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Co-integration Rank Testing under Conditional Heteroskedasticity*

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Abstract

In this paper we analyse the properties of the conventional Gaussian-based co-integrating rank tests of Johansen (1996) in the case where the vector of series under test is driven by possibly non-stationary, conditionally heteroskedastic (martingale difference) innovations. We first demonstrate that the limiting null distributions of the rank statistics coincide with those derived by previous authors who assume either i.i.d. or stationary martingale difference innovations. We then propose wild bootstrap implementations of the co-integrating rank tests and demonstrate that the associated bootstrap rank statistics replicate the first-order asymptotic null distributions of the rank statistics. We show that the same is also true of the corresponding rank tests based on the i.i.d. bootstrap of Swensen (2006). The wild bootstrap, however, has the important property that, unlike the i.i.d. bootstrap, it preserves in the re-sampled data the pattern of heteroskedasticity present in the original shocks. Consistent with this, numerical evidence suggests that, relative to tests based on the asymptotic critical values or the i.i.d. bootstrap, the wild bootstrap rank tests perform very well in small samples under a variety of conditionally heteroskedastic innovation processes. An empirical application to the term structure of interest rates is also given.

Keywords: Co-integration; trace and maximum eigenvalue rank tests; conditional heteroskedasticity; i.i.d. bootstrap; wild bootstrap.

J.E.L. Classifications: C30, C32.

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1 Introduction

In a recent paper, Gonçalves and Kilian (2004) argue that "... the failure of the i.i.d. assumption is well-documented in empirical finance ... many monthly macroeconomic variables also exhibit evidence of conditional heteroskedasticity." (2004,p.92); see Section 2 of Gonçalves and Kilian (2004) for detailed discussion and empirical evidence on this point. Gonçalves and Kilian (2004,2007) show that, so far as inference in stationary univariate autoregressive models is concerned, standard residual-based bootstraps based on an i.i.d. re-sampling scheme are invalid under conditional heteroskedasticity. They demonstrate that in such cases inference based on the wild bootstrap is asymptotically valid and delivers substantial improvements over both residual-based i.i.d. bootstrap tests and standard tests based on asymptotic critical values. Cavaliere and Taylor (2008) show that analogous properties also hold when using wild bootstrap methods in the context of the univariate unit root testing problem.

The trace and maximum eigenvalue co-integrating rank tests of Johansen (1996) are derived under the assumption of Gaussian i.i.d. innovations. Recently, however, Rahbek, Hansen and Dennis (2002) [RHD] have demonstrated that the assumption required on the innovation process can be considerably weakened to that of a (strict and second-order) stationary and ergodic vector martingale difference sequence (with constant unconditional variance and satisfying certain mild regularity conditions) without altering the asymptotic null distributions of the rank statistics. In this paper we first show that these limiting null distributions still pertain for the rank statistics even in the presence of possibly non-stationary, conditionally heteroskedastic shocks satisfying certain moment conditions. Moreover, we show that the maximum likelihood estimator [MLE] of the error correction model which assumes Gaussian i.i.d. disturbances also remains consistent under these weaker conditions.

Although, the standard rank tests based on asymptotic critical values therefore remain asymptotically valid even in the presence of conditionally heteroskedastic shocks, the construction of these tests does not utilise sample information relating to any conditional heteroskedasticity present in the shocks. Given this result, and the observation of Gonçalves and Kilian (2004) that conditional heteroskedasticity is a relatively common occurrence in macroeconomic and financial time series, it is clearly important and practically relevant to also consider bootstrap testing procedures in the multivariate time series setting which are asymptotically valid in the presence of conditional heteroskedasticity. We therefore develop bootstrap versions of the standard co-integrating rank tests. Our approach builds on the residual-based bootstrap co-integrating rank tests of van Giersbergen (1996), Harris and Judge (1998), Mantalos and Shukur (2001), Trenkler (2008) and, most notably, Swensen (2006).

Unlike Swensen (2006) and these other authors, we do not assume in our analysis that the innovations are independent and identically distributed (i.i.d.), nor indeed that they are covariance stationary. In particular, we make use of the wild bootstrap re-sampling scheme, since this replicates in the re-sampled data the pattern of heteroskedasticity present in the original shocks. The wild bootstrap scheme we use has also been considered in the co-integration rank testing scenario by Cavaliere, Rahbek and Taylor (2007) [CRT] in the fundamentally different scenario where the innovations display non-stationary volatility; that is, cases where the *unconditional* variance of the innovation vector varies over time in a systematic fashion. CRT demonstrate that in such cases, under the assumption of an absence of any conditional heteroskedasticity, the conventional co-integrating rank statistics do not have the same form as given in Johansen (1996), rather they depend on nuisance parameters relating the the underlying volatility process. They demonstrate, however, that the wild bootstrap rank statistics can replicate this limit distribution, to first order. Consequently, although the wild bootstrap algorithm we use here is the same as that in CRT, it is being used in the context of a quite different statistical model.

We show that wild bootstrap co-integrating rank statistics replicate the first-order asymptotic null distributions of the rank statistics, such that the corresponding bootstrap tests are asymptotically valid, in the presence of conditionally heteroskedastic innovations. The same is shown to be true of the corresponding i.i.d. bootstrap tests of Swensen (2006). It is not our aim in this paper to establish that the wild bootstrap provides a superior approximation to the conventional asymptotic approximation or to the i.i.d. bootstrap approximation. Rather we detail a less restrictive set of conditions than is adopted in the extant literature under which both the asymptotic test and both the wild and i.i.d. bootstrap approaches are asymptotically valid. However, since the wild bootstrap incorporates sample information on the conditional heteroskedasticity where present, one might anticipate that the wild bootstrap would provide a superior approximation to that provided by the asymptotic and i.i.d. bootstrap approximations which do not incorporate such sample information. Simulation evidence for a variety of conditionally heteroskedastic innovation models is supportive of this view. Taken together, the results in this paper coupled with those in CRT demonstrate that the wild bootstrap is a very powerful and useful tool, able to handle time-dependent behaviour in both the conditional and unconditional variance of the innovations. The question of whether there are conditions under which the wild bootstrap approach will provide asymptotic refinements is left for future research.

The paper is organized as follows. Section 2 outlines our reference co-integrated VAR model driven by possibly non-stationary, conditionally heteroskedastic (martingale difference) innovations. Here we show that the standard rank statistics attain the same first-order limiting null distribution as given in Johansen (1996) and RHD under different (i.i.d. and stationary MDS, respectively) assumptions. Here we also show that the MLE of the parameters from our co-integrated VAR model remain consistent in the presence of conditional heteroskedasticity. Our wild bootstrap-based approach, which also incorporates a sieve procedure using the (consistently) estimated coefficient matrices from the co-integrated VAR model, is outlined in Section 3. Here it is shown that the wild bootstrap statistics are asymptotically valid, attaining the same first-order limiting null distribution as given for the standard statistics in section 2. The same result is shown to hold for the i.i.d. re-sampling bootstrap rank tests of Swensen (2006). In Section 4, the finite sample properties of the tests are explored through Monte Carlo methods and compared with the standard asymptotic tests and with the i.i.d. bootstrap tests, for a variety of conditionally heteroskedastic error processes. In section 5 we apply our tests to bond market data from several major economies. Section 6 concludes. All proofs are contained in the Appendix.

In the following '$\xrightarrow{w}$' denotes weak convergence, '$\xrightarrow{p}$' convergence in probability, and '$\xrightarrow{w}_p$' weak convergence in probability (Giné and Zinn, 1990; Hansen, 1996), in each case as the sample size diverges to positive infinity; $\mathbb{I}(\cdot)$ denotes the indicator function and '$x := y$' ('$x =: y$') indicates that x is defined by y (y is defined by x); $\lfloor \cdot \rfloor$ denotes the integer part of its argument. The space spanned by the columns of any $m \times n$ matrix A is denoted as $\mathsf{col}(A)$; if A is of full column rank $n < m$, then $A_\perp$ denotes an $m \times (m-n)$ matrix of full column rank satisfying $A'_\perp A = 0$. For any square matrix, A, $|A|$ is used to denote the determinant of A, $\|A\|$ the norm $\|A\|^2 := \mathsf{tr}\{A'A\}$, where $\mathsf{tr}\{A\}$ denotes the trace of A, and $\rho(A)$ its spectral radius (that is, the maximal modulus of the eigenvalues of A). For any vector, x, $\|x\|$ denotes the usual Euclidean norm, $\|x\| := (x'x)^{1/2}$.

2 The Conditionally Heteroskedastic Co-integration Model

We consider the following VAR(k) model in error correction format:

$$\Delta X_t = \Pi X_{t-1} + \Psi U_t + \mu D_t + \varepsilon_t,\ t = 1, ..., T \tag{2.1}$$

where: X_t and ε_t are $p \times 1$, $U_t := \left(\Delta X'_{t-1}, ..., \Delta X'_{t-k+1}\right)'$ is $p(k-1) \times 1$ and $\Psi := (\Gamma_1, ..., \Gamma_{k-1})$, where $\{\Gamma_i\}_{i=1}^{k-1}$ are $p \times p$ lag coefficient matrices and the impact matrix $\Pi := \alpha\beta'$ where α and β are full column $p \times r$ matrices, $r \leq p$. The term D_t collects all deterministic components, and in this paper we focus on the leading case of a linear trend, $D_t := (1, t)'$, with associated coefficients $\mu := (\mu'_1, \mu'_2)'$. The initial values, $\mathbb{X}_0 := \left(X'_0, ..., X'_{-k+1}\right)'$, are taken to be fixed.

Throughout the paper the process in (2.1) is assumed to satisfy the following assumptions.

Assumption 1: (a) *all the characteristic roots associated with (2.1); that is of* $A(z) := (1-z) I_p - \alpha\beta' z - \Gamma_1 z (1-z) - \cdots - \Gamma_{k-1} z^{k-1} (1-z) = 0$, *are outside the unit circle or equal to* 1; (b) $\det(\alpha'_\perp \Gamma \beta_\perp) \neq 0$, *with* $\Gamma := I_p - \Gamma_1 - \cdots - \Gamma_{k-1}$.

Assumption 2: *The innovations* $\{\varepsilon_t\}$ *form a martingale difference sequence with respect to the filtration* $\mathcal{F}_t$, *where* $\mathcal{F}_{t-1} \subseteq \mathcal{F}_t$ *for* $t = ..., -1, 0, 1, 2, ...$, *satisfying: (i)*

$$\frac{1}{T} \sum_{t=1}^{T} E\left(\varepsilon_t \varepsilon'_t | \mathcal{F}_{t-1}\right) \xrightarrow{p} \Sigma > 0, \tag{2.2}$$

and (ii) $E\|\varepsilon_t\|^4 \leq K < \infty$.

Remark 2.1. While Assumption 1 is standard in the co-integration testing literature, Assumption 2 is not. This assumption implies that ε_t is a serially uncorrelated, potentially conditionally heteroskedastic process. This contrasts with the assumption that ε_t is i.i.d. as made in Johansen (1996) and Swensen (2006). Moreover, and in contrast to RHD, Assumption 2 imposes neither strict stationarity nor second-order stationarity on ε_t. In particular, the second order moments $\Sigma_t := E\left(\varepsilon_t\varepsilon_t'\right)$ are allowed to change over time, in such a way that they satisfy the condition in (2.2).

Remark 2.2. Under Assumption 2, a functional central limit theorem [FCLT] as in Brown (1971) applies to ε_t; *viz*,

$$\frac{1}{\sqrt{T}}\sum_{t=1}^{\lfloor T\cdot\rfloor}\varepsilon_t \xrightarrow{w} W\left(\cdot\right), \tag{2.3}$$

where W is a Brownian motion with covariance matrix Σ, as defined in (2.2). This result follows using the convergence result in (2.2) and noting that the assumption of finite fourth order moments implies the Lindeberg-type condition

$$T^{-1}\Sigma_{t=1}^{T}E\left(\left\|\varepsilon_t\right\|^2\cdot\mathbb{I}\left\{\left\|\varepsilon_t\right\|>\delta\sqrt{T}\right\}\middle|\mathcal{F}_{t-1}\right)\xrightarrow{p}0\ .$$

As is standard in the time series literature, an innovation process which admits the FCLT in (2.3) will be referred to as a vector $I(0)$ process. Assumption 2 also ensures that conditions (5) and (6) in Hannan and Heyde (1972, Theorem 1) hold, implying that the empirical average, $T^{-1}\sum_{i=1}^{T}s_i$, and empirical autocovariances, $T^{-1}\sum_{t=1}^{T}s_ts_{t+k}'$, where $s_t := \sum_{i=0}^{\infty}\theta_i\varepsilon_{t-i}$ with $\sum_{i=0}^{\infty}\|\theta_i\|<\infty$, converge in probability to 0 and $\sum_{i=0}^{\infty}\theta_i\Sigma\theta_{i+k}'$, respectively.

Remark 2.3. The conditions in Assumption 2 ensure that a FCLT applies to the MDS, $\{\varepsilon_t\}$, and that the product moments converge, as detailed in Remark 2.2. Both the convergence in (2.2) and the convergence of the product moments would also be implied by assuming geometric ergodicity of the $\{\varepsilon_t\}$ sequence, since the law of large numbers applies to functions of geoemtrically ergodic processes; see Jensen and Rahbek (2007) for details. Geometric ergodicity is satisfied for a rich class of (G)ARCH processes; see, for example, the discussion in Kristensen and Rahbek (2005a,b) and the references therein. □

For unknown parameters α, β, Ψ, μ, and when α and β are $p\times r$ matrices, not necessarily of full rank, (2.1) denotes our conditionally heteroskedastic co-integrated VAR model, which we denote as $H(r)$. The model may then be written in the compact form

$$Z_{0t} = \alpha\beta^{*\prime}Z_{1t} + \mu_2 Z_{2t} + \varepsilon_t \tag{2.4}$$

with $Z_{0t} := \Delta X_t$, and Z_{1t} and Z_{2t} defined according to the following three cases for the deterministic terms, as in Johansen (1996, p.81):

(i) $\mu D_t = 0$ in (2.1), $Z_{1t} := X_{t-1}$ and $Z_{2t} := U_t$ (no deterministic components);

(ii) $\mu D_t = \mu_1 = \alpha\rho_1'$ in (2.1), $Z_{1t} := (X_{t-1}', 1)'$ and $Z_{2t} := U_t$ (restricted constant);

(iii) $\mu D_t = \mu_1 + \mu_2 t$ with $\mu_2 = \alpha\rho_2'$ in (2.1), $Z_{1t} := (X_{t-1}', t)'$ and $Z_{2t} := (U_t', 1)'$ (restricted linear trend);

As is standard, let $M_{ij} := T^{-1}\sum_{t=1}^{T} Z_{it}Z_{jt}'$, $i, j = 0, 1, 2$, with Z_{it} defined as in (2.4), and let $S_{ij} := M_{ij.2} := M_{ij} - M_{i2}M_{22}^{-1}M_{2j}$, $i, j = 0, 1$. Under the assumption of i.i.d. Gaussian disturbances, the pseudo Gaussian likelihood function depends on the vector $\theta^{PML} := (\alpha, \beta, \Psi, \mu, \Sigma)$ (throughout we apply the usual norming or identication as in Johansen, 1996, section 13.2). We denote the corresponding pseudo Maximum Likelihood (PML) estimator as $\hat{\theta}^{PML} := (\hat{\alpha}, \hat{\beta}, \hat{\Psi}, \hat{\mu}, \hat{\Sigma})$. Write the maximized (pseudo) log-likelihood under $H(r)$, say $\ell(r)$, as

$$\ell(r) = -\frac{T}{2}\log|S_{00}| - \frac{T}{2}\sum_{i=1}^{r}\log\left(1 - \hat{\lambda}_i\right)$$

where $\hat{\lambda}_1 > \ldots > \hat{\lambda}_p$, solve the eigenvalue problem

$$\left|\lambda S_{11} - S_{10}S_{00}^{-1}S_{01}\right| = 0. \tag{2.5}$$

The pseudo LR (PLR) test for $H(r)$ vs $H(p)$ then rejects for large value of the statistic

$$Q_r := -2\left(\ell(r) - \ell(p)\right) = -T\sum_{i=r+1}^{p}\log\left(1 - \hat{\lambda}_i\right). \tag{2.6}$$

We now demonstrate the validity of the following theorem concerning the limiting null distribution of the Q_r statistic under conditional heteroskedasticity of the form specified in Assumption 2. To keep the presentation simple we consider, for the present, the case of no deterministics in the model and in the estimation (so that $\hat{\mu}$ is omitted from the definition of θ^{PML} above). This will be subsequently relaxed in Remark 2.5.

Theorem 1 *Let $\{X_t\}$ be generated as in (2.1) under Assumptions 1 and 2, with $\mu = 0$. Then, under the hypothesis $H(r)$,*

$$Q_r \xrightarrow{w} \mathsf{tr}(\mathcal{Q}_B) =: Q_{r,\infty} \tag{2.7}$$

where

$$\mathcal{Q}_B := \int_0^1 (dB(u))B(u)'\left(\int_0^1 B(u)B(u)'du\right)^{-1}\int_0^1 B(u)(dB(u))' \tag{2.8}$$

with $B(\cdot)$ a $(p-r)$-variate standard Brownian motion.

Remark 2.4. The representation for the limiting null distribution of Q_r given in (2.7) coincides with that given in Johansen (1996) for the case of independent Gaussian innovations and in RHD for covariance stationary martingale difference innovations.

Remark 2.5. The result in Theorem 1 can be generalized to cover the four additional cases for the deterministic component considered just below (2.4). It is an entirely straightforward extension of the result in Theorem 1 to establish that in such a case the asymptotic null distribution of Q_r is given by (2.7) but now with $\mathcal{Q}_B := \mathsf{tr}(\int (dB(u))F(u)' \left(\int F(u)F(u)'\right)^{-1} \times \int F(u)(dB(u))')$, where B is as defined in Theorem 1, and F is a function of B whose precise form depends on the deterministic term. More specifically, decomposing B as $B := (B_1', B_2)'$, where B_2 is one-dimensional and using the notation $a|b := a(\cdot) - \int a(s)b(s)'ds(\int b(s)b(s)'ds)^{-1}b(\cdot)$ to denote the projection residuals of a onto b:

(i) if $\mu D_t = 0$ in (2.1), then $F := B$, as in Theorem 1;

(ii) if $\mu D_t = \alpha\rho_1'$ in (2.1), then $F := (B', 1)'$;

(iii) if $\mu D_t = \mu_1 + \alpha\rho_2' t$ in (2.1), then $F := (B', u|1)'$.

Remark 2.6. The discussion outlined in this section extends to the so-called maximum eigenvalue test; that is, a PLR test based for $H(r)$ vs $H(r+1)$. As is well known, this test rejects for large values of the statistic

$$Q_{r,\max} := -2\left(\ell\left(r\right) - \ell\left(r+1\right)\right) = -T\log(1 - \hat{\lambda}_{r+1})\ ,$$

see, for example, Equation (6.19) of Johansen (1996). It then follows trivially from the preceding results that the null asymptotic distribution of $Q_{r,\max}$ corresponds to the distribution of the maximum eigenvalue of the real symmetric random matrix $\mathcal{Q}_B$.

Remark 2.7. As in Johansen (1996), under $H(r)$, the r largest eigenvalues solving (2.5), $\hat{\lambda}_1, \ldots, \hat{\lambda}_r$, converge in probability to positive numbers, while $T\hat{\lambda}_{r+1}, \ldots, T\hat{\lambda}_p$ are of $O_p(1)$. Consequently, the PLR test based on either Q_r or $Q_{r,\max}$ will be consistent at rate $O_p(T)$ if the true co-integration rank is, say, $r_0 > r$. This implies, therefore, that the sequential approach to determining the co-integration rank[1] outlined in Johansen (1996) will still lead to the selection of the correct co-integrating rank with probability $(1-\xi)$ in large samples, as in the i.i.d. Gaussian case. The same results also hold under cases (ii)-(iii) of Remark 2.5. □

We conclude this section by demonstrating that even though based on a mis-specified model the PML estimator, $\hat{\theta}^{PML}$, is consistent. This will turn out to be a key property needed to establish the validity of the bootstrap PLR tests we propose in section 3.

Theorem 2 *Under the conditions of Theorem 1,* $T^{1/2}(\hat{\beta} - \beta) \xrightarrow{p} 0$*. Moreover,* $\hat{\alpha} \xrightarrow{p} \alpha$*,* $\hat{\Psi} \xrightarrow{p} \Psi$*, and* $\hat{\Sigma} \xrightarrow{p} \Sigma$*.*

[1] This procedure starts with $r = 0$ and sequentially raises r by one until for $r = \hat{r}$ the test statistic $Q_{\hat{r}}$ (or $Q_{\hat{r},\max}$) does not exceed the ξ level critical value for the test.

Remark 2.8. Theorem 2 shows that in the presence of conditional heteroskedasticity of the form specified in Assumption 2, the PML estimators of α, β, Σ and Ψ remain consistent. Under cases (ii)-(iii) of Remark 2.5 it can additionally be shown that $\hat{\mu}$, the PML estimator of μ, also remains consistent. □

3 Bootstrap PLR Tests

In section 3.1 we first outline our wild bootstrap algorithm. Subsequently in section 3.2 we show that because, as was shown in the previous section, we can still consistently estimate α, β, μ and Ψ in the presence of conditional heteroskedasticity, (asymptotically) pivotal null p-values can be obtained using wild bootstrap re-sampling methods, regardless of whether conditional heteroskedasticity is present or not in the shocks. In section 3.3 we then demonstrate that the i.i.d. bootstrap rank tests of Swensen (2006) share the same large sample properties as the wild bootstrap.

The re-sampling algorithm discussed in section 3.1 draws on the wild bootstrap literature (see, *inter alia*, Wu, 1986; Liu, 1988; Mammen, 1993) and allows us to construct bootstrap co-integration rank tests which are asymptotically robust to conditional heteroskedasticity. In the context of the present problem, we focus our primary attention on the wild bootstrap scheme because, unlike the i.i.d. residual re-sampling schemes used for other bootstrap co-integration tests proposed in the literature; see, e.g., Swensen (2006) and, in the univariate ($p = 1$) case, Inoue and Kilian (2002), Paparoditis and Politis (2003), Park (2003), the wild bootstrap replicates the pattern of heteroskedasticity present in the original shocks, and, hence, preserves the temporal ordering in the conditional heteroskedasticity. The wild bootstrap might therefore be expected to deliver improved finite sample size properties relative to the standard and i.i.d. bootstrap rank tests in the presence of conditional heteroskedasticity. The simulations results presented in section 4 support this conjecture.

3.1 The Wild Bootstrap Algorithm

Let us start by considering the problem of testing the null hypothesis $H(r)$ against $H(p)$, $r < p$. Swensen (2006, section 2) discusses at length a way of implementing a bootstrap version of the well known trace test in this case. Here we extend his approach by modifying his re-sampling scheme in order to account the presence of conditional heteroskedasticity by means of the wild bootstrap. Implementation of the wild bootstrap requires us only to estimate the VAR(k) model under $H(p)$ (i.e., the unrestricted VAR) and under $H(r)$.

As in section 2, let $\hat{\Psi} := (\hat{\Gamma}_1, ..., \hat{\Gamma}_{k-1})$ and, where appropriate, $\hat{\mu}$ denote the PML estimates of Ψ and μ, respectively, from the model under $H(p)$; the corresponding unrestricted residuals are denoted by $\hat{\varepsilon}_t$, $t = 1, ..., T$. In addition, let $\hat{\alpha}, \hat{\beta}$ denote the PML estimates of α,β under the null hypothesis $H(r)$. The bootstrap algorithm we consider in this section requires that the roots of the equation $|\hat{A}^* (z)| = 0$ are either one or outside the unit circle, where

$$\hat{A}^{*}(z) := (1-z) I_p - \hat{\alpha}\hat{\beta}' z - \hat{\Gamma}_1 (1-z) z - \ldots - \hat{\Gamma}_{k-1}(1-z) z^{k-1} ;$$

moreover, we also require that $|\hat{\alpha}_{\perp}' \hat{\Gamma} \hat{\beta}_{\perp}| \neq 0$, ($\hat{\Gamma} := I_p - \hat{\Gamma}_1 - \ldots - \hat{\Gamma}_{k-1}$). While the latter condition is always satisfied in practice, if the former condition is not met, then the bootstrap algorithm cannot be implemented, because the bootstrap samples may become explosive; cf. Swensen (2006, Remark 1). However, in such cases any estimated root which has modulus greater than unity could be shrunk to have modulus strictly less than unity; cf. Burridge and Taylor (2001,p.73).

