from each of the variables in the system, to the row-i variable. Similarly, the columns of $\theta_{i,j}(t+h)$ facilitates the analysis of how the shock to one given variable, spills over to each of the other variables in the system.

As a summary measure for the total level of spillovers between the included variables can be obtained as the sum of all the off-diagonal elements, as the diagonal elements contain the size of own-variable spillovers, normalised by the number of variables in the system (see Diebold and Yilmaz (2012)):

$$S = \frac{\sum_{\substack{i,j=1 \\ i \neq j}}^{N} \theta_{i,j}(t+h)}{N} \tag{26}$$

where N is the number of variables in the VAR, i.e. $N = 7$.

Based on (26) specific-purpose spillover-indices can be designed to track the spillover between subsets of the variables in the VAR model. For example, it is relevant to measure the amount of spillovers from US variables to EA variables, and from EA variables to US variables. This is achieved by summing over a subset row and column intersections of $\theta_{i,j}(t+h)$. Let the impacted (spillover to) variables be collected in the set $\mathbb{T}$, and let the impacting (spillover from) variables be collected in the set $\mathbb{F}$, the sub-index is then defined as:

$$S^* = \frac{\sum_{\substack{i \in \mathbb{T} \\ j \in \mathbb{F}}} \theta_{i,j}(t+h)}{N} \tag{27}$$

The empirical analysis is performed for the VAR model in (23), by using subsample estimates to track the degree of spillover among the included variables over time. Spillover estimates are generated for successive data-windows comprising 250 observations, where the window is rolled forward by one observation point per spillover estimate, until the end of the sample is reached. This gives a time series of 2523 estimates for the relevant spillover gauges.

The optimal lag-length for the VAR model in (23) is determined by the SIC criterion, and it shows that a one-lag model is optimal for all subsamples.[7] Visual inspection of the data reveals that some subsamples may not be stationary, and indeed, using the augmented Dickey-Fuller test and Johansen's cointegration test, Johansen (1995), a number of the subsamples covered by the data show evidence of I(1)-ness and cointegration between the included variables. An optimally fitting model specification to each subsample would therefore require a mixture of VARs and VEC models to be applied. Given that the spillover analysis derives from normalised squared impulse-response functions (i.e. from variance decompositions), see (24), and given that I focus on short forecast horizons of ten daily observations (which is typical for spillover analysis), the impulse-responses, even for VARs including cointegrated variables, are unbiased, see Phillips (1998). I will therefore apply a VAR(1) specification to each of the subsamples, and derive spillovers herefrom.

4 Results

With the purpose to investigate the degree of spillovers between US and EA term-structures I focus on spillovers a specific set metrics. These are: (i) short term rates, (ii) 10 year term premia, and (iii) 10 year risk-free rates. And, to allow for possible currency impacts, also the spot EUR/USD exchange rate is included in the analysis.

Summary measures for the general spillover-tendency between US and EA term structures are shown in figure 10. Three measures are displayed: an overall index that portrays the spillovers between all the variables included in the VAR, following (26), and two sub-indices following (27). The first sub-index captures the spillover to the US short rate, US 10-year term premium, and the US 10-year risk-free rate, from the EA variables and the exchange rate, and the second sub-index traces the spillover to the EA short rate, EA 10-year term premium, and the EA 10-year risk-free rate, from the US variables and the exchange rate.

[** Insert Figure 10 around here **]

The overall index shows that spillovers between US and EA yield curves and the EUR/USD exchange rate has increased during the analysed data period. In 2006 the level of spillovers stood

[7] In comparison, the AIC creterion points to one, two or four lags being optimal, depending on the individual subsamples. However, since empirical investigation shows that there is no qualitative difference between the derived spillover measures when a one lag model is compared to a four lag model, the results from using the SIC criterion is used and a one-lag model is therefore chosen for all subsamples

at 31%, and it had increased to 44% at the end of the period, in 2016. Given the global reach of the crisis it is natural that spillovers between yield curve variables and the exchange rate grow in importance, as seen in figure 10: As a response to the financial crisis, that began in 2008, and the euro area sovereign debt crisis that took its beginning in 2010, central banks have implemented measures to control not only the short end of the yield curve, but also term-premia throughout the maturity spectrum via bond purchases, the future path of the policy rate via forward guidance as well as bond purchases, and indirectly the exchange rate.

[** Insert Table 2 around here **]

Spillovers can be local and global. The two sub-indices in figure 10 show the amount of transatlantic spillovers: to US from EA, and to EA from US. In 2006 a modest degree of spillover, of around 5 to 6%, is observed for both of these indices, which grows to around 12% in 2016. In total, this represents a rise of 11%-points (5 and 6%-points from the US and EA sub-indices, respectively) in spillovers between US and EA monetary policies, and it accounts for the larger part of the observed increase in the overall spillover-index over the period from 2006 to 2016. Naturally, the total index and the sub-indices are not directly comparable, because the basis for their calculations are different: the overall index includes positive and negative contributions from all variables (apart from the own-variable effect, i.e. the diagonal of the forecast error variance decomposition matrix), while the sub-indices only account for the spillover from US variable to EA variables, and from EA variables to US variables.

Table 2 further outlines the changes on the spillovers of the included variables, the overall-, and the sub-indices. The upper panel shows the changes from 2006 to 2016 to each variables and the composition of the overall index, while the lower panel shows the respective changes decomposed for the transatlantic sub-indices. A recorded positive change implies that the respective variable/index has increased over the period, and that its spillover impact thus has grown, conversely, a negative value corresponds to a decrease in the spillover of this variable/index. Looking at the columns in the upper panel it is clear that the US term premium and the US risk-free rate account for the largest part of the spillovers, respectively, 4.71%-points and 4.69%-points. The EA variables contribute relatively less with the term premium and the risk-free rate each represent changes of 1.71%-points and 1.69%-points. Also the exchange rate plays an important role with an increase of 1.13%-points. At the same time, it is noted that the spillover contributions from the short rates are negligible. These observations correspond well with the observed policy behaviour of the Fed and the ECB, who have increasingly relied on unconventional policies during the period under analysis, particularly after the policy rates were lowered to close to zero around 2009. In such an interest rate environment there is clearly very little scope for conventional policy actions; and, in stead, unconventional policies, bond purchase programmes and forward guidance, has been used with the aim to impact yields at maturities that are well beyond that of the short term policy rate. The growing relative importance of the spillovers from term premia and the risk-free 10Y rates, to the other variables in the VAR model, is therefore expected.

It is recalled that the overall index, and the upper panel of Table 2, do not distinguish between local and global spillovers. In order to separate domestic and transatlantic spillovers, I turn again to the sub-indices shown Figure 10 and the additional information provided on these indices in the lower panel of Table 2. Conventional wisdom suggests that there should be very little spillover from the EA monetary policy rate to US variables, and likewise, very little spillover from the US monetary policy rate to EA variables. This conjecture is rooted in the fact that traditional transmission channels are local, these being domestic money market rates and rate expectations. Once a policy signal is transmitted via the money market, it naturally spreads through asset prices to the rest of the economy, and from here to global asset prices. The result shown in Table 2 confirms that also during the period from 2006 to to 2016, very little spillover is seen from the monetary policy rates, with a spillover of 0.06%-points from the US short rate to the EA variables, and a spillover of 0.71%-points from the EA short rate to the US variables. As regards spillovers from term premia and the risk-free 10 year rates, as mentioned above, an increase over the period is seen between US and EA variables. This increase is however not monotonic, rather, it is characterised by a mixture of relatively persistent regimes of high and low spillovers. Figure 10 shows that since mid-2014 in the case of 'to EA from US'-spillovers, and since end-2014 in the case of 'to US from EA'-spillovers, a higher level of transatlantic spillovers are seen, with spillover 'to US from EA' showing an increase of 6.01%-points and spillovers 'to EA from US' having increased by 4.80%-points.

