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Source: *The Journal of Finance*, Vol. 30, No. 3 (Jun., 1975), pp. 761-771
Published by: Blackwell Publishing for the American Finance Association
Stable URL: http://www.jstor.org/stable/2326856
Accessed: 30/03/2010 21:11

THE TERM STRUCTURE OF INTEREST RATES: A TEST OF THE EXPECTATIONS HYPOTHESIS

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I

THE LAST TEN YEARS have witnessed an active interest in the term structure of interest rates. While the proliferation of studies has failed to lead to a widely accepted view, work by D. Meiselman [27], J. Wood [39], F. Modigliani and R. Sutch [28] [29] [30] and others have found evidence to support the contention that the term structure is determined by some version of the "expectations" hypothesis.[1] These studies differ primarily on specific hypothesis about the formation of expectations in the bond market. The expectations hypothesis has also been expanded to include the existence of liquidity premiums [5] [25].

One of the most novel and important contributions to the term structure discussion in the last several years has been made by R. Roll [32] and T. J. Sargent [36]. Based on the theory of forward prices developed by P. Samuelson [34] and B. Mandelbrot [26], a very general model of stochastic price change is employed to provide a framework for studying various hypotheses about the term structure. The chief characteristic of the model is the requirement that the bond market be "efficient," to use Roll's terminology. That is, whatever mechanism is used to form expectations, it must be based on all of the available market information.

The primary difference between the Roll-Sargent formulation of the expectations hypothesis and earlier formulations resides in the explicit recognition that information be efficiently incorporated into expectations of future rates of interest. According to Sargent, the expectations hypothesis is in reality two hypotheses: (1) the yield structure is determined by expected future rates of interest and (2), expectations are formed within the context of an efficient market. Failure to require that expectations be rational allows the expectations hypothesis to become

". . . much freer, being capable of accommodating all sorts of *ad hoc* plausible hypothesis about the formation of expectations. Yet salvaging the expectations theory in that way involves building a model of the term structure that, while requiring there be no room for profitable arbitrage on the basis of current expectations of the future, also permits expectations to be formed via a process that could utilize available information more efficiently and so enhance profits. That seems to be an extremely odd procedure." [36, p. 97].

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1. The major portion of work on the term structure over the last several years has considered the evidence for the U.S. [2] [4] [5] [6] [7] [9] [10] [11] [13] [22] [23] [25] [27] [28] [29] [30] [32] [33] [35] [36] [39]; some of the studies using British data include [2] [3] [4] [14] [15] [16] [19] [20] [21] [31].

In addition to explicitly incorporating the notion of an efficient market, a large number of approaches to the term structure which have appeared in the literature can be viewed as special cases of the more general efficient market model. Thus restricting the investigation to testing implications of the general model provides information on a large class of specific versions of the expectations hypothesis.

The objective of this study is to extend the evidence on the expectations hypothesis within the framework of the recent contributions by Samuelson, Mandelbrot, Sargent and Roll. The data has been compiled by J. A. Grant [20] and D. Fisher [15] and represents quarterly observations over a wide maturity range of yields for the British government securities market. The Grant data cover the period from December 1924 to September 1962 while the Fisher data cover the period from March 1951 through December 1968. The data cover a long period of time and a wide maturity range and should provide some meaningful evidence on the expectations hypothesis outside the U.S. bond market. In addition, the results should go some way in clearing up the controversy [3] [14] [15] [16] [19] [20] [21] over the validity of the expectations hypothesis for the British bond market. Grant's original purpose in constructing yield curves was to test Meiselman's version of the hypothesis for a wide range of interest rates on a quarterly basis. He concluded that the Meiselman hypothesis was ". . . seriously called into question"; however, Grant was challenged by Fisher for not subjecting the data to the appropriate test as well as raising questions about the method used by Grant to construct yield curves. Fisher constructed his own yield curves and found the results to be more favorable to the Meiselman model. C. W. J. Granger and H. J. B. Rees employed spectral methods to analyze Grant's data and found the results consistent ". . . with Meiselman's form of the expectations hypothesis when suitably amended" [19, p. 76].

