On-/Off-the-Run Yield Spread Puzzle: Evidence from Chinese Treasury Markets

22

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Contents

Abstract

In this chapter, we document a negative on-/off-the-run yield spread in Chinese Treasury markets. This is in contrast with a positive on-/off-the-run yield spread in most other countries and could be called an "on-/off-the-run yield spread puzzle." To explain this puzzle, we introduce a latent factor in the pricing of Chinese off-the-run government bonds and use this factor to model the yield

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difference between Chinese on-the-run and off-the-run issues. We use the nonlinear Kalman filter approach to estimate the model. Regressions results suggest that liquidity difference, market-wide liquidity condition, and disposition effect (unwillingness to sell old bonds) could help explain the dynamics of a latent factor in Chinese Treasury markets. The empirical results of this chapter show evidence of phenomena that are quite specific in emerging markets such as China.

The Kalman filter is a mathematical method named after Rudolf E. Kalman. It is a set of mathematical equations that provides an efficient computational (recursive) means to estimate the state of a process, in a way that minimizes the mean of the squared error. The nonlinear Kalman filter is the nonlinear version of the Kalman filter which linearizes about the current mean and covariance. The filter is very powerful in several aspects: it supports estimations of past, present, and even future states, and it can do so even when the precise nature of the modeled system is unknown.

Keywords
On-/off-the-run yield spread • Liquidity • Disposition effect • CIR model • Nonlinear Kalman filter • Quasi-maximum likelihood

22.1 Introduction

It is well known that there exists an on-the-run phenomenon in worldwide Treasury markets. This phenomenon refers to the fact that just-issued (on-the-run or new) government bonds of a certain maturity are generally traded at a higher price or lower yield than previously issued (off-the-run or old) government bonds maturing on similar dates. For example, Amihud and Mendelson (1991), Warga (1992), Kamara (1994), Furfine and Remolona (2002), Goldreich et al. (2005), and Pasquariello and Vega (2009) report the existence of positive on-/off-the-run yield spread in the US Treasury market with different frequency data. Mason (1987) and Boudoukh and Whitelaw (1991, 1993) provide similar evidence in Japan. In spite of different opinions on the information content of the yield spread, there is no disagreement in the literature that the on-/off-the-run yield spread in Treasury markets is significantly positive.

Academics have proposed many theories to explain the positive on-/off-the-run yield spread. Early studies directly attribute this spread to the liquidity difference between new bonds and old bonds (Amihud and Mendelson 1991; Warga 1992; Kamara 1994). More recent work provides some other possible explanations, such as different tax treatment (Strebulaev 2002), specialness in the repo market[1] (Krishnamurthy 2002), the value of future liquidity (Goldreich et al. 2005), search

[1]Specialness refers to the phenomenon that loans collateralized by on-the-run bonds offer lower interest rates than their off-the-run counterparts in repo markets.

costs (Vayanos and Weill 2008), and market frictions of information heterogeneity and imperfect competition among informed traders (Pasquariello and Vega 2009). No matter what arguments are proposed, however, the important role that liquidity plays in the positive on-/off-the-run yield spread and the liquidity premium hypothesis (Amihud and Mendelson 1986) has never been denied. It is widely accepted, by both practitioners and academics, that off-the-run bonds with a lower liquidity level tend to have a higher yield than otherwise similar, yet more liquid, on-the-run bonds.

In this chapter, we document a negative on-/off-the-run yield spread in Chinese Treasury markets, which is contrary to the usual on-the-run phenomenon in other countries and could be called the on-/off-the-run yield spread puzzle in China. Guo and Wu (2006) and Li and He (2008) report that on-/off-the-run yield spread in Chinese Treasury markets is significantly positive, but they did not match the on-the-run and off-the-run bonds correctly. For example, they compare the yield of a just-issued 7-year government bond with that of a previously issued 7-year government bond that has a different maturity. This is not consistent with the calculation of the usual on-/off-the-run yield spread. In order to calculate the spread correctly, we need to match the bonds in terms of maturity date. For example, we compare a just-issued 1-year government bond and a previously issued government bond maturing on similar dates. The maturities are both about 1 year and the durations are close to each other.

To explain on-/off-the-run yield spread puzzle, we introduce a latent factor in the pricing of Chinese off-the-run bonds. This latent factor is used to model the yield difference between on-the-run bonds and off-the-run bonds. We employ a nonlinear Kalman filter to estimate the model and examine the temporal properties of the latent factor. We find that the liquidity premium hypothesis still holds in Chinese Treasury markets. In particular, the change of the latent factor is positively related to the liquidity difference between off-the-run and on-the-run bonds and positively related to the market-wide liquidity condition. Both findings are consistent with the liquidity premium hypothesis. On the other hand, disposition effect (unwillingness to sell old bonds in bear markets) dramatically changes the sign of the yield spread and causes the puzzle. The change of latent factor in Chinese Treasury markets is negatively related to 7-day repo rates. When interest rates go up and the returns of the bond markets are negative, the holders of off-the-run bonds are reluctant to realize loss and will not sell their bonds, which consequently leads to a relatively low yield level of off-the-run bonds and a negative on-/off-the-run yield spread.

Our article makes several contributions to the literature. We document a negative on-/off-the-run yield spread in China. We introduce a latent factor to explain the yield difference between on-the-run bonds and off-the-run bonds and employ the nonlinear Kalman filter in estimation. Our basic ideas are in line with Longstaff et al. (2005) and Lin et al. (2011). We also provide evidence of irrational investor behavior that is quite specific in emerging Treasury markets such as China. In China, the liquidity premium hypothesis still holds, whereas the existence of disposition effect causes the puzzle.

The chapter is organized as follows. In Sect. 22.2, we present a pricing model of government bonds that introduces a latent factor for the off-the-run bonds.

In Sect. 22.3, we describe the data, report the estimation results, and perform a variety of regression analyses. We present our conclusions in Sect. 22.4.

22.2 Bond Pricing Models

22.2.1 On-the-Run Bond Pricing Model

We use the Cox et al. (1985, CIR) model to price the Chinese on-the-run government bonds. The CIR model has been a benchmark interest rate model because of its analytical tractability and other good properties. In this model, the risk-free short rate, r_t, is assumed to follow a square-root process as

$$dr_t = \kappa(\theta - r_t)dt + \sigma_r\sqrt{r_t}dW_{r,t}, \tag{22.1}$$

under the risk-neutral measure Q. κ is the speed of mean reversion, θ is the long-term mean value, σ_r is the volatility parameter of r_t, and W_r denotes a standard Brownian motion under Q. Such specification allows for both mean reversion and conditional heteroskedasticity and guarantees that interest rates are nonnegative.