[** Insert Figure 11 around here **]

[** Insert Figure 12 around here **]

[** Insert Figure 13 around here **]

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For the latter part of the data sample, after 2010, there is a strong tendency for the transatlantic spillovers to occur at the same time, i.e. it is observed that when the spillover to the EA from the US increases, so does the spillover to the US from EA. This is most likely a consequence of the evolution of the international business-cycle during this period, which has been characterised by waves of financial and sovereign crisis with a global reach. Curiously, the adjustment process to near-zero policy rates, that was undertaken by the Fed from 2008 to 2009, and by the ECB from late-2008 to 2009, did not result in a similar degree of spillovers across the Atlantic. The first period of this monetary policy adjustment process, that was seen during 2007, impacted the spillover indices only to a minor degree. Only one short burst of spillovers is observed during this period, at the very end of 2008, to the US from EA policies. This period is characterised by EA policy rate staying at an elevated level, while the US policy rate underwent a sharp downward revision. Figures 11, 12, 13 show that this sharp burst of spillover to the US from the EA is primarily driven by impacts (i) to the US short rate from the EA short rate, (ii) to the US term premium from the EA short rate and risk-free 10 year rate, and (iii) to the US 10 year risk-free rate from the EA short rate.

Two periods of isolated spillovers to the EA policy from US policy, are observed. The first of these periods covers the first six months of 2009, and the second period covers the latter part of 2010. Figures 14, 15, 16 show that these episodes emerge due to spillovers (i) to the EA short rate from the US short rate and the US risk-free 10 year rate, (ii) to the EA term premium from the US term premium, and (iii) to the EA 10 year risk-free rate from the US short rate, US term premium, and the US 10 year risk-free rate.

After 2010, when the global financial crisis unfolded, there is a tendency for transatlantic spillovers to occur at the same time. The first period of 'mutual-spillovers' is observed from 2010 to 2011, with a peak around the start of 2011. And, the second period starts mid-2014, and that is still ongoing at the end of the data sample, in January 2016.

During the period from 2010 to 2011, Figure 11 shows a minor impact to US short rate from the EA term premium, and, Figures 12 and 13 show, respectively, that the stronger impact is on the US term premium from the EA term premium and EA 10 year risk-free rate, and on the US risk-free 10 year rate, again from the EA term premium and EA 10 year risk-free rate. Similarly, for the latter episode, which took its beginning mid-2014, the major impacts are seen on the US term premium, from the EA term premium and EA risk-free rate, and on the US risk-free rate from the EA term premium and the EA risk-free rate.

Looking at these two periods from the EA perspective, Figures 14, 15, and 16 show that from 2010 to 2012, impacts to the EA short rate is seen from the US short rate, and the US term premium, the EA term premium is mainly impacted by the US short rate, while the EA 10 year risk-free rate is impacted by the US term premium. For the second period, starting mid-2014, the spillovers are seen to impact the EA term premium from the US term premium and risk-free rate, and impacts are seen on the EA 10 year risk-free rate from the US 10 year risk-free rate.

Finally, the lower panel of Table 2 shows that the exchange rate contributes with positive spillovers, on average, over the period from 2006 to 2016, to both the developments in the US and EA monetary policy instruments. These impacts are not large, amounting to 0.47%-points for the US, and 0.66%-points the EA. However, during the last spill-over period, i.e. the one starting mid-2014, it is seen that the exchange rate plays a more important role for the developments in the EA than in the US. While only the US term premium is impacted, all three EA variables are affected by the exchange rate variable.

5 Conclusion

I show that the conduct of conventional and unconventional monetary policies by the Fed and the ECB have been impacted by transatlantic term-structure spillovers during the period from January 2005 to January 2016. Spillovers can accentuate or mute implemented policies, and, by implication, making it more difficult for monetary authorities to assess the impact of implemented policies. In particular, since spillovers are found to be time-varying, it is challenging to include their effect into policy response functions. Also, in the presence of spillovers, it is a complex task to assess the impact on financial variables of implemented policies. All in all - and this is not new - the job of central banks is far from straight-forward, given the financial and economic backdrop that has unfolded since 2008. What is new, however, is that transatlantic term-structure spillovers add to these complexities.

To reach this conclusion, I first develop a discrete-time arbitrage-free term structure model that is close in spirit to the Dynamic Nelson-Siegel modelling framework (see, e.g. Diebold and Li (2006), Christensen, Diebold, and Rudebusch (2011), Diebold and Rudebusch (2013)), but where the short rate appears as one of the yield curve factors, along with the slope and the curvature factors. This model is used to extract term-structure metrics that can be used to gauge conventional and unconventional monetary policies; taking the short-rate factor to reflect conventional monetary policy, and the 10 year term premium and the 10 year risk-free rate as instruments for unconventional policies. Based on e.g. Taylor (1993), and the observation that monetary authorities exercise control over the short end of the term structure, it is reasonable to assume that the short rate factor reflect conventional monetary policy. Unconventional policies, such as forward guidance and quantitative easing, aim at affecting the market's perception on the future path of the policy rate, and longer maturity rates via the term premium, respectively (see, e.g. Vayanos and Vila (2009), Joyce, Miles, Scott, and Vayanos (2012), D'Amico, English, López-Salido, and Nelson (2012), and Christensen and Rudebusch (2012)). And, it is therefore assumed that the estimated 10 year term premium and 10 year risk-free rate can be used as instruments for unconventional policies.

The term-structure metrics are extracted from daily zero-coupon data covering the period from January 2005 to January 2016 from the US and euro area. The resulting short rates, 10 year term-premia, and 10 year risk-free rates are combined in a VAR model with spot EUR/USD exchange rate. The analysis framework developed by Diebold and Yilmaz (2009) is used to estimate spillovers between the US and euro area, on a 250 observation rolling-window basis, where the VAR model is re-estimated for each data window rolled forward by one observation until the end of the data sample is reached.

The empirical results document that spillovers are present in the data, with a time-varying intensity. It is found that the degree of transatlantic policy spillovers increased by 11%-points over the sample period; however, this increase is not so much a result of a general upward sloping trend, as much as it reflects that the economy since mid-2014 is experiencing an episode of high spillovers, while the start of the data sample is characterised by a period of relatively low spillovers. Looking at total spillovers, and thus also including the intra-market spillovers, i.e. spillovers among the group of US variables, and the group of euro area variables, a clearly increasing trend is however visible.

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Tables and Figures

Area	3M	1Y	2Y	3Y	4Y	5Y	6Y	7Y	8Y	9Y	10Y
Euro area	0.047	0.056	0.032	0.016	0.021	0.026	0.024	0.016	0.007	0.015	0.032
US	0.052	0.057	0.049	0.012	0.027	0.040	0.038	0.026	0.008	0.022	0.049

