Extracting Market Expectations from Yield Curves Augmented by Money Market Interest Rates: The Case of Japan

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Abstract

This paper attempts to extract market expectations about the Japanese economy and the BOJ's policy stance from the Japanese yen yield curves augmented by money market interest rates on a daily basis. We focus on the period after the end of the quantitative easing policy (March 2006). We use (i) the swap yield curves augmented by OIS interest rates (OIS/Swap), and (ii) the JGB yield curve augmented by FB/TB interest rates. First, using the Nelson-Siegel [1987] model, we estimate three latent factors. Following Diebold-Li [2006], we interpret those factors as the expectations components about (i) the long-term growth rate of the Japanese economy or the long-term neutral interest rate, (ii) the pace of the BOJ's rate hikes, and (iii) the medium-term risk. Second, we investigate the relative importance of price discovery for each factor between OIS/Swap and FBTB/JGB, and find that the former has a more dominant role of price discovery for all factors than the latter. Third, we estimate the efficient price for each latent factor common to both yield curves using a time-series structural model, and decompose the changes in each latent factor into the changes in the efficient price and idiosyncratic factors specific to each yield curve.

Key Words: Yield Curve, Market Expectations, Monetary Policy, Overnight Index Swap, Price Discovery, Structural Time-series Model, Swap Spread

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1. Introduction

This paper attempts to extract market expectations about the Japanese economy and the Bank of Japan's (BOJ) monetary policy stance from the Japanese yen yield curves augmented by money markets interest rates. The period covered in this paper is after the quantitative easing policy (QEP) was lifted in March 2006. Since then, the BOJ has raised its policy rate twice (July 2006 and February 2007), and yen money and fixed income markets have experienced large swings caused by fluctuations in expectations following such events as the CPI rebasing in August 2006.

As argued by Baba et al. [2005], the yen money markets had almost lost their function under the zero interest rate policy (ZIRP) and QEP.[1] The level and volatility of short-term interest rates became so low that almost nothing about the future course of interest rates seemed to have been priced into those rates. As the end of the QEP approached, however, the yen money markets started to become active again and to price in future hikes of the policy rate by the BOJ. In fact, a new derivatives transaction named the overnight index swap (OIS), in which the compounded uncollateralized overnight (O/N) call rate is exchanged for the fixed rate, emerged around the spring of 2006. The volume of OIS transactions has grown rapidly and substantially, and the amount outstanding of OIS as of the end of May 2007 reached 971 trillion yen, corresponding to 20-30 percent of interest rate swaps including OIS (Bank of Japan [2007]).[2]

As market liquidity of OIS transactions improved, many market participants started to see the OIS rate as one of the most important reference rates in the yen money markets. In particular, they use the OIS rate to extract market expectations about a near-term policy rate hike by the BOJ based on the fact that the underlying floating rate of OIS is the BOJ's policy rate itself.

It should also be noted that as the end of the QEP approached, overseas investors,

[1] The BOJ initiated the ZIRP in April 1999, when it promised to keep the interest rate at zero until deflationary concerns disappeared. The BOJ adopted the QEP in March 2001, when the policy target was changed from the uncollateralized call rate to the outstanding balance of current accounts held by financial institutions at the BOJ. The BOJ lifted the QEP in March 2006 and ZIRP in July 2006.

[2] For more details of the yen OIS market, see Ooka, Nagano, and Baba [2006], Nagano, Ooka, and Baba [2007], and Bank of Japan [2007].

particularly hedge funds, started to invest in the yen interest rate markets very actively. Their presence has substantially increased, particularly in yen interest rate derivatives including interest rate swaps (IRS) and options. As a result, their transaction volumes exceeded those of domestic investors in such markets as IRS, Euroyen interest futures, and interest rate options, as well as Japanese government bonds (JGB). Their investment strategy is typically based on their so-called normalization scenario of interest rates by the BOJ, backed by the recovery of the Japanese economy. Hence, they place considerable importance on the extraction of market expectations about the future state of the Japanese economy and the BOJ's monetary policy stance.

In light of the improvement in market liquidity in the overall yen money markets and overseas investors' strategy since the end of the QEP, this paper attempts to extract market expectations about the Japanese economy and the BOJ's monetary policy stance from the yield curves augmented by money market interest rates. We use the daily yield curve data, which is the highest frequency available, to analyze the daily fluctuations of market expectations that have been heavily influenced by a series of data releases and the policy-related press reports since the end of the QEP. In this paper, we use the Nelson and Siegel [1987] model to estimate three latent factors and follow Diebold and Li [2006] to interpret those as reflecting market expectations about the future state of the Japan's economy and BOJ's monetary policy stance.

We also compare the possible information contents between the following two yen yield curves.[3] One is constructed from the cash bond yields of FB/TB (financial bills/Treasury bills) and JGB, and the other is constructed from the swap yields of OIS and IRS. Specifically, from these yield curves we first extract the market expectations about (i) the long-term nominal growth rate of the economy or the long-term neutral interest rate, (ii) the pace of rate hikes by the BOJ, and (iii) medium-term risk. Each expectations component corresponds to the long-term level factor, short-term slope factor, and medium-term curvature factor estimated by the Nelson-Siegel model, respectively.

[3] Attempts to extract market expectations have been done so far with a view to extracting the expected duration of the ZIRP when the ZIRP was put in place. See Ueno, Baba, and Sakurai [2006].

Second, we compare the relative importance of price discovery for each expectations component between the two yield curves. Information contents from the swap markets may be different from those from the cash bond markets, particularly for short-term money markets in Japan. The OIS market is more liquid than the FB/TB markets. However, the OIS market participants are predominantly overseas investors, and hence the OIS rate may not reflect the views of domestic investors. As for the FB/TB markets, market participants are more diversified, but the liquidity is fairly limited in the secondary market. In this sense, both rates have advantages and disadvantages in extracting market expectations, and for monitoring the daily market, it is crucial to understand which market rates reflect fundamentals more closely. Here, we use both a reduced-form model proposed by Gonzalo and Granger [1995] and Hasbrouck [1995], and a time-series structural model based on the state space model.

Third, we decompose the changes in each expectations component into the changes in the efficient price common to both yield curves and idiosyncratic components specific to each curve. This type of decomposition enables us to closely monitor the market expectations after controlling for the temporary supply-demand balances specific to the markets.

The rest of the paper is organized as follows. Section 2 estimates three latent dynamic factors that likely capture specific aspects of market expectations from the yield curves augmented by money market interest rates: OIS and FB/TB rates, using the Nelson-Siegel model. Section 3 compares the relative role of price discovery for each latent factor between swaps (OIS/Swap) and cash bonds (FBTB/JGB) using the reduced-form model. Section 4 estimates the efficient price for each latent factor common to both yield curves using a time-series structural model, and decomposes the changes in each latent factor into the changes in the efficient price and idiosyncratic factors specific to each yield curve. Section 5 concludes the paper.

2. Estimation of Latent Dynamic Factors Capturing Market Expectations

2.1 Nelson-Siegel Model

As stated by Söderlind and Svensson [1997], yield curves can be estimated either by a structural model for interest rate dynamics or by simple curve fitting. The former is appropriate when the purpose is to predict future changes in the yield curve, while the latter is appropriate when the purpose is to extract market expectations about future interest rates without making additional assumptions about the model structure. Since our purpose is to extract market expectations, we use the latter approach. Among others, we use the following Nelson and Siegel [1987] model to extract three latent dynamic factors from the yield curves augmented by money market interest rates:

$$f_t(\tau) = \beta_{0t} + \beta_{1t} e^{-\tau/\lambda_t} + \beta_{2t}\, \tau/\lambda_t\, e^{-\tau/\lambda_t}, \tag{1}$$

$$y_t(\tau) = \beta_{0t} + \beta_{1t}\left(\frac{1-e^{-\tau/\lambda_t}}{\tau/\lambda_t}\right) + \beta_{2t}\left[\frac{1-e^{-\tau/\lambda_t}}{\tau/\lambda_t} - e^{-\tau/\lambda_t}\right], \tag{2}$$

where $f_t(\tau)$ and $y_t(\tau)$ denote the forward rate and the corresponding spot rate for time t and maturity τ, respectively. The main reasons for choosing the Nelson-Siegel model are its handiness and ease of interpreting the parameters in economic terms, as will be described later.[4] As shown in Nelson and Siegel [1987], the shape of yield curve model (2) may be upward sloping, downward sloping, humped, or inverted, depending on the values of β_{1t} and β_{2t}.