At time t, the price of an on-the-run government bond maturing at t_M could be written as

$$P_t^{on} = E_t^Q\left[\sum_{m=1}^{M} C_m \exp\left(-\int_t^{t_m} r_s ds\right)\right], \tag{22.2}$$

where P_t^{on} is the on-the-run bond price, C_m is the cash flow payments at time t_m, and M is the total number of cash flow payments. That is, the price of a government bond is the expected present value of the cash flow payments under the risk-neutral measure.

Solving Eq. 22.2 gives

$$P_t^{on} = \sum_{m=1}^{M} C_m A_{m,t} \exp\left(-B_{m,t} r_t\right), \tag{22.3}$$

where

$$A_{m,t} = \left[\frac{2h\exp\{(\kappa+h)(t_m-t)/2\}}{2h+(\kappa+h)(\exp\{(t_m-t)h\}-1)}\right]^{2\kappa\theta/\sigma_r^2},$$

$$B_{m,t} = \frac{2(\exp\{(t_m-t)h\}-1)}{2h+(\kappa+h)(\exp\{(t_m-t)h\}-1)},$$

and

$$h = \sqrt{\kappa^2 + 2\sigma_r^2}.$$

22.2.2 Off-the-Run Bond Pricing Model

In order to model the on-/off-the-run yield spread in Chinese Treasury markets, we next incorporate a latent component, l, into the pricing model of Chinese off-the-run government bonds and extend (22.2) to

$$P_t^{off} = E_t^Q\left[\sum_{m=1}^{M} C_m \exp\left(-\int_t^{t_m} (r_s + l_s)ds\right)\right], \tag{22.4}$$

where P_t^{off} is the off-the-run bond price. Similar to Longstaff et al. (2005) and Lin et al. (2011), we assume that under the risk-neutral measure Q,

$$dl_t = \sigma_l dW_{l,t}, \tag{22.5}$$

where W_l is a standard Brownian motion independent of W_r under Q and σ_l is the volatility parameter.

Given the stochastic processes in (22.1) and (22.5), we can obtain the analytical solution for the pricing formula of (22.4),

$$P_t^{off} = \sum_{m=1}^{M} C_m A_{m,t} \exp\left(D_{m,t} - B_{m,t} r_t - (t_m - t) l_t\right), \tag{22.6}$$

where $D_{m,t} = \frac{\sigma_l^2 (t_m - t)}{6}$ and other notations are the same as in (22.3).

22.3 Data and Empirical Estimation

22.3.1 Data Summary

We use the price of Chinese government bonds in the interbank market to estimate the pricing model. The data are from the RESSET dataset. There are two main bond markets in China. One is the interbank bond market, while the other is the exchange bond market. The interbank bond market is a quote-driven over-the-counter market, and the participants are mainly institutional investors. Its outstanding value and trading volume account for over 90 % of Chinese bond markets. The number of bonds traded in the interbank market is at least three times that traded in the exchange market. This is very important for our empirical study, since we need enough bonds to match new and old ones.

Table 22.1 Summary statistics

	Off-the-run		On-the-run		
	Mean	Std	Mean	Std	Difference
One year					
Yield (%)	2.24	0.92	2.31	0.72	−0.07
Modified duration (years)	0.68	0.25	0.73	0.22	−0.05
Age (years)	4.3	2.92	0.26	0.22	4.04[a]
Coupon (%)	2.95	2.73	1.39	1.46	1.63[a]
Three years					
Yield (%)	2.72	0.78	2.83	0.79	−0.11[b]
Modified duration (years)	2.47	0.33	2.48	0.31	−0.01
Age (years)	3.05	1.45	0.38	0.32	2.67[a]
Coupon (%)	3.39	2.32	2.89	0.62	0.50

This table reports the summary statistics of the Chinese 1-year and 3-year on-the-run and off-the-run government bonds between December 2003 and February 2009. The coupon rate and yield are in percentages, while age and modified duration are in years. This table also reports the difference between the off-the-run bonds and the on-the-run bonds

[a]and[b] indicate statistical significance at the 5 % and 1 % level, respectively

Our sample period is from December 2003 to February 2009. We use monthly data and choose the actively traded government bonds with 1 year and 3 years to maturity. Thus, for each month in our sample period, a most recently issued 1-year and 3-year government bonds are selected as the on-the-run bonds, and we get another old bond maturing on similar dates to match each on-the-run bond.[2] Altogether, 63 matched pairs of 1-year government bonds and 63 matched pairs of 3-year government bonds are included in the final sample.

Table 22.1 reports the summary statistics for the sample bonds. As expected, the modified durations of off-the-run and on-the-run bonds are quite close to each other. This means if interest rate risk is the only risk factor, these bonds should be traded at similar yields. To examine whether the same on-the-run phenomenon exists in Chinese Treasury markets, we compute the on-/off-the-run yield spread as

$$\Delta y_{M,t} = y_{M,t}^{off} - y_{M,t}^{on}, \tag{22.7}$$

where $y_{M,t}^{off}$ and $y_{M,t}^{on}$ are the time t yield of the off-the-run bond and the on-the-run bond maturing at t_M, respectively. In our sample, $t_M - t$ is equal to 1 year or 3 years. Figure 22.1 plots the time series of $\Delta y_{M,t}$ of the 1-year bond and 3-year bond.

Table 22.1 also reports the means of on-/off-the-run yield spreads and their statistical significance. Both the 1-year on-/off-the-run yield spread and the 3-year on-/off-the-run yield spread are negative, which is inconsistent with the findings in other markets. Moreover, the 3-year on-/off-the-run yield spread is significantly

[2]The main reason for the data selection comes from the concern of trading activity. Trading in Chinese Treasury markets is not active, especially in the earlier period.

