

Long Memory and the Relation Between Implied and Realized Volatility

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ABSTRACT

We argue that the predictive regression between implied volatility (regressor) and realized volatility over the remaining life of a European option (regressand) is likely to be a fractional cointegrating relation. Because cointegration is associated with long-run comovements, this classical regression cannot be used to test for option market efficiency and short-term unbiasedness of implied volatility as a predictor of realized volatility. Using narrow-band spectral methods, we provide consistent estimates of the long-run relation between implied and realized volatility *even* when implied volatility is measured with error and/or volatility is priced but the volatility risk premium is unobservable. Although little can be said about short-term unbiasedness, our results largely support a notion of long-run unbiasedness of implied volatility as a predictor of realized volatility.

KEYWORDS: fractional cointegration, implied volatility, long memory, predictive regression, realized volatility

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Implied volatility is widely regarded as the market's best forecast of the future volatility of the asset an option is written on. As a consequence, there has been substantial interest in verifying whether implied volatility is an unbiased forecast of future realized volatility. Consider the regression

$$\sigma_t^R = \alpha + \beta \sigma_t^{BS} + \varepsilon_t, \quad (1)$$

where σ_t^{BS} denotes Black–Scholes implied volatility at time t , σ_t^R denotes realized volatility until the option's expiration time T (with $T > t$), and ε_t is a forecast error. Unbiasedness is evaluated by testing whether the slope and the intercept of this classical regression are equal to 1 and 0, respectively.

The early studies on this topic have generally maintained that implied volatility is an informative but biased forecast of future realized volatility. An interested reader is referred to Poteshman (2000), for example, for a discussion of the literature. Nevertheless, recent work has pointed out that the evidence in favor of unbiasedness is stronger once the three issues that are believed to contaminate the relevant predictive regression are properly accounted for—namely, errors-in-variables [see, e.g., Christensen and Prabhala (1998), Poteshman (2000), and Chernov (2006)], overlapping data [see, e.g., Christensen and Prabhala (1998)], and missing variables [see, e.g., Poteshman (2000) and Chernov (2006)]. This evidence is generally employed to support option market efficiency and short-term unbiasedness of implied volatility as a predictor of realized volatility over the option's life.

This article proposes a different interpretation of the classical implied/realized volatility regression. We find that both realized volatility and implied volatility are fractionally integrated [Taylor (1986), Dacorogna et al. (1993), and Ding, Granger, and Engle (1993) are important early references on the relevance of long-range dependence in volatility measures; Baillie, Bollerslev, and Mikkelsen (1996), Bollerslev and Mikkelsen (1996, 1999), Comte and Renault (1998), Comte, Coutin, and Renault (2003), Ray and Tsay (2000), Andersen et al. (2001a,b), among others, provide more recent evidence]. More importantly for our purposes, we show that the relation between implied and realized volatility is likely to be a fractionally cointegrating relation. Because cointegration is associated with long-run comovements, the classical predictive regression of realized volatility on implied volatility should not be regarded as providing information about either option market efficiency or short-term unbiasedness of implied volatility as a predictor of realized volatility. Rather, this regression provides information about the nature of the long-run relation between the two volatility proxies.

Having made these points, we proceed to the estimation of the model. Due to measurement errors and the likely presence of an unobservable volatility risk premium, ordinary least squares (OLS) cannot provide consistent estimates of the implied/realized volatility cointegrating vector. To this extent, we employ methods that focus on frequencies in the neighborhood of zero and hence on long-run movements, namely, narrow-band spectral least squares (NBSL)

methods. Consider the existence of a volatility risk premium [Poteshman (2000), Chernov (2006)], for example. Traditional semimartingale option pricing implies that the expected value of realized volatility depends (approximately) linearly on implied volatility and a volatility risk premium. A neglected risk premium is then likely to induce correlation between the regression residuals and implied volatility. If so, OLS would only estimate the projection of realized volatility on implied volatility, not the realized/implied volatility cointegrating vector. The use of NBLS allows us to estimate the long-run relation between implied and realized volatility consistently even if a risk premium plays a role. Importantly, our consistency result does not depend on a potentially ad hoc parametrization of the risk premium and the explicit inclusion of the risk premium in the predictive regression, as in Chernov (2006) for example.

Even though short-term unbiasedness cannot be studied, using three data sets [the VIX and the S&P 100 index, S&P 100 option prices and the S&P 100 index, and option prices on Deutschemark-Dollar (DM) futures] as well as three commonly used transformations of the data (variances, standard deviations, and logarithmic standard deviations), we find rather strong empirical support for a long-run notion of the conventional unbiasedness hypothesis.

The article is organized as follows. Section 1 contains a description of the data and an analysis of the fractional cointegration properties of realized and implied volatility series. In Section 2, we present our econometric approach. Section 3 confirms the validity of our econometric method through simulations relying on an option pricing model with long-memory stochastic volatility and leverage effects. The estimated relation between realized and implied volatility is reported in Section 4. Section 5 concludes. The Appendix contains further simulation results and discussions.

1 THE DATA

To motivate our analysis, we first describe the data and verify the fractional integration and cointegration properties of our volatility measures.

Our main data set consists of observations on the VIX (the CBOE Market Volatility index) and the S&P 100 (OEX) index from January 1988 to October 2003. Note that the CBOE has recently changed the ticker symbol for the S&P 100 implied volatility to VXO, whereas VIX now refers to the S&P 500 implied volatility. Throughout this article, we continue to use the symbol VIX to refer to the S&P 100 implied volatility. The VIX is the (annualized) implied volatility of a nontraded (synthetic) at-the-money option contract with one month to maturity. This measure is believed to be less affected by the problems that pollute standard implied volatility measures extracted from OEX contracts [for instance, the potential nonsynchronous measurement of option and index levels, early exercise and dividends, bid–ask spreads, as well as the wildcard option in the OEX market; see Christensen and Prabhala (1998) for discussions]. The VIX has been employed in predictive regressions of the type analyzed here by Chernov (2006). We use monthly nonoverlapping observations to control the correlation

structure of the regression errors by taking the closing value of each month, as suggested by Christensen and Prabhala (1998). We also multiply the VIX data by a constant factor equal to $(\frac{252}{365})^{1/2}$ to account for the difference between trading days and calendar days in a year [Schwert (2002)].

As in the early work by French, Schwert, and Stambaugh (1987) and Schwert (1989), we compute the realized volatility over the remaining life (one month) of the option as

$$\sigma_t^R = \sqrt{\frac{1}{n_t} \sum_{j=1}^{n_t} r_j^2} \times 252, \quad (2)$$

where $r_j = \log(S_j/S_{j-1})$, S_j is the closing value of the S&P 100 index on the j th trading day of month t , and n_t is the number of trading days in month t .

In sum, the data manipulations result in two monthly time series, σ_t^{BS} and σ_t^R , where σ_t^{BS} is the annualized (assuming 252 trading days per year) Black–Scholes implied standard deviation for a synthetic, at-the-money, option contract with one month to maturity, as given by the VIX, and σ_t^R is the annualized realized standard deviation of the S&P 100 index over the remaining life (one month) of the option. Both series contain 191 nonoverlapping observations.

Table 1 provides descriptive statistics for the two volatility measures.

Both implied volatility and realized volatility display heavy tails and positive skewness. As typically the case with volatility measures, a simple logarithmic transformation (not reported here) would almost lead to normality [see, e.g., Andersen, Bollerslev, and Diebold (2006)]. The mean of implied volatility is larger than the mean of realized volatility, suggesting a possible risk premium.

We now analyze the persistence properties of the data. As discussed in the introduction, we model persistence in volatility through a long-memory model. The long-memory parameter d is estimated in a semiparametric fashion. We report results for both the standard log-periodogram estimator [Geweke and Porter-Hudak (1983), GPH henceforth] and the gaussian semiparametric local Whittle estimator [Künsch (1987), Robinson (1995b)]. We have also considered

Table 1 Descriptive statistics.

	Mean	Standard deviation	Skewness	Kurtosis
Implied volatility (σ^{BS})	0.1793	0.0608	0.89	3.97
Realized volatility (σ^R)	0.1606	0.0741	1.21	4.35

The table reports descriptive statistics for realized and implied volatility series obtained using the S&P 100 index and the VIX (the CBOE Market Volatility index) from January 1988 to October 2003 (191 monthly nonoverlapping observations). We report mean, standard deviation, skewness, and kurtosis. The skewness and kurtosis are computed after studentizing the relevant quantity, θ , say, as $t_\theta = \frac{(\theta_t - \bar{\theta})}{\sigma(\theta)}$, where $\sigma(\theta)$ is the standard deviation of θ . The two measures are equal to $\frac{1}{n-1} \sum t_\theta^3$ and $\frac{1}{n-1} \sum t_\theta^4$, respectively.

the modified log-periodogram estimators of Andrews and Guggenberger (2003) and Sun and Phillips (2003) as well as the modified Whittle estimators of Andrews and Sun (2004) and Hurvich and Ray (2003). Our main findings are not affected by the choice of estimator. The corresponding results are available on request.

The GPH estimator ($\hat{d}_{n,m}$) is obtained as the OLS estimate of d in the frequency-domain regression

$$\ln P(\lambda_s) = c - d \ln \left(4 \left(\sin^2 \left(\frac{\lambda_s}{2} \right) \right) \right) + \varepsilon(\lambda_s), \quad (3)$$

where $P(\cdot)$ is the periodogram of the data computed at the harmonic frequencies $\lambda_s = \frac{2\pi s}{n}$ with $s = 1, \dots, m < \frac{n}{2}$. The asymptotic standard errors are derived from the result

$$\sqrt{m}(\hat{d}_{n,m} - d) \Rightarrow \mathbf{N}\left(0, \frac{\pi^2}{24}\right). \quad (4)$$

Under gaussian assumptions, the limiting distribution in Equation (4) was obtained by Robinson (1995a) in the presence of stationary data and by Velasco (1999) in the presence of nonstationary data with $\frac{1}{2} \leq d < \frac{3}{4}$. Moreover, for $\frac{1}{2} < d < 1$ the GPH estimator is known to be consistent [Velasco (1999)]. Milder conditions can be invoked for this result to be valid as shown by Kim and Phillips (1999a) and Velasco (2000) using a tapered version of the GPH estimator.

