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The response of euro area sovereign spreads
to the ECB unconventional monetary policies



Working Paper Research

by Hans Dewachter, Leonardo Iania, Jean-Charles Wijnandts

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The response of euro area sovereign spreads to the ECB unconventional monetary policies

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October 7, 2016

Abstract

We analyse variations in sovereign bond yields and spreads following unconventional monetary policy announcements by the European Central Bank. Using a two-country, arbitrage-free, shadow-rate dynamic term structure model (SR-DTSM), we decompose countries' yields into expectation and risk premium components. By means of an event study analysis, we show that the ECB's announcements reduced both the average expected instantaneous spread and risk repricing components of Italian and Spanish spreads. For countries such as Belgium and France, the ECB announcements impacted primarily the risk repricing component of the spread.

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1 Introduction

Since the onset of the financial crisis in 2007, the global economy has faced an unprecedented combination of adverse economic conditions and financial stress. The liquidity crisis of August 2007 triggered a series of events which turned into a global financial crisis within less than a year. Moreover, in the euro area, the financial crisis spread from financial institutions to sovereign states toward the end of 2009 and resulted in a sovereign debt crisis¹.

In response to these exceptional challenges, central banks around the globe implemented both standard and non-standard monetary policy measures. Standard policy measures consisted in lowering the reference policy rate to zero, while non-standard policy measures consisted in using novel balance sheet instruments as well as communication tools. In the US, starting from August 2007, the Federal Reserve tried to reduce the long-term interest rates (i) by lowering the target federal fund rate by 5.25 % in sixteen months, (ii) by introducing several large-scale asset purchase programmes (LSAPs) from November 2008 until October 2014 in order to reduce yields in several segments of the bond market and (iii) by making use of forward guidance to influence private sector expectations of future short rate path. In the euro area (EA), the European Central Bank (ECB) tried to ease money market distress and to reduce sovereign spreads mainly (i) by drastically lowering its main refinancing operation interest rate (MRO), (ii) by providing unprecedented amounts of liquidity support against a broader set of asset used as collateral, (iii) by using forward guidance and, more recently, (iv) by introducing quantitative easing in the form of the Asset Purchase Programme (APP).

In recent years, several studies have analysed the impact of the different types of non-conventional monetary policy programmes on yields of major developed countries. [Christensen and Rudebusch \(2012\)](#) use an event study approach to assess the impact of the U.S and U.K. quantitative easing programs on the sovereign yield curve. By adopting a dynamic term structure model (DTSM) to decompose long-term yields into an expected and a term

¹The sovereign debt crisis was characterized by (i) an increased divergence of sovereign yield in the euro area, as some countries were hit more than others by the crisis, and by (ii) the formation of the so-called “redenomination risk”, i.e. the possibility of the breakup of the euro area.

premium component, they find that quantitative easing programmes worked through the signalling channel in the U.S. and via the portfolio balance channel in the U.K. [Christensen and Rudebusch \(2016\)](#) revisit the impact of quantitative easing on long-term treasury yields using a shadow-rate DTSM to account for the zero lower bound (ZLB) on interest rate. Overall, when accounting properly for the ZLB, they find that a slightly larger part of the total reduction in ten-year Treasury bond yield could be attributed to the expectation (signalling) channel.

Regarding the euro area, a few papers tried to assess the impact of some specific unconventional monetary policy (UMP) programmes of the ECB. [Eser and Schwaab \(2016\)](#) use a time series panel data regression setting to assess the impact of the Securities Markets Programme (SMP) on five-year sovereign bond yields for Greece, Spain, Ireland, Italy, and Portugal. The authors regress daily yield variations on ECB's purchase data, observed covariates and announcement dummies. Their main findings are that the SMP had important effects on announcement days and also additional daily purchase effects over the duration of the programme. The main channels of transmission of the programme were concentrated on decreasing the liquidity risk premiums and default risk signalling effects². Finally, the authors document lower volatility on sovereign bond markets on intervention days.

[Altavilla et al. \(2015\)](#) analyse the effectiveness of the Asset Purchase Programme (APP) using a controlled event study accounting explicitly for macroeconomic news release. They find that although the programme was announced at a time of low financial market turmoil, the APP had important effects of lowering bond yields with an impact increasing with the maturity and riskiness of the bonds. Furthermore, the authors find that in addition to its direct effect on sovereign yields, the APP had also an impact on bank lending conditions.

To the best of our knowledge, the only paper trying to assess the impact of several UMP programmes in the euro area is [Krishnamurthy et al. \(2015\)](#) who analyse the impact and channels of transmission on sovereign yields of three ECB UMP programs (SMP, OMT and LTRO) in an event-study framework. The main contribution of their paper is to identify euro-wide

²By which the ECB sent signals to the market that the level of sovereign yields for distressed countries were too high compared to the country's fundamentals.

(expected short-rate and term premiums) and country-specific (default risk premium, redenomination risk premium and market segmentation) channels of transmission. They use US dollars sovereign bond spread³ to capture default risk and euro-denominated corporate bonds of large domestic companies to capture redenomination risk. The market segmentation component is then identified as a residual country-specific latent component. Using data on the period 2010-2012, the authors find that default risk and segmentation effects were the main channels of transmission of the SMP and OMT for Italy and Spain. The redenomination channel was of lesser importance for Spain and Portugal and did not seem to be an important channel of transmission in the case of Italy. LTRO mainly affected Spain through the segmentation channel⁴.

In this paper, we address a number of questions that have not been considered in other studies. First, we assess the impact of the lower-bound constraint on the decomposition of the EA risk-free bond yields into expected and term premium components. Comparing a linear and a shadow-rate term structure model, we show that the linear model produces excessively large negative term premia. Properly accounting for a lower bound on the interest rate is hence important for the identification of the expectation and term premium components. Second, we extend the shadow rate model to a two-market setting by jointly modelling the risk-free yield curve and a EA sovereign yield curve. We decompose sovereign yields variations into four components: (i) the expected component of the risk free curve, (ii) the term premium component of the risk free curve, (iii) the (country-specific) average expected instantaneous spread and (iv) the (country-specific) risk repricing component. Our main findings are that (i) for peripheral countries expected spreads reached more than 100 bp at the height of the crisis, (ii) expected spreads are absent for non peripheral countries and (iii) risk repricing is the most important component of spreads during the financial crisis. Third, we consider an event-study analysis of the impact of the different unconventional monetary policies studied in the literature⁵. We assess the difference in the

³With respect to the US dollar swap rate of corresponding maturity.

⁴The authors argue that the reason for this result is that Spanish banks bought up a larger share of outstanding sovereign debt in the month following the introduction of the program.

⁵Namely, the SMP, the OMT, three-year Longer-Term Refinancing Operations (VLTROs), Targeted Longer-Term Refinancing Operations (TLTROs), Forward Guidance

effects of the different UMP programs on the four aforementioned sovereign bond yields components for Italy, Spain, Belgium and France. Our main finding is that at the peak of the crisis, UMP announcements contribute to reduce on average the expected spreads by more than 20%. Fourth, we show that the different non-conventional monetary policy measures impacted differently on the expectation and risk premium components.

The remainder of the paper is organized as follows: Section 2 presents the data used in the analysis and the different UMP announcement dates considered. Section 3 introduces the models used in the empirical analysis to quantify the impact of using a shadow-rate model for the risk-free yield curve. Section 4 presents the results of the event-study analysis of risk-free and sovereign yields around UMP announcements and finally section 5 concludes.

2 Data and non conventional monetary policy announcements

2.1 Data

The estimation data cover the period from 7 January 2000 to 24 June 2016 at the weekly frequency (Friday, end-of-day data). Interest rates are extracted from Bloomberg. The maturities considered are 3 and 6 months and 1, 2, 3, 5, 7 and 10 years. The remainder of this section provides details on the OIS rates and sovereign bond yields.

The risk-free yield curve for the euro area is proxied by the Overnight Indexed Swap (OIS) rates. As noted in [Dubecq et al. \(2016\)](#), OIS interest rates are increasingly considered by market participants as the reference risk-free rates. Before 2005, quoted OIS rates on longer-than-one-year maturities are not available and we replace these missing values by EURIBOR swap rates of corresponding maturities. In addition, we adjust the EURIBOR swap rates at each maturity for the average EURIBOR-OIS spread for period 2005-2006⁶. We convert OIS and EURIBOR rates into continuously compounded rate

(FG) and Asset Purchase Programme (APP).

⁶Using this period, we exclude the liquidity crisis which occurred during the summer of 2007. Indeed, we observed a widening of the EURIBOR-OIS spread during this period due to heightened concerns about credit and liquidity risk.

is the methodology outlined in Appendix A.1. As noted in Renne (2016), swap yields are homogeneous to coupon-bond yields and we thus obtain zero-coupon OIS yields using classic bootstrapping methods⁷. Sovereign yield data for Belgium, France, Italy and Spain are obtained from the Bloomberg Fair Value Market Curve database and coupon-bonds are converted into zero-coupon bonds using classic bootstrapping methods.

2.2 Non-conventional monetary policy announcements

We present briefly the programmes that we consider in our analysis and the set of announcements. Table 7 in Appendix A.2 summarizes the announcement dates for the different programmes together with a small description of the events occurring on the announcement dates.

The first programme we consider is the Securities Markets Programme (SMP) whose aim was to fix liquidity problems in targeted euro area sovereign markets without influencing the monetary policy stance or the underlying market fundamentals⁸. The ECB introduced the SMP on 10 May 2010 and initially targeted Greek, Portuguese and Irish sovereign debt markets. On 8 August 2011, the SMP scope was extended to Spain and Italy. We will consider these two dates in our analysis. Note that the SMP was terminated on 6 September 2012 with the official launch of the Outright Monetary Transactions programme (OMT).

The second programme we consider is related to the different extensions of the conventional refinancing operations that we will group under the denomination of Longer-Term Refinancing Operations (LTROs). First, the 36-month LTROs which we will refer to as Very Long Term Operations (VLTROs) were introduced by the ECB to provide liquidity to the financial sector. They consist in an extension of conventional Main Refinancing Operations (with maturities up to 1 year) to fixed rate tender procedure with full allotment and a maturity of 36 months⁹. We follow Krishnamurthy et al. (2015) and consider two dates for the VLTROs: the official announcement on 8 December 2011 and the speech on 1 December 2011 of the then ECB Gov-

⁷OIS rates with maturities shorter than one year are already homogeneous to zero-coupon bonds and no further adjustment is needed.

⁸In order to ensure this last part, the ECB carried out weekly sterilization of SMP purchases over the whole duration of the programme.

⁹With an early reimbursement option after 1 year

ernor Draghi where he spoke to the European Parliament and said that “we are aware of the scarcity of eligible collateral” [for banks] and suggests that the “the most important thing for the ECB is to repair the credit channel.”. This speech was considered as a strong hint that the ECB was preparing a liquidity-providing plan for the euro area financial sector. In addition, Targeted Longer-Term Refinancing Operations (TLTROs) were introduced on 5 June 2014 with the double objective of easing the credit constraint of the financial sector and of stimulating bank lending to the real economy¹⁰. The borrowing period under this programme can go up to four years.

The third programme we consider is the OMT which was introduced in order to address the impairments in monetary policy transmission across the euro area and the tail-risk of seeing several distressed countries forced to exit the euro area. The program was introduced on 6 September 2012 (and first announced on 2 August 2012). The programme targets the short-term part of the yield curve for sovereign bonds (1- to 3-year government bonds) and the access to this programme is conditional on the implementation by the country requesting access of a fiscal adjustment programme. Note that to date no country requested the activation of the programme. We will however concentrate our analysis on the two announcement dates (launch on August 2 and additional technical details on September 6) related to the OMT programme and Mario Draghi’s ”London Speech” on 26 July 2012 that the ECB would do ”whatever it takes” to save the euro within the limits of its mandate.

The ECB introduced Forward Guidance (FG) measures on 4 July 2013 in order to provide additional monetary stimulus in a near lower-bound environment. FG provides transparent information about the likely reaction of the ECB to the evolution of macroeconomic aggregates and anchors market expectations of future short-rate interest rates on a path consistent with the ECB’s mandate of price stability over the medium term. We consider the following three announcements in our analysis: i) On 4 July 2013 the Governing Council expects the key ECB interest rates to remain at present or lower levels for *an extended period of time* . ii) On 9 January 2014 the Governing Council strongly emphasises that it will maintain an accommodative stance

¹⁰To this end, borrowing limits for a given financial institution are tied to the total outstanding loans to the non-financial European private sector. Besides, the interest rate to be applied to refinancing operations is linked to the participating banks’ lending patterns.

of monetary policy *for as long as necessary* and it firmly reiterates its FG. iii) On 6 March 2014 the outlook of medium-term price and growth evolution fully confirms the decision to *maintain an accommodative monetary policy stance for as long as necessary*.

The last programme we analyse is the Asset Purchase Programme (APP). The main goals of the programme are to maintain the monetary policy transmission mechanism in a period in which interest rates are near their lower bound and to stimulate credit provision to the real economy by providing liquidity to the banking sector in exchange for the securities purchased under the programme. The APP is composed of four sub-programmes targeting different types of securities which we detail below. Those programmes are the asset-backed securities purchase programme (ABSPP) and the third covered bonds purchase programme (CBPP3) which were both announced on 2 October 2014. The public sector purchase programme (PSPP) which was announced on 22 January 2015 targets the purchase of securities issued by euro area governments, agencies and EU institutions. Finally, the corporate sector purchase programme (CSPP) was announced on 10 March 2016 and focus on outright purchases of investment-grade euro-denominated bonds issued by non-bank corporations established in the euro area¹¹. These sub-programmes amount jointly to €80 billion monthly purchases on average¹². As pointed in [Altavilla et al. \(2015\)](#), the APP was anticipated by market participants as early as August 2014 and focusing solely on the official announcement dates could underestimate the overall impact of the APP. We add three additional events concerning communications by Mario Draghi where he alluded to the implementation of a quantitative easing programme for the euro area¹³.

¹¹Note that while both the CSPP and the second round of the TLTROs were announced on 10 March 2016, we will focus on the CSPP announcement for this date assuming that markets attributed relatively more importance to this programme announcement.

¹²For the period from March 2015 until March 2016, this monthly purchases average was €60 billion.

¹³Details on the additional announcements considered are provided in [Appendix A.2](#).