Recently, Diebold and Li [2006] reinterpreted the Nelson-Siegel model as a dynamic three latent factor model by fixing λ_t as a pre-specified constant. Based on this reinterpretation, Diebold, Rudebusch, and Aruoba [2006], and Fabozzi, Martellini, and Priaulet [2005], among others, examined the empirical performance of the model using U.S. dollar yield curve data. Meanwhile, Diebold, Piazzesi, and Rudebusch [2005] and Christensen, Diebold, and Rudebusch [2007] deepened the model from a theoretical perspective by imposing the "no-arbitrage condition." In the paper, we extract three latent factors following Diebold and Li [2006] and

[4] Another possible way to extract market expectations about monetary policy stance is to look at the futures interest rate. Kuttner [2001] decomposed the change in Federal funds futures rates into anticipated and unanticipated components. In the Japanese case, Euroyen interest futures rates are available, but since the sole maturity is 3 months and the underlying rate is TIBOR (Tokyo Interbank Offered Rate), we cannot directly gauge market expectations about the BOJ's near-term monetary policy changes with the uncollateralized overnight call rate as its policy target.

interpret each factor as follows.[5]

First, the loading on β_{0t} is one, a constant that does not decay to zero in the limit. Hence, it can be viewed as a long-term level factor. According to interviews we had with hedge fund managers in London, those with the so-called global macro strategy typically regard it as the long-term nominal growth rate of the economy or the long-term neutral interest rate perceived by market participants.[6]

Second, the loading on β_{1t} is a function that starts at one, but decays monotonically and quickly to zero. Hence, it can be viewed as a short-term slope factor. Our interviews showed that many hedge fund managers use it to gauge market expectations about the pace of rate hikes by the BOJ.

Third, the loading on β_{2t} is a function that starts at zero, increases, and then decays to zero. Hence, it can be viewed as a medium-term curvature factor, which is likely to reflect the medium-term risk relative to the pace of rate hikes perceived by market participants.

Below, we estimate three latent factors by the following two steps: (i) estimating λ_t and three latent factors by calibrating the spot yield curve model (2) to the daily interest rate data, treating each parameter including λ_t as a free parameter, and (ii) re-estimating model (2) by fixing λ_t at the average value of λ_t estimated in the first step.

2.2 Data

Throughout the paper, we use the following two combinations of money market interest rates with maturities shorter than one year and interest rates with maturities equal to or longer than one year to construct the full yield curves: (i) OIS and IRS yields and (ii) FB/TB and JGB yields. We

[5] An alternative approach to estimating the latent factors was proposed by Diebold, Rudebusch, and Aruoba [2006]. They simultaneously fitted the yield curve at each point in time and estimated the underlying dynamics of the factors represented as the VAR(1) system, using the state space model. A major advantage of this approach is that it suffers less from the overfitting problem. A major disadvantage is that it requires a tough numerical optimization with a more complex VAR system, and hence it may not be able to efficiently capture a high persistence in yields over time.

[6] Definitions of the long-term (nominal) neutral interest rate differ across market participants. The most common definition is the interest rate that can be achieved in the long run, and that is neutral to cyclical factors including monetary policy.

call the first one the OIS/Swap yield curve and the second one the FBTB/JGB yield curve.

We use the daily spot rates of these instruments. The sample period is from April 3, 2006 to July 31, 2007 and the number of observations is 329.[7] The maturities consist of (i) 12 shorter-than-one-year maturities (1, 2, …, 12 months) and (ii) 21 one-year or longer-than-one-year maturities (1.5, 2, …, 9.5, 10 and 12, 15, and 20 years).

For the OIS/Swap yield curve, we use the OIS closing rates reported by Meitan Tradition Co., Ltd. and the zero-coupon swap rates estimated from the Tokyo Swap Reference Rate released by Reuters. Both rates are as of 15:00 Tokyo time. It should be noted that the underlying floating rate of OIS is the uncollateralized call rate (O/N), and that of swaps is 6-month LIBOR.[8] This difference in the underlying rates inevitably causes a discontinuous kink over the yield curves. Hence, we adjust the rate differential by deducting the sample-average rate differential (14.2 basis points) between the 1-year OIS rate and the 1-year swap rate from swap rates.

For the FBTB/JGB yield curve, we use the FB/TB rates and the JGB zero-coupon yields.[9] FBs are currently issued with 3-month maturity, and TBs are issued with 6- and 12-month maturities as discount bonds, not paying periodic coupons. The 3-month FBs are issued at weekly auctions and the 6/12-month TBs are issued at monthly auctions. We estimate one to eleven month spot rates by linearly interpolating the FB/TB rates of nearby maturities using the newly issued 12-month TB rate as the 1-year money market rate. As is the case with the OIS/Swap yield curve, a rate differential remains between the TB rate and the JGB rate at 1-year maturity. This mainly comes from the difference in funding costs for each bond. Investors typically use repo transactions (repurchase agreement, spot/next) for funding FB/TBs, while they purchase JGBs using their own yen cash. The Japanese repo rate is constantly higher and more volatile than the

[7] The OIS rate is available only from April 3, 2006 since the OIS market emerged in the spring of 2006.
[8] LIBOR is London Interbank Offered Rate.
[9] JGB zero-coupon yields are estimated from the price of coupon bonds with 5-, 10-, and 20-year maturities at issue by McCulloch's [1971, 1990] method.

uncollateralized call rate, despite the fact that repo transactions are collateralized.[10] Hence, we deduct the spread between the repo rate (S/N) and the call rate (O/N) from the FB/TB rates for adjustment.

The above-mentioned adjustments enabled us to smoothly draw both the OIS/Swap and FBTB/JGB yield curves without any kinks.

2.3 Result of Estimating Latent Factors

Chart 1 (i) shows an example of fitting the Nelson-Siegel model for both the OIS/Swap and FBTB/JGB yield curves, and Chart 1 (ii) shows the average pricing errors over the full sample period. It shows that the Nelson-Siegel model performs well in tracing both yield curves, and the performance is better for the OIS/Swap yield curve than the FBTB/JGB yield curve for almost all of the maturities.

Next, Chart 2 (i) compares the average pricing errors of the OIS/Swap and FBTB/JGB yield curves (full yield curves) to those of the Swap and JGB yield curves that are not augmented by money market interest rates. The average pricing errors of the OIS/Swap and FBTB/JGB yield curves are evidently lower than those of the Swap and JGB yield curves for maturities equal to or shorter than one year. Chart 2 (ii) shows that the O/N rates implied by the yield curves augmented by money market rates are closer to the policy target rates, suggesting that the augmented yield curves more properly capture the term structure of short-term money market yields.

Chart 3 plots the estimates of the three latent dynamic factors from each full yield curve. First, Chart 3 (i) shows that the long-term level factors from both yield curves are largely within the range between 2.4 and 3.2 percent. Specifically, the long-term level factor from the OIS/Swap yield curve is largely within the range of 2.8–3.2 percent, while that from the FBTB/JGB curve is within the range of 2.4–3.0 percent. Market participants suggest that the long-term nominal

[10] For the reasons for higher and volatile repo rates, see the Bank of Japan [2006], and Baba and Inamura [2004].

neutral interest rate is in the range of 2.5–3.0 percent in this period, so the estimated long-term level factors seem to be consistent with the market views. They were on an uptrend until October 2006, turned to a declining trend toward the end of 2006, and have moved without a clear direction since then. Also, the factor is constantly higher for the OIS/Swap yield curve than for the FBTB/JGB yield curve, particularly in 2006. One possible reason for this differential is the counterparty risk associated with OIS/Swap transactions, but the difference in the composition of market participants between the OIS/Swap and FBTB/JGB markets also likely plays a role. We will examine this issue later.

Second, Chart 3 (ii) shows that the short-term slope factor is constantly negative, and the negativity is larger for the OIS/Swap yield curve than for the FBTB/JGB yield curve. The negative short-term slope factor means an upward-sloping yield curve, and hence this result shows that the OIS/Swap yield curve constantly has a steeper slope than the FBTB/JGB yield curve. The short-term slope factors from both curves were almost directionless until October 2006, on an uptrend toward the end of 2006, and have moved without a clear direction since then. Since this factor can be interpreted as the pace of rate hikes by the BOJ perceived by market participants, these results have the following interesting implications.

As emphasized by Ooka, Nagano, and Baba [2006] and the Bank of Japan [2007], the yen OIS market has been dominated by non-Japanese financial institutions, while cash bond markets like FB/TBs have a more balanced composition of investors between Japanese and non-Japanese financial institutions. Anecdotal evidence suggests that non-Japanese market participants have expected the BOJ to hike its policy rate at a more rapid pace than their Japanese counterparts, backed by strong expectations of higher growth of the Japanese economy. The difference in the short-term slope factor may reflect such a perception gap between Japanese and non-Japanese market participants. From our interviews with non-Japanese financial institutions, their expectations of the BOJ's rate hike peaked around May 2006, lost steam between October and December 2006 when the CPI inflation rate was successively weaker than expected, and heightened again toward the MPM in February 2007, when the policy rate was hiked. The movement of the short-term slope factor seems to capture such a swing of market expectations.

