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ECB MONETARY POLICY SURPRISES

IDENTIFICATION THROUGH COJUMPS IN INTEREST RATES

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In 2014 all ECB publications feature a motif taken from the €20 banknote.

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Abstract

This paper proposes a new econometric approach to disentangle two distinct response patterns of the yield curve to monetary policy announcements. Based on cojumps in intraday tick-data of a short and long term interest rate, we develop a day-wise test that detects the occurrence of a significant policy surprise and identifies the market perceived source of the surprise. The new test is applied to 133 policy announcements of the European Central Bank (ECB) in the period from 2001-2012. Our main findings indicate a good predictability of ECB policy decisions and remarkably stable perceptions about the ECB's policy preferences.

Keywords: Central bank communication; yield curve; spectral cojump estimator; non-synchronous and noisy high frequency tick-data.
JEL classification: E58, C14, C58

Non-technical summary

The present paper proposes a new econometric tool to monitor markets' perceptions about monetary policy announcements. We study the instantaneous effect of an announcement on yields along the term structure of interest rates. Based on high-frequency statistics of intraday tick-data on a policy announcement day, the new approach provides answers to the following questions:

- Do markets infer new and relevant information from the policy announcement?
- What do markets perceive about the source of the new information?
  - Is it changing markets' expectations about current and future economic conditions?
  - Is it triggering changes in market perceived policy preferences?

Studying the different sources of news (surprises) is important not only for central banks to evaluate whether intentions of a policy decision are well-communicated, but also for market participants to appropriately adjust their individual forecasting device for future monetary policy actions. Particularly during crisis times it appears as a pressing question whether a significant policy easing or an announcement of a non-standard policy measure is interpreted by market participants to reflect a change in policy preferences or a response to revisions in the economic outlook.

We apply the new econometric tool to tick-data of short and long term German government bond futures from 2001 to 2012. The focus of the empirical part is on 133 policy announcement days of the European Central Bank (ECB). ECB announcement days comprise the actual decision on the key interest rate published via a press release and a subsequent press conference that provides further explanations and forward guidance. Therefore, we report besides aggregated results for a single announcement day also an intradaily response pattern that allows to isolate effects of the different communication channels.

Empirical results suggest that 15% of the ECB policy announcement days are interpreted by market participants to provide news about the state of the economy. In contrast, less than 1% can be considered to be driven by perceived adjustments in ECB policy preferences. We find that perceptions about policy preferences have become more accurate after the ECB's clarification of its monetary policy strategy in 2003. Perceptions remain remarkable stable during the recent global financial and European sovereign dept crisis. While there are a few adjustments in the yield curve as a result of the market being surprised by the policy rate announcement itself, the majority of significant yield curve reactions occur during the ECB's communication in the subsequent press conference. We show that providing information about current and future economic developments through press conferences has gained in importance during the recent global financial and European sovereign debt crisis. All in all, the results reflect a credible monetary policy conduct and clear communication. It appears that markets have well understood the ECB's policy reaction function with regard to the achievement of its policy objective.

1 Introduction

Understanding market responses to monetary policy announcements is of great interest for policy makers, financial market participants and academia alike. As central banks typically steer a very short term interest rate, a focal point of research has been on the transmission of monetary policy from the key policy rate to longer-term market interest rates.

The predominant approach to investigate the response pattern of the yield curve traces back to Cook and Hahn (1989) and Kuttner (2001), who regress changes in interest rates of single maturities on a monetary policy surprise variable.[1] While such regressions have established that the shorter-end of the yield curve consistently moves in the direction of the policy surprise, regression results for the longer-end of the yield curve are rather mixed and elusive. For the example of a ten year maturity of different countries or sample periods, empirical studies report inverse (e.g. Goldberg and Leonard, 2003), non-significant (e.g. Beechey and Wright, 2009) and positive (e.g. Gürkaynak et al., 2005) responses to the policy surprise variable.

The mixed regression results suggest that the response pattern of the yield curve is more sophisticated than a conventional surprise variable is able to explain. In fact, the theoretical models of Ellingsen and Söderström (2001) and Rudebusch and Wu (2008) show that it is not the occurrence and size of a policy surprise but the market perceived *source* of the surprise that determines the response pattern of the yield curve. Referring to a Taylor (1993) monetary policy reaction function, the models show that a policy surprise induced by news about economic conditions shifts all interest rate maturities in the same direction (*level shift* of the yield curve). In contrast, a policy surprise triggered by changes in central bank policy preferences drive the short and long end of the yield curve in opposite directions (*rotation* of the yield curve). These findings suggest to isolate the effect of a single policy announcement rather than studying average response patterns of the yield curve across years of monetary policy. However, econometric approaches are lacking to independently test single policy announcements for the occurrence of significant shifts and rotations of the yield curve.

The present paper aims at closing that gap. Our main contributions are both methodological and empirical. We propose a statistical test based on simultaneous jumps (cojumps) in intraday tick-data of a short and long term interest rate to discriminate between significant *level shifts* and *rotations* of the yield curve. In line with Lahaye et al. (2011), among others, (co)jumps in intraday data reflect adjustments to the news flow in the markets.

[1] The surprise is usually defined as an unexpected changes in the key rate. Measures of monetary policy surprises employ derivative prices (Kuttner, 2001), survey expectations (Ehrmann and Fratzscher, 2003) or jumps in short term interest rates (Winkelmann, 2013).

Hence, the occurrence of a cojump within an intraday time interval around a central bank announcement detects a significant monetary policy surprise. The basic idea of the paper is to gain further information from the relative direction of simultaneous jumps at the short and long end of term structure. According to Ellingsen and Söderström (2001), distinguishing between instantaneous shifts and rotations of the term structure allows to determine the underlying source of a policy surprise. We detect level shifts through unidirectional jumps and rotations by cojumps where the short and long end of the yield curve jump in opposite directions.[2] To test for significant level shifts and rotations, we employ the cojump estimator and test proposed by Bibinger and Winkelmann (2013). The day-wise test is based on spectral estimation of a bivariate semimartingale and extends the work of Reiß (2011) and Bibinger and Reiß (2014). In comparison to the cojump estimators of Jacod and Todorov (2009) and Mancini and Gobbi (2012), one crucial advantage of the spectral estimator is its robustness to market microstructure frictions and non-synchronous observations.[3] Utilizing tick-data around second by second observations instead of skip-sampling to e.g. five minute intervals appears important to preserve information on particular intraday time intervals where central banks communicate with markets. The high frequency perspective and the localizing features of the spectral estimator allow us to isolate significant responses to a single policy announcement and to achieve statistical independence of adjacent days. This is in sharp contrast to previous techniques like the classification of shifts and rotations via a factor model of the term structure with daily data by Claus and Dungey (2012).

We investigate markets' perceptions about 133 policy announcement days of the European Central Bank (ECB) from 2001 to 2012. Due to the absence of a mutual Euro Area bond market (Eurobonds), the empirical analysis is based on the term structure of German government bonds. Using intraday tick-data of short and long term interest rate futures, offers a unique way of studying the instantaneous response pattern of the yield curve to a single monetary policy announcement. As demonstrated by Ehrmann and Fratzscher (2009) and Conrad and Lamla (2010), ECB announcement days not only affect markets through a press release on the actual decision on the key interest rate, but also move markets through a subsequent press conference that provides important information about the reasons behind the policy decision. Our approach allows to pin down surprises induced by the two communication channels. We use detected cojumps in response to the press

[2]Note that Ellingsen and Söderström (2001) define shifts and rotations in the way that the whole term structure moves, i.e. both the short *and* long end adjust. We follow that idea. However, one can think about rotations triggered by idiosyncratic jumps at either the short or long end. For cojumps in response to the ECB's press release about the actual change in the key policy rate, regressions show that we do not miss a significant number of policy surprises by focusing on cojumps only, see Section 5.3 and Appendix D.

[3]See Aït-Sahalia et al. (2005) and Zhang (2011) for a discussion why accounting for market microstructure frictions and non-synchronous observations is important for high-frequency data at observation frequencies higher than ≈ 5 minutes.

releases and press conferences to set up regressions that justify the focus on cojumps to detect policy surprises and to support the empirical validity of the structural implications of the Ellingsen and Söderström (2001) and Rudebusch and Wu (2008) models.

Our empirical results indicate that 15% of ECB policy announcements are interpreted by market participants to provide news about the current and future state of the economy. In contrast, less than 1% can be considered to be driven by perceived adjustments in ECB policy preferences. In particular, we find that perceptions about policy preferences have become more accurate after the ECB's clarification of its monetary policy strategy in 2003. Our results confirm the general ability of central banks to guide market expectations. While there are a few adjustments in the yield curve as a result of the market being surprised by the policy rate announcement itself, the majority of significant yield curve reactions occur during the ECB's communication in the subsequent press conference. We show that providing information about current and future economic developments through press conferences has gained in importance during the recent global financial and European sovereign debt crisis, compare the discussion by Woodford (2012). All in all, the results reflect a credible monetary policy conduct and clear communication. It appears that markets have well understood the ECB's policy reaction function with regard to the achievement of its policy objective.

