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# Size Distortions of Tests of the Null Hypothesis of Stationarity: Evidence and Implications for Applied Work

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# Size Distortions of
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**Abstract**

It is common in applied econometrics to test the null hypothesis of a level-stationary process against the alternative of a unit root process. We show that the use of conventional asymptotic critical values for the stationarity tests of Kwiatkowski et al. (1992) and Leybourne and McCabe (1994) may cause extreme size distortions, if the model under the null hypothesis is highly persistent. The existence of such size distortions has not been recognized in the previous literature. We illustrate the practical importance of these distortions for the problem of testing for long-run purchasing power parity under the recent float. Size distortions of tests of the unit root null hypothesis may be overcome by the use of finite-sample or bootstrap critical values. We show that such corrections are not possible for tests of the null hypothesis of stationarity. Our results suggest that the common practice of viewing tests of stationarity as complementary to tests of the unit root null will tend to result in contradictions or in spurious acceptances of the unit root hypothesis. We conclude that tests of the null hypothesis of stationarity cannot be recommended for applied work unless the sample size is very large.



*Key Words*: I(0) null hypothesis; finite-sample critical values; size; Monte Carlo simulation.

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# 1 Introduction

Recently, there has been increasing interest in unit root tests that compare the null hypothesis of a level stationary process (or more precisely I(0) process) against the alternative of a difference stationary (or I(1)) process. These tests are widely used in applied work both in their own right and as complements to more traditional tests of the unit root null hypothesis (see, for example, Choi (1994), Lewbel (1996), Culver and Papell (1997a,b), Lee et al. (1997), Collins and Anderson (1998), Wolters et al. (1998)). They have also been modified for the purpose of testing the null of cointegration (see Harris and Inder (1994), Shin (1994), McCabe, Leybourne, and Shin (1997)). Caner (1998) discusses applications of stationarity tests at seasonal frequencies.

The two most widely used tests of the I(0) null hypothesis are due to Kwiatkowski et al. (1992), henceforth KPSS test, and to Leybourne and McCabe (1994), henceforth LMC test. Asymptotic critical values for both tests are given in Kwiatkowski et al. (1992). However, these critical values make no distinction between a process that is white noise and a highly persistent stationary process. We provide important new evidence that in models with roots close to unity the use of asymptotic critical values may cause extreme size distortions. The existence of such size distortions has not been recognized in the previous literature. Our findings are of immediate practical interest because it is well known that the relevant comparison from an economic point of view involves a highly persistent stationary null and a unit root alternative (see Rudebusch (1993), Diebold and Senhadji (1996)). Given the size distortions of the KPSS and LMC tests it is all but impossible to interpret the results of these tests in applied work.

Moreover, ignoring the evidence of size distortions is likely to result in spurious inference. For example, it is common practice in applied work to test both the null hypothesis of a unit root and that of stationarity. Evidence against the stationarity null, but not the unit root null is interpreted as conclusive evidence that the underlying process is difference stationary (see, for example, Baillie and Pecchenino (1991), Cheung and Chinn (1997), Ely and Robinson (1997), Moreno (1998)). Our results imply that applied users will tend to spuriously accept the difference stationary model in practice. Rejections of stationarity in favor of a unit root process are indeed common in applied work. Moreover, our results suggest that size distortions of stationarity tests may generate contradictory test results with both null hypotheses being rejected.

We illustrate the practical importance of this point for the example of testing for long-run purchasing power parity (PPP) in the post-Bretton Woods period. The emerging consensus view in the literature is that real exchange rates are stationary, but highly persistent with half-lives of 3-5 years (see Abuaf and Jorion (1990), Froot and Rogoff (1995), Rogoff (1996)). This consensus view implies roots as large as 0.9885 under the null hypothesis for monthly data and 0.9808 for quarterly data. Thus, we would expect a large number of rejections of the null hypothesis of stationarity, even if stationarity holds. We show that indeed stationarity tests have a tendency to reject the stationarity null for monthly and quarterly real exchange rates in the post-Bretton Woods period. For example, the LMC test based on asymptotic critical values rejects the null hypothesis of stationarity at the 5 percent significance level in favor of a unit root for *all* 17 countries for which monthly real exchange rate data are available. Using quarterly data, we still reject the null hypothesis for 17 of 20 countries. This result is not only consistent with the evidence of size distortions, but it directly contradicts results for the asymptotically efficient DF-GLS test of the unit root null hypothesis. The latter test comes close to the asymptotic power envelope of unit root tests, and its size can be controlled using finite-sample critical values (see Elliott, Rothenberg, and Stock, 1996). For the same data set, for which the LMC test rejects the I(0) null for all countries at the monthly frequency and for all but three countries at the quarterly frequency, the DF-GLS test rejects the unit root null at the 10 percent level for 7 of the 17 countries for which monthly data are available and for 15 of the 20 countries for which quarterly data are available. While the DF-GLS test may have low power against some stationary alternatives, the fact that we *are* able to reject the unit root null hypothesis, despite the small sample size, is unequivocal evidence against the unit root hypothesis. This finding supports the interpretation that the strong rejection of stationarity using the LMC test is likely to be spurious, and accounts for the apparent contradictions in the test results. For the KPSS test, for the same data sets, we observe only eight rejections (of which two contradict the DF-GLS test result) at the monthly frequency and five rejections (one contradiction) at the quarterly frequency.