Third, Chart 3 (iii) shows that the medium-term curvature factors were on a consistent downtrend until October 2006, and have moved without a clear direction since then. This result seems to be consistent with the market sentiment that the expectations of higher interest rates based on the upbeat outlook for the Japanese economy peaked around the spring of 2006, and have substantially receded since the CPI rebasing in August 2006.[11]

Furthermore, to examine more closely the market expectations priced into the market interest rates, we also estimated the short-term slope factor and the medium-term curvature factor only from the OIS and FBTB yield curves whose maturities are up to one year. We call them money market yield curves. In doing so, we fixed the long-term factor at 2.92, which is the mean of the factor estimated from OIS/Swap and FBTB/JGB yield curves over the full sample period.

Chart 4 (i) and Chart 4 (ii) plot the thus-estimated short-term slope factor and the medium-term curvature factor, respectively. The medium-term curvature factor shows a similar time-series pattern to that estimated from the full yield curves, but the short-term slope factor has a more striking time-series pattern than that from the full yield curves. Since the time horizon of the money market yield curves is up to one year, the immediate rate hikes can be more easily priced in as the flattening of the curves. We can see that each slope factor rapidly rose toward the MPMs when the BOJ raised the policy rate (July 14, 2006 and February 21, 2007), which suggests that money market yield curves priced in the immediate rate hikes in the form of the flattening of the curve.[12] Evidently, the OIS yield curve has led the FBTB curve in pricing in the immediate rate hikes thus far.

3. Evaluating the Price Discovery using a Reduced-form Model

3.1 Price Discovery Measures under a Reduced-form Model

[11] As a result of the CPI rebasing in August 2006, the national core CPI inflation rate was revised downward by 0.4 percentage points.

[12] We can also see the rises in the short-term slope factors toward the MPM in January 2007. In this period, the yen money markets, the OIS market in particular, were substantially disturbed by noisy media releases about the timing of the immediate policy rate hike.

In this section, we investigate which yield curve, the OIS/Swap or FBTB/JGB yield curve, has a more dominant role of price discovery for each factor using a reduced-form model.

Broadly speaking, there are two empirical approaches that have attracted academic attention for investigating price discovery. One is the permanent-transitory (PT) model developed by Gonzalo and Granger [1995], and the other is the information share (IS) model developed by Hasbrouck [1995]. Both models start with the estimation of the vector error-correction model (VECM) of market prices:

$$\Delta\beta_t^{OIS} = \lambda_1\left(\beta_{t-1}^{OIS} - \alpha_1\beta_{t-1}^{FB} - C\right) + \sum_{j=1}^{p}\gamma_{1j}^{OIS}\Delta\beta_{t-j}^{OIS} + \sum_{j=1}^{p}\eta_{1j}^{FB}\Delta\beta_{t-j}^{FB} + \varepsilon_t^{OIS} \tag{6}$$

$$\Delta\beta_t^{FB} = \lambda_2\left(\beta_{t-1}^{OIS} - \alpha_1\beta_{t-1}^{FB} - C\right) + \sum_{j=1}^{p}\gamma_{2j}^{OIS}\Delta\beta_{t-j}^{OIS} + \sum_{j=1}^{p}\eta_{2j}^{FB}\Delta\beta_{t-j}^{FB} + \varepsilon_t^{FB} . \tag{7}$$

where β_t^{OIS} (β_t^{FB}) denotes the latent factor in time t estimated from the OIS/Swap (FBTB/JGB) yield curve, and ε_t^{OIS} (ε_t^{FB}) is the corresponding i.i.d. residual. For simplicity, we drop the subscript i for latent factors. An underlying assumption is that there is an unobservable efficient price for each factor that is common to both yield curve factors.

Based on the VECM above, the PT model decomposes the efficient price itself, and attributes a more dominant role of price discovery to the market that adjusts less to price movements in the other market. As stated in Engle and Granger [1987], the existence of cointegration assures that at least one market has to adjust. Specifically, price discovery for the OIS/Swap yield curve factor under the PT model can be measured by

$$\mathrm{PT} = \frac{\lambda_2}{\lambda_2 - \lambda_1} . \tag{8}$$

On the other hand, the IS model decomposes the variance of the efficient price under the assumption that price volatility reflects new information flows, and hence the market that contributes more to the variance of the innovations to the efficient price is considered to contribute more to price discovery. Specifically, price discovery for the OIS/Swap yield curve factor market under the IS model can be measured by

$$\mathrm{IS}_1 = \frac{\lambda_2^2\left(\sigma_1^2 - \dfrac{\sigma_{12}^2}{\sigma_2^2}\right)}{\lambda_2^2\sigma_1^2 - 2\lambda_1\lambda_2\sigma_{12} + \lambda_1^2\sigma_2^2} \quad \text{and} \quad \mathrm{IS}_2 = \frac{\left(\lambda_2\sigma_1 - \lambda_1\dfrac{\sigma_{12}}{\sigma_1}\right)^2}{\lambda_2^2\sigma_1^2 - 2\lambda_1\lambda_2\sigma_{12} + \lambda_1^2\sigma_2^2}, \qquad (9)$$

where σ_1^2, σ_2^2, and σ_{12} are factors in the covariance matrix of ε_t^{OIS} and ε_t^{FB}. IS_1 and IS_2 measure the lower and higher bounds of information share, where the difference between two bounds is positively related to the correlation between residuals. Baillie et al. [2002] argue that the average of these two bounds provides a sensible estimate of price discovery when the data frequency is high. Also note that PT ignores the correlation between the markets, and hence if the residuals are strongly correlated, then both models can provide substantially different results.

3.2. Result of Estimating Price Discovery Measures

Chart 5 shows the estimation results of price discovery measures for the three latent factors estimated from the two full yield curves.[13] First, Chart 5 (i) reports the result of the Johansen cointegration test. The same factors estimated from the two yield curves have a cointegration relationship at the 10 percent significance level for the long-term level factor and the slope factor, and at the 5 percent level for the medium-term curvature factor.[14] We also tested the restriction of the theoretically complete relationship characterized as a vector (1, –1) between the two yield curves, and found that the restriction was not rejected significantly.

Second, Chart 5 (ii) shows the result of estimating the two price discovery measures. Both PT and IS measures of price discovery suggest that the OIS/Swap yield curve has a more dominant role of price discovery than the FBTB/JGB yield curve for all three latent factors.

Third, Chart 6 shows the generalized impulse responses of each factor.[15] For each

[13] Both the Augmented Dickey-Fuller and the Phipps-Perron tests (not shown) suggest that all three factors are I(1) at least at the 5 percent significance level. The result is available upon request.

[14] We included a trend term in the cointegration test since the differences in the same factors estimated from the two yield curves constantly become narrower throughout the sample period.

[15] We use the "generalized" impulse responses proposed by Pesaran and Shin [1998] instead of the impulse responses derived from the conventional "orthogonalized" Cholesky decomposition. The generalized impulse responses have an advantage in that they are invariant to the ordering of the variables in the VAR system.

factor, the responses of the FBTB/JGB factor to the OIS/Swap factor are generally larger than vice versa. In particular, the responses of the FBTB/JGB factor to the OIS/Swap factor become larger than the responses of the FBTB/JGB factor to itself several days after the shock.

Next, Chart 7 shows the result of estimating price discovery measures for the short-term slope factor and the medium-term curvature factor estimated from the money market yield curves. First, Chart 7 (i) shows that each factor has a cointegration relationship between OIS and FBTB yield curves at least at the 5 percent significance level, and the theoretical restriction of the vector (1, –1) was not significantly rejected for the medium-term curvature factor.

Second, Chart 7 (ii) shows that the OIS yield curve has a more dominant role of price discovery for both factors. Last, Chart 8 shows the impulse responses. A similar tendency can be observed as is the case of the full yield curves. The dynamic effects of the OIS factors on the FBTB factors are larger than vice versa, particularly for the short-term slope factor.

