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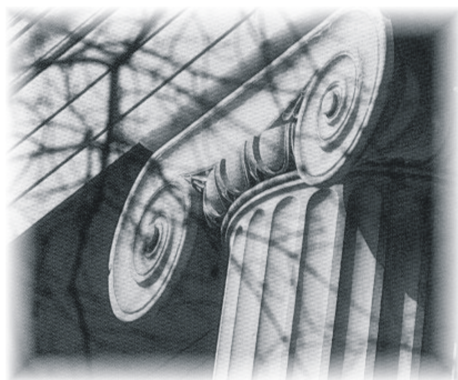

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Information in the U. S. Treasury Term Structure of Interest Rates

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This paper provides an update to Fama's (1984a) regression approach for measuring the information in forward interest rates and introduces both a curve fitting method and an alternative data source. Regression results are compared using Fama's original data (only available to March 2000), Fama's original data smoothed, and smoothed constant maturity Treasury (CMT) data (widely available from the Board of Governors of the Federal Reserve System). Unlike Fama (1984a), we find the results for recent periods suggest there is more information in the term structure about future interest rates than about expected returns, a departure from prior empirical findings.

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1. Introduction

In 1984, Eugene Fama published two papers in the *Journal of Financial Economics* that focused on the term structure of interest rates. Fama (1984a) studies one to six month Treasury bills for the period 1959 to 1982 to examine the existence of information in the term structure of interest rates. He demonstrates for most forecasting horizons that the current rate is the best forecast of future spot rates. This evidence suggests that there exists more information in the term structure about expected holding period returns than about expected future interest rates. Fama (1984b) examines expected returns on Treasury bills and bond portfolios. In this work, he finds evidence that average holding period returns rise for about eight or nine months and then decline.

In an October 2000 Dimensional Funds Advisors Inc. (DFA) unpublished trade document, James Davis provides an update to Fama's 1984 papers by examining Treasury bill data from June 1964 through November 1999. By the time of Davis' work, the Center for Research in Security Prices (CRSP) included information for Treasury bills with maturities up to one year. Consequently, Davis provides results for maturities out 11 months instead of only six. In this respect, Davis' work not only serves as an update, but also contributes by examining longer maturities than only the six months reported by Fama (1984a). The results of Davis indicate that the patterns found in Fama (1984a) and Fama (1984b) were still in place for the June 1964 through November 1999 time period and for two sub-periods, June 1964 through July 1982 and August 1982 through November 1999.

Fama and Bliss (1987) examine longer term forecast horizons and find they have predictive ability, "... attributing this forecast power to slow mean reversion of the spot rate that only becomes evident over long horizons" (p. 359). Fama (2006) re-examines the Fama and Bliss (1987) result with more recent data and concludes that the forecast power remains, but attributes this forecast power to time-varying mean reversion.

The purpose of this paper is two-fold. First, we extend the work of Fama (1984a) using constant maturity Treasury (CMT) data and a common curve fitting procedure based on the work of Nelson and Siegel (1987) and Svensson (1995). A curve fitting procedure is required since a complete set of prices for each maturity is not available for CMT data. We find that the essential analytical conclusions remain the same whether one uses the original Fama Treasury Bills Term Structure files (Fama data) contained on the CRSP Monthly U. S. Treasury Database, the smoothed Fama data, or the smoothed CMT data. [1] This result is important as the full 12 month Fama data does not exist after March 31, 2000, due to changes in U. S. Treasury bill auctions. However, six month Fama data does exist after this period.

Second, we extend the time period examined through December 2007. Using data from August 1982 through December 2007, the regression results appear to further support the main findings of Fama (1984a). However, following Fama's (1984a) approach, an analysis of five year subperiods reveals a dramatic change in the nature of the information contained in the U. S. Treasury term structure. Specifically, in recent periods, the term structure seems to convey more information about the expected course of interest rates than expected holding period returns. This

[1] The smoothed Fama data provides a basis to understand how smoothing may impact the regression results. The CMT data is freely available from the Board of Governors of the Federal Reserve System and is not restricted to the first twelve months. The data is also available daily, removing the restriction of monthly analysis.

shifting of information has important implications for monetary policy, money market fund management, and corporate debt policy. Because the U. S. Treasury term structure is such a vital component of the financial marketplace, this research impacts other areas as well.

The outline of the paper is as follows: Section 2 reviews the data and describes the curve fitting method employed. Section 3 presents the general framework for representing the term structure of interest rates, provides a brief review of the literature, and discusses the regressions used in this empirical study. Empirical results of these regressions are presented in Section 4. In Section 5 more specific tests of the information contained in the term structure are examined and results are reported in Section 6. Section 7 concludes the paper and presents a summary of the findings.

2. Data and Curve Fitting Procedure

2.1. Data

The data used in the tests that follow consist of the Fama data available on CRSP and the CMT data freely available from the H 15 file produced by the Board of Governors of the Federal Reserve System. Using the curve fitting method described below, we build a database of monthly discount factors. Our curve fitting methodology follows Nelson and Siegel (1987) and Willner (1996), which was extended by Svensson (1995). This curve fitting technique was also applied by Brooks and Yan (1999).

Determining an appropriate notation is fraught with difficult trade-offs and no approach is ideal. We follow roughly the approach taken by Fama (1984a), although an alternative can be found in Fama and Bliss (1987) and Fama (2006). The approach taken here is very detailed at the expense of being a bit more cumbersome. The advantage of our approach is that time series perspective (t) is clearly delineated from cross sectional perspective (τ). The notation used in this paper is summarized here:

τ
: denotes term to maturity; for example, for zero coupon bond, expressed in fraction of year, also used as a corresponding measure of the period of calendar time that elapses

t
: denotes calendar time, expressed in fraction of year

$r(\tau_j : t_i)$ - τ_j
: term yield to maturity, continuously compounded, on a reference bond observed at time t_i

$r(\tau_1 : t_i) = r(t_i)$
: one period spot yield to maturity (spot rate), continuously compounded, on a reference bond observed at time t_i

$\tilde{h}(\tau_j, \tau_k : t_i + \tau_j - \tau_k)$ - $\tau_j > \tau_k$
: holding period rate of return, continuously compounded, τ_j is the term to maturity on the reference bond when purchased, τ_k is the term to maturity on the reference bond when sold, contemplated at time t_i, holding period rate of return realized at point in time $t_i + \tau_j - \tau_k$

$f(\tau_j, \tau_k : t_i)$ - $\tau_j > \tau_k$
: forward rate, continuously compounded, where τ_j denotes the final point on the term structure, τ_k denotes the initial point on the term structure, observed at time t_i, $f(\tau_1, \tau_0 : t_i) = r(t_i)$