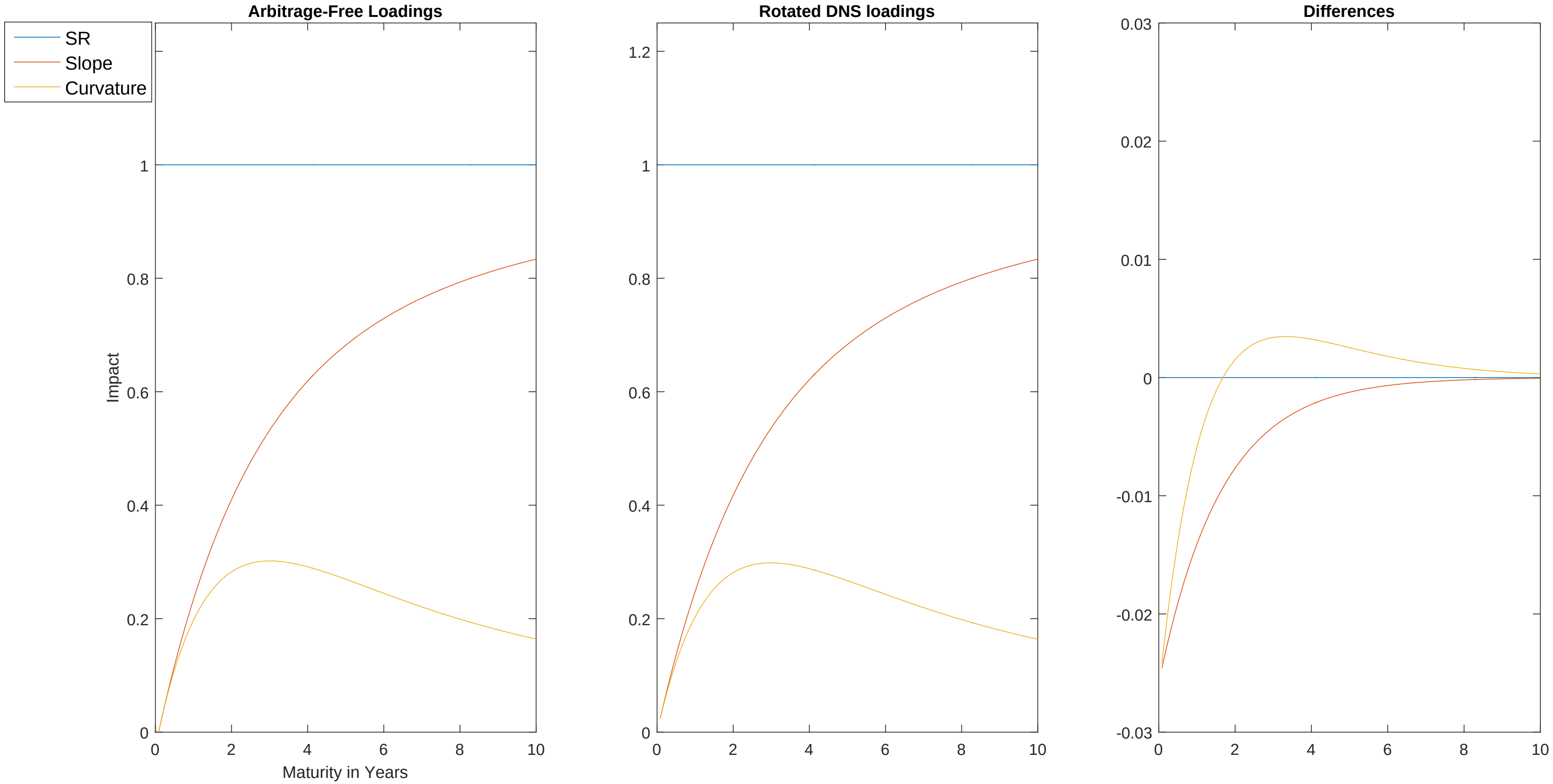
The table shows summary statistics for the fit of the yield curve model to Euro area and US data. Root mean squared error are shown (RMSE) in percentage points.

Table 1: Yield curve fit: RMSE

to \from	SR US	SR EA	TP US	TP EA	RF 10Y US	RF 10Y EA	EUR/USD	Total Index
US Short Rate (SR US)	-0.63	0.78	-0.29	-0.14	0.50	-0.56	0.34	0.63
EA Short Rate (SR EA)	0.18	0.71	0.72	-0.50	0.15	0.02	-1.29	-0.71
US Term Premium 10Y (TP US)	-0.65	-0.13	-2.96	1.11	1.39	1.39	-0.15	2.96
EA term premium 10Y (TP EA)	0.00	-0.15	0.44	-1.59	1.16	-0.82	0.97	1.59
US Risk Free 10Y Rate (RF 10Y US)	-1.09	0.03	2.17	1.84	-4.93	1.68	0.29	4.93
EA Risk Free 10Y Rate (RF 10Y EA)	-0.12	-0.61	1.14	-0.80	1.14	-1.72	0.98	1.72
Spot Exchange Rate (EUR/USD)	1.18	-0.13	0.53	0.23	0.35	-0.04	-2.13	2.13
sum	-0.50	-0.21	4.71	1.74	4.69	1.67	1.13	13.24
								sub-Index
to US	-	0.69	-	2.81	-	2.51	0.47	6.49
to EA	0.06	-	2.29	-	2.45	-	0.66	5.46
to FX	1.18	-0.13	0.53	0.23	0.35	-0.04	-	2.13

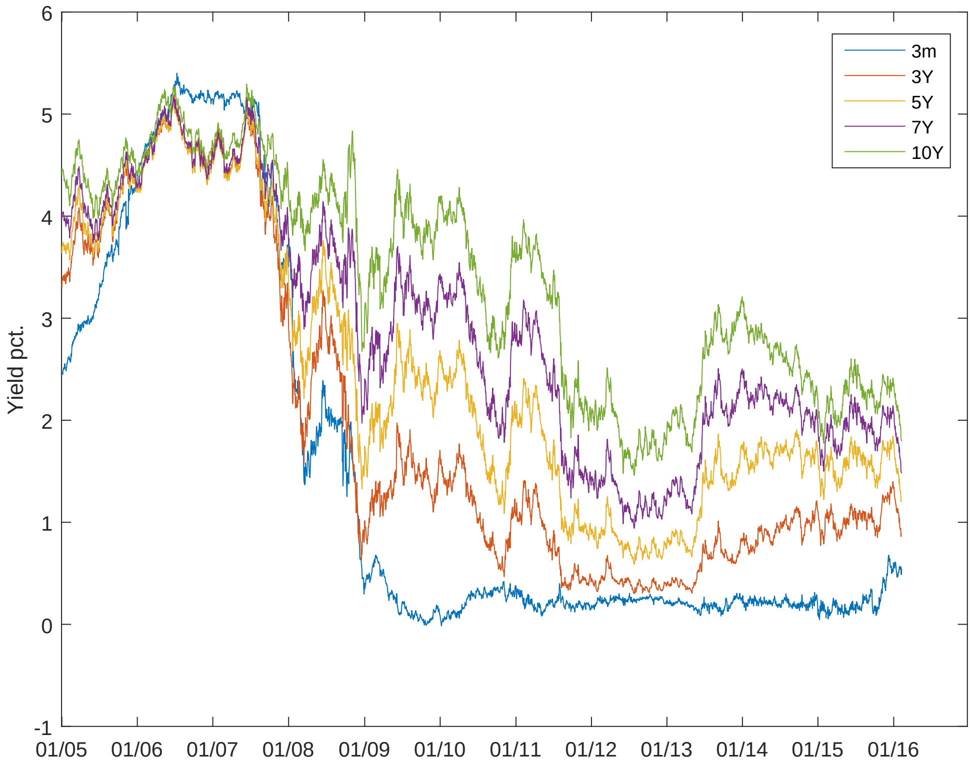
The table shows the percentage-point changes in the spillovers to each variable included in the VAR, from each of the other variables. Spillovers are calculated on the basis of the error variance decomposition in (25), and the reported indices follow from equations (26) and (27). Time series of the spillovers between the individual variables, and consequently the generated indices, are constructed by a rolling data window analysis, where a forecast error variance decomposition for a horizon of 10 days is calculated for sub-samples containing 250 daily observations. The first data point is generated for the data sample covering January 2005 to January 206, and each subsequent data point is found by rolling this 250 observation data-window forward by one day, and by repeating the estimation of the VAR model and the error variance decomposition, until the end of the data sample is reached. Changes to the individual variables are calculated as the last minus the first observation in the generated spillover time series. This is done for the individual variables as well as for the indices. The 'Overall' index is calculated as the sum of the off-diagonal elements of the forecast error variance at the horizon of 10 days. By summing the off-diagonal elements this index captures the total spillover between the variables included in the VAR model, i.e. the short rate, the 10Y term premium, the 10Y risk-free rate for the euro area and the US economies, and the EUR/USD spot exchange rate. Similarly, the sub-indices 'to US from EA' and 'to EA from US', show, respectively, the spillover to the US variables from EA variables and the exchange rate, and the spillover to the EA variables from the US variables and the exchange rate. These to sub-indices are calculated, as shown in (27), by summing over the relevant crosses of the forecast error variance matrix, at the horizon of 10 days. Each observation point of the shown indices is generated by calculating the forecast error variance decomposition for subsamples containing 250 daily observations, and by consecutively rolling the data sample forward, by one observation, until the end of the data sample is reached.