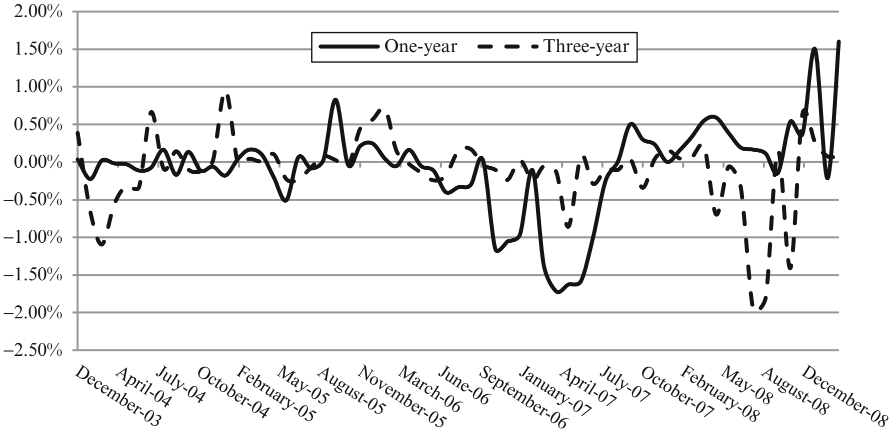

Fig. 22.1 Time series of Chinese on-/off-the-run yield spread. This figure plots the yield difference between the off-the-run and on-the-run Chinese government bonds between December 2003 and February 2009

negative at the 10 % level, which suggests the existence of a significantly negative on-/off-the-run yield spread and remains a puzzle. The 1-year on-/off-the-run yield spread is negative but not significant. However, this spread has some noise, since the difference of coupon rate between the on-the-run issues and off-the-run issues is 1.63 % and significant at the 1 % level. This difference could affect the significance of the on-/off-the-run spread at the 1-year level. Generally speaking, we find evidence of a negative on-/off-the-run spread, which is contrary to the established fact of a positive on-/off-the-run yield spread in most other countries and could be called the on-/off-the-run yield spread puzzle in China.

22.3.2 Empirical Methodology

To explain the on-/off-the-run yield spread puzzle in China, we use the CIR model to price the on-the-run issues and the CIR model with the latent factor to price the off-the-run issues. We first estimate the parameters of the CIR model using all on-the-run bonds. Given the parameters of the CIR process, we further estimate the parameters of the latent factor using off-the-run bonds. Thus, the latent factor represents the yield difference between on-the-run and off-the-run bonds.

In our empirical study, we employ the Kalman filter to estimate the parameters.[3] The standard Kalman filter is not appropriate here because it requires linear state functions and the measurement functions, while Eqs. 22.3 and 22.6 are nonlinear.

[3]See Hamilton (1994) for an explanation of Kalman filter.

Table 22.2 Estimates of pricing models

	On-the-run issues $dr_t = \kappa(\theta - r_t)dt + \sigma_r\sqrt{r_t}dW_{r,t}$		Off-the-run issues $dr_t = \kappa(\theta - r_t)dt + \sigma_r\sqrt{r_t}dW_{r,t}$ $dl_t = \sigma_l dW_{l,t}$	
The state function	$r_t = \gamma + \phi r_{t-1} + \varepsilon_t$		$r_t = \gamma + \phi r_{t-1} + \varepsilon_t l_t = l_{t-1} + \sigma_l(\eta_t - \eta_{t-1})$	
The measurement function	$\mathbf{y}_t^{on} = \boldsymbol{\alpha}_t^{on} + \boldsymbol{\beta}_t^{on} r_t + \boldsymbol{\omega}_t^{on}$		$\mathbf{y}_t^{off} = \boldsymbol{\alpha}_t^{off} + \boldsymbol{\beta}_t^{off} r_t + \boldsymbol{\xi}_t^{off} l_t + \boldsymbol{\omega}_t^{off}$	
κ	0.089(6.403)[a]			
θ	0.023(6.486)[a]			
σ_r	0.063(247.921)[a]			
σ_l			0.009(8.530)[a]	
var(ε_t)	0.000008			
var(η_t)			0.000007	
	One year	Three years	One year	Three years
var($\boldsymbol{\omega}_t^{on}$)	0.000035	0.000020		
var($\boldsymbol{\omega}_t^{off}$)			0.000011	0.0000006
RMSE	0.0045	0.0038	0.0062	0.0058
MAD	0.0596	0.0517	0.0705	0.0672

This table reports the estimate results of pricing models for on-the-run and off-the-run Chinese government bonds. The parameters of the CIR model are estimated from monthly on-the-run bond data. These parameters are then used to estimate the latent factor in the monthly off-the-run bond data. We use a nonlinear Kalman filter approach to estimate the parameters. $\mathbf{y}_t^{on} = \begin{bmatrix} y_{1,t}^{on} \\ y_{3,t}^{on} \end{bmatrix}$, $\mathbf{y}_t^{off} = \begin{bmatrix} y_{1,t}^{off} \\ y_{3,t}^{off} \end{bmatrix}$, $\boldsymbol{\omega}_t^{on} = \begin{bmatrix} \omega_{1,t}^{on} \\ \omega_{3,t}^{on} \end{bmatrix}$, and $\boldsymbol{\omega}_t^{off} = \begin{bmatrix} \omega_{1,t}^{off} \\ \omega_{3,t}^{off} \end{bmatrix}$, where subscript *1* and *3* denote 1-year and 3-year bonds and superscript *on* and *off* denote on-the-run and off-the-run bonds, respectively. The numbers in parentheses are *t* values

[a]indicates statistical significance at the 1 % level respectively. RMSE and MAD are root mean square error and mean absolute deviation, respectively

We therefore use the nonlinear Kalman filter for estimation. The details of the nonlinear Kalman filter with its Matlab codes are reported in the Appendix.

After we estimate the parameters, we then study the dynamic of the latent component and examine its temporal properties to explore the explanations of the on-/off-the-run yield spread puzzle in China.

22.3.3 Estimation Results

22.3.3.1 Estimation Results of On-the-Run Issue

The left-hand column of Table 22.2 reports the estimation results of the CIR model using on-the-run bonds. As shown, all the parameters are significant at the 1 % level. The long-term mean value, the speed of mean reversion, and the volatility parameter of r are 0.023, 0.089, and 0.063, respectively. These results are reasonable and close to the results of other research on dynamic models in the Chinese interest rate (Hong et al. 2010).