II

The Samuelson-Mandelbrot concept on an efficient market has been cast in terms of commodity markets and employed as a framework for empirical investigations[2] of the behavior of futures prices. The basic point made by the Samuelson-Mandelbrot model is that in a well functioning competitive commodity market, expectations underlie futures price behavior; and in addition, these expectations are based on all of the available information in the market. They are the optimal forecasts in terms of the available information.

The basic point of the model can be illustrated by considering the forecast of a spot price for a particular commodity. The spot price is the cash price of the commodity traded in the market. The forecast is embodied in a futures price. Today's futures price for, say corn, is a forecast of the spot price to prevail at the time of delivery sometime in the future. According to Samuelson's *Axiom of Mathematically Expected*

2. For example, see T. F. Cargill and G. C. Rausser [8].

Price Formation, an efficient market will equate today's futures price to the mathematical expectation of the future spot price conditional on the history of spot prices:

$$FP(T + t, t) = E[SP(T + t) \mid SP(t), SP(t - 1), \ldots] \tag{1}$$

where FP(T + t, t) represents the futures price at time t for a commodity to be delivered at time t + T while SP(T + t) represents the spot price of the commodity T periods in the future.

Expression (1) implies that expectations of the terminal spot price determine futures price behavior and that the expectations are based on all of the available information, i.e., the probability function describing the evolution of the spot price. The theorem implies that the futures price sequence will conform to a fair game or martingale sequence. This is often referred to as a random walk where increments in futures prices over the life of a particular contract are uncorrelated.[3]

The similarity between bond and commodity markets[4] and the amount of attention the expectations hypothesis has received in the term structure literature has led to a restatement of the Samuelson-Mandelbrot model within the context of a bond market. The model can easily be extended to the term structure by substituting the concept of a spot rate of interest on one-period loans in place of the spot or cash price of a particular commodity and substituting the concept of a forward rate of interest in place of a futures price.

There are several implications [34] [36] [37] for term structure behavior within the context of the Samuelson-Mandelbrot model. The model states that the sequence

$$\{FR(T + t, t), FR(T + t, t + 1), \ldots, FR(T + t, T + t - 1), FR(T + t, T + t)\} \tag{2}$$

follows a martingale process where FR(T + t, t) denotes the forward rate of interest at time t on a one-period loan at time T + t in the future and FR(T + t, T + t) = SR(T + t), the spot rate of interest on one-period loans at time T + t. Three properties of the martingale sequence have been emphasized:

$$E[FR(T + t, t + 1) - FR(T + t, t)] = 0 \tag{3}$$

$$COV[FR(T + t, t + 1) - FR(T + t, t), FR(T + t, t) - FR(T + t, t - 1), \ldots] = 0 \tag{4}$$

$$COV[FR(T + t, t + 1) - FR(T + t, t), FR(T + t - 1, t) - FR(T + t - 1, t - 1), \ldots] = 0. \tag{5}$$

3. It is not entirely correct to refer to a martingale process as a random walk since a process can be a martingale and still exhibit some degree of correlation in the increments.

4. Commodity and bond markets are both essentially futures markets. In a commodity market, a futures price exists today for a commodity to be delivered sometime in the future. In a bond market, there is also an implicit price for money to be delivered sometime in the future. Implicit in the current term structure of interest rates are interest rate "futures." A 10 year bond can be regarded as an average of 1 year yields running over the maturity of the bond and similarly, an 11 year bond can be regarded as an average of 1 year yields over an 11 year period. There is then an implicit forward or future rate of interest for 1 year loans 10 years later that can be derived from the existing term structure.