$\tilde{\Pi}_{Long}(\tau_j, \tau_{j-1} : t_i + \Delta\tau) = f(\tau_j, \tau_{j-1} : t_i) - \tilde{f}(\tau_{j-1}, \tau_{j-2} : t_i + \Delta\tau)$
: long position in forward rate contract, expressed in rates

$\tilde{\Pi}_{Short}(\tau_j, \tau_{j-1} : t_i + \Delta\tau) = \tilde{f}(\tau_{j-1}, \tau_{j-2} : t_i + \Delta\tau) - f(\tau_j, \tau_{j-1} : t_i)$
: short position in forward rate contract, expressed in rates

Table 1 provides the period profile for a typical observation of the variables. Prices or yields are observed at the end of period t and are used to calculate the one period spot rate $r(t_i)$, single period forward rates $f(\tau_j, \tau_{j-1} : t_i)$, and the implied forward-spot differential $f(\tau_j, \tau_{j-1} : t_i) - r(t_i)$. In order to maintain consistency with other variables, period profits $\tilde{\Pi}_{Long}(\tau_j, \tau_{j-1} : t_i + \Delta\tau)$ or $\tilde{\Pi}_{Short}(\tau_j, \tau_{j-1} : t_i + \Delta\tau)$ are expressed in continuously compounded period rates. Finally at the end of the calendar period $t + (j-1)\Delta t$, the future spot rate $r(t_i + (j-1)\Delta t)$ for the single period $t + j\Delta t$ is observed which is used to calculate the cumulative change in the spot rate $r(t_i + (j-1)\Delta t) - r(t_i)$.

Figure 1 illustrates the behavior of the smoothed Fama one month spot rate annualized and the smoothed CMT data. Several observations can be made from this figure. First, on average, the spot rates decline over our period of study. Second, the cross-sectional smoothing technique provides fairly accurate estimates of the one month spot rates. Finally, there appears to be significant variability in spot rates over this period of time. Prior to July 31, 2001, one month CMT is not available. Hence, we observed some deviation of CMT estimates from Fama estimates prior to July 31, 2001.

Figure 2 further illustrates the estimation error between Fama smoothed data (FSD) and Fama original data (FOD) as well as that between CMT smoothed data (CMT) and FSD. Clearly, the addition of one month CMT in 2001 decreased the deviation between CMT and FSD considerably.

2.2. Curve Fitting Procedure

After July 31, 2001, CMT data is available for 1, 3, and 6 months as well as 1-5, 7, 10, 20, and 30 years. In this study, monthly horizons are examined. Hence, a methodology is needed to estimate a monthly CMT curve. An accurate methodology was developed by Svensson (1995) based on the work of Nelson and Siegel (1987). Steeley (2008) provides a detailed examination of a variety of term structure estimation methods applied to the U. K. STRIPS market and finds the general method presented here performs very well. We call this approach the LSC model for level, slope, and curvature. We use the general form that can be expressed as

$$r(\tau_j : t_i) = \sum_{n=0}^{N} b_{n,t} C_{j,n}(\tau_j; s_{n-1})$$

$$C_{j,0}\left(\tau_j;s_{-1}\right)=1$$

$$C_{j,1}\left(\tau_j;s_0\right)=\frac{\tau_j}{s_1}\left[1-\exp\left\{-\frac{s_1}{\tau_j}\right\}\right]$$

$$C_{j,n}\left(\tau_j;s_{n-1}\right)=\frac{\tau_j}{s_{n-1}}\left[1-\exp\left\{-\frac{s_{n-1}}{\tau_j}\right\}\right]-\exp\left\{-\frac{s_{n-1}}{\tau_j}\right\};\ \text{for } n>1$$

where s_n denotes a scalar that applies various weights to different locations on the term structure. The five parameter version with scalars 0.25, 0.75, 2.0, and 4.0 is applied for CMT and 0.2, 0.4, 0.6 and 0.8 for Fama smoothed data. A range of scalars were applied and the results are similar as long as more than two scalars are used. (See Appendix A for mathematical details related to the LSC model.)

3. Forward-Spot Differential

Following Fama (1984a, 1984b, and 2006), the forward-spot differential can be expressed as

$$\begin{aligned} f\left(\tau_j,\tau_{j-1}:t_i\right)-r\left(t_i\right) &= E_{t_i}\left[\tilde{r}\left(t_i+(j-1)\Delta\tau\right)\right]-r\left(t_i\right)+E_{t_i}\left[R\tilde{P}\left(\tau_j:t_i+\Delta\tau\right)\right] \\ &+\sum_{k=2}^{j-1}\left\{E_{t_i}\left[R\tilde{P}\left(\tau_{j-k+1}:t_i+k\Delta\tau\right)-R\tilde{P}\left(\tau_{j-k+1}:t_i+(k-1)\Delta\tau\right)\right]\right\} \end{aligned}$$

for all forward rates j, and all time t_i, where E_{t_i} is the conditional expectations operator over time t_i information and $R\tilde{P}\left(\tau_{j-k+1}:t_i+k\Delta\tau\right)$ is the return premium defined as the excess holding period rate of return over the current spot rate. The return premium in this context can be viewed as the profits on a portfolio of forward contracts

$$R\tilde{P}\left(\tau_j:t_i\right)=\sum_{k=2}^{j}\tilde{\Pi}_{Long}\left(\tau_k,\tau_{k-1}:t_i+\Delta\tau\right)=\sum_{k=2}^{j}\left\{f\left(\tau_k,\tau_{k-1}:t_i\right)-\tilde{f}\left(\tau_{k-1},\tau_{k-2}:t_i+\Delta\tau\right)\right\}$$

Most studies of the expectations hypothesis of the term structure of interest rates find little empirical support for the theory. Some of the most compelling results are as follows:

Shiller, Campbell, and Schoenholtz (1983), Campbell and Shiller (1987), Fama and Bliss (1987), Shiller (1990), Campbell and Shiller (1991), and Evans and Lewis (1994). For a more exhaustive survey of these rejections, see Cook and Hahn (1990), Brooks and Livingston (1992), and Rudebusch (1994). The lack of empirical support is generally explained by the expected return premium not being constant. Interestingly, while the finding against the hypothesis for short term rates is quite strong, the literature is still not unanimous regarding its plausibility with long term rates.