An important question is to what extent the size distortions of stationarity tests may be mitigated by replacing the asymptotic critical values by finite-sample critical values. For example, it is well-known that size distortions of tests of the unit root null hypothesis may be overcome by the use of finite-sample (or bootstrap) critical values. We show that it is not possible to use similar corrections for tests of the null hypothesis of stationarity. This result means that tests of the null hypothesis of stationarity cannot be recommended unless the sample size is very large. Moreover, it implies that the common practice in applied work of using stationarity tests as complements to tests of the unit root null hypothesis is highly questionable.

In section 2, we review the construction of the KPSS and LMC tests of stationarity (with special attention to the choice of starting values for the maximum likelihood estimator used for the LMC test). In section 3 we document the size distortions of the KPSS and LMC tests based on asymptotic critical values. In section 4, we demonstrate the impossibility of using conventional finite-sample corrections to improve the reliability of tests of stationarity in small samples. In section 5, we illustrate the practical importance of the size distortions for applied work. Section 6 concludes.

## 2 A Review of the Two Leading Examples of Tests of Stationarity

The two most widely used tests of the I(0) null hypothesis are due to Kwiatkowski et al. (1992) and to Leybourne and McCabe (1994). These two tests differ in how they account for serial correlation under $H_0$. Whereas the KPSS test uses a nonparametric correction similar to the Phillips-Perron test, the LMC test allows for additional autoregressive lags similar to the augmented Dickey-Fuller (ADF) test. Although both tests have the same asymptotic distribution, the LMC test statistic converges at rate $O_P(T)$ compared to a rate of only $O_P(T / l)$ for the KPSS statistic where *l* is the autocorrelation truncation lag. Moreover, the LMC test is robust to the choice of lag order, whereas the KPSS test can be sensitive to the choice of $l$ (see Leybourne and McCabe (1994), Lee (1996)).

### 2.1 Leybourne-McCabe Test

Following Leybourne and McCabe (1994), we consider the generalized local levels model

$$\Phi(L)\, y_t = a_t + b\, t + e_t \tag{1}$$

and

$$a_t = a_{t-1} + h_t\,,\; a_0 = a\,,\; t = 1, \ldots, T\,, \tag{2}$$

where $\Phi(L) = 1 - f_1 L - f_2 L^2 - \ldots - f_p L^p$ is a *p*th-order autoregressive polynomial in the lag operator *L* with roots outside the unit circle. We assume that $e_t$ is distributed iid $(0, s_e^2)$ and $h_t$ is distributed iid $(0, s_h^2)$. We also assume that $e_t$ and $h_t$ are mutually independent. Under regularity conditions, the structural model (1) and (2) can be shown to be second-order equivalent to the ARIMA(p,1,1) reduced form process:

$$\Phi(L)\,(1 - L)\, y_t = b + (1 - q\, L)\, z_t\,, \tag{3}$$

with suitably defined MA coefficient $q$ and iid innovations $z_t$ with distribution $(0, s_z^2)$. It can be shown that $0 < q < 1$ for $s_h^2 < \infty$. This specification accounts for the presence of a nonzero MA(1) component in the growth rates of many economic time series. A test of the null hypothesis that $y_t$ follows a trend-stationary ARIMA(p,0,0) process against the alternative of an ARIMA(p,1,1) model with positive MA coefficient can be stated as $H_0 : s_h^2 = 0$ against $H_1 : s_h^2 > 0$ in the structural model with $b \neq 0$.

To implement the LMC test we construct the series:

$$y_t^* = y_t - \sum_{i=1}^{p} f_i^* y_{t-i}$$

where the $f_i^*$ are the maximum likelihood estimates of $f_i$ from the fitted ARIMA(p,1,1) model

$$\Delta y_t = b + \sum_{i=1}^{p} f_i \Delta y_{t-i} + z_t - q z_{t-1} \qquad (4)$$

and then calculate the residuals from the least-squares regression of $y_t^*$ on an intercept and deterministic time trend. Denoting these residuals $\hat{e}_t$, the test is based on

$$\hat{s}_b = \hat{s}_e^{-2} T^{-2} \hat{e}' V \hat{e}$$

where $\hat{s}_e^2 = \hat{e}' \hat{e} / T$ is a consistent estimator of $s_e^2$ and $V$ is a *T x T* matrix with *ij*th element equal to the minimum of *i* and *j*. We reject the null hypothesis of stationarity if the test statistic exceeds its critical value under $H_0$.

