BREAKING FORWARD PREMIUM PUZZLE USING SECOND AND THIRD MOMENTS OF DAILY CURRENCY RETURN

By

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Abstract

I investigate whether second and third moments in daily foreign exchange (FX) returns can shed some light on the forward premium puzzle. I find that my premium estimation was effective at accounting for the premium component in the forward discount, as I was able to increase the statistical significance of forward discounts for most of eleven currencies analyzed in this paper. My results render further evidence to the existence of time-varying risk premia and they help explain why violations of UIP occur. I also document some evidence of nonlinear relationship between the spot rate and the forward discount. Finally, I challenge the validity of rational expectation due to narrowing interest rate differentials and discuss how one may overestimate the premium component if rational expectation is formed in the traditional way.

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1 Introduction

There has been much empirical work on the relationship between the forward foreign exchange rates and the future spot exchange rates. While forward contracts are primarily used to hedge against unfavorable future exchange rate movement, forward rates are in reality known to have very little power to predict future spot rates. This gave rise to a long list of literature on whether forward rates contain variation in premiums. Indeed, Fama (1984) found that most of the variation in forward exchange rates stems from variation in premiums, and that the premium and expectation of future spot rate changes are negatively correlated – a phenomenon now famously dubbed as the "forward premium puzzle". This puzzle has grown particular relevance in the literature for carry trades which is a well-known trading strategy that borrows in currencies with low interest rates and invests in currencies with high interest rates. According to uncovered interest parity (UIP), carry trades should not provide any excess returns since exchange rate changes will eliminate any gain arising from the differential in interest rates across countries. However, a number of empirical studies show that the opposite holds true and the violation of the UIP is precisely what makes the carry trade profitable on average. A straightforward interpretation from standard asset pricing perspective is that the carry trade profits are merely a compensation for low returns during "bad times". However, the empirical literature has not been able to identify factors that drive these premia until recently.

Brunnermeier, Nagel and Pedersen (2009) document that investment currencies are subject to crash risk, that is, positive interest rate differentials are associated with negative skewness of exchange rate movements. The negative skewness arises from an asymmetric response of speculators to fundamental shocks. Shocks that lead to speculator losses are amplified when speculators hit funding constraints and unwind their positions, further depressing prices, increasing funding problems, and margins, and so on. Conversely, shocks that lead to speculator gains are not amplified, thus resulting in a return distribution with long tail on the left. Therefore, they conjecture that crash risk is what may explain the puzzle. Similarly, a more recent study by Menkhoff et al (2012) suggests that global foreign exchange (FX) volatility is a key driver of risk premia that explains the carry trade returns and by extension, the puzzle. Both Brunnermeier, Nagel and Pedersen (2009) and Menkhoff et al (2012) arrive at their conclusions by constructing long-short carry trade portfolios which vary through time depending on which currency has the highest or lowest interest rates. Surprisingly, what the literature has yet to show is how their findings of premia can be directly applied to Fama's original work to solve the puzzle. Therefore, my main contribution to the existing literature is empirically showing that their findings can work as a proxy for the premium component in the framework of Fama's work. First, a brief discussion of the regression from Fama (1984) is warranted.

$$S_{t+k} - S_t = \beta_0 + \beta_1(F_t - S_t) + u_t \qquad (1)$$

I denote the logarithm of the spot and forward exchange rates (units of foreign currency per dollar) by

$$S_t \text{ or } F_t = \log(\text{spot or forward exchange rate})$$

Due to no arbitrage condition,

$$F_t - S_t \approx I_t^f - I_t^d \qquad (2)$$

where I_t^f represents foreign interest rate and I_t^d represents domestic interest rate, both in logarithm at time *t*. Also, following the related literature since Fama (1984), $F_t - S_t$ will be referred to as "forward discount" from here on. Eq. (2) illustrates the covered interest rate parity (CIP) which states that lending domestic currency yields the same proceeds as purchasing and lending in foreign currency and selling for domestic currency at a forward rate contracted at time *t*. Substituting this no arbitrage condition into Eq. (1), we derive an equation that can be used to test the null hypothesis of UIP.

$$S_{t+k} - S_t = \beta_0 + \beta_1(I_t^f - I_t^d) + u_t \qquad (3)$$

If UIP were to hold, we should expect $\beta_1 = 1$ in Eq. (3). The puzzle arises because the estimates of β_1 are not only statistically different from the value of one, but they are typically negative. When using more recent data in the regression (Fama's observations were from 1973 to 1982), the forward premium puzzle becomes even more puzzling.

Table 1. Equation (1) regression result

	1994 - 2016 (Full-Sample)				**1994 - 2007 (Sub-Sample)**			
	Beta Estimate		**T-stat**		**Beta Estimate**		**T-stat**	
	Monthly	Quarterly	Monthly	Quarterly	Monthly	Quarterly	Monthly	Quarterly
EUR	0.10	-0.01	0.48	-0.04	0.14	-0.01	0.78	-0.03
JPY	0.06	-0.31	0.10	-0.32	-0.19	-1.50	-0.21	-1.27
CAD	1.12	-0.05	1.85	-0.06	0.25	-1.06	0.49	-1.43
AUD	0.11	-0.63	0.14	-0.57	-0.18	-2.95	-0.23	-2.22
NZD	0.53	0.85	0.83	0.64	-0.29	-1.68	-0.40	-1.58
CHF	0.55	-1.29	0.94	-1.75	-0.38	-2.85	-0.55	-3.10
GBP	0.66	0.51	1.11	0.40	0.52	-1.14	0.77	-1.12
NOK	0.23	-0.24	0.45	-0.28	-0.01	-1.42	-0.02	-1.63
SEK	0.17	-0.61	0.35	-0.92	-0.09	-1.73	-0.15	-2.57
SGD	-0.24	-0.52	-0.46	-0.84	-0.64	-0.69	-0.92	-0.86
ZAR	-0.68	-1.32	-1.32	-1.78	-1.00	-1.48	-1.43	-1.66

Note: Standard errors are adjusted for heteroscedasticity and serial correlation with a Newey-West covariance matrix with 5 lags (Andrews and Monohan, 1992) when applicable. See the appendix for test results on each currency's residuals.

For the full sample period using quarterly data, I was able to find results consistent with Fama's findings. That is, all beta estimates except for New Zealand Dollar and British Pound are negative. When using monthly data however (frequency used in Fama (1984)), most estimates are actually positive, rendering some evidence of UIP. Interestingly, when the post-crisis period (i.e. low interest rate environment) is excluded, all estimates at quarterly frequency carry negative signs and they are generally more statistically significant. Similar observations can be made at the monthly frequency, although nothing conclusive can be said about improvement in statistical significance. What is evident from this preliminary analysis is that the overall statistical significance of beta estimates has deteriorated since Fama's findings. Average t-statistics for nine currencies considered in Fama (1984) was 1.40 while that of eleven currencies in this study are 0.77 and 0.54 for full and partial sample periods, respectively.[1] What could explain such drastic fall in the explanatory power of forward discount? Fama (1984) showed that the beta estimate of Eq (1) can be broken down to the following.

$$\beta_1 = \frac{\text{cov}\,(S_{t+k} - S_t\,, F_t - S_t)}{\sigma^2\,(F_t - S_t)}$$

$$= \frac{\sigma^2\,(E(S_{t+k} - S_t)) + \text{cov}\,(P_t,\ E(S_{t+k} - S_t))}{\sigma^2\,(P_t) + \sigma^2\,(E(S_{t+k} - S_t)) + \text{cov}\,(P_t,\ E(S_{t+k} - S_t))} \qquad (4)$$

The biggest change regarding the terms in Eq. (4) since Fama (1984) is likely the expected change in the spot exchange rate. As illustrated early on, rational expectation of spot rate changes is derived directly from the interest rate differential. As the differentials have generally narrowed since the 1980's and especially following the financial crisis in 2008, the first term on the numerator, the variance of rational expectation, must have also

[1] Currencies that were covered in this study but not in Fama (1984) are AUD, NZD, NOR, SEK, SGD and ZAR (Table 8).

gotten smaller than before. As well, if the rational expectation has gotten smaller, then it must be the case that the second term on the numerator, covariance of premium and rational expectation, has diminished over time unless the premium has also diminished in a similar magnitude. However, there is no empirical evidence to date that corroborates diminished role of the premium component in the forward exchange rate. In fact, this can be easily proven from another regression test proposed by Fama (1984).

$$F_t - S_{t+k} = \beta_0 + \beta_2(F_t - S_t) + u_t \qquad (5)$$

Again, beta estimates of Eq. (4) can be expressed as,

$$\beta_2 = \frac{\text{cov}\,(F_t - S_{t+k}\,, F_t - S_t)}{\sigma^2\,(F_t - S_t)}$$

$$= \frac{\sigma^2\,(P_t) + \text{cov}\,(P_t,\ E(S_{t+k} - S_t))}{\sigma^2\,(P_t) + \sigma^2\,(E(S_{t+k} - S_t)) + \text{cov}\,(P_t,\ E(S_{t+k} - S_t))} \qquad (6)$$

The only difference between Eq. (4) and (6) is the first term in the numerator. Since Eq. (6) has the variance of the premium component as its first term, statistically significant estimates of β_2 would indicate that the premium component of $F_t - S_t$ has not diminished over time. Indeed, I find that the t-statistics are overall much higher for β_2 as shown below.