4. Extracting Market Expectations using a Structural Time-series Model

4.1 Structural Model

Next, we use a structural time-series model (state space model) to directly extract market expectations in the form of the efficient prices that are common to OIS/Swap and FBTB/JGB full yield curves or OIS and FBTB money market yield curves. Various specifications exist for structural time-series models. In this paper, we adopt the specification that is an extension of the local level model into the setting of multiple market prices with a common factor as a state variable, following Lehmann [2002] and others:

$$\begin{pmatrix} \beta_t^{OIS} \\ \beta_t^{FB} \end{pmatrix} = \begin{pmatrix} 1 \\ 1 \end{pmatrix} m_t + \begin{pmatrix} T_t^{OIS} \\ T_t^{FB} \end{pmatrix} + \begin{pmatrix} \varepsilon_t^{OIS} \\ \varepsilon_t^{FB} \end{pmatrix} \quad \varepsilon_{it}^{OIS} \sim N\left(0, \sigma_{\varepsilon OIS}^2\right), \varepsilon_{it}^{FB} \sim N\left(0, \sigma_{\varepsilon FB}^2\right) \tag{10}$$

$$m_{t+1} = m_t + s_{t+1}^m \qquad s_t^m \sim N\left(0, \sigma_m^2\right) \tag{11}$$

$$T_{t+1}^{OIS} = b^{OIS} + c^{OIS} T^{OIS} + s_{t+1}^{OIS} \qquad s_{t+1}^{OIS} \sim N\left(0, \sigma_{sOIS}^2\right) \tag{12}$$

$$T_{t+1}^{FB} = c^{FB} T_t^{FB} + s_{t+1}^{FB} \quad s_t^{FB} \sim N\left(0, \sigma_{sFB}^2\right) \tag{13}$$

$$0 < c^{OIS} < 1, \; 0 < c^{FB} < 1.$$

Here, we drop the subscript i for latent factors. Each latent factor consists of the following three price components: (i) the efficient price (m_t), (ii) the idiosyncratic factor (T_t^{OIS} or T_t^{FB}), and (iii) the idiosyncratic temporary noise (ε_t^{OIS} or ε_t^{FB}).

First, m_t is the efficient price that is common to OIS/Swap and FBTB/JGB yield curve factors. m_t is assumed to follow a random walk process (11), following a conventional practice in finance literature.[16]

Second, T_t^{OIS} or T_t^{FB} represents the idiosyncratic factors specific to the OIS/Swap or FBTB/JGB factor, respectively. These factors are assumed to follow a mean-reverting process.[17] Under this specification, a "swap spread" for each factor can be written as

$$E_t[Swap\,Spread_{t+1}] = b^{OIS} + c^{OIS} T_t^{OIS} - c^{FB} T_t^{FB}. \tag{14}$$

Recent studies on interest rate swaps, such as Duffie and Singleton [1997] and Kambhu [2006], point out that the swap spreads tend to converge to their normal level, and hence follow an I(0) mean-reverting process. Moreover, Kambhu [2006] argues that both idiosyncratic factors specific to swaps and government bonds influence the spread spreads. Our specification of the swap spread follows these findings. As for the specification of the OIS and FBTB money market yield curves, b^{OIS} is assumed to be zero because the average level of the swap spread has already been adjusted by applying the same long-term level factor, 2.92, in calculating the two latent factors.

Third, ε_t^{OIS} and ε_t^{FB} are the idiosyncratic temporary noises, possibly reflecting transient market-microstructure shocks arising from temporary supply-demand shocks at auctions, for instance. In what follows, we assume that each shock is mutually independent. The parameters

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16 The random walk representation of the efficient price dates back to Samuelson [1965].

17 A constant parameter, b, is included only in the OIS/Swap process because the swap spread is the spread added to the FBTB/JGB curve by definition, and hence the long-run average of each T_i^{FB} can be safely treated as zero.

in the model are well identified, and are estimated by maximizing the log-likelihood that can be evaluated by the Kalman filter.[18]

4.2 Estimation Result: Full Yield Curves

Chart 9 reports the result of estimating the structural model for each latent factor estimated from the full yield curves. All the coefficients except c^{OIS} for β_2 are significant at least at the 5 percent level. The long-run mean level of T_t^{OIS} calculated as $b^{OIS}/\left(1-c^{OIS}\right)$ is 0.220 for β_0, –0.182 for β_1, and –0.227 for β_2, respectively. This result suggests that in the long run, (i) the long-term level factor of the swap spread converges to the 0.220 percent level, (ii) the swap spread has a positive slope, and (iii) a negative curvature.

Furthermore, we computed the following signal-to-noise ratio to assess the relative importance of price discovery between the two yield curves, which is defined as the share of the efficient price variance in the total variance for each factor:[19]

$$SIS(i) \equiv \sigma_m^2 \Big/ \left(\sigma_m^2 + \sigma_{si}^2 + \sigma_{\varepsilon i}^2\right). \quad \text{For } i = \text{OIS/Swap or FBTB/JGB} \tag{15}$$

We call this measure "structural information share (SIS)" in this paper. As shown in Chart 9, SIS is higher for the OIS/Swap than the FBTB/JGB for each factor. The result is consistent with the result of estimating price discovery measures using the reduced-form model reported in Section 3.

4.3 Factor Decomposition: Full Yield Curves

Using the estimation result above, we can decompose a change in each factor into the changes in the efficient price and the idiosyncratic factor as follows:

$$\beta_{t+1}^{OIS} - \beta_t^{OIS} = \left(\overline{m}_{t+1} - m_t\right) + \left(\overline{T}_{t+1}^{OIS} - \overline{T}_t^{OIS}\right) + \varepsilon_{t+1}^{OIS} - \varepsilon_t^{OIS} \tag{16}$$

---

[18] See Durbin and Koopman [2001] for details of the state space model and the Kalman filter.

[19] The conventional definition of the signal-to-noise ratio is the ratio of the efficient price variance to stochastic noise variance. We use our form of the signal-to-noise ratio primarily for ease of comparison.

$$\beta_{t+1}^{FB} - \beta_t^{FB} = \left(\overline{m}_{t+1} - \overline{m}_t\right) + \left(\overline{T}_{t+1}^{FB} - \overline{T}_t^{FB}\right) + \varepsilon_{t+1}^{FB} - \varepsilon_t^{FB}, \tag{17}$$

where $\overline{m}_t$, $\overline{T}_t^{OIS}$, and $\overline{T}_t^{FB}$ are filtered state variables. The first term on the right-hand side of equations (16) and (17) indicates the forecast errors of the efficient price, and the remaining terms correspond to those of the total idiosyncratic factors. Note here that this is *not* the decomposition of forecast errors, but just the simple factor decomposition.

Chart 10 shows the result of the factor decomposition for each latent factor. The left figures show the decomposition of daily factor changes, and the right ones show the accumulated daily changes from the second date of our sample period, April 3, 2007. The efficient price for each factor shows a very similar time-series pattern to each latent factor itself shown in Chart 3. An interesting point here is that the idiosyncratic factors for FBTB/JGB seem to have a trend, and fluctuate much more widely than those for OIS/Swap. This result suggests that the efficient price follows the factor estimated from the OIS/Swap yield curve much more closely, which is consistent with the result that the OIS/Swap yield curve has a more dominant role in price discovery than the FBTB/JGB yield curve.

4.4 Estimation Result: Money Market Yield Curves

Next, Chart 11 shows the result for estimating the short-term slope factor estimated from the money market yield curves.[20] All the coefficients except $\sigma^2_{\varepsilon OIS}$ are significant at the 1 percent level. This result suggests that the idiosyncratic temporary noises are statistically negligible in the OIS market. Also note that c^{OIS} is estimated to be closer to 1 (0.944), which is higher than the case of the full yield curves (0.609). SIS is higher for the OIS slope factor than the FBTB/JGB slope factor, suggesting that the OIS slope factor has a more dominant role in price discovery than the FBTB slope factor. The result is consistent with the case of the full yield curves.

Chart 12 shows the result of the factor decomposition. The time-series pattern of the efficient price has a distinctive feature. Specifically, from about one month before the MPMs

[20] The result for the medium-term curvature factor is available upon request.

where market participants strongly expected the BOJ to raise the policy rate, the efficient price started to rise rapidly, and hence flattened the short-term yield curve. Then, once the policy rate was raised, it remained or gradually declined until market expectations about the next rate hike were reignited. Also note that the idiosyncratic factor is more volatile for FBTB than OIS throughout the sample period. This result is consistent with the case of the full yield curves and probably reflects temporary supply-demand imbalances in the bond markets, as has often been suggested by market participants.

5. Concluding Remarks

This paper has attempted to extract market expectations about the Japanese economy and the BOJ's policy stance from the Japanese yen yield curves augmented by money market interest rates on a daily basis. We focused on the period after the end of the quantitative easing policy (March 2006). We used (i) the swap yield curves augmented by OIS interest rates (OIS/Swap), and (ii) the JGB yield curve augmented by FB/TB interest rates. The main findings are summarized as follows.