The local Whittle estimator ($\tilde{d}_{n,m}$) of Künsch (1987) and Robinson (1995b) maximizes a frequency-domain gaussian likelihood for frequencies in the neighborhood of zero, that is,

$$\log \left[\frac{1}{m} \sum_{s=1}^m \lambda_s^{2d} P(\lambda_s) \right] - 2 \frac{d}{m} \sum_{s=1}^m \log \lambda_s.$$

Robinson (1995b) derived the asymptotic behavior of this estimator:

$$\sqrt{m}(\tilde{d}_{n,m} - d) \Rightarrow \mathbf{N}\left(0, \frac{1}{4}\right).$$

Since $\frac{1}{4} < \frac{\pi^2}{24} \approx 0.4112$, the local Whittle estimator is asymptotically more efficient than the GPH estimator for the same choice of m .

Both of our d estimators require the use of a bandwidth parameter m that determines the locality of the estimates. The choice of m typically involves a standard bias/variance trade-off. Some data-dependent rules have been proposed, for example, by Hurvich and Deo (1999) and Andrews and Guggenberger (2003). However, we feel that it is necessary to explore the robustness of our

results to the choice of bandwidth. Accordingly, in the figures we document our findings for values of the bandwidth parameter m between $[\sqrt{n}]$ and $[n^{0.8}] + 1$, where $[x]$ is the integer part of x .

In Figure 1, we report the d estimates and the corresponding 95% confidence bands for the original volatility series σ_t^{BS} and σ_t^R as well as for their difference [i.e., the residuals obtained by imposing the unbiasedness hypothesis in Equation (1)] and the OLS residuals from running the regression in Equation (1). As we discuss below, there are reasons to believe that the cointegrating vector between implied and realized volatility could be different from $(1, -1)$, so the use of the differences should be seen as illustrative. Moreover, because OLS are, in general, consistent for the cointegrating vector only in the nonstationary case ($d_{\sigma^{BS}} \geq 0.5$), and because there is uncertainty as to whether the data are stationary or not (see below), the OLS results should also be seen as illustrative only. For clarity, in Table 2 we report the estimated d values and the corresponding standard errors for a few selected bandwidths.

In the presence of fractional cointegration, the long-memory parameters of the two volatility series should be equal to each other, whereas the long-memory parameter of the residuals should be less than that of the original volatility series. Figure 1 provides graphical evidence for this result in our data. As typical in fractional models, the d parameter estimates are fairly imprecise with large standard error bands [see, e.g., Baillie (1996)]. Nevertheless, these estimates are rather stable over a wide range of bandwidths and similar across volatility measures. Because both sets of residuals tend to have a lower degree of fractional integration than the volatility series, our results suggest cointegration of the fractional type. Interestingly, cointegration in the nonstationary region appears to be possible.

To sharpen our estimates of the long-memory parameter, Table 2 includes joint estimates constraining the d parameters for implied volatility and realized volatility to be the same. We use the multivariate constrained GPH estimator suggested by Robinson (1995a) and the multivariate local Whittle estimator studied by Lobato (1999). Robinson proposed two versions of the multivariate GPH estimator: one that uses OLS to compute the constrained estimator (reported in the table) and the other that uses GLS. Although the GLS estimator has an asymptotic efficiency advantage over the OLS estimator, this estimator is inconsistent under cointegration because the covariance matrix to be inverted is singular in this case. Similarly, the multivariate Whittle estimator is inconsistent under cointegration [Marinucci and Robinson (2001)]. The multivariate GPH OLS estimates tend to be between the corresponding univariate estimates for implied and realized volatility. The local Whittle estimates tend to be lower than either of the univariate estimates.

We have verified the robustness of our finding of fractional cointegration by applying the previous approach to two additional data sets that were employed in previous studies. The first data set was used in Christensen and Prabhala (1998) and consists of monthly data on the S&P 100 index and OEX options between

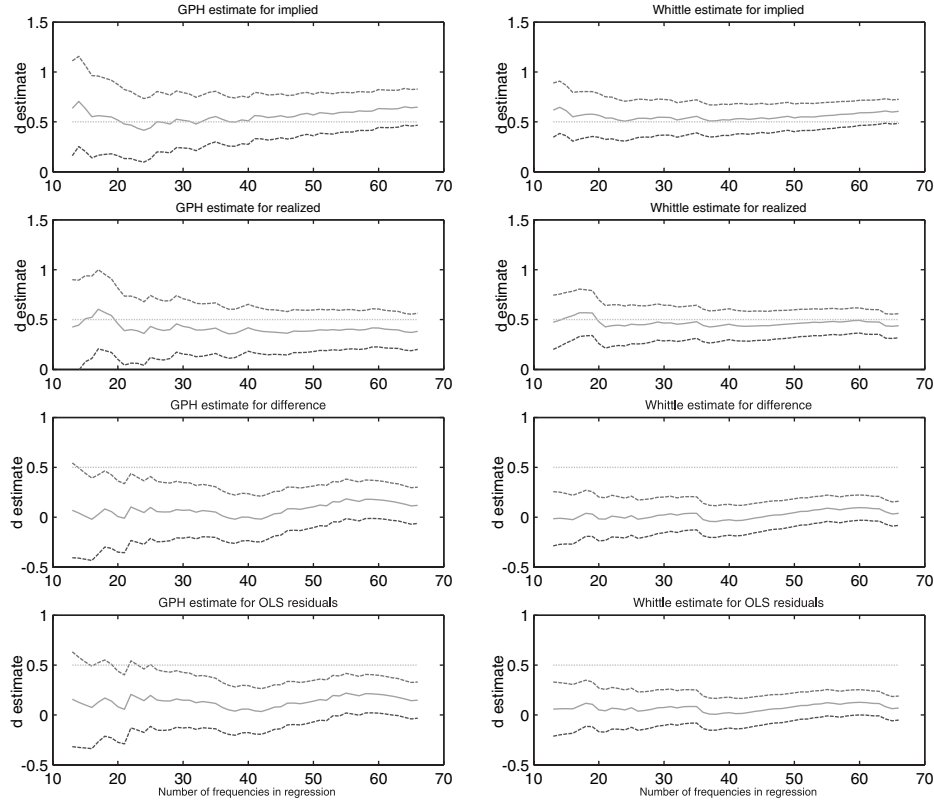


Figure 1 Geweke–Porter–Hudak (GPH) and local Whittle estimates of the long-memory parameter d as a function of the number of frequencies. We estimate d for implied volatility, realized volatility, their difference, and the OLS residuals from a regression of realized volatility on implied volatility. The confidence bands are asymptotic confidence bands. We use S&P 100 index data and the VIX.

Table 2 Estimates of d : S&P 100 index and the VIX.

m	\hat{d} (implied)		\hat{d} (realized)		\hat{d} (common)		\hat{d} (differences)	
	GPH	Whittle	GPH	Whittle	GPH	Whittle	GPH	Whittle
$[n^{0.5}] = 13$	0.636 (0.243)	0.642 (0.139)	0.425 (0.243)	0.473 (0.139)	0.530 (0.172)	0.433 (0.098)	0.070 (0.243)	-0.015 (0.139)
$[n^{0.6}] = 23$	0.437 (0.167)	0.518 (0.104)	0.388 (0.167)	0.445 (0.104)	0.412 (0.118)	0.374 (0.074)	0.074 (0.167)	0.003 (0.104)
$[n^{0.7}] = 39$	0.519 (0.122)	0.521 (0.080)	0.392 (0.122)	0.443 (0.080)	0.455 (0.086)	0.370 (0.057)	0.001 (0.122)	-0.032 (0.080)

The table reports long-memory parameter estimates for implied volatility σ^{BS} and realized volatility σ^R using the Geweke–Porter–Hudak (GPH) estimator and the local Whittle estimator. The number of Fourier frequencies used is equal to the integer part of $n^{0.5}$, $n^{0.6}$, and $n^{0.7}$. We also report estimates based on joint estimation using the multivariate constrained GPH estimator suggested by Robinson (1995a) and the multivariate local Whittle estimator suggested by Lobato (1999). The last two columns report long-memory parameter estimates for the differences $\sigma^R - \sigma^{BS}$. Asymptotic standard errors are in parentheses.

January 1988 and May 1995 for a total of 89 nonoverlapping observations. The data are obtained by examining at-the-money call options with a month to expiration sampled right after the previous expiration date. The second data set consists of monthly data on options on DM futures from the Chicago Mercantile Exchange (CME). The time frame is January 1990 to November 1998 for a total of 107 nonoverlapping observations. Similar data are used in Jorion (1995), but the sample there covers the January 1985 to February 1992 period. This market moved from quarterly option expiration dates to monthly expiration dates in 1987. We work with data from 1990 to avoid any potential adjustment/learning effects that this change might have caused. Jorion (1995) discussed the advantages of CME options on foreign currency features over the OEX options. Specifically, empirical work based on the former is expected to be less contaminated by measurement errors since option and underlying trade side by side. The results are presented in Figures 2 and 3 and Tables 3 and 4.

Our finding of fractional cointegration appears to be a stylized fact. As a final robustness check (not reported here for brevity, but available from the authors on request), we have considered two additional transformations of the data that have been implemented in previous research—namely, variances and logarithmic volatilities. Our original formulation, that is, standard deviations, is used in Canina and Figlewski (1993), Jorion (1995), Fleming (1998), Christensen and Prabhala (1998), and Potesman (2000), among others. Day and Lewis (1992, 1993), Lamoureux and Lastrapes (1993), and Chernov (2006), among others, use variances. Logarithmic transformations are used in Christensen and Prabhala (1998) and Christensen and Nielsen (2006), among others. The conclusions we draw are consistent with our previous findings.