It should be noted that expectations of future rates will still determine the term structure within the context of an efficient bond market even if (3) is not satisfied as long as (4) and (5) are satisfied. Property (3) rules out the existence of "normal backwardation" in the case of commodity markets and liquidity premiums in the case of bond markets. As long as the liquidity premiums are constant over time, then the process becomes a submartingale. While there are a number of justifications for time-varying liquidity premiums, their possibility presents a serious methodological problem for empirical work on the term structure of interest rates within the context of an efficient market. If one obtained evidence that the sequence of forward rates of interest had nonzero covariances, one could still devise a set of time-varying liquidity premiums which would act as a filter on the forward rate sequence in such a manner that it would yield zero covariances. Sargent emphasizes that ". . . while this procedure has its merits in certain instances, it is essentially arbitrary . . . . Their arbitrary nature probably explains the considerable disarray in which the literature on the subject stands" [36, p. 97].

It is also possible to derive an additional condition of the expectations hypothesis with or without liquidity premiums which was proposed by Sargent; however, as pointed out by both Sargent and Schiller, the test is more restrictive than the general model. The test is based on three assumptions: (1) one-period spot rates of interest follow a covariance stationary process, (2) available information consists of only past history of interest rates and (3), forecasting rules are linear. By assuming covariance stationarity, Sargent was able to use a well-known decompositional theorem due to H. Wold to establish that any yield can be expressed as a one-sided distributed lag function of any other yield:

$$R(n, t) = \sum_{i=0}^{\infty} \beta(i)\, R(j, t - i) \qquad n \neq j \tag{6}$$

where R(n, t) represents the yield at time t for a bond of n periods. The specific form of the distributed lag is dependent on the particular assumptions made about the evolution of the spot rate over time.

III

This section presents evidence on the consistency of the British securities market with the expectations hypothesis either in the pure form or allowing for the presence of liquidity premiums. Two tests of the efficient market model are employed both using modern techniques of time series analysis. The first concerns the Samuelson-Mandelbrot model in the most general form while the second is a more restrictive test based on a linear forecasting version. In addition to providing evidence on the expectations hypothesis, the second test will also provide information on the existence of long distributed lags between short and long rates of interest as found in several U.S. studies.

A. *Test of the General Model*

There are several approaches to testing the general model. Expressions (2) and (4) are most often employed in the context of commodity markets; however, in the context of bond markets, expression (5) will be the most useful. Evidence inconsistent with (5) is sufficient to contradict the general expectations hypothesis with or without liquidity premiums.

At each calendar date, information in the most general sense flows into the bond market and is rapidly reflected by changes in expectations about future spot rates of interest. The efficiency of the bond market is dependent on the existence of large numbers of competitive market participants motivated by profit maximization who have more or less equal access to the emerging market information. Randomly emerging information, competitive behavior on the part of market participants, and the uncertainty as to the exact equilibrium future interest rate, imparts a random movement to increments in forward rates on successive calendar dates.

According to expression (5), the increments in forward rates on successive dates, i.e., FR(t + T, t + 1) − FR(t + T, t), should be serially uncorrelated. Grant's data permit the calculation[5] of 152 forward rates for T = 1, . . . , 11 years while Fisher's data permit the calculation of 72 forward rates for T = 1, . . . , 9 years.

The integrated periodogram (IP) is employed as a general test of nonrandomness for the sequence of increments in forward rates. The IP has recently been employed in several econometric studies, most notably, as a test of serial correlation in the residuals of linear regression models.[6] The incremental forward rate sequence for each T is denoted by x(t).