3 Dynamic Term structure models and estimation

3.1 Modelling of the *risk-free* yield curve

3.1.1 The Arbitrage-Free Nelson-Siegel term structure model

Here we present the baseline assumptions for the Affine Term Structure Model (ATSM) and the additional restrictions imposed to obtain the Arbitrage-Free Nelson-Siegel (AFNS) model introduced in [Christensen et al. \(2011\)](#). The risk-free short rate, r_t^{rf} , is modelled as an affine function of a set of n risk factors, \mathbf{x}_t^{rf} :

$$r_t^{rf} = \rho_0^{rf} + \boldsymbol{\rho}_1^{rf\top} \mathbf{x}_t^{rf} \quad (1)$$

The state dynamics of the risk factors \mathbf{x}_t^{rf} under the risk-neutral \mathbb{Q} -measure solve the following SDEs :

$$d\mathbf{x}_t^{rf} = \boldsymbol{\kappa}_{rf}^{\mathbb{Q}} \left(\boldsymbol{\theta}_{rf}^{\mathbb{Q}} - \mathbf{x}_t^{rf} \right) dt + \boldsymbol{\sigma}_{rf} d\mathbf{w}_t^{rf,\mathbb{Q}} \quad (2)$$

where $\boldsymbol{\sigma}_{rf}$ is lower triangular and $\mathbf{w}_t^{rf,\mathbb{Q}}$ is a standard Brownian motion in \mathbb{R}^n . In this setting, [Duffie and Kan \(1996\)](#) show that the period t yield of a maturity τ zero-coupon bond is an affine function of the risk factors:

$$\begin{aligned} y_t^{rf}(\tau) &= -\frac{1}{\tau} \log \mathbb{E}^{\mathbb{Q}} \left[e^{-\int_t^{t+\tau} r_v^{rf} dv} \right] \\ &= -\frac{1}{\tau} a^{rf}(\tau) - \frac{1}{\tau} \mathbf{b}^{rf}(\tau)^\top \mathbf{x}_t^{rf} \end{aligned} \quad (3)$$

where $a^{rf}(\tau)$ and $\mathbf{b}^{rf}(\tau)$ solve the following system of ODEs :

$$\begin{aligned} \frac{da^{rf}(\tau)}{d\tau} &= -\boldsymbol{\rho}_0^{rf} + \mathbf{b}^{rf}(\tau)^\top \boldsymbol{\kappa}_{rf}^{\mathbb{Q}} \boldsymbol{\theta}_{rf}^{\mathbb{Q}} \\ &\quad + \frac{1}{2} tr \left(\boldsymbol{\sigma}_{rf}^\top \mathbf{b}^{rf}(\tau) \mathbf{b}^{rf}(\tau)^\top \boldsymbol{\sigma}_{rf} \right), \quad a^{rf}(0) = 0 \end{aligned} \quad (4)$$

$$\frac{d\mathbf{b}^{rf}(\tau)}{d\tau} = -\boldsymbol{\rho}_1^{rf} - \boldsymbol{\kappa}_{rf}^{\mathbb{Q}\top} \mathbf{b}^{rf}(\tau), \quad \mathbf{b}^{rf}(0) = 0 \quad (5)$$

Furthermore, assuming that the market price of risk γ_t is of the essentially affine form introduced in [Duffee \(2002\)](#) (see equation (6)), the dynamics under the historical probability measure \mathbb{P} of the risk factors follow a multivariate Ornstein-Uhlenbeck process¹⁴ :

$$\gamma_t = \gamma_0 + \gamma_1 \mathbf{x}_t^{rf} \quad (6)$$

$$d\mathbf{x}_t^{rf} = \boldsymbol{\kappa}_{rf}^{\mathbb{P}} (\boldsymbol{\theta}_{rf}^{\mathbb{P}} - \mathbf{x}_t^{\mathbb{P}}) dt + \boldsymbol{\sigma}_{rf} d\mathbf{w}_t^{rf, \mathbb{P}} \quad (7)$$

where $\mathbf{w}_t^{rf, \mathbb{P}}$ is a standard Brownian motion under \mathbb{P} . In the rest of our analysis, Following [Christensen et al. \(2011\)](#), we restrict $\boldsymbol{\sigma}_{rf}$ to be diagonal¹⁵ and we impose the restrictions stated in proposition 1 in [Christensen et al. \(2011\)](#) to obtain the model-implied Arbitrage-Free Nelson-Siegel yield function¹⁶:

$$\begin{aligned} y_t^{rf}(\tau) &= -\frac{1}{\tau} a^{rf}(\tau) - \frac{1}{\tau} \mathbf{b}^{rf}(\tau)^\top \mathbf{x}_t^{rf} = A^{rf}(\tau) + \mathbf{B}^{rf}(\tau)^\top \mathbf{x}_t^{rf} \\ &= A^{rf}(\tau) + x_{l,t}^{rf} + \frac{1 - e^{-\tau \kappa_{rf}^{\mathbb{Q}}}}{\tau \kappa_{rf}^{\mathbb{Q}}} x_{s,t}^{rf} + \left[\frac{1 - e^{-\tau \kappa_{rf}^{\mathbb{Q}}}}{\tau \kappa_{rf}^{\mathbb{Q}}} - e^{-\tau \kappa_{rf}^{\mathbb{Q}}} \right] x_{c,t}^{rf} \quad (8) \end{aligned}$$

By virtue of these additional restrictions, the risk factor loadings in $\mathbf{B}^{rf}(\tau)$ now correspond respectively to level, slope and curvature. If we set the market price of risk to zero in equation (6) we see that the system of ODEs (4)-(5) boils down to:

¹⁴Here, we use Girsanov's theorem and the change of measure $d\mathbf{w}_t^{rf, \mathbb{Q}} = d\mathbf{w}_t^{rf, \mathbb{P}} + \gamma_t dt$. Substituting this expression into equation (2) we see that the parameters under the two equivalent measures are linked via:

$$\begin{aligned} \boldsymbol{\kappa}_{rf}^{\mathbb{Q}} &= \boldsymbol{\kappa}_{rf}^{\mathbb{P}} + \boldsymbol{\sigma}_{rf} \gamma_1 \\ \boldsymbol{\kappa}_{rf}^{\mathbb{Q}} \boldsymbol{\theta}_{rf}^{\mathbb{Q}} &= \boldsymbol{\kappa}_{rf}^{\mathbb{P}} \boldsymbol{\theta}_{rf}^{\mathbb{P}} - \boldsymbol{\sigma}_{rf} \gamma_0 \end{aligned}$$

¹⁵[Christensen et al. \(2011\)](#) find that models estimated with unrestricted lower-triangular covariance matrix lead to in-sample overfitting and inferior out-of-sample forecasting performance.

¹⁶We summarize these restrictions in Appendix B.1 for clarity.

$$\begin{aligned}\frac{da^{ec}(\tau)}{d\tau} &= \mathbf{b}^{ec}(\tau)^\top \boldsymbol{\kappa}_{rf}^{\mathbb{P}} \boldsymbol{\theta}_{rf}^{\mathbb{P}} + \frac{1}{2} \text{tr} \left(\boldsymbol{\sigma}_{rf}^\top \mathbf{b}^{ec}(\tau) \mathbf{b}^{ec}(\tau)^\top \boldsymbol{\sigma}_{rf} \right), \quad a^{ec}(0) = 0 \\ \frac{d\mathbf{b}^{ec}(\tau)}{d\tau} &= -\boldsymbol{\rho}_1^{rf} - \boldsymbol{\kappa}_{rf}^{\mathbb{P}} \mathbf{b}^{ec}(\tau), \quad \mathbf{b}^{ec}(0) = 0\end{aligned}$$

We can thus define the expected component of the risk-free rate at maturity τ as the risk-free bond yield that would prevail if the compensation required for being exposed to risk factors was zero:

$$ec_t^{rf}(\tau) = -\frac{1}{\tau} \left(a^{ec}(\tau) + \mathbf{b}^{ec}(\tau)^\top \mathbf{x}_t^{rf} \right) \quad (9)$$

The term premium component of the risk-free rate is then given by the difference between the model-implied risk-free yield at maturity τ and the corresponding expected component:

$$tp_t^{rf}(\tau) = y_t^{rf}(\tau) - ec_t^{rf}(\tau) \quad (10)$$

The difference between the model-implied yield and the expected component for a given maturity is determined by the risk premiums γ_t defined in equation (6).

Since the AFNS model leaves the specification of the mean reversion matrix under the historical dynamics $\boldsymbol{\kappa}_{rf}^{\mathbb{P}}$ unrestricted, we follow [Christensen and Rudebusch \(2012\)](#) and carry out a general-to-specific model selection in which we sequentially remove the least significant parameter of $\boldsymbol{\kappa}_{rf}^{\mathbb{P}}$ until we reach the most parsimonious specification (diagonal $\boldsymbol{\kappa}_{rf}^{\mathbb{P}}$). The estimation of the model is done by maximum likelihood and the Kalman filter algorithm is used to evaluate the log-likelihood in the optimization procedure¹⁷. The estimation period considered is from January 2000 until end of June 2016. The range of maturities for OIS bond yields is from three months to ten years. For each specification of the mean reversion matrix $\boldsymbol{\kappa}_{rf}^{\mathbb{P}}$, we save the value of the log-likelihood at the optimum together with the associated Akaike and Bayesian information criteria. Table 1 below reports the summary statistics for our model selection process. The final specification is chosen based on the optimal value of the Bayesian Information Criteria (BIC).

¹⁷Details on the estimation procedure are outlined in Appendix [B.1.1](#)

Table 1: Evaluation of alternative specifications of the affine AFNS model for OIS yields.

Alternative specifications	LogL	k	AIC	BIC
(1) Full $\kappa_{rf}^{\mathbb{P}}$	40598,04	17	-81162,08	-81081,20
(2) $\kappa_{32}^{\mathbb{P}} = 0$	40598,04	16	-81164,08	-81087,95
(3) $\kappa_{31}^{\mathbb{P}} = \kappa_{32}^{\mathbb{P}} = 0$	40598,03	15	-81166,06	-81094,69
(4) $\kappa_{13}^{\mathbb{P}} = \dots = \kappa_{32}^{\mathbb{P}} = 0$	40595,89	14	-81163,78	-81097,17
(5) $\kappa_{12}^{\mathbb{P}} = \dots = \kappa_{32}^{\mathbb{P}} = 0$	40584,61	13	-81143,22	-81081,37
(6) $\kappa_{21}^{\mathbb{P}} = \dots = \kappa_{32}^{\mathbb{P}} = 0$	40573,19	12	-81122,38	-81065,28
(7) Diagonal $\kappa_{rf}^{\mathbb{P}}$	40563,86	11	-81105,71	-81053,37

Estimation period is January 2000 until June 2016 (weekly observations). We consider maturities 3-m, 6m, 1y, 2y, 3y, 5y, 7y and 10y. For each specification, we report the Log-likelihood at the optimum (LogL), the number of parameters for the given specification (k) and the Akaike and Bayesian Information Criteria for each specification (optimal value for each criteria is indicated in bold).

The model specification minimizing the Bayesian Information Criteria is:

Table 2: Parameter estimates for the preferred AFNS specification of the OIS yield curve model

	$\kappa_{.,1}^{\mathbb{P}}$	$\kappa_{.,2}^{\mathbb{P}}$	$\kappa_{.,3}^{\mathbb{P}}$	$\theta_i^{\mathbb{P}}$	σ_i
$\kappa_{1,.}^{\mathbb{P}}$	-0,1255 (0,1076)	-0,3105 (0,1116)		0,0416 (0,0206)	0,0037 (0,0001)
$\kappa_{2,.}^{\mathbb{P}}$	0,4607 (0,1841)	0,6331 (0,1935)	-0,6443 (0,1165)	-0,0139 (0,0122)	0,0054 (0,0001)
$\kappa_{3,.}^{\mathbb{P}}$			0,6204 (0,3127)	-0,0172 (0,0065)	0,0179 (0,0005)
$\kappa_{rf}^{\mathbb{Q}}$:	0,4735 (0,0024)	Loglike:	40595,89	BIC:	-81097,17

Note: Standard errors are reported between parenthesis below the corresponding parameter estimate.

3.1.2 The shadow-rate term structure model

Several recent papers demonstrate the necessity of accounting appropriately for lower-bound constraints on interest rate in order to capture key features of the term structure of bond yields both in-sample and out-of-sample (see inter alia [Kim and Singleton \(2012\)](#), [Andreasen and Meldrum \(2014\)](#) or [Christensen and Rudebusch \(2015\)](#)). While different types of models can account for lower-bound constraints on interest rates¹⁸, we use the structure of the shadow-rate AFNS (SR-AFNS) model of [Christensen and Rudebusch \(2016\)](#). This model is based on the option-based approximation of [Krippner \(2012\)](#) to solve for the non-linear yield representation. The reason for this choice is that the SR-AFNS offers tractability in estimation due to its proximity to its Gaussian affine counterpart while exhibiting superior in-sample and out-of-sample fit of the term structure of bond yields in a lower-bound environment compared to affine models¹⁹.

The shadow rate has dynamics similar to the short rate in the equation (26):

$$r_t^{rf} = x_{t,t}^{rf} + x_{s,t}^{rf}$$

The new feature introduced is that the lower-bound-constrained short rate is now given by the maximum between the shadow rate and the lower bound:

$$r_t^{rf} = \max(r_t^{rf}, r_t^{lb}), \quad r_t^{lb} = \min(r_t^d, 0) \quad (11)$$

where r_t^d is the time-varying lower bound determined by the monetary authority²⁰. We now introduce the option-based approximation of lower-bound constrained yields derived in [Krippner \(2012\)](#) for the general Gaussian case and applied to the AFNS framework in [Christensen and Rudebusch \(2015\)](#). [Krippner \(2012\)](#) derives the following generic formula for the lower-bound constrained instantaneous forward rate in the Gaussian affine framework²¹:

¹⁸ We mention the Gaussian quadratic term structure models, the square-root processes, the shadow-rate model based on [Black \(1995\)](#), the AutoRegressive Gamma (ARG) zero processes of [Monfort et al. \(2015\)](#) or the linear-rational term structure models of [Filipovic et al. \(2016\)](#).

¹⁹As documented in [Christensen and Rudebusch \(2016\)](#)

²⁰In our empirical application, the lower bound will be given by the marginal deposit rate of the ECB when this rate falls below zero (see (11)).