Table 2. Equation (5) regression result

	1994 - 2016 (Full-Sample)				1994 - 2007 (Sub-Sample)			
	Beta Estimate		T-stat		Beta Estimate		T-stat	
	Monthly	Quarterly	Monthly	Quarterly	Monthly	Quarterly	Monthly	Quarterly
EUR	0.90	1.01	4.54	2.78	0.86	1.01	4.61	2.65
JPY	0.94	1.31	1.40	1.38	1.19	2.50	1.31	2.11
CAD	-0.12	1.05	-0.20	1.39	0.75	2.06	1.47	2.78
AUD	0.89	1.63	1.17	1.46	1.18	3.95	1.50	2.97
NZD	0.47	0.15	0.73	0.11	1.29	2.68	1.78	2.52
CHF	0.45	2.29	0.76	3.11	1.38	3.85	2.01	4.18
GBP	0.34	0.49	0.57	0.39	0.48	2.14	0.72	2.10
NOK	0.77	1.24	1.49	1.46	1.01	2.42	1.72	2.78
SEK	0.83	1.61	1.76	2.43	1.09	2.73	1.76	4.06
SGD	1.24	1.52	2.35	2.45	1.64	1.69	2.36	2.12
ZAR	1.68	2.32	3.25	3.14	2.00	2.48	2.85	2.79

Note: Standard errors are adjusted for heteroscedasticity and serial correlation with a Newey-West covariance matrix with 5 lags (Andrews and Monohan, 1992) when applicable. See the appendix for test results on each currency's residuals.

Therefore, the deterioration in the statistical significance is most likely due to narrower interest rate differentials. Later on, I discuss how this challenges the validity of rational expectation and how the forward premium puzzle becomes even more difficult to unravel.

There are mainly two ways to enhance the statistical significance of Eq (1). As Fama (1984) showed, a forward discount can be expressed as the following,

$$F_t - S_t = P_t + E(S_{t+k} - S_t) \qquad (7)$$

By substituting the arbitrage condition Eq. (2) into regression Eq. (1), one implicitly assumes that the premium component in Eq. (7) is zero. Therefore, a sensible way to enhance its statistical significance is to account for this premium component. This can be done by incorporating what Brunnermeier, Nagel and Pedersen (2009) found; that is, skewness of daily FX rate changes is a proxy for risk premium. Alternatively, one may be able to relax the rational expectation assumption since it was shown earlier that the statistical deterioration is likely due to the expectation component. In fact, Froot and Frankel (1989) and Chinn and Frankel (1994, 2002) documented that it is difficult to reject UIP when one uses survey-based measures of exchange rate depreciation instead. However, this paper will focus on solving the puzzle through the lens of time varying risk premia by incorporating recent breakthroughs in the related literature.

When premium is accounted for using skewness of daily FX rate changes as a proxy, I find that the statistical significance of forward discounts improve for most currencies while their coefficient estimates edge closer to positive one both under monthly and quarterly data. As well, I was able to find robust results when I assumed nonlinearity between the premium and future changes in the spot rate. However, my methodology is not robust to pre-financial crisis period, possibly due to overly conservative measure of FX volatility spikes. The remainder of this paper is structured as follows: Section 2 provides a brief summary of related papers, Section 3 describes the data and methodology, Section 4 presents the empirical results, Section 5 shares ideas for future research, and Section 6 concludes.

2 Related Literature

There is an extensive literature in macroeconomics and finance on the forward premium puzzle since Fama (1984). Froot and Thaler (1990), Engel (1996) and Frankel (2007) all provide nice background knowledge. Often cited in this line of research is the work of Messe and Rogoff (1983), who find that a random walk model consistently forecasts future spot rates better than alternative models, including the forward rate. The forward premium puzzle is also related to a long list of literature on purchasing power parity (PPP). Taylor and Taylor (2004) perhaps offer the most holistic analysis on the PPP to date.

My paper is closely related to two contributions in the recent literature. First, as in Brunnermeier, Nagel and Pedersen (2009), I show that negative skewness of FX daily changes can be used as a proxy for risk premiums. This proxy was then used to explain the UIP violation in the context of Fama's (1984) original work. This is my main contribution to the existing literature. Second, Menkhoff et al (2012) find that global FX volatility is a key driver of risk premia in the cross-section of carry trade returns. While my methodology is closer to the findings of Brunnermeier, Nagel and Pedersen (2009), my proxy for global FX volatility plays a key role during times of market turmoil, confirming their finding that excess returns to carry trades are indeed a compensation for higher risk-exposure. Ranaldo and Soderlind's (2007) finding that safe-haven currencies appreciate when stock market volatility (VIX) increases is also relevant since my global FX volatility measure closely resembles the VIX index (*See chart 3 in the Appendix*). Lastly, my findings are consistent with Baillie and Bollerslev (2000) who argue that there is a nonlinearity in the relationship between the spot rate and the forward discount.

In my empirical analysis, I follow much of the recent literature and sort currencies into artificial carry portfolios according to given criteria. Lustig, Roussanov, and Verdelhan (2010) were among the first to use this approach. Variation of this methodology is also adopted by both Brunnermeier, Nagel and Pedersen (2009) and Menkhoff et al (2012).

Using FX skewness as a proxy for risk premium is naturally related to a strand of literature that argues liquidity risk as the predominant factor for violations of UIP.

Burnside et al. (2006) find that the return of the carry trade portfolio is uncorrelated to standard risk factors, attributing instead the forward premium to market frictions (bid-ask spreads, price pressure, and time-varying adverse selection in Burnside, Eichenbaum, and Rebelo [2007]). Plantin and Shin (2006) is perhaps closest to this paper, as they find that a currency with a high interest rate will exhibit the classic price pattern of "going up by the stairs, and coming down in the elevator". This is an accurate characterization of negatively skewed distribution in FX returns.

3 Data and Methodology

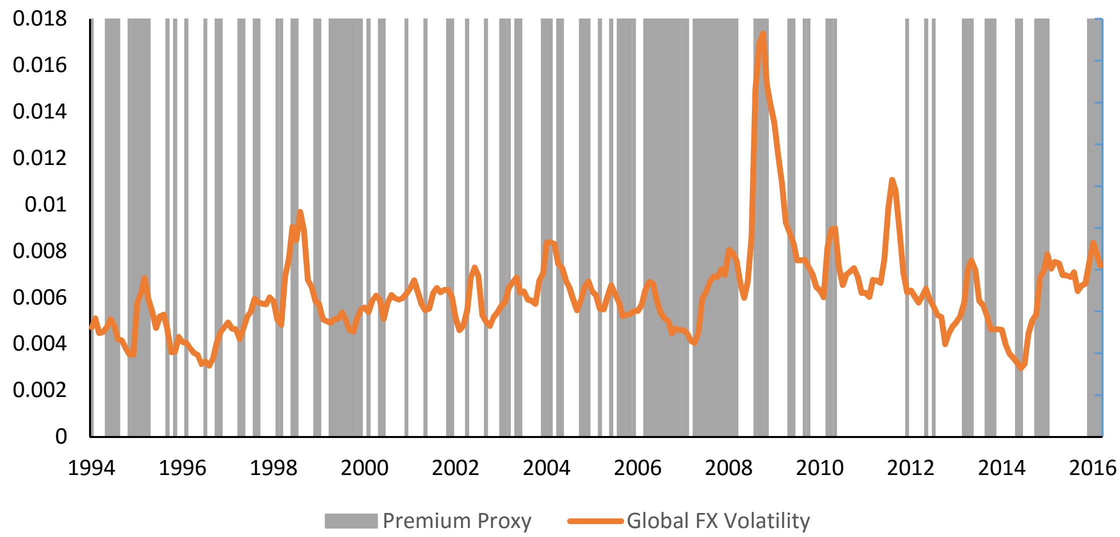
The data for spot exchange rates and forward exchange rates versus the US dollar (USD) cover the sample period from January 1994 to May 2016, and are obtained from Reuters via Datastream. The empirical analysis is carried out using 1-month and 3-month forward rates with respective spot rates. For instance, a 3-month forward discounts would be regressed on 3-month changes in the spot rates. Daily data is used to construct proxies for skewness and volatility. My total sample consists of the following 11 countries: Euro area (EUR), Japan (JPY), Canada (CAD), Australia (AUD), New Zealand (NZD), Switzerland (CHF), Great Britain (GBP), Norway (NOK), Sweden (SEK), Singapore (SGD), and South Africa (ZAR). This basket of currencies is comparable to that of Brunnermeier, Nagel and Pedersen (2009) and as before, all spot and forward rates are expressed in logarithms. I also study a smaller sub-sample that excludes the post-financial crisis period to observe the effects, if any, low interest rate environment had on the validity of UIP. The rest of this section explains how the premium component is estimated.

3.1 Premium Proxy

Premium Proxy is obtained by identifying currencies with the most negative skewness among eleven currencies. More specifically, I calculate the 3-month skewness for each currency at the end of each month based on daily log returns in the respective periods.[2] For instance, skewness at the end of March is based on daily log returns from the beginning of January to end of March. Here I assume that there are 252 trading days in a year (21 per month) for convenience. Then, skewness is ranked at t + 3 and 3 currencies with the most negative skewness receives a premium at time t. If there were only 2 currencies with negative skewness, then only those 2 currencies would receive premiums instead of 3. The same idea can be applied to funding currencies as well. Since Brunnermeier, Nagel, and Pedersen (2009) found that investment currencies are associated with negative FX skewness, funding currencies must be then associated with positive FX skewness. In total, up to 6 currencies (3 investment and 3 funding) would receive premiums at any given time. The remaining currencies receive zero premium so that currencies that are typically not used in carry trade portfolios are not penalized from this methodology. In other words, this methodology attempts to identify and allocate premium to carry currency pairs in a systematic way. This type of method is in line with most of the recent literature on UIP, including Brunnermeier, Nagel, and Pedersen (2009), Menkhoff et al (2012), Lustig, Roussanov, and Verdelhan (2010), and more. It is assuring to see in *Chart 1* that this methodology frequently assigns risk premium to AUD in between 2000 and 2008 because AUD was believed to be a popular investment currency choice among carry strategists during this period.