The present paper is arranged in six upcoming sections. Section 2 reviews the link between monetary policy surprises and level shifts and rotations of the yield curve. The spectral estimator of cojumps and the test for level shifts and rotations of the yield curve are introduced in Section 3. Section 4 presents the high frequency tick-data of the yield curve. Empirical results are discussed in Section 5. Section 6 concludes.

2 Sources of policy surprises and the yield curve

Following the pathbreaking work of Taylor (1993), Clarida et al. (1998) and Clarida et al. (1999), an extensive theoretical and empirical literature has studied interest rate settings by central banks. A broad consensus has emerged that monetary policy can be described by a simple rule that connects changes in a central bank's key interest rate Δr_t with changes in main economic variables, i.e. in inflation $\Delta\pi_t$ and output Δy_t:

$$\Delta r_t = \lambda\Delta\pi_t + (1-\lambda)\Delta y_t, \quad \lambda \in [0,1]. \tag{1}$$

The rule simply implies that central banks increase (decrease) their key rate when inflation rises (falls) or when output expands (weakens), in order to reduce (induce) future inflationary pressure. In accordance with Taylor (1993), rules like (1) are called Taylor-rules.

Although Taylor-rules rules are remarkably adept at describing central banks' interest rate decisions empirically, the implementation of reaction functions is not officially confirmed by central banks. Therefore, interest rate rules remain rather implicit and markets' expectations about future policy decisions depend on individual assessments about the future economic variables as well as the central bank's preference parameter λ, see e.g. Schmidt and Nautz (2012). In this context, monetary policy surprises can be triggered by two distinct sources: First, news about π_t and y_t, such that markets readjust expectations about current and future economic conditions. Second, changes in the preference parameter λ, such that markets change the weighting of the economic variables in their individual interest rate rules. In both cases markets update their expectations about future key rates and price the changes into the yield curve.[4]

The stylized macroeconomic model of Ellingsen and Söderström (2001) suggests the identification of the market perceived sources of policy surprises through the particular response pattern of the yield curve.[5] They extend a dynamic version of a simple aggregate supply-aggregate demand model by the expectations hypothesis of interest rates. An interest rate rule like (1) determines the optimal strategy of monetary policy in that framework. Inducing information asymmetries between market participants and the monetary policy authority, they find two distinct response patterns of the yield curve that disentangle the two sources of monetary policy surprises. First, in the case where markets interpret the policy surprise to provide news about current and future economic conditions, changes in expected future key rates shift all yields of the maturity structure in the same direction (level shift). Second, if markets perceive the policy surprise to reflect changes in policy preferences, revisions of expected future key rates drive the short and long end of the yield curve in opposite directions (rotation).

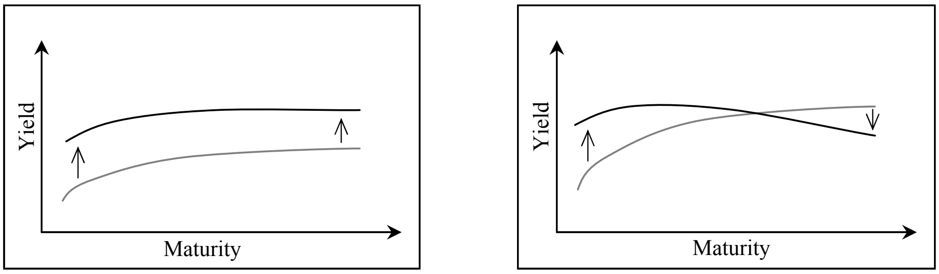
In economic terms, level shifts and rotations can mainly be explained by the connection of interest rates and markets' inflation expectations, compare Ehrmann et al. (2011). While changes in shorter-term rates are mostly driven by the current key rate, responses of longer-term interest rates are determined by policy effects on future inflation. Due to relatively strong inflation persistence, documented in e.g. Hassler and Wolters (1995) and Meller and Nautz (2012), news that significantly affect the current rate of inflation translate to revisions of inflation expectations along *all* maturity horizons, see also the discussion in Gürkaynak et al. (2007).[6] Therefore, a positive (negative) policy surprise that reflects significant news about an increase (decrease) in current inflation and output

[4]Note that the market perceived inflation target is assumed to be constant. In that framework changes in perceived policy preferences are fully captured by the parameter λ.

[5]We focus here on Ellingsen and Söderström (2001). However, similar conclusions can be drawn from a standard DSGE model (Ellingsen and Söderström, 2006) and, with a slightly different terminology, from a macro-finance model (Rudebusch and Wu 2008).

[6]Note that the joint movements appear as a necessary condition of level shifts and rotations.

Figure 1: Upward level shift (left) and a rotation (right) of a yield curve.



Notes: Adapted from Figure 1 and Figure 2 in Ellingsen and Söderström (2001).

increases (decreases) inflation expectations at every expectation horizon. As illustrated by the left hand plot of Figure 1, in this case, the yield curve shifts upwards (downwards). In contrast, a positive (negative) policy surprise observed to increase (decrease) the weight on inflation, decreases (increases) inflation persistence. Consequently, shocks to inflation decay faster (slower) and longer-term inflation expectations drop (move up).[7] The right hand plot of Figure 1 displays an example of a resulting rotation of the yield curve.

In the following, we provide a test for level shifts and rotations of the yield curve. We refer to high-frequency tick-data of interest rates on monetary policy announcement days to distinguish between the two response patterns of the yield curve.

3 Methodology: Level shifts and rotations of the yield curve

The test for level shifts and rotations is based on the spectral cojump estimator and test proposed by Bibinger and Winkelmann (2013). First, we highlight the estimation problem in the context of tick-data of the short and long end of the term structure. Second, a review and discussion of the spectral estimator of cojumps in the bivariate case is given. Finally, we introduce the test for level shifts and rotations of the yield curve.

3.1 Non-parametric volatility model

Due to the imperfections of trading processes, tick-data is widely known to be very noisy, see e.g. Hautsch (2012). The noise comes from a vast array of issues collectively known as market microstructure, including price discreteness, infrequent trading and bid-ask bounce effects. A common modeling framework for noise perturbation in high-frequency data is

[7] This argument requires the increase (decrease) of the weight on inflation to be taken during times where inflation is above (underneath) a target or steady state value.

to treat the microstructure as observation error, see e.g. Aït-Sahalia et al. (2005). In the following, the notation $t \in [0,1]$ refers to the trading time of a single day. Thus, we aim at presenting cojump statistics for each day separately.

Let $Y^{(q)} = (Y_i^{(q)})_{i=0,..,T^{(q)}}$ denote the log of discretely observed high-frequency prices with $q = 1$ the short end and $q = 2$ the long end of the maturity structure. The index $i = 0, ..., T^{(q)}$ counts respective intraday observations. The observed processes are then expressed as the latent, true log-price processes $X^{(q)} = (X_i^{(q)})_{0 \le i \le T^{(q)}}$, recorded at – in general – non-synchronous observation times $t_i^{(q)}$ plus market microstructure noise $\varepsilon_i^{(q)}$.

$$Y_i^{(q)} = X_i^{(q)} + \varepsilon_i^{(q)}, \quad q = 1, 2\,,\ i = 0, 1, ..., T^{(q)}\,. \tag{2}$$

The microstructure noise is a mean zero, i.i.d. sequence with standard deviation $\eta^{(q)}$ and independent of $X^{(q)}$. In accordance with term structure models of e.g. Duffie and Kan (1996) and Dai and Singleton (2000), we utilize the class of semimartingales to model the true bond price processes $X^{(q)}$. The short and long end of the maturity structure evolves as

$$dX_t^{(q)} = \mu_t^{(q)} dt + \sigma_t^{(q)} dW_t^{(q)} + dJ_t^{(q)}\,, \quad q = 1, 2\,,\ t \in [0, 1]\,, \tag{3}$$

where $\mu_t^{(q)}$ is a drift, $\sigma_t^{(q)}$ the spot volatility, $W_t^{(1)}$ and $W_t^{(2)}$ correlated standard Brownian motions with $d[W^{(1)}, W^{(2)}]_s = \rho_s\, ds$ and $J_t^{(1)},\ J_t^{(2)}$ possibly correlated pure jump processes.

The main goal is to provide an estimator of simultaneous jumps under (2). The general idea to achieve this goal stems from the non-noisy case and considers occasions where the product of jump sizes $\Delta J_t^{(1)} \Delta J_t^{(2)}$ is different from zero, compare Mancini and Gobbi (2012). Therefore, the cojump estimation is usually based on the quadratic covariation between the true log-prices:

$$[X^{(1)}, X^{(2)}] = \int_0^1 \rho_t \sigma_t^{(1)} \sigma_t^{(2)} dt + \sum_{0 \le t \le 1} \Delta J_t^{(1)} \Delta J_t^{(2)}\,, \quad t \in [0, 1]. \tag{4}$$

The covariation comprises two parts, the integrated covolatility and the cojumps. The integrated covolatility is made up of the spot volatilities $\sigma_t^{(q)}$ and the correlation ρ_t between the two Brownian semimartingale parts. The cojumps are given by the sum of cross products between simultaneous jumps. To estimate the two parts in (4) under noisy and non-synchronous observations, we utilize the spectral cojump estimator of Bibinger and Winkelmann (2013).