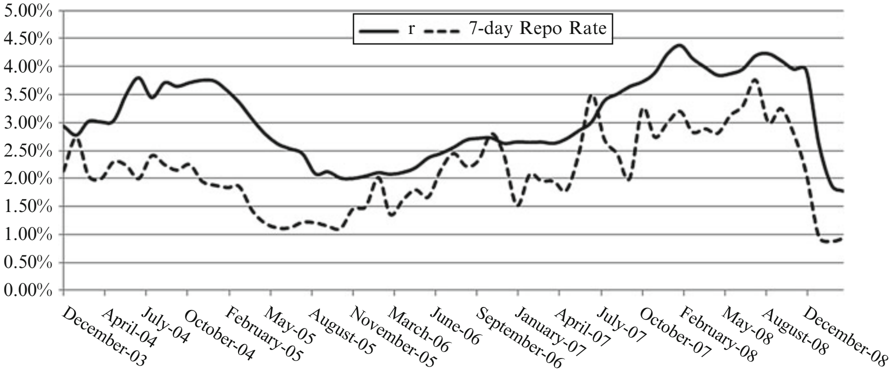

Fig. 22.2 Time series of implied risk-free interest rate and 7-day repo rate in Chinese interbank market. This figure plots the time series of implied risk-free interest rate estimated from the CIR model using Chinese on-the-run government bonds, and the time series of 7-day repo rate in Chinese interbank market

Figure 22.2 plots the time series of r estimated from the model. Most of the time, the value of r is in the interval between 2 % and 4 %. We also plot the time series of the 7-day repo rate in the Chinese interbank market. Similar trends in these two curves suggest that r does capture the change of the market interest rate.

22.3.3.2 Estimation Results of Off-the-Run Issue

With all the parameters obtained for r, we next estimate the parameters of l using the data of off-the-run bonds.[4] The right-hand column of Table 22.2 reports the estimation results. The parameter of σ_l is significant at the 1 % level.

Figure 22.3 plots the time series of l estimated from the data. As we can see from the figure, most of l are negative. We conduct the t-test and find the average of l is significantly negative at the 5 % level (the t-statistic is −017). Since l represents the yield difference between off-the-run bonds and on-the-run bonds, negative l provides further, strong evidence of the on-/off-the-run yield spread puzzle in Chinese Treasury markets.

22.3.4 Regression Analysis

The analysis so far reveals that on average, the off-the-run bonds are traded at a higher price or lower yield than the on-the-run bonds in Chinese Treasury markets, which is hard to explain rationally. We next explore the information contained in this negative yield spread by examining the temporal properties of the latent component, l.

[4]We also estimate the parameters of r and l jointly using the on-the-run and off-the-run data together and find the results are quite similar.

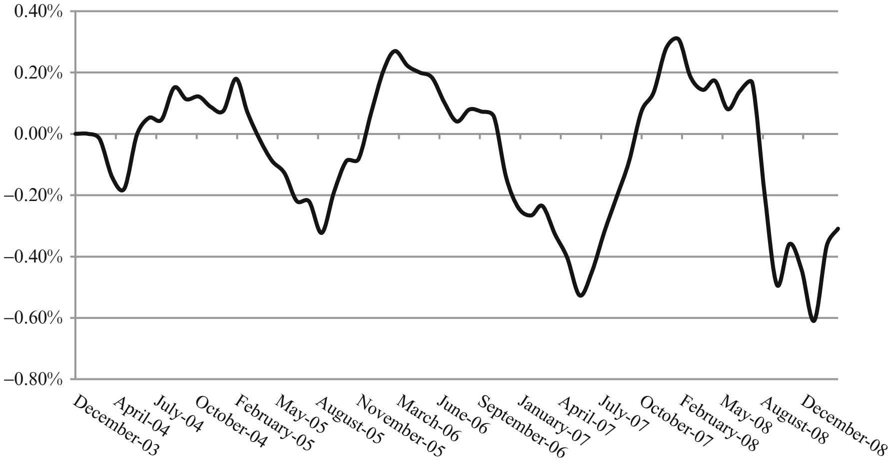

Fig. 22.3 Time series of latent factor. This figure plots the time series of latent factor estimated from the Chinese off-the-run government bonds

In order to explain the temporal properties of the latent component, we introduce several variables. One is the turnover ratio difference between on-the-run issues and off-the-run issues as a measure of liquidity difference, and it is used to examine whether an on-/off-the-run yield spread in Chinese Treasury markets is related to the difference in liquidity conditions. The turnover ratio difference between on-the-run issues and off-the-run issues is defined as

$$TR_t = \frac{\left(TR_{1,t}^{off} - TR_{1,t}^{on}\right) + \left(TR_{3,t}^{off} - TR_{3,t}^{on}\right)}{2} \times 10^{-5},$$

where *TR* is the turnover ratio, the subscript *1* and *3* denote 1-year bonds and 3-year bonds, and the superscript *on* and *off* denote on-the-run bonds and off-the-run bonds.

Pasquariello and Vega (2007, 2009) find that the release of macroeconomic news changes liquidity, and hence the on-/off-the-run yield spread, in the US Treasury market. For example, when macroeconomic news brings more funds into the bond market, market-wide liquidity conditions will be better, investors might trade old bonds more actively, and the yield difference between off-the-run bonds and on-the-run bonds might decrease, and vice versa. Similarly, we introduce the percentage change of a broad money supply measure, ΔM2, as a proxy of market-wide liquidity conditions to examine whether there is covariation of the latent component with changes in market-wide liquidity conditions. We use one lagged ΔM2 to examine the impact of macroeconomic conditions on Δl_t.

The last factor we investigate is investors' behavior. It is observed that in Chinese bond markets, there exists a "disposition effect." Bond holders are reluctant to realize loss and will not sell old bonds if they have a loss from the investment. Consequently, old bonds might be traded at a lower yield than new bonds. In China, the 7-day repo market is one of the most active bond markets, and

Table 22.3 Time regression results

	(1)	(2)	(3)	(4)
	$\Delta l_t = \beta_0 + \beta_1 TR_t + \varepsilon_t$	$\Delta l_t = \beta_0 + \beta_1 \Delta M2_{t-1} + \varepsilon_t$	$\Delta l_t = \beta_0 + \beta_1 R_{t-1} + \varepsilon_t$	$\Delta l_t = \beta_0 + \beta_1 TR_t + \beta_2 \Delta M2_{t-1} + \beta_3 R_{t-1} + \varepsilon_t$
Intercept	4.330(0.253)	−0.001(−2.349)[a]	0.001(2.348)[a]	0.0005(0.905)
TR_t	0.904(1.625)[b]			−0.231(−0.390)
$\Delta M2_{t-1}$		0.037(2.263)[a]		0.027(1.663)[b]
R_{t-1}			−0.057(−2.703)[c]	−0.045(−1.930)[a]
Adj. R^2	0.043	0.084	0.114	0.163

This table reports the results of regressing the change of latent component, Δl_t, on the on-/off-the-run turnover ratio difference (TR_t), the lagged percentage change of M2 ($\Delta M2_{t-1}$), and the lagged 7-day repo rate (R_{t-1}). The numbers in parentheses are t values

[a], [b], and [c] indicate statistical significance at the 10 %, 5 %, and 1 % level, respectively

Univariate regression of Δl_t on the turnover ratio difference

$\Delta l_t = \beta_0 + \beta_1 TR_t + \varepsilon_t$.