The IP for a time series of N observations is estimated by

$$\hat{I}_{xx}(f_K) = \frac{1}{N\,\hat{\sigma}_x^{\,2}} \sum_{i=1}^{K} \hat{P}_{xx}(f_i) \tag{7}$$

where $\hat{\sigma}_x^{\,2}$ is an estimate of the variance of the time series; $f_k = k/N$, $k = 1, \ldots, N/2$; $f_i = i/N$, $i = 1, \ldots, N/2$; and $\hat{P}_{xx}(f_k)$ is an estimate of the periodogram. The periodogram or unweighted spectral density function is derived according to

$$\hat{P}_{xx}(f_k) = \frac{a}{N}\left\{\left(\sum_{t=1}^{N} x(t)\cos 2\pi f_k t\right)^2 + \left(\sum_{t=1}^{N} x(t)\sin 2\pi f_k t\right)^2\right\} \tag{8}$$

5. The forward rate of interest at calendar time t on a one period loan in a subsequent period is calculated from the existing term structure according to

$$FR(T - 1 + t, t) = \frac{[1 + R(T, t)]^{T}}{[1 + R(T - 1, t)]^{T-1}} - 1.$$

It is obvious from this expression that the calculation of forward rates is sensitive to any errors in the yields to maturity; however, the error is probably less for longer than shorter term yields. The formula assumes continuous compounding and a lump sum coupon at the end of the maturity of the bond.

6. In this regard, see the paper by J. Durbin [12].

where

$$a = \begin{cases} 2, \text{ for } k = 1, \ldots, (N/2) - 1 \\ 1, \text{ for } k = N/2 \end{cases}$$

at the harmonic frequencies f_k. Expression (8) is slightly different when N is odd.

The theoretical periodogram of the random series $\epsilon(t)$ is $P_{xx}(f_k) = 2\sigma_\epsilon^2 f_k$. Dividing the latter by σ_ϵ^2 yields a straight line through the points (0, 0), (1, 1) when $I_{xx}(f_k)/\sigma_\epsilon^2$ is plotted against $2f_k$. This relationship provides the IP representation for a white noise process.

$$I_{xx}(f_k) = 2k/N, \; k = 0, \ldots, N/2 \tag{9}$$

To determine whether an estimated IP is statistically different from (9), the Kolmogorov-Smornov test statistic is employed. The maximum difference, D, between the estimated and theoretical IP is obtained and then compared to a critical value D* at a given level of significance. If $D \geq D^*$, one rejects the hypothesis that the empirical IP was selected from a population whose theoretical IP is that of a random series. Rather than use the asymptotic Kolmogorov-Smirnov critical values, use is made of the values recently published by J. Durbin [12] to test for significant departures from linearity.

The IP for each futures sequence was estimated according to (7) and (8) and compared to the theoretical IP for a white noise process. Table 1 presents the D statistic for each sequence tested. Each of the forward rate sequences are serially correlated at the .05 level.

B. *Test of the Model Based on Linear Forecasting Rules*

Estimation of two-sided distributed lag functions between various yields to maturity can serve as an additional test of the expectations hypothesis if we adopt Sargent's suggestion that only past rates be

TABLE 1
RESULTS OF RANDOMNESS TEST FOR
FR(T + t, t) − FR(T + t, t − 1)

T	Data Source: Fisher	D. Statistic[a] Grant
1	.56	.49
2	.62	.50
3	.64	.34
4	.64	.35
5	.62	.38
6	.61	.36
7	.60	.42
8	.59	.50
9	.45	.45
10	—	.47
11	—	.45

[a] All statistics significant at .05 level.

employed in linear forecasting rules. While more restrictive than the above test, these assumptions have often been employed in the literature on the term structure. The implied shape of the distributed lag need not be *a priori* specified; the only condition is that the lag be one-sided. The distributed lag estimates can also provide some information on whether there are long lags between short and long yields. The existence of long lags has been subject to some controversy as evidenced by V. K. Chetty [9], Modigliani and Sutch [28] [29] [30], Sargent [36], and T. F. Cargill and R. A. Meyer [6] [7].