3.2 Spectral estimator of cojumps

The spectral estimator of cojumps by Bibinger and Winkelmann (2013) is build on Reiß (2011) and Bibinger and Reiß (2014). It provides a cojump estimator via thresholding increments of the estimated quadratic covariation (4). Estimation in the spectral domain benefits from the orthogonality of the transform, hence, reduces the estimator's variance. The trading time $t \in [0,1]$ is split into h^{-1} non-overlapping blocks. The block-wise map of observed returns $\Delta_i Y^{(q)} = Y_i^{(q)} - Y_{i-1}^{(q)}$, $i = 1, ..., T^{(q)}$, $q = 1, 2$, in the frequency domain is accomplished via the sine basis. The spectral statistic for block $k = 0, ..., h^{-1} - 1$ and frequency $j = 1, ..., J$ is given by

$$S_{jk}^{(q)} = \frac{\sqrt{2h}}{j\pi} \sum_{i=2}^{T^{(q)}} \Delta_i Y^{(q)} \sin\Big(j\pi h^{-1}(t_i^{(q)} - kh)\Big) \mathbb{1}_{[kh,(k+1)h]}(t_i^{(q)}), \tag{5}$$

where the indicator function $\mathbb{1}$ evaluates the transform on block k. The spectral statistics are the key elements of our statistical methods. As localized Fourier coefficients, by orthogonality of the sine functions, they de-correlate the noisy returns and form their block-wise principal components. Hence, the map in the frequency domain results in independent statistics $S_{jk}^{(q)}$, $j \geq 1$. Information from non-synchronous intraday returns within each block k is translated to the synchronous spectral statistics $S_{jk}^{(1)}, S_{jk}^{(2)}$, $k = 0, ..., h^{-1} - 1$. The expansion (5) can be considered a linear combination of weighted (with the sine) pre-averages of the return series that smooth out the microstructure. Higher frequencies contain diminishing information about the process (3), thus, we discard frequencies above a spectral cut-off J.

Block-wise increments in the quadratic covariation (4) between the short and long term interest rate are provided by the **SP**ectral **E**stimator of the **C**o**V**ariation

$$\Delta_k \mathbf{SPECV}(Y^{(1)}, Y^{(2)}) = h \sum_{j=1}^{J} w_{jk} \frac{\pi^2 j^2}{h^2} S_{jk}^{(1)} S_{jk}^{(2)}, \quad k = 0, ..., h^{-1} - 1, \tag{6}$$

such that on $t \in [0,1]$ for $T^{(q)} \to \infty$

$$\sum_{k=0}^{h^{-1}-1} \Delta_k \mathbf{SPECV}(Y^{(1)}, Y^{(2)}) \xrightarrow{\mathbb{P}} [X^{(1)}, X^{(2)}]. \tag{7}$$

The spectral estimation methodology has been motivated by Reiß (2011) founded on an asymptotic equivalence of the non-parametric and a locally (block-wise) parametric model as the block length $h \to 0$. Bibinger and Reiß (2014) have constructed such an estimator in order to infer on the integrated covolatility in the absence of jumps. The estimator in (7) arises as a Riemann sum over blocks of local parametric covariation estimates which rely on an optimal linear combination of cross products of spectral statistics over different frequencies in the Fourier domain. The optimal weights w_{jk}, with $\sum_j w_{jk} = 1$, are proportional to local Fisher information and minimize the estimator's mean square error, see Bibinger and Winkelmann (2013) for their explicit form. The method attains the optimal convergence rate and, moreover, its asymptotic variance coincides with the statistical lower bound as shown by Bibinger et al. (2013). Thus, the asymptotic properties of the statistical method can not be further improved by any other approach which is called asymptotic efficiency.

Bibinger and Winkelmann (2013) proved that in the presence of cojumps the entire quadratic covariation (4) between the true price processes $X^{(q)}$ is consistently estimated by the approach. Under vanishing microstructure noise all frequencies are weighted equally and the estimator reduces to the realized covolatility, the natural choice in this situation. From (4) it follows that the absolute value of increments of quadratic covariation (6) are much larger on blocks k where the product of jump sizes is different from zero. Therefore, cojumps can be detected and estimated via thresholding the increments of the quadratic covariation. The daily **SP**ectral **E**stimator of **CoJ**umps in interest rates based on a locally adaptive threshold u_k is given by

$$\mathbf{SPECJ}(Y^{(1)}, Y^{(2)}, u_k) = \sum_{k=0}^{h^{-1}-1} \Delta_k \mathbf{SPECV}(Y^{(1)}, Y^{(2)}) \mathbb{1}_{\{|\Delta_k \mathbf{SPECV}(Y^{(1)}, Y^{(2)})| > u_k\}}, \quad (8)$$

with $T^{(q)} \to \infty$ on $t \in [0, 1]$ satisfying

$$\mathbf{SPECJ}(Y^{(1)}, Y^{(2)}, u_k) \xrightarrow{\mathbb{P}} \sum_{0 \le t \le 1} \Delta J_t^{(1)} \Delta J_t^{(2)}. \quad (9)$$

If an increment in quadratic covariation estimates on a given block k is below the threshold u_k, it contributes to the integrated covolatility. In contrast, increments above the threshold localize and consistently sum up to cojumps. Since increments of the Brownian components in (3) are normally distributed, extreme value theory provides a supremum of block-wise increments of the integrated covolatility. One core result of Bibinger and Winkelmann (2013) is that the truncated integrated covolatility estimator where large block-wise estimates are excluded attains the same optimal asymptotic properties as the spectral estimator in absence of cojumps. This means asymptotically we can precisely disentangle cojumps from the continuous movement. In practice, we shall use the locally adapted threshold $\hat{u}_k = 2\log(h^{-1}) h \sigma_k^{(1,2)}$, with $k = 0, ..., h^{-1} - 1$ and $\sigma_k^{(1,2)}$ a pilot estimator of the spot covolatility, to separate the integrated covolatility and cojumps. To obtain a feasible pilot estimator, we refer to local averages of (6) in the neighborhood of k with equally weighted spectral statistics.

The sign of the spectral estimator of cojumps (8) can be interpreted like the sign of a correlation coefficient. It reflects whether the relation between the short and long end of the term structure is positive or negative. Thus, up to the block length h, $h \to 0$ asymptotically, we can detect cojumps and also verify whether they are unidirectional or point in different directions. We emphasize that the block width h does not cause any (finite-sample) bias in the estimates. It is chosen large enough to sufficiently smooth out noise dilution and as small as possible to allow a high resolution over the intraday clock. The approach is quite robust to different choices of h, for applications to trades within one day typically h between 20 and 60 is an adequate range. This is confirmed by a Monte Carlo study incorporating different specifications of h by Altmeyer and Bibinger (2014).

As our focus is on disentangling cojumps and covolatility, the threshold becomes the most important parameter (or function) to adjust. The locally adaptive block-wise rule by Bibinger and Winkelmann (2013), stated above, is eligible to account for intraday volatility shape and at the same time guarantees a well-founded data-driven selection without further tuning parameters involved. If cojumps are small it gets harder to detect them with thresholding, but our major interest is in significant cojumps that reflect reactions to relevant monetary policy surprises. The finite-sample properties of the procedure are considered in a Monte Carlo study in Appendix A below. Next, we propose the test to detect level shifts and rotations of the yield curve.

3.3 The test for level shifts and rotations

Based on the spectral estimator of cojumps (8) for noisy and non-synchronous tick-data of a short and long term interest rate, we provide a test for level shifts and rotations of the term structure. For a single trading day, the test evaluates the direction of simultaneous jumps. We formalize the alternative hypotheses as follows:

Level shift hypothesis: $H_1^L := \left(\sum_{0\le t\le 1} \Delta J_t^{(1)} \Delta J_t^{(2)}\right) > 0$

- The short end ($q = 1$) and long end ($q = 2$) of the yield curve jump in the same direction. Significant cojumps lead to a parallel shift of the term structure.

Rotation hypothesis: $H_1^R := \left(\sum_{0\le t\le 1} \Delta J_t^{(1)} \Delta J_t^{(2)}\right) < 0$

- The short end ($q = 1$) and long end ($q = 2$) of the yield curve jump in opposite directions. Significant cojumps tilt the term structure.