The following steps constitute our wild bootstrap algorithm, which coincides with Algorithm 1 of CRT:

Algorithm 1 (Wild Bootstrap Co-integration Test)

Step 1: *Generate T bootstrap residuals ε_t^b, $t = 1, ..., T$, according to the device*

$$\varepsilon_t^b := \hat{\varepsilon}_t w_t \tag{3.1}$$

where $\{w_t\}_{t=1}^T$ denotes an independent $N(0,1)$ scalar sequence;

Step 2: *Construct the bootstrap sample recursively from*

$$\Delta X_t^b := \hat{\alpha}\hat{\beta}' X_{t-1}^b + \hat{\Gamma}_1 \Delta X_{t-1}^b + \ldots + \hat{\Gamma}_{k-1}\Delta X_{t-k+1}^b + \varepsilon_t^b,\ t = 1, ..., T,$$

with initial values, $X_{-k+1}^b, ..., X_0^b$;

Step 3: *Using the bootstrap sample, $\{X_t^b\}$, obtain the bootstrap test statistic, $Q_r^b := -2\left(\ell^b(r) - \ell^b(p)\right)$, where $\ell^b(r)$ and $\ell^b(p)$ denote the bootstrap analogues of $\ell(r)$ and $\ell(p)$, respectively;*

Step 4: *Bootstrap p-values are then computed as, $p_{r,T}^b := 1 - G_{r,T}^b(Q_r)$, where $G_{r,T}^b(\cdot)$ denotes the conditional (on the original data) cumulative distribution function (cdf) of Q_r^b.* $\square$

Remark 3.1. Notice that the bootstrap shocks, ε_t^b, replicate the pattern of heteroskedasticity present in the original shocks since, conditionally on $\hat{\varepsilon}_t$, ε_t^b is independent over time with zero mean and variance matrix $\hat{\varepsilon}_t\hat{\varepsilon}_t'$. Specifically, notice that, conditionally on the data,

$$T^{-1/2}\sum_{i=1}^{\lfloor Tu \rfloor} \varepsilon_t^b = T^{-1/2}\sum_{i=1}^{\lfloor Tu \rfloor} \hat{\varepsilon}_t w_t \sim N\left(0, \frac{1}{T}\sum_{t=1}^{\lfloor Tu \rfloor} \hat{\varepsilon}_t\hat{\varepsilon}_t'\right)$$

where $T^{-1}\sum_{t=1}^{\lfloor Tu \rfloor} \hat{\varepsilon}_t\hat{\varepsilon}_t' \approx u\Sigma$ with Σ being the average conditional variance, cf. Remark 2.1.

Remark 3.2. As is standard, the bootstrap samples are generated by imposing the null co-integration rank on the re-sampling scheme, thereby avoiding the difficulties with the use of unrestricted estimates of the impact matrix Π; see Basawa *et al.* (1991) in the univariate case and Swensen (2006) in the multivariate case.

Remark 3.3. As is well known in the wild bootstrap literature (see Davidson and Flachaire, 2001, for a review) in certain cases improved accuracy can be obtained by replacing the Gaussian distribution used for generating the pseudo-data by an asymmetric distribution with $E(w_t) = 0$, $E(w_t^2) = 1$ and $E(w_t^3) = 1$ (Liu, 1988). A well known example is Mammen's (1993) two-point distribution: $P(w_t = -0.5(\sqrt{5}-1) = 0.5(\sqrt{5}+1)/\sqrt{5} = p$, $P(w_t = 0.5(\sqrt{5}+1)) = 1-p$. Davidson and Flachaire (2001) also consider the Rademacher distribution: $P(w_t = 1) = 1/2 = P(w_t = -1)$. We found no discernible differences between the finite sample properties of the bootstrap unit root tests based on the Gaussian or the Mammen or Rademacher distributions. This finding is consistent with evidence reported in Table 5 of Gonçalves and Kilian (2004,p.105) in the context of hypothesis testing using the wild bootstrap in stationary univariate autoregressive models driven by conditionally heteroskedastic innovations. Notice also that the wild bootstrap re-sampling scheme in (3.1) is no harder (arguably easier) to implement than the i.i.d. re-sampling scheme of Swensen (2006).

Remark 3.4. In practice, the cdf $G_{r,T}^b(\cdot)$ required in Step 4 of Algorithm 1 will not be known, but can be approximated in the usual way through numerical simulation; cf. Hansen (1996) and Andrews and Buchinsky (2000). This is achieved by generating N (conditionally) independent bootstrap statistics, $Q_{n:r}^b$, $n = 1, ..., N$, computed as above but recursively from

$$\Delta X_{n:t}^b := \hat{\alpha}\hat{\beta}' X_{n:t-1}^b + \hat{\Gamma}_1 \Delta X_{n:t-1}^b + ... + \hat{\Gamma}_{k-1}\Delta X_{n:t-k+1}^b + \varepsilon_{n:t}^b,\ t = 1, ..., T,$$

for some initial values $X_{n:-k+1}^b, ..., X_{n:0}^b$ and with $\{\{w_{n:t}\}_{t=1}^T\}_{n=1}^N$ a doubly independent $N(0,1)$ sequence. The simulated bootstrap p-value is then computed as $\tilde{p}_{r,T}^b := N^{-1}\sum_{n=1}^N \mathbb{I}\left(Q_{n:r}^b > Q_r\right)$, and is such that $\tilde{p}_{r,T}^b \overset{a.s.}{\to} p_{r,T}^b$ as $N \to \infty$. Note that an asymptotic standard error for $\tilde{p}_{r,T}^b$ is given by $(\tilde{p}_{r,T}^b(1-\tilde{p}_{r,T}^b)/N)^{1/2}$; cf. Hansen (1996, p.419).

Remark 3.5. The maximum eigenvalue statistic, $Q_{r,\max}$ for $H(r)$ vs $H(r+1)$ can be bootstrapped in the same way as outlined for Q_r above, replacing Q_r^b with $Q_{r,\max}^b := -2\left(\ell^b(r) - \ell^b(r+1)\right)$ in Steps 3 and 4 of Algorithm 1, and similarly in Remark 3.4.

3.2 Asymptotic Theory for the Wild Bootstrap

The asymptotic validity of the wild bootstrap method outlined in Algorithm 1 under conditional heteroskedasticity is now established in Theorem 3. In order to keep our presentation simple, we demonstrate our result for the case of no deterministic variables. The equivalence of the first-order limiting null distributions of the Q_r^b and Q_r statistics can also be shown to hold for cases (ii)-(iii) of Remark 2.5. Again this is a straightforward extension of the results in Theorem 3 and is omitted in the interests of brevity.

Theorem 3 *Let the conditions of Theorem 1 hold. Then, under the null hypothesis* $H(r)$*,* $Q_r^b \xrightarrow{w}_p Q_{r,\infty}$*. Moreover,* $p_T^b \xrightarrow{w} U[0,1]$*.*

Remark 3.6. A comparison of the result for Q_r^b in Theorem 3 with that given for Q_r in Theorem 1 demonstrates the usefulness of the wild bootstrap: as the number of observations diverges, the wild bootstrapped statistic has the same first-order null distribution as the original test statistic. Consequently, the bootstrap p-values are (asymptotically) uniformly distributed under the null hypothesis, leading to tests with (asymptotically) correct size in the presence of conditional heteroskedasticity of the form given in Assumption 2.

Remark 3.7. It can be shown that the sequential procedure of Johansen (1996), see footnote 1, employed using the wild bootstrap Q_r^b, $r = 0, ..., p-1$, test statistics is consistent in the sense that correctly selects the true co-integrating rank with probability $(1-\xi)$ in large samples (ξ denoting the nominal significance level used in each test in the procedure) in the presence of conditional heteroskedasticity satisfying Assumption 2. Specifically, Proposition 2 of Swensen (2006), strengthened with additional conditions outlined in Swensen (2008), which shows that a sequential procedure based on the i.i.d. bootstrap in the homoskedastic case is consistent, also holds for a sequential procedure based on the wild bootstrap in the conditionally heteroskedastic case. To see this, it suffices to observe that Lemmas 3 and 4 in Swensen (2006), which are used to establish Lemma 2 therein, do not depend on the specific bootstrap re-sampling scheme being used. Specifically, under the additional conditions of Swensen (2008), they hold given the representation for the original data X_t in Lemma A.1 of Appendix A, and given the consistency of the unrestricted OLS estimators. This result implies that our Lemma A.4, which is equivalent to Lemma 1 in Swensen (2006), also holds for each rank $r = 0, 1, ..., p-1$, in the conditionally heteroskedastic case. That is, under the additional conditions of Swensen (2008), the wild bootstrap analogues of Lemma 2 and Proposition 2 of Swensen (2006), both hold when the data are conditionally heteroskedastic in the sense of Assumption 2.

Remark 3.8. Given the results in Theorem 3, it follows straightforwardly that the limiting null distribution of the bootstrap maximum eigenvalue statistic, $Q_{r,\max}^b$, coincides with that given in Remark 2.6, so that again our wild bootstrap procedure will deliver (asymptotically) correctly sized maximum eigenvalue co-integration tests under the conditions of Theorem 3. The results of Remark 3.7 also apply for the sequential procedure based on the bootstrap maximum eigenvalue statistic. $\square$

3.3 Swensen's i.i.d. Bootstrap

The i.i.d. bootstrap method outlined in Swensen (2006) follows the same steps as the wild bootstrap method outlined above in section 3.1, except that Step 1 of Algorithm

1 is replaced by the following:

Step 1: *Generate T bootstrap residuals ε_t^s, $t = 1, ..., T$, as independent draws with replacement from the centred residuals $\{\hat{\varepsilon}_t - T^{-1}\sum_{i=1}^T \hat{\varepsilon}_i\}_{t=1}^T$.*

The algorithm for the i.i.d. bootstrap rank tests then continues exactly as in Algorithm 1, but using the centred[2] i.i.d. bootstrap residuals, ε_t^s, in place of the wild bootstrap residuals, ε_t^b. We denote the resulting i.i.d. bootstrap rank statistic by Q_r^s and the associated i.i.d. bootstrap p-value as $p_{r,T}^s$. The same conditions on the roots of the equation $|\hat{A}^*(z)| = 0$ as were required for the wild bootstrap must also hold here, as must the condition that that $|\hat{\alpha}'_\perp \hat{\Gamma} \hat{\beta}_\perp| \neq 0$. Again any estimated root with modulus greater than unity may again be shrunk to have modulus strictly less than unity.

Under the (homoskedastic) assumption that $\varepsilon_t \sim$ i.i.d.$(\mathbf{0}, \mathbf{\Sigma})$ with finite fourth moments, Swensen (2006) demonstrates that the i.i.d. bootstrap rank statistic Q_r^s replicates the first-order asymptotic null distribution of the standard trace statistic, Q_r of (2.6). In Theorem 4 we now establish that the i.i.d. bootstrap method of Swensen (2006) remains asymptotically valid under the weaker conditionally heteroskedastic conditions placed on the innovations in this paper. This result is demonstrated for the case of no deterministic variables. The equivalence of the first-order limiting null distributions of the Q_r^s and Q_r statistics under cases (ii)-(iii) of Remark 2.5 is again a straightforward extension of the results in Theorem 4.

Theorem 4 *Let the conditions of Theorem 1 hold. Then, under the null hypothesis $H(r)$, $Q_r^s \xrightarrow{w}_p Q_{r,\infty}$. Moreover, $p_{r,T}^s \xrightarrow{w} U[0,1]$.*

Remark 3.10. As in Remark 3.4, the cdf of Q_r^s used in Step 4 of the bootstrap algorithm can again be approximated through numerical simulation. Moreover, an i.i.d. bootstrap analogue of the maximum eigenvalue statistic can also be obtained in an obvious way through the same principles as were outlined in Remark 3.5. Again it follows immediately from the results in Theorem 4 that this statistic has the same limiting null distribution as that given for $Q_{r,\max}$ in Remark 2.6.

Remark 3.11. The results regarding the consistency of the sequential procedure for the determination of the co-integration rank (specifically, Proposition 2 of Swensen, 2006) given in Remark 4.2 are also valid for the i.i.d. bootstrap. That is, the sequential procedure based on the i.i.d. bootstrap, as suggested in Swensen (2006), with the additional restrictions outlined in Swensen (2008), for the homoskedastic case, remains consistent under conditional heteroskedasticity of the form given in Assumption 2.

The finite sample behaviour of the standard Q_r and the corresponding i.i.d. and wild bootstrap tests in the presence of a variety of conditionally heteroskedastic innovation processes is explored numerically in the next section.

[2]Notice that if the estimated unrestricted VAR contains a constant, then $T^{-1}\sum_{t=1}^T \hat{\varepsilon}_t = 0$ and, hence, the residuals would not need to be centred prior to re-sampling.

4 Finite Sample Simulations

In this section we use Monte Carlo simulation methods to compare the finite sample size and power properties of the PLR co-integration rank test of Johansen (1996) with its wild bootstrap version proposed in Section 3 together with the corresponding i.i.d. bootstrap test of Swensen (2006). We also compare the properties of the sequential approach of Johansen (1996) when applied using the PLR test and the two bootstrap analogue methods. The simulation model we consider generalises that used by previous authors in that we are allowing for conditional heteroskedasticity in the innovation process driving the VAR model.

In sections 4.1, and 4.2 we follow Johansen (2002) and Swensen (2006), and consider as our simulation DGP an $I(1)$, possibly co-integrated, $VAR(1)$ process of dimension p. We allow the dimension of the VAR process to vary over $p = 2, ..., 5$, and consider both the case of no co-integration ($r = 0$) [section 4.1], and of a single co-integrating vector ($r = 1$) [section 4.2]. In section 4.3 we will subsequently report results for $r = 0$ in a VAR(2) model, thereby also investigating the finite sample impact of higher-order serial correlation.

The DGP considered in section 4.1 is the multivariate martingale process,

$$\Delta X_t = \varepsilon_t,$$

while a generalisation of this DGP to the non-co-integrated VAR(2) case is detailed in section 4.3. In section 4.2., the DGP is the co-integrated VAR(1) model

$$\Delta X_t = \alpha\beta' X_{t-1} + \varepsilon_t$$

where α and β are $p \times 1$ vectors. In each case $\varepsilon_t := (\varepsilon_{1,t}, ..., \varepsilon_{p,t})'$ is a p-dimensional martingale difference sequence with respect to the filtration $\mathcal{F}_t := \sigma(\varepsilon_t, \varepsilon_{t-1}, ...)$. Following van der Weide (2002), we assume that ε_t may be written as the linear map

$$\varepsilon_t = \Lambda e_t \tag{4.1}$$

where Λ is an invertible $p \times p$ matrix which is constant over time, while the p components of $e_t := (e_{1,t}, ..., e_{p,t})'$ are independent across $i = 1, ..., p$. In the case where the individual components follow a standard $GARCH(1, 1)$ process (as is the case with Models A and B below), van der Weide (2002) refers to ε_t as a $GO - GARCH(1, 1)$ process.

Notice that, by definition, the PLR statistic does not depend on the matrix Λ, as the eigenvalue problem in (2.5) has the same eigenvalues upon re-scaling (as can be seen by simply pre- and post-multiplying by Λ^{-1} in (2.5)). This allows us to set $\Lambda = I_p$ in the simulations, without loss of generality. Moreover, in the $r = 1$ case considered in section 4.2, we follow Johansen (2002) and Swensen (2006) by considering DGPs with $\beta := (1, 0, ..., 0)'$ and $\alpha := (a_1, a_2, 0, ..., 0)'$. This leads to the model

$$\begin{aligned}
\Delta X_{1,t} &= a_1 X_{1,t-1} + \varepsilon_{1,t} \\
\Delta X_{2,t} &= a_2 X_{1,t-1} + \varepsilon_{2,t} \\
\Delta X_{i,t} &= \varepsilon_{i,t}, \qquad i = 3, ..., p.
\end{aligned}$$

In our reported simulations we set $a_1 = a_2 = -0.4$, as in Swensen (2006, Table 2).

Within the context of (4.1) we consider for the individual components of e_t the univariate innovation processes and parameter configurations used in Section 4 of Gonçalves and Kilian (2004), to which the reader is referred for further discussion. These are as follows:

- **Model A** is a standard $GARCH(1,1)$ process driven by standard normal innovations of the form $e_{it} = h_{it}^{1/2} v_{it}$, $i = 1, ..., p$, where v_{it} is i.i.d. $N(0,1)$, independent across i, and $h_{it} = \omega + d_0 e_{it-1}^2 + d_1 h_{it-1}$, $t = 0, ..., T$. Results are reported for $(d_0, d_1) \in \{(0.5, 0.0), (0.3, 0.65), (0.2, 0.79), (0.05, 0.94)\}$.

- **Model B** is the same as Model A except that the v_{it}, $i = 1, ..., p$, are independent i.i.d. t_5 (normalised to unit variance) variates.

- **Model C** is the exponential $GARCH(1,1)$ ($EGARCH(1,1)$) model of Nelson (1991) with $e_{it} = h_{it}^{1/2} v_{it}$, $\ln(h_{it}) = -0.23 + 0.9 \ln(h_{it-1}) + 0.25[|v_{it-1}^2| - 0.3 v_{it-1}]$, with $v_{it} \sim$ i.i.d. $N(0,1)$, independent across $i = 1, ..., p$.

- **Model D** is the asymmetric $GARCH(1,1)$ ($AGARCH(1,1)$) model of Engle (1990) with $e_{it} = h_{it}^{1/2} v_{it}$, $h_{it} = 0.0216 + 0.6896 h_{it-1} + 0.3174[e_{it-1} - 0.1108]^2$, with $v_{it} \sim$ i.i.d. $N(0,1)$, independent across $i = 1, ..., p$.

- **Model E** is the $GJR - GARCH(1,1)$ model of Glosten *et al.* (1993) with $e_{it} = h_{it}^{1/2} v_{it}$, $h_{it} = 0.005 + 0.7 h_{it-1} + 0.28[|e_{it-1}| - 0.23 e_{it-1}]^2$, with $v_{it} \sim$ i.i.d. $N(0,1)$, independent across $i = 1, ..., p$.

- **Model F** is the first-order AR stochastic volatility model: $e_{it} = v_{it} \exp(h_{it})$, $h_{it} = \lambda h_{it-1} + 0.5 \xi_{it}$, with $(\xi_{it}, v_{it}) \sim$ i.i.d. $N(0, \mathrm{diag}(\sigma_\xi^2, 1))$, independent across $i = 1, ..., p$. Results are reported for $(\lambda, \sigma_\xi) = \{(0.936, 0.424), (0.951, 0.314)\}$.

The reported simulations were programmed using the **rndKMn** function of Gauss 7.0. All experiments were conducted using $10,000$ replications. The sample sizes were chosen within the set $\{50, 100, 200\}$ and the number of replications used in the wild bootstrap algorithm was set to 399. All tests were conducted at the nominal 0.05 significance level. For the reasons outlined on page 12 of RHD, relating to similarity with respect to initial values (see also Nielsen and Rahbek, 2000), the VAR model was fitted with a restricted constant (i.e. deterministic case (ii) of Remark 2.5), when calculating all of the tests. For the standard PLR tests we employed asymptotic critical values as reported in Table 15.2 of Johansen (1996).

We have shown that the standard PLR Q_r test of Johansen (1996), together with the wild bootstrap Q_r^b test outlined in section 3.1 and the i.i.d. bootstrap Q_r^s test of Swensen (2006) are all asymptotically valid under conditional heteroskedastiticy of the form given in Assumption 2. However, and unlike the wild bootstrap re-sampled data in (3.1), the i.i.d. re-sampled data will clearly not preserve the temporal ordering in the conditional heteroskedasticity present in the original data. We would therefore expect its finite sample performance to be quite similar to that of the asymptotic tests and to not perform as well as the wild bootstrap tests in the presence of conditional heteroskedasticity.

4.1 The Non-Co-Integrated Model ($r = 0$)

Table 1 reports the finite sample (empirical) size properties of both the standard PLR test, Q_0, and its wild and i.i.d. bootstrap analogue tests, Q_0^b and Q_0^s respectively, for $H(0) : r = 0$ against $H(p) : r = p$, for $p = 2, ..., 5$, in the presence of conditional heteroskedasticity of the types outlined above. Tables 2,3,4 and 5 report for $p = 2$, 3, 4 and 5, respectively, the corresponding properties of the sequential procedures of Johansen (1996) using the Q_r, Q_r^b and Q_r^s ($r = 0, ..., p-1$) tests (as described in footnote 1 with significance level $\xi = 0.05$) in the column blocks headed Q-based, Q^b-based and Q^s-based, respectively.

Tables 1 – 5 about here

Consider first the results in Table 1. Under constant conditional variances (the cases where $d_0 = d_1 = 0$ in Models A and B) it can be seen from the first two panels of Table 1 that both the Q_0^b and Q_0^s tests display finite sample sizes which are closer to the nominal level than the standard Q_0 test based on asymptotic critical values (the wild bootstrap can, however, be a little undersized); for example, in the case of Model A for $p = 5$, while the standard PLR test has size of 8.1% for $T = 100$, the corresponding wild and i.i.d. bootstrap tests have size of 4.4% and 4.7% respectively.

It is, however, where the innovation process displays conditional heteroskedasticity that the benefits of the wild bootstrap over the other tests become clear. The results in Table 1 show that both the Q_0 and Q_0^s tests can display quite unreliable size properties, even for samples as large as $T = 200$, in the presence of conditional heteroskedasticity. In contrast, the size properties of our wild bootstrap PLR test, Q_0^b, seem largely satisfactory throughout.

The size distortions seen in the Q_0 and Q_0^s tests are generally worse, other things being equal, the higher is the VAR dimension, p. For example, in the case of Model A with $d_0 = 0.3$, $d_1 = 0.65$ and $T = 200$, the Q_0 and Q_0^s have size of 10% and 9.3%, respectively, for $p = 2$ rising to 13.9% and 10.9%, respectively, for $p = 5$. In contrast, here the Q_0^b test has size of 5.6% and 5.7% for $p = 2$ and $p = 5$, respectively. The precise model of conditional heteroskedasticity can also make quite a substantial difference to the size properties of the tests. For example, comparing the results for Models A and B, we see that t_5 innovations tend to cause rather less size inflation than is seen for standard normal innovations. Of all the models considered, it is the autoregressive stochastic volatility case, Model F, which has the strongest impact on the size of the tests. The two parameter configurations both imply relatively strong serial dependence in the conditional variance of the innovation process (although in both cases the process does formally satisfy Assumption 2). Here the standard PLR test, Q_0, displays size of between around 20% to 40% depending on p and the parameter configuration, while the i.i.d. bootstrap test, Q_0^s, performs only slightly better. Although the wild bootstrap test, Q_0^b, does also show a degree of over-size under Model F, it still represents an enormous improvement on the size properties of the other tests. Moreover, what size distortions there are in the wild bootstrap tests are ameliorated, other things equal, as the sample size is increased. Notice that this last observation is not the case for the Q_0 and Q_0^s tests where the size distortions *increase* as the sample size increases. Very significant over-sizing, although not as bad as for Model F, is also seen for the Q_0 and Q_0^s tests in each of Models C, D and E. Again here the wild bootstrap test is much better behaved throughout.

Consider next the results in Tables 2-5. Since all of the tests were run at the 5% significance level, the standard and bootstrap sequential procedures should, in the limit, select $r = 0$ with probability 95% and $r > 0$ with (combined) probability 5%. Consistent with the results in Table 1, we see that, in general, the procedure based on the wild bootstrap PLR tests gets considerably closer to these proportions in small samples than do the procedures based on the standard and i.i.d. bootstrap PLR tests, the latter two tending to perform worse the higher is p. Indeed these latter two procedures can perform very poorly indeed under conditional heteroskedasticity. For example, under Model F for the first parameter configuration and $p = 5$ the procedures based on the standard and i.i.d. PLR tests select the correct co-integrating rank only 62.9% and 69.2% of the time, respectively, even for $T = 200$; indeed, each will wrongly indicate that the true co-integrating rank is two about 5% of the time. In contrast, the procedure based on the wild bootstrap PLR tests appears to perform very well in practice, with its empirical probability of selecting the true co-integrating rank of zero converging rapidly towards 95% throughout; cf. Remark 3.7. In the same example as above, the wild bootstrap-based procedure selects the true co-integrating rank 92.1% of the time, and a rank of two only around 1% of the time.

4.2 The Co-Integrated Model ($r = 1$)

Consider first the results in Table 6 for the empirical sizes of the standard PLR Q_1 test and its i.i.d. and wild bootstrap analogues. The results here are very much in line with those seen in Table 1 with the standard PLR and its i.i.d. bootstrap analogue test not displaying anything like adequate size control in the presence of conditional heteroskedasticity. The observed size distortions again worsen, others things being equal, as p is increased. Again the worst distortions are seen in these tests under Model F, with serious over-size problems also seen under Models C, D and E. For the $GO-GARCH(1,1)$ case (Models A and B) the observed size distortions are again generally smaller under t_5 innovations than $N(0,1)$ innovations. In contrast to the standard and i.i.d. bootstrap PLR tests, the wild bootstrap PLR test displays very good size control throughout, with size only ever exceeding 7% in the case of Model F, where although still a little over-sized it does, nonetheless, still represent a massive improvement over the other tests.