First, using the Nelson-Siegel [1987] model, we estimated three dynamic latent factors. Following Diebold and Li [2006], they are likely to capture the expectations components about (i) the long-term nominal growth rate of the Japanese economy or the long-term neutral interest rate, (ii) the pace of the BOJ's rate hikes, and (iii) the medium-term risk.

Second, we investigated the relative role of price discovery for each factor between OIS/Swap and FBTB/JGB, and found that for all the factors, the OIS/Swap yield curve has a more dominant role of price discovery than the FBTB/JGB yield curve.

Third, we estimated the efficient price for each latent factor common to both yield curves using a time-series structural model, and decomposed the changes in each latent factor into the changes in the efficient price and idiosyncratic factors specific to each yield curve. We found that each state variable much more closely follows the OIS/Swap factors than the FBTB/JGB factors, and the idiosyncratic component is much more volatile for the FBTB/JGB factors than the OIS/Swap factors.

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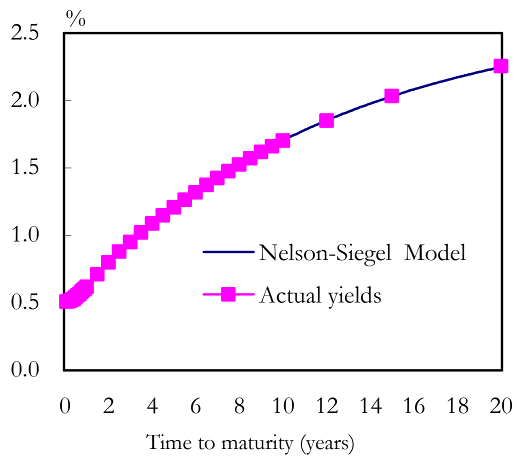
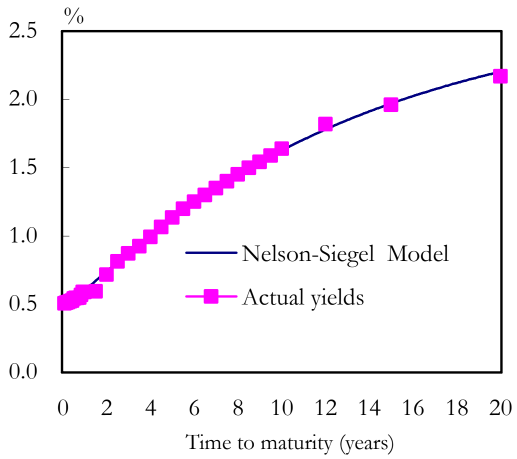
Chart 1: Fitting Performance of the Nelson-Siegel Model

(i) Fitting Example of the Nelson-Siegel Model

a. OIS/Swap Yield Curve

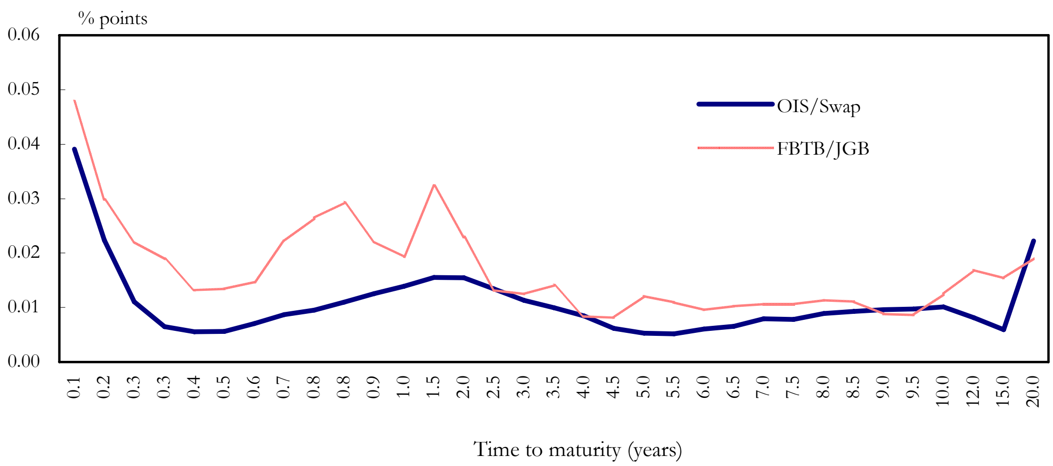


b. FBTB/JGB Yield Curve



Note: The fitting example is as of March 30, 2007.

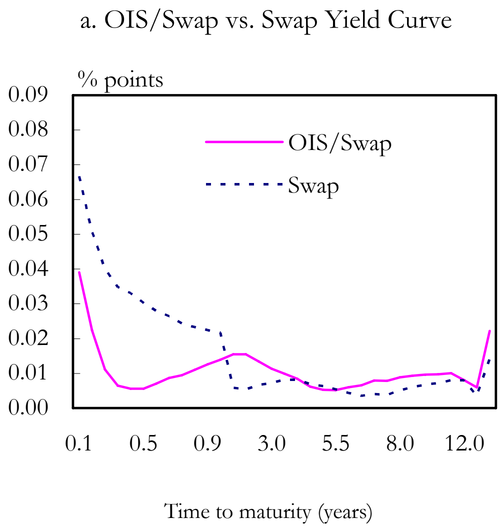
(ii) Average Pricing Errors

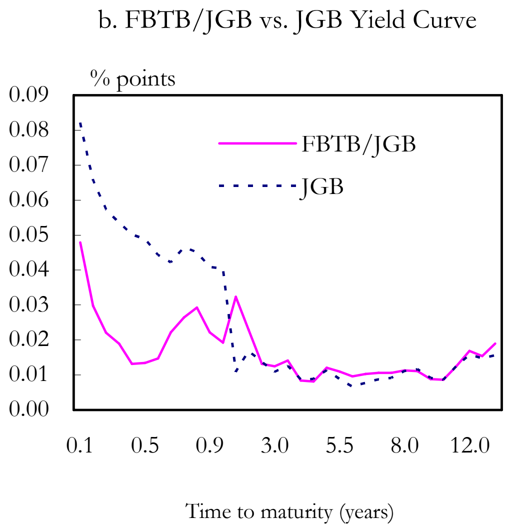


Note: Average pricing errors are calculated as the absolute values of pricing errors over the full sample period.

Chart 2: Comparison between Full Yield Curves and Yield Curves without Money Market Rates

(i) Average Pricing Errors





Note: Average pricing errors are calculated as the absolute values of pricing errors over the full sample period.