Having documented fractional cointegration in our data (a fact that necessarily changes our understanding and interpretation of the classical implied/

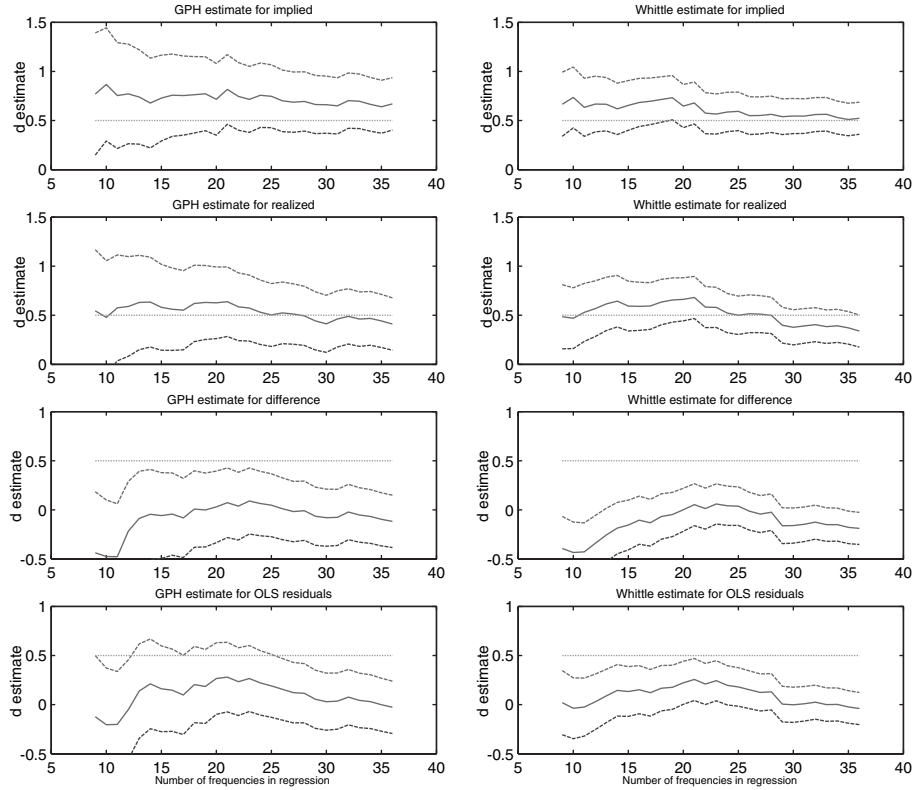


Figure 2 Geweke–Porter–Hudak (GPH) and local Whittle estimates of the long-memory parameter d as a function of the number of frequencies. We estimate d for implied volatility, realized volatility, their difference, and the OLS residuals from a regression of realized volatility on implied volatility. The confidence bands are asymptotic confidence bands. We use S&P 100 index data and S&P 100 option data.

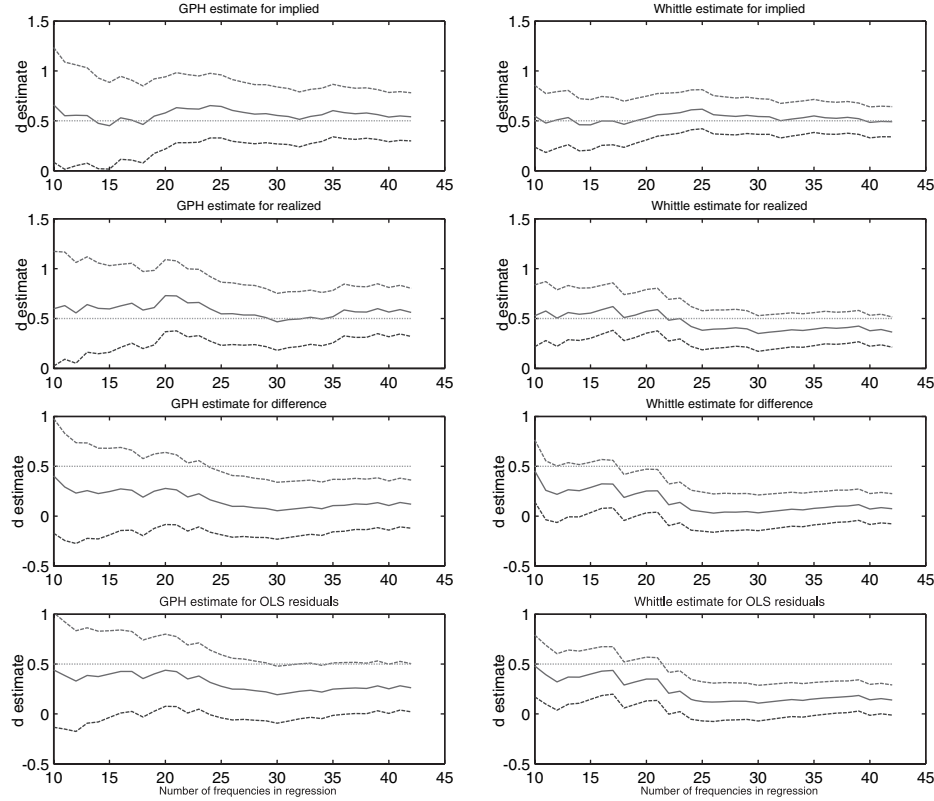


Figure 3 Geweke–Porter–Hudak (GPH) and local Whittle estimates of the long-memory parameter d as a function of the number of frequencies. We estimate d for implied volatility, realized volatility, their difference, and the OLS residuals from a regression of realized volatility on implied volatility. The confidence bands are asymptotic confidence bands. We use DM futures data and data on DM futures options.

Table 3 Estimates of d : S&P 100 index and S&P 100 options.

m	\hat{d} (implied)		\hat{d} (realized)		\hat{d} (common)		\hat{d} (differences)	
	GPH	Whittle	GPH	Whittle	GPH	Whittle	GPH	Whittle
$[n^{0.5}] = 9$	0.770 (0.318)	0.666 (0.167)	0.545 (0.318)	0.485 (0.167)	0.657 (0.225)	0.349 (0.118)	-0.437 (0.318)	-0.393 (0.167)
$[n^{0.6}] = 14$	0.678 (0.233)	0.619 (0.134)	0.634 (0.233)	0.644 (0.134)	0.656 (0.165)	0.461 (0.095)	-0.045 (0.233)	-0.185 (0.134)
$[n^{0.7}] = 23$	0.715 (0.171)	0.566 (0.104)	0.573 (0.171)	0.580 (0.104)	0.644 (0.121)	0.475 (0.074)	0.090 (0.171)	0.061 (0.104)

See Table 2.

Table 4 Estimates of d : DM futures and options on DM futures.

m	\hat{d} (implied)		\hat{d} (realized)		\hat{d} (common)		\hat{d} (differences)	
	GPH	Whittle	GPH	Whittle	GPH	Whittle	GPH	Whittle
$[n^{0.5}] = 10$	0.660 (0.293)	0.546 (0.158)	0.598 (0.293)	0.527 (0.158)	0.629 (0.207)	0.517 (0.112)	0.404 (0.293)	0.455 (0.158)
$[n^{0.6}] = 16$	0.530 (0.213)	0.499 (0.125)	0.627 (0.213)	0.589 (0.125)	0.579 (0.150)	0.446 (0.088)	0.273 (0.213)	0.324 (0.125)
$[n^{0.7}] = 26$	0.604 (0.158)	0.561 (0.098)	0.549 (0.158)	0.394 (0.098)	0.576 (0.111)	0.360 (0.069)	0.098 (0.158)	0.031 (0.098)

See Table 2.

realized volatility predictive regression), we now turn to an econometric model that accounts for fractional cointegration while providing a solution to the issues that the existing literature has indicated as crucially affecting standard OLS inference in the implied/realized volatility predictive regression.

2 ECONOMETRIC FRAMEWORK

Two main econometric issues have been discussed in the literature on the predictive power of implied volatility, namely, the presence of an unobserved volatility risk premium and measurement error in implied volatility.

We start with the former. Much recent work has emphasized the importance of explicitly allowing for a time-varying volatility risk premium in option pricing [see, e.g., Benzoni (1998) and Pan (2002)] and in the context of the implied/realized volatility regression [see, e.g., Poteshman (2000) and Chernov (2006)]. The regression then becomes

$$\sigma_t^R = \alpha^* + \beta^* \sigma_t^{BS} + \gamma^* RP_t + e_t, \quad (5)$$

where RP_t denotes a time-varying volatility risk premium. To explicitly account for a risk premium, the existing work relies on tight parametrizations for it. Unfortunately, simple no-arbitrage principles do not provide us with an expression for the risk premium. If volatility is not a traded asset, markets are incomplete and an infinite number of martingale measures are compatible with the absence of arbitrage. Only a fully specified equilibrium model could shed some light on the features of the volatility premium [see, e.g., Pham and Touzi (1996)].

From an econometric standpoint, any parametric assumption about the risk premium is, therefore, arbitrary and potentially misleading. In what follows we account for a risk premium but treat it as unobservable. Exploiting fractional cointegration, and using NBLS, we are able to estimate the (long-run) relation between implied and realized volatility consistently even when a risk premium correlated with implied volatility plays a role. As we explain below, we do so without having to proxy for the risk premium. In this context, OLS would only estimate the projection of realized volatility on implied volatility. It would not estimate consistently the realized/implied volatility cointegrating vector.

Moreover, measurement error in implied volatility could arise from the nonsynchronous measurement of options and index levels as well as bid–ask spreads in option and underlying prices [see the discussion in Christensen and Prabhala (1998)]. Similar to the presence of an unobserved (and unaccounted for) risk premium correlated with implied volatility, measurement error in implied volatility induces inconsistent OLS estimates of the cointegrating vector. NBLS provide consistent estimates of this vector.

With these observations in mind, we now turn to the estimated model. Denote by E the unconditional expectation and define

$$y_t = \sigma_t^R, \quad (6)$$

$$x_t = \sigma_t^{BS} + u_t^{BS}, \quad (7)$$

$$\delta_t = \gamma^* \{RP_t - E(RP_t)\}, \quad (8)$$

$$\alpha = \alpha^* + \gamma^* E(RP_t), \quad (9)$$

$$\beta = \beta^*, \quad (10)$$

where y_t and x_t are the observable volatility series and the shock u_t^{BS} denotes measurement error in implied volatility. Measurement error in realized volatility, as in Poteshman (2000) and Chernov (2006), can also be easily accommodated without any effects on our results. Equation (5) then leads to the regression

$$y_t = \alpha + \beta(x_t - u_t^{BS}) + \delta_t + e_t, \quad (11)$$

or

$$y_t = \alpha + \beta x_t + \varepsilon_t \quad (12)$$

with $\varepsilon_t = -\beta u_t^{BS} + \delta_t + e_t$. Consistent with the empirical evidence in Section 1, we model x_t and ε_t as linear processes with spectra satisfying

$$f_x(\lambda) \approx \lambda^{-2d_x} \quad \text{as } \lambda \rightarrow 0^+, \quad (13)$$

$$f_\varepsilon(\lambda) \approx \lambda^{-2d_\varepsilon} \quad \text{as } \lambda \rightarrow 0^+, \quad (14)$$

respectively. We recognize the fractional cointegration between y_t and x_t by assuming that the parameters d_x and d_ε satisfy $d_x > d_\varepsilon$. In light of our discussion of the data in Section 1, the fractional parameter d_x can be either in the stationary region ($d_x < \frac{1}{2}$) or in the nonstationary region ($d_x \geq \frac{1}{2}$).