The null hypothesis stresses that no cojump occurs, i.e. $H_0 := \left(\sum_{0\le t\le 1} \Delta J_t^{(1)} \Delta J_t^{(2)}\right) = 0$. To test the hypotheses, we utilize one-sided alternatives of the wild bootstrap type of test proposed by Bibinger and Winkelmann (2013). The wild bootstrap principle avoids that the test statistic degenerates under H_0 by disturbing its block-wise increments in the case of no cojumps. Similar to the cojumps estimator (8), the test statistic is based on the increments in quadratic covariation (6):

$$\mathcal{T}(Y) = T_{min}^{\frac{1}{4}} \sum_{k=0}^{h^{-1}-1} \Delta_k \mathbf{SPECV}(Y^{(1)}, Y^{(2)}) \left(1 - \zeta_k \mathbb{1}_{\{|\Delta_k \mathbf{SPECV}(Y^{(1)},Y^{(2)})| \leq u_k\}}\right), \quad (10)$$

where T_{min} denotes $\min\left(T^{(1)}, T^{(2)}\right)$, $\mathbb{1}$ is the indicator function and ζ_k are i.i.d. random disturbance terms on each intraday block k. For $\zeta_k = 1$ for all k, $\mathcal{T}(Y)$ is simply $T_{min}^{1/4}\mathbf{SPECJ}(Y^{(1)}, Y^{(2)}, u_k)$. With ζ_k a binomial process, satisfying $\mathbb{P}(\zeta_k = 0.9) = 0.5 = \mathbb{P}(\zeta_k = 1.1)$, and the self-normalized test statistic $\widetilde{\mathcal{T}}(Y)$, Bibinger and Winkelmann (2013) establish a central limit theorem under the null of no cojumps:

$$\widetilde{\mathcal{T}}(Y) = \left(T_{min}^{\frac{1}{2}} \sum_{k=0}^{h^{-1}-1} \left(\Delta_k \mathbf{SPECV}(Y^{(1)}, Y^{(2)})\right)^2 var(\zeta_k)\right)^{-\frac{1}{2}} \mathcal{T}(Y) \rightsquigarrow N(0,1), \quad (11)$$

where $\rightsquigarrow$ means convergence in law. Thus, the standard normal distribution and its quantiles provide critical values to test the null hypotheses. The Monte Carlo study in Appendix A explores the accuracy of the asymptotic results for finite-sample applications. Since the cojump estimator constitutes the dominating term of $\widetilde{\mathcal{T}}(Y)$ under the alternative, see the proof of Theorem 3 in Bibinger and Winkelmann (2013), the test statistic satisfies under the alternative $\widetilde{\mathcal{T}}(Y) \to \pm\infty$ and the sign comes from negative or positive cojumps, respectively. Thereby, we implicitly obtain one-sided test procedures with the asymptotic normality on the hypothesis which we exploit in the following. In particular, the sign of $\widetilde{\mathcal{T}}(Y)$ enables the discrimination between the level shift and rotation hypothesis. The test for shifts and rotations is summarized by the following diagram.

$$\begin{cases} H_1^L := \left(\sum_{0\leq t\leq 1} \Delta J_t^{(1)} \Delta J_t^{(2)}\right) > 0 & \text{if } \widetilde{\mathcal{T}}(Y) > c_{1-\alpha} & \Leftrightarrow & \text{level shift} \\ H_1^R := \left(\sum_{0\leq t\leq 1} \Delta J_t^{(1)} \Delta J_t^{(2)}\right) < 0 & \text{if } \widetilde{\mathcal{T}}(Y) < c_{\alpha} & \Leftrightarrow & \text{rotation} \\ H_0 := \left(\sum_{0\leq t\leq 1} \Delta J_t^{(1)} \Delta J_t^{(2)}\right) = 0 & \text{if } |\widetilde{\mathcal{T}}(Y)| \leq c_{1-\alpha} & \Leftrightarrow & \text{no cojump} \end{cases}$$

The test can be seen as a mixture of two one-sided tests. Since both are based on the same test statistic and differ by their sign only, we take them as a single test. The practical implementation works as follows: We choose a significance level α and compute the test statistic. If $\widetilde{\mathcal{T}}(Y)$ is positive, we compare the test statistic with the upper critical value $c_{1-\alpha}$. In the case where the test statistic is larger than $c_{1-\alpha}$, we detect a level shift of the yield curve. If $\widetilde{\mathcal{T}}(Y)$ is negative, we take the lower critical value c_α. A test statistic smaller than c_α, detects a rotation. If both critical values are not exceeded, we find no significant shift or rotation of the yield curve.[8]

We now introduce the high-frequency interest rate data to test ECB announcement days for shifts and rotations of the yield curve.

4 Yield curve data

To study the individual response pattern of the yield curve to monetary policy announcements of the ECB, we refer to tick-data on German government bonds. Instead of picking actually traded bonds, we utilize futures data from the derivative exchange EUREX.[9] Compared to bonds, futures usually have the advantages to be traded more frequently and to represent constant maturity prices. As evidenced by Dungey and Hvozdyk (2012), high frequency prices of government bond futures share closely related dynamics with the underlying bond market, especially the occurrence of jumps are strongly correlated.

The short end of the term structure is represented by the Euro-Schatz Futures (FGBS), whose underlying is a fictive German government bond maturing in about 2 years having a coupon of six percent. The FGBS closely captures the medium term policy horizon of the ECB. While the 2 year maturity is sufficiently long to prevent a close control via monetary policy, it is sufficiently short to be consistent with the direction of money market responses to monetary policy announcements.[10]The long end of the term structure is captured by the Euro-Bund Futures (FGBL), which calls for the delivery of a fictive 10 year German government bond with a coupon of six percent. The 10 year horizon of FGBL is important for investment and saving decisions, however, not explicitly triggered by monetary policy.

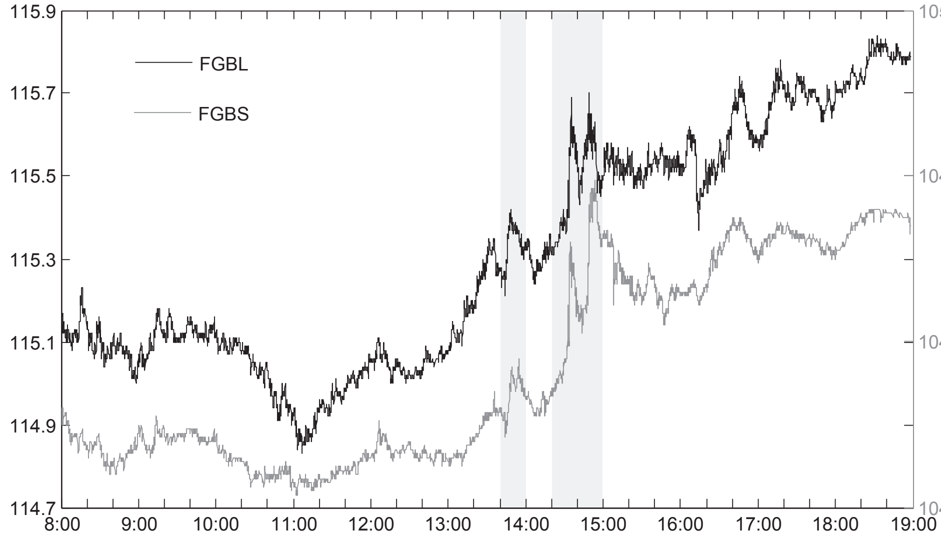
Our sample includes tick-data of FGBS and FGBL from January 2001 to August 2012. For both futures we take the most frequently traded contract month, which is the three month expiring horizon. Allowing for recurring response patterns, we focus on 133 scheduled ECB policy announcements, which typically take place on the first Thursday of each month. On each announcement day the ECB follows a fixed communication scheme. The decision on the key rate is published via a press release at 13:45 CET and is further explained in a subsequent press conference starting at 14:30 CET. The press conference consists of two parts, the reading out of an introductory statement by the ECB's president followed by a question and answer session. Besides the announcement days, we take 458 Thursdays without ECB policy announcements to compare the average response patterns.

[8]Note that the null hypothesis includes disjoint jumps at either the short or long end of the term structure.

[9]The data is provided by the "Research Data Center" of the CRC 649.

[10]E.g. Gürkaynak et al. (2005) and Brand et al. (2010) report a positive relation between monetary policy surprises and a 2 year rate. Appendix D provides evidence that the 2 year German bond futures jump in the direction of the policy surprise. Thus, using a shorter than 2 year (e.g. money market) maturity does not change the test results on level shifts and rotations.

Figure 2: German government bond futures on October, 2. 2008.



Notes: Price notation. FGBS (grey) represents the 2 year maturity, FGBL (black) the 10 year maturity. Number of ticks: FGBL 7,710; FGBL 14,849. Intervals where the ECB communicates with markets are emphasized.

We fix the trading time from 8:00 CET to 19:00 CET. The average number of trades per day is around 10,000 for the FGBL series and around 5,000 for FGBS. The different numbers of observations in the short and long term futures markets are a consequence of non-synchronous transactions. As widely acknowledged, intraday tick-data is affected by market microstructure noise, see further discussion in Appendix B. The spectral estimation approach is designed for these typical characteristics of high frequency data.

Figure 2 provides an example of the tick-data for October, 2. 2008. The figure reflects positively correlated dynamics of the 2 and 10 year prices. Particularly around the shaded time intervals where the ECB communicates with markets, both series appear to be tied together more closely than during the rest of the day. Due to decreasing yields (increasing prices) at either the short and long end of the term structure, this policy announcement day most likely induces a level shift. Particularly the strong movements around 14:20 to 15:00 CET may reflect the arrival of new information during the press conference.

In the next section, we apply the test for level shifts and rotations to each of the 133 policy announcement days. We evaluate whether the comovements are sufficiently strong to identify policy surprises.

5 Empirical evidence from ECB monetary policy announcements

This section provides empirical evidence about level shifts and rotations of the German yield curve on ECB policy announcement days. First, we apply the cojump estimation and testing procedure introduced in Section 3. The focus is on daily statistics, thus, we determine for each policy announcement day independently whether a level shift, a rotation or no significant joint movement prevails. As discussed in Section 2, we utilize the response pattern of the yield curve to draw conclusions about the market perceived source of a policy surprise. Second, we evaluate the daily results of shifts and rotations. We localize cojumps on intraday time intervals to establish a direct link between the timing of cojumps and the policy communication via press releases and press conferences. We utilize the detected cojumps to set up regressions that justify the focus on cojumps to detect policy surprises and to support the conclusions about the market perceived sources of policy surprises.