Tables 6 – 10 about here

Tables 7, 8, 9 and 10 report corresponding results for the sequential procedure of Johansen (1996) for each of the three tests for $p = 2, 3, 4$ and 5, respectively. Again the procedures based on the Q_r, Q_r^b and Q_r^s $(r = 0, ..., p-1)$ tests are reported in the column blocks headed Q-based, Q^b-based and Q^s-based, respectively. Since now the co-integrating rank is one, these procedures should, in the limit, select $r = 0$ with probability 0%, $r = 1$ with probability 95% and $r > 1$ with (combined) probability 5%. While these proportions are largely maintained, at least for $T = 200$, by the wild bootstrap-based procedure, the same cannot be said for the procedures based on the standard PLR and i.i.d. bootstrap PLR tests, which as with the corresponding results in Tables 2-5 can display a strong tendency to over-estimate the co-integrating rank under conditional heteroskedasticity, even in quite large samples. It is also interesting to also note that in the smaller sample sizes considered the standard and i.i.d. bootstrap-based procedures display a lesser tendency to under-estimate the true co-integration rank than the wild bootstrap-based procedure: for example, when $p = 3$ and $T = 50$, under Model D the procedure based on the standard PLR tests selects a co-integrating rank of zero 26.6% of the time, while the wild bootstrap procedure does so 40.1% of the time. This result is, of course, an artefact of the uncontrolled size of the standard Q_0 test, this test in fact having size of 14.4% in this case; cf. Table 1.

Finally, in the case where volatility is constant (models A and B with $d_0 = d_1 = 0$), and for the larger sample sizes considered (so that the standard Q_0 test is not heavily over-sized when $r = 0$ - see Table 1), observe from Tables 7-10 that the Q_0^b test does not lose power against $r = 1$, relative to the Q_0 and Q_0^s tests. This is very encouraging because it implies that in cases where the tests are all approximately correctly sized the wild bootstrap does not lose power relative to the other tests, despite displaying far superior size properties than the other tests where conditional heteroskedasticity does occur; cf. Tables 1 and 6.

4.3 The Non-Co-Integrated VAR(2) Model

To conclude this section, and following Johansen (2002, p.1940), we report some additional results investigating the finite sample behaviour under the null hypothesis of tests for $\Pi = 0$ in the VAR(2) model

$$\Delta X_t = \Pi X_{t-1} + \Gamma_1 \Delta X_{t-1} + \varepsilon_t$$

with $\Gamma_1 = \xi I_p$, $-1 < \xi < 1$. This model is an interesting extension of the conditionally heteroskedastic VAR(1) model considered in sections 4.1 and 4.2 because it allows for higher-order stationary serial correlation. To that end we set $\xi = 0.5$, which allows for a moderate degree of stationary serial correlation in the process. As regards the innovation term, ε_t, we again considered each of Models A-F, reporting results for a subset of the parameter configurations reported for Models A, B and F in sections

4.1 and 4.2.[3] A restricted constant was again included in the estimated model. Table 11 reports results for both the standard PLR test and its wild and i.i.d. bootstrap analogue tests for $H(0): r = 0$ against $H(p): r = p$, for $p = 2, ..., 5$.

Table 11 about here

In general, it can be seen from the results in Table 11 that higher-order stationary serial correlation tends to inflate the finite sample size of the standard PLR test, Q_0, further above its nominal level, relative to the corresponding results for the VAR(1) case in Table 1. This is true in both the conditionally homoskedastic and conditionally heteroskedastic cases. To illustrate, for $p = 4$ in the i.i.d. innovations case (Model A with $d_0 = d_1 = 0$) the Q_0 test has size of 41.5% for $T = 50$, reducing to 10.9 % for $T = 200$, as compared to 8.7% and 6.5% respectively for the VAR(1) case in Table 1. Both bootstrap tests also display a degree of over-size for $T = 50$ in this case, but these distortions are much smaller than for the Q_0 test (8.5% for the Q^b test and 8.9% for the Q^s test) and are all but eliminated by $T = 200$. As a second example, under Model C for $p = 5$ the Q_0 test has size of 73% for $T = 50$ (22.5 % for $T = 200$) compared with 20% (14.7%) in the corresponding VAR(1) model. Again the higher-order serial correlation does affect the finite sample size of both bootstrap tests, but again this is to a much lesser extent than for the Q_0 test: in the last example, the size of the Q^b and Q^s bootstrap tests are 12.5% and 15.6% (6.5% and 10.2% for $T = 200$), respectively, compared to 7.1% and 10.1% (5.7% and 11.2% for $T = 200$), respectively, in Table 1. Overall, both bootstrap tests deal much better with higher-order serial correlation than does the Q_0 test.

As with the results in Table 1 for the VAR(1) case, in the VAR(2) case the results in Table 11 show that the wild bootstrap Q_0^b test again displays far more robust finite sample size properties than either the Q_0 or the Q_0^s test in the presence of conditional heteroskedasticity.

5 Empirical application

In this section we illustrate the methods discussed in this paper with a short application to the term structure of interest rates; see Campbell and Shiller (1987) for an early reference. According to traditional theory, aside from a constant or stationary risk premium, long-term interest rates are an average of current and expected future short term rates over the life of the investment. Hence, provided interest rates are well described as $I(1)$ variables, bond rates at different maturities should be driven by a single common stochastic trend, with the spreads between rates at different maturities being stationary. Although early studies tend to corroborate this view, see, for example, Hall *et al.* (1992), more recent research, based on broader sets of maturities, suggests that yields are better characterised by *more* than one common trend, reflecting possible

[3] This was done in the interests of space, the additional results qualitatively adding very little to what is reported.

non-stationarities in the risk premia and additional risk factors, such as the slope and curvature of the yield curve; see, for example, Diebold, Ji and Li (2007) and Giese (2006).

We consider monthly interest rate data from the United States, Canada, the United Kingdom, and Japan, taken from the OECD/MEI database. For each country a single long-run interest rate, L_t, and a variety of short-run rates, S_{it}, were used in the co-integration analysis. Specifically, these were as follows. United States (1978:1–2002:12): L_t = government composite bond yield (> 10 years); S_{1t} = federal funds rate; S_{2t} = prime rate; S_{3t} = rate on certificates of deposit; S_{4t} = US dollar in London, 3-month deposit rate. Canada (1982:6–2002:12): L_t = benchmark bond yield (10 years); S_{1t} = official discount rate; S_{2t} = overnight money market rate; S_{3t} = rate on 90-day deposits. United Kingdom (1978:1–2002:12): L_t = yield on 10-year government bonds; S_{1t} = London clearing banks rate; S_{2t} = overnight interbank rate; S_{3t} = rate on 3-month interbank loans. Japan (1989:1–2002:12): L_t = yield on interest bearing government bonds (10 years); S_{1t} = official discount rate; S_{2t} = un-collateralized overnight rate; S_{3t} = rate on 90-day certificates of deposit.

For each country let $X_t := (L_t, S_{1t}, ..., S_{p-1,t})'$, where $p = 4$ for all but the U.S. where $p = 5$. As is standard, we fit a VAR model for X_t with restricted intercept; that is, $D_{2t} = 0$ and $D_{1t} = 1$ in (2.4). The VAR was estimated using Gaussian maximum likelihood under the assumption of constant volatility; cf. Section 2. For each country the number of lags, k, was estimated using the BIC: for the U.K., Japan and the U.S. $k = 2$ was chosen, while for Canada $k = 1$ obtained. For each country the residuals from the fitted VAR(k) model were subjected to both single-equation and vector diagnostic tests against non-normality, GARCH(1,1), and general heteroskedasticity (using White's test both with and without cross-variable terms).[4] In the case of the U.K. and the U.S. all of the single-equation and vector tests rejected at the 1% level. For Canada this was also the case, except that two of the single equation GARCH(1,1) were not significant. For Japan, all of the vector tests rejected at the 1% level, as did all of the single-equation normality tests. However, none of the GARCH(1,1) tests were significant, while White's single-equation tests delivered three (two) out of four significant outcomes at the 1% level when cross-variable terms were (were not) included. In summary, the interest rate data for all of the countries considered display (to varying degrees) statistically significant evidence of heteroskedasticity.

Table 12 about here

Table 12 reports the results of the standard, wild and i.i.d. bootstrap co-integration rank tests for each country. For the standard tests (asymptotic) p-values were computed as suggested in MacKinnon, Haug and Michelis (1999). For both of the bootstrap methods the number of bootstrap replications was set to 399.

For each country, the standard sequential procedure detects two co-integrating relations at any conventional significance level, with a third co-integration relation being

[4]The complete set of diagnostic test results can be obtained from the authors on request.

significant at the 10% level (with a p-value of 0.08) in the case of the U.S. data. The same conclusions are drawn using the corresponding procedure based on the i.i.d. bootstrap tests of Swensen (2006), except that the third co-integrating vector in the case of the U.S. is deemed insignificant at the 10% level (with a p-value of 0.12). In line with what would be expected from the Monte Carlo simulation results in section 4 for series displaying a significant degree of heteroskedasticity, the wild bootstrap-based procedure consistently delivers a higher p-value for a given hypothesised co-integrating rank. For both the U.K. and Canada this does not lead us to a different conclusion on the co-integrating rank (of two) as was drawn from the standard and i.i.d. bootstrap tests. However, for both Japan and the U.S. only one co-integrating vector is uncovered by the wild bootstrap procedure, implying the presence of four common trends in the five-dimensional U.S. system, and three common trends in the four-dimensional Japanese system.

These results all therefore contradict the traditional view of the expectation hypothesis of the term structure, suggesting the presence of additional risk factors, since the hypothesis of $p-1$ stationary relations (p being the number of interest rates considered) is never accepted, thereby providing further support in favour of recent multi-factor theories of the term structure; see, for example, Diebold, Ji and Li (2007). It is worth noting, however, that in the case of the U.S. data the p-value for testing $p-2$ against $p-1$ co-integrating relations is 12% using the asymptotic test and 15% using the i.i.d. bootstrap test. For the wild bootstrap this p-value rises sharply to 62%. The case of the U.S. data shows the biggest differences between the wild bootstrap procedure and those based on either the asymptotic test or the i.i.d. bootstrap tests of Swensen (2006). Given the significant heteroskedasticity found in the U.S. data (indeed the outcomes of the diagnostic test statistics were consistently much larger for the U.S. than for the other countries considered) the inferences from the wild bootstrap-based procedure would appear to be the most reliable.

6 Conclusions

In this paper we have demonstrated that the conventional co-integration rank tests of Johansen (1996) retain their usual limiting null distributions in the case where the innovations follow a possibly non-stationary, conditionally heteroskedastic (martingale difference) process. We have also proposed wild bootstrap-based implementations of the co-integration rank tests in order to exploit the information in sample on the conditional heteroskedasticity, where present. As with any bootstrap procedure, no tables of critical values are required as the procedure automatically delivers a p-value for the hypothesis being tested. Both our proposed wild bootstrap scheme and the i.i.d. bootstrap scheme of Swensen (2006) were demonstrated to deliver rank statistics which share the same first-order limiting null distributions as the corresponding standard rank statistic. Monte Carlo evidence presented suggests that the proposed wild bootstrap co-integrating rank tests perform very well in finite samples, being considerably more robust than both the standard PLR tests based on asymptotic critical values and i.i.d. residual-based bootstrap analogues of the PLR tests, when the innovations are conditionally heteroskedastic. An empirical application to interest rate data from several major economies was also reported which suggested the presence of more than one common trend in bond yields over different maturities, consistent with recent multi-factor theories of the term structure.

A Appendix

This section contains the proofs of the main theorems given in the paper. Proofs for Theorems 1 and 2 are collected in section A.1. The proof of the validity of the wild bootstrap co-integration test is reported in section A.2, while the corresponding result for the i.i.d. bootstrap test of Swensen (2006) is detailed in section A.3.

A.1 Proof of Theorems 1 and 2

Under the stated assumptions, the process X_t has the representation below in Lemma A.1 which is essential for the proofs of Lemmas A.2 and A.3. Lemma A.1 generalises the usual Granger-type representation in Johansen (1996) in that, rather than being *i.i.d.*, the ε_t sequence is now, by assumption, a (possibly non-stationary) MDS.

Lemmas A.2 and A.3 immediately imply that the proofs of Theorem 11.1 and Lemma 13.1 in Johansen (1996) hold, establishing Theorem 1 and 2 respectively. □

Lemma A.1 *Under the conditions of Theorem 1,*

$$X_t = C\sum_{i=1}^{t}\varepsilon_i + S_t + C_0. \tag{A.1}$$

Here the $(p\times p)-$*dimensional matrices* $C := \beta_\perp\left(\alpha'_\perp\Gamma\beta_\perp\right)^{-1}\alpha'_\perp$ *and* $C_0 := C(I_p, -\Psi)\mathbb{X}_0$. *Define the* $(r+p(k-1))$*-dimensional autoregressive process* $\mathbb{X}_{\beta t}$ *where* $\mathbb{X}_{\beta t} := \beta' X_t$ *for* $k=1$, *and otherwise,* $\mathbb{X}_{\beta t} := \left(X'_t\beta, \Delta X'_t, ..., \Delta X'_{t-k+1}\right)'$. *Then the p-dimensional process* $S_t := (\alpha, \Psi)\, Q\mathbb{X}_{\beta t}$, *where* $\mathbb{X}_{\beta t}$ *has the* $MA(\infty)$ *representation,* $\mathbb{X}_{\beta t} = \Phi\left(L\right)\eta_t = \sum_{i=0}^{\infty}\Phi^i\eta_{t-i}$. *Here* $\eta_t := (\beta, I_p, 0, ..., 0)'\,\varepsilon_t$ *and the spectral radius of* Φ *is smaller than one;* $\rho\left(\Phi\right) < 1$. *The* $(r+p(k-1))\times(r+p(k-1))$ *dimensional matrix* Q *is non-singular.*

Proof: With $\mathbb{X}_t := \left(X'_t, ..., X'_{t-k+1}\right)'$ the system can be written in companion form as,

$$\Delta\mathbb{X}_t = \mathbb{A}\mathbb{B}'\mathbb{X}_{t-1} + e_t \tag{A.2}$$

with $e_t := (\varepsilon_t', 0, ..., 0)'$, $\mathbb{X}_0$ fixed and

$$\mathbb{A} := \begin{pmatrix} \alpha & \Gamma_1 & \Gamma_2 & ... & \Gamma_{k-1} \\ 0 & I_p & 0 & ... & 0 \\ 0 & 0 & I_p & ... & 0 \\ ... & ... & ... & ... & ... \\ 0 & 0 & 0 & ... & I_p \end{pmatrix} \quad \mathbb{B} := \begin{pmatrix} \beta & I_p & 0 & ... & 0 \\ 0 & -I_p & I_p & ... & 0 \\ 0 & 0 & -I_p & ... & 0 \\ ... & ... & ... & ... & ... \\ 0 & 0 & 0 & ... & -I_p \end{pmatrix}. \tag{A.3}$$

Note that with $\mathbb{X}_{\beta t} := \mathbb{B}'\mathbb{X}_t$, $\Phi := \left(I_{r+p(k-1)} + \mathbb{B}'\mathbb{A}\right)$, then $\mathbb{X}_{\beta t} = \Phi\mathbb{X}_{\beta t-1} + \mathbb{B}'e_t$. By Assumption 1, $\rho(\Phi) < 1$ and $\mathbb{X}_{\beta t}$ has the stated MA(∞) representation. Standard arguments and recursions give,

$$\mathbb{X}_t = \mathbb{C}\sum_{i=1}^{t} e_i + \mathbb{S}_t + \mathbb{C}\mathbb{X}_0 \tag{A.4}$$

where $\mathbb{C} := \mathbb{B}_\perp(\mathbb{A}_\perp'\mathbb{B}_\perp)^{-1}\mathbb{A}_\perp'$, and $\mathbb{S}_t := \mathbb{A}\left(\mathbb{B}'\mathbb{A}\right)^{-1}\mathbb{X}_{\beta t}$. As $X_t = (I_p, 0, ..., 0)\,\mathbb{X}_t$, the results in Lemma A.1 hold with $S_t = (I_p, 0, ..., 0)\,\mathbb{S}_t = (\alpha, \Psi)\,Q\mathbb{X}_{\beta t}$, $Q := (\mathbb{B}'\mathbb{A})^{-1}$. Noting that,

$$\mathbb{A}_\perp = (I_p, -\Gamma_1, ..., -\Gamma_{k-1})'\,\alpha_\perp, \quad \mathbb{B}_\perp = (I_p, ..., I_p)'\,\beta_\perp$$

the various expressions follow by simple algebraic identities. □

Let $\Omega_{\beta\beta} := \operatorname*{plim}_{T\to\infty} T^{-1}\sum_{t=1}^{T}\beta' Z_{1t}Z_{1t}'\beta$, $\Omega_{\beta i} := \operatorname*{plim}_{T\to\infty} T^{-1}\sum_{t=1}^{T}\beta' Z_{1t}Z_{it}'$ for $i = 0, 2$, and $\Omega_{ij} := \operatorname*{plim}_{T\to\infty} T^{-1}\sum_{t=1}^{T} Z_{it}Z_{jt}'$, $i, j = 0, 2$. By Lemma A.1, these are well-defined as infinite sums in terms of exponentially decaying coefficients. For example, since $\rho(\Phi) < 1$,

$$\Omega_{\beta 0} = \beta'(\alpha, \Psi)\,Q\sum_{i=0}^{\infty}\left[\Phi^i(\beta, I_p, 0, ..., 0)'\,\Sigma\,(\beta, I_p, 0, ..., 0)\,\Phi^{i\prime}\right](\alpha, \Psi)'.$$

In terms of these moment matrices we have the following results.

Lemma A.2 *Under the conditions of Theorem 1, and as $T \to \infty$,*

$$S_{00} \xrightarrow{p} \Sigma_{00},\ \beta' S_{10} \xrightarrow{p} \Sigma_{\beta 0} \text{ and } \beta' S_{11}\beta \xrightarrow{p} \Sigma_{\beta\beta} \tag{A.5}$$

where $\Sigma_{ij} = \Omega_{ij} - \Omega_{i2}\Omega_{22}^{-1}\Omega_{2j}$, $i, j = 0, 1, \beta$. Moreover, the following identities hold,

$$\Sigma_{00} = \alpha\Sigma_{\beta 0} + \Sigma,\ \Sigma_{0\beta} = \alpha\Sigma_{\beta\beta} \tag{A.6}$$

and

$$\Sigma_{00}^{-1} - \Sigma_{00}^{-1}\alpha(\alpha'\Sigma_{00}^{-1}\alpha)^{-1}\alpha'\Sigma_{00}^{-1} = \alpha_\perp(\alpha_\perp'\Sigma\alpha_\perp)^{-1}\alpha_\perp'. \tag{A.7}$$

Proof: Consider $\beta' S_{10} = \beta' M_{10} - \beta' M_{12}M_{22}^{-1}M_{20}$. Using Lemma A.1 and the fact that, by definition,

$$\Delta X_t = \alpha\beta' X_{t-1} + \Psi U_t + \varepsilon_t = (\alpha, \Psi)\,\mathbb{X}_{\beta t-1} + \varepsilon_t, \tag{A.8}$$

the first term equals,

$$\beta' M_{10} = \frac{1}{T}\sum_{t=1}^{T} \beta' X_{t-1}\Delta X_t' = \frac{1}{T}\sum_{t=1}^{T} \beta' S_{t-1}\left(\left(\alpha, \Psi\right)\mathbb{X}_{\beta t-1} + \varepsilon_t\right)'.$$

As mentioned in section 2, the strong law of large numbers in Hennan and Heyde (1972) can be applied by Assumption 2 and the fact that the coefficients Φ^i in the representation for $\mathbb{X}_{\beta t}$ in are exponentially decreasing by Lemma A.1. We then obtain directly that:

$$\beta' M_{10} \xrightarrow{p} \Omega_{\beta 0} := \beta'\left(\alpha, \Psi\right) Q \sum_{i=0}^{\infty}\left[\Phi^i\left(\beta, I_p, 0, ..., 0\right)' \Sigma\left(\beta, I_p, 0, ..., 0\right)\Phi^{i\prime}\right]\left(\alpha, \Psi\right)'.$$

Likewise, the terms $\beta' M_{12}$, M_{22} and M_{20} converge in probability and we conclude that

$$\beta' S_{10} \xrightarrow{p} \Sigma_{\beta 0} := \Omega_{\beta 0} - \Omega_{\beta 2}\Omega_{22}^{-1}\Omega_{20}\ .$$

Identical arguments lead to the other results in (A.5).

The identities in (A.6) follow by post-multiplying (A.8) by (the transpose of) $\beta' X_{t-1}, \Delta X_t$ and U_t respectively, taking averages and applying the law of large numbers as above, and solving the resulting system of equations. To prove the identity in (A.7) use the projection identity

$$I_p = \Sigma_{00}^{-1}\alpha(\alpha'\Sigma_{00}^{-1}\alpha)^{-1}\alpha' + \alpha_\perp(\alpha_\perp'\Sigma_{00}\alpha_\perp)^{-1}\alpha_\perp'\Sigma_{00}$$

and $\alpha_\perp'\Sigma_{00} = \alpha_\perp'\Sigma$; see (A.6). □

Lemma A.3 *Define the* $(p-r)$*-dimensional process,*

$$G(u) := \beta_\perp' C W(u), \tag{A.9}$$

where $W(\cdot)$ *is a* p*-dimensional Browian motion with covariance* Σ*. Then under the conditions of Theorem 1, as* $T \to \infty$*,*

$$\frac{1}{\sqrt{T}}\beta_\perp' X_{\lfloor Tu \rfloor} \xrightarrow{w} G(u) \tag{A.10}$$

$$\beta_\perp' S_{10}\alpha_\perp = \beta_\perp' S_{12}\alpha_\perp \xrightarrow{w} \int_0^1 G\left(s\right) dW\left(s\right)'\alpha_\perp \tag{A.11}$$

$$\frac{1}{T}\beta_\perp' S_{11}\beta_\perp \xrightarrow{w} \int_0^1 G(s)G(s)' ds \tag{A.12}$$

and furthermore,

$$\sqrt{T}\beta' S_{10}\alpha_\perp = \sqrt{T}\beta' S_{1\varepsilon}\alpha_\perp \xrightarrow{w} N_{r\times p-r}(0, \Sigma_{\beta\beta}\otimes\alpha_\perp'\Sigma\alpha_\perp) \tag{A.13}$$

$$\beta' S_{11}\beta_\perp \in O_p(1). \tag{A.14}$$

PROOF: The result in (A.10) holds by using the FCLT in Brown (1971) (see Remark 2.2) applied to ε_t as Lemma A.1 implies directly that $\beta'_\perp X_{\lfloor T\cdot\rfloor} = \beta'_\perp C \sum_1^{\lfloor T\cdot\rfloor} \varepsilon_t + o_p(\sqrt{T})$. To prove (A.11) note that

$$\beta'_\perp S_{1\varepsilon} = \beta'_\perp M_{1\varepsilon} - \beta'_\perp M_{12} M_{22}^{-1} M_{2\varepsilon}$$

where $M_{1\varepsilon} := T^{-1} \sum_{t=1}^T \Delta X_t \varepsilon'_t$. Consider first $\beta'_\perp M_{1\varepsilon}$ and use the representation of X_t given in (A.1) to see that

$$\beta'_\perp M_{1\varepsilon} = \frac{1}{T}\left(\beta'_\perp C \sum\nolimits_{t=1}^{T} (\sum\nolimits_{i=1}^{t-1} \varepsilon_i)\varepsilon'_t + \beta'_\perp \sum\nolimits_{t=1}^{T} S_{t-1}\varepsilon'_t + \beta'_\perp C_0 \sum\nolimits_{t=1}^{T} \varepsilon'_t\right)$$

which by Hansen (1992), the LLN and the fact that ε_t and ε_{t-1} are uncorrelated, weakly converges to $\int_0^1 G(s)\, dW(s)'$. Next, $M_{\varepsilon 2} := T^{-1}\sum_{t=1}^T \varepsilon_t U'_t$ tends to zero in probability by the law of large numbers. Since $\beta'_\perp M_{12} \in O_p(1)$ and M_{22} converges in probability by the law of large numbers, we conclude that (A.11) holds. The result in (A.12) follows immediately from (A.10) and the continuous mapping theorem. Finally (A.13) holds by applying the central limit theorem to the MDS $\beta' X_{t-1}\varepsilon'_t$, rewriting $S_{1\varepsilon}$ as above. □

A.2 Proof of Theorem 3

While our results are new and generalize the results in Swensen (2006), we closely follow the sequence of arguments in Swensen (2006). As there we use P^* to denote the bootstrap probability and likewise E^* to denote expectation under P^*. Thus, as in Swensen (2006, proof of Proposition 1), the weak convergence in probability result in Theorem 3, $Q_r^b \xrightarrow{w}_p Q_{r,\infty}$, can be shown to hold by using Lemmas A.6 and A.7 below. These extend Lemmas A.2 and A.3 in the proof of Theorem 1 to the case of the wild bootstrap data. Specifically, Lemmas A.4, A.5, A.7 and A.6 below extend and generalize Lemmas 1, S1 and S2 used in Swensen (2006, proof of Proposition 1) for IID bootstrap shocks.