Fama (1986) finds that the yield curve for U.S. Treasury bills from six to 12 months has no predictive power for the subsequent six month rate, but does find some predictive power for the CD yield curve from six to 12 months. Fama and Bliss (1987) regress short term rate changes on the linear combinations of two different yield spreads, which they call "forward premia," and find the forecasting power of the term structure to be quite strong for large yield spreads. Campbell and Shiller (1991) rejected the expectations hypothesis for all combinations of the short term and long term rates when the long term maturity was less than four years, but did so only once when the long term maturity was four years or greater. Cochrane and Piazzesi (2002) studied monetary policy shocks, defined from federal funds target movements relative to daily interest rate data, for the period 1984 to 2001, and found long term rates to be a far more effective predictor of Federal Reserve moves than short term rates. Specifically, they discovered that the spread between the two and the five year rates is the best predictor of the change in the federal funds rate target. This discovery contradicts the logic of the expectations hypothesis, which suggests that the shorter term interest rates should have the most predictive power. They claim that this phenomenon suggests that interest rates forecast target moves by the Federal

Reserve, because the Federal Reserve responds to expected inflation information in long term rates, not just from the information according to the expectations hypothesis.

Based on the expectations hypothesis, Fama (1984a) estimates the following time series regressions to assess the predictive ability of forward rates:

$$RP(\tau_j : t_i + \Delta\tau) = \alpha_1 + \beta_1 (f(\tau_j, \tau_{j-1} : t_i) - r(t_i)) + \varepsilon_{t+1} \qquad \text{(Regression 1)}$$

$$r(t_i + (j-1)\Delta\tau) - r(t_i) = \alpha_2 + \beta_2 (f(\tau_j, \tau_{j-1} : t_i) - r(t_i)) + \eta_{t+\tau-1} \qquad \text{(Regression 2)}$$

These regressions determine whether the current forward-spot differential $f(\tau_j, \tau_{j-1} : t_i) - r(t_i)$ has power to predict either the return premium $RP(\tau_j : t_i + \Delta\tau)$ or the future change in the one period spot rate $r(t_i + (j-1)\Delta\tau) - r(t_i)$. Results suggesting that β_1 is significantly positive indicate that the forward rate observed at time t contains information regarding the return premium to be observed at time $t_i + \Delta\tau$. Results suggesting that β_2 is significantly positive indicate that the forward rate observed at time t contains information regarding the one period spot rate to be observed at time $t_i + (j-1)\Delta\tau$.

Under the pure expectations hypothesis, forward rates contain no return premiums, and consequently are unbiased predictors of future spot rates. Thus, the expectations hypothesis in its purest form suggests that the slope coefficient in regression (1) be 0.0 and the slope coefficient in regression (2) be 1.0. Alternatively, in the case where the forward rate contains information regarding future spot rates and return premiums do exist, both slope coefficients may be greater than 0.0.

4. Empirical Results

The investigation here first seeks to replicate the work of Fama (1984a) based on an updated original data set (Fama unsmoothed), a smoothing procedure applied to the original data set (Fama smoothed), and smoothed rates derived from CMT yields (CMT). Specifically, in this section, regressions (1) and (2) are run on monthly continuously compounded forward rates derived from these three datasets from August 1982 to December 2007. The goal is to determine empirically if implied forward rates contain information about return premiums $RP(\tau_j : t_i + \Delta\tau)$ or the future change in the one period spot rate $r(t_i + (j-1)\Delta\tau) - r(t_i)$ in these three datasets. The presentation of our results follows closely Fama (1984a) for comparison purposes.

The autocorrelations, means, and standard deviations for the entire period for the spot rate, spot rate change, forward rate minus spot rate, and the return premiums were carefully reviewed, but the tables are not reported here. However, selected observations are made in regard to this. Comparing these results with Fama (1984a), the mean spot rate is lower (0.00411 here compared with 0.00464 reported in Fama) and the standard deviation is lower (0.00182 here compared with 0.00251 reported in Fama). The change in rates is negative here and positive in Fama (1984a), and the rate change standard deviation is almost half that of Fama's. For both forward minus spot and the return premium, the mean and standard deviations are also much lower. The autocorrelation results were similar with a few exceptions. For example, the first forward minus spot autocorrelation for the first two lags were much lower than previously reported. The autocorrelations for the first few lags were higher for both forward minus spot and return premiums for the updated Fama dataset.

The Fama smoothed data results are very similar to the original dataset. The standard deviations of the forward minus spot were slightly lower due to the effect of smoothing. Also, the standard deviations of the return premiums were not materially different between the unsmoothed and smoothed Fama datasets. The CMT results are similar to the Fama smoothed dataset, but the autocorrelations are higher for the forward minus spot and lower for the return premiums.

Table 2a exhibits the standard deviations of differences between forward rates and subsequently observed spot rates, as well as the standard deviations of the changes in the spot rates for the same horizon. The results presented here are fundamentally different from Fama (1984a). In this study, the rate change standard deviation is higher for maturities two through four (Fama unsmoothed and CMT smoothed) or five (Fama smoothed), whereas for the fifth and sixth month, the opposite occurs. Thus, there appears to be some difference with this more recent time period. Furthermore, the error in forward rate forecasts of future spot rates is lower for short maturities, whereas the error in the naïve forecast based on current rates is lower for the longer maturities. Table 2b reports similar results for the last five year subperiod. The overall rate volatility is lower and the pattern remains very different from Fama (1984a). Note that the significantly higher standard deviation of the Fama data for month six is due in part to a negative estimated forward rate in the original Fama data on July 31, 2003.

Table 3 reports the results for regression (1) and (2) for the full sample period as well as for five subperiods of five years' duration. The return premium regressions address whether the forward minus spot differential contains information regarding the return premium $RP(\tau_j : t_i + \Delta\tau)$, and the rate change regressions address whether the forward minus spot differential contains information regarding the subsequent spot rate changes. Although not reported here, we replicate the results reported in Davis (2000) for the August 1982 to November 1999 period.

Table 3 documents that over the entire sample period the CMT smoothed data results in statistically significant beta coefficients for both return premium regressions and rate change regressions. A similar pattern is found in the subperiod results through August 1997. However, there is a dramatic departure in the last two subperiod results where the information appears to be contained primarily in the rate change and not the return premium. Although not reported here, the results using Fama unsmoothed and smoothed data are consistent with the CMT results.