Table 2: Changes in spillovers from 2006 to 2016



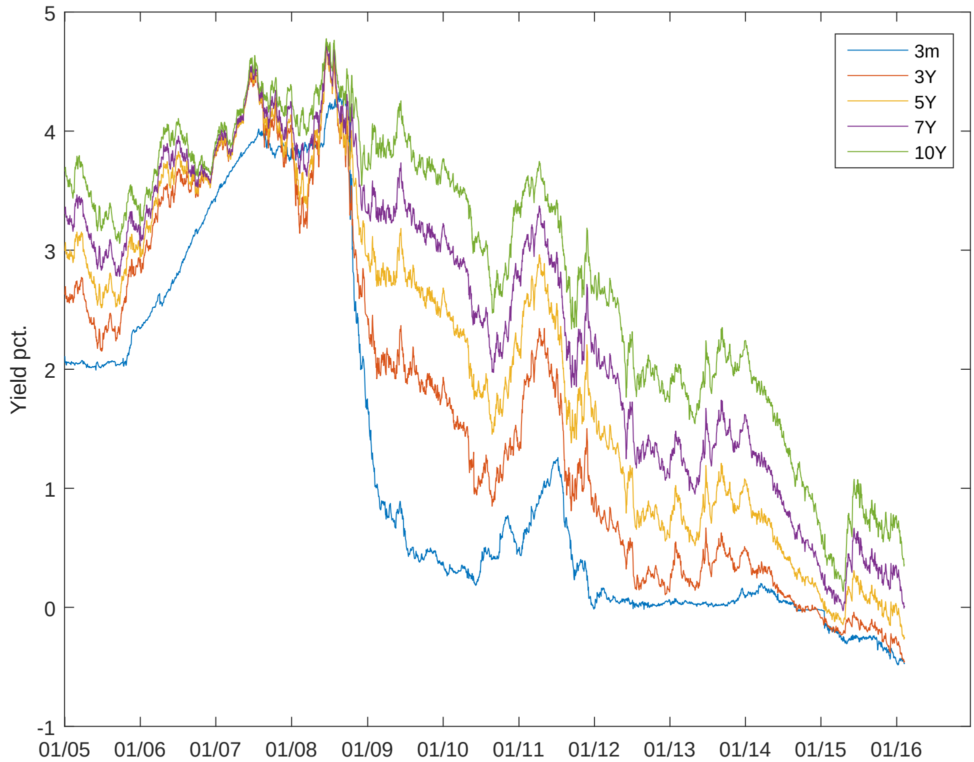
This figure compares the loading structure of an arbitrage free model with factors that can be interpreted as the short rate, the slope and the curvature to that of a rotated Dynamic Nelson-Siegel (rDNS) model having a similar factor interpretation. The free parameters are chosen as $\theta = 0.05$ and thus $\gamma = 0.95$ for illustrative purposes. It is noted that the autoregressive structure under $\mathbb{Q}$ dictates that $\gamma = 1 - \theta$. The left panel shows the loading structure of the arbitrage-free model, the middle panel shows the loading structure of the rDNS model; and the right panel shows the difference between the loading structure of the two model.

Figure 1: Loading Structures



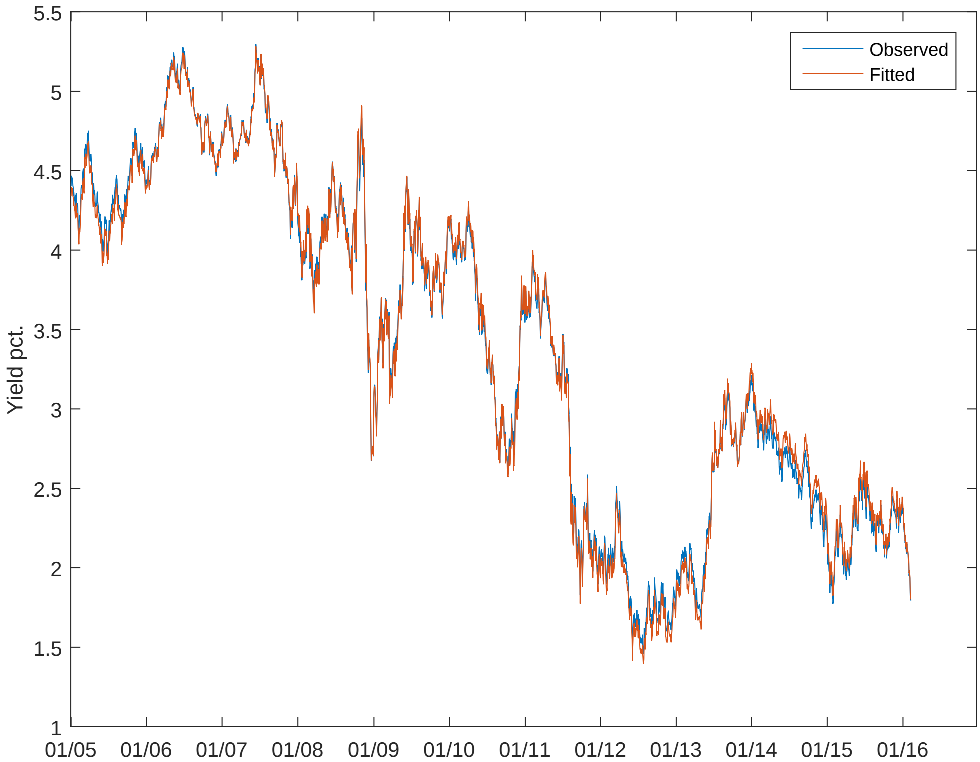
The figure shows the US zero-coupon yield curve data, for selected maturities. Data are observed daily and covers the period from January 2005 to February 2016.

Figure 2: US data



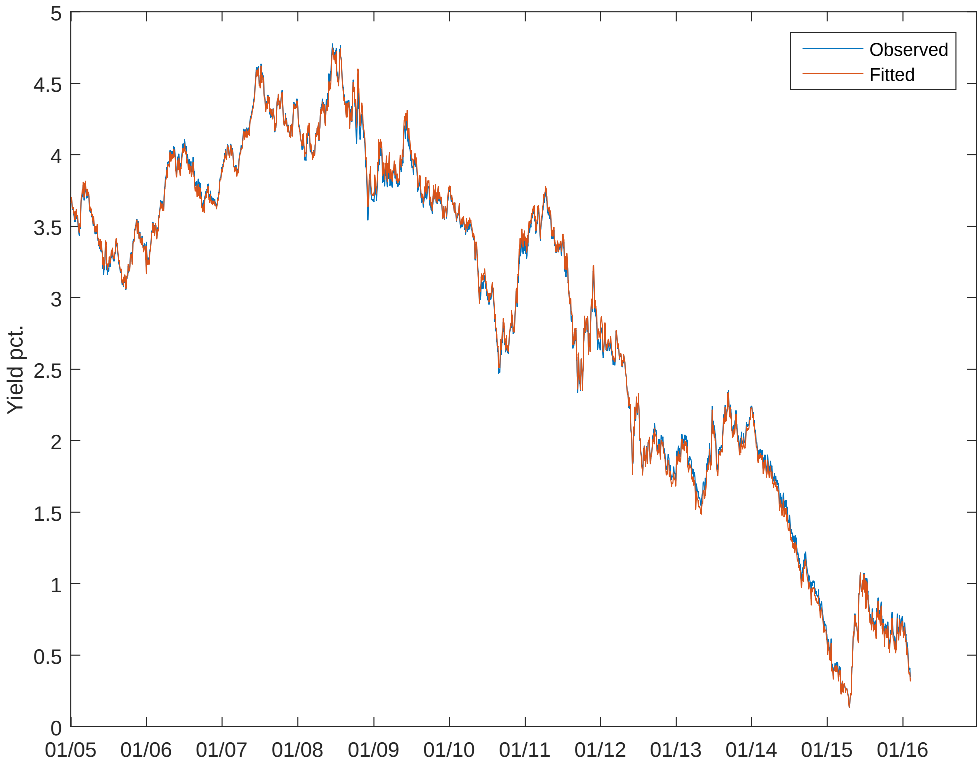
The figure shows the euro area zero-coupon yield curve data, for selected maturities. Data are observed daily and covers the period from January 2005 to February 2016.