(ii) Implied O/N Rates

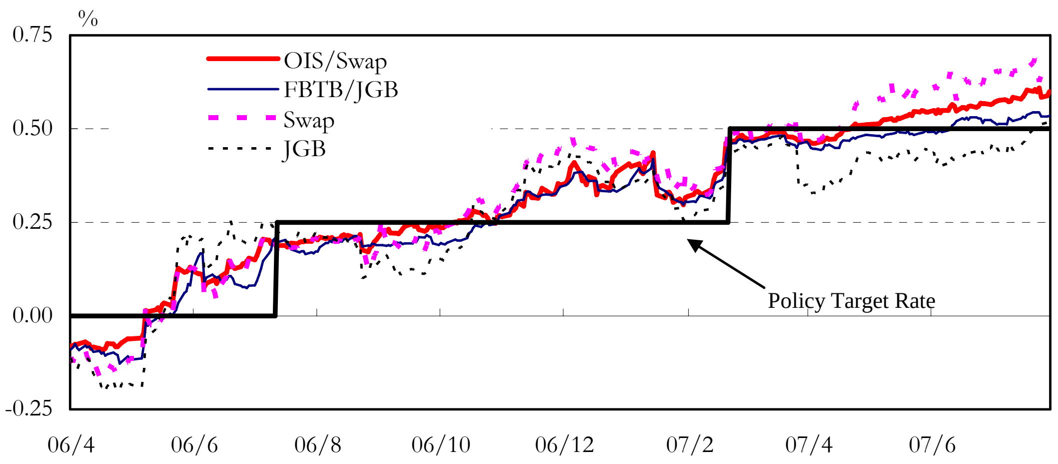
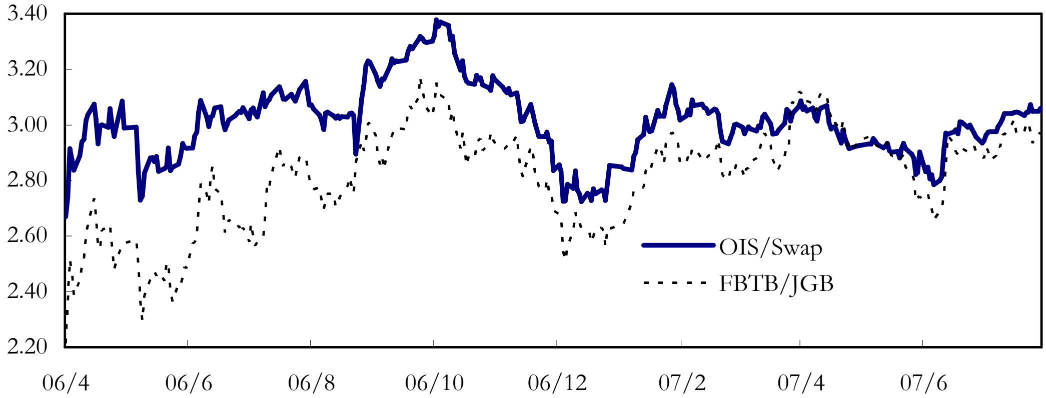
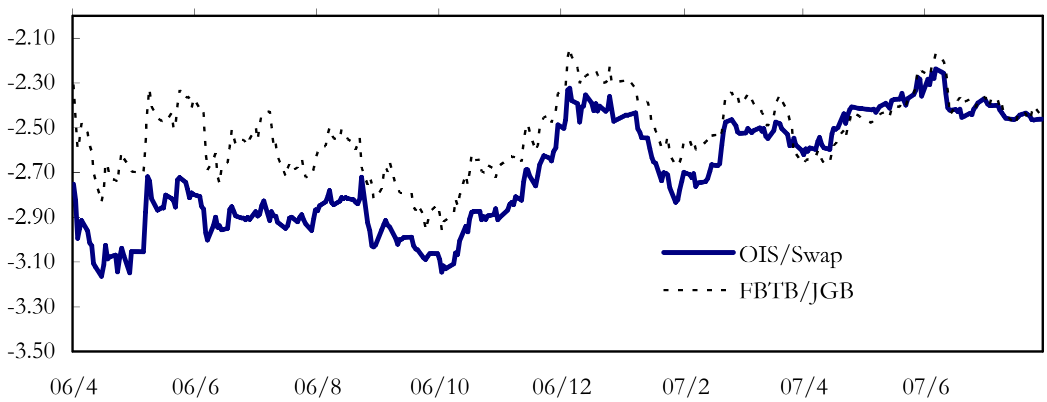


Chart 3: Three Latent Factors Estimated from Full Yield Curves

(i) β0: Long-term Level Factor



(ii) β1: Short-term Slope Factor



(iii) β2: Medium-term Curvature Factor

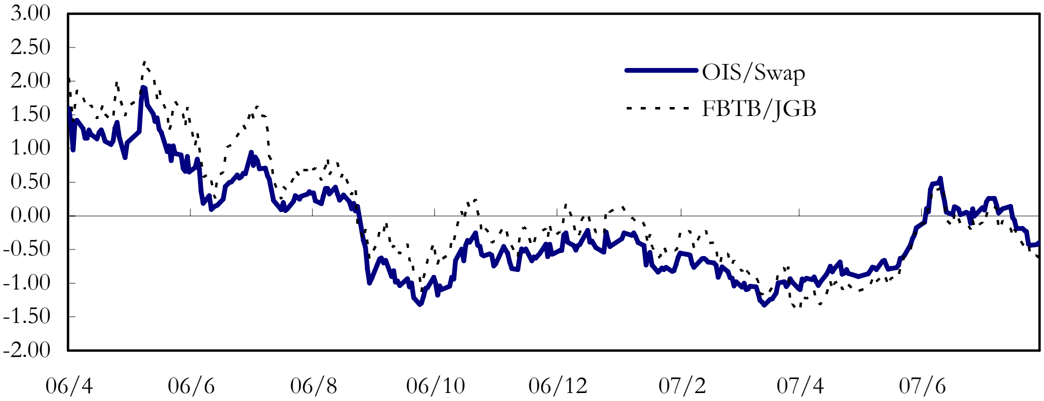
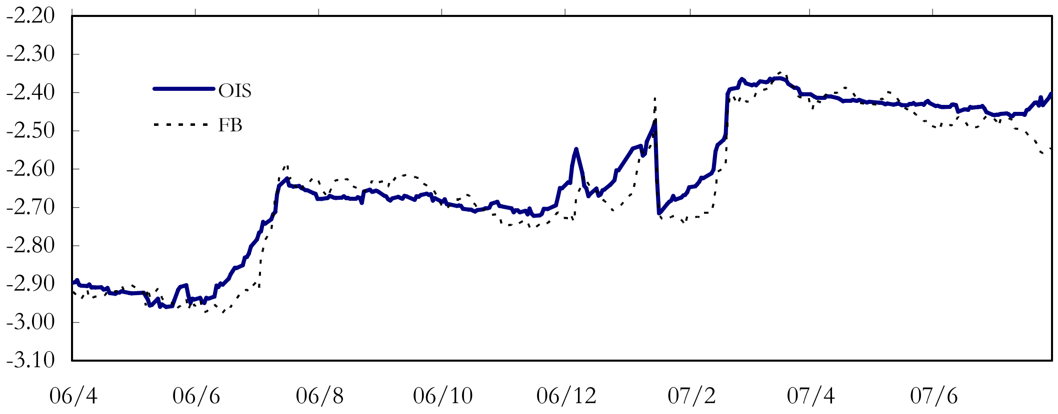
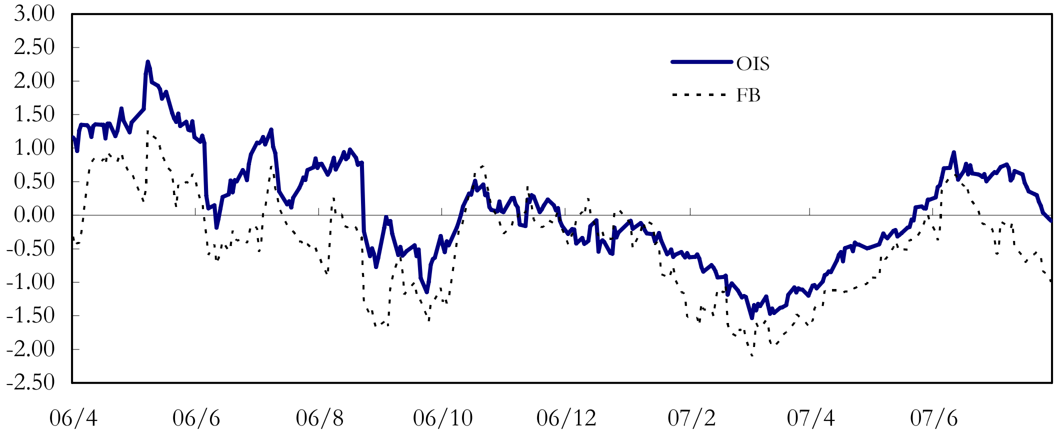


Chart 4: Two Factors Estimated from Money Market Yield Curves

(i) β1: Short-term Slope Factor



(ii) β2: Medium-term Curvature Factor



Note: β0 is fixed at 2.92.

Chart 5: Price Discovery Measures from Full Yield Curves (OIS/Swap vs. FBTB/JGB Yield Curve)

(i) Cointegration Analysis

(a) β0 Sample Period: April 3, 2006-July 31, 2007 (Number of Observations: 329)

Cointegration Rank Test				
H0	Eigenvalue	Trace	Max Eigen	Lags
None	0.05	24.08 *	17.57 *	2
At most 1	0.02	6.51	6.51	

Cointegration Vector			
OIS/Swap	FBTB/JGB	Constant	Trend
1.000	-0.917	-0.624	0.001
LR statistic for cointegration vector = (1, -1)		Chi-squared = 0.453	*p*-value = 0.501

(b) β1 Sample Period: April 3, 2006-July 31, 2007 (Number of Observations: 329)

Cointegration Rank Test				
H0	Eigenvalue	Trace	Max Eigen	Lags
None	0.05	25.10 *	18.24 *	2
At most 1	0.02	6.86	6.86	

Cointegration Vector			
OIS/Swap	FBTB/JGB	Constant	Trend
1.000	-0.941	0.550	-0.001
LR statistic for cointegration vector = (1, -1)		Chi-squared = 0.343	*p*-value = 0.558

(c) β2 Sample Period: April 3, 2006-July 31, 2007 (Number of Observations: 329)

Cointegration Rank Test				
H0	Eigenvalue	Trace	Max Eigen	Lags
None	0.07	27.48 **	23.61 **	2
At most 1	0.01	3.87	3.87	

Cointegration Vector			
OIS/Swap	FBTB/JGB	Constant	Trend
1.000	-1.077	0.737	-0.003
LR statistic for cointegration vector = (1, -1)		Chi-squared = 1.626	*p*-value = 0.202

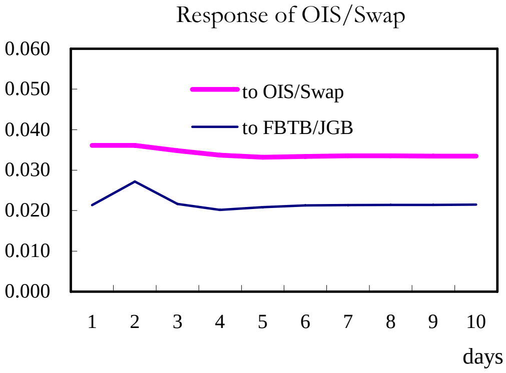
Notes: 1. The number of lags is chosen by SIC.
2. *, **, and *** denote significance at the 10%, 5%, and 1% level, respectively.
3. LR (likelihood ratio) statistic examines the hypothesis that the parameters of OIS/Swap and FBTB/JGB in the cointegration vector are the same.