Univariate regression of Δl_t on the lagged percentage change of the money supply:

$\Delta l_t = \beta_0 + \beta_1 \Delta M2_{t-1} + \varepsilon_t$.

Univariate regression of Δl_t on the lagged 7-day repo rate:

$\Delta l_t = \beta_0 + \beta_1 R_{t-1} + \varepsilon_t$.

Multivariate regression of Δl_t on the turnover ratio difference, lagged percentage change of the money supply, and lagged 7-day repo rate:

$\Delta l_t = \beta_0 + \beta_1 TR_t + \beta_2 \Delta M2_{t-1} + \beta_3 R_{t-1} + \varepsilon_t$

the change of the 7-day repo rate is a good measure of market conditions. When the 7-day repo rate goes up, the bond investment will generate a loss for the investors and the disposition effect might occur. We use the interbank 7-day repo rates as the proxy of the market interest rate to investigate whether the on-/off-the-run yield spread puzzle in China is related to this irrational behavior. If the investors are rational and the liquidity premium hypothesis holds, the liquidity of the whole market will decrease in the bear market, and the old bonds will be traded at a higher yield. Thus, detecting the response of the on-/off-the-run yield spread to the change of the 7-day repo rate could help us distinguish whether the disposition effect or the liquidity factor dominates. Similarly, we use one lagged 7-day repo rate in the time series regression.

In what follows, we first run univariate time series regressions of Δl_t against each variable and then conduct multivariate regression analysis against all the three factors. The regression models are specified as follows:

Univariate regression of Δl_t on the turnover ratio difference, TR_t:

$$\Delta l_t = \beta_0 + \beta_1 TR_t + \varepsilon_t.$$

Univariate regression of Δl_t on the lagged percentage change of the money supply, $\Delta M2_{t-1}$:

$$\Delta l_t = \beta_0 + \beta_1 \Delta M2_{t-1} + \varepsilon_t.$$

Univariate regression of Δl_t on the lagged 7-day repo rate, R_{t-1}:

$$\Delta l_t = \beta_0 + \beta_1 R_{t-1} + \varepsilon_t.$$

Multivariate regression of Δl_t on the turnover ratio difference, lagged percentage change of money supply, and lagged 7-day repo rate:

$$\Delta l_t = \beta_0 + \beta_1 TR_t + \beta_2 \Delta M2_{t-1} + \beta_3 R_{t-1} + \varepsilon_t.$$

22.3.4.1 Univariate Regression Analysis

Columns (1), (2), and (3) of Table 22.3 report the results of univariate time series regressions of Δl_t against the turnover ratio difference, the lagged percentage change of the money supply, and the lagged 7-day repo rate, respectively. As shown, all coefficients are significant, indicating that all these factors are useful to explain the change of the on-/off-the-run yield spread in China. It is an interesting finding that is worth further exploring.

The coefficients for TR and the lagged ΔM2 are significantly positive at the 10 % level and the 5 % level, respectively. That means the latent component contains information about liquidity conditions. In particular, since l_t is negative most of the time, the positive sign of coefficients implies that when the explanatory variable increases, the on-/off-the-run yield spread will increase and move close to zero. In other words, there will be less difference between off-the-run bond yields and on-the-run bond yields. The significantly positive coefficient of TR suggests that if the on-/off-the-run turnover ratio difference increases, that is, the liquidity of old bonds becomes better, the yield difference between off-the-run bonds and on-the-run bonds declines, and vice versa. This is consistent with the liquidity premium hypothesis. Similarly, the significantly positive coefficient of lagged ΔM2 reveals that if the money supply increases and market-wide liquidity improves, the yield difference between old bonds and new bonds declines, and vice versa. Both results provide evidence of a liquidity premium in Chinese government bond yields. The liquidity premium hypothesis still holds in Chinese Treasury markets despite the existence of the on-/off-the-run yield spread puzzle.

The lagged 7-day repo rate is significantly negatively related to Δl_t. That is, when the market interest rate goes up and the bond investors have a loss, the yield difference between old bonds and new bonds increases and the on-/off the run spread becomes more negative. This indicates the disposition effect dominates the effect of liquidity. When investors have a loss, the unwillingness to sell old bonds leads to a lower yield for old bonds and a negative on-/off-the-run yield spread. The regression against the lagged 7-day repo rate has the largest adjusted R square, which implies the disposition effect could better explain the change in the on-/off-the-run yield spread in China than the liquidity condition.

22.3.4.2 Multivariate Regression Analysis

Column (4) of Table 22.3 reports the results of multivariate regression. The coefficient of TR is not significant any more, indicating that after controlling for market-wide liquidity conditions and the disposition effect, the liquidity difference has no influence on the on-/off-the-run yield spread. On the other hand, market-wide liquidity and the disposition effect are still significant at the 10 % level.

The adjusted R square of the multivariate is about 16 %. This suggests that the on-/off-the-run spread could be partly explained by the change in market-wide liquidity conditions and the disposition effect.

22.4 Conclusion

In this chapter, we document a negative on-/off-the-run yield spread in Chinese Treasury markets. This is contrary to the positive on-/off-the-run yield spread found in most other countries and could be called the "on-/off-the-run yield spread puzzle." We introduce a latent factor into the pricing formula of off-the-run bonds to capture the yield spread and estimate this factor by the nonlinear Kalman filter. The result confirms the existence of the puzzle.

To reveal the information content of the negative on-/off-the-run yield spread, we perform univariate and multivariate time series regressions of the change of the latent factor against the turnover ratio difference between off-the-run issues and on-the-run issues (a measure of the liquidity difference between off-the-run issues and on-the-run issues), the lagged percentage change of M2 (a measure of market-wide liquidity conditions), and the lagged 7-day repo rates (a measure of disposition effect). We find that the liquidity premium hypothesis still holds in Chinese Treasury markets. The yield spread, however, is dominated by the irrational disposition effect. When the investors have a loss from the bond investment, they are more reluctant to sell old bonds, which leads to a higher price and a lower yield for old bonds and hence causes the puzzle.

Our study is an attempt to explore the coexistence of a standard theoretical hypothesis and irrational behavior in emerging Treasury markets such as China. These markets have been a topic of interest increasingly, as the role of the emerging markets in the global economy becomes more and more important.