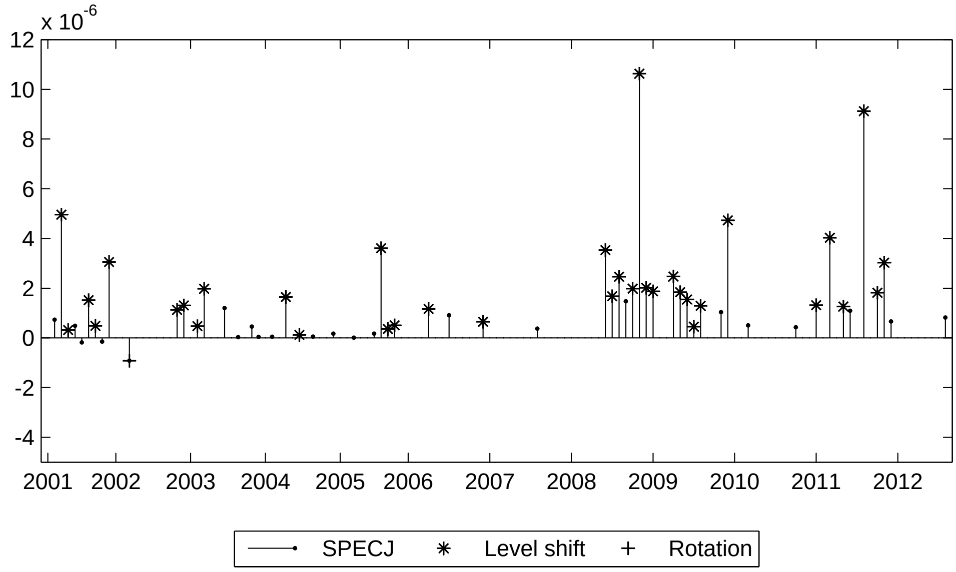
5.1 Shifts and rotations on policy announcement days

In this subsection we present the main results of our test for level shifts and rotations of the term structure. Since the test is based on cojumps, we also report cojump estimates (8) for each of the 133 ECB announcement days. For the daily estimates, we refer to the noisy and non-synchronous intraday tick-data of government bond futures presented in Section 4. We set $h^{-1} = 33$, thus, detect cojumps on 20 minutes time intervals (33 blocks per day). Blocks of 20 minutes appear as a reasonable number to study the timing of shifts and rotations to the ECB's press releases (13:45 CET) and press conferences (starting 14:30 CET). The blocks are sufficiently large to smooth out the microstructure, see the discussion in Section 3.2. We set the frequency cut-off $J = 35$ and refer to a 5% significance level. We find that our economic conclusions do not critically depend on the specific values of these parameters.

Figure 3 summarizes the main results. The bars display the value of the cojump estimator (8) at respective policy announcement days. Since the cojump estimator equals zero in the case where none of the intradaily increments in quadratic covaration exceed the threshold, the majority of the policy announcement days indicate no cojump activity. On 58 out of the 133 ECB announcements, the cojump estimator is different from zero. The larger the absolute size of the estimate, the stronger is the effect of the cojump on the yield curve.[11]

[11] Quantifying the yield curve movement in terms of basis points from the covariance type of estimator is not feasible. The largest tick increase in the 2Y futures is approx. 30 basis points and for the 10Y futures around 80 basis points.

Figure 3: Shifts and rotations of the yield curve on ECB announcement days.



Notes: SPECJ is the cojump estimator (8). *The detection of level shifts and rotations are based on the cojump test (Section 4) and a 5% significance level. Daily estimates and tests refer to tick-data of the short (2 year) and long (10 year) term interest rate.*

However, if on a particular day the intradaily variation is very high, it is possible that even larger estimated cojumps are non-significant. In the same way, relatively small cojumps can be statistically significant if the intradaily variation is very low. The test for level shifts and rotations detects the significant cojumps.

First, we take the negative cojump estimates and verify whether they imply yield curve rotations. The test reveals that only one out of three negative cojump estimates rotates the yield curve. In Figure 3 the rotation is highlighted by a plus sign.[12] Interestingly, policy announcements associated with negative cojump estimates occur in the beginning of the sample around late 2001 and early 2002 only. In terms of identification, negative cojumps suggest that markets tend to interpret the policy announcements to reflect revisions in ECB policy preferences during that time. The finding matches with the assessments of Schmidt and Nautz (2012). For a period before 2003, they find that markets were uncertain about the ECB's reaction function with respect to arising risks to price stability. This also corresponds to the period in which the ECB's Governing Council clarified the ECB's definition of price stability (inflation should be below but close to 2%), see ECB (2003). According to Schmidt and Nautz (2012), this clarification of the policy strategy was an important step towards a more transparent reaction function of the ECB. The test for level

[12]The rotation occurred on March, 7. 2002. More detailed information is provided in Appendix C.

shifts and rotations confirms this finding. Since the policy clarification in 2003, cojump estimates on policy announcement days are exclusively positive. Thus, monetary policy surprises no longer reflect perceived changes in ECB's policy preferences.

Our second focus is on the positive cojump estimates. Significant cojumps that shift the level of the term structure are marked by stars in Figure 3. In total, out of 55 positive cojump estimates 35 are evaluated as level shifts. Level shifts occur more regularly during the global financial crisis (starting around late 2008) and the European sovereign debt crisis (since 2011). As put forward in Section 2, level shifts identify policy surprises perceived to provide news about the current and future state of the economy. Since deep financial turbulence usually reflect uncertain macroeconomic conditions, the state of the economy is more difficult to evaluate during times of financial stress. Particularly during crisis times, the ECB's guidance about macroeconomic variables plays an important role. The more frequent and stronger level shifts around 2008 and 2011 appear as a natural consequence.

The test results suggest a stable and well-communicated policy implementation. In particular, the policy communication during the global financial and European sovereign debt crisis appears to be successful. We observe no adjustments in markets' perceptions about policy preferences during the crisis periods. This provides evidence that financial markets do not perceive the non-standard or unconventional measures, summarized by Eser et al. (2012) and the reference therein, to change the ECB's policy preferences.[13]

5.2 Verification of the test results

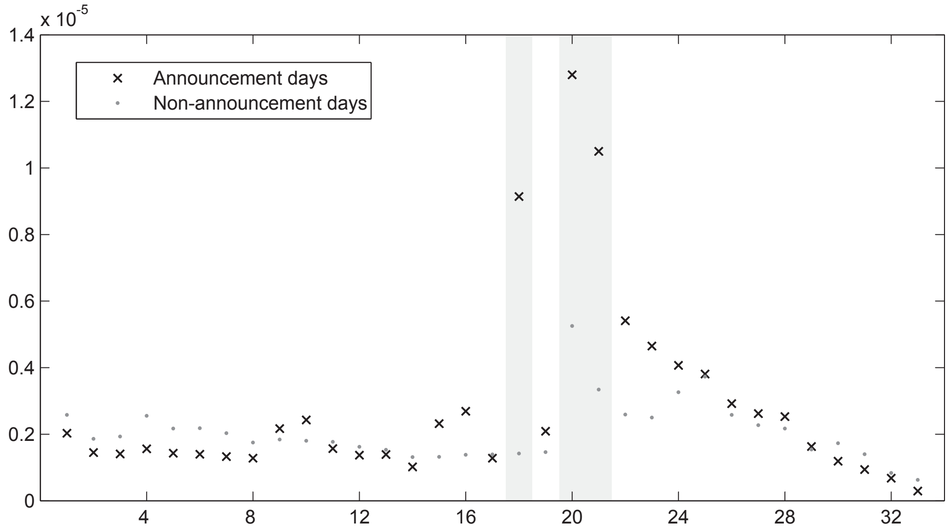
In this subsection we provide evidence that the test for level shifts and rotations detects monetary policy surprises and identifies the market perceived source of a policy surprise. First, we locate the average intradaily timing of shifts and rotations. Second, we set up regressions that explain the intradaily occurrence of cojumps by standard survey measures of monetary policy surprises and wording indicators of the ECB's press conferences.

5.2.1 Intraday localization of cojumps

If level shifts and rotations of the yield curve are driven by monetary policy surprises, they should occur within intraday time intervals where the ECB communicates with markets. To study this relation, we take advantage of the localizing features of the cojump estimator. We refer to average absolute increments in quadratic covariation estimates (6) on the 20 minutes intraday blocks. According to the cojump estimator and test, large increments locate significant shifts and rotations of the yield curve.

[13] Note that the majority of non-standard or unconventional measures were announced in press conferences on policy announcement days.

Figure 4: Average intradaily increments in quadratic covariation estimates.



Notes: The figure depicts average increments of SPECV on each intraday block for the 133 policy announcement and 458 non-announcement days from 2001 to 2012. The x-axis refers to the 33 20 minute intraday blocks. Blocks where the ECB communicates with markets are emphasized.