Two observations are important. First, the residuals ε_t can be long-range dependent. Even if the measurement error u_t^{BS} were short-range dependent, the long memory of the residuals may be induced by the quantity δ_t (which is a linear function of the de-measured volatility risk premium). Second, we allow for potential correlation between δ_t and the implied volatility proxy x_t and, as a consequence, between ε_t and x_t . Both properties are important because spot volatility has been documented to be long-range dependent [see, e.g., Bollerslev and Mikkelsen (1996)]. If the unobserved risk premium depends on the underlying spot volatility as often assumed, then the risk premium possesses long memory in general, and correlation between the implied volatility proxy (the regressor) and the regression residuals containing the risk premium follows immediately.

2.1 The NBLS Estimates

We now turn to the details of the econometric procedure. Equation (12) implies

$$y_t - \bar{y} = \beta(x_t - \bar{x}) + (\varepsilon_t - \bar{\varepsilon}), \quad (15)$$

where $\bar{a} = (\sum_{t=1}^n a_t)/n$ for a generic time series $\{a_t : t = 1, \dots, n\}$. We define the discrete Fourier transforms

$$\varpi_y(\lambda_s) := \frac{1}{\sqrt{2\pi n}} \sum_{t=1}^n y_t e^{it\lambda_s} = \frac{1}{\sqrt{2\pi n}} \sum_{t=1}^n (y_t - \bar{y}) e^{it\lambda_s}, \quad (16)$$

$$\varpi_x(\lambda_s) := \frac{1}{\sqrt{2\pi n}} \sum_{t=1}^n x_t e^{it\lambda_s} = \frac{1}{\sqrt{2\pi n}} \sum_{t=1}^n (x_t - \bar{x}) e^{it\lambda_s}, \quad (17)$$

$$\varpi_e(\lambda_s) := \frac{1}{\sqrt{2\pi n}} \sum_{t=1}^n e_t e^{it\lambda_s} = \frac{1}{\sqrt{2\pi n}} \sum_{t=1}^n (e_t - \bar{e}) e^{it\lambda_s}, \quad (18)$$

at the harmonic (Fourier) frequencies $\lambda_s = \frac{2\pi s}{n}$, where $s = 0, 1, \dots, n-1$. The (cross-)periodogram between y and x , say, is given by

$$P_{xy}(\lambda_s) = \varpi_y(\lambda_s) \overline{\varpi_x(\lambda_s)}, \quad (19)$$

where $\overline{\varpi_x(\lambda_s)}$ is the complex conjugate of $\varpi_x(\lambda_s)$. The NBLS estimator of β is defined as

$$\hat{\beta}_{n,m} = \frac{\operatorname{Re}(\hat{F}_{xy}(1, m))}{\hat{F}_{xx}(1, m)} = \frac{\operatorname{Re}(\hat{F}_{xy}(0, m)) - \bar{x}\bar{y}}{\hat{F}_{xx}(0, m) - \bar{x}^2}, \quad (20)$$

where

$$\hat{F}_{xy}(l, m) = \frac{2\pi}{n} \sum_{s=l}^m P_{xy}(\lambda_s) \quad l = 1, 0 \quad (21)$$

with $m < \frac{n}{2}$. In other words, NBLS can be interpreted as OLS in the frequency domain over the first m frequencies. We will assume that $m \rightarrow \infty$ as the sample size n diverges to infinity and $\frac{m}{n} \rightarrow 0$, so that we estimate over a degenerating window of frequencies. The parameter α is identified by

$$\hat{\alpha}_{n,m} = \bar{y} - \hat{\beta}_{n,m} \bar{x}. \quad (22)$$

Some remarks are in order. We start with the stationary case ($d_x < \frac{1}{2}$). If regressand and regressor are linked by a cointegrating relation, NBLS are consistent for this relation [Robinson (1994a)]. In the presence of correlation between the regressor and the residuals, OLS are not. In our framework, correlation between the regressor and the regression errors is induced by the correlation between x_t (proxy for implied volatility), the quantity δ_t (which contains the de-measured volatility risk premium), and measurement error. If the risk premium is of lower order of integration than implied volatility (below we come back to this assumption), then its spectrum is dominated by that of implied volatility near the zero frequency. Performing least squares over a degenerating band of frequencies in the neighborhood of the origin exploits this property, thereby yielding

consistent estimates. This intuition is formalized in the following proposition whose proof follows from that of Robinson (1994a) and is therefore omitted.

Proposition Consider the predictive model for realized volatility y_t given an implied volatility proxy x_t

$$y_t = \alpha + \beta x_t + \varepsilon_t \quad (23)$$

with $\varepsilon_t = -\beta u_t^{BS} + \delta_t + e_t$, where u_t^{BS} is a measurement error in implied volatility as in Equation (7), e_t is a forecast error, and δ_t is a linear function of the de-measured time-varying volatility risk premium as in Equation (8). Assume δ_t is correlated with x_t . Also, assume the spectra of x_t and ε_t satisfy

$$f_x(\lambda) \approx \lambda^{-2d_x} \quad \text{as } \lambda \rightarrow 0^+, \quad (24)$$

$$f_\varepsilon(\lambda) \approx \lambda^{-2d_\varepsilon} \quad \text{as } \lambda \rightarrow 0^+, \quad (25)$$

respectively, and $d_x > d_\varepsilon$ with $0 \leq d_x, d_\varepsilon < \frac{1}{2}$. Then, the NBLS estimates defined in Equations (20) and (22) are consistent in probability if $1/m + m/n \rightarrow 0$ as $n \rightarrow \infty$.

We now turn to the nonstationary case ($d_x \geq \frac{1}{2}$). Typically, in cointegrating relations of the I(1)/I(0) type OLS are consistent even in the presence of regression residuals that are correlated with the regressor because endogeneity only requires second-order adjustments to the asymptotic distribution of the OLS parameter estimates [Park and Phillips (1988)]. The same result trivially emerges from fractionally cointegrating regressions of the type analyzed here as shown by Kim and Phillips (1999b) and Robinson and Marinucci (2001, 2003), among others. Nevertheless, NBLS methods may entail faster rates of convergence than OLS in some cases [Robinson and Marinucci (2001, 2003)], thereby providing justification for their use even in situations where more conventional tools could be employed.

To assess the statistical significance of the regression estimates, we rely on subsampling [see Politis, Romano, and Wolf (1999) for a thorough discussion]. We prefer subsampling over the usual bootstrap because of its wider applicability. The only requirements for its validity are the existence of a limiting distribution and conditions limiting the dependence of either the data or the subsampled statistics. For example, subsampling is applicable to the case of an autoregression with a unit root, whereas the standard bootstrap is not. Another advantage of subsampling over the bootstrap is that the rate of convergence to the asymptotic distribution does not have to be known and can be estimated [see, e.g., Bertail, Politis, and Romano (1999)]. This property is particularly attractive given that there is uncertainty as to whether we are in the stationary range or not and the convergence rates depend on the long-memory parameters of both the regressor and the residuals. Moreover, it is likely that the rates of convergence of the constant and slope estimators are different. Our subsampling approach can

estimate these different rates consistently. Politis, Romano, and Wolf (1999) used long memory and the different rates of convergence of the sample mean in the stationary and nonstationary case as a motivating example for the need to estimate convergence rates (see their Example 8.1.3).

In our framework, the conditions of Theorems 8.2.2 (consistent estimation of the unknown convergence rate) and 8.3.1 (validity of subsampling with a consistently estimated convergence rate) of Politis, Romano, and Wolf (1999) are satisfied under some very standard asymptotic requirements. First, if the parameter of interest is ϑ , then $n^\delta(\hat{\vartheta} - \vartheta_0)$ must have a limiting cumulative distribution function that is continuous and strictly increasing for some $\delta > 0$. Virtually all known theoretical results currently available for NBLS take this form, whether the data are stationary or not, as long as the bandwidth is selected to be a fractional power of the sample size. Second, the size b of the subsamples must grow to infinity with the ratio b/n vanishing as the sample size diverges to infinity. This is accomplished by taking subsamples of size $b = \lfloor n^\beta \rfloor$ [see Politis and Romano (1994) and Bertail, Politis, and Romano (1999) for a similar choice], and resampling the couple (y_t, x_t) to preserve the correlation between the regressor and the residuals. We compute statistics on all $n - b + 1$ subsamples of b successive observations and choose m_b , the number of Fourier frequencies to compute the NBLS estimator for each subsample, to be the same fraction of the sample size as in the original data, namely, $\frac{m_b}{b} = \frac{m}{n}$. Under these conditions, we can obtain asymptotically valid confidence intervals without imposing either stationarity or nonstationarity. In the next section, we illustrate the finite sample performance of our subsampling procedure through simulations.

In recent work, Christensen and Nielsen (2006) have provided an important theoretical contribution, namely the asymptotic distribution of the NBLS estimator in the stationary fractionally cointegrated case. Christensen and Nielsen's findings complement the weak convergence results that Robinson and Marinucci (2001) have derived in the nonstationary fractionally cointegrated situation. For completeness, along with subsampling bands, in our empirical work we report both Christensen and Nielsen's confidence bands (when applicable in the stationary case) and Robinson and Marinucci's confidence bands in the nonstationary case.

2.2 Interpretation of the Slope Estimates

Our interest is in estimating the long-run relation between implied and realized volatility over the option's life. We will estimate β and test whether $\beta = 1$, but we will not give our β estimates a structural interpretation.

There are two reasons why the true coefficient could be different from one. The first reason has a statistical flavor stemming from our cointegrating framework. The second reason has a superior economic appeal and would be valid even in more conventional settings with short-range dependence [see, e.g., Renault (2001)].