If $b$ is known to be zero in population, the residuals $\hat{e}_t$ are obtained from regressing $y_t^*$ on an intercept alone. The resulting test statistic is:

$$\hat{s}_a = \hat{s}_e^{-2} T^{-2} \hat{e}' V \hat{e}$$

Asymptotic critical values for both of these statistics are provided in Kwiatkowski et al. (1992).

We follow Leybourne and McCabe in programming the test in GAUSS. A key issue in the implementation of the LMC test that is not discussed in their paper is the choice of starting values for the ARIMA(*p*,1,1) model. Rather than rely on the standard optimization algorithm used by the GAUSS-ARIMA routine, Leybourne and McCabe evaluate the likelihood function for a grid of initial values for the moving average parameter, $q^0$, ranging from 0 to -1 in increments of 0.05, with the initial value of the autoregressive parameter(s) fixed at $q^0 - 0.1$. In particular, for $p$ = 1, the initial guess for the AR parameter is defined as $f_1^0 = q^0 - 0.1$. For $p$ > 1, the initial guess is $f_1^0 = \ldots = f_p^0 = q^0 - 0.1$. The starting value for the drift parameter is set equal to 0.1. In this paper, we extend Leybourne and McCabe's procedure by including among the candidate models the model selected based on the default initial values supplied by the GAUSS-ARIMA routine. The model that achieves the highest likelihood is selected for the final analysis. The GAUSS code for our estimation procedure is available upon request.[2]

## 2.2 KPSS Test

The KPSS test of stationarity is based on the same model as the LMC test and has the same general structure. The KPSS test statistic for the model with time trend is computed as

$$\hat{d}_b = \hat{s}_e^{-2}\, T^{-2}\, \hat{e}'\, V\, \hat{e}\ ,$$

where $\hat{e}_t$ is the least-squares residual from a regression of $y_t^*$ on an intercept and deterministic time trend. The difference to the LMC test is that KPSS test relies on a nonparametric estimator of the long-run variance of $e_t$:

$$\hat{s}_e^2 = \hat{e}_t'\hat{e}_t / T + 2\sum_{i=1}^{l} w(i,l)\, \hat{e}_t'\hat{e}_{t-i} / T\ ,$$

where $w(i,l)$ = 1- $i/(l+1)$ is the Bartlett kernel. This estimator is consistent if the truncation lag $l$ increases with the sample size at a suitable rate. We set $l = \text{int}[\,12\,(T/100)^{1/4}\,]$ where *int* denotes the integer part (see Kwiatkowski et. al. (1992), Lee (1996)).[3]

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[2] It can be shown that this modified algorithm results in considerably lower size distortions than use of the initial values supplied by the GAUSS-ARIMA routine, if the test is based on asymptotic critical values. Hobijn et al. (1998) uses yet another procedure for initializing the GAUSS-ARIMA routine based on Yule-Walker estimates of the model under the null hypothesis. This choice of starting values has no theoretical justification under the alternative hypothesis. In this paper, we therefore rely on the procedure originally proposed by Leybourne and McCabe.

Similarly, for $b = 0$, the residuals $\hat{e}_t$ are obtained from regressing $y_t^*$ on an intercept alone. The resulting test statistic is:

$$\hat{d}_a = \hat{s}_e^{-2}\, T^{-2}\, \hat{e}'\, V\, \hat{e}\,,$$

where $\hat{s}_e^{2}$ is defined as before. The asymptotic critical values for these statistics are identical to those for the LMC test.

## 3 Evidence of Size Distortions

This is not the first paper to examine the size of tests of stationarity. For example, Kwiatkowski et al. (1992) and Lee (1996) have provided size results for a range of sample sizes and values of $r$. However, their results are limited to the AR(1) model with slope parameter $r \leq 0.8$. Kwiatkowski et. al. make the case that "$r = 0.8$ is a plausible parameter value since, if we take most series to be stationary, their first-order autocorrelations will often be in this range" (p. 171/172). This view may be plausible for some of the annual Nelson and Plosser (1982) data analyzed in Kwiatkowski et al., but it is highly unrealistic for most monthly and quarterly data.