[2] This is the length of period Brunnermeier, Nagel, and Pedersen (2009) used in their study.

Chart 1: Global FX volatility and Premium Proxy for AUD



This methodology inevitably assumes that positive skewness to the USD (equivalent to negative skewness to AUD, for instance) can adequately capture the skewness of carry portfolios. Carry traders, however, do not necessarily take positions relative to the USD. For example, to exploit the high interest rates in AUD and the low interest rates in JPY, carry traders may have taken a long position in AUD which is financed by borrowing in JPY. Thus, while this approach does not directly form the carry trade strategies that investors might engage in, most of the recent literature conclude that this approach is nevertheless informative about carry trades in reality.

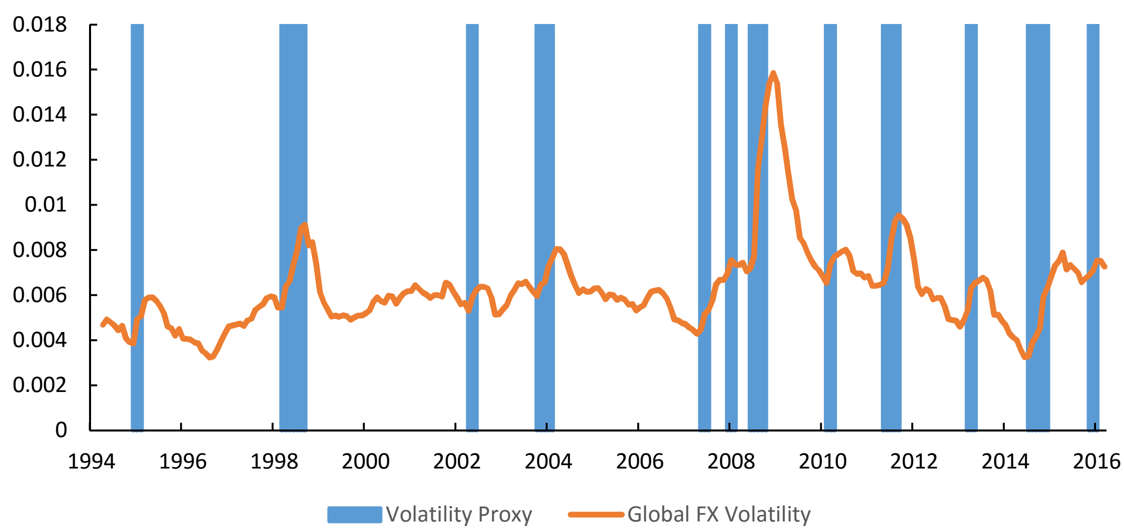
3.2 FX Volatility Proxy

First, standard deviation is calculated for each currency at each month based on daily log returns. I then average over all currencies to come up with a global FX volatility measure (Global Vol), as shown in orange line in *Chart 2*. In order to pick up the apparent spikes in volatility, I take the first difference of this volatility measure and again calculate the standard deviation of the first difference. Periods with volatility uptick greater than this standard deviation is then measured as my volatility proxy (blue bars in *Chart 2*). This volatility proxy is used to assign proper sign to premium proxies.

$$\mathrm{Vol}_{\mathrm{Proxy}} = \begin{cases} -1, & \text{Global Volatility is relatively low} \\ 1, & \text{Global Volatility is high} \end{cases}$$

Let us take AUD and JPY as an example again. When volatility is low, investment currencies such as AUD will tend to exhibit negative skewness in their daily return distributions. Volatility proxy then assigns an opposite sign of rational expectation to AUD's premium proxy. If, for instance, interest rate differential predicted depreciation of AUD, the premium proxy would carry a positive sign, implying appreciation of AUD or depreciation of JPY instead. During times of market turmoil, however, funding currencies will tend to exhibit negative skewness as global investors will pile on securities that are deemed safe. Thus, premium proxy in these instances would carry the same sign as rational expectation, implying depreciation of AUD and appreciation of JPY. This methodology would be consistent with the findings from Menkhoff et al (2012).

Chart 2: Global FX volatility and Volatility Proxy



3.3 Premium Estimation

I have so far discussed how premium gets assigned conditional on volatility. Next step in estimating premium is scaling this combined proxy to an appropriate level. First, let us recap Eq. (1) and (7).

$$S_{t+k} - S_t = \beta_0 + \beta_1(F_t - S_t) + u_t \qquad (1)$$

Where,

$$F_t - S_t = P_t + E(S_{t+k} - S_t) \qquad (7)$$

If UIP were to hold, the left hand side of Eq. (7) simply equals the second term on the right hand side, the rational expectation of future spot rate changes. However, a negative estimate of β_1 would suggest the existence of the premium component which carries the opposite sign of the expectation component. As well, the size of the premium component must be greater than the expectation component in order for β_1 to be negative. A reasonable way to scale this premium component is to make it a multiple of the rational expectation. That is,

$$P_t = \gamma(\mathrm{Vol}_{\mathrm{Proxy}})(F_t - S_t) \qquad (8)$$

Substituting Eq. (7) and (8) into Eq. (1), we derive

$$S_{t+k} - S_t = \beta_0 + \beta_1\big(\gamma(\mathrm{Vol}_{\mathrm{Proxy}})(F_t - S_t) + E(S_{t+k} - S_t)\big) + u_t$$

And since rational expectation states that

$$E(S_{t+k} - S_t) = F_t - S_t$$

Eq. (1) becomes

$$S_{t+k} - S_t = \beta_0 + \beta_1\big((\mathrm{Vol}_{\mathrm{Proxy}})\gamma(F_t - S_t) + (F_t - S_t)\big) + u_t \qquad (9)$$

Note that Eq. (9) does not always equal Eq. (10) because the volatility proxy varies between +1 and -1.

$$S_{t+k} - S_t = \beta_0 + \beta_1((1+\gamma)(F_t - S_t)) + u_t \quad (10)$$

When rational expectation is used as the base of the premium estimation, γ would simply translate to how far off rational expectation was to actual changes in the spot rates. The challenge of course is determining what value γ should take. A possible base case value for γ is 2 which means that 6 (or less) currencies with most negative/positive FX skewness (i.e. investment/funding currencies) would carry risk premium that would imply the exact opposite of rational expectation when added together. To illustrate, during times of market calm ($\text{Vol}_{\text{Proxy}} = -1$), Eq. (9) for investment and funding currencies implied by my premium proxy becomes

$$S_{t+k} - S_t = \beta_0 + \beta_1(-(F_t - S_t)) + u_t \quad (11)$$

In other words, when γ = 2, signs of beta coefficient estimates would likely flip, thus providing the missing piece in the forward premium puzzle. While the value of 2 for γ may sound suitable, it is rather arbitrary and it is also unreasonable to assume that eleven different currency pairs all have exactly the same response function when some currencies are clearly more liquid than the others in both the spot and forward FX market. Nevertheless, it gives us a useful perspective and I use it as the benchmark value throughout the analysis.

Finally, there are 270 months covering the period January, 1994, to May 2016 for the full sample and 170 months ending in December 2007 for the sub sample. When using the 3-month rates, there are overlaps in quarterly time periods. Table 6 and 7 show full sample means, standard deviations, and autocorrelations of $S_{t+k} - S_t$ (change in the spot rate), $F_t - S_{t+k}$ (forward rate minus the spot rate observed in the future), and $F_t - S_t$ (forward rate minus the current spot rate) for monthly and quarterly periods, respectively.

Table 7 shows non-overlapping quarterly time periods to avoid showing artificial autocorrelations. As a comparison, Fama (1984) used 122 monthly observations covering from 1973 to 1982 (Table 8).

Consistent with the well-known theory of random walk, the autocorrelations of changes in spot rates, $S_{t+k} - S_t$ are close to zero. Also, as documented by Fama (1984), $F_t - S_{t+k}$ show little autocorrelation. The autocorrelations of $F_t - S_t$ are evidently present at lag 1 for some currencies in the monthly data. However, this is a stark difference from the data used in Fama (1984) who found that the first-order autocorrelations are 0.65 or greater (Table 8). Autocorrelations in my dataset are as low as 0.11 (CAD). Since $F_t - S_t$ is the premium plus the expected change in the spot rates (Eq. 7), lack of autocorrelations would indicate that autocorrelations in P_t and/or $E(S_{t+k} - S_t)$ have disappeared over 30 years.

4 Regression Tests

4.1 Base Case OLS Estimates

I begin with the base case regression where gamma is 2. Table 3 highlights the improvement in both beta estimates and their statistical significance from the original regression result (Table 1) in yellow.

Table 3: Base case regression (Eq. 9 with γ = 2)[3]

	1994 - 2016				1994 - 2007			
	Beta Estimate		T-stat		Beta Estimate		T-stat	
	Monthly	Quarterly	Monthly	Quarterly	Monthly	Quarterly	Monthly	Quarterly
EUR	0.09	0.41	0.52	1.52	0.07	0.37	0.46	1.38
JPY	0.15	0.14	0.36	0.28	0.00	-0.08	-0.01	-0.14
CAD	0.64	0.47	1.38	0.76	-0.47	0.44	-1.09	0.87
AUD	0.80	0.11	1.44	0.18	0.40	0.57	0.72	0.97
NZD	-0.03	0.49	-0.07	0.97	-0.06	0.23	-0.13	0.44
CHF	0.79	-0.31	1.80	-0.75	0.60	-0.46	1.26	-1.05
GBP	0.18	0.24	0.35	0.35	-0.54	-0.62	-0.93	-0.87
NOK	0.65	0.29	1.58	0.53	0.30	-0.76	0.60	-1.39
SEK	-0.13	-0.57	-0.36	-1.14	-0.29	-1.43	-0.58	-2.48
SGD	0.20	-0.43	0.54	-1.11	0.20	-0.31	0.47	-0.78
ZAR	0.58	-0.36	2.25	-1.54	0.68	-0.66	1.83	-2.33

Note: Standard errors are adjusted for heteroscedasticity and serial correlation with a Newey-West covariance matrix with 5 lags (Andrews and Monohan, 1992) when applicable. See the appendix for test results on each currency's residuals.