We start with the first explanation. The above proposition assumes that the risk premium is of lower order of integration than implied volatility. However, it is possible for the risk premium to be of the same order of integration as implied volatility and cointegrated with it. Assume realized volatility is cointegrated with implied volatility and the risk premium [with a cointegrating vector equal to $(1, -1, -\gamma^*)$, say], and the risk premium is cointegrated with implied volatility [with a cointegrating vector equal to $(1, -\theta)$, say], then the true cointegrating vector between realized and implied volatility would not be $(1, -1)$ but $(1, -(1 + \gamma^*\theta))$. A risk premium that is a linear function of the unobservable spot volatility as in Heston's model [Heston (1993)] would deliver this result. In this case, $\hat{\alpha}_{n,m}$ and $\hat{\beta}_{n,m}$ would nevertheless be consistent estimates of the parameters of the true long-run relation between implied and realized volatility. However, $\hat{\beta}_{n,m}$ would be a consistent estimate of $(1 + \gamma^*\theta)$. Admittedly, $(1 + \gamma^*\theta)$ can be smaller or larger than 1 depending on γ^* and the features of the cointegrating vector between implied volatility and the risk premium, as summarized by the coefficient θ .

In sum, our treatment of the risk premium as unobservable leads to two relevant cases: either the risk premium is part of the regression residuals (and does not matter asymptotically) or it is cointegrated with implied volatility and affects the cointegrating vector. Either way, our methods lead to consistent estimates of the true long-run relation between implied and realized volatility series.

We now turn to the second explanation for a cointegrating slope different from one, namely, the existence of a nonzero correlation between innovations to the underlying's returns and innovations to the underlying's spot volatility process (leverage effects). In the context of a continuous-time model for the underlying with long-memory stochastic spot volatility and leverage ρ , Comte, Coutin, and Renault (2003), CCR henceforth, obtained

$$\sigma_t^{BS} \approx \left(\sqrt{(1 - \rho^2)} \right) \mathbf{E}_t(\sigma_t^R) + RP_t. \quad (26)$$

If $\rho \neq 0$, as documented by a substantial amount of recent evidence, CCR's approximation implies that the cointegrating slope should be larger than one and equal to $\frac{1}{\sqrt{(1 - \rho^2)}}$. Chernov (2006) has recently emphasized that this approximation might be less accurate than the approximation relying on $\beta = 1$. These contributions suggest that the cointegrating slope is likely to be somewhere in the interval $\left[1, \frac{1}{\sqrt{(1 - \rho^2)}} \right]$, which is consistent with our simulation results reported below.

Of course, both effects could occur at the same time, thereby leading to further complications that cannot be addressed unless one is willing to impose more structure on the problem. In this article, we do not take a stand on the

correct β value. *Regardless of the true value of β* , the interpretation of our regression as an evaluation of the long-run comovement between volatility series remains intact. In other words, long-run unbiasedness can readily be tested.

3 SIMULATIONS

This section evaluates the performance of our econometric approach through simulations. Specifically, we are interested in analyzing the impact of long memory on the predictive regression between implied and realized volatility, the behavior of our proposed NBLS estimator versus OLS, and the performance of our subsampling inference.

We simulate a continuous-time process for the underlying's returns with square-root long-memory stochastic volatility and leverage as in CCR (2003). Using this process, we price a European call option, compute the Black-Scholes implied volatility, and relate implied volatility to the realized volatility of the underlying. The simulated model under the risk neutral measure is given by

$$\frac{dS_t}{S_t} = rdt + \sqrt{V_t}dW_t^1, \quad (27)$$

$$V_t = \tilde{v} + In^{(d)}(\tilde{V}_t - \tilde{v}), \quad (28)$$

with

$$d\tilde{V}_t = k(\tilde{v} - \tilde{V}_t)dt + \sigma\sqrt{\tilde{V}_t}(\rho dW_t^1 + \sqrt{1 - \rho^2}dW_t^2), \quad (29)$$

where $\{W_t^1, W_t^2 : t \geq 0\}$ is a standard Wiener process on the plane and $In^{(d)}$ is a fractional integration operator used to convert the short-memory spot volatility process \tilde{V}_t into a long-memory process V_t with order of fractional integration d [see CCR (2003) for details]. As shown by CCR both realized volatility and implied volatility display long memory if spot volatility does. Moreover, realized and implied volatility are cointegrated in that case. Hence, CCR's theoretical framework is consistent with our empirical results.

We use the discretized version of the model provided by CCR (2003), with an increment Δ of 2 hours (1/12 of a day), to generate sample paths of the underlying price process. We normalize the logarithmic stock price to be 0 at time 0. We then use the series expansion in Lewis (2000) to compute a sample of 191 implied volatilities given the generated paths of spot volatilities and stock prices. Realized volatility is computed by summing the squares of the daily continuously compounded returns over the life of the option, namely, 22 squared returns corresponding to every 12th simulated value of the logarithmic price process. We replicate this procedure 1,000 times.

The parameter values are set at those estimated by Ohanissian, Russell, and Tsay (2004) using S&P 500 index data, that is, $r = 0.03$, $\bar{v} = 0.037$, $k = 2.16$, $\sigma = 0.45$, $\rho = -0.48$, and $d = 0.34$. Finally, to introduce a likely source of correlation between implied volatility and the regression residuals, we run an experiment in which we add measurement error to the implied volatility series. Because our goal is to verify the properties of NBLS in the presence of correlation between implied volatility and the residuals, adding a measurement error to implied volatility achieves this goal. The measurement error is independent over time and is normally distributed with zero mean and variance equal to the variance of the 191 implied volatility realizations over the corresponding replication.

We can easily relate the assumed measurement error in implied volatility to well-known market frictions, such as bid–ask spreads in option prices and bid–ask spreads in the underlying price, and provide back-of-the-envelope calculations. Given the parameters of the model, the implied volatility mean is 0.1846 in annual terms and its variance is 0.0013. Thus, neglecting nonlinear effects, our measurement error has, on average, a variance of 0.0013. If implied volatility can take only two values with equal probabilities, namely, $0.1846 + c$ and $0.1846 - c$, then we need $c = \sqrt{0.0013} = 0.036$ to replicate this type of measurement error. Hence, in this stylized setup, implied volatility must bounce between 0.1485 and 0.2206. This effect can be accomplished by perturbing any observable variable in the Black–Scholes formula, but we concentrate on the option price and on the price of the underlying. The Black–Scholes price of an at-the-money call option with a month to maturity and a volatility of 18.46% per year with an underlying price of 1 is 0.02306. If implied volatility were 22.06% (14.85%), the option price would be 0.0273 (0.0188). Thus, we need an option bid–ask spread of 0.0085, or about 37% of the Black–Scholes price, to rationalize our measurement error. Figlewski (1997) considered option's bid–ask bounces of up to 25% of the option price. Alternatively, if we keep the strike price constant, we need the underlying to bounce between 1.0075 and 0.9916, a total spread of about 1.6% of the stock price, for implied volatility to have a variance of 0.0013. Figlewski (1997) considered underlying bid–ask bounces of up to 2% of the stock price. Our assumed measurement error is purposely large. Our explorations suggest that the relation between size of the measurement error and contaminations in the regression estimates is monotonic. Hence, for brevity, we only report results for the large noise case and the no noise case.

For each replication, we estimate the d parameter for both volatility proxies. In Table 5 we report results of the estimation of the degree of long memory using both the GPH and the Whittle estimator. We now consider three bandwidths corresponding to $n^{0.5}$, $n^{0.6}$, and $n^{0.7}$ with $n = 191$.

In agreement with the existing literature [see, e.g., Andrews and Guggenberger (2003)], we find that the d estimates are consistently upward biased in a finite sample. Furthermore, without measurement error, both the GPH and the Whittle estimator deliver point estimates for the fractional d

parameter that are higher for implied than for realized volatility. Finally, as suggested by theory, the Whittle estimator is more precise than the GPH estimator. The addition of measurement error reduces the upward bias of the d estimates.

For each replication, we also run a linear regression of realized volatility on a constant and the implied volatility proxy. This regression is estimated by OLS and NBLS with six choices of bandwidth corresponding to powers of the sample size ranging from $n^{0.25}$ to $n^{0.8}$. With our sample size of 191 observations (for the VIX data), these choices amount to including 3, 8, 13, 23, 39, and 66 Fourier frequencies in the relevant regression. We recall that OLS employ all 95 Fourier frequencies.

Table 6 contains the means of the quantities of interest (intercept and slope) across the replications as well as the standard deviations (in parentheses, underneath). The left panel of the table reports results without measurement error, whereas the right panel provides the same information after adding measurement error to implied volatility. The first column of each panel refers to the estimation of the intercept α , whereas the second column refers to the estimation of the slope β . As expected, in the absence of correlation between regressor and residuals (without measurement error), OLS provide good results, with a mean estimated slope of about 1.06. NBLS deliver a slightly higher mean slope of about 1.08 when using the three smallest bandwidth choices. The addition of measurement error induces a very strong negative relation between mean estimates and the number of frequencies as it introduces correlation between regressor and residuals. In this case, OLS provide very downward-biased estimates of the cointegrating slope in that this slope is estimated to be only 0.53. NBLS

Table 5 Simulation results—long-memory parameter.

m	\hat{d} (implied)				\hat{d} (common)					
	without error		with error		\hat{d} (realized)		without error		with error	
	GPH	Whittle	GPH	Whittle	GPH	Whittle	GPH	Whittle	GPH	Whittle
$[n^{0.5}]$	0.685 (0.266)	0.671 (0.232)	0.566 (0.235)	0.540 (0.201)	0.609 (0.258)	0.594 (0.225)	0.647 (0.250)	0.375 (0.175)	0.656 (0.268)	0.350 (0.170)
$[n^{0.6}]$	0.838 (0.194)	0.842 (0.173)	0.562 (0.145)	0.544 (0.110)	0.642 (0.179)	0.632 (0.146)	0.740 (0.173)	0.494 (0.135)	0.748 (0.177)	0.415 (0.114)
$[n^{0.7}]$	0.965 (0.146)	0.976 (0.132)	0.504 (0.096)	0.482 (0.068)	0.598 (0.130)	0.578 (0.103)	0.782 (0.123)	0.612 (0.112)	0.786 (0.123)	0.430 (0.076)

The table reports long-memory parameter estimates for implied volatility and realized volatility using the Geweke–Porter–Hudak (GPH) estimator and the local Whittle estimator. The number of Fourier frequencies used is equal to the integer part of $n^{0.5}$, $n^{0.6}$, and $n^{0.7}$. We also report estimates based on joint estimation using the multivariate constrained GPH estimator suggested by Robinson (1995a) and the multivariate local Whittle estimator suggested by Lobato (1999). The table contains the means of the estimates across simulations (with standard deviations in parentheses). The true parameter is $d = 0.34$.

Table 6 Simulation results—cointegration relation.