Appendix 1: Nonlinear Kalman Filter

Let $y^{on}_{M,t}$ represent the time t yield of an on-the-run government bond maturing at t_M. Equation 22.3 could be written as

$$P^{on}_t = \sum_{m=1}^{M} C_m A_{m,t} \exp\left(-B_{m,t} r_t\right) = \sum_{m=1}^{M} C_m \exp\left(-y^{on}_{M,t}(t_m - t)\right). \tag{22.8}$$

As shown, $y^{on}_{M,t}$ is a nonlinear function of r_t, which is inconsistent with the requirements of the standard Kalman filter that state functions and measurement functions should be linear. So we use the extended (nonlinear) Kalman filter to linearize nonlinear functions. The idea is to employ the Taylor expansions around the estimate at each step. That is, we express $y^{on}_{M,t}$ as

$$y^{on}_{M,t}(r_t) \approx y^{on}_{M,t}\left(\hat{r}_{t|t-1}\right) + \frac{\partial y^{on}_{M,t}}{\partial r_t}\Big|_{r_t=\hat{r}_{t|t-1}} \cdot \left(r_t - \hat{r}_{t|t-1}\right), \tag{22.9}$$

where $\hat{r}_{t|t-1}$ is the estimate of r_t at time t–1.

To get $\frac{\partial y^{on}_{M,t}}{\partial r_t}$, we calculate the first-order derivative of P^{on}_t with respect to r_t,

$$\frac{\partial P^{on}_t}{\partial r_t} = -\sum_{m=1}^{M} C_m A_{m,t} B_{m,t} \exp\left(-B_{m,t} r_t\right) = \frac{\partial P^{on}_t}{\partial y^{on}_{M,t}} \frac{\partial y^{on}_{M,t}}{\partial r_t}. \tag{22.10}$$

Thus, we have

$$\frac{\partial y^{on}_{M,t}}{\partial r_t} = \frac{\sum_{m=1}^{M} C_m A_{m,t} B_{m,t} \exp\left(-B_{m,t} r_t\right)}{\sum_{m=1}^{M} C_m (t_m - t) \exp\left(-y^{on}_{M,t} \cdot (t_m - t)\right)}. \tag{22.11}$$

Given $\hat{r}_{t|t-1}$, we can use Eq. 22.8 to calculate $y^{on}_{M,t}\left(\hat{r}_{t|t-1}\right)$ and then use Eq. 22.11 to get $\frac{\partial y^{on}_{M,t}}{\partial r_t}$

Finally, the linearized measurement model for the on-the-run issues at time t is

$$\mathbf{y}^{\mathbf{on}}_{\mathbf{t}} = \boldsymbol{\alpha}^{\mathbf{on}}_{\mathbf{t}} + \boldsymbol{\beta}^{\mathbf{on}}_{\mathbf{t}} r_t + \boldsymbol{\omega}^{\mathbf{on}}_{\mathbf{t}} \tag{22.12}$$

where

$$\mathbf{y}^{\mathbf{on}}_{\mathbf{t}} = \begin{bmatrix} y^{on}_{1,t} \\ y^{on}_{3,t} \end{bmatrix},$$

$$\boldsymbol{\alpha}^{\mathbf{on}}_{\mathbf{t}} = \begin{bmatrix} y^{on}_{1,t}\left(\hat{r}_{t|t-1}\right) - \hat{r}_{t|t-1} \cdot \dfrac{\partial y^{on}_{1,t}}{\partial r_t}\Big|_{r_t=\hat{r}_{t|t-1}} \\ y^{on}_{3,t}\left(\hat{r}_{t|t-1}\right) - \hat{r}_{t|t-1} \cdot \dfrac{\partial y^{on}_{3,t}}{\partial r}\Big|_{r_t=\hat{r}_{t|t-1}} \end{bmatrix},$$

$$\boldsymbol{\beta}^{\mathbf{on}}_{\mathbf{t}} = \begin{bmatrix} \dfrac{\partial y^{on}_{1,t}}{\partial r_t}\Big|_{r_t=\hat{r}_{t|t-1}} \\ \dfrac{\partial y^{on}_{3,t}}{\partial r_t}\Big|_{r_t=\hat{r}_{t|t-1}} \end{bmatrix},$$

and $\boldsymbol{\omega}^{\mathrm{on}}_{\mathrm{t}}$ is the error term,

$$\boldsymbol{\omega}^{\mathbf{on}}_{\mathbf{t}} = \begin{bmatrix} \omega^{on}_{1,t} \\ \omega^{on}_{3,t} \end{bmatrix},$$

where the subscript of *1* and *3* represent the 1-year bonds and 3-year bonds, while the superscript *on* refers to on-the-run bonds.

After we get the measurement function, the third step is to rewrite (22.1) as a discrete state function,

$$r_t = \gamma + \phi r_{t-1} + \varepsilon_t, \tag{22.13}$$

where

$$\gamma = \theta(1 - \exp(-\kappa \cdot \Delta t)),$$
$$\phi = \exp(-\kappa \cdot \Delta t),$$

and ε_t is the error term of r_t and Δt is the size of the time interval in the discrete sample. In our study, $\Delta t = 0.0833$. The conditional mean and conditional variance of r_t are

$$\begin{aligned} \hat{r}_{t|t-1} &= \theta(1 - \exp(-k\Delta t)) + \exp(-k\Delta t) \cdot r_{t-1} \\ Var\left(r_{t|t-1}\right) &= \sigma_r^2\left(\frac{1 - \exp(-k\Delta t)}{k}\right)\left(\frac{1}{2}\theta(1 - \exp(-k\Delta t) + \exp(-k\Delta t) \cdot r_{t-1})\right). \end{aligned} \tag{22.14}$$

Similarly, the state functions of the off-the-run issues are

$$\begin{aligned} r_t &= \gamma + \phi r_{t-1} + \varepsilon_t \\ l_t &= l_{t-1} + \sigma_l e_t. \end{aligned} \tag{22.15}$$

The conditional mean and conditional variance of l_t are l_{t-1} and $\sigma_l^2 \Delta t$, respectively.