²¹Here we provide a slightly more general version in which the lower bound can be different from zero.

$$\begin{aligned} \underline{f}_t^{rf}(\tau) &= r_t^{lb} + (f_t^{rf}(\tau) - r_t^{lb}) \Phi \left(\frac{f_t^{rf}(\tau) - r_t^{lb}}{\omega_t(\tau)} \right) \\ &+ \omega_t(\tau) \frac{1}{\sqrt{2\pi}} \exp \left(-\frac{1}{2} \left[\frac{f_t^{rf}(\tau) - r_t^{lb}}{\omega_t(\tau)} \right]^2 \right) \end{aligned} \quad (12)$$

Where $f_t^{rf}(\tau)$ is the shadow-rate instantaneous forward rate and $\omega_t(\tau)$ is related to the conditional variance of the shadow bond European call option²². The zero-coupon bond yields representation, consistent with the existence of a lower-bound constraint is:

$$\underline{y}_t^{rf}(\tau) = \frac{1}{\tau} \int_0^\tau \underline{f}_t^{rf}(v) dv \quad (13)$$

An interesting feature of the option-based approximation for empirical implementation is that it only requires solving a one-dimensional integral over the maturity to obtain the LB-constrained zero-coupon yield²³. The decomposition of zero-coupon yields into expected and term premium components must be adjusted to account for the lower-bound constraint. We follow [Christensen and Rudebusch \(2016\)](#) and define the expected component of the LB-constrained risk-free rate at maturity τ in the following way:

$$\underline{ec}_t^{rf}(\tau) = \frac{1}{\tau} \int_t^{t+\tau} \mathbb{E}_t^{\mathbb{P}} [r_v] dv \quad (14)$$

where the conditional expectation of the LB-constrained short rate under the \mathbb{P} dynamics is given by:

$$\begin{aligned} \mathbb{E}_t^{\mathbb{P}} [r_v] &= r_t^{lb} + (\mathbb{E}_t^{\mathbb{P}} [r_v] - r_t^{lb}) \Phi \left(\frac{(\mathbb{E}_t^{\mathbb{P}} [r_v] - r_t^{lb})}{\sqrt{\mathbb{V}^{\mathbb{P}} [r_v]}} \right) \\ &+ \sqrt{\mathbb{V}^{\mathbb{P}} [r_v]} \frac{1}{\sqrt{2\pi}} \exp \left(-\frac{1}{2} \left[\frac{(\mathbb{E}_t^{\mathbb{P}} [r_v] - r_t^{lb})}{\sqrt{\mathbb{V}^{\mathbb{P}} [r_v]}} \right]^2 \right) \end{aligned} \quad (15)$$

²²See appendix B.2 for details on the derivation

²³In our empirical implementation of the SR-AFNS we will compute the integral in equation (13) using rectangular/mid-ordinate integration rule with constant increments.

where $\mathbb{E}_t^{\mathbb{P}} [r_v]$ and $\mathbb{V}^{\mathbb{P}} [r_v]$ are respectively the conditional mean and conditional variance of the shadow rate²⁴. Finally, the term premium component for the risk-free zero-coupon bond yield at maturity τ is obtained in the usual way:

$$\underline{t}p_t^{rf}(\tau) = \underline{y}_t^{rf}(\tau) - \underline{e}c_t^{rf}(\tau) \quad (16)$$

We follow [Christensen and Rudebusch \(2016\)](#) and estimate the shadow-rate version of the affine specification selected in section 3.1.1. The intuition for this approach is that when interest rates are far from their lower bound, the shadow-rate model collapses to its affine counterpart. Table 3 below reports the parameter estimates for the SR-AFNS together with standard errors reported between brackets below the corresponding parameter estimate:

Table 3: Parameter estimates for the preferred SR-AFNS specification of the OIS yield curve model

	$\kappa_{\cdot,1}^{\mathbb{P}}$	$\kappa_{\cdot,2}^{\mathbb{P}}$	$\kappa_{\cdot,3}^{\mathbb{P}}$	$\theta_i^{\mathbb{P}}$	σ_i
$\kappa_{1,\cdot}^{\mathbb{P}}$	-0,0759 (0,1002)	-0,3369 (0,1475)		0,0368 (0,0073)	0,0050 (0,0002)
$\kappa_{2,\cdot}^{\mathbb{P}}$	0,5278 (0,2953)	0,7677 (0,4272)	-0,5904 (0,1724)	-0,0105 (0,0084)	0,0090 (0,0002)
$\kappa_{3,\cdot}^{\mathbb{P}}$			0,1192 (0,1419)	-0,0172 (0,0174)	0,0185 (0,0005)
κ^{ois} :	0,5541 (0,0030)	Loglike:	41296,71	BIC:	-82498,81

Note: Standard errors are reported between parenthesis below the corresponding parameter estimate.

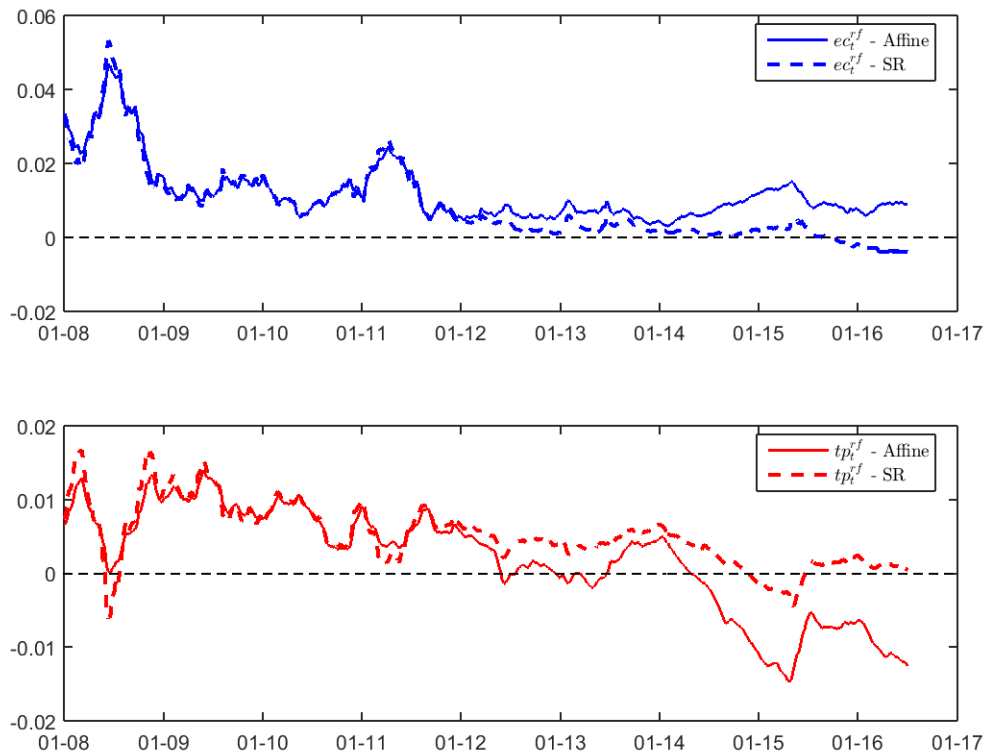
As documented in [Kim and Singleton \(2012\)](#), shadow-rate models tend to produce risk premium estimates which are economically more plausible than the ones produced by their affine counterparts. In particular, the authors provide evidence using Japanese yield data that term premiums derived from affine DTSM tend to be too volatile and take implausibly large negative values during episodes of low interest rate level. Term premiums derived from shadow-rate models on the other hand tend to take near-zero values during periods where the level of interest rate is low. We confirm these observations

²⁴Details on their computations are provided in appendix B.2.

for EA yields by comparing in Figure 1 the expected components derived from the affine and shadow-rate specifications (top panel) and the term premium components derived from the respective models (bottom panel) for the five-year OIS bond yield.

Focusing first on the top panel of Figure 1, we see that the introduction of the lower bound in the SR-AFNS and the increased persistence of the historical dynamics associated with it lead to expectations of the short rate at the five-year horizon remaining closer to the lower bound compared to the affine specification. Turning to the bottom panel, our results confirm the analysis in [Kim and Singleton \(2012\)](#) with the term premium from the shadow-rate model staying close to zero during the lower-bound period while the term premium from the affine model drops progressively to large negative values after 2014 with substantially larger volatility in its variations compared to the shadow-rate case.

Figure 1: Comparison of decomposition for 5-year OIS bond yield into expected component (ec_t^{rf}) and term premium component (tp_t^{rf}). The top panel compares the expected components from the affine (solid line) and shadow-rate model (dotted line) and the bottom panel compares the corresponding term premium components



Our analysis of the impact of the lower-bound constraint on interest rates and their associated risk premium features justifies the use of the shadow-rate specification in our empirical analysis since it tends to deliver expectations of the short rate and term premiums which are economically more meaningful compared to the affine DTSM.

3.2 Modelling of the country-specific sovereign yield curves

For the modelling of country yield curve, we follow [Christensen et al. \(2014\)](#) and add two sovereign risk factors modeling modelling the spread between the instantaneous sovereign yield and the instantaneous risk-free rate. The short rate for country i is given by:

$$r_t^i = r_t^{rf} + s_t^i \quad (17)$$

where s_t^i is the instantaneous sovereign spread of country i over the risk-free short rate²⁵. The instantaneous spread is affine in the risk factors:

$$\begin{aligned} s_t^i &= \rho_0^i + \boldsymbol{\rho}_1^{i\top} \tilde{\mathbf{x}}_t^i \\ &= \rho_l^i x_{l,t}^{rf} + \rho_s^i x_{s,t}^{rf} + x_{l,t}^i + x_{s,t}^i \end{aligned} \quad (18)$$

where we restrict ρ_0^i to be zero and we define $\tilde{\mathbf{x}}_t^i = [\mathbf{x}_t^{rf\top} \ \mathbf{x}_t^{i\top}]^\top$ to be the relevant set of risk factors for country i .

The joint state dynamics of the risk-free risk factors and of the country-specific factors \mathbf{x}_t^i under the historical \mathbb{P} -measure solve the following SDEs:

$$d \begin{pmatrix} \mathbf{x}_t^{rf} \\ \mathbf{x}_t^i \end{pmatrix} = \begin{pmatrix} \boldsymbol{\kappa}_{rf}^{\mathbb{P}} & \mathbf{0} \\ \boldsymbol{\kappa}_{rf \rightarrow i}^{\mathbb{P}} & \boldsymbol{\kappa}_i^{\mathbb{P}} \end{pmatrix} \left[\begin{pmatrix} \boldsymbol{\theta}_{rf}^{\mathbb{P}} \\ \boldsymbol{\theta}_i^{\mathbb{P}} \end{pmatrix} - \begin{pmatrix} \mathbf{x}_t^{rf} \\ \mathbf{x}_t^i \end{pmatrix} \right] dt + \begin{bmatrix} \boldsymbol{\sigma}_{rf} & \mathbf{0} \\ \mathbf{0} & \boldsymbol{\sigma}_i \end{bmatrix} \begin{bmatrix} d\mathbf{w}_t^{rf,\mathbb{P}} \\ d\mathbf{w}_t^{i,\mathbb{P}} \end{bmatrix}$$

where $\mathbf{w}_t^{i,\mathbb{P}}$ is a standard Brownian motion under \mathbb{P} and $\boldsymbol{\sigma}_i$ is also restricted to be diagonal. Here we impose the restriction of no feedback effect of the country-specific risk factors on the risk-free factors (i.e. $\boldsymbol{\kappa}_{i \rightarrow rf}^{\mathbb{P}} = \mathbf{0}$) which can be intuitively justified by the fact that the risk factors common to all countries (the risk-free factors) only react to their own past values and not to past values of country-specific risk factors²⁶.

We can write the system above in a more compact form:

$$d\tilde{\mathbf{x}}_t^i = \tilde{\boldsymbol{\kappa}}_i^{\mathbb{P}} (\tilde{\boldsymbol{\theta}}_i^{\mathbb{P}} - \tilde{\mathbf{x}}_t^i) dt + \tilde{\boldsymbol{\sigma}}_i^{\mathbb{P}} d\tilde{\mathbf{w}}_t^{i,\mathbb{P}} \quad (19)$$

²⁵Note that we implicitly work here under the Recovery of Market Value (RMV) framework of [Duffie and Singleton \(1999\)](#) in which $s_t = (1 - \pi_t^{\mathbb{Q}})\lambda_t^{\mathbb{Q}}$ with $\pi_t^{\mathbb{Q}}$ being the recovery rate and $\lambda_t^{\mathbb{Q}}$ the default intensity. We focus on the product of the two processes, the instantaneous sovereign spread, for identification purpose.

²⁶In addition, this modelling assumption will also guarantee that the dynamics of the risk-free factors are the same for all the country models estimated.

Following steps similar to the risk-free case, we can write the maturity τ zero-coupon bond yield for country i as the sum of the risk-free bond yield and country i zero-coupon sovereign yield spread at maturity τ , $s_t^i(\tau)$, which is also affine in the risk factors given our Gaussian affine setting:

$$\begin{aligned} y_t^i(\tau) &= y_t^{rf}(\tau) + s_t^i(\tau) \\ s_t^i(\tau) &= A_s^i(\tau) + \mathbf{B}_s^i(\tau)^\top \tilde{\mathbf{x}}_t^i \end{aligned}$$

where the expression for $A_s^i(\tau)$ is provided in appendix B.3 and country i sovereign yield spread loadings $\mathbf{B}_s^i(\tau)$ are also of the Nelson-Siegel type:

$$\begin{aligned} s_t^i(\tau) &= A_s^i(\tau) + \rho_l^i x_{l,t}^{rf} + \rho_s^i \frac{1 - e^{-\tau \kappa_{rf}^{\mathbb{Q}}}}{\kappa_{rf}^{\mathbb{Q}} \tau} x_{s,t}^{rf} \\ &+ \rho_s^i \left[\frac{1 - e^{-\tau \kappa_{rf}^{\mathbb{Q}}}}{\kappa_{rf}^{\mathbb{Q}} \tau} - e^{-\tau \kappa_{rf}^{\mathbb{Q}}} \right] x_{c,t}^{rf} + x_{l,t}^i + \frac{1 - e^{-\kappa_i^{\mathbb{Q}} \tau}}{\kappa_i^{\mathbb{Q}} \tau} x_{s,t}^i \end{aligned} \quad (20)$$

In the same spirit as the decomposition of zero-coupon risk-free bond yields into an expected component and a term premium component (see equations (9)-(10)), we can decompose the zero-coupon sovereign spread of country i with maturity τ into the expected evolution of the instantaneous spread over τ and a risk compensation related to the fact that the realized future short term spread might be different from the expected one. We label the first term average expected instantaneous spread or expected spread for short ($es_t^{spr}(\tau)$). The term capturing the risk compensation required by investors in order to compensate them for variations in sovereign default losses over their investment horizon is called the repricing of risk ($rr_t^{spr}(\tau)$). Note that this decomposition of yield spreads into a risk premium component and another component respecting the expectation hypothesis is reminiscent of Pan and Singleton (2008) and Dubecq et al. (2016) among others.