Figure 4 shows the average increment for each of the 33 20 minutes intraday blocks across the 133 policy announcement days. Increments on policy announcement days (cross) within the shaded intervals clearly indicate that press releases (13:45 CET, block 18) and press conferences (starting at 14:30 CET, block 20, 21) have on average a strong impact on the yield curve. In contrast, the intraday pattern on non-announcement days (gray dots) is rather flat.[14] Thus, the detected level shifts and rotations occur instantaneously in response to the ECB's communication.

The magnitude of increments in quadratic covariation (Figure 4) reflects that the press conferences have on average a stronger effect on the maturity structure than the actual decision on the key rate. The important role of the press conference is also confirmed by focusing on each of the 133 policy announcement days separately, see examples in Appendix C. Out of the 133 announcement days, we detect three days (2% of policy announcements) where yields exclusively cojump in response to the press release. On six days (5% of policy announcements) we find cojumps in response to both the press release and press conference. On twelve days (9% of policy announcements) it is only the press conference that triggers the joint movements in the yield curve. The rare cojumps in response to press releases reflect a good predictability of actual decisions on the key

[14]The spike on non-announcement days on block 20 can be explained by the publication of weekly US jobless claims on Thursdays at 14:30 CET.

policy rate. The relatively more cojumps during the ECB's press conferences emphasize the meaning of press conferences to communicate intentions of policy decisions and to guide markets' expectations, compare Ehrmann and Fratzscher (2009) and Conrad and Lamla (2010). In the context of the structural explanations for level shifts and rotations (Section 2), we conclude that press conferences help market participants to infer the source of policy surprises and to adjust expectations about future policy decisions appropriately.

5.2.2 Explaining the cojumps in regressions

If the theoretical considerations reviewed in Section 2 hold true and if the test proposed in Section 3 consistently detects level shifts and rotations of the yield curve, the test results should be explainable in a regression study. Since the occurrence of rotations is too rare to display a repeating pattern, the focus of this analysis is on the detected level shifts. Inspired by regressions of Lahaye et al. (2011), we explain level shifts that occur on the intraday time intervals of press releases (block $k = 18$) and press conferences (block $k = 20$) in two separate probit regressions.

$$\Pr\left(LS_{k,i} = 1 \,|\, X_{k,i}\right) = \Phi(X_{k,i}\beta), \qquad k = 18, 20,\ i = 1, ..., 133. \tag{12}$$

$LS_{k,i}$ is a level shift indicator at block k and policy announcement day i. It equals one if a significant level shift is detected at day i and the increment in quadratic covariation (6) at block k is above the threshold $\hat{u}_k$. $\Phi(\cdot)$ is the cumulative distribution function of the standard normal distribution and β the vector of regression coefficients. The two regressions incorporate explanatory variables $X_{k,i}$ that cover information given during the respective intraday blocks. We study the whole sample period of 133 policy announcement days from 2001 to 2012.

Level shifts in response to press releases

Level shifts occurring on the intraday time interval where the ECB announces the actual change in the key policy rate ($LS_{18,i}$) are regressed on a target surprise and dispersion measure ($X_{18,i}$). The target surprise is the absolute deviation of Bloomberg survey expectations from the actual decision on the key interest rate. The dispersion measures the heterogeneity of individual survey responses. Table 1 indicates that the conventional monetary policy surprise measures explain the occurrence of level shifts of the yield curve. The larger the target surprise, the more likely is a level shift on the press release block. Furthermore, a more pronounced heterogeneity of the expectations about the decision on the key rate (dispersion) increases the probability of a level shift of the term structure.
The regression on the press release block documents that the test for level shifts and

Table 1: Probit models for level shifts.

Intraday event: Level shift indicator: $LS_{k,i}$	Press release $\Pr(LS_{18,i} = 1 \mid X_{18,i})$	Press conference $\Pr(LS_{20,i} = 1 \mid X_{20,i})$
Survey expectations		
· Target surprise	0.62^{***} (0.12)	-0.02 (0.24)
· Dispersion	4.80^{***} (0.96)	1.99 (1.20)
Wording indicators: Economic news		
· Staff projections: Inflation		5.76^{***} (2.10)
· Staff projections: GDP		4.18^{**} (1.68)
· KOF index (inflation)		2.01^{*} (1.22)
Control variables		
· Code word: 'Vigilance' dummy		-0.18 (0.54)
· 'non-standard measure' dummy		1.99^{***} (0.55)
· US jobless claims surprise		0.43^{*} (0.22)
McFadden R^2	0.44	0.27

Notes: ML estimates of the Probit model (12) on intraday blocks ($k = 18, 20$) for $i = 1, ..., 133$ monetary policy announcement days. *,**,*** indicates significance at the 10%, 5% and 1% level, respectively. Robust standard errors are given in parenthesis. The robustness refers to certain misspecifications of the underlying conditional distribution of $LS_{k,i}$. Considered time period: 2001-2012.

rotations detects monetary policy surprises. By focusing on cojumps, we do net miss a significant number of policy surprises. The results provide a link to the standard linear regression literature of Cook and Hahn (1989) and Kuttner (2001). As documented in e.g. Andersson et al. (2009) and Brand et al. (2009), responses of single maturities along the term structure to ECB policy surprises are uniformly positive. Our test for level shifts and rotations confirms that finding and suggests that the majority of yield curve responses are simultaneous adjustments at both the short and long end of the maturity structure.

Level shifts in response to press conferences

Level shifts during the intraday time interval where the ECB holds its press conference ($LS_{20,i}$) are studies in a second probit regression. Explanatory variables $X_{20,i}$ include $X_{18,i}$ to allow for systematic readjustments to the actual decision. Furthermore, wording indicators measure information provided within the press conferences. In every third press conference the ECB staff macroeconomic projections are read out. We consider absolute revisions of one year ahead projections on inflation and the GDP to provide relevant news. Forward looking statements during the press conference regarding risks to price stability are modeled by the KOF Monetary Policy Communicator.[15] Besides this three major economic variables, we include two dummies and surprises of weekly US jobless claim announcements as control variables. The control variables are meant to account for further potential sources of cojumps during the press conferences, e.g. US jobless claims are published on Thursdays at 14:30 CET, thus coincide with the beginning of the ECB's press conference.

Regression results presented in Table 1 suggest that significant yield curve movements during the ECB's press conferences can not be explained by readjustments to surprise about the actual decision on the key interest rate. Both survey expectations measures are non-significant. In the context of regressions with EURIBOR futures by Ehrmann and Fratzscher (2009), our finding indicates that readjustments may occur at the shorter-end of the yield curve, but do not trigger simultaneous adjustments at the long end of the maturity structure. In contrast to the survey expectations, wording indicators about macroeconomic conditions display a significant impact. Particularly the announcements of the ECB staff projections trigger level shifts of the term structure. The stronger the absolute revision of mean projections compared to the previous quarter, the more likely the occurrence of a level shift. Confirming the impact of the communication about key macroeconomic variables, also the KOF index (Monetary Policy Communicator) is statistically significant. Thus, similar to EUR/USD exchange rates studied by Conrad and Lamla (2010), pronounced statements during ECB's press conferences concerning risks to price stability trigger significant adjustments of the yield curve.
The considered wording indicators provide a prime example where the ECB provides information about the current and future state of the economy. The significant responses of the yield curve to information about inflation and output demonstrate the ECB's ability to directly steer markets' expectations. In the context of the structural interpretation of level shifts (Section 2), it supports the theory that level shifts reflect adjustments to news about the current and future state of the economy.

All in all the regressions show that the test for level shifts and rotations consistently detects monetary policy surprises. Furthermore, we find supporting results for the theoretical relations discussed in Section 2. The test for level shifts and rotations identifies the market perceived source of a policy surprise.

[15]We kindly thank the KOF Swiss Economic Institute for recording and providing the indicator. The indicator is explained in more detail in e.g. Conrad and Lamla (2010).

6 Conclusion

This paper contributes to the literature on yield curve responses to monetary policy announcements. We propose an empirical test to distinguish between *level shifts* and *rotations* of the yield curve. The test is based on daily high-frequency statistics and discriminates response patterns through cojumps of a short and long term interest rate. The cojump approach is consistent with the traditional regression studies of Cook and Hahn (1989) and Kuttner (2001), however, allows to zoom in to single monetary policy announcements and to study the response pattern of the yield curve for each announcement day independently.

The practical value of the new test is motivated by the theoretical work of Ellingsen and Söderström (2001) and Rudebush and Wu (2008). The response of the yield curve on a particular monetary policy announcement day detects the occurrence of a policy surprise and identifies markets' perceptions about the *source* of the surprise. Thus, the test enables central banks to monitor markets' understanding about monetary policy and to learn whether intentions of a policy decision are well-communicated.

The empirical example of ECB monetary policy announcements from 2001 to 2012 suggests stable and well-communicated policy preferences. Ever since the ECB's clarification of the monetary policy strategy in 2003, we find that markets' perceptions about policy preferences have been remarkably stable. Overall, our results lend to support the theory that central banks can effectively guide market expectations via its policy announcements and communication. In fact, major central banks around the world have recently moved into the direction of providing greater market guidance to steer expectations of future interest rates. Our results indicate that for the ECB, the press conference is indeed seen as providing valuable information about macroeconomic conditions and hence can significantly shift the yield curve. This gives some indication on the effectiveness of monetary policy communication in steering expectations about future interest rates.