Establishing that $Q_r^b \xrightarrow{w}_p Q_{r,\infty}$ implies $G_{r,T}^b(\cdot) \to G_{r,\infty}(\cdot)$, uniformly in probability, where $G_{r,\infty}$ denotes the cumulative distribution function of $Q_{r,\infty}$. Then, using the same arguments as in the proof of Theorem 5 in Hansen (2000b), it is entirely straightforward to prove that $p_{r,T}^b \xrightarrow{w} U[0,1]$ given the foregoing results. This completes the proof.

We now move to establishing the intermediate lemmas referred to above, establishing a Granger-type representation and an invariance principle for the bootstrap data, analogous to those given for the original data in Lemmas A.1 and A.3 respectively.

Lemma A.4 *Under the conditions of Theorem 1,*

$$X_t^b = \hat{C}\sum_{i=1}^{t} \varepsilon_i^b + T^{1/2} R_t^b$$

where for all $\eta > 0$, $P^*\left(\max_{t=1,\ldots,T} \left\|R_t^b\right\| > \eta\right) \to 0$ *in probability as* $T \to \infty$.

PROOF: From the proof of Lemma A.1 with $\mathbb{X}_t^b := \left(X_t^{b\prime}, ..., X_{t-k+1}^{b\prime}\right)'$ and $\mathbb{X}_0^b := 0$ we find directly as in (A.4) that $X_t^b = (I_p, 0, ..., 0)\, \mathbb{X}_t^b$ has the representation,

$$X_t^b = \hat{C} \sum_{i=1}^{t} \varepsilon_i^b + T^{1/2} R_t^b$$

with

$$\begin{aligned} \hat{C} &:= (I_p, 0, ..., 0)\, \widehat{\mathbb{B}}_\perp (\widehat{\mathbb{A}}_\perp' \widehat{\mathbb{B}}_\perp)^{-1} \widehat{\mathbb{A}}' = \hat{\beta}_\perp (\hat{\alpha}_\perp' \hat{\Gamma} \hat{\beta}_\perp)^{-1} \hat{\alpha}_\perp' \\ R_t^b &:= (\hat{\alpha}, \hat{\Psi})(\widehat{\mathbb{B}}' \widehat{\mathbb{A}})^{-1} \sum_{i=0}^{t-1} \hat{\Phi}^i (T^{-1/2} \widehat{\mathbb{B}}' e_{t-i}^b) \end{aligned}$$

and where $\hat{\Phi} := (I_{pk} + \widehat{\mathbb{B}}' \widehat{\mathbb{A}})$ and $\hat{\Psi} := (\hat{\Gamma}_1, ..., \hat{\Gamma}_{k-1})$. Note that in the definition of R_t^b the sum is *not* infinite as the bootstrap residuals are defined for $t \geq 1$ only. The matrices $\widehat{\mathbb{A}}$ and $\widehat{\mathbb{B}}$ are defined as $\mathbb{A}$,$\mathbb{B}$ of (A.3) with α and β replaced by the corresponding estimators $\hat{\alpha}, \hat{\beta}$, and $e_t^b := \left(\varepsilon_t^{b\prime}, 0, ..., 0\right)'$. Next, note that

$$\max_{t=1,...,T} \left\| R_t^b \right\| \leq \max_{t=1,...,T} \left\| (\hat{\alpha}, \hat{\Psi})(\widehat{\mathbb{B}}' \widehat{\mathbb{A}})^{-1} \sum_{i=0}^{t-1} \hat{\Phi}^i \left(T^{-1/2} \widehat{\mathbb{B}}' e_{t-i}^b \right) \right\| \leq \psi_T \max_{t=1,...,T} \left\| T^{-1/2} \eta_t^b \right\|$$

where $\eta_t^b = \widehat{\mathbb{B}}' e_t^b = \left(\hat{\beta}, I_p, 0, ..., 0\right)' \varepsilon_t^b$ and $\psi_T = \left\| (\hat{\alpha}, \hat{\Psi})(\widehat{\mathbb{B}}' \widehat{\mathbb{A}})^{-1} \right\| \left\| \sum_{i=0}^{T-1} \hat{\Phi}^i \right\|$. It follows that $\psi_T \xrightarrow{p} \psi$ by using the established consistency of the estimators in Theorem 2. In particular, note that for sufficiently large T we have, by continuity, that $\rho(\hat{\Phi}) < 1$, which implies that $||\hat{\Phi}^i|| \leq$const.λ^i for some $0 < \lambda < 1$, uniformly over i. Finally, showing that $P^* \left(\max_{t=1,...,T} \left\| T^{-1/2} \eta_t^b \right\| > \eta \right)$ is of order $o_p(1)$ implies the desired result that $P^* \left(\max_{t=1,...,T} \left\| R_t^b \right\| > \eta \right) \xrightarrow{p} 0$. This again holds if $P^* \left(T^{-1/2} \max_{t=1,...,T} \left\| \varepsilon_t^b \right\| > \eta \right) = o_p(1)$, which holds since

$$P^* \left(T^{-1/2} \max_{t=1,...,T} \left\| \varepsilon_t^b \right\| > \eta \right) \leq \frac{1}{\eta^4 T^2} \sum_{t=1}^{T} E^* \left(\varepsilon_t^{b\prime} \varepsilon_t^b \right)^2 = \frac{3}{\eta^4 T^2} \sum_{t=1}^{T} \left(\hat{\varepsilon}_t' \hat{\varepsilon}_t \right)^2 \xrightarrow{p} 0$$

since $T^{-1} \sum_{t=1}^{T} \left(\hat{\varepsilon}_t' \hat{\varepsilon}_t \right)^2 = O_p(1)$ under the assumption that ε_t has bounded fourth moment. □

Lemma A.5 *Under the conditions of Theorem 1,*

$$S_T^b(\cdot) := \frac{1}{T^{1/2}} \sum_{t=1}^{\lfloor T \cdot \rfloor} \varepsilon_t^b \xrightarrow{w}_p W(\cdot) \quad .$$

PROOF: Conditionally on $\{\hat{\varepsilon}_t\}_{t=1}^T$, $S_T^b(\cdot)$ is a Gaussian process with independent increments and covariance matrix

$$E^* \left(S_T^b(\cdot)\, S_T^b(\cdot)' \right) = \frac{1}{T} \sum_{t=1}^{\lfloor T \cdot \rfloor} \hat{\varepsilon}_t \hat{\varepsilon}_t'.$$

Consequently, Lemma A.5 follows if $T^{-1}\sum_{t=1}^{\lfloor Tu \rfloor}\hat{\varepsilon}_t\hat{\varepsilon}_t' \to u\Sigma$ in probability, uniformly for all $u \in [0,1]$. Now, since $T^{-1}\sum_{t=1}^{\lfloor Tu \rfloor}\hat{\varepsilon}_t\hat{\varepsilon}_t'$ is monotonically increasing in u and the limit function is continuous in u, it suffices to prove pointwise convergence; cf. Hansen (2000a, proof of Lemma A.10). Pointwise convergence follows by noticing that

$$\frac{1}{T}\sum_{t=1}^{\lfloor Tu \rfloor}\hat{\varepsilon}_t\hat{\varepsilon}_t' = \frac{1}{T}\sum_{t=1}^{\lfloor Tu \rfloor}\varepsilon_t\varepsilon_t' + o_p(1)$$

where $T^{-1}\sum_{t=1}^{\lfloor Tu \rfloor}\varepsilon_t\varepsilon_t' \to u\Sigma$, by the law of large numbers. □

Lemma A.6 *Let $G(\cdot)$ be defined as in (A.9). Then under the conditions of Theorem 1,*

$$\tfrac{1}{\sqrt{T}}\hat{\beta}_\perp' X^b_{\lfloor Tu \rfloor} \overset{w}{\to}_p G(u) \tag{A.15}$$

$$\hat{\beta}_\perp' S^b_{10}\alpha_\perp = \hat{\beta}_\perp' S^b_{12}\alpha_\perp \overset{w}{\to}_p \int_0^1 G(s)\,dW(s)'\,\alpha_\perp \tag{A.16}$$

$$\tfrac{1}{T}\hat{\beta}_\perp' S^b_{11}\hat{\beta}_\perp \overset{w}{\to}_p \int_0^1 G(s)G(s)'ds \tag{A.17}$$

and furthermore,

$$\sqrt{T}\hat{\beta}' S^b_{10}\hat{\alpha}_\perp = \sqrt{T}\hat{\beta}' S^b_{1\varepsilon}\hat{\alpha}_\perp \overset{w}{\to}_p N_{r\times p-r}(0,\Sigma_{\beta\beta}\otimes\alpha_\perp'\Sigma\alpha_\perp) \tag{A.18}$$

$$\hat{\beta}' S^b_{11}\hat{\beta} \in O_{p^*}(1) \tag{A.19}$$

in probability as $T \to \infty$.

Proof: Applying Lemma A.4 and Lemma A.5, the results hold as in Lemma S2 of Swensen (2006). □

Lemma A.7 *Under the conditions of Theorem 3,*

$$P^*\left(\left\|S^b_{00} - \Sigma_{00}\right\| > \eta\right) \to 0 \tag{A.20}$$

$$P^*\left(\left\|S^b_{01}\hat{\beta} - \Sigma_{0\beta}\right\| > \eta\right) \to 0 \tag{A.21}$$

$$P^*\left(\left\|\hat{\beta}' S^b_{11}\hat{\beta} - \Sigma_{\beta\beta}\right\| > \eta\right) \to 0 \tag{A.22}$$

in probability as $T \to \infty$.

Proof: In the interests of brevity, we only provide a proof of (A.20) here. Proofs of (A.21) and (A.22) can be obtained on request. Notice that $S^b_{00} = M^b_{00} - M^b_{02}\left(M^b_{22}\right)^{-1}M^b_{20}$ where the M^b_{ij} are the product moments in terms of the bootstrap data. Hence, as noted in Swensen (2006), (A.20) follows by establishing that $P^*\left(\left\|M^b-\Sigma_M\right\|>\eta\right)\to 0$, where

$$M:=\frac{1}{T}\sum_{t=1}^{T}\Delta\mathbb{X}_t\Delta\mathbb{X}_t',\ M^b:=\frac{1}{T}\sum_{t=1}^{T}\Delta\mathbb{X}_t^b\Delta\mathbb{X}_t^{b\prime}\ \text{ and }\ \Sigma_M:=\operatorname*{plim}_{T\to\infty}M$$

with $\mathbb{X}_t := \left(X_t',...,X_{t-k+1}'\right)'$ and $\mathbb{X}_t^b := \left(X_t^{b\prime},...,X_{t-k+1}^{b\prime}\right)'$. By Lemma A.1, $\mathbb{X}_{\beta t}=\sum_{i=0}^{\infty}\Phi^i\eta_{t-i}$ and, hence, (A.2), implies that

$$\Delta\mathbb{X}_t=\mathbb{A}\sum_{i=1}^{\infty}\Phi^{i-1}\left(\beta,I,0,...,0\right)'\varepsilon_{t-i}+\left(I,0,...,0\right)'\varepsilon_t:=\sum_{i=0}^{\infty}\theta_i\varepsilon_{t-i}. \tag{A.23}$$

Similarly, $\Delta\mathbb{X}_t^b=\sum_{i=0}^{t-1}\hat{\theta}_i\varepsilon_{t-i}^b$, $\varepsilon_t^b=\hat{\varepsilon}_t w_t$. As previously noted in the proof of Lemma A.4, for sufficiently large T, $\|\Phi^i\|,\left\|\hat{\Phi}^i\right\|<c\lambda^i$ for some generic constant $c>0$, $0<\lambda<1$, uniformly in i. In particular, the coefficients θ_i and $\hat{\theta}_i$ are exponentially decreasing. Next recall that $\Sigma_M=\sum_{i=0}^{\infty}\theta_i\Sigma\theta_i'$, and observe that with $\Sigma_{M^b}:=E^*\left(M^b\right)$,

$$\left\|M^b-\Sigma_M\right\|\le\left\|M^b-\Sigma_{M^b}\right\|+\left\|\Sigma_{M^b}-\Sigma_M\right\|.$$

To see that $\|\Sigma_{M^b}-\Sigma_M\|$ tends to zero in probability rewrite first Σ_{M^b} as:

$$\begin{aligned}\Sigma_{M^b}&=E^*\left(\frac{1}{T}\sum_{t=1}^{T}\left(\sum_{i=0}^{t-1}\hat{\theta}_i\varepsilon_{t-i}^b\right)\left(\sum_{i=0}^{t-1}\hat{\theta}_i\varepsilon_{t-i}^b\right)'\right)=\frac{1}{T}\sum_{t=1}^{T}\left(\sum_{i=0}^{t-1}\hat{\theta}_i\hat{\varepsilon}_{t-i}\hat{\varepsilon}_{t-i}'\hat{\theta}_i'\right)\\&=\frac{1}{T}\sum_{t=1}^{T}\left(\sum_{i=0}^{T-t}\hat{\theta}_i\hat{\varepsilon}_t\hat{\varepsilon}_t'\hat{\theta}_i'\right)=\frac{1}{T}\sum_{t=1}^{T}\left(\sum_{i=0}^{\infty}\hat{\theta}_i\hat{\varepsilon}_t\hat{\varepsilon}_t'\hat{\theta}_i'\right)-V_{1T},\end{aligned}$$

where $V_{1T}:=\frac{1}{T}\sum_{t=1}^{T}\left(\sum_{i=T-t+1}^{\infty}\hat{\theta}_i\hat{\varepsilon}_t\hat{\varepsilon}_t'\hat{\theta}_i'\right)=o_p(1)$. To see this, use the fact that $\theta_i=A\Phi^iB$, where A and B are constant matrices, see (A.23), and $\hat{\theta}_i=\hat{A}\hat{\Phi}^i\hat{B}$. In particular, for sufficiently large T, $\left\|\hat{\theta}_i\right\|\le c\lambda^i$, uniformly in i, and the result holds as $E\left\|\varepsilon_t\right\|^4<K<\infty$ and $\sum_{i=T-t+1}^{\infty}\lambda^{T-i}\to 0$ as $T\to\infty$. Next, observe that

$$\begin{aligned}&\frac{1}{T}\sum_{t=1}^{T}\left(\sum_{i=0}^{\infty}\hat{\theta}_i\hat{\varepsilon}_t\hat{\varepsilon}_t'\hat{\theta}_i'\right)-\Sigma_M\\&=\left(\sum_{i=0}^{\infty}\hat{\theta}_i\left(\frac{1}{T}\sum_{t=1}^{T}\hat{\varepsilon}_t\hat{\varepsilon}_t'\right)\hat{\theta}_i'-\sum_{i=0}^{\infty}\hat{\theta}_i\Sigma\hat{\theta}_i'\right)+\left(\sum_{i=0}^{\infty}\hat{\theta}_i\Sigma\hat{\theta}_i'-\Sigma_M\right)\\&=:V_{2T}+V_{3T}.\end{aligned}$$

It then follows that, as $T\to\infty$,

$$\|V_{2T}\|\le\left\|\sum_{i=0}^{\infty}\left(\hat{\theta}_i\otimes\hat{\theta}_i\right)\right\|\left\|\frac{1}{T}\sum_{t=1}^{T}\hat{\varepsilon}_t\hat{\varepsilon}_t'-\Sigma\right\|\xrightarrow{p}0$$

by the result that $T^{-1}\sum_{t=1}^{T}\hat{\varepsilon}_t\hat{\varepsilon}_t' \xrightarrow{p} \Sigma$ (see Theorem 2), and because $\left\|\sum_{i=0}^{\infty}\left(\hat{\theta}_i\otimes\hat{\theta}_i\right)\right\|$ is of order one. Also,

$$\mathsf{vec}\left(V_{3T}\right)=\left(\sum_{i=0}^{\infty}\left(\hat{\theta}_i\otimes\hat{\theta}_i\right)-\sum_{i=0}^{\infty}\left(\theta_i\otimes\theta_i\right)\right)\mathsf{vec}\left(\Sigma\right)\xrightarrow{p}0,$$

using, as above, the fact that $\theta_i=A\Phi^iB$ and $\hat{\theta}_i=\hat{A}\hat{\Phi}^i\hat{B}$.

Finally, consider the term $\left\|M^b-\Sigma_{M^b}\right\|$. We have

$$\begin{aligned}
M^b&=\frac{1}{T}\sum_{t=1}^{T}\left(\sum_{i=0}^{t-1}\hat{\theta}_i\varepsilon_{t-i}^b\right)\left(\sum_{i=0}^{t-1}\hat{\theta}_i\varepsilon_{t-i}^b\right)'\\
&=\frac{1}{T}\sum_{t=1}^{T}\left(\sum_{i=0}^{t-1}\hat{\theta}_i\varepsilon_{t-i}^b\left(\hat{\theta}_i\varepsilon_{t-i}^b\right)'\right)+\frac{1}{T}\sum_{t=1}^{T}\left(\sum_{i,j=0,i\neq j}^{t-1}\hat{\theta}_i\varepsilon_{t-i}^b\varepsilon_{t-j}^{b\prime}\hat{\theta}_j'\right)\\
&=:M_1^b+M_2^b.
\end{aligned}$$

First, notice that

$$M_1^b-\Sigma_{M^b}=\frac{1}{T}\sum_{t=1}^{T}\left(\sum_{i=0}^{t-1}\hat{\theta}_i\hat{\varepsilon}_{t-i}\hat{\varepsilon}_{t-i}'\hat{\theta}_i'\kappa_{t-i}\right)$$

with $\kappa_t:=\left(w_t^2-1\right)$ an i.i.d. process with mean zero and finite moments of all order. Now, since

$$\begin{aligned}
\frac{1}{T}\sum_{t=1}^{T}\left(\sum_{i=0}^{t-1}\mathsf{vec}\left(\hat{\theta}_i\hat{\varepsilon}_{t-i}\hat{\varepsilon}_{t-i}'\hat{\theta}_i'\kappa_{t-i}\right)\right)&=\frac{1}{T}\sum_{t=1}^{T}\left(\sum_{i=0}^{t-1}\kappa_{t-i}\left(\hat{\theta}_i\otimes\hat{\theta}_i\right)\mathsf{vec}\left(\hat{\varepsilon}_{t-i}\hat{\varepsilon}_{t-i}'\right)\right)\\
&=\frac{1}{T}\sum_{t=1}^{T}\kappa_t\sum_{i=0}^{T-t}\left(\hat{\theta}_i\otimes\hat{\theta}_i\right)\mathsf{vec}\left(\hat{\varepsilon}_t\hat{\varepsilon}_t'\right),
\end{aligned}$$

it therefore follows that,

$$\begin{aligned}
P^*\left(\left\|\frac{1}{T}\sum_{t=1}^{T}\left(\sum_{i=0}^{t-1}\hat{\theta}_i\hat{\varepsilon}_{t-i}\hat{\varepsilon}_{t-i}'\hat{\theta}_i'\kappa_{t-i}\right)\right\|>\delta\right)&\leq\frac{1}{T^2\delta^2}\sum_{t=1}^{T}E^*\left\|\kappa_t\sum_{i=0}^{T-t}\left(\hat{\theta}_i\otimes\hat{\theta}_i\right)\mathsf{vec}\left(\hat{\varepsilon}_t\hat{\varepsilon}_t'\right)\right\|^2\\
&\leq\frac{E\left(\kappa_t^2\right)}{T\delta^2}\left(\frac{1}{T}\sum_{t=1}^{T}\left\|\sum_{i=0}^{T-t}\left(\hat{\theta}_i\otimes\hat{\theta}_i\right)\mathsf{vec}\left(\hat{\varepsilon}_t\hat{\varepsilon}_t'\right)\right\|^2\right).
\end{aligned}$$

Thus, with $c_T=c+o_p(1)$,

$$\frac{1}{T}\sum_{t=1}^{T}\left\|\left(\sum_{i=0}^{T-t}\hat{\theta}_i\otimes\hat{\theta}_i\right)\mathsf{vec}\left(\hat{\varepsilon}_t\hat{\varepsilon}_t'\right)\right\|^2\leq\frac{c_T}{T}\sum_{t=1}^{T}\left\|\mathsf{vec}\left(\hat{\varepsilon}_t\hat{\varepsilon}_t'\right)\right\|^2$$

which converges in probability as ε_t has bounded fourth order moment. This establishes the result that $M_1^b-\Sigma_{M^b}=o_p(1)$. It can similarly be shown that $M_2^b=o_p(1)$, which completes the proof. □

A.3 Proof of Theorem 4

We proceed as in the proof of Theorem 3. Specifically, we establish that the results in Lemmas A.4, A.5, A.7 and A.6 also hold for the i.i.d. bootstrap. Without causing confusion, we now denote by P^* the i.i.d. bootstrap probability and likewise E^* denotes expectation under P^*. Objects with a superscript s in what follows are understood to be the i.i.d. bootstrap analogues of the corresponding wild bootstrap quantities with a superscript b.

Consider first the analogue of Lemma A.4.

Lemma A.8 *Under the conditions of Theorem 1, the i.i.d. bootstrap data satisfy,*

$$X_t^s = \hat{C} \sum_{i=1}^{t} \varepsilon_i^s + T^{1/2} R_t^s$$

where for all $\eta > 0$*,* $P^* \left(\max_{t=1,\ldots,T} \|R_t^*\| > \eta \right) \to 0$ *in probability as* $T \to \infty$*.*

Proof: The arguments are identical to the proof of Lemma A.4 apart from the final evaluation of $P^* \left(T^{-1/2} \max_{t=1,\ldots,T} \left\| \varepsilon_t^b \right\| > \eta \right)$ in the i.i.d. case. Using that under i.i.d. bootstrap,

$$E^* \left(\varepsilon_t^{s\prime} \varepsilon_t^s \right)^2 = \frac{1}{T} \sum_{t=1}^{T} \left(\hat{\varepsilon}_t^{\prime} \hat{\varepsilon}_t \right)^2,$$

one finds,

$$P^* \left(T^{-1/2} \max_{t=1,\ldots,T} \|\varepsilon_t^s\| > \eta \right) \leq \frac{1}{\eta^4 T^2} \sum_{t=1}^{T} E^* \left(\varepsilon_t^{s\prime} \varepsilon_t^s \right)^2 = \frac{1}{\eta^4 T^2} \sum_{t=1}^{T} \left(\hat{\varepsilon}_t^{\prime} \hat{\varepsilon}_t \right)^2 = O_p \left(\frac{1}{T} \right) \xrightarrow{p} 0$$

□

That Lemmas A.5 and A.7 hold for the i.i.d. bootstrap case holds by Lemma S2 of Swensen (2006). Finally, we need the analogue of Lemma A.7 for the i.i.d. case:

Lemma A.9 *For the i.i.d. bootstrap and under the conditions of Theorem 4,*

$$P^* \left(\|S_{00}^s - \Sigma_{00}\| > \eta \right) \to 0 \quad \text{(A.24)}$$

$$P^* \left(\left\| S_{01}^s \hat{\beta} - \Sigma_{0\beta} \right\| > \eta \right) \to 0 \quad \text{(A.25)}$$

$$P^* \left(\left\| \hat{\beta}^{\prime} S_{11}^s \hat{\beta} - \Sigma_{\beta\beta} \right\| > \eta \right) \to 0 \quad \text{(A.26)}$$

in probability as $T \to \infty$*.*

PROOF: Proceed as in the proof of Lemma A.7 to reach the identical inequality:

$$\|M^s - \Sigma_M\| \leq \|M^s - \Sigma_{M^s}\| + \|\Sigma_{M^s} - \Sigma_M\|.$$

For evaluation of the last term, re-write Σ_{M^s} as:

$$\Sigma_{M^s} = E^*\left(\frac{1}{T}\sum_{t=1}^{T}\left(\sum_{i=0}^{t-1}\hat{\theta}_i\varepsilon^s_{t-i}\right)\left(\sum_{i=0}^{t-1}\hat{\theta}_i\varepsilon^s_{t-i}\right)'\right) = \frac{1}{T}\sum_{t=1}^{T}\left(\sum_{i=0}^{t-1}\sum_{j=0}^{t-1}\hat{\theta}_i E^*\left(\varepsilon^s_{t-i}\varepsilon^{s\prime}_{t-j}\right)\hat{\theta}'_j\right)$$
$$= \frac{1}{T}\sum_{t=1}^{T}\left(\sum_{i=0}^{t-1}\hat{\theta}_i\hat{\Sigma}_T\hat{\theta}'_i\right)$$

where $\hat{\Sigma}_T = \frac{1}{T}\sum_{t=1}^{T}\hat{\varepsilon}_t\hat{\varepsilon}'_t$, and making use of the fact that ε^s_t are conditionally independent. Re-write again,

$$\Sigma_{M^s} = \frac{1}{T}\sum_{t=1}^{T}\left(\sum_{i=0}^{t-1}\hat{\theta}_i\hat{\Sigma}_T\hat{\theta}'_i\right) = \sum_{i=0}^{\infty}\hat{\theta}_i\hat{\Sigma}_T\hat{\theta}'_i - \frac{1}{T}\sum_{t=1}^{T}\left(\sum_{i=T-t+1}^{\infty}\hat{\theta}_i\hat{\Sigma}_T\hat{\theta}'_i\right). \tag{A.27}$$

The last term tends to zero by the arguments in the proof of Lemma A.7 for $V_{1T} \xrightarrow{p} 0$ and using the result that $\hat{\Sigma}_T \xrightarrow{p} \Sigma$ by consistency. Likewise, the first term in (A.27) tends in probability to Σ_M as desired. This holds by rewriting it as $V_{2T} + V_{3T}$, these objects defined analogously as in the proof of Lemma A.7, and using the arguments there to show that $V_{2T} \to 0$, while $V_{3T} \to \Sigma$ in probability.