5. More Specific Tests

Since regression (2) measures the cumulative change in the one period spot rate from t to $t+\tau+1$, overlapping observations exist in the dependent variable. It is possible that the significant positive β_2 coefficients for longer maturities in these results are driven only by the significance of one particular maturity contract. To test exactly which forward rates contain information, Fama (1984a) supplements regressions (1) and (2) with the following regressions:

$$\Pi_{Long}(\tau_j, \tau_{j-1} : t_i + \Delta\tau) = \alpha_1 + \beta_1 (f(\tau_j, \tau_{j-1} : t_i) - f(\tau_{j-1}, \tau_{j-2} : t_i)) + \varepsilon_{t+1} \quad \text{(Regression 3)}$$

$$r(t_i + (j-1)\Delta\tau) - r(t_i + (j-2)\Delta\tau) = \alpha_2 + \beta_2 (f(\tau_j, \tau_{j-1} : t_i) - f(\tau_{j-1}, \tau_{j-2} : t_i)) + \eta_{t+\tau-1} \quad \text{(Regression 4)}$$

These tests provide more precise evidence of exactly where information manifests itself by considering the forecast power of adjacent maturities.

Regressions (3) and (4) determine whether the current forward rate spread between two adjacent maturity forward rates $f(\tau_j, \tau_{j-1} : t_i) - f(\tau_{j-1}, \tau_{j-2} : t_i)$ has power to predict either the forward contract profits (components of the return premium) $\Pi_{Long}(\tau_j, \tau_{j-1} : t_i + \Delta\tau)$ in regression (3), or the difference in the one month spot rate $r(t_i + (j-1)\Delta\tau) - r(t_i)$ in regression (4). Regression (3) compliments regression (1) by testing whether forward rates are reliable predictors of holding period returns on adjacent maturities.

Regression (4) compliments regression (2) by confining the forecast power of forward rates on the specific one period change in the spot rate. Fama (1984a) discovered coefficients β_3 and β_4 to be positive and less than one, indicating that the forward rate has power to predict both the holding period returns and changes in spot rates. Specifically, they found for the sample period June 1964 to November 1999 that the one month forward rate has power to predict the spot rate one month ahead. They also found that the relation between forward rates and future holding period returns is much stronger than the relation between forward rates and spot rates. Their regression results indicate that for the same sample period, forward rates are useful predictors of the next period holding period's return for every maturity.

6. More Specific Tests and Empirical Results

Table 4 reports the results for regression (3) and (4) for the full sample period as well as for five subperiods of five years' duration. The profit regressions address whether the forward rate spread contains information regarding the profit on a forward rate agreement $\Pi_{Long}(\tau_j, \tau_{j-1} : t_i + \Delta\tau)$, while the incremental rate change regressions address whether the forward rate spread contains information regarding the subsequent incremental spot rate changes. Although not reported here, we replicate the results reported in Davis (2000) for the August 1982 to November 1999 period.

The results reported in Table 4 for the entire period are similar to Fama (1984a), with statistically significant beta coefficients for both profit regressions and incremental rate change regressions. Although not reported here, the results are similar for both Fama smoothed and unsmoothed data. A somewhat similar pattern is found in the subperiods through August 1997. However, in the last two subperiods, the forward rate spread appears to explain subsequent incremental movements in the spot rate, not FRA profits. Hence, this appears to be a dramatic departure from prior time periods.

Table 5 reports the standard deviations of FRA profits, forward rate spreads, and changes in spot rates. When compared to Fama (1984a), the standard deviations are much lower for this time period. Although not reported here, the Fama smoothed and unsmoothed data provided similar results. Overall, the standard deviations fell over this time period to an unusually low level in the last five year subperiod. Interestingly, during this updated time period, the decreased variability in *ex post* returns (FRA profits) and changes in spot rates are apparently compensated by proportional decreases in the variability of their expected returns. (See Fama (1984a), pages 521-522.)

7. Conclusion

This paper uses an updated dataset, CMT yields, and a smoothing procedure to assess information in the U. S. Treasury term structure of interest rates. The results presented here suggest that forward rates have power to forecast spot rates but not return premiums for recent periods of U. S. Treasury market activity. This result contrasts with the findings of Fama (1984a), which finds that forward rates have power to predict U.S. Treasury bill return premiums for an earlier time period.

This research is important for at least two reasons: First, it provides an update of important term structure research. Second, since CMT data is available for longer maturities than U.S. Treasury bills and is available on a daily basis, this study lays the groundwork for investigating the information contained in longer maturity forward rates as well as in holding periods shorter than one month.

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Appendix A. Details of the LSC Model

The LSC model can be used to estimate a wide variety of interest rates related to the term structure. The goal of the estimation exercise is to approximate some rate across a wide array of maturities, typically with only a handful of observed market prices. The set of discount factors, $d(\tau_j : t_i)$, is defined based on either spot rates, $r(\tau_j : t_i)$, or instantaneous forward rates, $f(\tau_j : t_i)$, as

$$d(\tau_j : t_i) \equiv e^{-r(\tau_j : t_i)\tau_j} \tag{A.1a}$$

or

$$d(\tau_j : t_i) \equiv e^{-\int_0^{\tau_j} f(u,: t_i)du} \tag{A.1b}$$

Thus, the instantaneous forward rate can be expressed as

$$f(\tau_j : t_i) = \frac{\partial}{\partial \tau_j}\left[-\ln d(\tau_j : t_i)\right] \tag{A.2}$$

Substituting from (A.1a),

$$f(\tau_j : t_i) = \frac{\partial}{\partial \tau_j}\left[r(\tau_j : t_i)\tau_j\right] = \frac{\partial r(\tau_j : t_i)}{\partial \tau_j}\tau_j + r(\tau_j : t_i) \tag{A.3}$$

Hence, the instantaneous forward rate is the current spot rate plus any marginal change in the spot rate curve.

The expanded version of Svensson (1995) and Nelson and Siegel (1987) can be expressed in the following theorem.

Theorem A1. If spot rates are expressed in terms of forward rates as

$$r(\tau_j : t_i)\tau_j = \int_0^{\tau_j} f(u,: t_i)du \tag{A.4}$$

and estimated forward rates can be expressed as

$$f(\tau_j : t_i) = a_0 + a_1 e^{-\tau_j/s_1} + \sum_{i=2}^{n} a_i\left[\frac{\tau_j}{s_{i-1}} e^{-\tau_j/s_{i-1}}\right] \tag{A.5}$$

then estimated spot rates are expressed as

$$r(\tau_j : t_i) = a_0 + a_1\left[\frac{1-e^{-\tau_j/s_1}}{\tau_j/s_1}\right] + \sum_{i=2}^{n} a_i\left[\frac{1-e^{-\tau_j/s_{i-1}}}{\tau_j/s_{i-1}} - e^{-\tau_j/s_{i-1}}\right] \qquad (A.6)$$

Proof: The proof is based on elementary integration properties and follows directly from the following two lemmas.