Figure 3: Euro area data



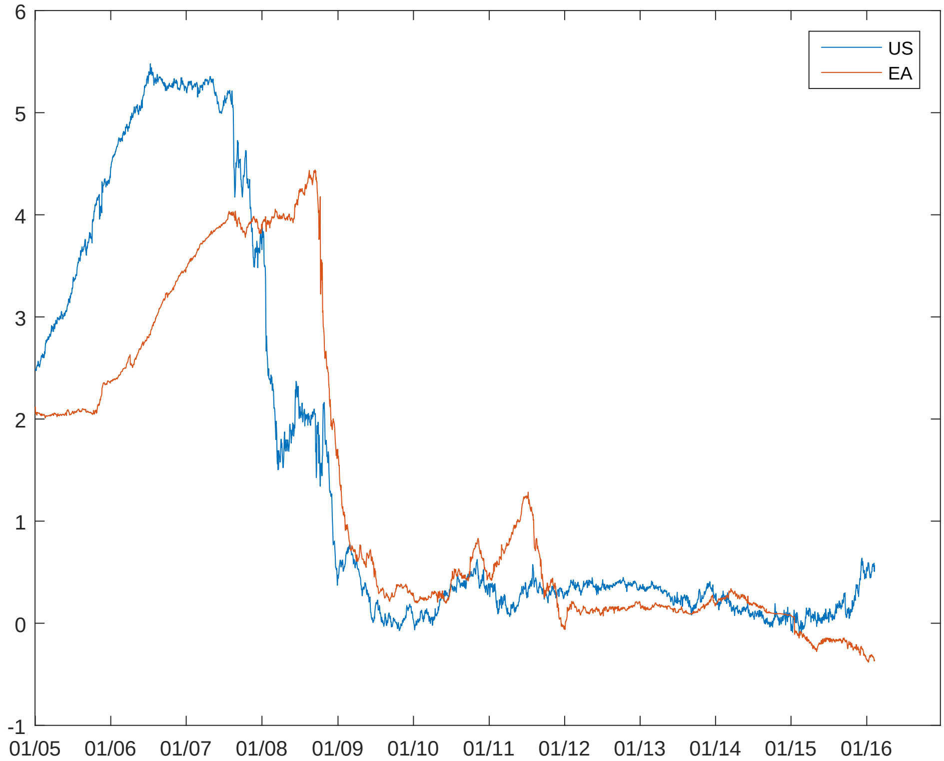
The figures compares the observed 10 year rate in the US with the 10 year rate that is produced by the fitted model (15).

Figure 4: US fit: 10Y segment



The figures compares the observed 10 year rate in the euro area with the 10 year rate that is produced by the fitted model (15).

Figure 5: Euro area fit: 10Y segment

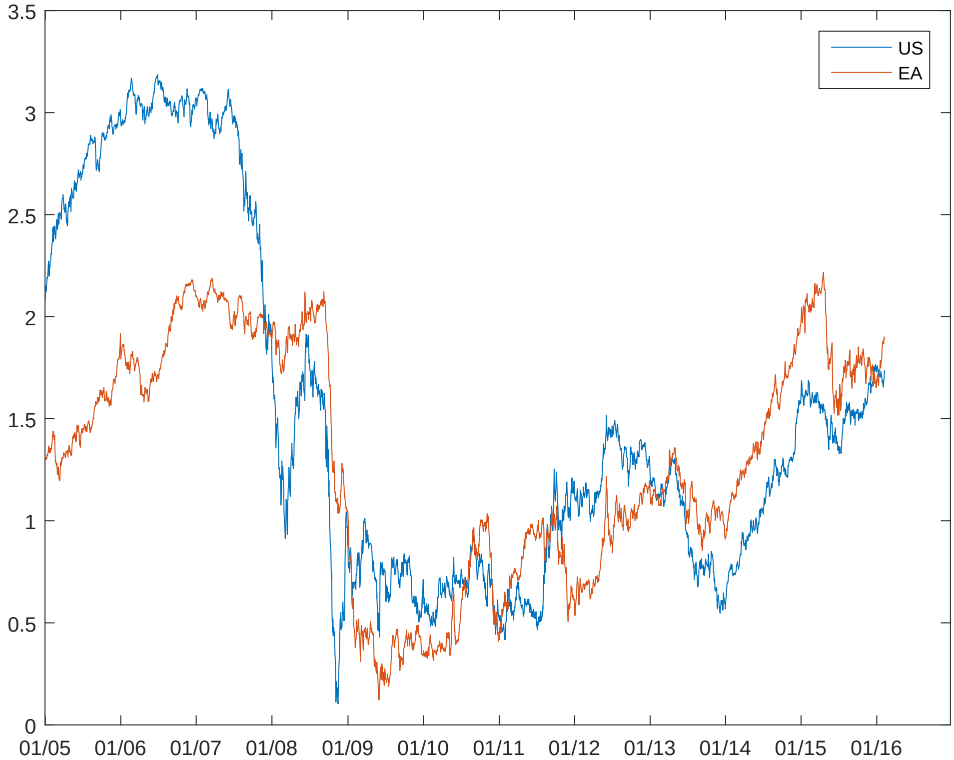


The figure shows the estimated short rates for the US and euro area economies calculated on the basis of (3). Data are observed daily and spans the period from January 2005 to February 2016. The yield curve model used to extract these metrics is described in section 2 of the paper.