		Without error		With error	
		α	β	α	β
OLS		−0.011 (0.014)	1.059 (0.077)	0.087 (0.017)	0.531 (0.057)
NBLS	$m = [n^{0.25}] = 3$	−0.015 (0.019) [66.1]	1.082 (0.104) [64.7] {35.1–90.3}	−0.006 (0.027) [77.2]	1.033 (0.144) [74.6] {32.7–58.7}
	$m = [n^{0.4}] = 8$	−0.014 (0.015) [67.0]	1.079 (0.084) [66.7] {51.7–91.1}	0.003 (0.020) [89.9]	0.988 (0.108) [89.4] {37.7–61.5}
	$m = [n^{0.5}] = 13$	−0.014 (0.015) [67.9]	1.077 (0.081) [66.4] {48.2–91.7}	0.011 (0.018) [91.9]	0.944 (0.098) [93.1] {36.9–65.6}
	$m = [n^{0.6}] = 23$	−0.013 (0.014) [63.3]	1.073 (0.079) [61.9] {53.2–92.1}	0.026 (0.017) [79.0]	0.862 (0.085) [81.0] {24.6–77.6}
	$m = [n^{0.7}] = 39$	−0.013 (0.014) [60.0]	1.069 (0.078) [59.9] {55.6–91.9}	0.045 (0.016) [47.9]	0.757 (0.076) [52.0] {4.4–88.6}
	$m = [n^{0.8}] = 66$	−0.012 (0.014) [59.6]	1.064 (0.078) [60.1] {58.7–92.5}	0.069 (0.016) [12.5]	0.627 (0.065) [13.9] {0.0–94.3}

The table reports simulation results from a linear regression of realized volatility on implied volatility. We estimate the model by OLS and NBLS with a number of Fourier frequencies equal to the integer part of $n^{0.25}$, $n^{0.4}$, $n^{0.5}$, $n^{0.6}$, $n^{0.7}$, and $n^{0.8}$. We report the means of the estimates across simulations (with standard deviations in parentheses). We also report the frequency that a 95% confidence interval computed using subsampling (in square brackets) and Christensen and Nielsen’s asymptotic theory (in braces) includes 1.14. Christensen and Nielsen’s asymptotic theory is only available for the slope parameter. To implement Christensen and Nielsen’s asymptotic theory, we estimate the long-memory d_x and d_c parameters with GPH and a bandwidth of $[n^{0.7}]$. The second number in braces is the percentage of replications for which Christensen and Nielsen’s variance could not be computed because the condition $\hat{d}_x + \hat{d}_c < 1/2$, which is necessary to obtain a positive asymptotic variance in Christensen and Nielsen’s framework, was violated. Christensen and Nielsen’s coverage rates are obtained by excluding those replications.

remove most of the bias with an estimated slope above 1.03 for the smallest bandwidth choice. The obvious downward trend to the estimates of β (as a function of the number of Fourier frequencies) should be imputed to the accumulation of short-run correlation. To put things in perspective, given our adopted parameter values, we recall that the slope coefficient implied by CCR’s approximate relation is $\frac{1}{\sqrt{1-\rho^2}} \approx 1.14$. The slope coefficient given by Chernov’s approximate relation is 1. As stressed in Section 2.2, it is believable that the true β value should lie somewhere between 1 and 1.14.

Below the standard deviation of the estimates, we report the frequency that our subsampling confidence intervals (in square brackets) and Christensen and Nielsen's confidence intervals (in braces) include CCR's theoretical value of 1.14 (we also report the frequency that our subsampling confidence intervals for the intercept contain the value of 0 but no asymptotic intervals are available in this case). The results for the Christensen and Nielsen intervals are obtained by using a bandwidth of $[n^{0.7}]$ when computing the values of d for the regressor and the residuals. There are two numbers in braces. The first number is the percentage of replications where the resulting interval includes 1.14 (among the replications where these intervals can be computed). The second number is the percentage of replications for which the variance of the estimator could not be computed because the condition $\hat{d}_x + \hat{d}_e < 1/2$, which is necessary to obtain a positive asymptotic variance in Christensen and Nielsen's framework, was violated. This phenomenon was quite frequent because of the upward bias (reported above) in the estimation of d . We eliminated these replications when computing coverage rates. Overall, the intervals have lower coverage than their nominal level of 95%. The coverage rate of the subsampling intervals is generally higher than the one of Christensen and Nielsen's intervals. Importantly, the subsampling intervals are less affected by the presence of measurement error, and intervals are also available for the constant, with comparable coverage rates.

To shed light on all of the issues raised by the option pricing simulations, in the Appendix, we report results from a different simulation experiment. To have complete control over the slope coefficient without invoking approximations, we consider a simple regression framework between two fractionally cointegrated variables with a common order of integration equal to 0.34. There are three main findings.

First, the presence of strong serial correlation in the underlying noise of the regressor (before integrating to fractional order) induces a large upward bias in the estimation of the regressor's d . Some experimentation suggests that this strong bias disappears slowly with an increasing sample size. This phenomenon might explain the larger d estimates obtained in this article relative to the estimates reported in the realized volatility literature (which uses high-frequency data and much larger sample sizes). Similarly, our option-based simulation in this section has strong serial correlation in the underlying noise (the square-root process for \tilde{V}_t). This finding explains the upward bias of the reported implied volatility d estimates in this section.

Second, the regressand has smaller d estimates than those of the regressor. Because the regressand (realized volatility in our application) is a linear combination of the regressor (implied volatility in our framework) and residuals, this result is due to measurement error in the regressand. The residual component drives the realized volatility d estimates downward with respect to the implied volatility d estimates in the no measurement error case.

Third, and importantly for our purposes, there is little effect of the serial correlation in the regressor's noise on either the regression point estimates or the

coverage rates of the confidence intervals. Because in these simulations we control the slope coefficient, we feel comfortable extending these findings to the option pricing context. As pointed out earlier, we think that the true slope should be between 1 and 1.14 with 1.08 (approximately our NBLS estimate in the no measurement error case) being a very likely candidate. This result is interesting and confirms that, with all probability, both CCR's and Chernov's approximations could be improved upon in that the true slope should lie somewhere between 1 and $\frac{1}{\sqrt{(1-\rho^2)}}$. Incidentally, the use of 1.08 as the right slope value would lead to much higher coverage rates than those reported in Table 6.

4 THE ESTIMATED RELATION BETWEEN IMPLIED AND REALIZED VOLATILITY

We now turn to the estimation of the model. NBLS estimation of the predictive regression model in Equation (12) is presented in Figure 4 as a function of the number of Fourier frequencies included in the spectral regression. We also report the results for a few selected bandwidths in Tables 7–9.

The first row of Figure 4 corresponds to the results for the S&P 100 index and VIX data. As in Section 1, we investigate the robustness of our findings by estimating the model in Equation (12) in the presence of two additional sets of data. The second row corresponds to the results for the S&P 100 index and S&P 100 options. The last row corresponds to the results for the DM futures options. Tables 8 and 9 are the relevant tables in these cases. Note that the last point on each graph (the point that includes all the Fourier frequencies) refers to the OLS estimate. The left panels contain results for the intercept α , whereas the right panels provide results for the slope coefficient β . We also report 95% confidence bands for both sets of parameters based on the subsampling algorithm described in Section 2. Finally, a horizontal line indicates the location of 0 for the intercept and 1 for the slope for the ease of interpretation.

We first discuss the S&P 100–VIX case. As expected, there is a slight downward trend to the slope coefficients (such a trend is more evident when analyzing the other two data sets). As the number of frequencies in the regression increases, a greater proportion of the high-frequency correlation between the residuals and the observed implied volatility series is included in the regression, leading to an increased bias of the slope estimates. Nevertheless, the confidence intervals for the slope coefficients include 1 for all choices of frequencies suggesting long-run unbiasedness. As far as the intercept estimates are concerned, their values might point to the existence of a slight (average) long-run compensation for volatility risk.

In addition to the information contained in Figure 4, Table 7 reports alternative confidence intervals. It includes confidence intervals for a different choice of subsample size ($[n^{3/4}]$) as well as confidence intervals using either Christensen and Nielsen's theory or Robinson and Marinucci's theory, depending on the estimated d for each bandwidth (Christensen and Nielsen's intervals are in

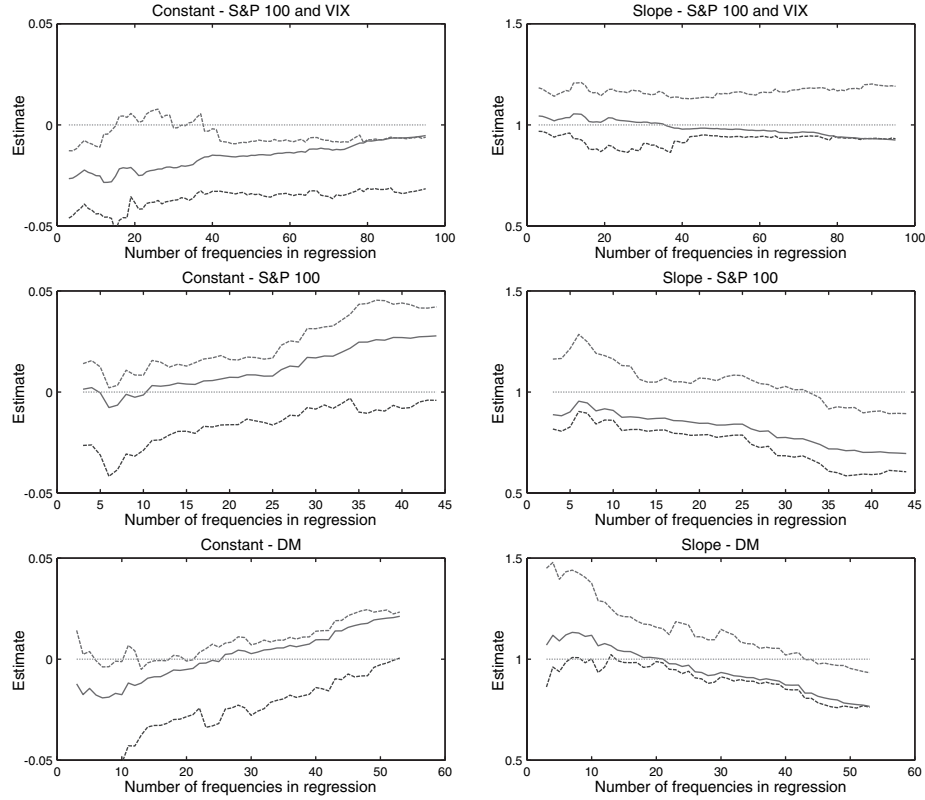


Figure 4 Narrow-band least squares estimates of a regression of realized volatility on implied volatility. We report constant and slope as a function of the number of frequencies. The confidence bands are obtained by subsampling. We consider three data sets: S&P 100 index and the VIX, S&P 100 index and S&P 100 options, DM futures and DM future options.