It is apparent from above that my premium estimation method has worked reasonably well for the full sample period. I was able to improve both the beta estimates and t-statistics for eight currencies in monthly data and seven currencies in quarterly data. However, results are not as clear-cut for the sub-sample period. This may be due to rather bold assumption on the size and non-variability of gamma in the base case regression. I

[3] Beta estimates were considered improved when its value edged closer to a value of one. T-statistics were considered improved if its absolute value has increased or remained greater than 1.4 (average t-statistics from Fama, 1984).

now relax this assumption and estimate the gamma for each currency and for two different sample periods.

4.2 Nonlinear Relationship

Different test results in the two sample periods support a well-established fact that there is a time-varying risk premium component in forward rates. Also, as discussed earlier on, it is unreasonable to assume that different currencies take on the same gamma value when some currencies are clearly more liquid than the others in the FX market. Both of these issues are addressed by estimating gamma rather than arbitrarily assigning a value. Recall Eq. (9),

$$S_{t+k} - S_t = \beta_0 + \beta_1\big(\gamma(F_t - S_t)(\mathrm{Vol}_{\mathrm{Proxy}}) + (F_t - S_t)\big) + u_t \qquad (9)$$

This is a nonlinear setup since it is not linear in the parameters ($\beta_1 * \gamma$). A reasonable range of initial values for both beta and gamma (-4 to 4) are tested and the combination with the highest statistical significance of gamma are reported in Table 4. Consistent with the base case model, nonlinear estimation was very effective at enhancing the statistical significance of beta. I was able to improve both the beta estimates and t-statistics for nine currencies in monthly data and eight currencies in quarterly data. This is a further improvement from the base case model (Table 3). The magnitude and signs of estimated gamma are worth discussing. First, it should be noted that not all gammas carry the expected positive sign since a negative gamma value would actually indicate that the premium component and the expectation component worked together, opposite of what Fama (1984) found.

Table 4: Non-linear estimation result (1994-2016)[4]

	Monthly		Quarterly		T-stats (monthly)		T-stats (quarterly)	
	Beta	Gamma	Beta	Gamma	Beta	Gamma	Beta	Gamma
EUR	0.17	2.43	0.16	6.73	0.76	0.80	0.45	0.48
JPY	0.37	2.44	-0.88	0.43	0.55	0.59	-1.48	0.70
CAD	0.74	-0.06	-0.15	-7.00	1.59	-0.05	-0.24	-0.22
AUD	0.15	5.95	-1.45	-0.70	0.24	0.25	-2.18	-1.06
NZD	-0.31	2.55	0.32	4.85	-0.52	0.54	0.42	0.43
CHF	0.19	-1.11	-1.26	-0.69	0.32	-0.15	-1.83	-0.89
GBP	0.60	0.62	-0.59	0.57	0.93	0.38	-0.92	0.27
NOK	0.44	2.55	-0.44	-1.12	0.80	0.89	-0.72	-0.38
SEK	0.38	1.29	-1.04	0.14	0.61	0.62	-1.75	0.16
SGD	-0.42	-1.81	-0.67	-0.44	-0.81	-0.57	-1.43	-0.47
ZAR	-0.35	-1.07	-1.24	0.34	-0.73	-0.46	-2.42	1.18

Note: Standard errors are adjusted for heteroscedasticity and serial correlation with a Newey-West covariance matrix with 5 lags (Andrews and Monohan, 1992) when applicable. See the appendix for test results on each currency's residuals.

Nevertheless, it is somewhat comforting to see that EUR, JPY, AUD and NZD all carry relatively big positive gammas in monthly data because these four currencies are anecdotally well-known currencies typically used for carry trades. The same holds for the quarterly data except for the AUD. Second thing to note here is that the absolute values of gamma are not necessarily greater in the quarterly data. This may indicate that deviations from UIP do not persist longer than a month for some currencies. As well, since the forward discount (recall that my premium proxy is a multiple of the forward discount) is greater for the quarterly data, the magnitude of gamma should not be necessarily greater. Let us now look at the sub-sample results.

[4] Again, yellow colored cells display improvement from the original Fama (1984) work. See footnote 3 for more detailed explanations.

Table 5: Non-linear estimation result (1994-2007)

	Monthly		Quarterly		T-stats (Monthly)		T-stats (Quarterly)	
	Beta	Gamma	Beta	Gamma	Beta	Gamma	Beta	Gamma
EUR	0.17	1.90	0.23	4.18	0.77	0.79	0.61	0.69
JPY	-0.61	2.08	-1.98	0.09	-0.63	0.75	-2.18	0.27
CAD	0.38	1.60	-0.54	-2.75	0.56	0.51	-0.70	-0.51
AUD	-0.60	1.98	-2.42	-1.34	-0.60	0.73	-2.89	-1.99
NZD	-0.39	0.78	-1.84	-0.23	-0.38	0.33	-1.90	-0.40
CHF	-0.35	-1.22	-3.19	0.18	-0.47	-0.26	-3.53	0.71
GBP	0.71	0.34	-0.86	-0.87	0.91	0.18	-1.15	-0.44
NOK	0.60	3.90	-1.40	0.11	0.90	1.00	-2.13	0.17
SEK	-0.35	4.57	-2.72	0.74	-0.49	0.52	-3.40	2.23
SGD	-1.08	-0.17	-1.44	0.10	-1.85	-0.22	-2.77	0.24
ZAR	-0.83	-0.41	-1.77	0.80	-1.24	-0.46	-3.09	2.52

Note: Standard errors are adjusted for heteroscedasticity and serial correlation with a Newey-West covariance matrix with 5 lags (Andrews and Monohan, 1992) when applicable. See the appendix for test results on each currency's residuals.

Again, nonlinear estimation was very effective at enhancing the statistical significance of forward discounts. It is noteworthy that seven currencies are statistically significant at the 0.05 level.[5] Similar to the full sample result, EUR, JPY, AUD and NZD all carry positive gammas in the monthly data while the same did not hold in the quarterly data. On the other hand, nonlinear estimation was rather poor at steering the beta estimates towards the theoretical value of one. This is very puzzling since accounting for the premium component somehow gave further evidence to violations of UIP. It is difficult to reconcile the results from these two sample periods. One possible reason why my methodology was not robust in the sub-sample period may be due to my volatility measure. As shown in Chart 2, the volatility proxy as shown in blue bars is much less frequent before the financial crisis in 2008. This is perhaps due to the fact that FX volatility spikes are bigger

[5] Fama (1984) only had one currency with statistical significance at 0.05 level, albeit he used monthly data.

and more frequent in the post-crisis period. As a result, my volatility proxy is not giving the proper sign to my premium proxy as many times as it should in the sub-sample period. This finding would actually complement Menkhoff et al's (2012) main finding that global FX volatility is a key driver of the risk premium component in forward rates. A more refined measure of spikes in FX volatility could improve the suboptimal results from the sub-sample period. I leave this for future work along with few additional ideas that one could build upon the methodology shared in this paper.

5 Future Research

The main purpose of estimating the gamma was to allow different currencies to have different levels of premium. One could also allow gamma to be time varying for each currency. My test results on just two sample periods showed that gammas can change considerably over eight years. Estimation of time varying gamma and its relationship, if any, with volatility measures such as the VIX index or the TED spread would be an interesting analysis.[6] Evidence of significant relationship would more strongly corroborate the findings of Menkhoff et al (2012).

My research also motivates the need for new ways of forming rational expectations. As discussed in the introduction section, the deterioration in the statistical significance was due to 1) implicit assumption that the premium component is zero and 2) diminishing variance of rational expectations. This paper solely focused on the existence of time varying risk premium and completely left out but nor dismissed the validity of rational expectations. However, as alluded to couple times throughout the paper, there is a

[6] TED spread is the difference between the 3-month LIBOR rate and the 3-month U.S. T-bill rate. TED spread is often used as a proxy for volatility both in academia and by financial practitioners.

problem with using forward discounts as rational expectation and also as the base of my premium estimation. That is, the variance of forward discounts (i.e. interest rate differentials) has continued to fall while the variance of future change in the spot rate has not (Table 1 and 2). This can also be seen from the last columns of Table 6 and 8, which show that the average standard deviation of future changes in the spot rates has increased from 2.84% to 3.08% while the analogue for the forward discounts has fallen from 0.40% to 0.38%. The gap is much wider for the quarterly data (Table 7). Therefore, without also addressing the rational expectation issue simultaneously, one would overestimate the premium component and may wrongly conclude that all of the bias in the forward discount is due to the premium component. A good starting point in dealing with rational expectation is using the survey data, as Froot and Frankel (1989) and Chinn and Frankel (1994, 2002) have documented.

6 Concluding Remarks

This paper sheds light on the forward premium puzzle using recent breakthroughs in the related literature. I document and confirm the findings that negative skewness (Brunnermeier, Nagel, and Pedersen (2009)) and volatility in FX daily returns (Menkhoff et al (2012)) are the main drivers of risk premia in the FX market. As well, I provide some evidence of nonlinearity in the relationship between the spot rate and the forward discount. The nonlinear relationship stems from empirical findings that the covariance between premium and expectation component is not negative during the times of market turmoil. This paper also raises questions on the validity of rational expectation. While bias in the expectation component has long been documented, I show that the expectation bias has become greater due to divergence of variance in forward discounts and changes in future spot rates. By addressing the premium and the expectation components together, one should be able to provide fuller explanations to why violations of UIP persist.