The use of two-sided distributed lag models is based on work by C. Sims [38] who has recently introduced a methodology for testing whether feedback exists between any two economic variables, i.e., whether it is possible to express one variable as a one-sided distributed lag of another variable. The procedure is an attempt to provide an operational method to test for the direction of causality as defined by Granger [18]. Sims' test involves regressing the yield for, say, a 1 year bond as a distributed lag on past and future values of another yield, say, for a 10 year bond and regressing the 10 year rate as a distributed lag on past and future values of the 1 year rate. Lead coefficients in each equation should not be statistically significant if a one-sided distributed lag characterization is adequate for yields to maturity.

The implied distributed lag between yields is not specific as to coefficient pattern and thus the method of estimation should not impose any smoothness constraints. There are a variety of methods available for estimating coefficients of distributed lag models; however, frequency domain methods appear to offer greater flexibility than time domain techniques. Time domain methods usually impose some sort of smoothness conditions and require strict assumptions about the absence of serial correlation in the residual process. Frequency domain methods on the other hand estimate unconstrained distributed lag coefficients and do not require the absence of serial correlation in the residual process. These techniques are chiefly due to E. J. Hannan [24].

To motivate an understanding of frequency domain regression, consider a two-variable distributed lag model in discrete form

$$y(t) = \sum_{i=-m_1}^{m_2} \beta(i)x(t-i) + \epsilon(t) \tag{10}$$

where x(t), y(t) and ϵ(t) are stationary normal sequences with zero means. It is further assumed that x(t) and ϵ(t) are independent. It is then possible [1] [17] to derive the estimating equation for the coefficients of (10) based on spectral and cross-spectral density functions that are maximum likelihood estimators. The coefficient estimator in matrix notation is

$$\hat{\beta} = H^{-1}d \tag{11}$$

where the elements in H are

$$h_{rs} = \sum_{j=-M+1}^{M} S_{\epsilon\epsilon}^{-1}(f_j)\hat{S}_{xx}(f_j)e^{2\pi f_j i(r-s)} \quad r,s = -m_1, \ldots, m_2 \tag{12}$$

and the elements of d are

$$d_r = \sum_{j=-M+1}^{M} \hat{S}_{\epsilon\epsilon}^{-1}(f_j)\hat{S}_{xy}(f_j)e^{2\pi f_j i(r-s)} \qquad r = -m_1, \ldots, m_2 \tag{13}$$

where $\hat{S}(f_j)$ represents computed spectral density functions. The asymptotic covariance matrix is

$$\mathrm{COV}[\hat{\beta}] = \frac{2M}{N} H^{-1}. \tag{14}$$

While the distribution theory associated with frequency domain regression is still undeveloped, Hannan and others have suggested that the estimates can be regarded as multivariate normal for large samples.

T. Amemiya and W. S. Fuller [1] have pointed out that the Hannan procedure is similar to Aitken's generalized least squares estimator where the covariance matrix is obtained from the sample spectra. However, frequency domain regression does not require parameterization of the residual process as is the case with time domain GLS estimators.

The estimator in (11) is referred to as Hannan's "efficient" estimator as compared to another and simpler "inefficient" procedure. The inefficient estimator is based on the assumption of a constant signal-to-noise ratio defined as

$$\frac{\hat{S}_{xx}(f)}{\hat{S}_{\epsilon\epsilon}(f)} = \frac{\hat{S}_{xx}(f)}{S_{yy}(f)[1 - \gamma_{xy}^2(f)]} \tag{15}$$

where $\gamma_{xy}^2(f)$ is an estimate of the coherence squared.

While the inefficient procedure is much simpler than the efficient estimator and does not involve the computation of a 3-dimensional matrix, the assumption of a constant signal-to-noise ratio is not likely to be meant in practice. The efficient procedure allows for a nonconstant ratio[7] and actually weights the covariances by the estimated signal-to-noise ratio. Prior to estimating the distributed lags between various yields, the signal-to-noise ratios for the yields to maturity were estimated and found to seriously violate the assumption of constancy.