Figure 6: Loading Structures

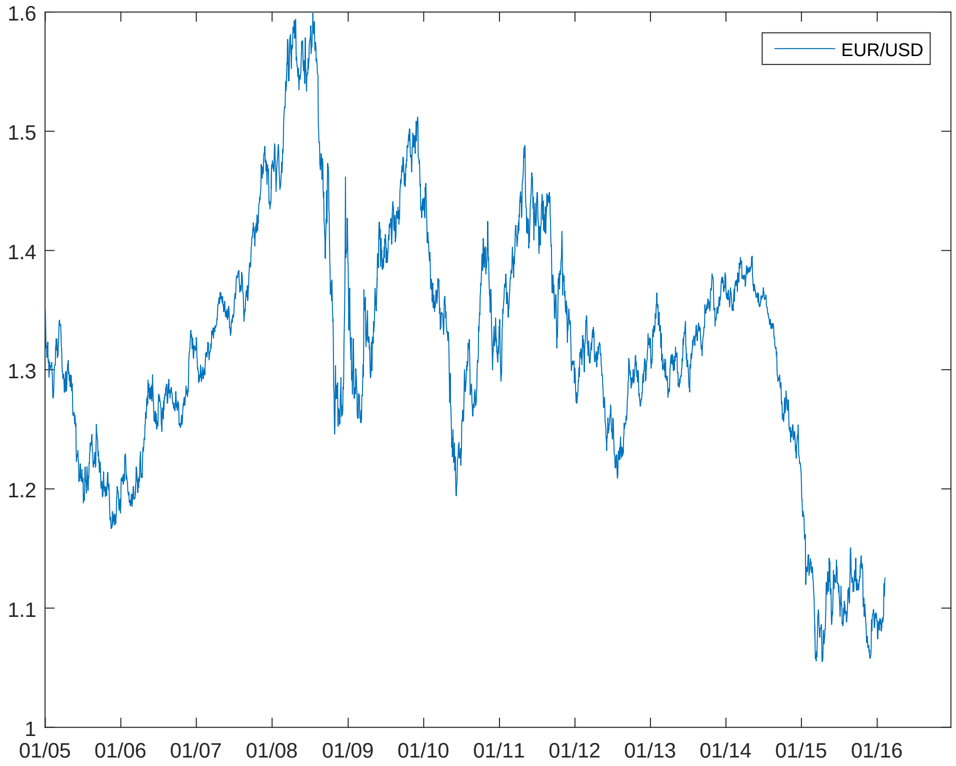
The figure shows the estimated 10Y term premia for the US and euro area economies calculated on the basis of (21). Data are observed daily and spans the period from January 2005 to February 2016. The yield curve model used to extract these metrics is described in section 2 of the paper.

Figure 7: 10 year term premia - US and EA



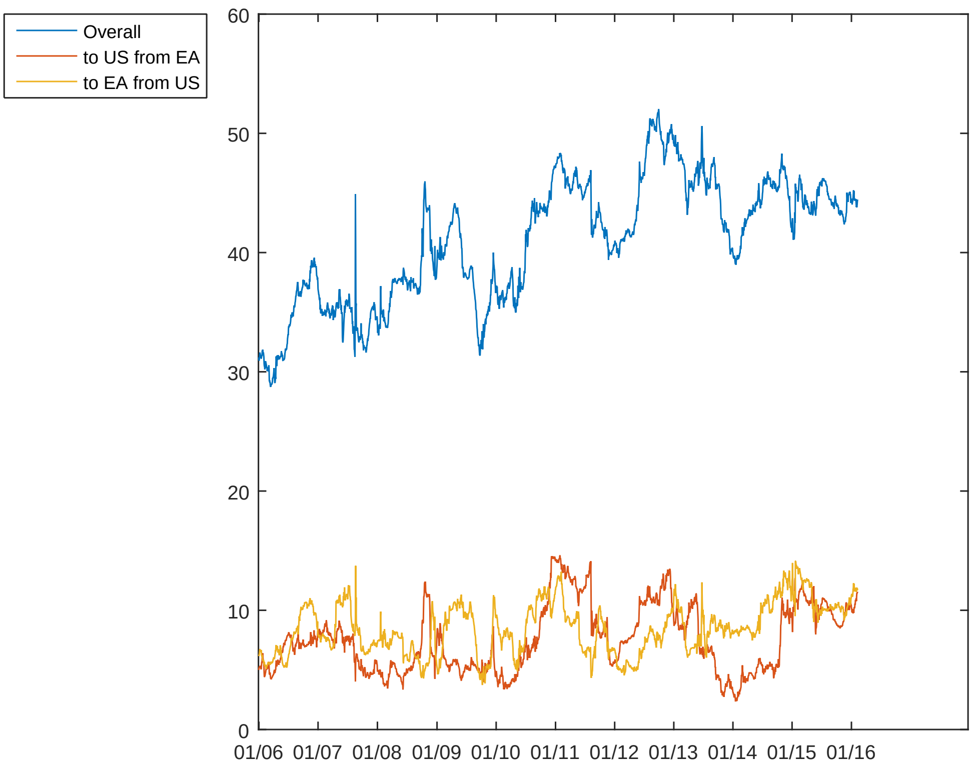
The figure shows the estimated 10Y risk-free rates for the US and euro area economies calculated on the basis of (20). Data are observed daily and spans the period from January 2005 to February 2016. The yield curve model used to extract these metrics is described in section 2 of the paper.

Figure 8: Risk-Free 10 year rates - US and EA



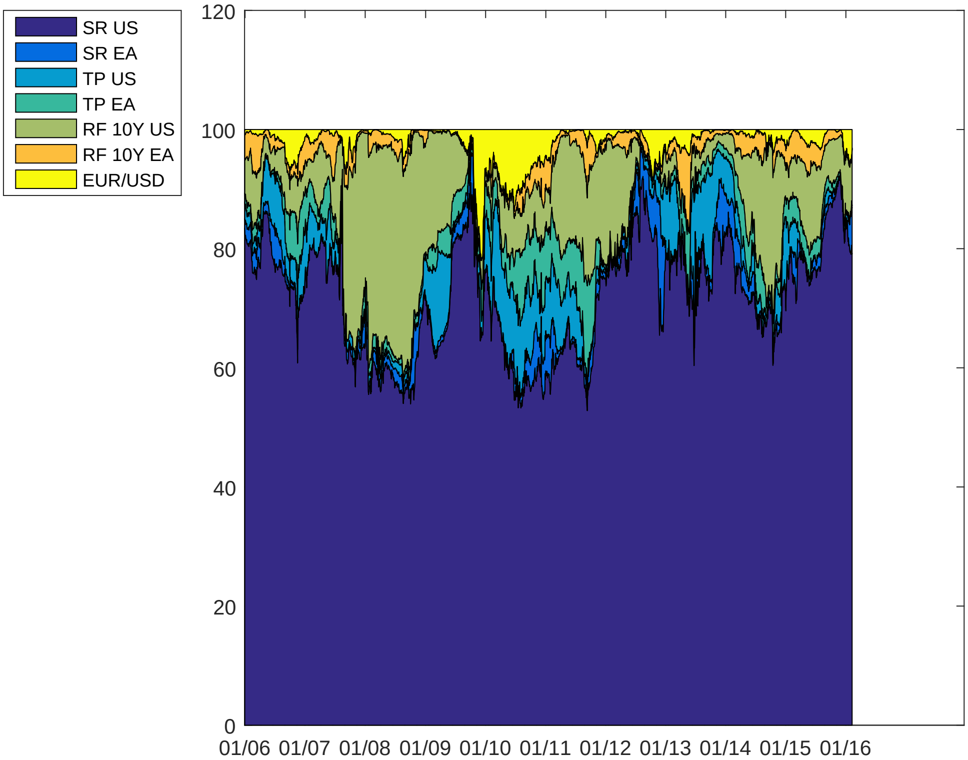
The figure shows the time series evolution of the spot EUR/USD exchange rate. Data are observed daily and spans the period from January 2005 to February 2016.