Appendix

Table 6: Autocorrelations, means, and standard deviations: January 1994 – May 2016 (Monthly), N = 269

	Lag 1	Lag 2	Lag 3	Lag 4	Lag 5	Lag 6	Lag 7	Lag 8	Lag 9	Lag 10	Lag 11	Lag 12	Mean	Std. Dev
							$S_{t+k} - S_t$							
EUR	0.01	-0.01	0.11	-0.07	0.00	0.05	-0.08	0.01	-0.01	0.09	-0.01	-0.06	0.00	2.88
JPY	0.01	0.13	-0.03	0.02	-0.19	-0.04	-0.07	0.11	0.08	0.09	0.13	-0.01	-0.01	3.20
CAD	-0.02	0.04	-0.05	0.15	-0.05	-0.05	-0.05	0.04	-0.11	0.06	0.04	0.11	0.00	2.39
AUD	0.07	-0.05	0.13	-0.03	0.02	0.05	-0.07	-0.05	-0.06	0.03	0.01	-0.06	-0.02	3.52
NZD	-0.01	-0.03	0.24	-0.08	-0.04	0.07	-0.03	0.02	-0.01	-0.06	-0.02	-0.01	-0.07	3.71
CHF	-0.08	-0.05	0.15	-0.15	0.00	0.02	-0.05	0.02	0.06	0.04	0.06	-0.11	-0.15	3.18
GBP	0.03	0.00	0.15	-0.04	-0.05	0.06	-0.27	-0.03	0.01	0.00	-0.04	0.07	0.01	2.49
NOK	0.02	0.09	0.08	-0.05	-0.01	0.06	-0.08	-0.03	-0.06	0.02	0.03	-0.04	0.04	3.12
SEK	0.00	0.00	0.13	0.01	0.01	0.05	-0.11	-0.05	-0.05	0.01	0.02	-0.04	0.00	3.25
SGD	-0.01	-0.02	0.00	-0.03	-0.01	0.15	-0.09	0.08	0.01	0.03	-0.04	0.02	-0.06	1.73
ZAR	0.08	-0.02	0.02	0.00	-0.05	-0.08	0.00	0.18	0.06	-0.05	0.08	-0.02	0.57	4.36
							$F_t - S_{t+k}$							
EUR	0.08	0.07	0.17	0.01	0.06	0.10	-0.02	0.06	0.04	0.12	0.04	-0.01	0.20	2.99
JPY	0.01	0.13	-0.02	0.02	-0.18	-0.03	-0.06	0.12	0.07	0.08	0.14	-0.02	-0.21	3.22
CAD	0.00	0.04	-0.03	0.14	-0.03	-0.04	-0.05	0.03	-0.10	0.06	0.02	0.09	-0.01	2.37
AUD	0.06	-0.04	0.14	-0.02	0.03	0.06	-0.07	-0.04	-0.05	0.04	0.01	-0.06	0.20	3.53
NZD	-0.02	-0.03	0.24	-0.06	-0.03	0.09	-0.02	0.02	0.00	-0.05	-0.03	-0.01	0.29	3.71
CHF	-0.07	-0.04	0.14	-0.14	0.00	0.02	-0.04	0.03	0.06	0.06	0.07	-0.10	0.00	3.17
GBP	0.04	0.02	0.16	-0.03	-0.03	0.07	-0.25	-0.02	0.00	0.00	-0.03	0.06	0.02	2.48
NOK	0.02	0.10	0.07	-0.05	-0.02	0.06	-0.08	-0.01	-0.04	0.02	0.04	-0.05	0.05	3.13
SEK	0.00	0.01	0.12	0.03	0.02	0.07	-0.11	-0.03	-0.03	0.01	0.02	-0.04	0.03	3.27
SGD	-0.02	-0.01	0.00	-0.03	-0.03	0.15	-0.08	0.08	0.00	0.03	-0.04	0.03	-0.03	1.74
ZAR	0.08	-0.01	0.02	0.01	-0.04	-0.05	0.01	0.19	0.07	-0.04	0.08	-0.04	0.05	4.43
							$F_t - S_t$							
EUR	0.88	0.86	0.81	0.77	0.70	0.66	0.60	0.55	0.50	0.45	0.40	0.37	0.20	0.89
JPY	0.26	0.35	0.28	0.23	0.29	0.24	0.23	0.28	0.23	0.19	0.27	0.18	-0.22	0.29
CAD	0.11	0.16	0.09	0.16	0.03	0.00	0.08	0.06	0.12	0.00	0.03	0.01	-0.01	0.29
AUD	0.16	0.20	0.11	0.08	0.12	-0.01	0.25	0.09	0.19	0.13	0.10	0.17	0.17	0.34
NZD	0.22	0.24	0.06	-0.01	0.01	-0.07	0.15	0.05	0.16	0.15	0.07	0.18	0.22	0.37
CHF	0.19	0.24	0.12	0.08	0.07	0.13	0.18	0.14	0.10	0.00	0.08	0.08	-0.16	0.33
GBP	0.28	0.18	0.20	0.13	0.01	0.02	0.02	0.07	0.03	0.04	0.11	0.08	0.03	0.26
NOK	0.13	0.12	0.09	0.18	-0.02	-0.02	0.08	0.07	0.13	-0.01	-0.01	0.02	0.08	0.39
SEK	0.12	0.15	0.14	0.15	0.00	0.10	0.08	0.13	0.14	0.09	0.17	0.09	0.03	0.39
SGD	0.40	0.34	0.47	0.42	0.35	0.25	0.30	0.23	0.26	0.26	0.17	0.22	-0.09	0.18
ZAR	0.34	0.39	0.20	0.14	0.12	0.16	0.22	0.16	0.18	0.20	0.10	0.20	0.61	0.51

The means and standard deviations of the variables are on a percent per month basis

Table 7: Autocorrelations, means, and standard deviations: January 1994 – May 2016 (Quarterly), N = 89

	Lag 1	Lag 2	Lag 3	Lag 4	Lag 5	Lag 6	Lag 7	Lag 8	Lag 9	Lag 10	Lag 11	Lag 12	Mean	Std. Dev
							$S_{t+k} - S_t$							
EUR	0.70	0.38	0.06	0.01	-0.01	-0.03	-0.05	-0.01	0.03	0.06	-0.03	-0.12	0.00	5.01
JPY	0.69	0.41	0.01	-0.10	-0.22	-0.16	-0.06	0.12	0.21	0.24	0.20	0.12	0.01	5.82
CAD	0.65	0.37	0.06	0.08	-0.02	-0.06	-0.12	-0.06	-0.04	0.06	0.06	0.03	-0.04	4.13
AUD	0.73	0.39	0.11	0.07	0.04	-0.02	-0.08	-0.11	-0.10	-0.06	-0.07	-0.09	-0.07	6.25
NZD	0.74	0.44	0.16	0.07	0.03	0.01	0.02	0.00	-0.05	-0.08	-0.08	-0.05	-0.21	6.34
CHF	0.67	0.32	-0.02	-0.08	-0.07	-0.08	-0.01	0.05	0.12	0.10	0.01	-0.12	-0.46	5.12
GBP	0.73	0.42	0.11	0.05	-0.08	-0.17	-0.25	-0.18	-0.11	-0.01	-0.01	0.02	0.04	4.39
NOK	0.72	0.43	0.10	0.04	-0.01	-0.03	-0.08	-0.09	-0.08	-0.03	-0.03	-0.09	0.11	5.63
SEK	0.71	0.43	0.14	0.12	0.06	-0.02	-0.13	-0.14	-0.11	-0.04	-0.05	-0.08	0.01	5.64
SGD	0.66	0.32	-0.03	0.01	0.03	0.09	0.05	0.08	0.02	0.03	-0.04	-0.05	-0.18	2.96
ZAR	0.70	0.35	0.02	-0.05	-0.10	-0.06	0.05	0.15	0.15	0.09	0.03	-0.04	1.65	7.91
							$F_t - S_{t+k}$							
EUR	0.71	0.40	0.09	0.05	0.02	0.01	-0.02	0.03	0.06	0.09	0.01	-0.08	0.15	5.10
JPY	0.69	0.42	0.03	-0.08	-0.20	-0.14	-0.04	0.13	0.21	0.24	0.20	0.12	-0.69	5.87
CAD	0.66	0.37	0.07	0.09	0.00	-0.05	-0.10	-0.05	-0.03	0.07	0.06	0.03	0.05	4.15
AUD	0.73	0.40	0.12	0.09	0.06	0.01	-0.05	-0.07	-0.07	-0.02	-0.04	-0.07	0.58	6.30
NZD	0.73	0.45	0.17	0.09	0.05	0.03	0.04	0.03	-0.03	-0.06	-0.06	-0.03	0.86	6.32
CHF	0.68	0.34	0.01	-0.05	-0.05	-0.05	0.02	0.08	0.14	0.13	0.04	-0.08	0.00	5.20
GBP	0.72	0.43	0.12	0.06	-0.05	-0.15	-0.23	-0.16	-0.09	0.01	0.01	0.04	0.13	4.39
NOK	0.71	0.44	0.11	0.05	0.00	-0.02	-0.06	-0.06	-0.05	0.00	-0.01	-0.08	0.12	5.67
SEK	0.71	0.43	0.16	0.15	0.09	0.01	-0.09	-0.10	-0.08	-0.02	-0.02	-0.06	0.04	5.70
SGD	0.65	0.31	-0.03	0.01	0.03	0.09	0.06	0.08	0.02	0.02	-0.04	-0.05	-0.07	3.01
ZAR	0.71	0.37	0.04	-0.03	-0.08	-0.04	0.07	0.18	0.18	0.10	0.04	-0.05	0.08	8.05
							$F_t - S_t$							
EUR	0.92	0.91	0.84	0.81	0.74	0.70	0.63	0.59	0.53	0.48	0.44	0.40	0.24	1.16
JPY	0.68	0.70	0.64	0.61	0.60	0.56	0.52	0.51	0.45	0.41	0.39	0.32	-0.97	0.49
CAD	0.64	0.58	0.57	0.58	0.49	0.45	0.43	0.43	0.41	0.36	0.29	0.22	-0.05	0.37
AUD	0.63	0.66	0.59	0.57	0.62	0.56	0.61	0.57	0.53	0.55	0.46	0.50	0.31	0.44
NZD	0.62	0.66	0.57	0.55	0.54	0.48	0.57	0.52	0.47	0.48	0.37	0.45	0.57	0.50
CHF	0.58	0.55	0.47	0.42	0.37	0.41	0.35	0.37	0.27	0.19	0.22	0.15	-0.65	0.46
GBP	0.60	0.58	0.55	0.51	0.45	0.46	0.40	0.44	0.36	0.33	0.34	0.27	0.22	0.36
NOK	0.72	0.71	0.65	0.65	0.54	0.52	0.49	0.49	0.41	0.36	0.33	0.28	0.13	0.62
SEK	0.69	0.71	0.62	0.63	0.57	0.61	0.49	0.56	0.48	0.48	0.46	0.39	-0.04	0.60
SGD	0.78	0.71	0.69	0.63	0.53	0.46	0.39	0.35	0.26	0.19	0.11	0.08	-0.39	0.38
ZAR	0.85	0.81	0.79	0.72	0.67	0.64	0.62	0.56	0.51	0.47	0.41	0.36	1.78	0.88