Table 7 Empirical results—S&P 100 index and the VIX.

NBLS bandwidth					
$m =$	3	10	15	40	95 (OLS)
NBLS point estimate	1.044	1.035	1.037	0.979	0.925
Subsampling 95% CIs					
Blocksize =					
$33([n^{2/3}])$	[0.823, 1.172]	[0.814, 1.160]	[0.819, 1.161]	[0.858, 1.107]	[0.877, 1.197]
$51([n^{3/4}])$	[0.968, 1.183]	[0.956, 1.170]	[0.909, 1.195]	[0.912, 1.130]	[0.931, 1.191]
Asymptotic 95% CIs					
Bandwidth for estimating d_x and d_e					
$[n^{0.5}]$	$\langle 1.035, 1.042 \rangle$	$\langle 1.017, 1.031 \rangle$	$\langle 1.013, 1.032 \rangle$	$\langle 0.905, 0.963 \rangle$	$\langle 0.766, 0.890 \rangle$
$\hat{d}_x = .530 \hat{d}_e =$	−0.016	0.002	−0.002	0.101	0.157
$[n^{0.6}]$	{.973, 1.114}	{.965, 1.105}	{.972, 1.103}	—	—
$\hat{d}_x = .412 \hat{d}_e =$	0.005	0.018	0.015	0.105	0.176
$[n^{0.7}]$	{1.007, 1.081}	{.997, 1.074}	{.999, 1.076}	{.917, 1.041}	—
$\hat{d}_x = .455 \hat{d}_e =$	−0.042	−0.033	−0.035	0.019	0.059

The table reports results from a linear regression of realized volatility on implied volatility. We estimate the model by OLS and NBLS with various bandwidth choices. We report the point estimates in the first row. The other rows report 95% confidence intervals. The intervals in square brackets are based on subsampling with subsamples of size $[n^{2/3}]$ and $[n^{3/4}]$. For each bandwidth choice for estimating d_x and d_e , we also report intervals based on either Christensen and Nielsen's theory (in braces when $\hat{d}_x < .5$) or Robinson and Marinucci's theory (in angled brackets when $\hat{d}_x > .5$). Some cells are empty (with the symbol—being used) when, despite the fact that $\hat{d}_x < .5$, the condition $\hat{d}_x + \hat{d}_e < .5$ is violated. This condition is necessary for the limiting variance of Christensen and Nielsen's distribution to be nonnegative.

braces, Robinson and Marinucci's intervals are in angled brackets). Consider, for example, a bandwidth of 3. The NBLS estimate is 1.044 with a subsampling interval between 0.82 and 1.17 for subsamples of size $[n^{2/3}] = 33$ and between 0.97 and 1.18 for subsamples of size $[n^{3/4}] = 51$. The asymptotic intervals are computed by using the joint OLS GPH estimator for d_x and the GPH estimator for d_e . We report confidence intervals for the same choice of bandwidth used in the estimation of d . If we chose to estimate d_x and d_e with $[n^{0.6}]$ frequencies, the estimate of d_x would be 0.412. Because this value is in the stationary region, we compute Christensen and Nielsen's interval. In this case, the residuals have an estimated d of 0.005, much lower than \hat{d}_x . The result is an interval between 0.973 and 1.114, quite close to the subsampling intervals. In most cases, we find the Christensen and Nielsen intervals to be pretty close to those based on subsampling, albeit somewhat narrower. On the contrary the Robinson and Marinucci's intervals tend to be quite narrow. Moreover, in this case the distribution of the estimator is entirely on one side of the estimated value. Proposition 6.1 of

Table 8 Empirical results—S&P 100 index and S&P 100 options.

NBLS bandwidth					
$m =$	3	10	15	40	44 (OLS)
NBLS point estimate	0.888	0.909	0.870	0.702	0.696
Subsampling 95% CIs					
Block size =					
$19(\lfloor n^{2/3} \rfloor)$	[0.794, 1.230]	[0.821, 1.254]	[0.774, 1.115]	[0.606, 0.965]	[0.640, 0.941]
$28(\lfloor n^{3/4} \rfloor)$	[0.817, 1.163]	[0.860, 1.163]	[0.811, 1.049]	[0.592, 0.903]	[0.605, 0.893]
Asymptotic 95% CIs					
Bandwidth for estimating d_x and d_e					
$[n^{0.5}]$	$\langle 0.891, 0.905 \rangle$	$\langle 0.915, 0.944 \rangle$	$\langle 0.877, 0.915 \rangle$	$\langle 0.705, 0.721 \rangle$	$\langle 0.698, 0.708 \rangle$
$\hat{d}_x = .657 \hat{d}_e =$	-0.281	-0.316	-0.253	-0.125	-0.123
$[n^{0.6}]$	$\langle 0.911, 1.024 \rangle$	$\langle 0.938, 1.091 \rangle$	$\langle 0.905, 1.087 \rangle$	$\langle 0.728, 0.860 \rangle$	$\langle 0.719, 0.841 \rangle$
$\hat{d}_x = .656 \hat{d}_e =$	0.074	0.048	0.095	0.210	0.212
$[n^{0.7}]$	$\langle 0.927, 1.137 \rangle$	$\langle 0.958, 1.215 \rangle$	$\langle 0.922, 1.201 \rangle$	$\langle 0.740, 0.937 \rangle$	$\langle 0.733, 0.907 \rangle$
$\hat{d}_x = .644 \hat{d}_e =$	0.172	0.154	0.186	0.264	0.266
See Table 7.					

Robinson and Marinucci (2001) implies that the direction of the interval is determined by the sign of the covariance between the innovations of the fractionally differenced residuals and the regressor.

The results pertaining to the other two data sets (bottom two rows of Figure 4 and Tables 8 and 9) reinforce our previous findings. The subsampling confidence intervals for the slope coefficient include 1 for a fairly broad choice of small number of frequencies. Coherently with a substantial amount of recent work in the short-memory framework, the use of OLS would lead to the rejection of the unbiasedness hypothesis. Furthermore, the downward trend in the point estimates is much more evident than in the case of the previous data. We interpret this finding as evidence that our use of the VIX as the implied volatility proxy leads to lower measurement error of implied volatility and, consequently, to lower correlation between the regressor and the regression residuals (i.e., the term u_t^{BS} is less important), thereby providing more similar slope estimates across different frequencies.

In general, our use of NBLS to remove the effect of the correlation between the residuals and implied volatility is robust to sensible choices of bandwidth. However, it would be desirable to investigate the possibility of a data-based method of bandwidth selection. Robinson (1994b) discussed the choice of optimal bandwidth for spectral estimation with long memory, but his work would have to be extended to the

Table 9 Empirical results—DM futures and options on DM futures.

NBLS bandwidth					
$m =$	3	10	15	40	53 (OLS)
NBLS point estimate	1.070	1.118	1.038	0.872	0.767
Subsampling 95% CIs					
Block size =					
$22(\lfloor n^{2/3} \rfloor)$	[0.195, 1.390]	[0.552, 1.347]	[0.744, 1.192]	[0.829, 1.017]	[0.715, 0.927]
$33(\lfloor n^{3/4} \rfloor)$	[0.863, 1.450]	[1.002, 1.375]	[0.983, 1.210]	[0.851, 1.020]	[0.762, 0.933]
Asymptotic 95% CIs					
Bandwidth for estimating d_x and d_e					
$[n^{0.5}]$	$\langle 0.111, 0.893 \rangle$	$\langle 0.403, 1.001 \rangle$	$\langle -0.037, 0.858 \rangle$	$\langle 0.600, 0.824 \rangle$	$\langle 0.771, 0.796 \rangle$
$\hat{d}_x = .629 \hat{d}_e =$	0.424	0.469	0.411	0.416	0.441
$[n^{0.6}]$	$\langle 1.086, 1.149 \rangle$	$\langle 1.139, 1.228 \rangle$	$\langle 1.060, 1.145 \rangle$	$\langle 0.894, 0.983 \rangle$	$\langle 0.877, 1.312 \rangle$
$\hat{d}_x = .579 \hat{d}_e =$	0.226	0.199	0.247	0.361	0.425
$[n^{0.7}]$	$\langle 1.070, 1.072 \rangle$	$\langle 1.122, 1.138 \rangle$	$\langle 1.032, 1.037 \rangle$	$\langle 0.776, 0.852 \rangle$	$\langle 0.563, 0.723 \rangle$
$\hat{d}_x = .576 \hat{d}_e =$	0.044	0.005	0.069	0.186	0.248
See Table 7.					

case of fractional cointegration. Bandwidth selection appears to involve a typical bias/variance trade-off as exemplified by the tendency for the confidence intervals to narrow down as more Fourier frequencies are included in the estimation.

As earlier in Section 1, the results are robust to the choice of the transformation used. Nevertheless, there is a general tendency for the slope estimates based on the logarithmic transformation to be highest, followed by the standard deviation and, lastly, by the variance. The corresponding figures can be provided by the authors on request.

5 CONCLUSIONS

We have argued that the persistence of measures of financial market volatility needs to be taken into account when assessing the relation between realized and implied volatility. This article uses a simple modeling approach based on long memory to capture persistence. In doing so, the features of the data suggest that the usual predictive regression between realized and implied volatility (regressand and regressor, respectively) is, in fact, a fractional cointegrating relation. This finding modifies the interpretation of such a regression as a tool to test for option market efficiency, as generally the case in the

existing literature, because only long-run comovements between the two volatility series can be investigated.

Fractional cointegration allows us to suggest an econometric approach to estimate the (long-run) relation between realized and implied volatility which is robust to the issues that have been raised in the previous literature as explanations for a slope coefficient estimated to be less than one, namely, measurement error and presence of an unobservable time-varying risk premium correlated with the regression residuals. In particular, our approach does not require choosing a particular parametrization for the risk premium and is thus robust to the likely misspecification that this choice would entail. More generally, our procedure is robust to other forms of nonorthogonality between the regressor (the implied volatility proxy) and the regression residuals.