Figure 9: Spot Exchange Rate



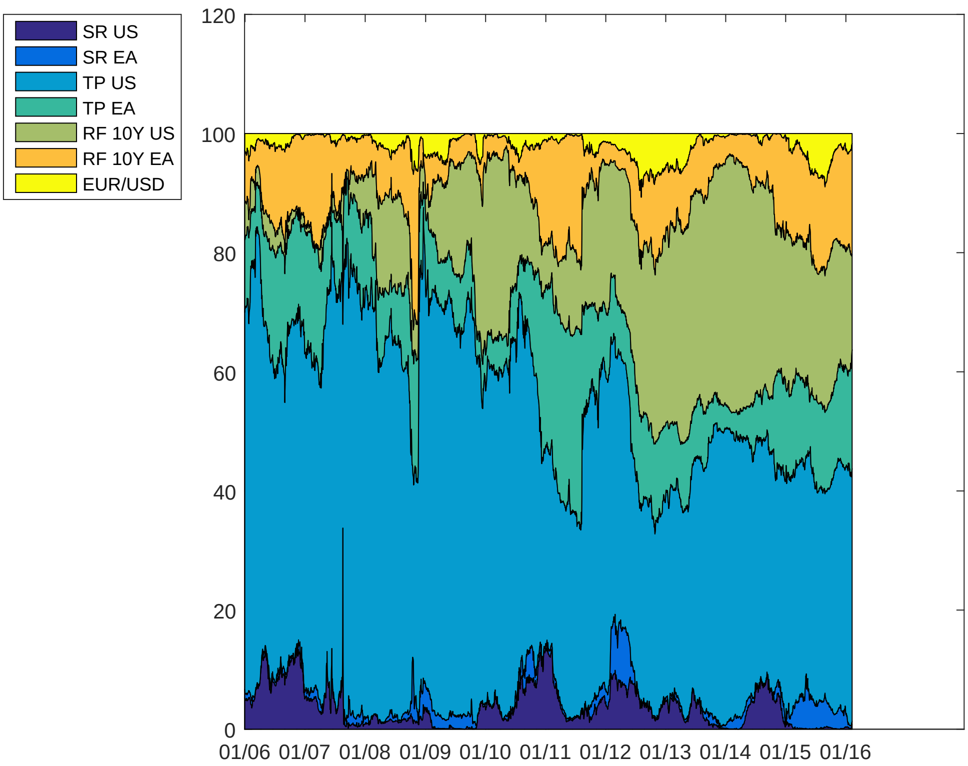
The figure shows the spillover indices calculated according to equations (26) and (27). The 'Overall' index is calculated as the sum of the off-diagonal elements of the forecast error variance at the horizon of 10 days. By summing the off-diagonal elements this index captures the total spillover between the variables included in the VAR model, i.e. the short rate, the 10Y term premium, the 10Y risk-free rate for the euro area and the US economies, and the EUR/USD spot exchange rate. Similarly, the sub-indices 'to US from EA' and 'to EA from US', show, respectively, the spillover to the US variables from EA variables and the exchange rate, and the spillover to the EA variables from the US variables and the exchange rate. These to sub-indices are calculated, as shown in (27), by summing over the relevant crosses of the forecast error variance matrix, at the horizon of 10 days. Each observation point of the shown indices is generated by calculating the forecast error variance decomposition for subsamples containing 250 daily observations, and by consecutively rolling the data sample forward, by one observation, until the end of the data sample is reached.

Figure 10: Spillover indices



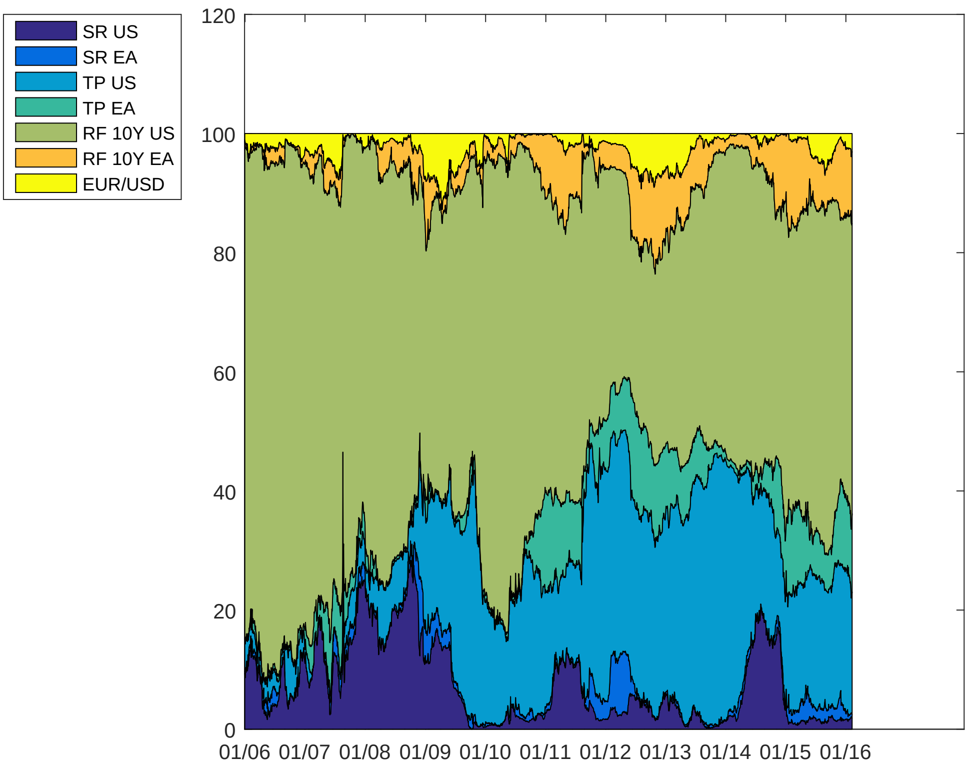
The figure shows the spillover the short rate, the 10Y term premium, the 10Y risk-free rate for the euro area and the US economies, and the EUR/USD spot exchange rate to the US short rate. Spillovers are defined following Diebold and Yilmaz (2009) but based on generalised error-variance decompositions. The variables included in the VAR model are derived from an arbitrage free term structure model, and the time series of spillovers shown the in figure are found by using a one-year window of data, i.e. 250 daily observations, for the estimation, which is then consecutively rolled forward by one observation until the end of the data sample is reached.

Figure 11: US Short Rate - spillover from others



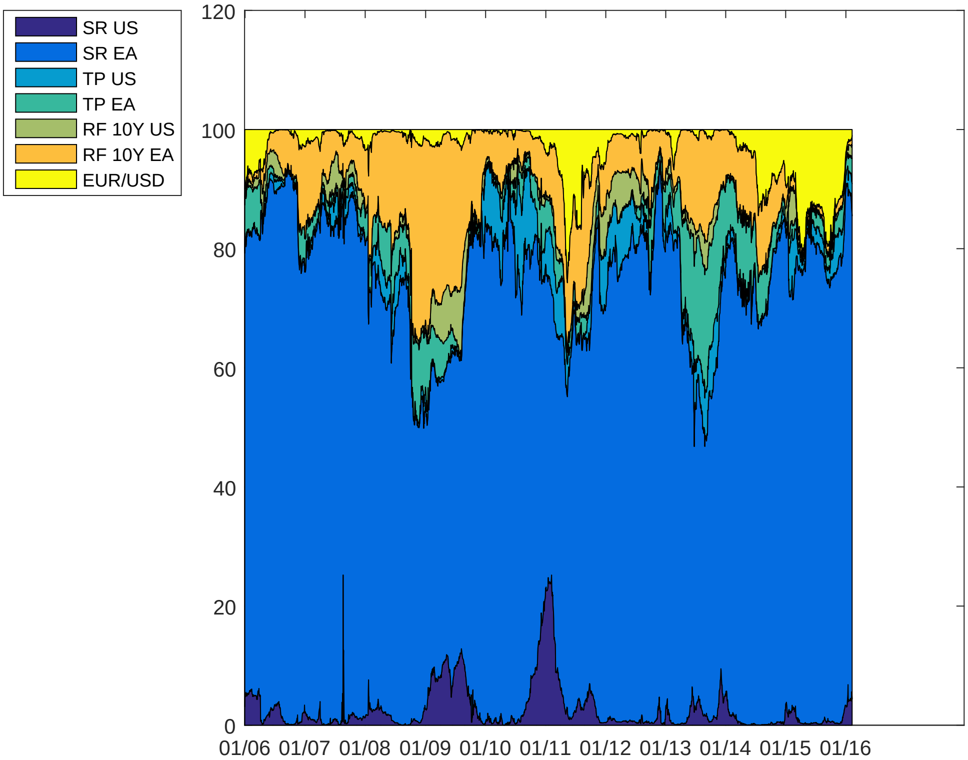
The figure shows the spillover the short rate, the 10Y term premium, the 10Y risk-free rate for the euro area and the US economies, and the EUR/USD spot exchange rate to the US 10Y term premium. Spillovers are defined following Diebold and Yilmaz (2009) but based on generalised error-variance decompositions. The variables included in the VAR model are derived from an arbitrage free term structure model, and the time series of spillovers shown the in figure are found by using a one-year window of data, i.e. 250 daily observations, for the estimation, which is then consecutively rolled forward by one observation until the end of the data sample is reached.