The means and standard deviations of the variables are on a percent per month basis

Table 8: Autocorrelations, means, and standard deviations from Fama (1984): August 1973 – December 1982 Monthly), N = 122

	Lag 1	Lag 2	Lag 3	Lag 4	Lag 5	Lag 6	Lag 7	Lag 8	Lag 9	Lag 10	Mean	Std. Dev
						$S_{t+k} - S_t$						
Belgium	0.05	0.08	0.07	-0.03	0.02	-0.03	-0.01	0.06	0.14	-0.07	-0.25	3.11
Canada	0.13	-0.24	0.08	0.05	0.03	0.00	-0.16	0.06	0.07	-0.15	-0.17	1.12
France	-0.04	0.06	0.14	-0.02	0.14	0.04	0.01	-0.02	0.10	-0.12	-0.43	3.01
Italy	0.01	0.15	-0.03	-0.11	0.09	-0.01	0.09	0.04	0.14	-0.17	-0.73	2.80
Japan	0.16	-0.11	0.03	0.13	0.15	-0.09	-0.04	0.07	0.05	-0.09	0.07	3.05
Netherlands	0.02	0.05	0.05	-0.14	-0.01	-0.01	-0.01	0.04	0.04	-0.06	-0.04	3.01
Switzerland	0.01	0.08	0.03	-0.11	0.09	0.01	-0.05	-0.08	0.01	-0.04	0.26	3.76
United Kingdom	0.15	0.04	0.10	-0.07	0.09	0.04	-0.16	0.01	0.02	0.07	-0.36	2.58
West Germany	0.01	0.08	0.01	-0.13	0.00	-0.04	0.02	0.06	0.07	-0.05	-0.03	3.08
						$F_t - S_{t+k}$						
Belgium	0.11	0.10	0.08	-0.02	0.02	-0.03	-0.03	0.04	0.11	-0.08	0.09	3.22
Canada	0.17	-0.21	0.07	0.04	0.01	-0.01	-0.16	0.04	0.06	-0.14	0.08	1.16
France	0.01	0.09	0.16	-0.01	0.14	0.04	0.00	-0.02	0.06	-0.10	0.17	3.10
Italy	0.08	0.17	-0.02	-0.11	0.07	-0.03	0.08	0.03	0.11	-0.17	-0.07	2.95
Japan	0.21	-0.05	0.07	0.13	0.14	-0.09	-0.05	0.05	0.05	-0.07	0.10	3.15
Netherlands	0.07	0.08	0.07	-0.11	0.01	0.00	0.00	0.04	0.04	-0.05	0.21	3.08
Switzerland	0.05	0.10	0.06	-0.09	0.09	0.01	-0.04	-0.08	0.01	-0.02	0.23	3.82
United Kingdom	0.19	0.08	0.12	-0.06	0.09	0.03	0.15	0.01	0.01	0.05	0.13	2.65
West Germany	0.03	0.09	0.03	-0.12	0.00	-0.04	0.02	0.05	0.07	-0.04	0.33	3.12
						$F_t - S_t$						
Belgium	0.67	0.44	0.33	0.33	0.18	0.04	-0.01	0.01	0.00	-0.01	-0.16	0.41
Canada	0.82	0.63	0.49	0.38	0.36	0.32	0.33	0.36	0.36	0.35	-0.09	0.17
France	0.65	0.45	0.36	0.28	0.24	0.18	0.17	0.18	0.23	0.28	-0.25	0.44
Italy	0.68	0.47	0.37	0.28	0.23	0.19	0.18	0.19	0.19	0.14	-0.80	0.66
Japan	0.85	0.69	0.61	0.47	0.34	0.30	0.22	0.16	0.21	0.24	0.17	0.64
Netherlands	0.72	0.55	0.40	0.28	0.24	0.20	0.20	0.23	0.22	0.21	0.17	0.32
Switzerland	0.86	0.73	0.61	0.52	0.47	0.46	0.48	0.49	0.50	0.49	0.48	0.37
United Kingdom	0.87	0.75	0.64	0.51	0.43	0.36	0.31	0.28	0.25	0.20	-0.23	0.35
West Germany	0.78	0.56	0.39	0.26	0.20	0.20	0.26	0.34	0.42	0.46	0.30	0.24

The means and standard deviations of the variables are on a percent per month basis

The following tables (9, 10 and 11) show the p-values from serial correlation (Durbin-Watson) and heteroscedasticity (Engel) tests.[7]

Table 9. Tests on Eq. 1 / Table 1

	Full-Sample				Sub-Sample			
	Durbin - Watson		Engel		Durbin - Watson		Engel	
	1-month	3-month	1-month	3-month	1-month	3-month	1-month	3-month
EUR	0.81	0.00	0.59	0.00	0.30	0.00	0.09	0.00
JPY	0.73	0.00	0.51	0.00	0.71	0.00	0.61	0.00
CAD	0.73	0.00	0.00	0.00	0.15	0.00	0.00	0.00
AUD	0.19	0.00	0.01	0.00	0.83	0.00	0.07	0.00
NZD	0.87	0.00	0.05	0.00	0.49	0.00	0.15	0.00
CHF	0.30	0.00	0.44	0.00	0.67	0.00	0.32	0.00
GBP	0.52	0.00	0.22	0.00	0.29	0.00	0.41	0.00
NOK	0.67	0.00	0.02	0.00	0.79	0.00	0.17	0.00
SEK	0.77	0.00	0.00	0.00	0.84	0.00	0.56	0.00
SGD	0.90	0.00	0.03	0.00	0.26	0.00	0.31	0.00
ZAR	0.13	0.00	0.02	0.00	0.14	0.00	0.01	0.00

Table 10. Tests on Eq. 9 – Base Case / Table 3

	Full-Sample				Sub-Sample			
	Durbin - Watson		Engel		Durbin - Watson		Engel	
	1-month	3-month	1-month	3-month	1-month	3-month	1-month	3-month
EUR	0.79	0.00	0.63	0.00	0.27	0.00	0.10	0.00
JPY	0.76	0.00	0.48	0.00	0.70	0.00	0.60	0.00
CAD	0.99	0.00	0.00	0.00	0.13	0.00	0.00	0.00
AUD	0.20	0.00	0.01	0.00	0.81	0.00	0.06	0.00
NZD	0.98	0.00	0.02	0.00	0.53	0.00	0.14	0.00
CHF	0.29	0.00	0.42	0.00	0.61	0.00	0.37	0.00
GBP	0.58	0.00	0.25	0.00	0.25	0.00	0.28	0.00
NOK	0.79	0.00	0.03	0.00	0.82	0.00	0.21	0.00
SEK	0.72	0.00	0.00	0.00	0.79	0.00	0.58	0.00
SGD	0.97	0.00	0.03	0.00	0.50	0.00	0.30	0.00
ZAR	0.23	0.00	0.06	0.00	0.17	0.00	0.01	0.00

[7] 3-month data for all currencies reject the null hypothesis of both tests. However, this is almost entirely due to using overlapping periods. Notice how autocorrelations are not very significant beyond lag 3 (Chart 5).