The average expected instantaneous spread at horizon τ , $es_t^{spr}(\tau)$ will be computed as follows:

$$es_t^{spr}(\tau) = -\frac{1}{\tau} (a^{es}(\tau) + \mathbf{b}^{es}(\tau)^\top \tilde{\mathbf{x}}_t^i) \quad (21)$$

where the derivation of $a^{es}(\tau)$ and $\mathbf{b}^{es}(\tau)$ is similar to the one for the expected component of the risk-free rate (see Appendix C.1). The component pertaining to investors' risk aversion for future changes in sovereign default losses over their investment horizon will be labelled repricing of risk and it will be computed as the difference between model implied zero-coupon sovereign yield spread and the expected spread of corresponding maturity:

$$rr_t^{spr}(\tau) = s_t^i(\tau) - es_t^{spr}(\tau) \quad (22)$$

When the risk-free yield curve is modeled with a shadow-rate specification, we assume that the specification of the short spread in equation (18) is still valid with the risk-free risk factors being now the shadow-rate factors. We further assume that the maturity τ zero-coupon bond yield for country i given by the sum of the risk-free bond yield respecting the lower-bound constraint and country i zero-coupon sovereign yield spread at maturity τ , $s_t^i(\tau)$, which is given in equation (20):

$$\underline{y}_t^i(\tau) = \underline{y}_t^{rf}(\tau) + s_t^i(\tau) \quad (23)$$

4 Results

We now turn to the analysis of the impact of UMP announcements on risk-free and sovereign bond yields and the channels of transmission of these programmes. The design of our event-study is close to the approach of [Christensen and Rudebusch \(2012\)](#) in which they compute the decomposition of US and UK risk-free bond yields into short-rate expectations and term premiums both prior to the announcement date and after the announcement date²⁷. Assuming that all the effects of the analysed programmes took place on announcement date, the channel of transmission of the UMP announcements is then assessed by looking at the variations of the respective channels around announcement time. We will consider four channels of transmission in our analysis: i) the expected component of the risk-free yield curve (ec_t^{rf}), ii) the term premium component of the risk-free yield curve (tp_t^{rf}), iii) the average expected instantaneous spread for the sovereign yield spread (es_t^{spr})

²⁷Using a one-day window around announcement dates.

and iv) the repricing of risk for the sovereign yield spread (rr_t^{spr}).

We make a small adjustment to the timing of the event study compared to [Christensen and Rudebusch \(2012\)](#) by using weekly data and considering the variation from the Friday preceding the announcement date to the Friday directly following the announcement ²⁸. In the rest of this section we analyse the impact of UMP announcements on the risk-free OIS yield curve and on the sovereign bond yields of Italy, Spain, Belgium and France. In order to keep the presentation of the results as streamlined as possible, we focus on the impact on 5-year maturity yields in the analyses of the results²⁹.

4.1 OIS yield curve

Table 4 shows the variations of five-year OIS yield around UMP announcements. If we first consider actual variations, we see that the largest decrease in five-year OIS bond yields occurred around the SMP announcements (-23 basis points). Actual variations around other programme announcements, on the other hand, were rather negligible in size. In fact, Table 8 in appendix C.1 confirms that almost all of the 23 basis point reduction in five-year OIS yields occurred around the second announcement of the SMP programme extending its application to Italy and Spain. A likely explanation for this result is that the euro area reached a peak in its business cycle in the third quarter of 2011 before slipping into a recession phase which lasted until the first quarter of 2013 according to the CEPR EA Business Cycle dating committee³⁰. The inversion of the short end (up to two-year maturity) of the yield curve that occurred during the second semester of 2011 and the strong declining pattern in 5-year OIS yields which can be observed with the solid black line in Figure 2 below tend to confirm that markets were factoring in concerns about the medium-term outlook of economic activity in the euro

²⁸Most of the announcements we analyse take place during the ECB's press conferences on Thursdays. The window considered for those announcements is thus 4 days before the announcement and 1 day after the announcement. There are only 4 exceptions: the two SMP announcements took place on Mondays and two of the APP announcements (08/22/14 and 11/21/14) took place on Fridays. See table 7 in appendix A.2 for further details.

²⁹Our arbitrage-free approach allows us to draw term structure implication of the different programmes

³⁰See the CEPR Euro Area Business Cycle Dating Committee Announcement at: <http://cepr.org/content/euro-area-business-cycle-dating-committee-announcements>

area. An important concern about the analysis presented so far is that we did not control for the fact that the ECB also announced policy rate cuts on the same announcement dates as some of the UMP announcements. The announcement dates concerned are the official VLTRO announcement (-25 bps), the announcement of the first TLTRO (-10 bps) and the official announcement of the ABSPP and CBPP3 (-5 bps). Table 8 in appendix C.1 shows that the actual variations in OIS 5-year yield on those dates were rather small or even positive for the TLTRO announcement. We conclude that our results are unlikely to be contaminated by announcement dates on which the ECB jointly announced policy rate cuts and UMP programmes.

Prog	Affine			SR		
	Actu	Δec_t^{rf}	$\Delta tp_t^{rf}(\tau)$	Actu	$\Delta \underline{ec}_t^{rf}$	$\Delta \underline{tp}_t^{rf}(\tau)$
SMP	-23	-37	14	-23	-36	13
LTRO	5	-17	19	5	-18	19
OMT	3	-11	16	3	-9	14
FG	-6	3	-4	-6	0	-1
APP	4	24	-22	4	1	-7

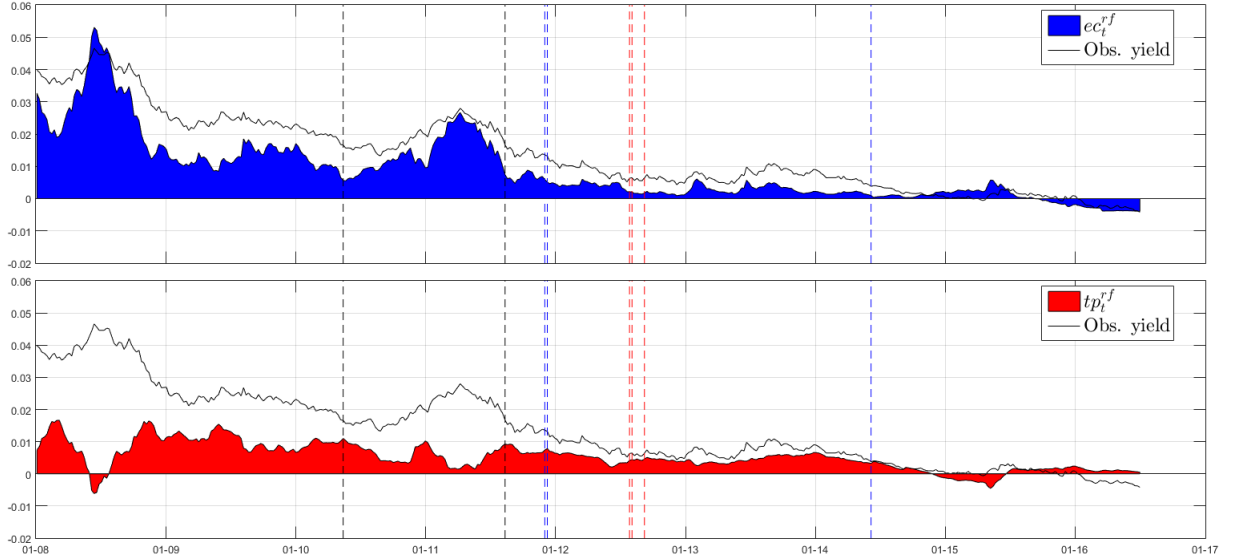
Table 4: Cumulative weekly variations in $ec_t^{rf}(\tau)$ and $tp_t^{rf}(\tau)$ components for 5-y OIS yields around announcements (in basis points)

We now turn to a more specific analysis of the different programme announcements with a focus on the differences introduced by accounting for the lower bound on interest rates. We first observe that the decompositions based on respectively the affine and shadow-rate models tend to produce very similar results when the lower bound is not binding. Indeed, the interest rate for ECB’s main refinancing operations (MRO) was set below 25 basis points only in June 2014³¹. After this date, we notice important differences for the APP programme between the two decompositions. The affine decomposition gives overall variations in the expected and term premium components which are of the same magnitude (in absolute terms) as the ones obtained for the SMP while the actual variations around APP announcements are several orders of magnitude smaller in absolute terms compared to the cor-

³¹At a value of 15 basis points to be precise. The deposit facility rate was also set below zero at -10 basis points for the first time at that date.

responding actual SMP variations. In other words, the decomposition based on the affine model attributes the small actual yield variations observed during the lower-bound period to large offsetting variations in both expected and term premium components. This result tends to confirm the graphical evidence in Figure 1 where we compared the decompositions from the affine and shadow-rate models. Starting in 2014, the respective expected short rate and term premium components start to diverge. The decomposition from the shadow-rate model seem economically more plausible with a five-year expected component staying closer to the lower bound and a term premium component taking values close to zero. Looking more closely at the contribution of the expected and term premium components to the evolution of the five-year OIS bond yield, we see in Figure 2 that most of the variations in OIS yields can be attributed to the expectation component. Furthermore, we notice that since the inception of the Public Sector Purchase Programme in January 2015 the expectation component of five-year OIS yields turned negative and reached the effective lower bound of -40 basis points towards the end of the studied sample. The term premium component also decreased noticeably over the period 2014-2015. Going back to the cumulative effect on the term premium component of the Forward Guidance and APP programmes (both taking place over this period) reported in Table 4, we can conjecture that the UMP programmes played a non-negligible role in the decrease recorded for the term premium component over this period.

Figure 2: Impact of UMPs on each component of 5-year OIS yield for the shadow-rate model (UMPs in dotted lines: SMP = black, (T)LTROs = blue and OMT = red)



Before leaving this section, we want to draw the attention of the reader to the fact that we will only consider the results from the shadow-rate model in the rest of the analysis. Furthermore, we will focus on the average expected instantaneous spread component and the repricing of risk component of countries' yields since we extensively analysed the expected and term premium components in this section.

4.2 Country analysis

In this section we focus on assessing the impact of UMP announcements on sovereign bond yields and the channels of transmission of these programmes. To help with the clarity of the exposition, we will group countries by pairs: Italy and Spain on the one hand and Belgium and France on the other hand.

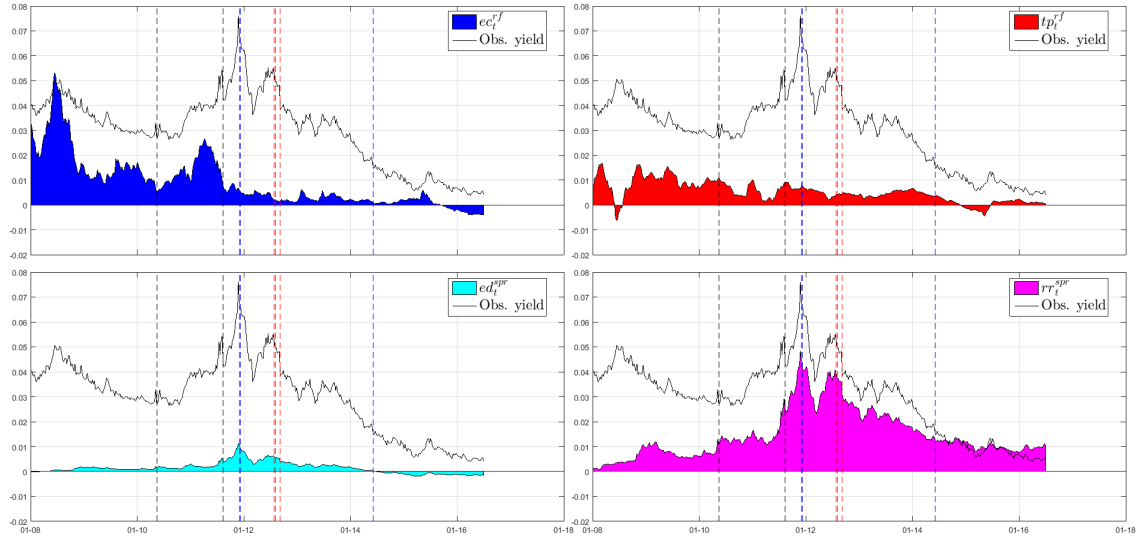
Each subsection starts with a graphical analysis of the decomposition of five-year sovereign bond yield (black solid line) into four components: 1) the

expected (blue curve) and 2) term premium (red curve) risk-free components as given by equations (14) and (16); 3) the average expected instantaneous spread (cyan curve) and 4) repricing of risk (magenta curve) for the spread components as given by equations (21) and (22). Each figure is divided into four panels, one for each component analysed. As explained at the end of the previous section, we will not comment on the expected and term premium risk-free components as they have been analysed for the OIS yield curve. We will then move to the analysis of the five-year sovereign bond yield variations around UMP announcements.

4.2.1 Italy and Spain

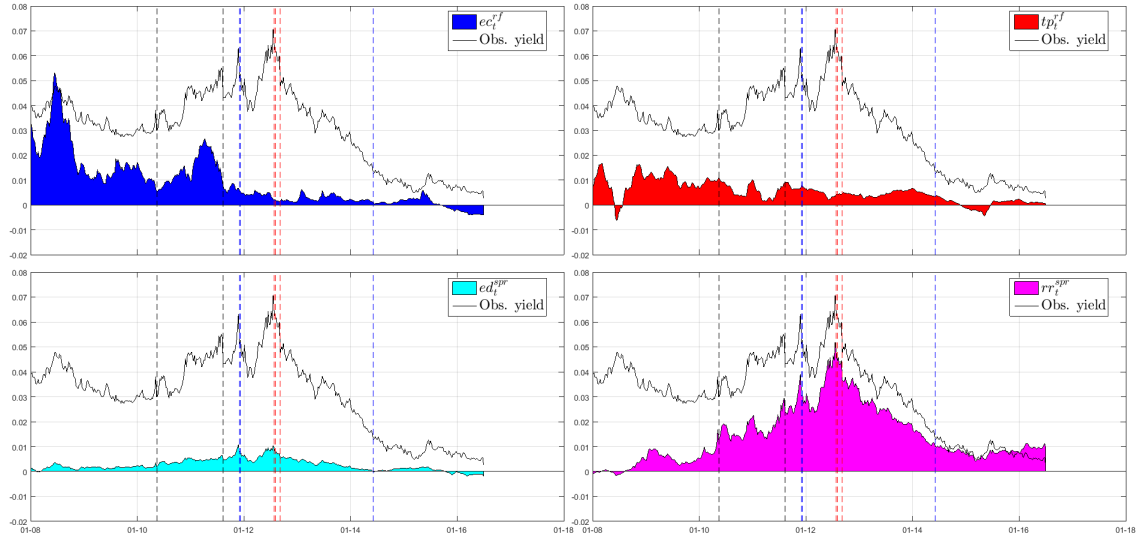
Figures 3 and 4 below show the decomposition results for the five-year Italian and Spanish yields. Focusing first on the average expected instantaneous spread component (expected spread for short), we notice that in the case of Italy the expected spread component started to increase quite abruptly at the end of the third quarter of 2011 to reach a maximum of 113 basis points at the beginning of December 2011. In the case of Spain, the expected spread component increased more gradually starting in mid-2010 (first SMP black dotted line) to reach its peak at 108 basis points at the beginning of December 2011. If we now consider the impact of UMP programmes on the expected spread component of each country, we see that the announcements surrounding the introduction of the 3-year LTROs (VLTROs) had the impact of bringing down durably the Italian expected spread component (blue dotted line). That effect was further re-enforced by the OMT announcement during the summer of 2012 (red dotted line). In the case of Spain, while the VLTROs announcements had the initial impact of bringing down the expected spread component, it then went back to values close to its maximum (104 bps at the end of July 2012) during the escalation of the redenomination risk episode that triggered the introduction of the OMT programme. After the OMT introduction, the Spanish expected spread component went back persistently to its pre-crisis level.