The corresponding measurement function is

$$\mathbf{y}_\mathbf{t}^\mathbf{off} = \boldsymbol{\alpha}_\mathbf{t}^\mathbf{off} + \boldsymbol{\beta}_\mathbf{t}^\mathbf{off} r_t + \boldsymbol{\xi}_\mathbf{t}^\mathbf{off} l_t + \boldsymbol{\omega}_\mathbf{t}^\mathbf{off}, \tag{22.16}$$

where *off* refers to off-the-run bonds,

$$\mathbf{y}_\mathbf{t}^\mathbf{off} = \begin{bmatrix} y_{1,t}^{off} \\ y_{3,t}^{off} \end{bmatrix},$$

$$\boldsymbol{\alpha}_\mathbf{t}^\mathbf{off} = \begin{bmatrix} y_{1,t}^{off}\left(\hat{r}_{t|t-1}, \hat{l}_{t|t-1}\right) - \hat{r}_{t|t-1} \cdot \dfrac{\partial y_{1,t}^{off}}{\partial r_t}\Big|_{r_t=\hat{r}_{t|t-1}} - \hat{l}_{t|t-1} \cdot \dfrac{\partial y_{1,t}^{off}}{\partial l_t}\Big|_{l_t=\hat{l}_{t|t-1}} \\ y_{3,t}^{off}\left(\hat{r}_{t|t-1}, \hat{l}_{t|t-1}\right) - \hat{r}_{t|t-1} \cdot \dfrac{\partial y_{3,t}^{off}}{\partial r_t}\Big|_{r_t=\hat{r}_{t|t-1}} - \hat{l}_{t|t-1} \cdot \dfrac{\partial y_{3,t}^{off}}{\partial l_t}\Big|_{l_t=\hat{l}_{t|t-1}} \end{bmatrix},$$

$$\boldsymbol{\beta}_\mathbf{t}^\mathbf{off} = \begin{bmatrix} \dfrac{\partial y_{1,t}^{off}}{\partial r_t}\Big|_{r_t=\hat{r}_{t|t-1}} \\ \dfrac{\partial y_{3,t}^{off}}{\partial r_t}\Big|_{r_t=\hat{r}_{t|t-1}} \end{bmatrix},$$

$$\boldsymbol{\xi}_\mathbf{t}^\mathbf{off} = \begin{bmatrix} \dfrac{\partial y_{1,t}^{off}}{\partial l_t}\Big|_{l_t=\hat{l}_{t|t-1}} \\ \dfrac{\partial y_{3,t}^{off}}{\partial \mathrm{l}_t}\Big|_{l_t=\hat{l}_{t|t-1}} \end{bmatrix},$$

$$\boldsymbol{\omega}_{\mathbf{t}}^{\mathbf{off}} = \begin{bmatrix} \omega_{1,t}^{off} \\ \omega_{3,t}^{off} \end{bmatrix},$$

$$\frac{\partial y_{M,t}^{off}}{\partial r_t} = \frac{\sum_{m=1}^{M} C_m A_{m,t} B_{m,t} \exp\left(D_{m,t} - B_{m,t} r_t - (t_m - t) l_t\right)}{\sum_{m=1}^{M} C_m (t_m - t) \exp\left(-y_{M,t}^{off} \cdot (t_m - t)\right)},$$

$$\frac{\partial y_{M,t}^{off}}{\partial l_t} = \frac{\sum_{m=1}^{M} C_m A_m (t_m - t) \exp\left(D_{m,t} - B_{m,t} r_t - (t_m - t) l_t\right)}{\sum_{m=1}^{M} C_m (t_m - t) \exp\left(-y_{M,t}^{off} \cdot (t_m - t)\right)},$$

and $\hat{l}_{t|t-1}$ is the estimate of l_t at time t–1.

Once we get the state functions and the measurement functions, we employ the regular iterative prediction-update procedure and the method of quasi-maximum likelihood to estimate the parameters. When estimating the parameters of the off-the-run issues, we use just the parameters γ and ϕ estimated from the on-the-run issues to identify σ_l.

Appendix 2: Matlab Codes

Codes for the On-the-Run Bonds

```
%************define the likelihood function**************%
  function [logfun v1 zz QQ RR rr]=kalfun(param)
  k=param(1);
  theta=param(2);
  sigm=param(3);
  sigm2=param(4);
  v1=zeros(63,2);
  v=zeros(2,1);
  rr=zeros(63,1);
  zz=zeros(63,2);
  RR=0;
  QQ=0;
  load data.mat
  z1=data(:,1); % YTMs of one-year bonds
  z3=data(:,3); % YTMs of three-year bonds
  c1=data(:,2); % cash flows of one-year bonds
  c3=data(:,4:6); % cash flows of three-year bonds
```

```
couponrate=data(:,7); % the coupon rate of three-year
bonds
z=[z1,z3];
%gam=sqrt(k^2+2*theta^2);
gam=sqrt(k^2+2*sigm^2);
tao=[1 2 3]';
dt=1/12;
a=zeros(3,1);
b=zeros(3,1);
for j=1:3
    a(j)=log((2*gam*exp(k*j/2+gam*j/2))/((k+gam)*(exp
(gam*j)-1)+2*gam)^(2*k*theta/sigm^2));
    b(j)=(2*exp(gam*j)-2)/((k+gam)*(exp(gam*j)-1)
+2*gam);
end
r_(1)=theta; %the initial value of r
A= exp(-k*dt);
P_=(1/(1-A^2))*
(sigm^2*(1-exp(-k*dt))/k)*(theta*(1-exp(-k*dt))/2+r_
(1)*exp(-k*dt)); %the initial value of P
C=theta*(1-exp(-k*dt)); %r(i)=C+A*r(i-1)
zm=zeros(63,2);     %the prediction of YTM
R=sigm2*[1 0;0 sqrt(1/3)]; %the covariance of measure-
ment functions
logfun=0;
for i=1:63
Q=(sigm^2*(1-exp(-k*dt))/k)*(theta*(1-exp(-k*dt))/2
+r_(i)*exp(-k*dt)); %the conditional variance of state
functions
pz1(i)=(c1(i)*b(1)*exp(a(1)-b(1)*r_(i)))/c1(i)*exp
(-z1(i)*1);    %the partial derivative of one year z against r
pz3(i)=sum(c3(i,:)'.*b.*exp(a-b*r_(i)))/sum(c3(i,:)'.
*tao.*exp(-z3(i)*tao)); %the partial derivative of three
year z against r
P1=c1(i)*exp(a(1)-b(1)*r_(i));   %the prediction price
of one-year bond
P3=sum(c3(i,:)'.*exp(a-b*r_(i)));  % the prediction
price of three-year bond
%zm1=bndyield(P1,c1(i),'20-Jan-1997','20-Jan-
1998',1);
zm1=-log(P1/c1(i));   %nonlinear measurement function
for one-year bonds
zm3=bndyield(P3,couponrate(i),'20-Jan-1997','20-Jan-
2000',1); %nonlinear measurement function for three-year
bonds
```

```
  H=[pz1(i) pz3(i)]';
  %C1=[zm1 zm3]'-H*r_(i);
  %zm(i,:)= C1+H*r_(i);
  %zm(i,:)= C1+H*r(i);
  zm(i,:)=[zm1 zm3]';   %the prediction of YTMs
  v=z(i,:)'-zm(i,:)'; %the error of measurement functions
  v1(i,:)=v';      % the error between the prediction and the
real value
  F=H*P_*H'+R;      %the kalman gain
  if det(F)<=0
       logfun=0;
       return
  end
  rr(i,:)=r_(i);
  zz(i,:)=zm(i,:);
  r(i)=r_(i)+P_*H'*inv(F)*v; %update r
  P=P_-P_*H'*inv(F)*H*P_;   %update P
  ll=-0.5*log(det(F))-0.5*v'*inv(F)*v;       %likelihood
function
  logfun=logfun+ll;
    r_(i+1)=A*r(i)+C;   %predict r
    P_=A*P*A'+Q;        %predict P
  end
  QQ=Q;
  RR=R;
  logfun=-logfun;
  function covv=covirance(param)
  covv=zeros(4,4);
  for i=1:4
    for j=1:4
    parama=param;
    paramb=param;
    paramab=param;
    parama(i)=param(i)*1.01;
    paramb(j)=param(j)*0.99;
    paramab(i)=param(i)*1.01;
    paramab(j)=paramab(j)*0.99;
    ua=kalfun(parama);
    db=kalfun(paramb);
    udab=kalfun(paramab);
    kk=kalfun(param);
            covv(i,j)=(ua+db-kk-udab)/((0.01*param(i))*
(0.01*param(j)));
  end
  end
```