Table 11. Tests on Eq. 9 – Nonlinear Estimate / Table 4

	Full-Sample				Sub-Sample			
	Durbin - Watson		Engel		Durbin - Watson		Engel	
	1-month	3-month	1-month	3-month	1-month	3-month	1-month	3-month
EUR	0.78	0.00	0.55	0.00	0.28	0.00	0.11	0.00
JPY	0.57	0.00	0.39	0.00	0.86	0.00	0.51	0.00
CAD	0.79	0.00	0.00	0.00	0.11	0.00	0.00	0.00
AUD	0.20	0.00	0.01	0.00	0.79	0.00	0.05	0.00
NZD	0.90	0.00	0.03	0.00	0.47	0.00	0.27	0.00
CHF	0.31	0.00	0.25	0.00	0.57	0.00	0.36	0.00
GBP	0.48	0.00	0.26	0.00	0.32	0.00	0.47	0.00
NOK	0.65	0.00	0.02	0.00	0.90	0.00	0.26	0.00
SEK	0.75	0.00	0.00	0.00	0.71	0.00	0.54	0.00
SGD	0.71	0.00	0.05	0.00	0.12	0.00	0.25	0.00
ZAR	0.11	0.00	0.01	0.00	0.10	0.00	0.01	0.00

Chart 3: VIX index and my Global FX volatility index

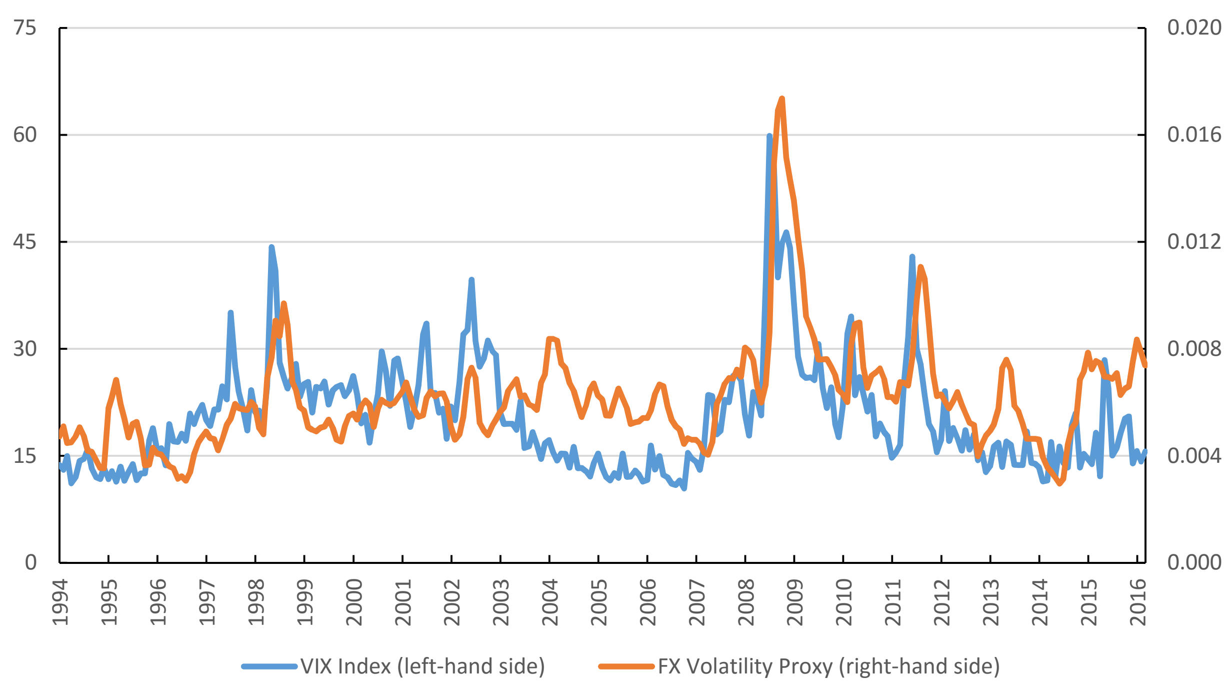
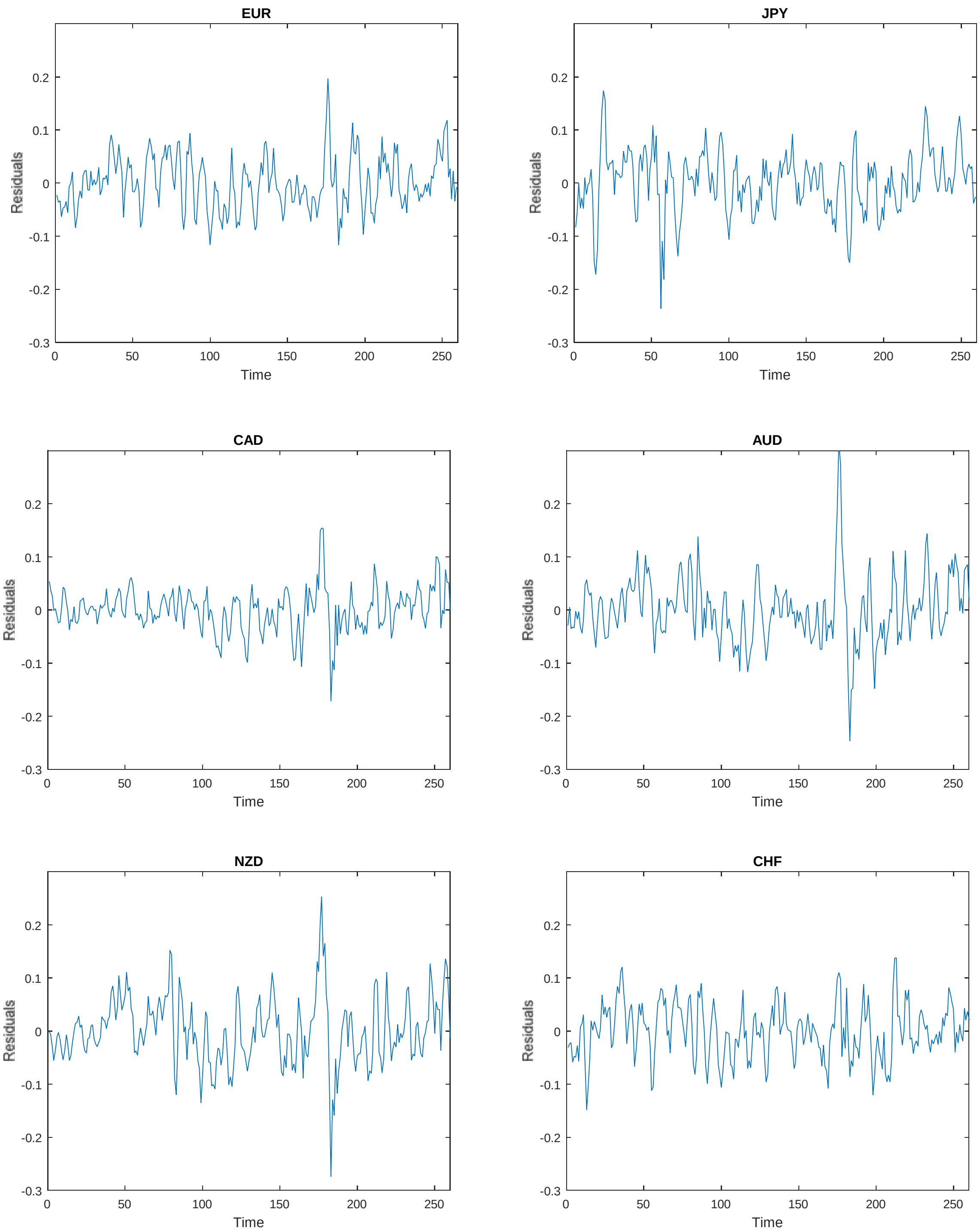
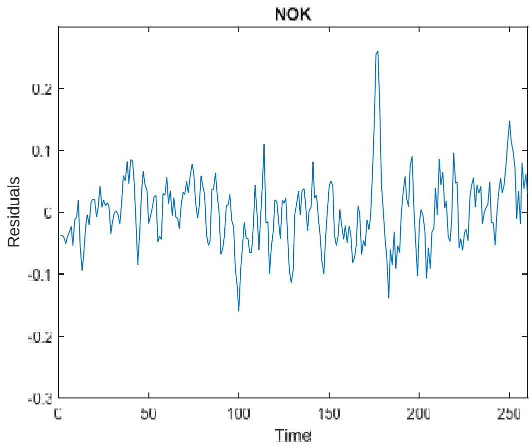
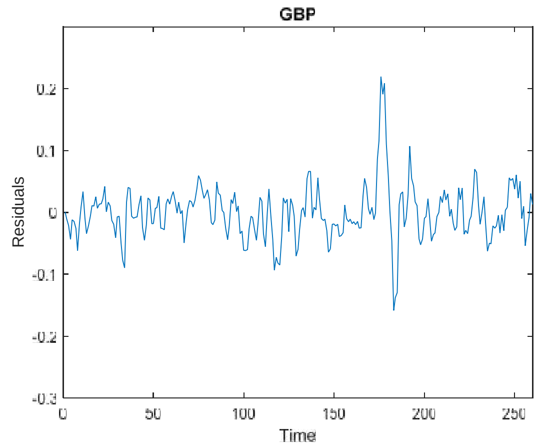
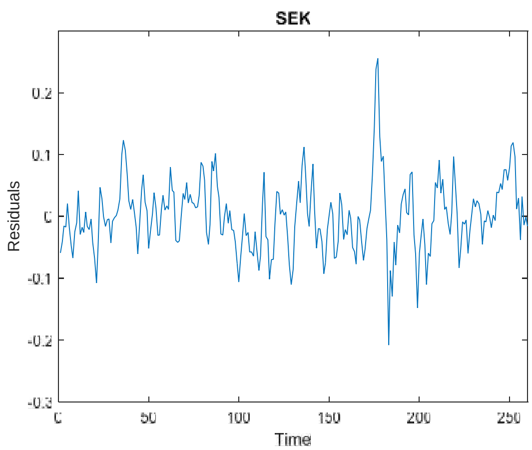


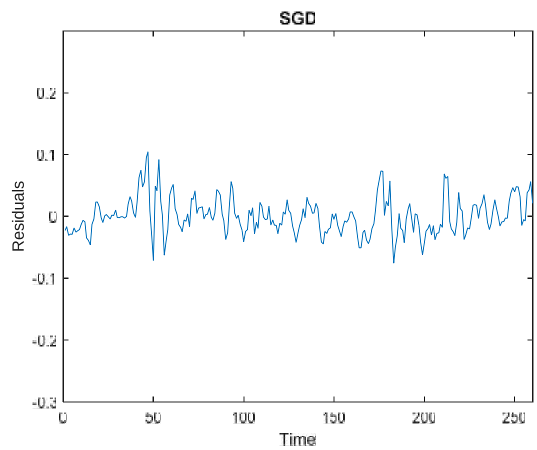
Chart 4: Time Series of Residuals from Eq. 7 (quarterly) with γ = 2 (1994 – 2016)