Consistent with some recent studies [see, e.g., Christensen and Prabhala (1998), Poteshman (2000), and Chernov (2006)], we find evidence of unbiasedness of implied volatility as a predictor of realized volatility but interpret this result in terms of presence of a long-run one-to-one comovement between volatility series. Little can be said about short-term unbiasedness, option market efficiency, and/or validity of a certain option pricing model, which are the focus of much existing work on the subject.

This article discusses an instance where the persistence of volatility measures, which is a stylized fact based on our results and much previous work, plays a role in modifying our interpretation and understanding of a well-established economic relation while forcing us to employ appropriate econometric methodologies. More generally, we believe that the persistence of volatility measures should be given more care anytime a notion of volatility is employed as a dependent or an independent variable in forecasting, as often the case in the empirical finance literature. Any approach used must be able to capture persistence and account for its implications. This is what our focus on long memory and fractional cointegration accomplishes.

APPENDIX

These simulations are designed to better understand the properties of NBLS. Specifically, we wish to re-create an environment where (i) the slope of the fractional cointegrating regression is known and (ii) the regressor's shocks u_t have different persistence properties. Both features are important but cannot be considered in the context of the option simulations in the main text. In that case, in fact, the true slope of the fractional cointegrating regression can only be approximated [as in CCR (2003) and Chernov (2006), for example] but is unknown in practice. In addition, simulating using shocks (the \tilde{V}_t 's in the main text) with different properties would take us outside of the realm of realistic processes for the underlying (\tilde{V}_t is known to be highly persistent). We simulate the following data generating process (DGP):

$$y_t = x_t^* + \varepsilon_t,$$
$$x_t^* = (1 - L)^{-d} u_t; \quad u_t = \rho u_{t-1} + v,$$
$$\begin{pmatrix} \varepsilon_t \\ v_t \end{pmatrix} \sim \text{i.i.d. } N(0, I_2),$$
$$d = 0.34,$$

Case 1: $x_t = x_t^*$ (no measurement error)
Case 2: $x_t = x_t^* + \sigma(x_t^*)\eta_t; \eta_t \sim \text{i.i.d. } N(0,1)$ (measurement error).
Our main findings from the simulations in this Appendix are:

1. Table A1. Without serial correlation in the u_t 's and measurement error, both the GPH and the local Whittle estimator of d are nearly unbiased. The local Whittle estimator is always more efficient. The presence of measurement error lowers the estimates of d relative to the same case without error. Similarly, the estimation of d using the regressand produces d estimates that are lower than those obtained

Table A1 Simulation results for the regression model—long-memory parameter.

	\widehat{d}_x				\widehat{d}_y		\widehat{d} (common)			
	Without error		With error				Without error		With error	
	GPH	Whittle	GPH	Whittle	GPH	Whittle	GPH	Whittle	GPH	Whittle
$\rho = 0$										
$m = [n^{0.5}]$	0.355 (0.240)	0.324 (0.209)	0.265 (0.242)	0.237 (0.199)	0.280 (0.234)	0.251 (0.202)	0.312 (0.216)	0.181 (0.152)	0.319 (0.226)	0.158 (0.147)
$m = [n^{0.6}]$	0.349 (0.166)	0.328 (0.141)	0.242 (0.162)	0.224 (0.133)	0.263 (0.166)	0.241 (0.136)	0.306 (0.152)	0.189 (0.105)	0.307 (0.156)	0.157 (0.100)
$m = [n^{0.7}]$	0.348 (0.118)	0.328 (0.096)	0.220 (0.116)	0.206 (0.092)	0.241 (0.120)	0.223 (0.095)	0.295 (0.107)	0.195 (0.075)	0.294 (0.108)	0.150 (0.071)
$\rho = 0.95$										
$m = [n^{0.5}]$	1.057 (0.244)	1.065 (0.208)	0.772 (0.201)	0.756 (0.158)	1.046 (0.249)	1.052 (0.206)	1.052 (0.244)	0.662 (0.191)	1.079 (0.258)	0.660 (0.193)
$m = [n^{0.6}]$	1.132 (0.178)	1.138 (0.146)	0.638 (0.124)	0.625 (0.089)	1.091 (0.177)	1.094 (0.144)	1.112 (0.173)	0.766 (0.139)	1.130 (0.176)	0.744 (0.135)
$m = [n^{0.7}]$	1.171 (0.141)	1.164 (0.113)	0.500 (0.095)	0.496 (0.057)	1.068 (0.128)	1.049 (0.101)	1.120 (0.128)	0.832 (0.107)	1.130 (0.128)	0.766 (0.100)

The table reports long-memory parameter estimates for both regressor and regressand using the Geweke–Porter–Hudak (GPH) estimator and the local Whittle estimator. The number of Fourier frequencies used is equal to the integer part of $n^{0.5}$, $n^{0.6}$, and $n^{0.7}$. We also report estimates based on joint estimation using the multivariate constrained GPH estimator suggested by Robinson (1995a) and the multivariate local Whittle estimator suggested by Lobato (1999). The table contains the means of the estimates across simulations (with standard deviations in parentheses). The true parameter is $d = 0.34$.

Table A2 Simulation results for the regression model—regression estimates.

			Without measurement error ($\eta_t = 0$)		With measurement error ($\eta_t \sim N(0, 1)$)	
			α	β	α	β
$\rho = 0$	OLS		−0.000 (0.075)	0.998 (0.065)	−0.007 (0.204)	0.501 (0.055)
		$m = \lceil n^{0.25} \rceil = 3$	0.002 (0.099) [81.5]	1.005 (0.192) [77.3] {77.7–9.5}	−0.005 (0.144) [79.1]	0.857 (0.245) [74.6] {75.6–4.7}
	NBLS	$m = \lceil n^{0.4} \rceil = 8$	0.001 (0.085) [85.9]	0.996 (0.130) [86.5] {84.1–9.3}	−0.004 (0.135) [83.3]	0.788 (0.152) [77.4] {62.0–5.4}
		$m = \lceil n^{0.5} \rceil = 13$	0.001 (0.082) [86.4]	0.995 (0.112) [90.0] {86.1–9.4}	−0.005 (0.141) [81.2]	0.745 (0.126) [68.0] {43.8–5.5}
		$m = \lceil n^{0.7} \rceil = 39$	0.000 (0.078) [81.4]	0.995 (0.084) [81.8] {88.2–10.8}	−0.006 (0.171) [69.3]	0.617 (0.081) [3.3] {5.0–12.7}

continued

Table A2 (continued)

		Without measurement error ($\eta_t = 0$)		With measurement error ($\eta_t \sim N(0, 1)$)	
		α	β	α	β
$\rho = .95$	OLS	−0.002 (0.099)	1.000 (0.011)	−0.064 (3.395)	0.502 (0.028)
	$m = \lceil n^{0.25} \rceil = 3$	−0.001 (0.107)	1.001 (0.014)	−0.004 (0.778)	0.976 (0.081)
		[88.2]	[87.0]	[85.6]	[84.3]
	$m = \lceil n^{0.4} \rceil = 8$	−0.002 (.101)	1.000 (0.012)	0.001 (0.836)	0.930 (0.065)
		[90.6]	[91.2]	[93.1]	[94.8]
	NBLS	−0.002 (0.099)	1.000 (0.012)	−0.005 (1.002)	0.887 (0.058)
	$m = \lceil n^{0.5} \rceil = 13$	−0.002 (0.099)	1.000 (0.012)	−0.005 (1.002)	0.887 (0.058)
		[91.1]	[91.6]	[91.8]	[91.6]
	$m = \lceil n^{0.7} \rceil = 39$	−0.002 (0.099)	1.000 (0.012)	−0.037 (2.010)	0.713 (0.040)
		[89.1]	[87.8]	[85.0]	[64.3]
			{100.0–99.9}		{0.0–99.9}

The table reports simulation results from a linear regression of y_t on x_t . We estimate the model by OLS and NBLS with a number of Fourier frequencies between $\lceil n^{0.25} \rceil$ and $\lceil n^{0.7} \rceil$. We report the means of the estimates (with standard deviations in parentheses). We also report the frequency that a 95% confidence interval computed using subsampling (in square brackets) and Christensen and Nielsen’s asymptotic theory (in braces) includes the true slope of 1. Christensen and Nielsen’s asymptotic theory is only available for the slope parameter. To implement Christensen and Nielsen’s asymptotic theory, we estimate the long-memory d_x and d_e parameters with Geweke–Porter–Hudak (GPH) and a bandwidth of $\lceil n^{0.7} \rceil$. The second number in braces is the percentage of replications for which Christensen and Nielsen’s variance could not be computed because the condition $\hat{d}_x + \hat{d}_e < 1/2$, which is necessary to obtain a positive asymptotic variance in Christensen and Nielsen’s framework, was violated. Christensen and Nielsen’s coverage rates are obtained by excluding those replications.

by using the regressor without error. This is because the regression residuals ε_t play the same role as classical measurement error.

2. Table A1. Serial correlation in the u_t 's biases the estimates of d upward dramatically. Whittle is a little less biased and more efficient than GPH.
3. Table A1. Contrary to the univariate estimators, joint estimation is almost not affected by measurement error. Joint GPH estimation does not lead to substantial efficiency gains. Joint Whittle estimation leads to downward-biased estimates.
4. Table A2. Without measurement error, all slope and intercept estimators are unbiased. Precision improves with the number of Fourier frequencies in the regression (the OLS estimator tends to be the estimator with the smallest variance).
5. Table A2. The presence of measurement error induces a negative relation between the number of Fourier frequencies and the point estimates (the OLS estimator is the most biased). NBLS remove some, but not all, of the downward bias. Estimation is less precise than without measurement error.
6. Table A2. With serial correlation in the underlying u_t 's, the slope estimators tend to be more precise without much effect on their bias, whereas the intercept estimators are biased. The presence of both measurement error and serial correlation makes the intercept estimators highly biased and less precise as we increase the number of Fourier frequencies in the regression.
7. Table A2. Overall, the subsampling intervals provide the most robust inference across the four cases. The presence of serial correlation has little effect on them, but the presence of measurement error deteriorates their coverage rate, especially for larger bandwidths because they do not fully capture the bias in the estimates.
8. Table A2. Christensen and Nielsen's asymptotic intervals perform best in the simplest case (no serial correlation, no measurement error). With serial correlation, the intervals can almost never be computed because of the upward bias in the estimation of d .

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