Figure 3: Impact of UMPs on each component of 5-year Italian yield (UMPs in dotted lines: SMP = black, (T)LTROs = blue and OMT = red)



Now turning to the repricing of risk component, we can observe that it accounts for the bulk of the variation in spreads in all countries considered. For Italy, it evolves in the same way as the expected spread by increasing rapidly from 100 basis points (bps) in the middle of 2011 to reach its maximum of 484 bps in December 2011 and then returning progressively to its pre-crisis level. For Spain the picture looks different since the repricing of risk component increased gradually from mid-2010 on until it reached its maximum in the middle of the redenomination risk episode (519 bps). Since at that period markets were pricing into sovereign yields a non negligible probability of a breakup of the euro area, the compensation required by investors for the uncertainty in the evolution of sovereign expected spread skyrocketed in distressed countries that would be the first to exit the monetary union in case of a breakup of the euro area. The commitment of Draghi to do *'whatever it takes'* to maintain the monetary union through its OMT programme thus had the effect of bringing down abruptly those risk premiums.

Figure 4: Impact of UMPs on each component of 5-year Spanish yield (UMPs in dotted lines: SMP = black, (T)LTROs = blue and OMT = red)



After this graphical analysis of the evolution of the different channels of transmission of the monetary policy, we now try to specifically quantify the impact of the different UMP announcements for Italy and Spain. Table 5 below summarizes the results for both countries aggregated at the programme level while Tables 9 and 10 in appendix C.2 - C.3 gives the detailed impact of each announcement.

For both countries, the SMP is by far the one having the largest actual variation in five-year sovereign yields around announcements (respectively -170 and -195 bps for Italy and Spain). It is interesting to note that almost all the difference between the two countries for the effect of the SMP comes from the first announcement while the second announcement extending the programme to the two countries had rather identical effect in both of them. In both countries the two programmes with the largest actual impact on sovereign yields after the SMP are the OMT and the LTROs in order of importance.

Table 5: Cumulative weekly variations in $\underline{ec}_t^{rf}(\tau)$, $\underline{tp}_t^{rf}(\tau)$, $es_t^{spr}(\tau)$ and $rr_t^{spr}(\tau)$ components for 5-y Italian and Spanish yields around announcements (in basis points)

Italy					
Prog	Actu	$\Delta \underline{ec}_t^{rf}$	$\Delta \underline{tp}_t^{rf}(\tau)$	$\Delta es_t^{spr}(\tau)$	$\Delta rr_t^{spr}(\tau)$
SMP	-170	-36	13	-16	-65
(T)LTRO	-125	-18	19	-20	-85
OMT	-152	-9	14	-19	-86
FG	-46	0	-1	-7	-26
APP	-49	1	-7	-8	-35
Spain					
Prog	Actu	$\Delta \underline{ec}_t^{rf}$	$\Delta \underline{tp}_t^{rf}(\tau)$	$\Delta es_t^{spr}(\tau)$	$\Delta rr_t^{spr}(\tau)$
SMP	-195	-36	13	-31	-98
(T)LTRO	-162	-18	19	-38	-120
OMT	-170	-9	14	-42	-124
FG	-54	0	-1	-8	-35
APP	-45	1	-7	-5	-35

Turning to the channels of transmission of the UMP programmes, we see that the three programmes with the largest actual impact on sovereign yields had large impact on the expected spread channel. If we take the peak value of the expected spread for each country as a reference point for comparison, we see that the programmes had an impact of between 14 (SMP) and 18 percent (LTROs) for Italy and between 29 (SMP) and 39 percent (OMT) for Spain. Concerning the repricing of risk channel, we see that it accounts for more than half of the actual variation in almost all cases for both countries³². Finally, we compare the variation in the repricing of risk channel for each country and each programme to their respective maximum value. We see that for the three programmes with the largest impact in terms of actual sovereign bond yield changes (SMP, LTROs, OMT), the reduction in repricing of risk is of an order of magnitude between 19 (SMP) and 24 (OMT) percent for Spain

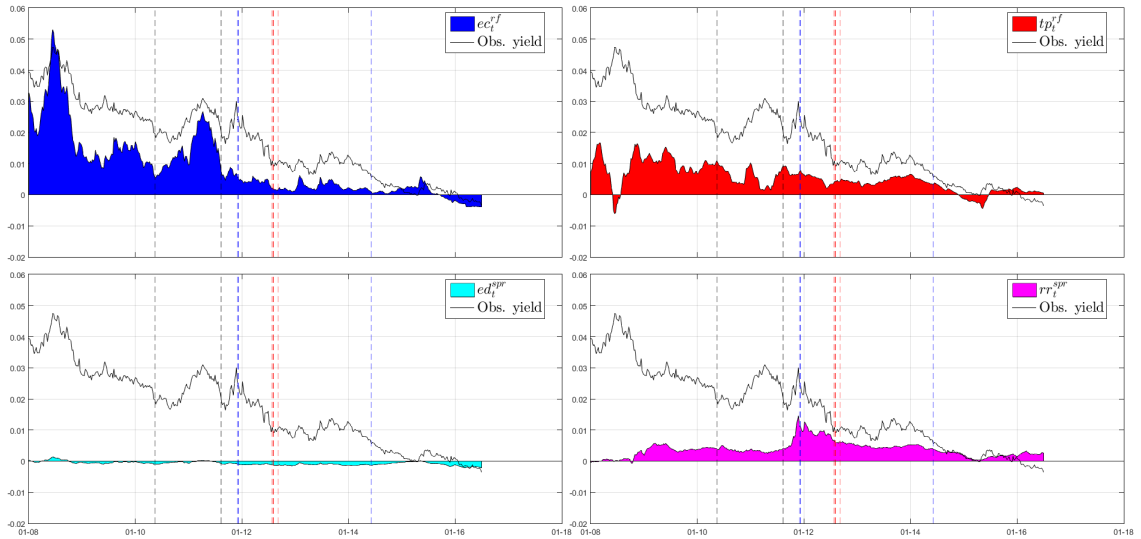
³²More precisely, the importance of the risk repricing channel ranges from 38 percent of actual yield variation for the SMP in Italy to 74 percent for the LTROs in Spain

and between 13 (SMP) and 18 (OMT) percent for Italy compared to their respective maximum value of the repricing of risk component.

4.2.2 Belgium and France

Figures 5 and 6 below show the decomposition results for the five-year French and Belgian yields. Focusing first on the average expected instantaneous spread component (expected spread for short), we notice that the expected spreads for France and Belgium are quite constant over the analysed period and stay close to zero at slightly negative values. We cannot pinpoint clear effects of the UMP announcements on the evolution of the average expected instantaneous spread for France and Belgium³³ and we thus decide to focus on the analysis of the repricing of risk component in the rest of the analysis.

Figure 5: Impact of UMPs on each component of 5-year French yield (UMPs in dotted lines: SMP = black, (T)LTROs = blue and OMT = red)



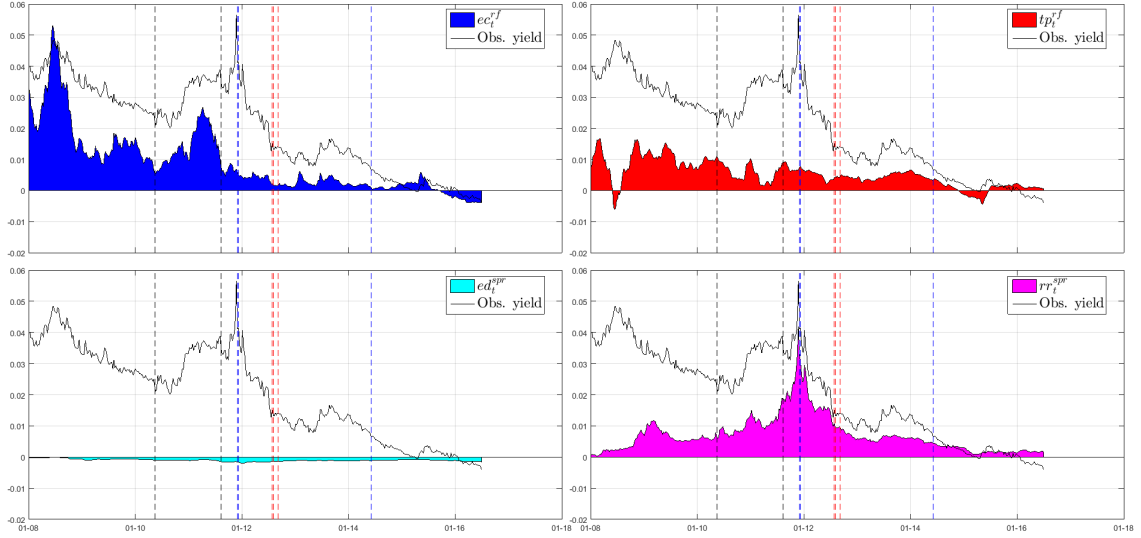
³³This is also confirmed by the relatively small variations of the expected spread component recorded in Table 6.

Focusing on the repricing of risk component, we see that this component reached its peak for both France and Belgium around the end of November 2011 with respectively 146 bps for France and 370 bps for Belgium. We observe a decrease in spreads for both countries from December 2011 onwards. For France, our model suggests that this decrease is mostly explained by the reduction of the repricing of risk component following the introduction of the VLTRO. In the case of Belgium, the reduction in the 5-year sovereign spread comes mostly from the reduction in the repricing of risk component but this reduction can be attributed to two events: the formation of a governing coalition after 18 months of negotiations and, possibly, the introduction of the VLTRO. We are not able however to disentangle the respective contributions of each event to this reduction of the spreads.

If we contrast the results for Belgium and France with the analysis for Italy and Spain, we see that the second half of 2011 was a turbulent period for EA financial markets and the historically high sovereign yield levels might have been caused by a combination of factors including concerns about fiscal sustainability, political uncertainty³⁴, contagion effects and country-specific factors. While most of the market concerns pertaining to the evolution of the pricing of risk factors in core countries were addressed after the introduction of the ECB longer-term refinancing operations, the uncertainty surrounding the evolution of non-core countries lead to subsequent increase in risk premiums required by market participants. The market concerns culminated with the redenomination risk crisis during the summer of 2012 and the introduction of the outright monetary transactions programme was instrumental in bringing back the repricing of risk component of non-core countries to pre-crisis levels.

³⁴In addition to the long period of political uncertainty in Belgium, we can mention that in Italy the Berlusconi government had to resign in November 2011 after losing support from the parliament.

Figure 6: Impact of UMPs on each component of 5-year Belgian yield UMPs in dotted lines: (SMP = black, (T)LTROs = blue and OMT = red)



We now move to the analysis of the impact of the different UMP announcements on the 5-year sovereign bond yields of France and Belgium. Table 6 below summarizes the results for both countries aggregated at the programme level while tables 11 and 12 in appendix C.4 - C.5 gives the detailed impact of each announcement.

The LTRO programme is the one having the largest actual variation in five-year sovereign yields around announcements (respectively - 43 and -122 bps for France and Belgium)³⁵. Similar to the analysis of the impact of the SMP on Italy and Spain, almost all the difference between the Belgium and France for the effect of the LTRO comes from the first announcement while the following announcements had rather identical effect in both of them. In both countries the two programmes with the largest actual impact on sovereign yields after the LTRO are the SMP and the OMT in order of importance.

³⁵As mentioned before, the introduction of the VLTRO almost exactly coincides with the formation of a governing coalition in Belgium. In that respect, one should be careful in the interpretation of the results for the LTRO programme for Belgium.

Table 6: Cumulative weekly variations in $ec_t^{rf}(\tau)$, $tp_t^{rf}(\tau)$, $es_t^{spr}(\tau)$ and $rr_t^{spr}(\tau)$ components for 5-y Belgian and French yields around announcements (in basis points)

Belgium - SR					
Prog	Actu	ec_t^{rf}	$tp_t^{rf}(\tau)$	$es_t^{spr}(\tau)$	$rr_t^{spr}(\tau)$
SMP	-66	-36	13	-1	-20
(T)LTRO	-122	-18	19	-1	-104
OMT	-37	-9	14	0	-20
FG	-9	0	-1	0	-5
APP	-1	1	-7	0	-7
France - SR					
Prog	Actu	ec_t^{rf}	$tp_t^{rf}(\tau)$	$es_t^{spr}(\tau)$	$rr_t^{spr}(\tau)$
SMP	-23	-36	13	-3	4
(T)LTRO	-43	-18	19	-3	-35
OMT	-23	-9	14	-1	-10
FG	-13	0	-1	0	-4
APP	2	1	-7	1	-6

Moving on to the channels of transmission of the different UMP programmes, the repricing of risk component accounts for more than half of the actual variations in 5-year Belgian yields around announcements in all the cases except for the SMP programme. In the case of France, the repricing of risk component has variations with magnitude similar to the risk-free expected component. Finally, we compare the variation in the repricing of risk channel for each country and each programme to their respective maximum value. We see that for the three programmes with the largest impact in terms of actual sovereign bond yield changes (SMP, LTROs, OMT), the reduction in repricing of risk explains between 5.41 (SMP and OMT) and 28 (LTROs) percent for Belgium and between 7 (OMT) and 24 (LTROs) percent for France when we use the maximum values of the repricing of risk component over the studied period as the reference basis³⁶.

³⁶Note that we did not consider the 4 bps increase in the repricing of risk component for France in the analysis.

5 Conclusion

In the recent financial crisis, the ECB deployed a battery of unconventional monetary policy programmes with different purposes. Some of these programmes (SMP, OMT and VLTRO) were aimed at correcting the fragmentation in the transmission of monetary stimulus between countries most affected by the sovereign debt crisis and other EA countries. Other programmes (TLTRO, FG and APP) had a more general goal of furthering the stance of the monetary policy in a lower-bound environment.