Lemma 1. Assuming c>0, then

$$\int_0^\tau e^{-u/c}du = \frac{1-e^{-\tau/c}}{1/c}$$

Proof of Lemma 1:

$$\int_0^\tau e^{-u/c}du = \left.\frac{e^{-u/c}}{-1/c}\right|_0^\tau = \frac{e^{-\tau/c}}{-1/c} - \frac{e^{-0/c}}{-1/c} = \frac{1-e^{-\tau/c}}{1/c}. \text{ QED.}$$

Lemma 2. Assuming c>0, then

$$\int_0^\tau \frac{u}{c}e^{-u/c}du = \frac{1-e^{-\tau/c}}{1/c} - \tau e^{-\tau/c}$$

Proof of Lemma 2: Let

$$F(u) = \frac{u}{c} \text{ and } G'(u) = e^{-u/c}$$

Thus,

$$F'(u) = \frac{1}{c} \text{ and } G(u) = -\frac{e^{-u/c}}{1/c}$$

Therefore, based on integration by parts

$$\int_0^\tau F(u)G'(u)du = F(u)G(u)\Big|_0^\tau - \int_0^\tau F'(u)G(u)du$$

$$\int_0^\tau \frac{u}{c}e^{-u/c}du = \left.\frac{u}{c}\frac{e^{-u/c}}{-1/c}\right|_0^\tau - \int_0^\tau \frac{1}{c}\frac{e^{-u/c}}{-1/c}du = -\tau e^{-\tau/c} + \int_0^\tau e^{-u/c}du$$

Using Lemma 1 and rearranging. QED.

Figure 1.
Comparison of Fama Data One Month Spot Rate Smoothed and CMT One Month Spot Rate Smoothed, Annualized

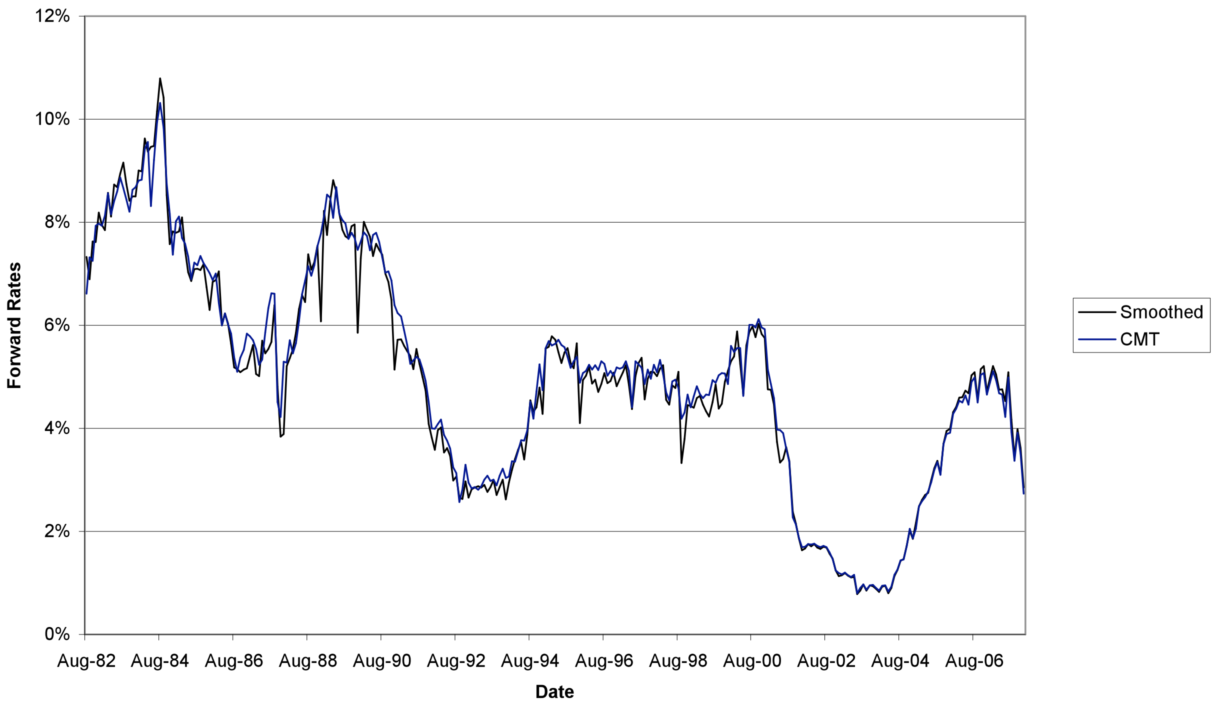

Figure 1 illustrates the behavior of the smoothed Fama one month spot rate annualized and the smoothed CMT data. Fama Data is from the Fama Treasury Bills Term Structure files contained on the CRSP Monthly U. S. Treasury Database. CMT is the constant maturity Treasury data available from the H 15 file produced by the Board of Governors of the Federal Reserve System. Both are smoothed based on level, slope, and curvature following Nelson and Siegel (1987).