Figure 12: US 10Y Term Premium - spillover from others



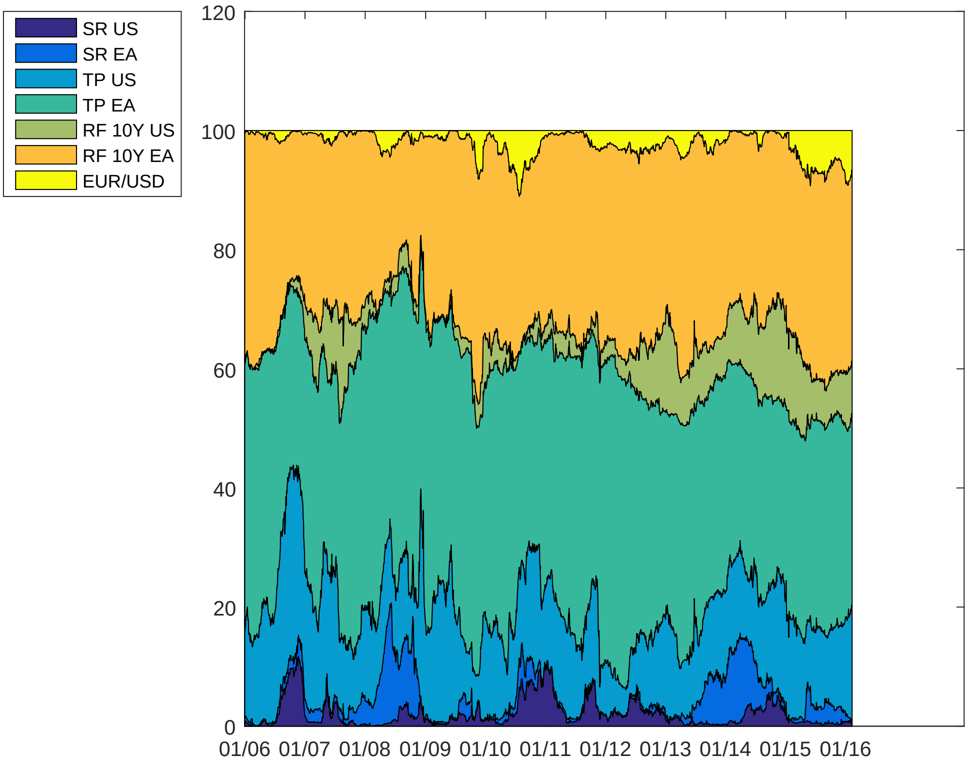
The figure shows the spillover the short rate, the 10Y term premium, the 10Y risk-free rate for the euro area and the US economies, and the EUR/USD spot exchange rate to the US risk free-rate. Spillovers are defined following Diebold and Yilmaz (2009) but based on generalised error-variance decompositions. The variables included in the VAR model are derived from an arbitrage free term structure model, and the time series of spillovers shown the in figure are found by using a one-year window of data, i.e. 250 daily observations, for the estimation, which is then consecutively rolled forward by one observation until the end of the data sample is reached.

Figure 13: US 10Y Risk-Free Rate - spillover from others



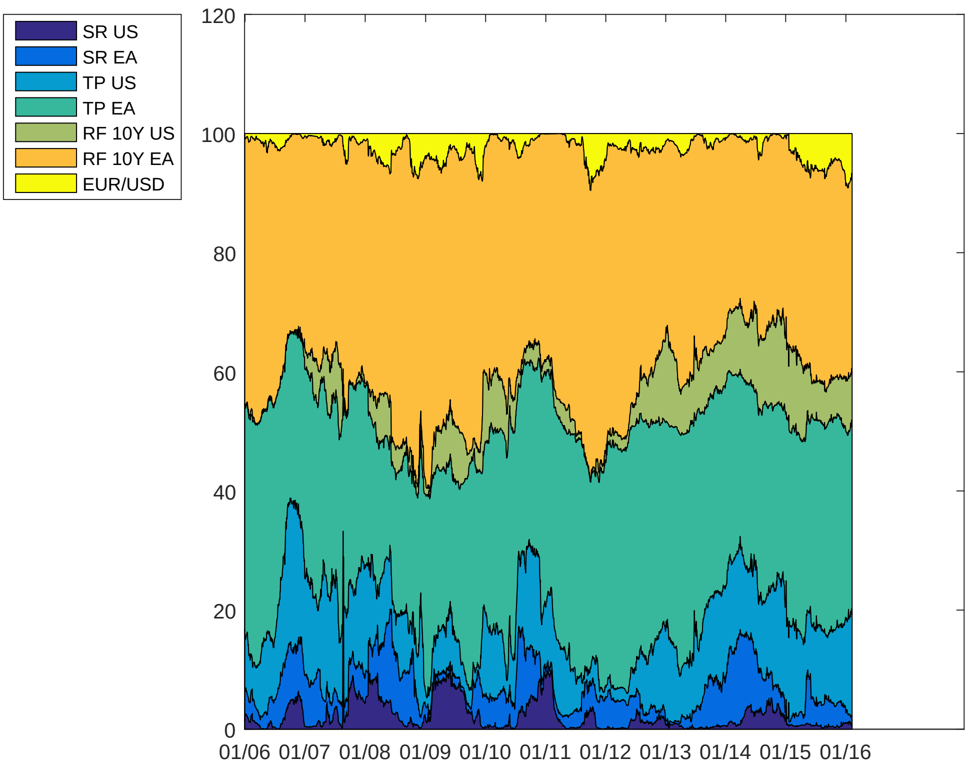
The figure shows the spillover the short rate, the 10Y term premium, the 10Y risk-free rate for the euro area and the US economies, and the EUR/USD spot exchange rate to the euro area short rate. Spillovers are defined following Diebold and Yilmaz (2009) but based on generalised error-variance decompositions. The variables included in the VAR model are derived from an arbitrage free term structure model, and the time series of spillovers shown the in figure are found by using a one-year window of data, i.e. 250 daily observations, for the estimation, which is then consecutively rolled forward by one observation until the end of the data sample is reached.

Figure 14: EA Short Rate - spillover from others



The figure shows the spillover the short rate, the 10Y term premium, the 10Y risk-free rate for the euro area and the US economies, and the EUR/USD spot exchange rate to the euro area 10Y term premium. Spillovers are defined following Diebold and Yilmaz (2009) but based on generalised error-variance decompositions. The variables included in the VAR model are derived from an arbitrage free term structure model, and the time series of spillovers shown the in figure are found by using a one-year window of data, i.e. 250 daily observations, for the estimation, which is then consecutively rolled forward by one observation until the end of the data sample is reached.

Figure 15: EA 10Y Term Premium - spillover from others



The figure shows the spillover the short rate, the 10Y term premium, the 10Y risk-free rate for the euro area and the US economies, and the EUR/USD spot exchange rate to the euro area risk-free rate. Spillovers are defined following Diebold and Yilmaz (2009) but based on generalised error-variance decompositions. The variables included in the VAR model are derived from an arbitrage free term structure model, and the time series of spillovers shown the in figure are found by using a one-year window of data, i.e. 250 daily observations, for the estimation, which is then consecutively rolled forward by one observation until the end of the data sample is reached.

Figure 16: EA 10Y Risk-Free Rate - spillover from others

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