Codes for the Off-the-Run Bonds

```
%************define the likelihood function *************%
  function [logfun LL zz v1 QQ RR]=kalfunL(paramL)
  sigm3=paramL(1);
  sigm4=paramL(2);
  load dataL.mat
  z1=dataL(:,1); %YTMs of one-year bonds
  z3=dataL(:,3); % YTMs of three-year bonds
  c1=dataL(:,2); % cash flows of one-year bonds
  c3=dataL(:,4:6); % cash flows of three-year bonds
  couponrate=dataL(:,7); %the coupon rate of three-year
bonds
  r=dataL(:,8); %the estimated r in the CIR model
  % the estimated parameters in the CIR model
  k=0.08899;
  theta=0.022659;
  sigm=0.063329;
  gam=sqrt(k^2+2*sigm^2);
  z=[z1,z3];
  tao=[1 2 3]';
  dt=1/12;
  a=zeros(3,1);
  b=zeros(3,1);
  e=zeros(3,1);
  zz=zeros(63,2);
  v1=zeros(63,2);
  v=zeros(2,1);
  RR=0;
  QQ=0;
  for j=1:3
      a(j)=log((2*gam*exp(k*j/2+gam*j/2))/((k+gam)*(exp
(gam*j)-1)+2*gam)^(2*k*theta/sigm^2));
          b(j)=(2*exp(gam*j)-2)/((k+gam)*(exp(gam*j)-1)
+2*gam);
     e(j)=(sigm3^2*tao(j)^3)/6;
  end
  L_(1)=0; %the initial value of L
  v1=zeros(63,2);
  v=zeros(2,1);
  P_=0;
  zm=zeros(63,2);      %the prediction of YTM
  R=sigm4*[1 0;0 sqrt(1/3)];   %the covariance of measure-
ment functions
  logfun=0;
```

```
  for i=1:63
  Q=sigm3^2*dt;       %the conditional variance of state
functions
  pz1(i)=(c1(i)*exp(a(1)-b(1)*r(i)+e(1)-L_(i)*1))/c1(i)
*exp(-z1(i)*1);%the partial derivative of one year z against r
  pz3(i)=sum(c3(i,:)'.*tao.*exp(a-b*r(i)+e-L_(i)
*tao))/sum(c3(i,:)'.*tao.*exp(-z3(i)*tao));    %the par-
tial derivative of three year z against r
  P1=c1(i)*exp(a(1)-b(1)*r(i)+e(1)-L_(i)*1);   %the pre-
diction price of one-year bond
  P3=sum(c3(i,:)'.*exp(a-b*r(i)+e-L_(i)*tao));     % the
prediction price of three-year bond
  %zm1=bndyield(P1,c1(i),'20-Jan-1997','20-Jan-
1998',1);
  zm1=-log(P1/c1(i));    %nonlinear measurement function
for one-year bonds
  zm3=bndyield(P3,couponrate(i),'20-Jan-1997','20-Jan-
2000',1);  %nonlinear measurement function for three-year
bonds
  H=[pz1(i) pz3(i)]';
  %C1=[zm1 zm3]'-H*r_(i);
  %zm(i,:)= C1+H*r_(i);
  %zm(i,:)= C1+H*r(i);
  zm(i,:)=[zm1 zm3]';   %the prediction of YTMs
  v=z(i,:)'-zm(i,:)';        %the  error  of  measurement
functions
  v1(i,:)=v';       % the error between the prediction and
the real value
  F=H*P_*H'+R;      %the kalman gain
  if det(F)<=0
      logfun=0;
      return
  end
  LL(i,:)=L_(i);
  zz(i,:)=zm(i,:);
  L(i)=L_(i)+P_*H'*inv(F)*v;  %update r
  P=P_-P_*H'*inv(F)*H*P_;     %update P
  ll=-0.5*log(det(F))-0.5*v'*inv(F)*v;
    logfun=logfun+ll;
    L_(i+1)=L(i);  %predict r
     P_=P+Q;       %predict P
  end
  QQ=Q;
  RR=R;
  logfun=-logfun;
```

```
function covvL=coviranceL(paramL)
covvL=zeros(2,2);
for i=1:2
   for j=1:2
   parama=paramL;
   paramb=paramL;
   paramab=paramL;
   parama(i)=paramL(i)*1.0000001;
   paramb(j)=paramL(j)*0.9999999;
   paramab(i)=paramL(i)*1.0000001;
   paramab(j)=paramab(j)*0.9999999;
   ua=kalfunL(parama);
   db=kalfunL(paramb);
   udab=kalfunL(paramab);
   kk=kalfunL(paramL);
      covvL(i,j)=(ua+db-kk-udab)/((0.0000001*paramL(i))*
(0.0000001*paramL(j)));
end
end
```

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