Figure 2.
Error in Estimating One Month Spot Rate

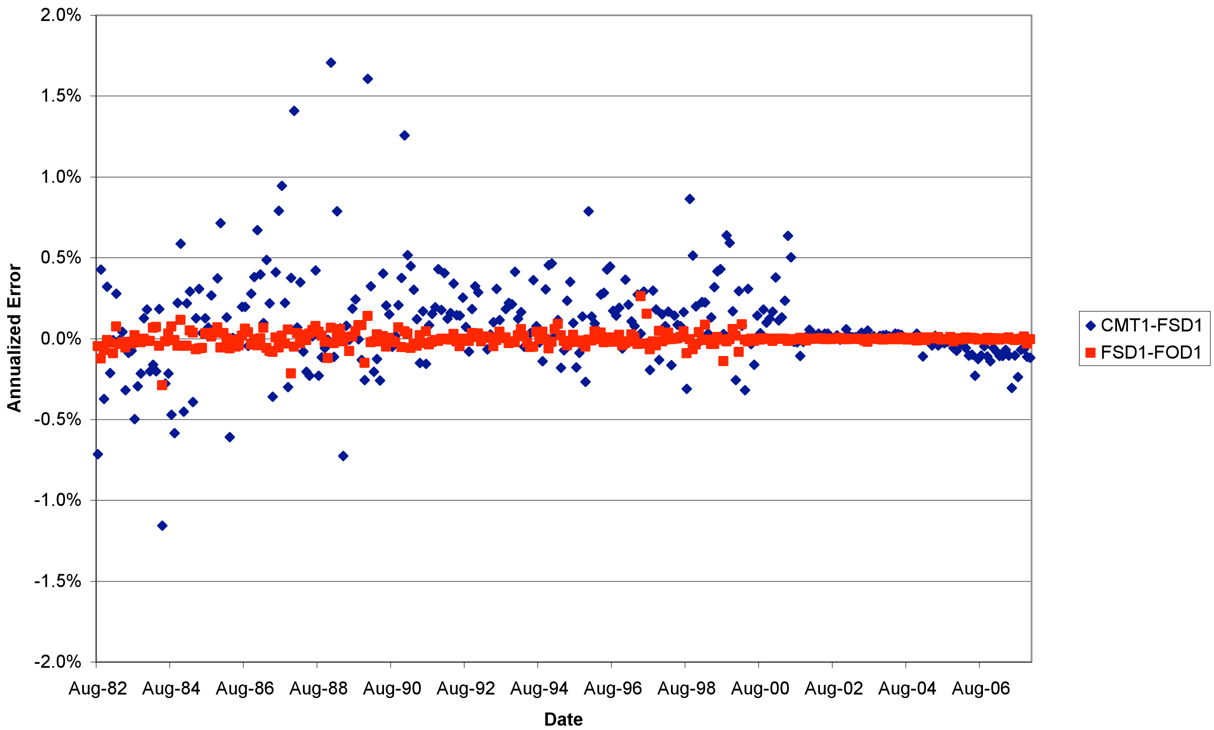

Figure 2 illustrates the estimation error between Fama smoothed data (FSD) and Fama original data (FOD) as well as CMT smoothed data (CMT) and FSD. Fama Data is from the Fama Treasury Bills Term Structure files contained on the CRSP Monthly U. S. Treasury Database. CMT is the constant maturity Treasury data available from the H 15 file produced by the Board of Governors of the Federal Reserve System. Data smoothing is based on level, slope, and curvature following Nelson and Siegel (1987).

Table 1
Period profile for a typical observation on each of the variables

Observation data		
t	$t + \Delta\tau$	$t + (j-1)\Delta\tau$
$f(\tau_j, \tau_{j-1} : t_i)$	$h(\tau_j, \tau_{j-1} : t_i + \Delta\tau)$	$r(t_i + (j-1)\Delta\tau)$
$r(t_i)$	$\Pi_{Long}(\tau_j, \tau_{j-1} : t_i + \Delta\tau)$	$r(t_i + (j-1)\Delta\tau) - r(t_i)$
$f(\tau_j, \tau_{j-1} : t_i) - r(t_i)$	$RP(\tau_j : t_i + \Delta\tau)$	
$f(\tau_j, \tau_{j-1} : t_i) - f(\tau_{j-1}, \tau_{j-2} : t_i)$		

$f(\tau_j, \tau_k : t_i)$ - $\tau_j > \tau_k$

forward rate, continuously compounded, τ_j is the final point on the term structure, τ_k is the initial point on the term structure, observed at time t_i, $f(\tau_1, \tau_0 : t_i) = r(t_i)$

$r(\tau_j : t_i)$ - τ_j

term yield to maturity, continuously compounded, on a reference bond observed at time t_i

$r(\tau_1 : t_i) = r(t_i)$

one period spot yield to maturity (spot rate), continuously compounded, on a reference bond observed at time t_i

$\tilde{h}(\tau_j, \tau_k : t_i + \tau_j - \tau_k)$ - $\tau_j > \tau_k$

holding period rate of return, continuously compounded, τ_j is the time to maturity on the reference bond when purchased, τ_k is the time to maturity on the reference bond when sold, contemplated at time t_i, holding period rate of return realized at point in time $t_i + \tau_j - \tau_k$

$\Pi_{Long}(\tau_j, \tau_{j-1} : t_i + \Delta\tau) = f(\tau_j, \tau_{j-1} : t_i) - f(\tau_{j-1}, \tau_{j-2} : t_i + \Delta\tau)$

long (short) a forward rate agreement is where one receives (pays) fixed, pays (receives) floating.

$RP(\tau_j : t_i + \Delta\tau) = h(\tau_j, \tau_{j-1} : t_i + \Delta\tau) - r(t_i) = \sum_{k=2}^{j-1} \Pi_{Long}(\tau_j, \tau_{j-1} : t_i + \Delta\tau)$

the return premium is defined as the excess holding period rate of return over the current single period spot rate, the return premium also equals the profit on a portfolio of appropriate forward contracts

Table 2a
Standard deviations of $f(\tau_j, \tau_{j-1} : t_i) - r(t_i + (j-1)\Delta\tau)$ and $r(t_i + (j-1)\Delta\tau) - r(t_i)$;
August 1982 to December 2007

Panel A: Fama Unsmoothed

τ	$s(f(\tau_j, \tau_{j-1} : t_i) - r(t_i + (j-1)\Delta\tau))$	$s(r(t_i + (j-1)\Delta\tau) - r(t_i))$
2	0.00034	0.00040
3	0.00046	0.00050
4	0.00052	0.00058
5	0.00068	0.00065
6	0.00077	0.00072

Panel B: Fama Smoothed

τ	$s(f(\tau_j, \tau_{j-1} : t_i) - r(t_i + (j-1)\Delta\tau))$	$s(r(t_i + (j-1)\Delta\tau) - r(t_i))$
2	0.00035	0.00039
3	0.00045	0.00050
4	0.00053	0.00058
5	0.00060	0.00065
6	0.00074	0.00072

Panel C: CMT Smoothed

τ	$s(f(\tau_j, \tau_{j-1} : t_i) - r(t_i + (j-1)\Delta\tau))$	$s(r(t_i + (j-1)\Delta\tau) - r(t_i))$
2	0.00028	0.00030
3	0.00041	0.00042
4	0.00049	0.00050
5	0.00058	0.00058
6	0.00068	0.00064

Table 2a reports the standard deviations for the full sample period August 1982 through December 2007. Fama Data is from the Fama Treasury Bills Term Structure files contained on the CRSP Monthly U. S. Treasury Database. CMT is the constant maturity Treasury data available from the H 15 file produced by the Board of Governors of the Federal Reserve System. Data smoothing is based on level, slope, and curvature following Nelson and Siegel (1987). $f(\tau_j, \tau_{j-1} : t_i) - r(t_i + (j-1)\Delta\tau)$ is the error of the forward rate $f(\tau_j, \tau_{j-1} : t_i)$, observed at t_i, as a forecast of the spot rate $r(t_i + (j-1)\Delta\tau)$. $r(t_i + (j-1)\Delta\tau) - r(t_i)$ is the error of the naïve forecast that $r(t_i + (j-1)\Delta\tau)$ will equal $r(t_i)$. For each additional maturity month, there is one less observation in this data.