Turning to the final term $\|M^s - \Sigma_{M^s}\|$, we have that

$$M^s = \frac{1}{T}\sum_{t=1}^{T}\left(\sum_{i=0}^{t-1}\hat{\theta}_i\varepsilon^s_{t-i}\left(\hat{\theta}_i\varepsilon^s_{t-i}\right)'\right) + \frac{1}{T}\sum_{t=1}^{T}\left(\sum_{i,j=0,i\neq j}^{t-1}\hat{\theta}_i\varepsilon^s_{t-i}\varepsilon^{s\prime}_{t-j}\hat{\theta}'_j\right) =: M^s_1 + M^s_2.$$

First, observe that,

$$M^s_1 - \Sigma_{M^s} = \frac{1}{T}\sum_{t=1}^{T}\left(\sum_{i=0}^{t-1}\hat{\theta}_i\left(\varepsilon^s_{t-i}\varepsilon^{s\prime}_{t-i} - \hat{\Sigma}_T\right)\hat{\theta}'_i\right).$$

Using the vec$(\cdot)$ operator and interchanging summation,

$$\frac{1}{T}\sum_{t=1}^{T}\left(\sum_{i=0}^{t-1}\mathsf{vec}\left(\hat{\theta}_i\left(\varepsilon^s_{t-i}\varepsilon^{s\prime}_{t-i} - \hat{\Sigma}_T\right)\hat{\theta}'_i\right)\right) = \frac{1}{T}\sum_{t=1}^{T}\sum_{i=0}^{T-t}\left(\hat{\theta}_i\otimes\hat{\theta}_i\right)\mathsf{vec}\left(\varepsilon^s_t\varepsilon^{s\prime}_t - \hat{\Sigma}_T\right).$$

Hence,

$$P^*\left(\left\|\frac{1}{T}\sum_{t=1}^{T}\left(\sum_{i=0}^{t-1}\hat{\theta}_i\left(\varepsilon^s_{t-i}\varepsilon^{s\prime}_{t-i} - \hat{\Sigma}_T\right)\hat{\theta}'_i\kappa_{t-i}\right)\right\| > \delta\right)$$
$$\leq \frac{1}{T^2\delta^2}\sum_{t=1}^{T}E^*\left\|\sum_{i=0}^{T-t}\left(\hat{\theta}_i\otimes\hat{\theta}_i\right)\mathsf{vec}\left(\varepsilon^s_t\varepsilon^{s\prime}_t - \hat{\Sigma}_T\right)\right\|^2.$$

Thus, with $c_T = c + o_p(1)$,

$$\frac{1}{T}\sum_{t=1}^{T} E^* \left\| \left(\sum_{i=0}^{T-t} \hat{\theta}_i \otimes \hat{\theta}_i \right) \mathsf{vec}\left(\varepsilon_t^s \varepsilon_t^{s\prime} - \hat{\Sigma}_T \right) \right\|^2 \leq \frac{c_T}{T} \sum_{t=1}^{T} E^* \left\| \mathsf{vec}\left(\varepsilon_t^s \varepsilon_t^{s\prime} - \hat{\Sigma}_T \right) \right\|^2 .$$

Use next that,

$$E^* \left\| \mathsf{vec}\left(\varepsilon_t^s \varepsilon_t^{s\prime} - \hat{\Sigma}_T \right) \right\|^2 = E^* tr \left(\varepsilon_t^s \varepsilon_t^{s\prime} - \hat{\Sigma}_T \right)^2 = \frac{1}{T} \sum_{t=1}^{T} tr \left(\hat{\varepsilon}_t \hat{\varepsilon}_t' - \hat{\Sigma}_T \right)^2$$

which converges in probability as a result of the assumption that ε_t has bounded fourth order moment. This establishes the result that $M_1^s - \Sigma_{M^s} = o_p(1)$. Similarly $M_2^s = o_p(1)$, which completes the proof. □

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Table 1: Size of Standard and Bootstrap PLR Tests for Rank = 0 Against Rank = p. True Rank is 0.

			$p=2$			$p=3$			$p=4$			$p=5$		
Model A: $\varepsilon_{i,t}=h_{i,t}^{1/2}v_{i,t}$, $h_{i,t}=\omega+d_0\varepsilon_{i,t-1}^2+d_1h_{i,t-1}$, $v_{i,t}\sim$ i.i.d. $N(0,1)$, $i=1,...,p$														
d_0	d_1	T	Q_0	Q_0^b	Q_0^s	Q_0	Q_0^b	Q_0^s	Q_0	Q_0^b	Q_0^s	Q_0	Q_0^b	Q_0^s
0.0	0.0	50	6.3	5.7	4.9	7.0	5.1	4.9	8.7	4.3	4.8	12.1	3.7	4.8
		100	5.3	4.9	4.6	6.6	5.1	5.5	7.3	5.0	5.1	8.1	4.4	4.7
		200	5.3	4.6	4.8	6.1	5.3	5.2	6.5	4.9	4.9	6.9	4.4	4.7
0.5	0.0	50	9.9	7.2	7.9	10.7	6.6	7.8	13.6	6.3	8.5	17.6	6.2	9.1
		100	7.3	5.3	6.5	9.8	6.3	7.9	11.2	6.3	8.3	12.6	5.4	8.2
		200	6.6	4.8	5.9	8.3	5.3	7.2	8.7	5.2	6.7	9.6	4.3	6.8
0.3	0.65	50	10.2	6.8	8.3	12.6	7.2	9.6	14.8	6.4	9.4	18.1	6.2	9.5
		100	9.9	5.6	8.5	12.3	6.5	10.3	13.7	6.2	10.7	14.8	6.3	10.0
		200	10.0	5.6	9.3	10.7	5.2	9.5	12.1	5.6	10.0	13.9	5.7	10.9
0.2	0.79	50	9.3	6.6	7.6	11.2	7.1	8.3	13.8	5.9	8.2	16.2	5.5	7.7
		100	9.9	5.6	8.7	11.4	6.4	9.8	13.1	6.2	9.9	14.0	5.5	9.2
		200	10.8	5.5	10.1	12.2	5.4	11.0	12.8	5.5	10.7	13.5	5.6	10.6
0.05	0.94	50	6.5	5.9	5.2	7.6	5.5	5.2	9.3	4.6	5.3	12.3	4.2	4.9
		100	5.8	4.9	5.2	7.0	5.4	5.6	8.1	5.2	5.8	8.8	4.4	4.9
		200	6.5	5.1	5.9	7.2	5.1	6.5	7.2	5.0	5.5	7.9	4.9	5.5
Model B: $\varepsilon_{i,t}=h_{i,t}^{1/2}v_{i,t}$, $h_{i,t}=\omega+d_0\varepsilon_{i,t-1}^2+d_1h_{i,t-1}$, $v_{i,t}\sim$ i.i.d. t_5, $i=1,...,p$														
d_0	d_1	T	Q_0	Q_0^b	Q_0^s	Q_0	Q_0^b	Q_0^s	Q_0	Q_0^b	Q_0^s	Q_0	Q_0^b	Q_0^s
0.0	0.0	50	6.6	5.2	5.1	8.0	4.9	5.8	9.3	4.4	5.6	12.8	3.6	5.0
		100	5.7	4.9	5.0	6.3	4.7	4.9	6.7	4.1	5.0	8.2	4.4	4.8
		200	5.5	4.7	5.0	5.8	4.6	4.6	6.3	4.8	4.9	6.5	3.8	4.4
0.5	0.0	50	8.5	6.0	6.8	11.3	6.4	7.9	12.7	5.6	8.2	15.9	4.8	7.4
		100	7.3	5.3	6.4	8.4	5.2	6.8	9.5	5.1	6.9	12.0	5.1	7.2
		200	6.5	5.0	5.6	6.9	4.7	5.9	8.1	4.9	6.4	8.6	4.3	6.1
0.3	0.65	50	8.7	5.8	7.1	11.0	6.2	7.8	12.6	5.9	7.9	15.8	4.9	7.2
		100	7.5	5.1	6.5	9.2	5.5	7.7	10.4	5.5	7.7	12.4	5.6	7.5
		200	7.2	5.2	6.6	8.2	5.2	7.1	9.5	5.1	7.4	10.2	4.7	7.2
0.2	0.79	50	8.0	5.6	6.4	10.5	6.0	7.6	11.7	5.2	7.3	14.5	4.7	6.4
		100	7.2	5.4	6.2	8.9	5.4	7.3	9.7	5.3	7.3	11.2	5.4	7.2
		200	7.1	5.0	6.2	8.3	5.0	7.0	8.7	5.1	7.4	9.7	4.5	6.6
0.05	0.94	50	6.9	5.2	5.3	8.9	5.4	6.2	9.9	4.6	5.9	13.1	3.9	5.2
		100	5.9	5.0	5.3	7.1	5.0	5.9	7.4	4.6	5.4	8.9	4.5	5.4
		200	5.8	4.7	5.4	6.5	4.6	5.5	7.2	5.1	5.8	7.2	4.0	4.8
Model C: $\varepsilon_{i,t}=h_{i,t}^{1/2}v_{i,t}$, $\ln(h_{i,t})=-0.23+0.9\ln(h_{i,t-1})+0.25[\lvert v_{i,t-1}^2\rvert-0.3v_{i,t-1}]$, $v_{i,t}\sim$ i.i.d. $N(0,1)$, $i=1,...,p$														
		T	Q_0	Q_0^b	Q_0^s	Q_0	Q_0^b	Q_0^s	Q_0	Q_0^b	Q_0^s	Q_0	Q_0^b	Q_0^s
		50	11.0	7.2	9.2	13.8	7.9	10.5	17.2	7.3	10.6	20.0	7.1	10.1
		100	10.3	5.6	9.2	12.9	6.6	10.7	14.6	6.3	11.1	16.8	7.0	11.8
		200	9.7	5.3	9.1	11.5	5.9	10.1	13.6	5.4	11.2	14.7	5.7	11.2
Model D: $\varepsilon_{i,t}=h_{i,t}^{1/2}v_{i,t}$, $h_{i,t}=0.0216+0.6896h_{i,t-1}+0.3174[\varepsilon_{i,t-1}-0.1108]^2$, $v_{i,t}\sim$ i.i.d. $N(0,1)$, $i=1,...,p$														
		T	Q_0	Q_0^b	Q_0^s	Q_0	Q_0^b	Q_0^s	Q_0	Q_0^b	Q_0^s	Q_0	Q_0^b	Q_0^s
		50	11.8	6.8	9.9	14.4	7.9	11.1	16.9	7.6	11.3	19.8	6.6	10.3
		100	12.7	6.2	11.5	15.0	6.9	13.1	16.6	6.9	13.1	18.7	6.5	13.2
		200	13.9	5.6	13.0	17.0	6.0	15.0	17.9	6.3	15.3	20.2	6.4	16.1
Model E: $\varepsilon_{i,t}=h_{i,t}^{1/2}v_{i,t}$, $h_{i,t}=0.005+0.7h_{i,t-1}+0.28[\lvert\varepsilon_{i,t-1}\rvert-0.23\varepsilon_{i,t-1}]^2$, $v_{i,t}\sim$ i.i.d. $N(0,1)$, $i=1,...,p$														
		T	Q_0	Q_0^b	Q_0^s	Q_0	Q_0^b	Q_0^s	Q_0	Q_0^b	Q_0^s	Q_0	Q_0^b	Q_0^s
		50	10.7	6.7	9.0	13.1	7.3	10.1	15.5	6.6	10.1	18.2	6.1	9.5
		100	11.1	5.7	10.0	13.0	6.3	11.2	14.9	6.2	11.8	16.1	5.8	11.4
		200	12.0	4.9	11.3	14.1	5.7	12.5	16.0	5.6	13.6	16.9	5.4	13.8
Model F: $\varepsilon_{i,t}=v_{i,t}\exp(h_{i,t})$, $h_{i,t}=\lambda h_{i,t-1}+0.5\xi_{i,t}$, $(\xi_{i,t},v_{i,t})\sim$ i.i.d. $N(0,\mathrm{diag}(\sigma_\xi^2,1))$, $i=1,...,p$														
λ	σ_ξ	T	Q_0	Q_0^b	Q_0^s	Q_0	Q_0^b	Q_0^s	Q_0	Q_0^b	Q_0^s	Q_0	Q_0^b	Q_0^s
0.936	0.424	50	19.3	8.4	16.9	24.5	9.1	19.1	29.3	9.7	20.8	35.0	11.0	22.2
		100	21.3	6.8	19.1	26.8	8.5	23.2	32.2	8.7	26.3	35.4	9.5	27.0
		200	22.0	6.8	20.1	27.3	7.6	24.6	32.7	7.8	28.1	37.1	7.9	30.8
0.951	0.314	50	16.5	7.1	13.7	20.0	8.2	16.3	24.0	8.4	16.5	28.1	9.0	17.3
		100	17.5	6.5	15.6	22.2	7.4	19.2	25.4	7.9	20.8	28.0	8.7	21.5
		200	18.6	6.6	17.2	22.8	6.7	20.5	25.9	6.6	22.2	30.5	7.7	24.9

Table 2: Standard and Bootstrap Sequential Procedures for Selecting the Co-integration Rank. $p = 2$, True Rank is 0.

			Q-based			Q^b-based			Q^s-based		
		$r =$	0	1	2	0	1	2	0	1	2
Model A: $\varepsilon_{i,t} = h_{i,t}^{1/2} v_{i,t}$, $h_{i,t} = \omega + d_0 \varepsilon_{i,t-1}^2 + d_1 h_{i,t-1}$, $v_{i,t} \sim$ i.i.d. $N(0,1)$, $i = 1, ..., p$											
d_0	d_1	T									
0.0	0.0	50	93.7	5.5	0.8	94.3	4.6	1.1	95.1	3.9	1.0
		100	94.7	5.0	0.4	95.1	4.2	0.6	95.4	4.1	0.5
		200	94.7	5.0	0.3	95.4	3.9	0.7	95.2	4.3	0.5
0.5	0.0	50	90.1	9.2	0.7	92.8	6.1	1.1	92.1	6.8	1.1
		100	92.7	6.7	0.6	94.7	4.6	0.7	93.5	5.7	0.8
		200	93.4	6.0	0.6	95.2	4.1	0.6	94.1	5.2	0.7
0.3	0.7	50	89.8	9.1	1.0	93.2	5.5	1.2	91.7	7.0	1.3
		100	90.1	9.1	0.7	94.4	5.0	0.6	91.5	7.4	1.1
		200	90.0	9.1	0.9	94.4	4.9	0.7	90.7	7.9	1.4
0.2	0.8	50	90.7	8.3	1.0	93.4	5.4	1.2	92.4	6.4	1.2
		100	90.1	9.1	0.9	94.4	4.8	0.8	91.3	7.5	1.3
		200	89.2	9.7	1.0	94.5	4.9	0.6	89.9	8.6	1.5
0.1	0.9	50	93.5	5.8	0.7	94.1	4.7	1.3	94.8	4.1	1.2
		100	94.2	5.5	0.3	95.1	4.1	0.8	94.8	4.7	0.6
		200	93.5	6.1	0.4	94.9	4.5	0.7	94.1	5.1	0.8
Model B: $\varepsilon_{i,t} = h_{i,t}^{1/2} v_{i,t}$, $h_{i,t} = \omega + d_0 \varepsilon_{i,t-1}^2 + d_1 h_{i,t-1}$, $v_{i,t} \sim$ i.i.d. t_5, $i = 1, ..., p$											
d_0	d_1	T									
0.0	0.0	50	93.4	6.0	0.6	94.8	4.2	1.1	94.9	4.2	1.0
		100	94.3	5.4	0.3	95.1	4.3	0.7	95.0	4.4	0.6
		200	94.5	5.0	0.5	95.3	4.1	0.6	95.0	4.2	0.8
0.5	0.0	50	91.5	7.7	0.8	94.0	4.8	1.2	93.2	5.8	1.0
		100	92.7	6.9	0.4	94.7	4.6	0.7	93.6	5.6	0.8
		200	93.5	6.1	0.5	95.0	4.4	0.6	94.4	4.8	0.8
0.3	0.7	50	91.3	8.0	0.7	94.2	4.7	1.1	92.9	6.1	1.0
		100	92.5	7.0	0.5	94.9	4.5	0.6	93.5	5.6	0.9
		200	92.8	6.5	0.6	94.8	4.6	0.7	93.4	5.7	0.9
0.2	0.8	50	92.0	7.3	0.8	94.4	4.5	1.1	93.6	5.3	1.1
		100	92.8	6.7	0.5	94.6	4.7	0.7	93.8	5.5	0.7
		200	92.9	6.5	0.6	95.0	4.4	0.6	93.8	5.5	0.8
0.1	0.9	50	93.1	6.2	0.7	94.8	4.2	1.0	94.7	4.4	0.9
		100	94.1	5.5	0.4	95.0	4.4	0.7	94.7	4.5	0.7
		200	94.2	5.3	0.5	95.3	4.0	0.7	94.6	4.5	0.8
Model C: $\varepsilon_{i,t} = h_{i,t}^{1/2} v_{i,t}$, $\ln(h_{i,t}) = -0.23 + 0.9 \ln(h_{i,t-1}) + 0.25[\lvert v_{i,t-1}^2 \rvert - 0.3 v_{i,t-1}]$, $v_{i,t} \sim$ i.i.d. $N(0,1)$, $i = 1, ..., p$											
		50	89.0	9.8	1.1	92.8	6.1	1.1	90.8	7.7	1.5
		100	89.7	9.4	0.9	94.4	4.9	0.7	90.8	8.0	1.2
		200	90.3	9.0	0.8	94.7	4.5	0.7	90.9	7.9	1.2
Model D: $\varepsilon_{i,t} = h_{i,t}^{1/2} v_{i,t}$, $h_{i,t} = 0.0216 + 0.6896 h_{i,t-1} + 0.3174[\varepsilon_{i,t-1} - 0.1108]^2$, $v_{i,t} \sim$ i.i.d. $N(0,1)$, $i = 1, ..., p$											
		50	88.2	10.6	1.2	93.2	5.5	1.3	90.1	8.2	1.7
		100	87.3	11.7	1.1	93.8	5.4	0.8	88.5	9.8	1.6
		200	86.1	12.6	1.3	94.4	4.9	0.7	87.0	11.1	2.0
Model E: $\varepsilon_{i,t} = h_{i,t}^{1/2} v_{i,t}$, $h_{i,t} = 0.005 + 0.7 h_{i,t-1} + 0.28[\lvert \varepsilon_{i,t-1} \rvert - 0.23 \varepsilon_{i,t-1}]^2$, $v_{i,t} \sim$ i.i.d. $N(0,1)$, $i = 1, ..., p$											
		50	89.3	9.6	1.2	93.3	5.6	1.2	91.0	7.6	1.5
		100	88.9	10.1	1.0	94.3	5.1	0.7	90.0	8.8	1.2
		200	88.0	10.7	1.3	95.1	4.1	0.8	88.7	9.7	1.6
Model F: $\varepsilon_{i,t} = v_{i,t} \exp(h_{i,t})$, $h_{i,t} = \lambda h_{i,t-1} + 0.5 \xi_{i,t}$, $(\xi_{i,t}, v_{i,t}) \sim$ i.i.d. $N(0, \mathrm{diag}(\sigma_\xi^2, 1))$, $i = 1, ..., p$											
λ	σ_ξ	T									
0.936	0.424	50	80.7	16.8	2.5	91.6	7.3	1.1	83.1	14.0	2.9
		100	78.7	19.0	2.4	93.2	5.9	1.0	80.9	16.4	2.6
		200	78.0	19.9	2.1	93.2	6.2	0.6	79.9	17.7	2.4
0.951	0.314	50	83.5	14.4	2.1	92.9	6.0	1.1	86.3	11.4	2.3
		100	82.5	15.6	1.9	93.5	5.5	1.0	84.4	13.2	2.3
		200	81.4	16.9	1.7	93.4	6.1	0.6	82.8	15.2	2.0

Table 3: Standard and Bootstrap Sequential Procedures for Selecting the Co-integration Rank. $p = 3$, True Rank is 0.