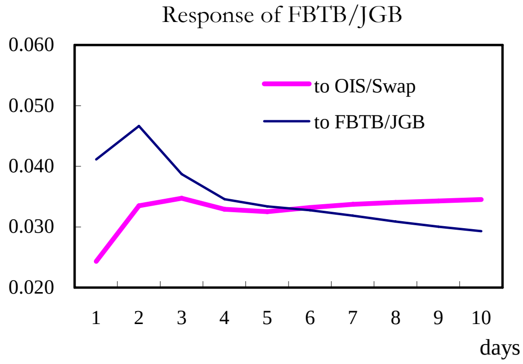
(ii) Price Discovery Measures: OIS/Swap vs. FBTB/JGB

	PT	IS		
		Higher	Lower	Mean
β0	0.91	0.99	0.57	0.78
β1	1.02	1.00	0.58	0.79
β2	0.93	1.00	0.45	0.73

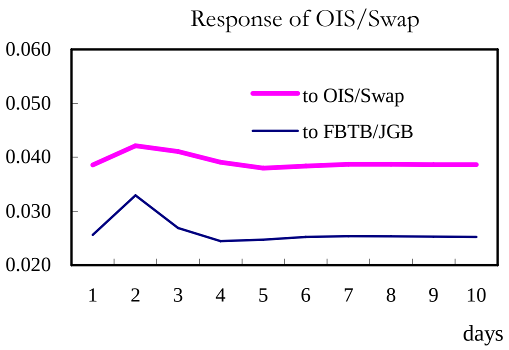
Chart 6: Impulse Reponses of Full Yield Curves

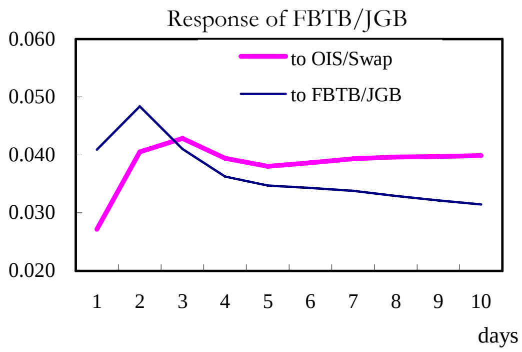
(i) β0: Long-term Level Factor



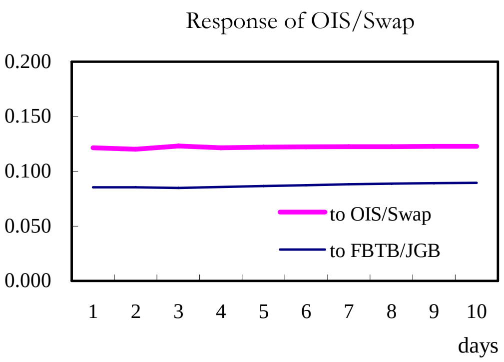


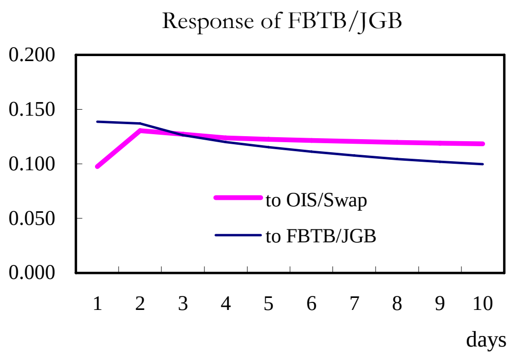
(ii) β1: Short-term Slope Factor





(iii) β2: Medium-term Curvature Factor





Note: Impulse responses are the responses of each factor to generalized one standard deviation of each factor.
See Pesaran and Shin [1998] for the estimation method.

Chart 7: Price Discovery Measures from Money Market Yield Curves (OIS vs. FBTB Yield Curve)

(i) Cointegration Analysis

(a) β1

Sample Period: April 3, 2006-July 31, 2007 (Number of Observations: 329)

Cointegration Rank Test				
H0	Eigenvalue	Trace	Max Eigen	Lags
None	0.11	46.09 ***	37.65 ***	1
At most 1	0.03	8.44	8.44	

Cointegration Vector			
OIS	FBTB	Constant	Trend
1.000	-0.720	0.819	-0.001
LR statistic for cointegration vector = (1, -1)		Chi-squared = 13.366	p-value = 0.000

(b) β2

Sample Period: April 3, 2006-July 31,2007 (Number of Observations: 329)

Cointegration Rank Test				
H0	Eigenvalue	Trace	Max Eigen	Lags
None	0.07	27.72 **	23.32 **	1
At most 1	0.01	4.40	4.40	

Cointegration Vector			
OIS	FBTB	Constant	Trend
1.000	-1.153	-0.651	0.000
LR statistic for cointegration vector = (1, -1)		Chi-squared = 0.974	p-value = 0.324

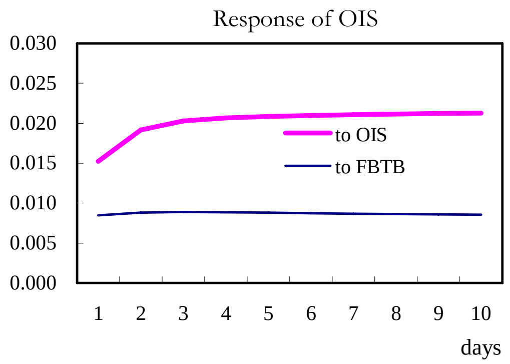
Notes:
1. The number of lags is chosen by SIC.
2. *, **, and *** denote significance at the 10%, 5%, and 1% level, respectively.
3. LR (likelihood ratio) statistic examines the hypothesis that the parameters of OIS and FBTB in the cointegration vector are the same.

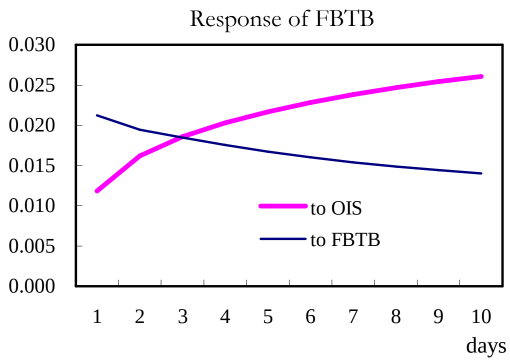
(ii) Price Discovery Measures of OIS relative to FBTB

	PT	IS		
		Higher	Lower	Mean
β1	1.19	0.96	0.86	0.91
β2	0.84	0.97	0.63	0.80

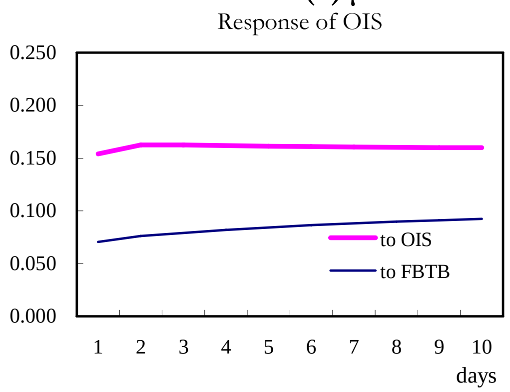
Chart 8: Impulse Responses of Money Market Yield Curves

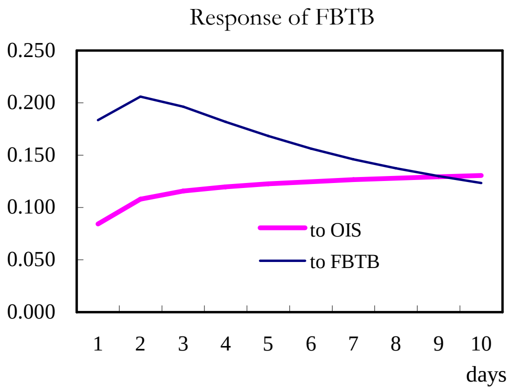
(i) β1: Short-term Slope Factor





(ii) β2: Medium-term Curvature Factor





Note: Impulse responses are the responses of each factor to generalized one standard deviation of each factor.
See Pesaran and Shin [1998] for the estimation method.