Table 2b
Standard deviations of $f(\tau_j, \tau_{j-1} : t_i) - r(t_i + (j-1)\Delta\tau)$ and $r(t_i + (j-1)\Delta\tau) - r(t_i)$;
August 2002 to July 2007

Panel A: Fama Unsmoothed

τ	$s(f(\tau_j, \tau_{j-1} : t_i) - r(t_i + (j-1)\Delta\tau))$	$s(r(t_i + (j-1)\Delta\tau) - r(t_i))$
2	0.00012	0.00019
3	0.00016	0.00025
4	0.00019	0.00028
5	0.00018	0.00035
6	0.00065	0.00041

Panel B: Fama Smoothed

τ	$s(f(\tau_j, \tau_{j-1} : t_i) - r(t_i + (j-1)\Delta\tau))$	$s(r(t_i + (j-1)\Delta\tau) - r(t_i))$
2	0.00012	0.00019
3	0.00015	0.00025
4	0.00016	0.00028
5	0.00017	0.00035
6	0.00064	0.00041

Panel C: CMT Smoothed

τ	$s(f(\tau_j, \tau_{j-1} : t_i) - r(t_i + (j-1)\Delta\tau))$	$s(r(t_i + (j-1)\Delta\tau) - r(t_i))$
2	0.00013	0.00020
3	0.00016	0.00024
4	0.00017	0.00028
5	0.00018	0.00035
6	0.00021	0.00040

Table 2b provides the standard deviations for the sample period August 1982 through July 2007. Fama Data is from the Fama Treasury Bills Term Structure files contained on the CRSP Monthly U. S. Treasury Database. CMT is the constant maturity Treasury data available from the H 15 file produced by the Board of Governors of the Federal Reserve System. Data smoothing is based on level, slope, and curvature following Nelson and Siegel (1987). $f(\tau_j, \tau_{j-1} : t_i) - r(t_i + (j-1)\Delta\tau)$ is the error of the forward rate $f(\tau_j, \tau_{j-1} : t_i)$, observed at t_i, as a forecast of the spot rate $r(t_i + (j-1)\Delta\tau)$. $r(t_i + (j-1)\Delta\tau) - r(t_i)$ is the error of the naïve forecast that $r(t_i + (j-1)\Delta\tau)$ will equal $r(t_i)$. For each additional maturity month, there is one less observation in this data.

Table 3
CMT Smoothed
Regression of the return premium, $RP(\tau_j : t_i + \Delta\tau)$, and the change in the spot rate, $r(t_i + (j-1)\Delta\tau) - r(t_i)$, on the forward rate minus the current spot rate, $f(\tau_j, \tau_{j-1} : t_i) - r(t_i)$.

$$RP(\tau_j : t_i + \Delta\tau) = \alpha_1 + \beta_1 (f(\tau_j, \tau_{j-1} : t_i) - r(t_i)) + \varepsilon_{t+1}$$

$$r(t_i + (j-1)\Delta\tau) - r(t_i) = \alpha_2 + \beta_2 (f(\tau_j, \tau_{j-1} : t_i) - r(t_i)) + \eta_{t+\tau-1}$$

	8/82-12/07 N = 307		8/82-8/87 N = 60		8/87-8/92 N = 60		8/92-8/97 N = 60		8/97-8/02 N = 60		8/02-8/07 N = 60	
Dependent	β	R^2	β	R^2	β	R^2	β	R^2	β	R^2	β	R^2
$RP(2 : t_i + \Delta\tau)$	0.44*** (6.92)	0.14	0.62*** (4.89)	0.30	0.33** (2.00)	0.07	0.33** (2.29)	0.08	0.34** (2.16)	0.08	-0.20 (-1.52)	0.04
$RP(3 : t_i + \Delta\tau)$	0.63*** (9.11)	0.22	0.95*** (6.49)	0.42	0.44*** (2.49)	0.10	0.39*** (2.94)	0.13	0.37** (2.13)	0.07	-0.14 (-1.24)	0.03
$RP(4 : t_i + \Delta\tau)$	0.79*** (9.52)	0.23	1.24*** (6.64)	0.44	0.51*** (2.47)	0.10	0.44*** (3.10)	0.14	0.35 (1.63)	0.04	-0.12 (-1.05)	0.02
$RP(5 : t_i + \Delta\tau)$	0.90*** (9.02)	0.21	1.47*** (6.22)	0.40	0.54** (2.18)	0.08	0.47*** (2.81)	0.12	0.26 (0.97)	0.02	-0.14 (-1.01)	0.02
$RP(6 : t_i + \Delta\tau)$	0.97*** (8.30)	0.19	1.65*** (5.71)	0.36	0.54* (1.82)	0.06	0.48*** (2.39)	0.09	0.11 (0.36)	0.00	-0.17 (-1.04)	0.02
$r(t_i + \Delta\tau) - r(t_i)$	0.56*** (8.83)	0.21	0.38*** (2.97)	0.13	0.67*** (4.03)	0.22	0.67*** (4.74)	0.28	0.66*** (4.17)	0.23	1.20*** (9.21)	0.60
$r(t_i + 2\Delta\tau) - r(t_i)$	0.52*** (9.32)	0.22	0.32*** (2.68)	0.11	0.87*** (6.37)	0.42	0.58*** (6.24)	0.41	0.72*** (5.05)	0.31	0.98*** (8.98)	0.59
$r(t_i + 3\Delta\tau) - r(t_i)$	0.51*** (9.45)	0.23	0.31*** (2.66)	0.11	0.82*** (6.65)	0.45	0.50*** (6.94)	0.47	0.82*** (5.59)	0.36	0.93*** (9.53)	0.62
$r(t_i + 4\Delta\tau) - r(t_i)$	0.48*** (8.71)	0.20	0.23* (1.96)	0.07	0.79*** (6.21)	0.42	0.58*** (7.55)	0.51	0.92*** (5.71)	0.38	1.11*** (12.65)	0.75
$r(t_i + 5\Delta\tau) - r(t_i)$	0.43 (0.43)	0.15	0.13 (0.13)	0.02	0.85 (0.85)	0.43	0.59 (0.59)	0.50	1.04 (1.04)	0.40	1.19 (1.19)	0.74

The number in parentheses below β is its t-statistic. * indicates significant at the 5% level, ** indicates significant at the 2.5% level, and *** indicates significant at the 1% level.