NOK
Residuals
Time
0.2
0.1
0
-0.1
-0.2
-0.3
0
50
100
150
200
250


GBP
Residuals
Time
0.2
0.1
0
-0.1
-0.2
-0.3
0
50
100
150
200
250


SEK
Residuals
Time
0.2
0.1
0
-0.1
-0.2
-0.3
0
50
100
150
200
250


SGD
Residuals
Time
0.2
0.1
0
-0.1
-0.2
-0.3
0
50
100
150
200
250

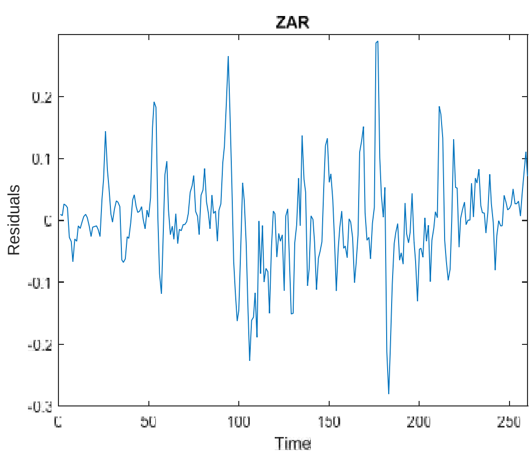
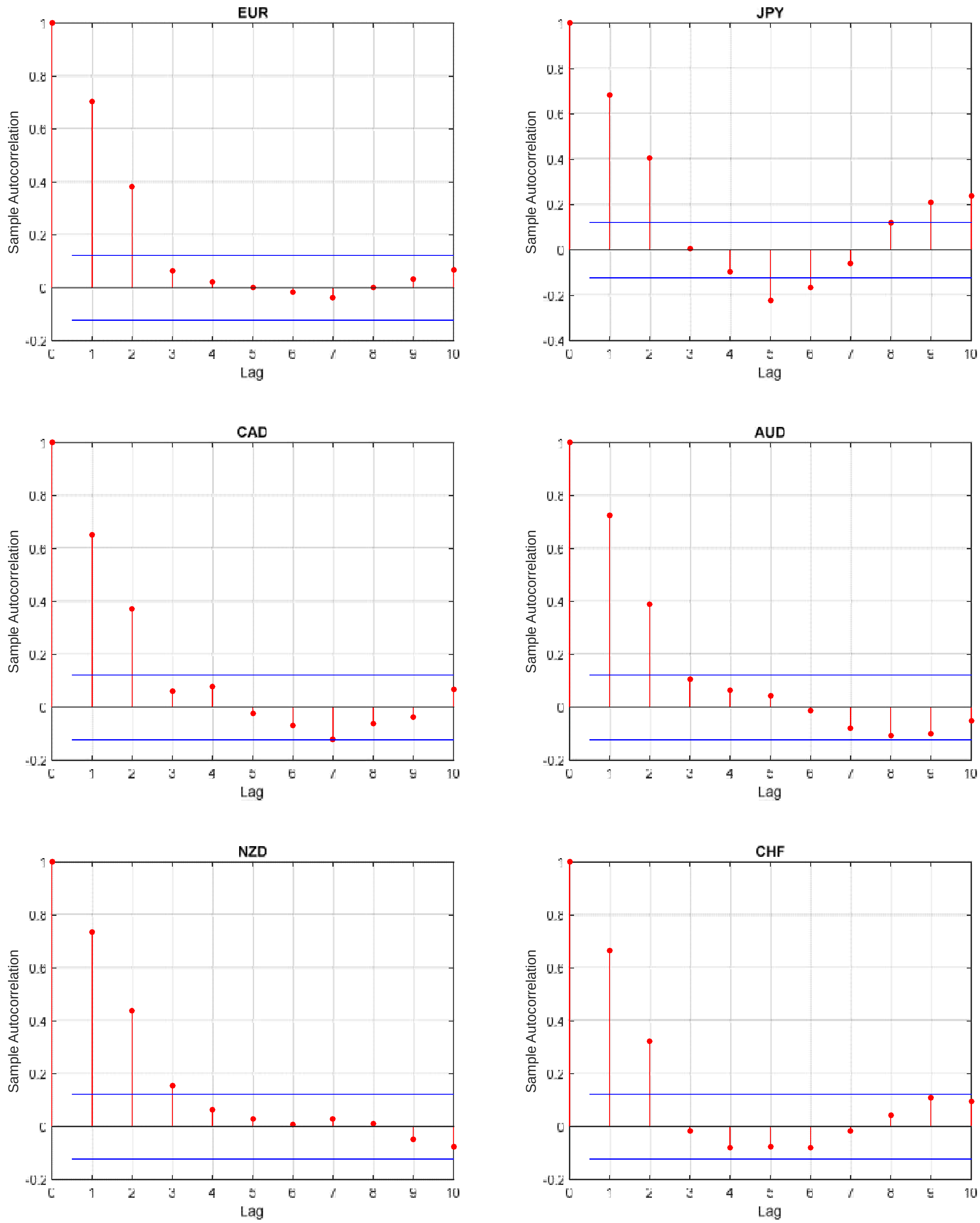
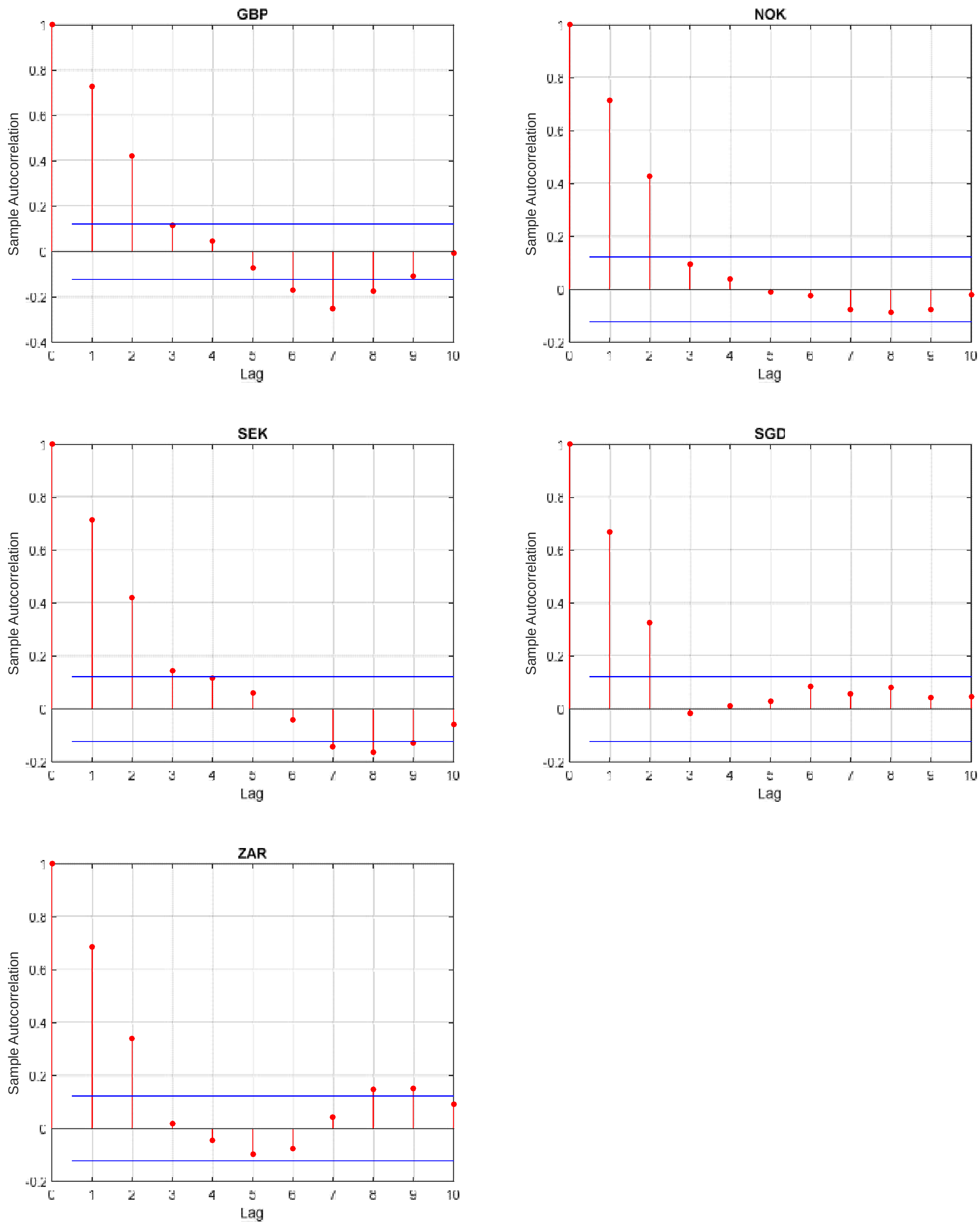

ZAR
Residuals
Time
0.2
0.1
0
-0.1
-0.2
-0.3
0
50
100
150
200
250

Chart 5: Autocorrelation of Residuals from Eq. 7 (quarterly) with $\gamma = 2$ (1994 – 2016)[8]



[8] Blue lines represent 95% confidence interval.



Note. Time-series and autocorrelation of residuals from nonlinear estimation were only marginally different from above and thus, they are unreported in the interest of conserving space.

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