			Q-based				Q^b-based				Q^s-based			
		$r=$	0	1	2	3	0	1	2	3	0	1	2	3
Model A: $\varepsilon_{i,t} = h_{i,t}^{1/2} v_{i,t}, h_{i,t} = \omega + d_0 \varepsilon_{i,t-1}^2 + d_1 h_{i,t-1}, v_{i,t} \sim i.i.d.\ N(0,1), i = 1, ..., p$														
d_0	d_1	T												
0.0	0.0	50	93.0	6.1	0.7	0.1	94.9	4.2	0.6	0.3	95.1	4.0	0.7	0.2
		100	93.4	6.0	0.6	0.1	94.9	4.4	0.5	0.2	94.5	4.8	0.6	0.1
		200	93.9	5.5	0.6	0.0	94.7	4.6	0.5	0.1	94.8	4.5	0.5	0.2
0.5	0.0	50	89.3	9.7	0.9	0.1	93.4	5.6	0.7	0.3	92.2	7.0	0.6	0.2
		100	90.2	8.8	0.9	0.1	93.7	5.5	0.6	0.2	92.1	6.9	0.8	0.2
		200	91.7	7.5	0.7	0.1	94.7	4.7	0.5	0.1	92.8	6.3	0.6	0.3
0.3	0.65	50	87.4	11.2	1.1	0.3	92.8	5.9	1.1	0.2	90.4	8.1	1.1	0.4
		100	87.7	11.1	1.0	0.2	93.5	5.7	0.6	0.3	89.7	8.8	1.1	0.3
		200	89.3	9.8	0.8	0.1	94.8	4.6	0.4	0.2	90.5	8.4	0.9	0.2
0.2	0.79	50	88.8	10.0	0.9	0.2	92.9	5.9	0.9	0.3	91.7	7.2	0.8	0.3
		100	88.6	10.1	1.1	0.2	93.6	5.4	0.8	0.2	90.2	8.4	1.1	0.3
		200	87.8	11.0	1.0	0.2	94.6	4.6	0.6	0.2	89.0	9.5	1.1	0.4
0.05	0.94	50	92.4	6.6	0.8	0.2	94.5	4.5	0.6	0.4	94.8	4.3	0.7	0.2
		100	93.0	6.2	0.6	0.2	94.6	4.5	0.6	0.2	94.4	4.9	0.6	0.2
		200	92.8	6.6	0.4	0.1	94.9	4.5	0.5	0.2	93.5	5.9	0.4	0.2
Model B: $\varepsilon_{i,t} = h_{i,t}^{1/2} v_{i,t}, h_{i,t} = \omega + d_0 \varepsilon_{i,t-1}^2 + d_1 h_{i,t-1}, v_{i,t} \sim i.i.d.\ t_5, i = 1, ..., p$														
d_0	d_1	T												
0.0	0.0	50	92.0	7.3	0.6	0.2	95.1	4.2	0.5	0.2	94.2	5.1	0.5	0.3
		100	93.7	5.7	0.4	0.1	95.3	4.0	0.5	0.2	95.1	4.2	0.4	0.2
		200	94.2	5.2	0.6	0.0	95.4	4.0	0.5	0.1	95.4	4.1	0.5	0.1
0.5	0.0	50	88.7	10.3	0.8	0.1	93.6	5.4	0.8	0.2	92.1	6.8	0.9	0.2
		100	91.6	7.7	0.5	0.2	94.8	4.4	0.7	0.2	93.2	6.0	0.7	0.2
		200	93.1	6.4	0.5	0.1	95.3	4.2	0.4	0.1	94.1	5.3	0.4	0.2
0.3	0.65	50	89.0	9.9	0.9	0.1	93.8	5.4	0.6	0.2	92.2	6.9	0.7	0.2
		100	90.8	8.3	0.7	0.2	94.5	4.6	0.6	0.3	92.3	6.7	0.8	0.3
		200	91.8	7.5	0.6	0.1	94.8	4.6	0.4	0.2	92.9	6.2	0.6	0.3
0.2	0.79	50	89.5	9.4	1.0	0.1	94.0	5.2	0.6	0.2	92.4	6.5	0.9	0.3
		100	91.1	7.9	0.8	0.2	94.6	4.6	0.6	0.3	92.7	6.2	0.7	0.3
		200	91.7	7.6	0.6	0.1	95.0	4.4	0.5	0.2	93.0	6.2	0.5	0.3
0.05	0.94	50	91.1	8.1	0.7	0.1	94.6	4.6	0.5	0.3	93.8	5.4	0.6	0.2
		100	92.9	6.5	0.4	0.2	95.0	4.2	0.5	0.3	94.1	5.1	0.4	0.3
		200	93.5	6.0	0.5	0.1	95.4	4.1	0.4	0.1	94.5	4.8	0.4	0.2
Model C: $\varepsilon_{i,t} = h_{i,t}^{1/2} v_{i,t}, \ln(h_{i,t}) = -0.23 + 0.9 \ln(h_{i,t-1}) + 0.25[\lvert v_{i,t-1}^2 \rvert - 0.3 v_{i,t-1}], v_{i,t} \sim i.i.d.\ N(0,1), i = 1, ..., p$														
		50	86.2	12.1	1.4	0.3	92.1	6.5	1.0	0.4	89.5	8.9	1.2	0.4
		100	87.1	11.6	1.2	0.1	93.4	5.7	0.7	0.2	89.3	9.1	1.4	0.3
		200	88.5	10.4	1.0	0.1	94.1	5.4	0.3	0.2	89.9	8.7	1.0	0.4
Model D: $\varepsilon_{i,t} = h_{i,t}^{1/2} v_{i,t}$, $h_{i,t} = 0.0216 + 0.6896 h_{i,t-1} + 0.3174[\varepsilon_{i,t-1} - 0.1108]^2$, $v_{i,t} \sim$ i.i.d. $N(0,1)$, $i = 1, ..., p$														
		50	85.6	12.6	1.5	0.3	92.1	6.5	1.1	0.4	88.9	9.4	1.2	0.5
		100	85.0	13.3	1.5	0.2	93.1	5.9	0.8	0.2	86.9	11.3	1.4	0.4
		200	83.0	15.0	1.8	0.3	94.0	5.2	0.6	0.2	85.0	12.6	1.9	0.5
Model E: $\varepsilon_{i,t} = h_{i,t}^{1/2} v_{i,t}$, $h_{i,t} = 0.005 + 0.7 h_{i,t-1} + 0.28[\lvert \varepsilon_{i,t-1} \rvert - 0.23 \varepsilon_{i,t-1}]^2$, $v_{i,t} \sim$ i.i.d. $N(0,1)$, $i = 1, ..., p$														
		50	86.9	11.6	1.3	0.2	92.7	6.1	0.9	0.3	89.9	8.5	1.0	0.6
		100	87.0	11.7	1.2	0.2	93.7	5.5	0.6	0.1	88.8	9.7	1.2	0.3
		200	85.9	12.8	1.2	0.1	94.3	5.1	0.5	0.1	87.5	10.7	1.5	0.3
Model F: $\varepsilon_{i,t} = v_{i,t} \exp(h_{i,t})$, $h_{i,t} = \lambda h_{i,t-1} + 0.5 \xi_{i,t}$, $(\xi_{i,t}, v_{i,t}) \sim$ i.i.d. $N(0, \mathrm{diag}(\sigma_\xi^2, 1))$, $i = 1, ..., p$														
λ	σ_ξ													
0.936	0.424	50	75.5	20.7	3.4	0.4	90.9	7.5	1.3	0.3	80.9	15.9	2.6	0.6
		100	73.2	22.3	3.8	0.6	91.5	7.4	0.9	0.2	76.8	19.1	3.2	0.8
		200	72.7	23.6	3.3	0.4	92.4	6.7	0.7	0.2	75.4	21.4	2.5	0.7
0.951	0.314	50	80.0	17.2	2.4	0.4	91.8	6.7	1.2	0.3	83.7	13.6	2.1	0.6
		100	77.8	18.8	3.0	0.5	92.6	6.4	0.9	0.2	80.8	15.9	2.5	0.8
		200	77.2	20.0	2.4	0.4	93.3	6.1	0.5	0.1	79.5	17.6	2.3	0.6

Table 4: Standard and Bootstrap Sequential Procedures for Selecting the Co-integration Rank. $p = 4$, True Rank is 0.

			Q-based					Q^b-based					Q^s-based				
		$r =$	0	1	2	3	4	0	1	2	3	4	0	1	2	3	4
Model A: $\varepsilon_{i,t} = h_{i,t}^{1/2} v_{i,t}, h_{i,t} = \omega + d_0 \varepsilon_{i,t-1}^2 + d_1 h_{i,t-1}, v_{i,t} \sim i.i.d.\ N(0,1), i = 1, ..., p$																	
d_0	d_1	T															
0.0	0.0	50	91.3	7.7	0.9	0.1	0.0	95.7	3.7	0.5	0.1	0.1	95.2	4.1	0.5	0.1	0.0
		100	92.7	6.4	0.7	0.2	0.0	95.0	4.2	0.6	0.2	0.0	94.9	4.3	0.6	0.2	0.0
		200	93.5	5.9	0.5	0.1	0.0	95.1	4.2	0.5	0.1	0.1	95.1	4.2	0.5	0.1	0.0
0.5	0.0	50	86.4	12.0	1.3	0.2	0.0	93.7	5.4	0.6	0.2	0.2	91.5	7.4	0.8	0.2	0.1
		100	88.8	10.0	1.0	0.2	0.0	93.7	5.5	0.4	0.2	0.1	91.7	7.1	0.7	0.3	0.1
		200	91.3	8.0	0.6	0.1	0.0	94.8	4.7	0.4	0.1	0.0	93.3	5.9	0.6	0.1	0.0
0.3	0.65	50	85.2	13.1	1.4	0.2	0.0	93.6	5.4	0.7	0.2	0.1	90.6	8.0	1.0	0.3	0.2
		100	86.3	12.0	1.5	0.2	0.0	93.8	5.3	0.7	0.2	0.1	89.3	9.2	1.3	0.2	0.1
		200	87.9	10.9	1.0	0.2	0.0	94.4	4.9	0.6	0.1	0.0	90.0	8.8	1.0	0.2	0.1
0.2	0.79	50	86.2	12.1	1.4	0.2	0.0	94.1	4.9	0.6	0.3	0.1	91.8	6.9	0.8	0.3	0.1
		100	86.9	11.5	1.3	0.2	0.0	93.8	5.3	0.8	0.1	0.0	90.1	8.3	1.2	0.3	0.1
		200	87.2	11.4	1.2	0.1	0.1	94.5	4.8	0.6	0.1	0.0	89.3	9.3	1.2	0.1	0.1
0.05	0.94	50	90.7	8.2	1.0	0.1	0.1	95.4	3.9	0.4	0.2	0.1	94.7	4.5	0.5	0.2	0.1
		100	91.9	7.3	0.7	0.1	0.0	94.8	4.5	0.4	0.3	0.1	94.2	4.9	0.6	0.2	0.0
		200	92.8	6.5	0.6	0.1	0.0	95.0	4.4	0.5	0.1	0.0	94.5	4.8	0.6	0.1	0.0
Model B: $\varepsilon_{i,t} = h_{i,t}^{1/2} v_{i,t}, h_{i,t} = \omega + d_0 \varepsilon_{i,t-1}^2 + d_1 h_{i,t-1}, v_{i,t} \sim i.i.d.\ t_5, i = 1, ..., p$																	
d_0	d_1	T															
0.0	0.0	50	90.7	8.2	0.9	0.2	0.0	95.6	3.6	0.6	0.1	0.1	94.4	4.9	0.5	0.2	0.0
		100	93.3	5.8	0.6	0.2	0.1	95.9	3.4	0.5	0.1	0.1	95.0	4.4	0.4	0.2	0.1
		200	93.7	5.6	0.6	0.0	0.0	95.2	4.2	0.6	0.0	0.0	95.1	4.2	0.7	0.1	0.0
0.5	0.0	50	87.3	11.2	1.1	0.3	0.0	94.4	4.8	0.6	0.2	0.0	91.8	7.2	0.7	0.2	0.1
		100	90.5	8.4	0.9	0.1	0.1	94.9	4.3	0.6	0.1	0.1	93.1	5.9	0.7	0.2	0.1
		200	91.9	7.4	0.6	0.1	0.0	95.1	4.4	0.4	0.1	0.1	93.6	5.8	0.4	0.2	0.1
0.3	0.65	50	87.4	10.9	1.4	0.2	0.0	94.1	5.1	0.6	0.1	0.1	92.1	6.8	0.8	0.2	0.1
		100	89.6	9.2	0.9	0.1	0.1	94.5	4.6	0.6	0.1	0.1	92.3	6.5	0.8	0.2	0.1
		200	90.5	8.6	0.7	0.1	0.0	94.9	4.5	0.5	0.1	0.1	92.6	6.6	0.6	0.1	0.1
0.2	0.79	50	88.3	10.1	1.3	0.2	0.1	94.8	4.5	0.5	0.1	0.1	92.7	6.3	0.7	0.2	0.1
		100	90.3	8.6	0.9	0.1	0.1	94.7	4.5	0.6	0.1	0.1	92.7	6.1	0.8	0.2	0.2
		200	91.3	7.8	0.6	0.2	0.0	94.9	4.4	0.5	0.1	0.1	92.6	6.5	0.7	0.1	0.1
0.05	0.94	50	90.1	8.8	0.9	0.2	0.0	95.4	3.8	0.6	0.1	0.1	94.1	5.1	0.6	0.2	0.0
		100	92.6	6.5	0.7	0.2	0.1	95.4	3.9	0.5	0.1	0.1	94.6	4.5	0.6	0.2	0.1
		200	92.8	6.5	0.6	0.0	0.0	94.9	4.5	0.5	0.1	0.0	94.2	5.0	0.7	0.0	0.0
Model C: $\varepsilon_{i,t} = h_{i,t}^{1/2} v_{i,t}, \ln(h_{i,t}) = -0.23 + 0.9 \ln(h_{i,t-1}) + 0.25[\lvert v_{i,t-1}^2 \rvert - 0.3 v_{i,t-1}], v_{i,t} \sim i.i.d.\ N(0,1), i = 1, ..., p$																	
		50	82.8	15.1	1.8	0.2	0.0	92.7	6.3	0.8	0.2	0.1	89.4	9.0	1.1	0.4	0.1
		100	85.4	12.8	1.6	0.2	0.0	93.7	5.3	0.7	0.2	0.1	88.9	9.4	1.2	0.3	0.1
		200	86.4	12.1	1.3	0.2	0.0	94.6	4.6	0.6	0.1	0.0	88.8	9.7	1.2	0.2	0.0
Model D: $\varepsilon_{i,t} = h_{i,t}^{1/2} v_{i,t},\ h_{i,t} = 0.0216 + 0.6896 h_{i,t-1} + 0.3174[\varepsilon_{i,t-1} - 0.1108]^2,\ v_{i,t} \sim \text{i.i.d. } N(0,1),\ i = 1, ..., p$																	
		50	83.1	14.6	2.0	0.3	0.0	92.4	6.4	0.8	0.3	0.0	88.7	9.7	1.2	0.3	0.0
		100	83.4	14.1	2.1	0.3	0.1	93.1	5.9	0.8	0.1	0.1	86.9	10.9	1.8	0.4	0.1
		200	82.1	15.4	2.2	0.2	0.1	93.7	5.4	0.6	0.2	0.0	84.7	13.0	1.9	0.3	0.1
Model E: $\varepsilon_{i,t} = h_{i,t}^{1/2} v_{i,t},\ h_{i,t} = 0.005 + 0.7 h_{i,t-1} + 0.28[\lvert\varepsilon_{i,t-1}\rvert - 0.23\varepsilon_{i,t-1}]^2,\ v_{i,t} \sim \text{i.i.d. } N(0,1),\ i = 1, ..., p$																	
		50	84.5	13.6	1.7	0.2	0.0	93.4	5.6	0.8	0.2	0.0	89.9	8.7	1.1	0.2	0.1
		100	85.1	13.1	1.4	0.2	0.1	93.8	5.3	0.7	0.1	0.1	88.2	10.1	1.3	0.2	0.1
		200	84.0	14.1	1.7	0.1	0.0	94.4	5.0	0.4	0.2	0.0	86.4	11.8	1.6	0.2	0.0
Model F: $\varepsilon_{i,t} = v_{i,t} \exp(h_{i,t}),\ h_{i,t} = \lambda h_{i,t-1} + 0.5\xi_{i,t},\ (\xi_{i,t}, v_{i,t}) \sim \text{i.i.d. } N(0, \text{diag}(\sigma_\xi^2, 1)),\ i = 1, ..., p$																	
λ	σ_ξ	T															
0.936	0.424	50	70.7	23.9	4.4	0.8	0.2	90.3	8.2	1.1	0.2	0.2	79.2	16.8	2.9	0.7	0.4
		100	67.8	26.0	5.2	0.8	0.2	91.3	7.5	0.9	0.2	0.1	73.7	21.3	4.0	0.7	0.3
		200	67.3	26.8	5.0	0.8	0.1	92.2	6.9	0.8	0.0	0.0	71.9	23.3	3.9	0.6	0.3
0.951	0.314	50	76.0	20.0	3.4	0.5	0.1	91.6	7.0	1.0	0.2	0.2	83.5	13.7	2.2	0.4	0.2
		100	74.6	20.8	3.9	0.4	0.2	92.1	6.7	1.0	0.1	0.1	79.2	16.9	3.1	0.5	0.3
		200	74.1	21.1	4.0	0.6	0.1	93.4	5.5	0.8	0.2	0.1	77.8	18.2	3.2	0.6	0.2

Table 5: Standard and Bootstrap Sequential Procedures for Selecting the Co-integration Rank. $p = 5$, True Rank is 0.

			Q-based					Q^b-based					Q^s-based				
		$r=$	0	1	2	3	4, 5	0	1	2	3	4, 5	0	1	2	3	4, 5
Model A: $\varepsilon_{i,t} = h_{i,t}^{1/2} v_{i,t}, h_{i,t} = \omega + d_0 \varepsilon_{i,t-1}^2 + d_1 h_{i,t-1}, v_{i,t} \sim i.i.d.\ N(0,1),\ i = 1, ..., p$																	
d_0	d_1	T															
0.0	0.0	50	87.9	10.6	1.2	0.3	0.1	96.3	3.1	0.4	0.2	0.0	95.2	4.1	0.6	0.1	0.0
		100	91.9	7.3	0.6	0.1	0.0	95.6	4.0	0.4	0.0	0.0	95.3	4.3	0.3	0.1	0.0
		200	93.1	6.1	0.7	0.1	0.0	95.6	3.7	0.6	0.1	0.0	95.3	4.0	0.5	0.1	0.0
0.5	0.0	50	82.4	15.3	2.0	0.3	0.0	93.8	5.4	0.6	0.2	0.0	90.9	8.3	0.8	0.1	0.0
		100	87.4	11.0	1.4	0.1	0.0	94.6	4.7	0.6	0.1	0.1	91.8	7.1	0.8	0.2	0.1
		200	90.4	8.8	0.8	0.1	0.0	95.7	3.9	0.4	0.0	0.0	93.2	6.0	0.6	0.1	0.0
0.3	0.65	50	81.9	15.3	2.5	0.2	0.1	93.8	5.2	0.9	0.1	0.1	90.5	8.1	1.2	0.1	0.0
		100	85.2	12.8	1.5	0.4	0.1	93.7	5.4	0.6	0.1	0.1	90.0	8.7	0.9	0.3	0.1
		200	86.1	12.3	1.4	0.2	0.0	94.3	5.1	0.6	0.1	0.0	89.1	9.5	1.2	0.2	0.1
0.2	0.79	50	83.8	13.8	2.1	0.3	0.1	94.5	4.5	0.8	0.2	0.0	92.3	6.4	1.0	0.3	0.1
		100	86.0	12.1	1.5	0.3	0.1	94.5	4.8	0.5	0.1	0.0	90.8	7.9	1.0	0.2	0.1
		200	86.5	11.8	1.5	0.2	0.0	94.4	4.8	0.7	0.1	0.0	89.4	9.0	1.3	0.3	0.0
0.05	0.94	50	87.7	10.8	1.2	0.3	0.1	95.8	3.5	0.5	0.2	0.0	95.1	4.1	0.6	0.2	0.0
		100	91.2	7.8	0.8	0.1	0.1	95.6	3.8	0.5	0.1	0.0	95.1	4.3	0.6	0.1	0.0
		200	92.1	7.1	0.7	0.1	0.0	95.1	4.3	0.5	0.1	0.0	94.5	4.9	0.6	0.1	0.0
Model B: $\varepsilon_{i,t} = h_{i,t}^{1/2} v_{i,t}, h_{i,t} = \omega + d_0 \varepsilon_{i,t-1}^2 + d_1 h_{i,t-1}, v_{i,t} \sim i.i.d.\ t_5,\ i = 1, ..., p$																	
d_0	d_1	T															
0.0	0.0	50	87.2	11.4	1.1	0.2	0.1	96.4	3.2	0.2	0.1	0.1	95.0	4.5	0.3	0.1	0.1
		100	91.8	7.3	0.8	0.1	0.0	95.6	3.9	0.3	0.1	0.0	95.2	4.3	0.4	0.0	0.1
		200	93.5	5.9	0.5	0.0	0.0	96.2	3.4	0.3	0.0	0.0	95.6	4.0	0.3	0.0	0.1
0.5	0.0	50	84.1	13.9	1.7	0.2	0.1	95.2	4.0	0.6	0.1	0.1	92.6	6.6	0.7	0.1	0.1
		100	88.0	10.6	1.2	0.1	0.0	94.9	4.4	0.5	0.1	0.0	92.8	6.4	0.7	0.1	0.0
		200	91.4	7.8	0.7	0.1	0.0	95.7	3.8	0.4	0.1	0.0	93.9	5.4	0.6	0.1	0.0
0.3	0.65	50	84.2	13.8	1.7	0.2	0.1	95.1	4.0	0.6	0.1	0.1	92.8	6.0	1.0	0.1	0.1
		100	87.6	11.1	1.1	0.1	0.1	94.4	5.0	0.4	0.1	0.0	92.5	6.6	0.7	0.1	0.1
		200	89.8	9.3	1.0	0.0	0.0	95.3	4.2	0.4	0.1	0.0	92.8	6.4	0.7	0.1	0.0
0.2	0.79	50	85.5	12.5	1.6	0.3	0.1	95.3	3.9	0.6	0.1	0.1	93.6	5.3	0.9	0.1	0.1
		100	88.8	9.9	1.2	0.1	0.0	94.6	4.8	0.4	0.1	0.1	92.8	6.3	0.7	0.1	0.1
		200	90.3	8.7	1.0	0.1	0.0	95.5	4.1	0.4	0.1	0.0	93.4	6.0	0.6	0.1	0.0
0.05	0.94	50	86.9	11.5	1.3	0.2	0.1	96.1	3.4	0.3	0.1	0.1	94.8	4.7	0.4	0.1	0.0
		100	91.1	8.0	0.9	0.1	0.0	95.5	3.9	0.5	0.1	0.0	94.6	4.7	0.6	0.1	0.0
		200	92.8	6.6	0.6	0.0	0.0	96.0	3.7	0.3	0.1	0.0	95.2	4.3	0.4	0.1	0.0
Model C: $\varepsilon_{i,t} = h_{i,t}^{1/2} v_{i,t}, \ln(h_{i,t}) = -0.23 + 0.9\ln(h_{i,t-1}) + 0.25[\lvert v_{i,t-1}^2\rvert - 0.3 v_{i,t-1}], v_{i,t} \sim i.i.d.\ N(0,1),\ i = 1, ..., p$																	
		50	80.0	16.9	2.7	0.3	0.1	92.9	5.9	0.9	0.1	0.1	89.9	8.7	1.1	0.2	0.1
		100	83.2	14.7	1.8	0.3	0.1	93.0	5.9	0.9	0.2	0.0	88.2	10.1	1.2	0.4	0.1
		200	85.3	13.0	1.6	0.1	0.0	94.3	5.0	0.6	0.1	0.0	88.8	9.9	1.2	0.2	0.0
Model D: $\varepsilon_{i,t} = h_{i,t}^{1/2} v_{i,t},\ h_{i,t} = 0.0216 + 0.6896 h_{i,t-1} + 0.3174[\varepsilon_{i,t-1} - 0.1108]^2,\ v_{i,t} \sim$ i.i.d. $N(0,1),\ i = 1, ..., p$																	
		50	80.2	16.5	2.7	0.5	0.1	93.4	5.4	0.8	0.3	0.1	89.7	8.3	1.6	0.4	0.1
		100	81.3	15.9	2.4	0.4	0.1	93.5	5.6	0.7	0.2	0.0	86.8	11.1	1.6	0.4	0.1
		200	79.8	17.1	2.8	0.3	0.1	93.6	5.3	0.9	0.1	0.1	83.9	13.3	2.2	0.5	0.1
Model E: $\varepsilon_{i,t} = h_{i,t}^{1/2} v_{i,t},\ h_{i,t} = 0.005 + 0.7 h_{i,t-1} + 0.28[\lvert\varepsilon_{i,t-1}\rvert - 0.23\varepsilon_{i,t-1}]^2,\ v_{i,t} \sim$ i.i.d. $N(0,1),\ i = 1, ..., p$																	
		50	81.8	15.2	2.6	0.4	0.1	93.9	4.9	0.9	0.2	0.1	90.5	7.8	1.4	0.2	0.1
		100	83.9	13.9	1.9	0.3	0.1	94.2	5.1	0.6	0.1	0.1	88.6	9.8	1.3	0.2	0.1
		200	83.1	14.7	1.8	0.3	0.0	94.6	4.6	0.5	0.1	0.0	86.2	11.7	1.6	0.3	0.1
Model F: $\varepsilon_{i,t} = v_{i,t}\exp(h_{i,t}),\ h_{i,t} = \lambda h_{i,t-1} + 0.5\xi_{i,t},\ (\xi_{i,t}, v_{i,t}) \sim$ i.i.d. $N(0, \mathrm{diag}(\sigma_\xi^2, 1)),\ i = 1, ..., p$																	
λ	σ_ξ	T															
0.936	0.424	50	65.0	26.4	6.9	1.3	0.3	89.0	8.9	1.6	0.4	0.1	77.8	17.0	3.9	1.0	0.3
		100	64.6	27.8	6.2	1.2	0.2	90.5	7.9	1.2	0.3	0.1	73.0	21.4	4.6	0.8	0.2
		200	62.9	28.7	7.0	1.3	0.1	92.1	6.6	1.1	0.2	0.0	69.2	23.9	5.6	1.1	0.2
0.951	0.314	50	71.9	22.0	5.0	1.0	0.2	91.0	7.4	1.2	0.2	0.1	82.7	13.8	2.7	0.6	0.2
		100	72.0	22.5	4.5	0.9	0.2	91.3	7.3	1.2	0.2	0.0	78.5	17.6	3.0	0.8	0.2
		200	69.5	24.8	4.8	0.8	0.1	92.3	6.7	0.8	0.2	0.0	75.1	20.4	3.5	0.9	0.1

Table 6: Size of Standard and Bootstrap PLR Tests for Rank = 0 Against Rank = p. True Rank is 1.