In this paper, we analyse how these UMP interventions impacted the EA OIS yield curve (proxying for the risk-free yield curve) and the sovereign bond yield spreads for Belgium, France, Italy and Spain. Using a two-country, arbitrage-free, shadow-rate dynamic term structure model (SR-DTSM) we decompose sovereign yields variations into four components: (i) the expected component of the risk free curve, (ii) the term premium component of the risk free curve, (iii) the (country-specific) average expected instantaneous spread and (iv) the (country-specific) risk repricing component.

We obtain the following results. First, shadow-rate models tend to produce risk premium estimates which are economically more plausible than the ones produced by their affine counterparts. For the OIS yield curve, term premiums obtained from the shadow-rate model tend to stay close to zero during the lower-bound period while the term premiums from the affine model drop progressively to large negative values after 2014, with substantially larger volatility compared to the shadow-rate case. Most of the variations in OIS yields can be attributed to the expectation component. Furthermore, we notice that since the start of the Public Sector Purchase Programme in January 2015 the expectation component of five-year OIS yields turned negative and reached the effective lower bound of -40 basis points towards the end of the studied sample.

Second, the repricing of risk component has been the main driver of sovereign yield variations around UMP announcements. For Italy and Spain, the average expected instantaneous spread was also an important component of sovereign yield variations reaching values above 100 bps on repeated occasions over the period ranging from the second half of 2011 until the summer of 2012.

Lastly, we notice that for France the introduction of the VLTRO had the effect of lowering persistently the levels of the risk repricing premiums back to

their pre-crisis values. In the case of Belgium, this decrease in the repricing of risk component was due to a combination of the VLTRO announcement and the formation of a governing coalition after a long period of political uncertainty. In the case of Italy and Spain, the OMT had a similar effect on both the average expected instantaneous spreads and the repricing of risk component.

Our analysis could be further refined along several lines. We could account for interactions between countries and model potential spillover/contagion effects by introducing a multicountry model. We could consider a larger set of channels of transmission by including additional risk factors such as liquidity or redenomination proxies. Finally, we could assess the impact of UMP announcements on sovereign yield volatility by allowing explicitly for time-varying volatility in the model specification. We leave these extensions for future research.

Appendix

A Data and non conventional monetary policy announcements

A.1 Conversion of interest rate data

We convert the Bloomberg data for OIS rates and EURIBOR swap rates into continuously compounded yields. Let the maturity- τ yield quoted at time t be $r_t(\tau)$, $p_t(\tau)$ is the corresponding zero-coupon bond price and $y_t(\tau)$ the continuously compounded yield. We can obtain an expression for the continuously compounded yield using the following relation:

$$\begin{aligned} p_t(\tau) &= \frac{1}{(1 + r_t(\tau))^\tau} = e^{-\tau y_t(\tau)} \\ \Leftrightarrow y_t(\tau) &= \ln(1 + r_t(\tau)) \end{aligned} \tag{24}$$

For maturities inferior to one year, we use the linear interest rate market convention. Equation (24) now becomes:

$$y_t(\tau) = \frac{1}{\tau} \ln(1 + \tau.r_t(\tau)) \tag{25}$$

A.2 Non conventional monetary policy announcements

Table 7: Identified event dates for unconventional monetary policy announcements

Announcement date	Program	Event
10/05/2010	SMP	Initial announcement
8/08/2011	SMP	Extension to Italy and Spain
1/12/2011	VLTRO	Draghi's speech at European parliament
8/12/2011	VLTRO	Announcement of 3-year VLTROs
26/07/2012	OMT	Draghi's "whatever it takes" speech
2/08/2012	OMT	OMT mentioned at conference press
6/09/2012	OMT	Official announcement
4/07/2013	FG	"expects the key ECB interest rates to remain at present or lower levels for an extended period of time"
9/01/2014	FG	Governing Council "firmly reiterated" its forward guidance
6/03/2014	FG	Governing Council reinforced the guidance formulation
5/06/2014	TLTRO	ABSPP and announcement of 4-year TLTROs
22/08/2014	APP	Draghi's speech at Jackson Hole
4/09/2014	APP	ABSPP and CBPP3
2/10/2014	APP	ABSPP and CBPP3
6/11/2014	APP	"Should it become necessary (...) commitment to using additional unconventional instruments within its mandate." Also mention of preparatory work for additional measures.
21/11/2014	APP	Draghi's speech at the Frankfurt European Banking Congress
22/01/2015	APP	PSPP
10/03/2016	APP	CSPP and announcement of new 4-year TLTROs

B Dynamic term structure models and estimation

B.1 The standard AFNS model

Following proposition 1 in [Christensen et al. \(2011\)](#), we have to impose a series of restriction on the maximally-flexible affine Gaussian DTSM to obtain the AFNS specification.

First, the short-rate is given by the sum of the level and slope factors. Equation (1) thus becomes:

$$r_t^{rf} = x_{l,t}^{rf} + x_{s,t}^{rf} \quad (26)$$

which implies $\rho_0^{rf} = 0$ and $\boldsymbol{\rho}_1^{rf} = [1 \ 1 \ 0]^\top$. The dynamics of the risk factors under the risk-neutral \mathbb{Q} -measure take the following form ensuring that the

risk factors are indeed identified as level, slope and curvature:

$$d \begin{pmatrix} x_{l,t}^{rf} \\ x_{s,t}^{rf} \\ x_{c,t}^{rf} \end{pmatrix} = - \begin{pmatrix} 0 & 0 & 0 \\ 0 & \kappa_{rf}^{\mathbb{Q}} & -\kappa_{rf}^{\mathbb{Q}} \\ 0 & 0 & \kappa_{rf}^{\mathbb{Q}} \end{pmatrix} \begin{pmatrix} x_{l,t}^{rf} \\ x_{s,t}^{rf} \\ x_{c,t}^{rf} \end{pmatrix} dt + \boldsymbol{\sigma}_{rf} d\mathbf{w}_t^{rf,\mathbb{Q}} \quad (27)$$

where the unconditional mean vector $\boldsymbol{\theta}_{rf}^{\mathbb{Q}}$ is set to zero without loss of generality for identification purpose. Plugging these information into equation (5) we can solve for the risk factor loadings which are indeed of the Nelson-Siegel form:

$$\begin{aligned} \mathbf{B}^{rf}(\tau) &= -\frac{1}{\tau} \mathbf{b}^{rf}(\tau) \\ &= -\frac{1}{\tau} \begin{bmatrix} -\tau \\ -\frac{1-e^{-\tau\kappa_{rf}^{\mathbb{Q}}}}{\kappa_{rf}^{\mathbb{Q}}} \\ \tau e^{-\tau\kappa_{rf}^{\mathbb{Q}}} - \frac{1-e^{-\tau\kappa_{rf}^{\mathbb{Q}}}}{\kappa_{rf}^{\mathbb{Q}}} \end{bmatrix} \end{aligned} \quad (28)$$

Given $\mathbf{b}^{rf}(\tau)$ we can solve equation (4) for $a^{rf}(\tau)$:

$$\begin{aligned} a^{rf}(\tau) &= \sigma_{l,rf}^2 \frac{\tau^3}{6} + \sigma_{s,rf}^2 \left(\frac{\tau}{2(\kappa_{rf}^{\mathbb{Q}})^2} - \frac{1-e^{-\kappa_{rf}^{\mathbb{Q}}\tau}}{(\kappa_{rf}^{\mathbb{Q}})^3} + \frac{1-e^{-2\kappa_{rf}^{\mathbb{Q}}\tau}}{4(\kappa_{rf}^{\mathbb{Q}})^3} \right) \\ &\quad + \sigma_{c,rf}^2 \left(\frac{\tau}{2(\kappa_{rf}^{\mathbb{Q}})^2} + \frac{\tau e^{-\kappa_{rf}^{\mathbb{Q}}\tau}}{(\kappa_{rf}^{\mathbb{Q}})^2} - \frac{\tau^2 e^{-2\kappa_{rf}^{\mathbb{Q}}\tau}}{4\kappa_{rf}^{\mathbb{Q}}} - \frac{3\tau e^{-2\kappa_{rf}^{\mathbb{Q}}\tau}}{4(\kappa_{rf}^{\mathbb{Q}})^2} - \frac{2(1-e^{-\kappa_{rf}^{\mathbb{Q}}\tau})}{(\kappa_{rf}^{\mathbb{Q}})^3} + \frac{5(1-e^{-2\kappa_{rf}^{\mathbb{Q}}\tau})}{8(\kappa_{rf}^{\mathbb{Q}})^3} \right) \end{aligned}$$

where the $\sigma_{j,rf}$, $j \in \{l, s, c\}$ are the diagonal elements of $\boldsymbol{\sigma}_{rf}$.

Note that the factor dynamics under the historical \mathbb{P} -measure are left unrestricted ³⁷:

$$d \begin{pmatrix} x_{l,t}^{rf} \\ x_{s,t}^{rf} \\ x_{c,t}^{rf} \end{pmatrix} = \begin{pmatrix} \kappa_{11}^{\mathbb{P}} & \kappa_{12}^{\mathbb{P}} & \kappa_{13}^{\mathbb{P}} \\ \kappa_{21}^{\mathbb{P}} & \kappa_{22}^{\mathbb{P}} & \kappa_{23}^{\mathbb{P}} \\ \kappa_{31}^{\mathbb{P}} & \kappa_{32}^{\mathbb{P}} & \kappa_{33}^{\mathbb{P}} \end{pmatrix} \left[\begin{pmatrix} \theta_1^{\mathbb{P}} \\ \theta_2^{\mathbb{P}} \\ \theta_3^{\mathbb{P}} \end{pmatrix} - \begin{pmatrix} x_{l,t}^{rf} \\ x_{s,t}^{rf} \\ x_{c,t}^{rf} \end{pmatrix} \right] dt + \boldsymbol{\sigma}^{rf} d\mathbf{w}_t^{rf,\mathbb{P}} \quad (29)$$

³⁷We omit the rf subscript from $\kappa_{rf}^{\mathbb{P}}$ and $\boldsymbol{\theta}_{rf}^{\mathbb{P}}$ for ease of notation.

B.1.1 Estimation of the AFNS model by maximum likelihood

Estimation of the AFNS model proceeds by maximum likelihood estimation using the Kalman filter algorithm to evaluate the log-likelihood. We first need to cast the model in state-space form. The measurement equation is given by adding measurement errors $\boldsymbol{\varepsilon}_t^{rf} \sim \mathcal{N}(0, \sigma_{y,rf}^2 \mathbf{I}_J)$ to equation (8)³⁸:

$$\mathbf{y}_t^{rf} = \mathbf{A}^{rf} + \mathbf{B}^{rf} \mathbf{x}_t^{rf} + \boldsymbol{\varepsilon}_t^{rf} \quad (30)$$

where $\mathbf{B}^{rf} = [\mathbf{B}^{rf}(0.25) \ \dots \ \mathbf{B}^{rf}(J)]^\top$ is the stacked version of the risk-free factor loadings for the J maturities. The transition equation is obtained by solving equation (7) for time step Δt between two consecutive observations and represents the factor dynamics under the historical probability measure \mathbb{P} :

$$\begin{aligned} \mathbf{x}_t^{rf} &= [\mathbf{I}_n - \exp(-\boldsymbol{\kappa}_{rf}^{\mathbb{P}} \Delta t)] \boldsymbol{\theta}_{rf}^{\mathbb{P}} + \exp(-\boldsymbol{\kappa}_{rf}^{\mathbb{P}} \Delta t) \mathbf{x}_{t-1}^{rf} + \boldsymbol{\eta}_t^{rf} \\ \mathbf{x}_t^{rf} &= \boldsymbol{\Phi}_0^{rf} + \boldsymbol{\Phi}_1^{rf} \mathbf{x}_{t-1}^{rf} + \boldsymbol{\eta}_t^{rf} \end{aligned} \quad (31)$$

where the shocks to the state variables are normally distributed: $\boldsymbol{\eta}_t^{rf} \sim \mathcal{N}(0, \mathbf{Q}_{rf})$ with the conditional covariance matrix \mathbf{Q}_{rf} being given by:

$$\mathbf{Q}_{rf} = \int_0^{\Delta t} e^{-\boldsymbol{\kappa}_{rf}^{\mathbb{P}} v} \boldsymbol{\sigma}_{rf} \boldsymbol{\sigma}_{rf}^\top e^{-\boldsymbol{\kappa}_{rf}^{\mathbb{P} \top} v} dv \quad (32)$$

In the estimation, we compute \mathbf{Q}_{rf} using the analytical formula provided in [Fisher and Gilles \(1996\)](#). Finally, collecting the parameters to be estimated in the vector $\boldsymbol{\psi}$, we can obtain standard errors using the following expression:

$$\boldsymbol{\Sigma}(\hat{\boldsymbol{\psi}}) = \frac{1}{T} \left[\frac{1}{T} \sum_{t=1}^T \frac{\partial \log l_t(\hat{\boldsymbol{\psi}})}{\partial \boldsymbol{\psi}} \frac{\partial \log l_t(\hat{\boldsymbol{\psi}})^\top}{\partial \boldsymbol{\psi}} \right]^{-1} \quad (33)$$

where $\hat{\boldsymbol{\psi}}$ is the ML vector of parameter estimates.

³⁸We stack together the J maturities.