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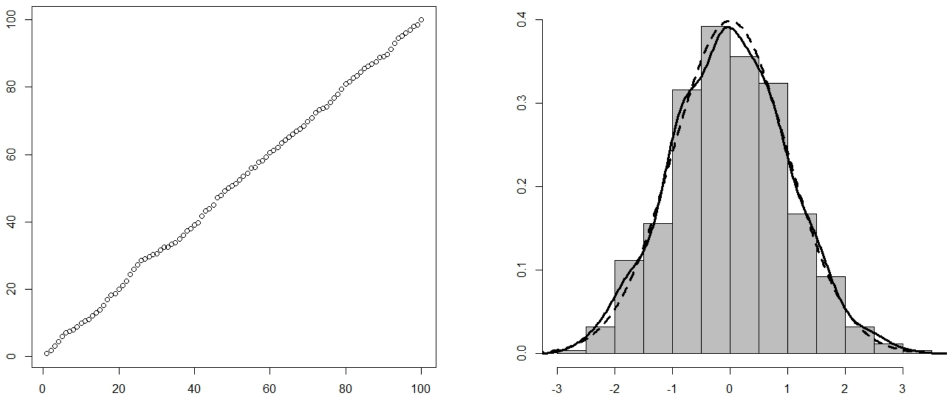
A Finite sample analysis of the statistical procedure

At this stage, we shall concisely illuminate the accuracy of our estimation and testing approach in finite samples. To this end, we simulate processes generated by continuous semimartingales and cojumps discretely recorded on $[0,1]$ at times $i/n, i = 0, \ldots, n$ with $n = 15000$.
In this Monte Carlo experiment, we simulate stochastic volatilities

$$\sigma_t^{(q)} = \Big(\int_0^t \tfrac{1}{2}\, dW_s^{(q)} + \int_0^t \tfrac{1}{2}\, dW_s^{(q),\perp}\Big) \cdot 0.1\Big(1 - t^{\frac{1}{3}} + 0.5t^2\Big)\,, t \in [0,1]\,, q = 1, 2\,, \quad (13)$$

comprising leverage, a typical intra-day shape (second factor) as well as random fluctuations. $W^{(q),\perp}, q = 1, 2$, are two independent standard Brownian motions independent of $W^{(q)}$, the Brownian motions driving $X_t^{(q)} = X_0^{(q)} + \int_0^t \sigma_t^{(q)}\, dW_t^{(q)} + J_t^{(q)}$, $q = 1, 2$. We set $\rho = 1/2$ as correlation of $W^{(1)}$ and $W^{(2)}$ such that the resulting integrated covolatility is positive. Discrete recordings $Y_i^{(q)} = X_{i/n}^{(q)} + \varepsilon_i^{(q)}$ are diluted with i.i.d. Gaussian errors with expectations zero and standard deviations $\eta^{(1)} = \eta^{(2)} = 0.001$ of realistic magnitude. Negligibility of drift components and non-synchronicity effects have been thoroughly addressed in the Monte Carlo studies by Bibinger and Winkelmann (2013) and Bibinger et al. (2013), while our main focus here shall be on the precision in disentangling jumps and continuous motion. We employ the block-wise adapted time-varying thresholding procedure by Bibinger and Winkelmann (2013), i.e. $\hat{u}_k = 2\log(h^{-1})h\sigma_k^{(1,2)}$, with $k = 0, ..., h^{-1} - 1$ and $\sigma_k^{(1,2)}$ the pilot estimator of the block-wise covolatility. We fix $J = 50$ as spectral cut-off frequency which is large enough such that higher frequencies are negligible. The number of blocks is set $h^{-1} = 30$, which is an adequate choice to smooth the noise here and as determined in Appendix B. Different choices within a reasonable range (20,...,60) will not cause substantial changes of the findings below.
In the sequel, we visualize the empirical size and power of the test by comparing empirical against theoretical asymptotic percentiles, i.e. the $q/100$-quantiles for $q = 1, \ldots, 99$ of the theoretical Gaussian limit distribution under the hypothesis. First, we simulate 1000 Monte Carlo iterations under the hypothesis with no cojumps to reveal the test's finite sample size. Idiosyncratic jumps are implemented according to a compound Pois-

Figure 5: Size of the cojump test in Monte Carlo.



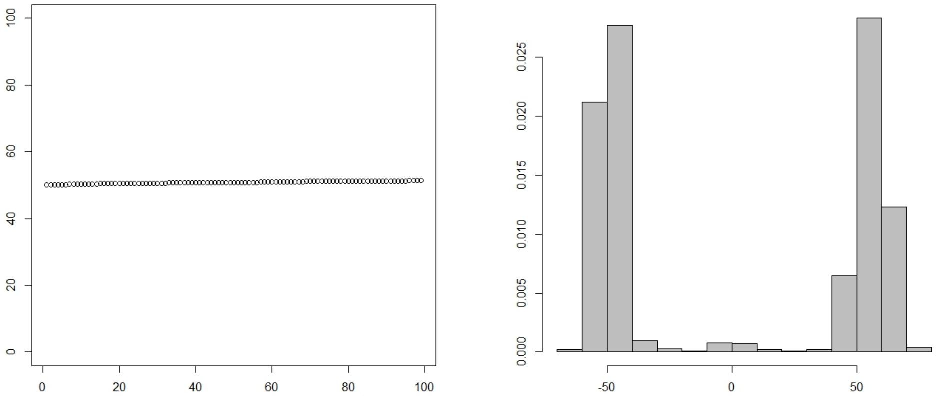
Note: Left plot depicts percentage of realized test statistics (y-axis) smaller or equal the theoretical percentiles of theoretical limit distribution (x-axis). Right plot gives empirical distribution of test statistics, dashed line theoretical limit and solid line kernel density estimate.

son process with one expected jump in each component and jump heights from a normal distribution $N(0.05, 0.0001) \cdot U$, where U determines the direction of a jump by taking values $\{-1, 1\}$, each with probability 1/2. Figure 5 visualizes the size of the test in the Monte Carlo experiment. The results confirm that the finite-sample behavior is very well-predicted by the asymptotic results.

Next, consider the finite-sample power. The same graphics as in Figure 5 in case that we simulate under the alternative portray the power. For this purpose we simulate 1000 iterations from the above scenario, but with one cojump occurring in each run at uniform on $[0, 1]$ distributed time. In each component we generate jumps $N(0.05, 0.0001) \cdot U$. This results with equal probability either in a unidirectional cojump (level shifts), or a cojump with opposite directions (rotation).

Figure 6 shows a finite-sample power very close to 1 for this Monte Carlo experiment. About one half of the iterations with unidirectional cojumps result in large positive values of the test statistic while cojumps in opposite directions lead to negative test statistics with large absolute values. The configuration appears to be realistic with moderate average jump sizes as in this setup for a cojump at t we have $|\Delta J_t^{(1)}| \approx |\Delta J_t^{(2)}| \approx 60\,\text{Mean}(|\Delta_i X^{(q)}|), q = 1, 2$, such that the jumps are ca. 60 times the average increment from the continuous motion (which are in practice often equal to smallest unit).
Finally, we apply the test to simulated data with cojumps of even smaller size, distributed according to $N(0.02, 0.0001) \cdot U$, to further explore the limits of feasibility of the truncation

Figure 6: Power of the cojump test in Monte Carlo (1).



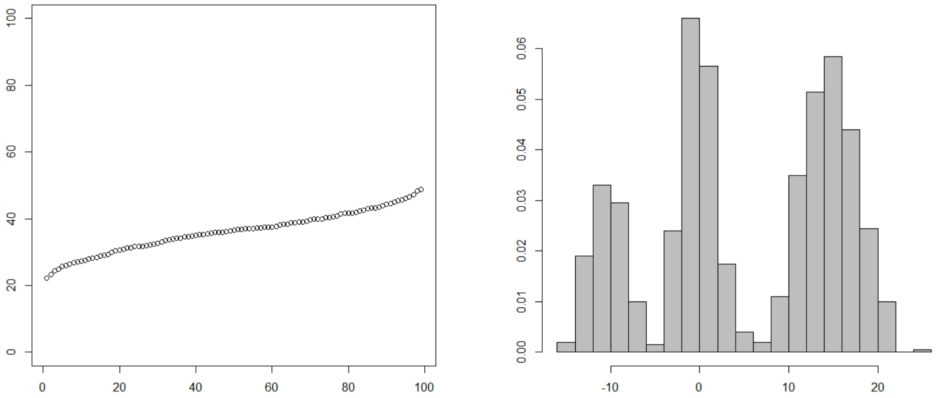
Note: Left plot depicts percentage of realized test statistics (y-axis) against theoretical percentiles of the limit distribution under the hypothesis (x-axis). Right plot gives empirical distribution of test statistics.

methodology. We disclose the properties of our test in this framework in Figure 7. In this setting $|\Delta J_t^{(1)}| \approx |\Delta J_t^{(2)}| \approx 20\,\text{Mean}(|\Delta_i X^{(q)}|), q = 1, 2$, the jump size is comparable to the magnitude of the threshold and hence only in about 66% of the 1000 iterations the cojumps are recovered based on the truncation principle. Furthermore, since the continuous part of covariation is always positive, in this configuration opposite cojumps are even harder to detect via thresholding which produces a slight asymmetry in Figure 7.