			$p=2$			$p=3$			$p=4$			$p=5$		
Model A: $\varepsilon_{i,t}=h_{i,t}^{1/2}v_{i,t}$, $h_{i,t}=\omega+d_0\varepsilon_{i,t-1}^2+d_1h_{i,t-1}$, $v_{i,t}\sim$ i.i.d. $N(0,1)$, $i=1,...,p$														
d_0	d_1	T	Q_1	Q_1^b	Q_1^s	Q_1	Q_1^b	Q_1^s	Q_1	Q_1^b	Q_1^s	Q_1	Q_1^b	Q_1^s
0.0	0.0	50	5.2	5.7	4.9	5.2	4.7	4.1	6.2	4.0	3.7	6.1	2.6	2.8
		100	5.8	5.6	5.5	5.9	5.2	5.0	6.9	5.2	5.0	7.3	4.6	4.6
		200	5.5	5.6	5.0	5.6	5.0	4.9	5.3	4.5	4.5	6.8	4.6	4.6
0.5	0.0	50	6.3	5.8	5.9	7.6	5.4	6.0	9.0	5.1	5.7	9.0	3.6	4.5
		100	6.4	6.0	6.0	7.9	5.5	6.6	8.5	5.2	6.2	10.6	5.8	7.4
		200	5.1	4.9	5.0	7.3	5.4	6.5	7.8	5.1	6.1	8.8	4.8	6.5
0.3	0.65	50	6.8	5.9	6.2	7.7	5.5	6.0	9.6	5.1	6.2	9.9	4.0	5.0
		100	7.7	5.8	7.4	10.2	5.9	8.2	11.2	6.2	8.6	12.3	5.6	8.6
		200	7.5	5.5	7.4	9.4	5.1	8.7	10.5	5.0	8.7	12.7	5.4	9.8
0.2	0.79	50	6.5	5.8	6.1	7.8	5.6	6.1	8.8	4.9	5.2	9.6	4.0	4.4
		100	8.0	5.9	7.5	10.1	5.7	8.0	10.6	5.5	8.3	12.1	5.1	8.1
		200	7.9	5.4	7.8	10.4	6.0	9.2	11.2	5.3	9.3	12.6	5.4	10.2
0.05	0.94	50	5.2	5.5	5.0	5.8	4.7	4.4	6.2	4.1	3.7	6.5	2.7	2.9
		100	6.1	5.6	5.9	6.9	5.1	5.6	7.1	5.3	5.2	7.9	4.8	4.9
		200	5.8	5.7	5.7	6.8	5.1	5.7	6.6	4.6	5.4	7.4	4.7	5.4
Model B: $\varepsilon_{i,t}=h_{i,t}^{1/2}v_{i,t}$, $h_{i,t}=\omega+d_0\varepsilon_{i,t-1}^2+d_1h_{i,t-1}$, $v_{i,t}\sim$ i.i.d. t_5, $i=1,...,p$														
d_0	d_1	T	Q_1	Q_1^b	Q_1^s	Q_1	Q_1^b	Q_1^s	Q_1	Q_1^b	Q_1^s	Q_1	Q_1^b	Q_1^s
0.0	0.0	50	5.1	6.0	4.6	6.5	5.4	4.7	6.7	4.3	3.9	7.3	2.7	3.3
		100	5.6	5.6	5.1	6.4	5.3	5.5	6.7	4.6	4.9	6.8	3.8	4.2
		200	4.9	4.6	4.3	5.6	4.6	4.6	6.4	4.6	4.8	6.6	4.1	4.7
0.5	0.0	50	6.2	6.3	5.6	7.8	5.6	6.0	7.8	4.5	5.0	9.9	3.6	4.4
		100	6.3	6.2	5.8	6.9	5.2	6.0	8.7	5.4	6.4	9.3	5.0	6.4
		200	5.5	4.8	4.9	6.5	5.2	5.5	7.4	4.7	5.9	7.9	4.7	5.6
0.3	0.65	50	6.5	6.4	6.2	7.8	5.7	6.4	8.2	4.5	5.2	9.7	3.4	4.7
		100	6.6	5.9	6.1	7.7	5.3	6.5	9.0	5.4	6.7	10.0	4.9	6.4
		200	5.9	4.9	5.4	7.2	5.0	6.1	8.3	4.9	6.8	9.0	4.8	6.6
0.2	0.79	50	6.4	6.3	5.9	7.5	5.6	6.0	7.6	4.4	5.0	9.0	3.3	4.3
		100	6.5	6.0	6.0	7.7	5.3	6.3	8.8	5.3	6.5	9.3	4.4	6.0
		200	5.8	4.5	5.6	7.4	4.9	6.3	8.4	5.0	6.9	9.0	4.7	6.5
0.05	0.94	50	5.7	6.1	5.0	6.7	5.1	5.0	6.4	4.0	4.0	7.7	3.0	3.5
		100	6.0	5.5	5.6	6.9	5.4	5.8	7.1	4.9	5.3	7.5	3.8	4.7
		200	5.5	4.8	5.0	6.2	4.8	5.0	6.9	5.0	5.6	7.3	4.3	5.2
Model C: $\varepsilon_{i,t}=h_{i,t}^{1/2}v_{i,t}$, $\ln(h_{i,t})=-0.23+0.9\ln(h_{i,t-1})+0.25[\lvert v_{i,t-1}^2\rvert-0.3v_{i,t-1}]$, $v_{i,t}\sim$ i.i.d. $N(0,1)$, $i=1,...,p$														
		T	Q_1	Q_1^b	Q_1^s	Q_1	Q_1^b	Q_1^s	Q_1	Q_1^b	Q_1^s	Q_1	Q_1^b	Q_1^s
		50	7.0	5.9	6.5	8.2	5.8	6.5	10.5	5.4	7.0	11.0	4.0	5.2
		100	7.7	5.9	7.2	10.3	6.3	8.8	11.9	5.7	9.0	13.9	6.6	9.6
		200	7.6	5.6	7.2	9.7	5.9	8.6	11.3	5.8	9.6	13.3	6.1	10.5
Model D: $\varepsilon_{i,t}=h_{i,t}^{1/2}v_{i,t}$, $h_{i,t}=0.0216+0.6896h_{i,t-1}+0.3174[\varepsilon_{i,t-1}-0.1108]^2$, $v_{i,t}\sim$ i.i.d. $N(0,1)$, $i=1,...,p$														
		T	Q_1	Q_1^b	Q_1^s	Q_1	Q_1^b	Q_1^s	Q_1	Q_1^b	Q_1^s	Q_1	Q_1^b	Q_1^s
		50	7.8	6.2	7.2	9.3	5.6	7.5	11.0	5.5	7.3	12.1	4.5	6.2
		100	9.8	6.5	9.2	13.2	6.9	11.2	14.0	6.2	11.3	15.7	5.5	11.3
		200	10.5	5.9	10.2	14.1	6.3	12.6	15.6	5.7	13.4	17.9	5.9	15.1
Model E: $\varepsilon_{i,t}=h_{i,t}^{1/2}v_{i,t}$, $h_{i,t}=0.005+0.7h_{i,t-1}+0.28[\lvert\varepsilon_{i,t-1}\rvert-0.23\varepsilon_{i,t-1}]^2$, $v_{i,t}\sim$ i.i.d. $N(0,1)$, $i=1,...,p$														
		T	Q_1	Q_1^b	Q_1^s	Q_1	Q_1^b	Q_1^s	Q_1	Q_1^b	Q_1^s	Q_1	Q_1^b	Q_1^s
		50	7.5	6.1	6.9	8.9	5.7	6.9	10.6	5.1	6.3	11.0	4.2	5.8
		100	9.2	6.2	8.5	11.7	6.5	9.9	12.6	5.9	10.1	13.5	5.5	9.5
		200	9.3	5.8	9.1	12.4	6.1	11.5	14.0	5.9	11.9	14.8	5.6	12.2
Model F: $\varepsilon_{i,t}=v_{i,t}\exp(h_{i,t})$, $h_{i,t}=\lambda h_{i,t-1}+0.5\xi_{i,t}$, $(\xi_{i,t},v_{i,t})\sim$ i.i.d. $N(0,\mathrm{diag}(\sigma_\xi^2,1))$, $i=1,...,p$														
λ	σ_ξ	T	Q_1	Q_1^b	Q_1^s	Q_1	Q_1^b	Q_1^s	Q_1	Q_1^b	Q_1^s	Q_1	Q_1^b	Q_1^s
0.936	0.424	50	10.5	7.0	10.1	15.1	7.1	11.7	19.4	7.8	13.8	21.8	7.6	13.3
		100	12.4	6.5	11.6	19.6	7.6	16.9	24.0	8.2	19.6	28.0	8.8	20.8
		200	12.0	6.1	11.5	18.9	6.6	17.0	25.5	7.4	21.9	30.3	7.9	25.4
0.951	0.314	50	9.2	6.7	9.0	12.7	7.0	10.5	15.3	6.6	10.6	17.9	6.3	10.7
		100	11.3	6.8	10.7	16.9	7.2	14.4	19.8	7.5	16.5	22.7	7.4	16.4
		200	10.9	5.5	10.4	16.2	6.1	14.3	21.0	6.5	17.9	25.3	7.1	20.7

Table 7: Standard and Bootstrap Sequential Procedures for Selecting the Co-integration Rank. $p = 2$, True Rank is 1.

			Q-based			Q^b-based			Q^s-based		
			$r=0$	$r=1$	$r=2$	$r=0$	$r=1$	$r=2$	$r=0$	$r=1$	$r=2$
Model A: $\varepsilon_{i,t} = h_{i,t}^{1/2} v_{i,t}$, $h_{i,t} = \omega + d_0 \varepsilon_{i,t-1}^2 + d_1 h_{i,t-1}$, $v_{i,t} \sim$ i.i.d. $N(0,1)$, $i = 1, ..., p$											
d_0	d_1	T									
0.0	0.0	50	9.4	85.4	5.2	14.8	79.5	5.7	12.0	83.1	4.8
		100	0.0	94.2	5.8	0.0	94.4	5.6	0.0	94.5	5.5
		200	0.0	94.5	5.5	0.0	94.4	5.6	0.0	95.0	5.0
0.5	0.0	50	9.8	83.9	6.3	18.0	76.4	5.6	12.5	81.7	5.8
		100	0.0	93.6	6.4	0.3	93.8	6.0	0.0	94.0	6.0
		200	0.0	94.9	5.1	0.0	95.1	4.9	0.0	95.0	5.0
0.3	0.65	50	12.5	80.7	6.8	21.2	73.1	5.8	14.7	79.0	6.2
		100	0.2	92.0	7.7	1.4	92.8	5.8	0.3	92.3	7.4
		200	0.0	92.5	7.5	0.1	94.4	5.5	0.0	92.6	7.4
0.2	0.79	50	14.3	79.3	6.5	22.3	72.0	5.7	17.0	76.9	6.1
		100	0.3	91.7	8.0	1.8	92.4	5.9	0.3	92.2	7.5
		200	0.0	92.1	7.9	0.1	94.6	5.4	0.0	92.2	7.8
0.05	0.94	50	11.7	83.1	5.2	16.6	77.9	5.5	14.2	80.8	5.0
		100	0.0	93.9	6.1	0.2	94.2	5.6	0.0	94.0	5.9
		200	0.0	94.2	5.8	0.0	94.3	5.7	0.0	94.3	5.7
Model B: $\varepsilon_{i,t} = h_{i,t}^{1/2} v_{i,t}$, $h_{i,t} = \omega + d_0 \varepsilon_{i,t-1}^2 + d_1 h_{i,t-1}$, $v_{i,t} \sim$ i.i.d. t_5, $i = 1, ..., p$											
d_0	d_1	T									
0.0	0.0	50	10.2	84.6	5.1	16.1	78.1	5.9	13.5	81.9	4.6
		100	0.0	94.4	5.6	0.1	94.2	5.6	0.0	94.8	5.1
		200	0.0	95.1	4.9	0.0	95.4	4.6	0.0	95.7	4.3
0.5	0.0	50	10.4	83.4	6.2	17.9	75.9	6.2	13.7	80.8	5.6
		100	0.0	93.7	6.3	0.3	93.6	6.2	0.1	94.1	5.8
		200	0.0	94.5	5.5	0.0	95.2	4.8	0.0	95.1	4.9
0.3	0.65	50	11.3	82.2	6.5	19.1	74.6	6.3	14.7	79.1	6.2
		100	0.1	93.3	6.6	0.6	93.5	5.9	0.1	93.7	6.1
		200	0.0	94.1	5.9	0.0	95.1	4.9	0.0	94.6	5.4
0.2	0.79	50	12.0	81.7	6.4	19.0	74.8	6.2	15.2	78.9	5.9
		100	0.1	93.4	6.5	0.6	93.4	6.0	0.2	93.9	6.0
		200	0.0	94.2	5.8	0.0	95.5	4.5	0.0	94.4	5.6
0.05	0.94	50	11.4	82.9	5.7	17.3	76.7	6.0	14.4	80.7	5.0
		100	0.1	93.9	6.0	0.3	94.2	5.5	0.1	94.3	5.6
		200	0.0	94.5	5.5	0.0	95.2	4.8	0.0	95.0	5.0
Model C: $\varepsilon_{i,t} = h_{i,t}^{1/2} v_{i,t}$, $\ln(h_{i,t}) = -0.23 + 0.9 \ln(h_{i,t-1}) + 0.25[\lvert v_{i,t-1}^2 \rvert - 0.3 v_{i,t-1}]$, $v_{i,t} \sim$ i.i.d. $N(0,1)$, $i = 1, ..., p$											
		50	12.2	80.8	7.0	21.7	72.5	5.8	14.8	78.6	6.5
		100	0.2	92.1	7.7	1.4	92.7	5.9	0.3	92.5	7.2
		200	0.0	92.4	7.6	0.1	94.3	5.6	0.0	92.8	7.2
Model D: $\varepsilon_{i,t} = h_{i,t}^{1/2} v_{i,t}$, $h_{i,t} = 0.0216 + 0.6896 h_{i,t-1} + 0.3174[\varepsilon_{i,t-1} - 0.1108]^2$, $v_{i,t} \sim$ i.i.d. $N(0,1)$, $i = 1, ..., p$											
		50	14.7	77.5	7.8	24.5	69.7	5.9	17.3	75.5	7.2
		100	0.6	89.7	9.8	3.0	90.5	6.5	0.7	90.1	9.2
		200	0.0	89.5	10.5	0.4	93.7	5.9	0.0	89.7	10.2
Model E: $\varepsilon_{i,t} = h_{i,t}^{1/2} v_{i,t}$, $h_{i,t} = 0.005 + 0.7 h_{i,t-1} + 0.28[\lvert\varepsilon_{i,t-1}\rvert - 0.23 \varepsilon_{i,t-1}]^2$, $v_{i,t} \sim$ i.i.d. $N(0,1)$, $i = 1, ..., p$											
		50	13.5	79.0	7.5	22.7	71.3	6.0	16.2	77.0	6.8
		100	0.5	90.3	9.2	2.5	91.3	6.2	0.5	91.0	8.5
		200	0.0	90.7	9.3	0.2	94.0	5.8	0.0	90.9	9.1
Model F: $\varepsilon_{i,t} = v_{i,t} \exp(h_{i,t})$, $h_{i,t} = \lambda h_{i,t-1} + 0.5 \xi_{i,t}$, $(\xi_{i,t}, v_{i,t}) \sim$ i.i.d. $N(0, \mathrm{diag}(\sigma_\xi^2, 1))$, $i = 1, ..., p$											
λ	σ_ξ	T									
0.936	0.424	50	16.0	73.5	10.5	29.5	64.5	6.0	19.3	70.8	9.9
		100	1.3	86.3	12.4	8.7	85.0	6.3	1.9	86.5	11.6
		200	0.0	88.0	12.0	1.2	92.7	6.0	0.0	88.5	11.5
0.951	0.314	50	15.9	74.9	9.2	27.8	66.2	6.0	18.9	72.3	8.8
		100	0.9	87.8	11.3	6.3	87.0	6.7	1.3	88.0	10.7
		200	0.0	89.1	10.9	0.7	93.8	5.5	0.0	89.6	10.4

Table 8: Standard and Bootstrap Sequential Procedures for Selecting the Co-integration Rank. $p=3$, True Rank is 1.

			Q-based				Q^b-based				Q^s-based			
		$r=$	0	1	2	3	0	1	2	3	0	1	2	3
Model A: $\varepsilon_{i,t}=h_{i,t}^{1/2}v_{i,t}$, $h_{i,t}=\omega+d_0\varepsilon_{i,t-1}^2+d_1h_{i,t-1}$, $v_{i,t}\sim$ i.i.d. $N(0,1)$, $i=1,...,p$														
d_0	d_1	T												
0.0	0.0	50	28.5	66.3	4.8	0.4	40.3	55.0	3.8	0.9	36.7	59.3	3.4	0.6
		100	0.2	93.9	5.5	0.5	0.4	94.3	4.5	0.7	0.3	94.7	4.4	0.6
		200	0.0	94.4	5.2	0.4	0.0	95.0	4.5	0.5	0.0	95.1	4.4	0.5
0.5	0.0	50	25.5	66.9	6.8	0.8	39.8	54.9	4.3	1.0	32.4	61.7	5.0	0.9
		100	0.8	91.3	7.3	0.6	2.1	92.3	4.7	0.8	1.1	92.4	5.7	0.9
		200	0.0	92.7	6.7	0.6	0.0	94.6	4.6	0.8	0.0	93.5	5.7	0.8
0.3	0.65	50	25.9	66.4	6.8	0.8	39.8	54.9	4.3	1.1	31.6	62.5	4.9	1.0
		100	1.8	88.0	9.1	1.1	5.1	89.0	5.0	1.0	2.4	89.4	6.9	1.3
		200	0.0	90.6	8.6	0.8	0.2	94.7	4.3	0.8	0.0	91.3	7.6	1.2
0.2	0.79	50	27.3	64.9	7.0	0.7	38.8	55.7	4.5	0.9	32.6	61.4	5.2	0.8
		100	2.5	87.4	9.0	1.1	6.1	88.3	4.7	0.9	3.1	89.0	6.6	1.3
		200	0.0	89.6	9.4	1.0	0.2	93.8	5.1	0.9	0.0	90.8	7.9	1.3
0.05	0.94	50	27.7	66.5	5.3	0.5	37.6	57.9	3.5	1.0	34.2	61.4	3.7	0.7
		100	0.8	92.3	6.3	0.6	1.9	93.1	4.3	0.8	1.6	92.9	4.8	0.8
		200	0.0	93.2	6.4	0.4	0.0	94.9	4.4	0.7	0.0	94.3	5.1	0.6
Model B: $\varepsilon_{i,t}=h_{i,t}^{1/2}v_{i,t}$, $h_{i,t}=\omega+d_0\varepsilon_{i,t-1}^2+d_1h_{i,t-1}$, $v_{i,t}\sim$ i.i.d. t_5, $i=1,...,p$														
d_0	d_1	T												
0.0	0.0	50	28.6	64.9	5.9	0.6	40.9	53.8	4.1	1.2	36.8	58.5	3.8	0.9
		100	0.5	93.1	5.7	0.7	1.1	93.7	4.2	1.0	0.8	93.7	4.7	0.8
		200	0.0	94.4	5.1	0.5	0.0	95.4	4.0	0.7	0.0	95.4	4.1	0.5
0.5	0.0	50	26.6	65.6	7.2	0.5	40.7	53.9	4.3	1.0	34.7	59.3	5.1	0.9
		100	0.5	92.6	6.2	0.7	2.0	92.8	4.2	1.1	1.0	93.0	5.0	0.9
		200	0.0	93.5	6.0	0.5	0.0	94.8	4.7	0.4	0.0	94.5	5.0	0.5
0.3	0.65	50	27.3	64.8	7.1	0.7	41.0	53.5	4.4	1.1	34.3	59.4	5.2	1.2
		100	0.9	91.5	7.0	0.7	2.7	91.9	4.4	1.0	1.2	92.3	5.6	0.9
		200	0.0	92.8	6.6	0.6	0.0	95.0	4.3	0.7	0.0	93.9	5.3	0.8
0.2	0.79	50	27.9	64.6	6.8	0.7	40.3	54.4	4.4	1.0	34.9	59.2	4.8	1.1
		100	1.0	91.3	7.0	0.7	2.8	91.9	4.4	0.9	1.3	92.3	5.6	0.8
		200	0.0	92.6	6.9	0.5	0.0	95.1	4.2	0.6	0.0	93.7	5.7	0.6
0.05	0.94	50	28.5	64.8	6.1	0.6	40.5	54.5	4.0	1.0	36.1	58.9	4.0	0.9
		100	0.7	92.4	6.3	0.6	1.7	92.9	4.3	1.2	1.0	93.1	5.0	0.9
		200	0.0	93.8	5.7	0.5	0.0	95.2	4.2	0.6	0.0	95.0	4.4	0.6
Model C: $\varepsilon_{i,t}=h_{i,t}^{1/2}v_{i,t}$, $\ln(h_{i,t})=-0.23+0.9\ln(h_{i,t-1})+0.25[\lvert v_{i,t-1}^2\rvert-0.3v_{i,t-1}]$, $v_{i,t}\sim$ i.i.d. $N(0,1)$, $i=1,...,p$														
		50	25.0	66.8	7.2	1.0	39.8	54.5	4.5	1.1	31.3	62.2	5.4	1.1
		100	1.7	88.0	9.3	1.0	5.4	88.4	5.3	1.0	2.3	88.8	7.7	1.2
		200	0.0	90.3	9.0	0.7	0.3	93.8	5.1	0.8	0.0	91.4	7.5	1.1
Model D: $\varepsilon_{i,t}=h_{i,t}^{1/2}v_{i,t}$, $h_{i,t}=0.0216+0.6896h_{i,t-1}+0.3174[\varepsilon_{i,t-1}-0.1108]^2$, $v_{i,t}\sim$ i.i.d. $N(0,1)$, $i=1,...,p$														
		50	26.6	64.1	8.4	1.0	40.1	54.4	4.6	0.8	31.6	61.0	6.3	1.1
		100	3.2	83.6	11.6	1.5	8.9	84.2	5.6	1.3	3.9	84.8	9.4	1.9
		200	0.0	85.9	12.5	1.6	0.7	93.0	5.1	1.1	0.0	87.3	10.8	1.9
Model E: $\varepsilon_{i,t}=h_{i,t}^{1/2}v_{i,t}$, $h_{i,t}=0.005+0.7h_{i,t-1}+0.28[\lvert\varepsilon_{i,t-1}\rvert-0.23\varepsilon_{i,t-1}]^2$, $v_{i,t}\sim$ i.i.d. $N(0,1)$, $i=1,...,p$														
		50	27.0	64.1	7.9	1.0	40.6	53.9	4.5	1.0	31.9	61.2	5.6	1.3
		100	2.8	85.5	10.4	1.3	7.9	85.7	5.5	1.0	3.4	86.6	8.2	1.7
		200	0.0	87.6	11.1	1.3	0.5	93.3	5.5	0.6	0.0	88.5	10.0	1.5
Model F: $\varepsilon_{i,t}=v_{i,t}\exp(h_{i,t})$, $h_{i,t}=\lambda h_{i,t-1}+0.5\xi_{i,t}$, $(\xi_{i,t},v_{i,t})\sim$ i.i.d. $N(0,\mathrm{diag}(\sigma_\xi^2,1))$, $i=1,...,p$														
0.936	0.424	50	23.4	61.5	13.1	2.0	42.0	51.4	5.3	1.3	28.7	59.7	9.6	2.1
		100	3.7	76.7	17.0	2.6	18.2	74.5	6.2	1.1	5.2	77.9	14.1	2.8
		200	0.1	81.0	16.9	2.0	2.3	91.1	5.8	0.8	0.1	82.9	14.6	2.4
0.951	0.314	50	24.9	62.5	11.0	1.7	41.1	52.4	5.1	1.4	29.9	59.7	8.4	2.1
		100	3.5	79.6	14.7	2.2	14.7	78.3	5.6	1.4	4.5	81.2	11.8	2.6
		200	0.1	83.8	14.7	1.5	1.5	92.4	5.2	0.8	0.1	85.6	12.3	2.0

Table 9: Standard and Bootstrap Sequential Procedures for Selecting the Co-integration Rank. $p = 4$, True Rank is 1.