B.2 The option-based approximation for lower-bound constrained yields

B.2.1 The SR-AFNS model

Krippner (2012) shows that the lower-bound constrained instantaneous forward rate $\underline{f}_t^{rf}(\tau)$ can be decomposed as follows:

$$\underline{f}_t^{rf}(\tau) = f_t^{rf}(\tau) + z_t(\tau) \quad (34)$$

The instantaneous shadow forward rate $f_t^{rf}(\tau)$ which enters the lower-bound constrained instantaneous forward rate $\underline{f}_t^{rf}(\tau)$ above is obtained by deriving the logarithmic bond price with respect to the maturity τ ³⁹:

$$\begin{aligned} f_t^{rf}(\tau) &= -\frac{\partial}{\partial \tau} \log p_t^{rf}(\tau) \\ &= x_{l,t}^{rf} + e^{-(\kappa_{rf}^{\mathbb{Q}}\tau)} x_{s,t}^{rf} + \kappa_{rf}^{\mathbb{Q}} \tau e^{-(\kappa_{rf}^{\mathbb{Q}}\tau)} x_{c,t}^{rf} + A_f^{rf}(\tau) \end{aligned} \quad (35)$$

where $A_f^{rf}(\tau)$ is obtained as:

$$\begin{aligned} A_f^{rf}(\tau) &= -\frac{\partial}{\partial \tau} \frac{a^{rf}(\tau)}{\tau} \\ &= -\frac{1}{2} \sigma_{l,rf}^2 \tau^2 - \frac{1}{2} \sigma_{s,rf}^2 \left(\frac{1 - e^{-\kappa_{rf}^{\mathbb{Q}}\tau}}{\tau} \right)^2 \\ &= -\frac{1}{2} \sigma_{c,rf}^2 \left(\tau e^{-\kappa_{rf}^{\mathbb{Q}}\tau} - \frac{1 - e^{-\kappa_{rf}^{\mathbb{Q}}\tau}}{\tau} \right)^2 \end{aligned} \quad (36)$$

The term $z_t(\tau)$ in equation (34) is given by:

$$z_t(\tau) = \lim_{\delta \rightarrow 0} \left[\frac{\partial}{\partial \delta} \frac{c_t^e(\tau, \tau + \delta; k)}{p_t^{rf}(\tau + \delta)} \right] \quad (37)$$

³⁹Here we use the relation:

$$\begin{aligned} p_t(\tau) &= e^{-\tau y_t(\tau)} \\ \Leftrightarrow -\log p_t(\tau) &= \tau y_t(\tau) \end{aligned}$$

Where $c_t^e(\tau, \tau + \delta; k)$ is the value of a European call option at time t with maturity τ and strike price k written on the shadow bond with maturity $\tau + \delta$, $p_t^{rf}(\tau + \delta)$. As noticed in [Christensen and Rudebusch \(2015\)](#), the Krippner framework is only an approximation to an arbitrage-free model. This can be seen by observing that price of the lower-bound constrained bond yield at maturity τ is given by:

$$\underline{p}_t^{rf}(\tau) = p_t^{rf}(\tau) + c_t^a(\tau, \tau; k)$$

Where $c_t^a(\tau, \tau; k)$ is the value of an American call option at time t with maturity τ and strike price k written on the shadow bond with maturity τ . For analytical tractability reasons, this arbitrage-free relation is approximated by the limiting case involving a European call option with corresponding characteristics. Using standard arguments of derivative pricing theory, the value of the European call option at time t with maturity τ and strike price k written on the shadow bond with maturity $\tau + \delta$ is given by:

$$c_t^e(\tau, \tau + \delta; k) = p_t^{rf}(\tau + \delta)\Phi(d_1) - k p_t^{rf}(\tau)\Phi(d_2)$$

The first term depends on d_1 which is given by:

$$d_1 = \frac{\ln\left(\frac{p_t^{rf}(\tau + \delta)}{k p_t^{rf}(\tau)}\right) + \frac{1}{2}v_t(\tau, \tau + \delta)}{\sqrt{v_t(\tau, \tau + \delta)}}$$

The second term depends on $d_2 = d_1 - \sqrt{v_t(\tau, \tau + \delta)}$.

$\omega_t(\tau)$ which enters the lower-bound constrained instantaneous forward rate $f_t^{rf}(\tau)$ in equation (12) is related to the conditional variance, $v_t(\tau, \tau + \delta)$, of the European call option written on the shadow bond with maturity $\tau + \delta$ in the following way⁴⁰:

⁴⁰See [Christensen and Rudebusch \(2015\)](#) for details on the computation of $v_t(\tau, \tau + \delta)$ and $\omega_t(\tau)$.

$$\begin{aligned}
\omega_t(\tau)^2 &= \frac{1}{2} \lim_{\delta \rightarrow 0} \frac{\partial^2 v_t(\tau, \tau + \delta)}{\partial \delta^2} \\
&= \sigma_{l,rf}^2 \tau + \sigma_{s,rf}^2 \left(\frac{1 - e^{-2\kappa_{rf}^{\mathbb{Q}} \tau}}{2\tau} \right) \\
&= \sigma_{c,rf}^2 \left(\frac{1 - e^{-2\kappa_{rf}^{\mathbb{Q}} \tau}}{4\tau} - \frac{1}{2} \tau e^{-2\kappa_{rf}^{\mathbb{Q}} \tau} - \frac{1}{2} \kappa_{rf}^{\mathbb{Q}} \tau^2 e^{-2\kappa_{rf}^{\mathbb{Q}} \tau} \right)
\end{aligned} \tag{38}$$

B.2.2 Estimation of the SR-AFNS model by maximum likelihood

When estimating the shadow-rate version of the model, we must account for the fact that the model-implied risk-free zero-coupon bond yields depend non-linearly on the risk factors:

$$\begin{aligned}
\underline{y}_t^{rf}(\tau) &= G(\tau; \psi, \mathbf{x}_t^{rf}) \\
&= \frac{1}{\tau} \int_0^\tau g(v; \psi, \mathbf{x}_t^{rf}) dv
\end{aligned} \tag{39}$$

Where $g(v; \psi, \mathbf{x}_t^{rf})$ is the lower-bound constrained instantaneous forward rate $\underline{f}_t^{rf}(\tau)$ given in equation (12). We follow the Extended Kalman filter approach and linearise this expression using a first-order Taylor expansion around the optimal one-step ahead state prediction $\mathbf{x}_{t|t-1}^{rf}$ obtained from equation (31):

$$G(\tau; \psi, \mathbf{x}_t^{rf}) \approx G(\tau; \psi, \mathbf{x}_{t|t-1}^{rf}) + \left. \frac{\partial G(\tau; \psi, \mathbf{x}_t^{rf})}{\partial \mathbf{x}_t^{rf}} \right|_{\mathbf{x}_t^{rf} = \mathbf{x}_{t|t-1}^{rf}} \left(\mathbf{x}_t^{rf} - \mathbf{x}_{t|t-1}^{rf} \right)$$

The modified measurement equation for a maturity τ risk-free bond yield now reads as:

$$\underline{y}_t^{rf}(\tau) = \mathbb{A}(\tau; \psi, \mathbf{x}_t^{rf}) + \mathbb{B}(\tau; \psi, \mathbf{x}_t^{rf})^\top \mathbf{x}_t^{rf} + \varepsilon_t^{rf}(\tau) \tag{40}$$

Where $\mathbb{A}(\tau; \psi, \mathbf{x}_t^{rf})$ and $\mathbb{B}(\tau; \psi, \mathbf{x}_t^{rf})$ are defined as:

$$\mathbb{A}(\tau; \psi, \mathbf{x}_t^{rf}) = G(\tau; \psi, \mathbf{x}_{t|t-1}^{rf}) - \frac{\partial G(\tau; \psi, \mathbf{x}_t^{rf})}{\partial \mathbf{x}_t^{rf}} \Big|_{\mathbf{x}_t^{rf} = \mathbf{x}_{t|t-1}^{rf}} \mathbf{x}_{t|t-1}^{rf} \quad (41)$$

$$\mathbb{B}(\tau; \psi, \mathbf{x}_t^{rf}) = \frac{\partial G(\tau; \psi, \mathbf{x}_t^{rf})}{\partial \mathbf{x}_t^{rf}} \Big|_{\mathbf{x}_t^{rf} = \mathbf{x}_{t|t-1}^{rf}} \quad (42)$$

The rest of the estimation proceeds as in the affine case.

B.3 Modelling of the country yield curve

In this section we detail the setting for country yield curve modelling. First, the joint dynamics of the risk-free and country-specific risk factors under the risk-neutral \mathbb{Q} -measure take the following form ensuring that the risk factors are indeed identified as level, slope and curvature (for the risk-free yield curve):

$$d \begin{pmatrix} \mathbf{x}_t^{rf} \\ \mathbf{x}_t^i \end{pmatrix} = - \begin{pmatrix} \boldsymbol{\kappa}_{rf}^{\mathbb{Q}} & \mathbf{0} \\ \mathbf{0} & \boldsymbol{\kappa}_i^{\mathbb{Q}} \end{pmatrix} \begin{pmatrix} \mathbf{x}_t^{rf} \\ \mathbf{x}_t^i \end{pmatrix} dt + \begin{bmatrix} \boldsymbol{\sigma}_{rf} & 0 \\ 0 & \boldsymbol{\sigma}_i \end{bmatrix} \begin{bmatrix} d\mathbf{w}_t^{rf, \mathbb{Q}} \\ d\mathbf{w}_t^{i, \mathbb{Q}} \end{bmatrix} \quad (43)$$

where $\boldsymbol{\kappa}_i^{\mathbb{Q}} = \begin{pmatrix} 0 & 0 \\ 0 & \kappa_i^{\mathbb{Q}} \end{pmatrix}$ is the mean reversion matrix of the country-specific level and slope factors under the risk-neutral \mathbb{Q} -measure. Furthermore, using the specification of country i short rate in equation (17) and the definition of no-arbitrage zero-coupon bond yield we can define the corresponding zero-coupon sovereign yield at maturity τ in the following way:

$$\begin{aligned} y_t^i(\tau) &= -\frac{1}{\tau} \log \mathbb{E}^{\mathbb{Q}} \left[e^{-\int_t^{t+\tau} r_v^i dv} \right] \\ &= -\frac{1}{\tau} \log \mathbb{E}^{\mathbb{Q}} \left[e^{-\int_t^{t+\tau} (r_v^{rf} + s_v^i) dv} \right] \\ &= -\frac{1}{\tau} (a^i(\tau) + \mathbf{b}^i(\tau)^\top \tilde{\mathbf{x}}_t^i) \\ &= A^i(\tau) + \mathbf{B}^i(\tau)^\top \tilde{\mathbf{x}}_t^i \end{aligned} \quad (44)$$

Given the dynamics in equation (43), the risk factor loadings $\mathbf{B}^i(\tau)$ take the following form:

$$\begin{aligned}
\mathbf{B}^i(\tau) &= -\frac{1}{\tau} \mathbf{b}^i(\tau) \\
&= -\frac{1}{\tau} \begin{bmatrix} -(1 + \rho_l^i)\tau \\ -(1 + \rho_s^i) \frac{1 - e^{-\tau \kappa_{rf}^{\mathbb{Q}}}}{\kappa_{rf}^{\mathbb{Q}}} \\ -(1 + \rho_s^i) \left[\frac{1 - e^{-\tau \kappa_{rf}^{\mathbb{Q}}}}{\kappa_{rf}^{\mathbb{Q}}} - e^{-\tau \kappa_{rf}^{\mathbb{Q}}} \tau \right] \\ -\tau \\ -\frac{1 - e^{-\kappa_i^{\mathbb{Q}} \tau}}{\kappa_i^{\mathbb{Q}}} \end{bmatrix} \quad (45)
\end{aligned}$$

$a^i(\tau)$ can be obtained following the same steps as in appendix B.1:

$$\begin{aligned}
a^i(\tau) &= (1 + \rho_l^i)^2 \sigma_{l,rf}^2 \frac{\tau^3}{6} + (1 + \rho_s^i)^2 \sigma_{s,rf}^2 \left(\frac{\tau}{2(\kappa_{rf}^{\mathbb{Q}})^2} - \frac{1 - e^{-\kappa_{rf}^{\mathbb{Q}} \tau}}{(\kappa_{rf}^{\mathbb{Q}})^3} + \frac{1 - e^{-2\kappa_{rf}^{\mathbb{Q}} \tau}}{4(\kappa_{rf}^{\mathbb{Q}})^3} \right) \\
&+ (1 + \rho_s^i)^2 \sigma_{c,rf}^2 \left(\frac{\tau}{2(\kappa_{rf}^{\mathbb{Q}})^2} + \frac{\tau e^{-\kappa_{rf}^{\mathbb{Q}} \tau}}{(\kappa_{rf}^{\mathbb{Q}})^2} - \frac{\tau^2 e^{-2\kappa_{rf}^{\mathbb{Q}} \tau}}{4\kappa_{rf}^{\mathbb{Q}}} - \frac{2(1 - e^{-\kappa_{rf}^{\mathbb{Q}} \tau})}{(\kappa_{rf}^{\mathbb{Q}})^3} \right) \\
&+ (1 + \rho_s^i)^2 \sigma_{c,rf}^2 \left(\frac{5(1 - e^{-2\kappa_{rf}^{\mathbb{Q}} \tau})}{8(\kappa_{rf}^{\mathbb{Q}})^3} - \frac{3\tau e^{-2\kappa_{rf}^{\mathbb{Q}} \tau}}{4(\kappa_{rf}^{\mathbb{Q}})^2} \right) + \sigma_{l,i}^2 \frac{\tau^3}{6} \\
&+ \sigma_{s,i}^2 \left(\frac{\tau}{2(\kappa_i^{\mathbb{Q}})^2} - \frac{1 - e^{-\kappa_i^{\mathbb{Q}} \tau}}{(\kappa_i^{\mathbb{Q}})^3} + \frac{1 - e^{-2\kappa_i^{\mathbb{Q}} \tau}}{4(\kappa_i^{\mathbb{Q}})^3} \right) \quad (46)
\end{aligned}$$

By implication, the corresponding zero-coupon sovereign yield spread at maturity τ is obtained by subtracting equation (3) from equation (44):

$$\begin{aligned}
s_t^i(\tau) &= y_t^i(\tau) - y_t^{rf}(\tau) \\
&= -\frac{1}{\tau} (a_s^i(\tau) + \mathbf{b}_s^i(\tau)^\top \tilde{\mathbf{x}}_t^i) \\
&= A_s^i(\tau) + \mathbf{B}_s^i(\tau)^\top \tilde{\mathbf{x}}_t^i
\end{aligned}$$

where the risk factor loadings $\mathbf{B}^i(\tau)$ for the zero-coupon sovereign yield

spread take the following form:

$$\begin{aligned}
\mathbf{B}_s^i(\tau) &= -\frac{1}{\tau} \mathbf{b}_s^i(\tau) \\
&= -\frac{1}{\tau} \begin{bmatrix} -\rho_l^i \tau \\ -\rho_s^i \frac{1-e^{-\tau \kappa_{rf}^{\mathbb{Q}}}}{\kappa_{rf}^{\mathbb{Q}}} \\ -\rho_s^i \left[\frac{1-e^{-\tau \kappa_{rf}^{\mathbb{Q}}}}{\kappa_{rf}^{\mathbb{Q}}} - e^{-\tau \kappa_{rf}^{\mathbb{Q}}} \tau \right] \\ -\tau \\ -\frac{1-e^{-\kappa_i^{\mathbb{Q}} \tau}}{\kappa_i^{\mathbb{Q}}} \end{bmatrix} \quad (47)
\end{aligned}$$

and the spread adjustment term ensuring absence of arbitrage opportunities $a_s^i(\tau)$ is given by:

$$\begin{aligned}
a_s^i(\tau) &= (\rho_l^i)^2 \sigma_{l,rf}^2 \frac{\tau^3}{6} + (\rho_s^i)^2 \sigma_{s,rf}^2 \left(\frac{\tau}{2(\kappa_{rf}^{\mathbb{Q}})^2} - \frac{1-e^{-\kappa_{rf}^{\mathbb{Q}} \tau}}{(\kappa_{rf}^{\mathbb{Q}})^3} + \frac{1-e^{-2\kappa_{rf}^{\mathbb{Q}} \tau}}{4(\kappa_{rf}^{\mathbb{Q}})^3} \right) \\
&+ (\rho_s^i)^2 \sigma_{c,rf}^2 \left(\frac{\tau}{2(\kappa_{rf}^{\mathbb{Q}})^2} + \frac{\tau e^{-\kappa_{rf}^{\mathbb{Q}} \tau}}{(\kappa_{rf}^{\mathbb{Q}})^2} - \frac{\tau^2 e^{-2\kappa_{rf}^{\mathbb{Q}} \tau}}{4\kappa_{rf}^{\mathbb{Q}}} - \frac{2(1-e^{-\kappa_{rf}^{\mathbb{Q}} \tau})}{(\kappa_{rf}^{\mathbb{Q}})^3} \right) \\
&+ (\rho_s^i)^2 \sigma_{c,rf}^2 \left(\frac{5(1-e^{-2\kappa_{rf}^{\mathbb{Q}} \tau})}{8(\kappa_{rf}^{\mathbb{Q}})^3} - \frac{3\tau e^{-2\kappa_{rf}^{\mathbb{Q}} \tau}}{4(\kappa_{rf}^{\mathbb{Q}})^2} \right) + \sigma_{l,i}^2 \frac{\tau^3}{6} \\
&+ \sigma_{s,i}^2 \left(\frac{\tau}{2(\kappa_i^{\mathbb{Q}})^2} - \frac{1-e^{-\kappa_i^{\mathbb{Q}} \tau}}{(\kappa_i^{\mathbb{Q}})^3} + \frac{1-e^{-2\kappa_i^{\mathbb{Q}} \tau}}{4(\kappa_i^{\mathbb{Q}})^3} \right) \quad (48)
\end{aligned}$$