Two sets of distributed lag functions are estimated each with $m_1 = 4$ and $m_2 = 8$. The first set expresses yields of 2 or more years as a function of the 1 year yield. The second set reverses the variables and expresses the 1 year yield as a function of yields 2 or more years. The spectra and cross-spectra underlying the distributed lag estimates are based on Parzen weighted covariances estimated at 30 lags. Prior to estimation, the data were transformed into first differences. First differencing acts as a filter to "flatten" the spectra to reduce problems with leakage between adjacent frequency components and, at the same time, the coefficients of the regression are invariant to the transformation. Table 2 presents two distributed lag functions for illustration.[8]

7. In the special case when the signal-to-noise ratio is constant, the inefficient and efficient estimator are identical.

8. The complete set of tables will be supplied upon request. To make sure that the results are not

TABLE 2
DISTRIBUTED LAG COEFFICIENTS AND RATIOS OF COEFFICIENTS TO STANDARD ERRORS ESTIMATED BY THE HANNAN EFFICIENT METHOD FOR THE TWO-SIDED MODEL

$$R(1, t) = \sum_{i=-4}^{8} \beta(i)R(5, t - i) + \epsilon(t)$$

Data Source:	Grant		Fisher	
Lag(i)	$\hat{\beta}(i)$	Ratio	$\hat{\beta}(i)$	Ratio
−4	−.01	−.21	.01	.42
−3	.05	1.36	−.00	−.06
−2	−.01	−.16	.02	.56
−1	−.02	−.48	.10*	2.40
0	.63*	16.20	.55*	13.66
1	.05	1.36	.11*	2.82
2	.03	.75	.03	.84
3	.08	1.95	.05	1.35
4	.04	1.07	−.00	−.05
5	−.05	−1.21	−.02	−.46
6	.02	.40	.04	1.06
7	−.03	−.87	−.05	−1.37
8	.01	.41	−.01	−.28
R^2 (adjusted)	.70		.72	

* Significant at the .05 level.

The regression results can be summarized by the following points: (1) computed R^2 values vary inversely with maturity, (2) except for some of the longer yields of Grant's data, there is little evidence of a long distributed lag of long rates in response to short rates; (3) both Fisher's and Grant's data exhibit some evidence of two sided distributed lag functions in that a number of regressions contain a significant coefficient at the front lead term.

IV

The expectations hypothesis has received considerable attention in the professional literature; however, little effort has been directed toward the manner in which expectations are formed. By expressing the expectations hypothesis within the context of an efficient market model, we explicitly require that all available information be rationally employed by market participants to forecast future rates of interest. The results of this paper are based on certain implications of the expectations hypothesis in the context of an efficient bond market. The results reject the hypothesis for the British bond market for a wide range of interest rates covering a

due to a particular estimating technique, the regressions were also estimated by the Cochrane-Orcutt iterative GLS estimator. There were no substantial differences in the estimated coefficients. It might be worth pointing out that the calculated $\hat{\rho}$'s for each regression used to transform the variables in the Cochrane-Orcutt procedure indicated the presence of marked serial correlation. This highlights the need to employ a GLS estimator whether a time or frequency domain estimator is used.

long period of time. While there is still room for doubt regarding the reliability of the data base or appropriateness of the procedures used in testing the implications of the expectations hypothesis, the results call into question the usefulness of the hypothesis in its most general form as an interpretation of the term structure of interest rates.

The results do not directly test the efficient market model, but only the expectations hypothesis based on that model. An expectations hypothesis with time varying liquidity premiums is consistent with the efficient market. In this case, the increments in the forward rate sequences would be correlated and a liquidity premium behavioral pattern could be determined which would transform the correlated forward rates into a white noise process.

However, one should not arbitrarily select time varying liquidity premiums to transform correlated forward sequences into uncorrelated sequences but rather expanded effort is needed in studying the economic justification of liquidity premiums and most importantly, their specific time varying behavior. A good example of the type of work needed in this direction is provided by Roll in a recent paper in this Journal [33].

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