Naturally the power is not as high as before. Still, the performance of the test gives reasonable results. Figure 8 shows the simulated noisy paths of one iteration in which the jumps are still visible - which is not always the case under this configuration. For convenience the cojump arrival time is marked by the dashed lines. This examples intends to shed a light on what is possible in practice and grasp insight about the capabilities to detect cojumps by truncation (in the depicted example the cojump is clearly detected from the spectral statistics).

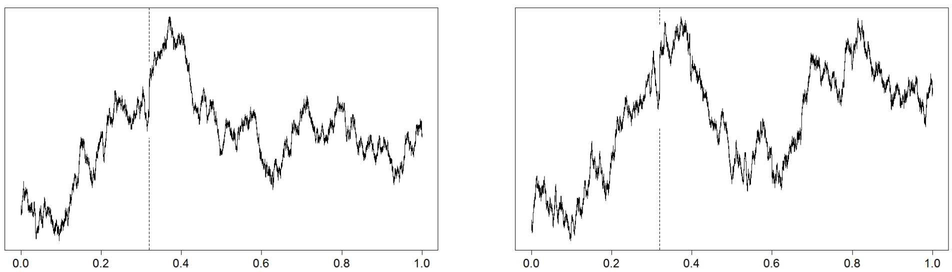
To sum up, the Monte Carlo example demonstrates the high practical value of the hybrid statistical approach combining truncation with the spectral covariation estimator. Our main objective is to infer on cojumps associated with relevant and significant price changes which are very precisely recovered by the method.

Figure 7: Power of the cojump test in Monte Carlo (2).



Note: Left plot depicts percentage of realized test statistics (y-axis) against theoretical percentiles of the limit distribution under the hypothesis (x-axis). Right plot gives empirical distribution of test statistics.

Figure 8: Example of simulated paths in Monte Carlo (2).

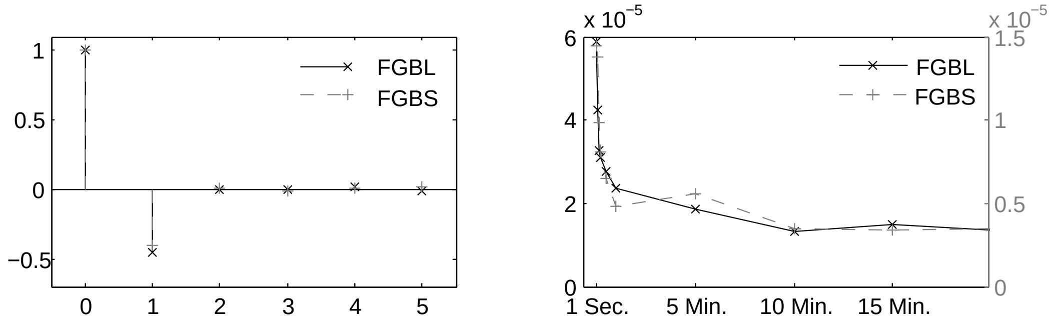


Note: Dashed segments highlight cojump arrival time.

B The role of microstructure noise

Due to the imperfections of trading processes, high-frequency (tick-data) is widely known to be very noisy, see Hautsch (2012) for a textbook exposition. The noise comes from a vast array of issues collectively known as market microstructure, including price discreteness, infrequent trading and bid-ask bounce effects. If microstructure frictions are present, single transaction prices no longer reflect the true price process. In this case, large observed returns do not consistently localize (co)jumps. Thus, it is of crucial importance that the econometric approach to estimate and test for cojumps explicitly accounts for the microstructure.

Figure 9: Autocorrelation (left) and signature plot (right) for FGBS and FGBL.



Notes: The autocorrelation up to five lags is based on tick-data on October, 2. 2008. The signature plot refers to the realized volatility (sum of squared returns) computed for each sampling frequency (x-axis) separately.

The observed processes in Figure 2 do not directly display a noise perturbation. As shown by Aït-Sahalia et al. (2005), the presence of microstructure frictions can be detected by a negative first order autocorrelation and an exponentially increasing realized volatility (sum of squared returns) the higher the sampling frequency. Therefore, Figure 9 depicts the autocorrelation structure and the signature plot of the observed processes. For both the FGBL and FGBS data a significant first order autocorrelation around -0.4 and a strongly increasing realized volatility, for sampling frequencies of 15 minute intervals to tick size, are evident.

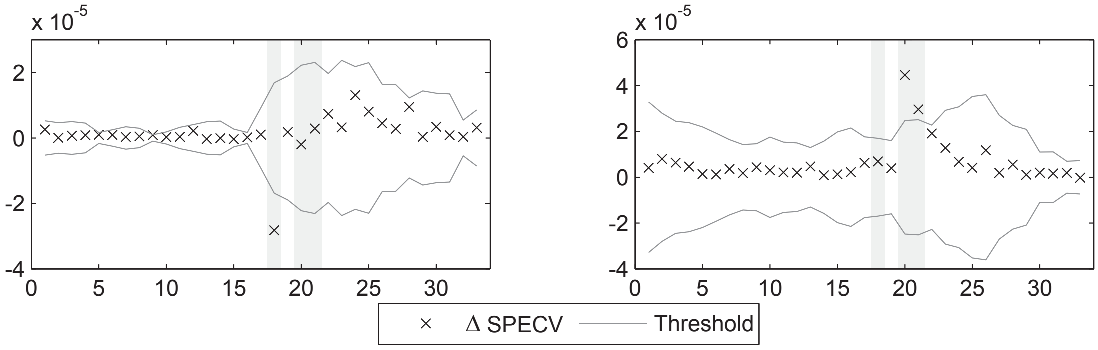
The pronounced evidence for market microstructure serves as an argument to employ the spectral estimator and test for cojumps of Bibinger and Winkelmann (2013).

C Examples of level shifts and rotations

This appendix illustrates how the day-wise estimation of cojumps works and provides news related arguments for particular shifts and rotations of the yield curve. We highlight two different examples of monetary policy announcement days. Based on the test results in Section 5.1, we pick the rotation of the yield curve on March, 7. 2002 and the level shift of the yield curve on October, 2. 2008. In Section 3.3 we define negative cojump estimates as rotations and positive estimates as level shifts of the yield curve. Figure 10 depicts increments in quadratic covariation estimates (6) and respective thresholds. The cojump estimator (8) shows that increments outside the threshold bands localize cojumps and sum up to the cojump estimate.

On March, 7. 2002, the negative cojump estimate is determined by the increment on

Figure 10: Rotation on 03/07/2002 (left) and level shifts on 10/02/2008 (right).



Notes: Cojump estimates are given by the sum of increments in SPECV (6) *outside the threshold bands. The x-axis displays the 33 20 minute intraday blocks. Blocks where the ECB communicates with markets are emphasized.*

block 18. Thus, the publication of the press release triggered a policy surprise on that day. With an unchanged key rate at 3.25%, some Bloomberg survey participants expected lower interest rates to boost the economic recovery after the 2000-2001 recession (average survey expectations were slightly below 3.25%). However, with annual inflation above 2%, the ECB emphasized with its interest rate decision the role of inflation more strongly than expected. Markets adjusted to that new information about policy preferences such that the yield curve rotated. The press conference (block 20 and 21) did not provide further significant surprises on that day.

In terms of policy response, the right hand plot of Figure 10 displays the exact opposite compared to the left hand plot. On October, 2. 2008 the positive cojump estimate is determined by the increments on block 20 and 21. According to the Bloomberg survey, on that day the decision on the key rate (unchanged at 4.25%) was fully expected. However, strong pronouncements of downside risks due to the intensification of the global financial crisis during the press conference lead to revisions of markets' economic outlook. The news about the economic conditions triggered level shifts of the yield curve.[16]

D The direction of level shifts

If the test for level shifts and rotations consistently detects monetary policy surprises, the level shifts should move the term structure in the direction of the surprise variable. We focus on upward and downward level shifts that occur in response to the press re-

[16]The wording of the introductory statement and the question and answer session can be find on the ECB webpage: http://www.ecb.int/press/pressconf/2008/html/index.en.html .

Table 2: Upward and downward level shifts.

Block	Press release ($k = 18$)	
Period	pre crisis	crisis
Policy surprise	0.48 * (0.22)	0.61 * (0.27)
Pseudo R^2	0.30	0.27

*Notes: Ordered probit regressions refer to a normal error distribution. Huber, White robust standard errors are given in parenthesis. * indicates significance at the 5% level. Results are based on 78 monetary policy announcement days in the pre-crisis period (2001-2007) and 55 in the crisis period (2008-2012).*

lease. Upward and downward level shifts are classified through the sign of average returns (evaluated by the sign of the spectral statistic's (5) lowest frequency component) on the respective intraday block. The difference between the actual decision on the key rate and mean expectations serves as a monetary policy surprise variable. Expectations are taken from the Bloomberg survey.

Regression results of the ordered variable on the survey measure are reported in Table 2. The significant coefficient estimates indicate that the test for level shifts and rotations consistently capture the direction of monetary policy surprises. If markets overestimate (underestimate) the decision on the key rate, the whole yield curve shifts downwards (upwards). This result also implies that taking a money market interest rate instead of the 2 year bond maturity to model the shorter end of the yield curve would not affect our results about shifts and rotations of the term structure reported in Section 5.