C Additional tables for the results

C.1 Decomposition of OIS bond yield variations around UMP announcements

Table 8: Decomposition of weekly variations around UMP announcements for the five-year OIS yield (Actu) into variations in expected component (Δec_t^{rf}) and variations in term premium component (Δtp_t^{rf}).

date	Prog	Affine			Shadow-rate		
		Actu	Δec_t^{rf}	Δtp_t^{rf}	Actu	Δec_t^{rf}	Δtp_t^{rf}
10/05/2010	SMP	-1	-8	7	-1	-9	8
8/08/2011	SMP	-21	-29	7	-21	-27	5
1/12/2011	VLTRO	-3	-9	7	-3	-10	8
8/12/2011	VLTRO	-4	-9	5	-4	-8	4
5/06/2014	TLTRO	12	1	7	12	0	7
26/07/2012	OMT	1	0	3	1	0	3
2/08/2012	OMT	9	6	2	9	3	5
6/09/2012	OMT	-7	-17	10	-7	-12	6
4/07/2013	FG	-4	-4	1	-4	-2	-1
9/01/2014	FG	4	7	-2	4	3	1
6/03/2014	FG	-6	0	-3	-6	-2	-1
22/08/2014	APP	0	5	-6	0	0	-2
4/09/2014	APP	-4	-1	-2	-4	-4	1
2/10/2014	APP	0	2	-2	0	1	-2
6/11/2014	APP	-3	1	-4	-3	-1	-1
21/11/2014	APP	1	4	-4	1	2	-2
22/01/2015	APP	3	4	-2	3	3	-2
10/03/2016	APP	7	10	-2	7	0	1

Note: the table compares the results for the affine specification (AFNS) and the specification imposing an explicit lower bound (SR-AFNS). All variations are reported in basis points.

C.2 Decomposition of Italian bond yield variations around UMP announcements

Table 9: Decomposition of weekly variations around UMP announcements for the five-year Italian yield (Actu) into variations in expected component ($\Delta \underline{ec}_t^{rf}$), variations in term premia component ($\Delta \underline{tp}_t^{rf}(\tau)$), variations in expected spread (Δes_t^{spr}) and variations in repricing of risk (Δrr_t^{spr}).

		Italy				
date	Prog	Actu	$\Delta \underline{ec}_t^{rf}$	$\Delta \underline{tp}_t^{rf}(\tau)$	$\Delta es_t^{spr}(\tau)$	$rr_t^{spr}(\tau)$
10-05-10	SMP	-56	-9	8	-5	-22
08-08-11	SMP	-114	-27	5	-11	-43
01-12-11	VLTRO	-105	-10	8	-12	-47
08-12-11	VLTRO	3	-8	4	-6	-23
05-06-14	TLTRO	-23	0	7	-1	-15
26-07-12	OMT	-32	0	3	-6	-22
02-08-12	OMT	-96	3	5	-10	-52
06-09-12	OMT	-25	-12	6	-3	-12
04-07-13	FG	-7	-2	-1	-1	-3
09-01-14	FG	-8	3	1	-2	-9
06-03-14	FG	-30	-2	-1	-4	-14
22-08-14	APP	-4	0	-2	-1	-2
04-09-14	APP	-16	-4	1	-2	-8
02-10-14	APP	-1	1	-2	0	0
06-11-14	APP	0	-1	-1	-1	1
21-11-14	APP	-13	2	-2	-2	-6
22-01-15	APP	-10	3	-2	-2	-10
10-03-16	APP	-6	0	1	-1	-11

Note: the table reports the results for the specification imposing an explicit lower bound (SR-AFNS). All variations are reported in basis points.

C.3 Decomposition of Spanish bond yield variations around UMP announcements

Table 10: Decomposition of weekly variations around UMP announcements for the five-year Spanish yield (Actu) into variations in expected component ($\Delta \underline{ec}_t^{rf}$), variations in term premia component ($\Delta \underline{tp}_t^{rf}(\tau)$), variations in expected spread (Δes_t^{spr}) and variations in repricing of risk (Δrr_t^{spr}).

		Spain				
date	Prog	Actu	$\Delta \underline{ec}_t^{rf}$	$\Delta \underline{tp}_t^{rf}(\tau)$	$\Delta es_t^{spr}(\tau)$	$rr_t^{spr}(\tau)$
10-05-10	SMP	-83	-9	8	-15	-41
08-08-11	SMP	-112	-27	5	-16	-57
01-12-11	VLTRO	-121	-10	8	-27	-86
08-12-11	VLTRO	17	-8	4	-2	6
05-06-14	TLTRO	-58	0	7	-9	-39
26-07-12	OMT	-31	0	3	-17	-36
02-08-12	OMT	-122	3	5	-19	-79
06-09-12	OMT	-17	-12	6	-7	-8
04-07-13	FG	-16	-2	-1	-2	-8
09-01-14	FG	-11	3	1	-1	-14
06-03-14	FG	-28	-2	-1	-5	-13
22-08-14	APP	-3	0	-2	0	-4
04-09-14	APP	-17	-4	1	-3	-8
02-10-14	APP	-4	1	-2	0	-2
06-11-14	APP	3	-1	-1	0	4
21-11-14	APP	-11	2	-2	0	-6
22-01-15	APP	-10	3	-2	-1	-11
10-03-16	APP	-4	0	1	-1	-9

Note: the table reports the results for the specification imposing an explicit lower bound (SR-AFNS). All variations are reported in basis points.

C.4 Decomposition of French bond yield variations around UMP announcements

Table 11: Decomposition of weekly variations around UMP announcements for the five-year Belgian yield (Actu) into variations in expected component ($\Delta \underline{ec}_t^{rf}$), variations in term premia component ($\Delta \underline{tp}_t^{rf}(\tau)$), variations in expected spread (Δes_t^{spr}) and variations in repricing of risk (Δrr_t^{spr}).

		France				
date	Prog	Actu	$\Delta \underline{ec}_t^{rf}$	$\Delta \underline{tp}_t^{rf}(\tau)$	$\Delta es_t^{spr}(\tau)$	$rr_t^{spr}(\tau)$
10/05/2010	SMP	-2	-9	8	-1	0
8/08/2011	SMP	-21	-27	5	-2	5
1/12/2011	VLTRO	-59	-10	8	-2	-32
8/12/2011	VLTRO	1	-8	4	-1	-4
5/06/2014	TLTRO	16	0	7	0	2
26/07/2012	OMT	-15	0	3	0	-8
2/08/2012	OMT	5	3	5	1	0
6/09/2012	OMT	-14	-12	6	-2	-1
4/07/2013	FG	-2	-2	-1	0	0
9/01/2014	FG	1	3	1	1	-2
6/03/2014	FG	-12	-2	-1	-1	-2
22/08/2014	APP	2	0	-2	0	1
4/09/2014	APP	-7	-4	1	-1	1
2/10/2014	APP	2	1	-2	0	0
6/11/2014	APP	0	-1	-1	0	2
21/11/2014	APP	2	2	-2	0	-1
22/01/2015	APP	1	3	-2	0	-4
10/03/2016	APP	2	0	1	0	-4

Note: the table reports the results for the specification imposing an explicit lower bound (SR-AFNS). All variations are reported in basis points.

C.5 Decomposition of Belgian bond yield variations around UMP announcements

Table 12: Decomposition of weekly variations around UMP announcements for the five-year Belgian yield (Actu) into variations in expected component ($\Delta \underline{ec}_t^{rf}$), variations in term premia component ($\Delta \underline{tp}_t^{rf}(\tau)$), variations in expected spread (Δes_t^{spr}) and variations in repricing of risk (Δrr_t^{spr}).

		Belgium				
date	Prog	Actu	$\Delta \underline{ec}_t^{rf}$	$\Delta \underline{tp}_t^{rf}(\tau)$	$\Delta es_t^{spr}(\tau)$	$rr_t^{spr}(\tau)$
10/05/2010	SMP	-24	-9	8	0	-14
8/08/2011	SMP	-42	-27	5	-1	-6
1/12/2011	VLTRO	-153	-10	8	-1	-88
8/12/2011	VLTRO	2	-8	4	0	-26
5/06/2014	TLTRO	28	0	7	0	10
26/07/2012	OMT	-22	0	3	1	-14
2/08/2012	OMT	-1	3	5	0	-4
6/09/2012	OMT	-13	-12	6	-1	-2
4/07/2013	FG	1	-2	-1	0	1
9/01/2014	FG	1	3	1	0	-3
6/03/2014	FG	-11	-2	-1	0	-3
22/08/2014	APP	3	0	-2	0	1
4/09/2014	APP	-8	-4	1	0	-1
2/10/2014	APP	0	1	-2	0	-1
6/11/2014	APP	0	-1	-1	0	2
21/11/2014	APP	3	2	-2	0	1
22/01/2015	APP	-1	3	-2	0	-5
10/03/2016	APP	1	0	1	0	-4

Note: the table reports the results for the specification imposing an explicit lower bound (SR-AFNS). All variations are reported in basis points.

References

- [1] Carlo Altavilla, Giacomo Carboni, and Roberto Motto. “Asset purchase programmes and financial markets: lessons from the euro area”. *ECB Working Paper Series* November N.1864 (2015).
- [2] Martin M. Andreasen and Andrew Meldrum. “Dynamic term structure models : The best way to enforce the zero lower bound”. 2014.
- [3] Fischer Black. “Interest Rates as Options”. *The Journal of Finance* 50.5 (1995), pp. 1371–1376.
- [4] Jens H.E. Christensen, Francis X. Diebold, and Glenn D. Rudebusch. “The affine arbitrage-free class of Nelson–Siegel term structure models”. *Journal of Econometrics* 164.1 (Sept. 2011), pp. 4–20.
- [5] Jens H.E. Christensen, Jose A. Lopez, and Glenn D. Rudebusch. “Do Central Bank Liquidity Facilities Affect Interbank Lending Rates?” *Journal of Business & Economic Statistics* 32.1 (Jan. 2014), pp. 136–151.
- [6] Jens H.E. Christensen and Glenn D. Rudebusch. “Estimating Shadow-Rate Term Structure Models with Near-Zero Yields”. *Journal of Financial Econometrics* 13.2 (Mar. 2015), pp. 226–259.
- [7] Jens H.E. Christensen and Glenn D. Rudebusch. “Modeling Yields at the Zero Lower Bound: Are Shadow Rates the Solution?” *Dynamic Factor Models*. Vol. 35. *Advances in Econometrics*. Emerald Group Publishing Limited, Jan. 2016, pp. 3–75.
- [8] Jens H.E. Christensen and Glenn D. Rudebusch. “The Response of Interest Rates to US and UK Quantitative Easing”. *The Economic Journal* 122.564 (2012), F385–F414.
- [9] Simon Dubecq et al. “Credit and liquidity in interbank rates: A quadratic approach”. *Journal of Banking and Finance* 68 (2016), pp. 29–46.
- [10] Gregory R. Duffee. “Term Premia and Interest Rate Forecasts in Affine Models”. *The Journal of Finance* 57.1 (Feb. 2002), pp. 405–443.
- [11] Darrell Duffie and Rui Kan. “A yield-factor model of interest rates”. *Mathematical Finance* 6.4 (Oct. 1996), pp. 379–406.
- [12] Darrell Duffie and Kenneth J. Singleton. “Modeling Term Structures of Defaultable Bonds”. *Review of Financial Studies* 12.4 (1999), pp. 687–720.

- [13] Fabian Eser and Bernd Schwaab. “Evaluating the impact of unconventional monetary policy measures: Empirical evidence from the ECB’s Securities Markets Programme”. *Journal of Financial Economics* 119.1 (Jan. 2016), pp. 147–167.
- [14] Damir Filipovic, Martin Larsson, and Anders Trolle. *Linear-Rational Term Structure Models*. Swiss Finance Institute Research Paper Series 14-15. Swiss Finance Institute, 2016.
- [15] Mark Fisher and Christian Gilles. “Term Premia in Exponential-Affine models of the Term Structure”. 1996.
- [16] Don H. Kim and Kenneth J. Singleton. “Term structure models and the zero bound: An empirical investigation of Japanese yields”. *Journal of Econometrics* 170.1 (2012), pp. 32–49.
- [17] Leo Krippner. *Modifying Gaussian term structure models when interest rates are near the zero lower bound*. CAMA Working Papers 2012-05. Centre for Applied Macroeconomic Analysis, Crawford School of Public Policy, The Australian National University, 2012.
- [18] Arvind Krishnamurthy, Stefan Nagel, and Annette Vissing-jorgensen. “ECB Policies Involving Government Bond Purchases: Impact and Channels”. 2015.
- [19] Alain Monfort et al. *Staying at Zero with Affine Processes: An Application to Term Structure Modelling*. Working papers 558. Banque de France, 2015.
- [20] Jun Pan and Kenneth J. Singleton. “Default and Recovery Implicit in the Term Structure of Sovereign CDS Spreads”. *The Journal of Finance* 63.5 (2008), pp. 2345–2384.
- [21] Jean-paul Renne. “A Model of the Euro-Area Yield Curve with Discrete Policy Rates”. *Studies in Nonlinear Dynamics & Econometrics* (2016).

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