			Q-based					Q^b-based					Q^s-based				
		$r =$	0	1	2	3	4	0	1	2	3	4	0	1	2	3	4
Model A: $\varepsilon_{i,t} = h_{i,t}^{1/2} v_{i,t}$, $h_{i,t} = \omega + d_0 \varepsilon_{i,t-1}^2 + d_1 h_{i,t-1}$, $v_{i,t} \sim$ i.i.d. $N(0,1)$, $i = 1, ..., p$																	
d_0	d_1	T															
0.0	0.0	50	42.5	51.2	5.5	0.7	0.1	60.3	35.7	3.1	0.6	0.3	56.1	40.2	3.0	0.4	0.2
		100	2.2	90.9	6.3	0.6	0.0	4.6	90.3	4.3	0.6	0.3	3.6	91.4	4.3	0.5	0.2
		200	0.0	94.7	4.8	0.4	0.0	0.0	95.5	3.9	0.5	0.1	0.0	95.5	4.0	0.4	0.1
0.5	0.0	50	36.6	54.3	8.0	0.8	0.3	58.0	37.1	4.1	0.5	0.3	48.5	45.9	4.8	0.5	0.4
		100	2.9	88.6	7.5	0.9	0.1	7.4	87.4	4.5	0.6	0.2	4.3	89.4	5.5	0.6	0.1
		200	0.0	92.2	7.2	0.5	0.1	0.0	94.8	4.6	0.4	0.1	0.0	93.9	5.4	0.5	0.1
0.3	0.65	50	34.5	55.9	8.4	0.8	0.3	54.6	40.4	4.0	0.5	0.4	45.5	48.3	5.3	0.6	0.3
		100	4.9	83.9	9.7	1.3	0.2	12.6	81.1	5.3	0.6	0.3	7.5	84.0	7.2	0.9	0.5
		200	0.0	89.5	9.2	1.1	0.2	0.4	94.6	4.3	0.5	0.2	0.0	91.2	7.5	1.0	0.2
0.2	0.79	50	35.7	55.5	7.5	1.0	0.3	51.8	43.4	3.9	0.5	0.3	45.2	49.7	4.2	0.6	0.3
		100	6.5	82.9	9.2	1.3	0.2	14.1	80.4	4.6	0.6	0.3	8.9	82.8	6.9	1.1	0.4
		200	0.0	88.8	9.9	1.0	0.2	0.4	94.3	4.5	0.6	0.3	0.0	90.7	7.9	1.0	0.4
0.05	0.94	50	39.5	54.3	5.2	0.8	0.1	56.0	39.9	3.3	0.5	0.3	51.0	45.4	2.9	0.4	0.3
		100	4.2	88.7	6.1	0.9	0.1	7.5	87.2	4.3	0.8	0.2	6.1	88.7	4.2	0.7	0.3
		200	0.0	93.4	5.9	0.7	0.0	0.0	95.4	4.0	0.5	0.2	0.0	94.6	4.6	0.5	0.2
Model B: $\varepsilon_{i,t} = h_{i,t}^{1/2} v_{i,t}$, $h_{i,t} = \omega + d_0 \varepsilon_{i,t-1}^2 + d_1 h_{i,t-1}$, $v_{i,t} \sim$ i.i.d. t_5, $i = 1, ..., p$																	
d_0	d_1	T															
0.0	0.0	50	43.4	49.9	5.7	0.8	0.1	61.9	34.1	3.1	0.7	0.2	57.0	39.2	3.0	0.8	0.1
		100	2.7	90.6	5.9	0.6	0.1	5.9	89.5	3.9	0.5	0.3	4.3	90.8	4.1	0.5	0.2
		200	0.0	93.6	5.9	0.4	0.1	0.0	95.4	4.1	0.4	0.1	0.0	95.2	4.1	0.5	0.2
0.5	0.0	50	39.6	52.6	6.8	0.9	0.1	58.8	36.9	3.5	0.8	0.2	51.6	43.4	4.1	0.7	0.2
		100	3.0	88.3	7.9	0.7	0.1	8.1	86.5	4.7	0.5	0.3	4.9	88.7	5.6	0.6	0.2
		200	0.0	92.6	6.6	0.7	0.0	0.0	95.2	4.2	0.4	0.1	0.0	94.1	5.1	0.6	0.1
0.3	0.65	50	39.6	52.2	7.2	0.8	0.1	58.4	37.2	3.4	0.7	0.3	51.5	43.4	4.1	0.8	0.2
		100	3.7	87.2	7.9	0.9	0.2	9.7	84.9	4.5	0.6	0.3	6.0	87.3	5.8	0.7	0.3
		200	0.0	91.7	7.6	0.7	0.1	0.0	95.0	4.3	0.5	0.1	0.0	93.2	5.9	0.8	0.2
0.2	0.79	50	40.4	52.1	6.5	0.9	0.2	58.6	37.2	3.2	0.8	0.3	52.3	42.8	4.0	0.7	0.2
		100	4.4	86.8	7.5	1.0	0.2	10.0	84.7	4.4	0.7	0.3	6.6	86.9	5.4	0.7	0.3
		200	0.0	91.6	7.7	0.6	0.1	0.1	95.0	4.3	0.5	0.1	0.0	93.1	6.3	0.5	0.1
0.05	0.94	50	42.3	51.3	5.4	0.7	0.2	60.1	36.1	2.9	0.6	0.3	54.2	41.8	3.2	0.5	0.3
		100	3.9	89.1	6.2	0.7	0.1	7.9	87.2	4.0	0.6	0.3	5.7	88.9	4.5	0.5	0.3
		200	0.0	93.1	6.3	0.4	0.2	0.0	95.0	4.3	0.5	0.1	0.0	94.4	4.9	0.4	0.2
Model C: $\varepsilon_{i,t} = h_{i,t}^{1/2} v_{i,t}$, $\ln(h_{i,t}) = -0.23 + 0.9 \ln(h_{i,t-1}) + 0.25[\lvert v_{i,t-1}^2 \rvert - 0.3 v_{i,t-1}]$, $v_{i,t} \sim$ i.i.d. $N(0,1)$, $i = 1, ..., p$																	
		50	33.9	55.7	9.0	1.2	0.2	54.2	40.6	4.1	0.7	0.3	44.4	48.6	5.8	0.8	0.4
		100	4.9	83.3	10.5	1.3	0.1	13.7	80.6	4.7	0.6	0.4	7.1	83.9	7.6	1.0	0.4
		200	0.0	88.7	10.1	1.0	0.2	0.5	93.7	5.0	0.6	0.3	0.0	90.4	8.4	1.0	0.3
Model D: $\varepsilon_{i,t} = h_{i,t}^{1/2} v_{i,t}$, $h_{i,t} = 0.0216 + 0.6896 h_{i,t-1} + 0.3174[\varepsilon_{i,t-1} - 0.1108]^2$, $v_{i,t} \sim$ i.i.d. $N(0,1)$, $i = 1, ..., p$																	
		50	33.3	55.8	9.3	1.4	0.3	51.6	43.1	4.2	0.9	0.3	42.4	50.4	5.9	1.1	0.3
		100	7.4	78.6	12.0	1.7	0.3	18.0	75.8	5.0	0.9	0.4	9.7	79.0	9.3	1.3	0.6
		200	0.1	84.4	13.5	1.8	0.2	1.6	92.7	4.7	0.7	0.3	0.1	86.5	11.1	1.8	0.5
Model E: $\varepsilon_{i,t} = h_{i,t}^{1/2} v_{i,t}$, $h_{i,t} = 0.005 + 0.7 h_{i,t-1} + 0.28[\lvert \varepsilon_{i,t-1} \rvert - 0.23 \varepsilon_{i,t-1}]^2$, $v_{i,t} \sim$ i.i.d. $N(0,1)$, $i = 1, ..., p$																	
		50	34.5	54.9	9.2	1.1	0.3	52.4	42.6	3.9	0.7	0.3	43.4	50.3	5.3	0.7	0.3
		100	6.7	80.7	10.7	1.5	0.4	16.9	77.2	4.7	0.9	0.3	9.4	80.4	8.2	1.3	0.6
		200	0.1	86.0	12.3	1.4	0.3	0.9	93.2	5.0	0.5	0.3	0.1	88.0	10.2	1.3	0.4
Model F: $\varepsilon_{i,t} = v_{i,t} \exp(h_{i,t})$, $h_{i,t} = \lambda h_{i,t-1} + 0.5 \xi_{i,t}$, $(\xi_{i,t}, v_{i,t}) \sim$ i.i.d. $N(0, \mathrm{diag}(\sigma_\xi^2, 1))$, $i = 1, ..., p$																	
λ	σ_ξ	T															
0.936	0.424	50	27.9	52.7	16.1	3.0	0.4	49.6	42.9	6.3	0.9	0.3	36.0	50.2	10.9	2.2	0.6
		100	7.9	68.1	20.3	3.2	0.4	26.7	65.4	6.4	1.2	0.3	10.9	69.5	16.2	2.7	0.7
		200	0.2	74.2	22.0	2.9	0.6	4.9	87.8	6.5	0.6	0.2	0.4	77.7	18.5	2.6	0.8
0.951	0.314	50	30.0	54.7	12.7	2.2	0.4	49.9	43.7	5.3	0.8	0.3	38.5	51.0	8.4	1.6	0.6
		100	7.8	72.4	17.1	2.4	0.4	23.9	68.7	6.2	0.9	0.3	10.5	73.0	14.0	1.7	0.8
		200	0.2	78.9	18.1	2.5	0.4	3.0	90.5	5.8	0.6	0.1	0.2	81.9	15.2	2.0	0.7

Table 10: Standard and Bootstrap Sequential Procedures for Selecting the Co-integration Rank. $p = 5$, True Rank is 1.

			Q-based					Q^b-based					Q^s-based				
		$r =$	0	1	2	3	4, 5	0	1	2	3	4, 5	0	1	2	3	4, 5
Model A: $\varepsilon_{i,t} = h_{i,t}^{1/2} v_{i,t}, h_{i,t} = \omega + d_0 \varepsilon_{i,t-1}^2 + d_1 h_{i,t-1}, v_{i,t} \sim i.i.d.\ N(0,1), i = 1, ..., p$																	
d_0	d_1	T															
0.0	0.0	50	51.5	42.4	5.3	0.6	0.1	75.4	22.1	2.1	0.2	0.2	71.0	26.3	2.3	0.3	0.1
		100	7.2	85.5	6.6	0.6	0.1	15.5	80.0	3.8	0.5	0.2	12.9	82.5	4.0	0.5	0.1
		200	0.0	93.2	6.0	0.7	0.1	0.0	95.4	4.0	0.4	0.2	0.0	95.4	4.0	0.5	0.1
0.5	0.0	50	44.7	46.3	7.9	0.9	0.2	71.4	25.0	3.1	0.3	0.2	63.1	32.4	3.8	0.4	0.3
		100	7.7	81.7	9.4	1.0	0.2	19.9	74.3	5.0	0.6	0.2	12.8	79.8	6.5	0.7	0.2
		200	0.0	91.2	8.0	0.7	0.1	0.0	95.2	4.3	0.3	0.1	0.0	93.5	5.8	0.5	0.1
0.3	0.65	50	41.5	48.6	8.7	1.1	0.1	65.6	30.4	3.4	0.5	0.1	57.4	37.7	4.2	0.6	0.1
		100	10.3	77.5	10.5	1.6	0.2	24.6	69.9	4.6	0.7	0.2	15.5	75.8	7.3	1.1	0.3
		200	0.0	87.2	11.5	1.1	0.2	1.0	93.6	4.7	0.6	0.1	0.1	90.1	8.5	1.1	0.2
0.2	0.79	50	41.8	48.5	8.4	1.0	0.3	64.0	32.0	3.3	0.5	0.2	56.2	39.3	3.7	0.5	0.2
		100	12.2	75.7	10.5	1.3	0.3	25.4	69.5	4.2	0.7	0.2	17.6	74.4	6.8	1.0	0.3
		200	0.2	87.2	11.1	1.4	0.2	1.3	93.3	4.8	0.4	0.2	0.3	89.5	8.7	1.2	0.3
0.05	0.94	50	47.6	45.8	5.6	0.7	0.2	70.6	26.7	2.1	0.4	0.2	64.9	32.3	2.4	0.3	0.1
		100	10.4	81.7	7.0	0.7	0.1	19.3	75.9	4.0	0.6	0.1	16.1	79.1	4.2	0.5	0.1
		200	0.0	92.6	6.7	0.6	0.1	0.1	95.2	4.2	0.4	0.1	0.0	94.6	4.8	0.4	0.2
Model B: $\varepsilon_{i,t} = h_{i,t}^{1/2} v_{i,t}, h_{i,t} = \omega + d_0 \varepsilon_{i,t-1}^2 + d_1 h_{i,t-1}, v_{i,t} \sim i.i.d.\ t_5, i = 1, ..., p$																	
d_0	d_1	T															
0.0	0.0	50	49.8	42.9	6.4	0.8	0.1	74.6	22.7	2.3	0.3	0.1	69.1	27.7	2.8	0.3	0.1
		100	7.8	85.4	6.1	0.6	0.1	16.6	79.6	3.5	0.2	0.1	13.5	82.3	3.8	0.4	0.1
		200	0.0	93.4	6.0	0.6	0.1	0.0	95.9	3.8	0.3	0.1	0.0	95.3	4.2	0.4	0.1
0.5	0.0	50	43.6	46.5	8.9	0.7	0.2	71.1	25.4	3.0	0.3	0.2	63.1	32.6	3.9	0.3	0.2
		100	8.1	82.7	8.2	0.9	0.2	19.5	75.5	4.4	0.5	0.2	13.4	80.2	5.7	0.5	0.2
		200	0.0	92.0	7.4	0.5	0.1	0.2	95.1	4.3	0.3	0.1	0.0	94.4	5.1	0.3	0.2
0.3	0.65	50	43.1	47.2	8.8	0.8	0.1	70.6	26.0	2.8	0.3	0.2	61.8	33.6	4.2	0.4	0.1
		100	8.7	81.3	9.0	0.9	0.2	20.0	75.1	4.4	0.4	0.1	14.1	79.5	5.7	0.6	0.2
		200	0.0	91.0	8.1	0.7	0.2	0.3	94.9	4.2	0.5	0.1	0.0	93.3	5.8	0.7	0.1
0.2	0.79	50	44.0	47.0	8.0	0.8	0.1	70.0	26.8	2.7	0.4	0.1	62.4	33.4	3.7	0.4	0.1
		100	8.8	81.9	8.2	1.0	0.1	20.1	75.5	3.9	0.3	0.1	14.8	79.2	5.3	0.6	0.2
		200	0.0	91.0	8.2	0.7	0.1	0.2	95.0	4.2	0.5	0.1	0.0	93.4	5.7	0.6	0.2
0.05	0.94	50	47.8	44.5	6.9	0.7	0.1	72.6	24.4	2.5	0.3	0.2	66.3	30.3	2.8	0.4	0.1
		100	9.0	83.5	6.8	0.5	0.1	17.9	78.2	3.4	0.3	0.1	14.9	80.4	4.2	0.4	0.1
		200	0.0	92.7	6.6	0.7	0.1	0.1	95.6	3.9	0.4	0.0	0.0	94.8	4.5	0.5	0.1
Model C: $\varepsilon_{i,t} = h_{i,t}^{1/2} v_{i,t}, \ln(h_{i,t}) = -0.23 + 0.9 \ln(h_{i,t-1}) + 0.25[\lvert v_{i,t-1}^2 \rvert - 0.3 v_{i,t-1}], v_{i,t} \sim i.i.d.\ N(0,1), i = 1, ..., p$																	
		50	39.4	49.6	9.6	1.2	0.2	65.0	31.0	3.3	0.5	0.2	55.5	39.4	4.3	0.6	0.2
		100	9.2	76.9	12.1	1.7	0.1	23.9	69.6	5.6	0.8	0.2	14.4	76.0	8.3	1.1	0.3
		200	0.1	86.6	11.9	1.2	0.2	0.8	93.2	5.3	0.6	0.2	0.1	89.4	9.2	0.9	0.4
Model D: $\varepsilon_{i,t} = h_{i,t}^{1/2} v_{i,t}$, $h_{i,t} = 0.0216 + 0.6896 h_{i,t-1} + 0.3174[\varepsilon_{i,t-1} - 0.1108]^2$, $v_{i,t} \sim$ i.i.d. $N(0,1)$, $i = 1, ..., p$																	
		50	38.8	49.1	10.2	1.6	0.3	61.0	34.5	3.4	0.8	0.3	52.7	41.2	5.0	0.9	0.3
		100	12.1	72.2	13.6	1.8	0.3	28.0	66.5	4.7	0.6	0.1	17.0	71.7	9.9	1.0	0.3
		200	0.2	81.9	15.2	2.4	0.3	3.3	90.8	4.9	0.7	0.3	0.4	84.5	12.5	1.9	0.7
Model E: $\varepsilon_{i,t} = h_{i,t}^{1/2} v_{i,t}$, $h_{i,t} = 0.005 + 0.7 h_{i,t-1} + 0.28[\lvert\varepsilon_{i,t-1}\rvert - 0.23 \varepsilon_{i,t-1}]^2$, $v_{i,t} \sim$ i.i.d. $N(0,1)$, $i = 1, ..., p$																	
		50	39.9	49.1	9.4	1.2	0.4	62.7	33.2	3.4	0.5	0.2	53.9	40.3	4.8	0.7	0.3
		100	11.4	75.1	11.7	1.6	0.3	26.3	68.2	4.7	0.6	0.2	16.2	74.3	8.3	0.9	0.3
		200	0.2	85.0	12.7	1.8	0.3	2.2	92.2	4.6	0.7	0.2	0.3	87.5	10.4	1.4	0.5
Model F: $\varepsilon_{i,t} = v_{i,t} \exp(h_{i,t})$, $h_{i,t} = \lambda h_{i,t-1} + 0.5 \xi_{i,t}$, $(\xi_{i,t}, v_{i,t}) \sim$ i.i.d. $N(0, \mathrm{diag}(\sigma_\xi^2, 1))$, $i = 1, ..., p$																	
λ	σ_ξ	T															
0.936	0.424	50	28.8	49.4	16.9	3.9	1.0	55.7	37.2	5.6	1.2	0.3	41.0	45.8	10.3	2.2	0.7
		100	11.8	60.2	22.7	4.7	0.6	34.3	57.1	7.2	1.2	0.2	16.3	62.9	17.0	2.9	0.8
		200	0.5	69.2	25.2	4.5	0.7	8.6	83.5	6.7	0.9	0.3	0.8	73.8	20.8	3.7	0.9
0.951	0.314	50	32.8	49.3	14.3	2.9	0.6	57.6	36.4	4.6	1.1	0.4	45.4	43.9	8.3	1.8	0.5
		100	12.3	65.0	18.9	3.2	0.6	32.6	60.1	6.2	0.9	0.2	17.2	66.4	13.4	2.5	0.4
		200	0.3	74.4	21.7	2.8	0.7	6.1	86.9	5.8	0.9	0.4	0.8	78.5	17.5	2.5	0.7

Table 11: Size of Standard and Bootstrap PLR Tests for Rank = 0 Against Rank = p. True Rank is 0. VAR(2) Case.

			$p=2$			$p=3$			$p=4$			$p=5$		
Model A: $\varepsilon_{i,t}=h_{i,t}^{1/2}v_{i,t}$, $h_{i,t}=\omega+d_0\varepsilon_{i,t-1}^2+d_1h_{i,t-1}$, $v_{i,t}\sim$ i.i.d. $N(0,1)$, $i=1,...,p$														
d_0	d_1	T	Q_0	Q_0^b	Q_0^s	Q_0	Q_0^b	Q_0^s	Q_0	Q_0^b	Q_0^s	Q_0	Q_0^b	Q_0^s
0.0	0.0	50	12.2	7.3	6.8	21.4	6.5	6.9	41.5	8.5	8.9	70.3	9.7	11.5
		100	8.9	6.0	6.2	12.5	5.6	5.9	18.9	5.2	5.9	32.0	6.5	7.4
		200	7.0	4.9	5.3	8.5	5.2	5.6	10.9	4.8	5.1	15.8	5.2	5.3
0.3	0.65	50	16.3	8.0	10.1	27.0	8.5	11.0	46.2	9.4	11.2	72.2	12.0	14.6
		100	12.9	6.7	9.4	17.3	7.1	10.1	25.4	7.0	10.6	38.1	8.6	12.5
		200	10.5	5.9	8.8	13.4	5.8	9.4	16.1	5.7	9.4	22.9	6.3	10.8
Model B: $\varepsilon_{i,t}=h_{i,t}^{1/2}v_{i,t}$, $h_{i,t}=\omega+d_0\varepsilon_{i,t-1}^2+d_1h_{i,t-1}$, $v_{i,t}\sim$ i.i.d. t_5, $i=1,...,p$														
d_0	d_1	T	Q_0	Q_0^b	Q_0^s	Q_0	Q_0^b	Q_0^s	Q_0	Q_0^b	Q_0^s	Q_0	Q_0^b	Q_0^s
0.0	0.0	50	12.3	6.2	6.7	22.0	6.9	7.6	41.3	7.7	8.7	70.2	10.2	11.1
		100	8.4	5.0	5.7	12.2	5.5	6.1	18.7	5.8	6.8	32.3	5.7	6.5
		200	7.3	5.4	5.6	8.7	5.1	5.5	10.9	5.2	5.8	16.8	5.9	6.4
0.3	0.65	50	14.3	7.2	8.0	24.6	8.0	9.6	44.7	8.6	10.5	72.4	11.0	12.6
		100	10.7	5.6	7.6	14.2	6.1	7.8	22.2	6.3	8.4	35.4	6.6	9.3
		200	9.0	5.9	7.4	11.0	5.9	7.5	13.5	5.2	7.3	19.8	6.1	8.1
Model C: $\varepsilon_{i,t}=h_{i,t}^{1/2}v_{i,t}$, $\ln(h_{i,t})=-0.23+0.9\ln(h_{i,t-1})+0.25[\lvert v_{i,t-1}^2\rvert-0.3v_{i,t-1}]$, $v_{i,t}\sim$ i.i.d. $N(0,1)$, $i=1,...,p$														
		T	Q_0	Q_0^b	Q_0^s	Q_0	Q_0^b	Q_0^s	Q_0	Q_0^b	Q_0^s	Q_0	Q_0^b	Q_0^s
		50	16.4	8.3	10.3	27.7	8.9	11.4	47.4	10.4	12.5	73.0	12.5	15.6
		100	13.3	6.7	9.1	18.0	7.0	10.6	25.5	7.6	11.4	39.9	8.5	12.6
		200	10.8	5.9	8.6	13.2	6.0	9.2	16.7	6.0	9.4	22.5	6.5	10.2
Model D: $\varepsilon_{i,t}=h_{i,t}^{1/2}v_{i,t}$, $h_{i,t}=0.0216+0.6896h_{i,t-1}+0.3174[\varepsilon_{i,t-1}-0.1108]^2$, $v_{i,t}\sim$ i.i.d. $N(0,1)$, $i=1,...,p$														
		T	Q_0	Q_0^b	Q_0^s	Q_0	Q_0^b	Q_0^s	Q_0	Q_0^b	Q_0^s	Q_0	Q_0^b	Q_0^s
		50	17.9	8.9	11.8	29.8	9.8	12.3	47.6	10.6	13.5	73.1	12.7	15.9
		100	16.0	7.3	12.4	21.0	7.8	12.9	29.7	8.0	13.8	42.8	9.3	14.8
		200	15.0	6.2	12.5	18.8	6.7	14.4	22.9	6.6	14.6	29.7	7.4	16.2
Model E: $\varepsilon_{i,t}=h_{i,t}^{1/2}v_{i,t}$, $h_{i,t}=0.005+0.7h_{i,t-1}+0.28[\lvert\varepsilon_{i,t-1}\rvert-0.23\varepsilon_{i,t-1}]^2$, $v_{i,t}\sim$ i.i.d. $N(0,1)$, $i=1,...,p$														
		T	Q_0	Q_0^b	Q_0^s	Q_0	Q_0^b	Q_0^s	Q_0	Q_0^b	Q_0^s	Q_0	Q_0^b	Q_0^s
		50	17.0	8.3	10.8	28.5	9.1	11.5	45.9	10.3	13.1	72.5	12.2	15.7
		100	14.4	7.0	10.8	19.9	7.4	12.2	27.4	7.4	12.4	40.9	8.2	13.3
		200	12.9	6.4	11.1	16.6	6.5	12.6	20.0	6.2	12.5	26.5	6.2	13.0
Model F: $\varepsilon_{i,t}=v_{i,t}\exp(h_{i,t})$, $h_{i,t}=\lambda h_{i,t-1}+0.5\xi_{i,t}$, $(\xi_{i,t},v_{i,t})\sim$ i.i.d. $N(0,\mathrm{diag}(\sigma_\xi^2,1))$, $i=1,...,p$														
λ	σ_ξ	T	Q_0	Q_0^b	Q_0^s	Q_0	Q_0^b	Q_0^s	Q_0	Q_0^b	Q_0^s	Q_0	Q_0^b	Q_0^s
0.951	0.314	50	21.7	8.8	14.1	33.0	10.6	16.1	52.2	13.4	19.8	76.0	16.5	22.7
		100	19.9	8.1	15.8	26.9	8.7	18.0	36.6	9.5	19.2	49.6	11.7	21.3
		200	16.9	5.9	13.8	22.6	6.7	16.9	30.2	7.3	20.7	37.2	8.1	21.4

Table 12: Standard and Bootstrap Co-integration Tests: UK, Japan, Canada and the U.S.

Country		Q_r Statistics					Asymptotic p-values					Wild Bootstrap p-values					I.I.D. Bootstrap p-values				
UK	$r =$	0	1	2	3		0	1	2	3		0	1	2	3		0	1	2	3	
		154.88	67.83	10.65	0.98		0.00	0.00	0.58	0.95		0.00	0.00	0.76	0.98		0.00	0.00	0.60	0.95	
Japan	$r =$	0	1	2	3		0	1	2	3		0	1	2	3		0	1	2	3	
		101.86	40.19	10.50	3.68		0.00	0.01	0.59	0.46		0.00	0.20	0.86	0.75		0.00	0.04	0.71	0.51	
Canada	$r =$	0	1	2	3		0	1	2	3		0	1	2	3		0	1	2	3	
		248.50	74.65	15.84	6.11		0.00	0.00	0.18	0.18		0.00	0.00	0.33	0.31		0.00	0.00	0.20	0.26	
USA	$r =$	0	1	2	3	4	0	1	2	3	4	0	1	2	3	4	0	1	2	3	4
		138.66	60.04	33.32	17.47	3.15	0.00	0.01	0.08	0.12	0.55	0.02	0.36	0.51	0.62	0.90	0.00	0.01	0.12	0.15	0.62