Chart 9: Estimated Result of Structural Model (Full Yield Curves)

Sample Period: April 4, 2006 to July 31, 2007 (Number of Observations: 329)

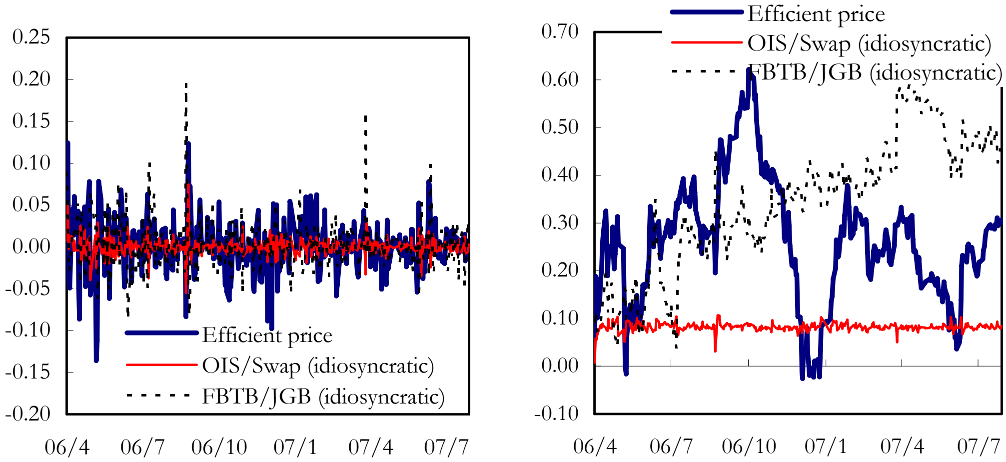
		$\beta 0$	$\beta 1$	$\beta 2$
b	OIS/Swap	0.009 ***	-0.071 **	-0.157 **
		[0.035]	[0.033]	[0.077]
c	OIS/Swap	0.590 ***	0.609 ***	0.308
		[0.176]	[0.202]	[0.302]
	FBTB/JGB	0.975 ***	0.980 ***	0.975 ***
		[0.011]	[0.010]	[0.014]
ln (σ^2)	m	-6.872 ***	-6.649 ***	-4.403 ***
		[0.101]	[0.093]	[0.094]
	s_{OIS}	-10.330 ***	-9.872 ***	-7.073 ***
		[3.564]	[2.338]	[1.701]
	s_{FB}	-7.204 ***	-7.491 ***	-5.528 ***
		[0.176]	[0.225]	[0.248]
	ε_{OIS}	-8.452 ***	-8.575 ***	-7.136 ***
		[0.403]	[0.479]	[1.372]
	ε_{FB}	-9.130 ***	-8.944 ***	-5.782 ***
		[0.715]	[0.625]	[0.247]
Log Likelihood		1244.22	1240.31	502.49
SIS (OIS)		0.808	0.843	0.882
SIS (FB)		0.549	0.653	0.634
SIS(OIS)-SIS(FB)		0.259	0.191	0.247

Note: ** and *** denote the 5% and 1% significance level, respectively.

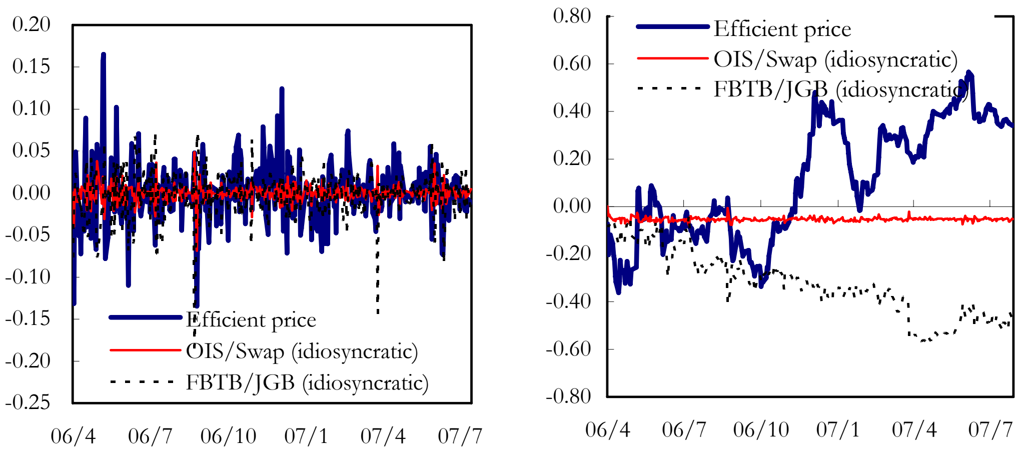
Chart 10: Factor Decomposition (Full Yield Curves)

Decomposition of Daily Factor Changes — Accumulated Daily Changes

(i) β0: Long-term Level Factor



(ii) β1: Short-term Slope Factor



(iii) β2: Medium-term Curvature Factor

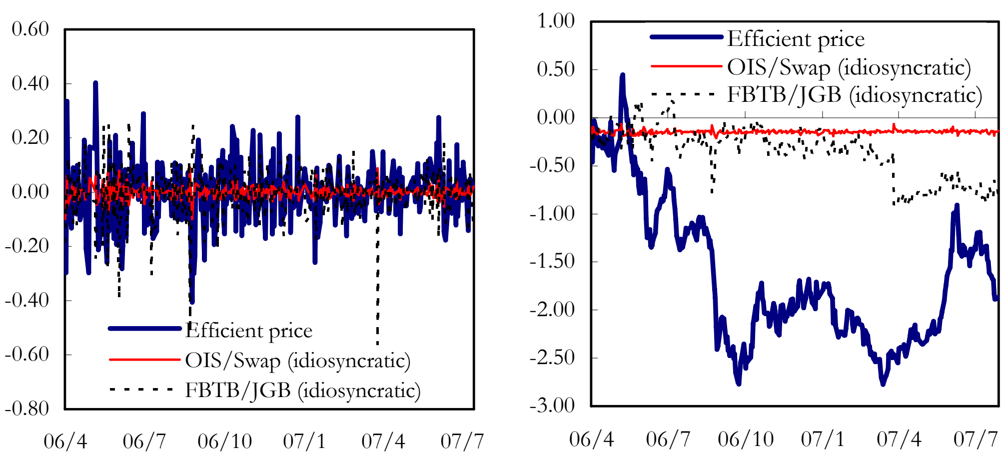


Chart 11: Estimated Result of Structural Model (Money Market Yield Curves)

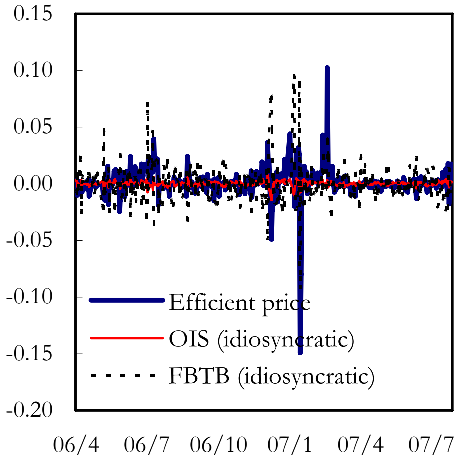
Sample Period: April 4, 2006 to July 31, 2007 (Number of Observations: 329)

		$\beta 1$	
c	OIS	0.944	***
		[0.081]	
	FBTB	0.956	***
		[0.021]	
ln (σ^2)	m	-8.434	***
		[0.106]	
	s_{OIS}	-10.250	***
		[0.451]	
	s_{FB}	-8.365	***
		[0.138]	
	ε_{OIS}	-28.100	
		[27.100]	
	ε_{FB}	-9.987	***
		[0.257]	
Log Likelihood		1732.49	
SIS (OIS)		0.860	
SIS (FB)		0.433	
SIS(OIS)-SIS(FB)		0.427	

Note: *** denotes the 1% significance level.

Chart 12: Factor Decomposition (Money Market Yield Curves)

Decomposition of Daily Factor Changes



Accumulated Daily Changes