Table 4
CMT Smoothed
Regression of the contract profit, $\Pi_{Long}(\tau_j,\tau_{j-1}:t_i+\Delta\tau)$, and the change in the spot rate, $r(t_i+(j-1)\Delta\tau)-r(t_i+(j-2)\Delta\tau)$, on the forward rate spread, $f(\tau_j,\tau_{j-1}:t_i)-f(\tau_{j-1},\tau_{j-2}:t_i)$.

$$\Pi_{Long}(\tau_j,\tau_{j-1}:t_i+\Delta\tau)=\alpha_1+\beta_1(f(\tau_j,\tau_{j-1}:t_i)-f(\tau_{j-1},\tau_{j-2}:t_i))+\varepsilon_{t+1}$$

$$r(t_i+(j-1)\Delta\tau)-r(t_i+(j-2)\Delta\tau)=\alpha_2+\beta_2(f(\tau_j,\tau_{j-1}:t_i)-f(\tau_{j-1},\tau_{j-2}:t_i))+\eta_{t+\tau-1}$$

	8/82-12/07 N = 307		8/82-8/87 N = 60		8/87-8/92 N = 60		8/92-8/97 N = 60		8/97-8/02 N = 60		8/02-8/07 N = 60	
Dependent	β	R^2	β	R^2	β	R^2	β	R^2	β	R^2	β	R^2
$\Pi_{Long}(2,1:t_i+\Delta\tau)$	0.44*** (6.92)	0.14	0.62*** (4.89)	0.30	0.33** (2.00)	0.07	0.33** (2.29)	0.08	0.34** (2.16)	0.08	-0.20 (1.52)	0.04
$\Pi_{Long}(3,2:t_i+\Delta\tau)$	0.87*** (9.51)	0.23	1.42*** (6.52)	0.43	0.55*** (2.49)	0.10	0.45*** (3.08)	0.14	0.30 (1.23)	0.03	-0.09 (-.69)	0.01
$\Pi_{Long}(4,3:t_i+\Delta\tau)$	0.98*** (6.61)	0.13	1.91*** (4.50)	0.26	0.43 (1.21)	0.03	0.40 (1.66)	0.05	-0.42 (-1.06)	0.02	-0.21 (-.90)	0.01
$\Pi_{Long}(5,4:t_i+\Delta\tau)$	0.82*** (4.36)	0.06	1.80*** (2.84)	0.12	0.08 (0.16)	0.00	0.22 (0.63)	0.01	-1.00 (-2.26)	0.08	-0.29 (-.93)	0.01
$\Pi_{Long}(6,5:t_i+\Delta\tau)$	0.72*** (3.48)	0.04	1.56** (2.03)	0.07	-0.12 (-.20)	0.00	0.06 (0.13)	0.00	-1.04** (-2.29)	0.08	-0.13 (-.36)	0.00
$r(t_i+\Delta\tau)-r(t_i)$	0.56*** (8.83)	0.21	0.38*** (2.97)	0.13	0.67*** (4.03)	0.22	0.67*** (4.74)	0.28	0.66*** (4.17)	0.23	1.20*** (9.21)	0.60
$r(t_i+2\Delta\tau)-r(t_i+\Delta\tau)$	0.50*** (4.45)	0.06	0.24 (1.09)	0.02	1.14*** (4.11)	0.23	0.43* (1.72)	0.05	0.87*** (2.73)	0.12	0.86*** (2.48)	0.10
$r(t_i+3\Delta\tau)-r(t_i+2\Delta\tau)$	0.42*** (2.67)	0.02	0.24 (0.69)	0.01	1.02*** (3.14)	0.15	0.39 (1.11)	0.02	1.21*** (2.42)	0.10	0.79 (1.61)	0.05
$r(t_i+4\Delta\tau)-r(t_i+3\Delta\tau)$	0.23 (1.23)	0.01	-0.52 (-1.13)	0.02	1.38*** (3.40)	0.18	0.68 (1.62)	0.05	1.28** (2.25)	0.09	1.13** (2.03)	0.07
$r(t_i+5\Delta\tau)-r(t_i+4\Delta\tau)$	0.30 (0.30)	0.01	-0.54 (-.54)	0.02	1.61 (1.61)	0.23	0.85 (0.85)	0.05	1.28 (1.28)	0.08	0.66 (0.66)	0.02

The number in parentheses below β is its t-statistic. * indicates significant at the 5% level, ** indicates significant at the 2.5% level, and *** indicates significant at the 1% level.

Table 5
CMT Smoothed
Standard deviations of adjacent maturity return spreads, $\Pi_{Long}(\tau_j, \tau_{j-1} : t_i + \Delta\tau)$, forward rate spreads, $f(\tau_j, \tau_{j-1} : t_i) - f(\tau_{j-1}, \tau_{j-2} : t_i)$, and the change in the spot rate, $r(t_i + \Delta\tau) - r(t_i)$;

Variable	N = 307 8/82-12/07	N = 60 8/82-8/87	N = 60 8/87-8/92	N = 60 8/92-8/97	N = 60 8/97-8/02	N = 60 8/02-8/07
$\Pi_{Long}(2,1 : t_i + \Delta\tau)$	0.00028	0.00039	0.00031	0.00021	0.00025	0.00013
$\Pi_{Long}(3,2 : t_i + \Delta\tau)$	0.00027	0.00045	0.00025	0.00015	0.00020	0.00007
$\Pi_{Long}(4,3 : t_i + \Delta\tau)$	0.00029	0.00050	0.00027	0.00016	0.00021	0.00010
$\Pi_{Long}(5,4 : t_i + \Delta\tau)$	0.00031	0.00051	0.00029	0.00019	0.00022	0.00011
$\Pi_{Long}(6,5 : t_i + \Delta\tau)$	0.00031	0.00049	0.00030	0.00021	0.00022	0.00012
$f(2,1 : t_i) - r(t_i)$	0.00024	0.00035	0.00024	0.00019	0.00020	0.00013
$f(3,2 : t_i) - f(2,1 : t_i)$	0.00015	0.00020	0.00014	0.00012	0.00011	0.00008
$f(4,3 : t_i) - f(3,2 : t_i)$	0.00011	0.00013	0.00010	0.00009	0.00007	0.00005
$f(5,4 : t_i) - f(4,3 : t_i)$	0.00009	0.00010	0.00008	0.00007	0.00006	0.00005
$f(6,5 : t_i) - f(5,4 : t_i)$	0.00008	0.00008	0.00007	0.00006	0.00006	0.00004
$r(t_i + \Delta\tau) - r(t_i)$	0.00030	0.00035	0.00034	0.00024	0.00028	0.00020

Table 5 reports the standard deviations of FRA profits, forward rate spreads, and changes in spot rates. Fama Data is from the Fama Treasury Bills Term Structure files contained on the CRSP Monthly U. S. Treasury Database. CMT is the constant maturity Treasury data available from the H 15 file produced by the Board of Governors of the Federal Reserve System. Data smoothing is based on level, slope, and curvature following Nelson and Siegel (1987).