In this paper, we make the case that many econometric applications of stationarity tests involve processes with roots much closer to unity (see Rudebusch (1993), Cheung and Chinn (1997)). While Leybourne and McCabe (1994) provide some additional small-sample evidence for the size of the LMC and KPSS tests, their evidence is limited to processes with roots between 0 and 0.9. As we will show, there is reason to expect the dominant root of many stationary processes to be closer to 0.94-0.99 in practice. Thus, the relevant comparison from an economic point of view involves a highly persistent stationary null and a unit root alternative. There is reason to doubt the finite-sample accuracy of the asymptotic critical values for such highly persistent processes. We illustrate this point by extending the simulation evidence for the KPSS test and the LMC test to processes with larger

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[3] Lee (1996) shows that some slight improvements may be possible if we use data-based selection procedures for *l*, but the differences tend to be small in practice.

roots. We use the critical values compiled by Kwiatkowski et al. (1992) and used in most applied work.[4]

The size of the KPSS test is highly sensitive to the choice of the truncation lag *l*. We therefore follow the recommendation of Kwiatkowski et al. (1992) and Lee (1996) and choose a comparatively large value of *l* such that $l = \mathrm{int}[12(T/100)^{1/4}]$. This choice tended to produce the most accurate test results in previous studies. For the LMC test we set $p = 1$, since the size of the test is not sensitive to the lag order used. The data generating process is an AR(1) process with root $r$ and NID(0,1) innovations. We set the start-up value to zero and discard the first 1,000 observations for each trial to eliminate transition dynamics.[5] The sample size is $T \in \{100, 300, 600\}$. Table 1 shows the effective size of both the KPSS and the LMC test. Results for the model without trend are shown in Table 1a and those for the model with trend in Table 1b. We focus on the nominal 5 percent test. Qualitatively similar results are obtained at the nominal 10 percent level.

Table 1a shows the rejection rate under the null hypothesis for a range of values of $r$ from 0 to 0.99. It is evident that the size distortions for roots near unity are large and increasing, unlike the size results in Kwiatkowski et al. (1992), Lee (1996) and Leybourne and McCabe (1994).[6] For example, for $r = 0.9$ and $T = 100$, the rejection rate of the nominal 5 percent LMC test based on conventional asymptotic critical values is 32 percent. For $r = 0.99$ and $T = 100$, the rejection rate rises to almost 74 percent. Even for $T = 600$, the rejection rate may be as high as 70 (45, 14, 9) percent for $r = 0.99$ (0.98, 0.95, 0.9). Similarly, the KPSS test rejects the null hypothesis in up to 77 percent of all trials. Based on this evidence, one would

[4] Sephton (1995) provides slightly more accurate critical values, but the differences are negligible for sample sizes in excess of 100.
[5] This fact accounts for a slight increase in the rejection rates compared to the results in Kwiatkowski et al. (1992) and Lee (1996).
[6] We were unable to replicate the size results for the LMC test reported in Leybourne and McCabe (1994) even using the GAUSS code provided to us by Steve Leybourne. Even for processes with low persistence, we find much higher size distortions for the LMC test than originally reported.

expect both tests to reject the null hypothesis of stationarity far too often in small samples. Qualitatively similar results hold for the model with trend in Table 1b.

**Table 1: Effective Size of the Leybourne-McCabe Test and the KPSS Test of the Null Hypothesis of Stationarity Using Asymptotic Critical Values for the Nominal 5 Percent Level**

### (a) No Trend

| *r* | Rejection Rates (in Percent) | | | | | |
|---|---|---|---|---|---|---|
| | *T* = 100 | | *T* = 300 | | *T* = 600 | |
| | $\hat{d}_a(l)$ | $\hat{s}_a(1)$ | $\hat{d}_a(l)$ | $\hat{s}_a(1)$ | $\hat{d}_a(l)$ | $\hat{s}_a(1)$ |
| 0 | 4.39 | 5.79 | 4.59 | 5.25 | 4.69 | 4.95 |
| 0.5 | 7.11 | 8.16 | 6.28 | 5.47 | 5.87 | 5.44 |
| 0.7 | 9.47 | 11.42 | 8.09 | 6.80 | 7.42 | 5.80 |
| 0.8 | 12.57 | 17.36 | 10.57 | 8.25 | 9.23 | 6.50 |
| 0.9 | 22.49 | 32.18 | 19.30 | 12.24 | 16.92 | 8.55 |
| 0.95 | 35.95 | 55.35 | 34.92 | 27.17 | 31.83 | 13.87 |
| 0.98 | 50.93 | 70.79 | 58.47 | 61.48 | 61.13 | 45.18 |
| 0.99 | 56.50 | 74.43 | 70.80 | 76.68 | 77.59 | 69.55 |

### (b) Trend

| *r* | Rejection Rates (in Percent) | | | | | |
|---|---|---|---|---|---|---|
| | *T* = 100 | | *T* = 300 | | *T* = 600 | |
| | $\hat{d}_b(l)$ | $\hat{s}_b(1)$ | $\hat{d}_b(l)$ | $\hat{s}_b(1)$ | $\hat{d}_b(l)$ | $\hat{s}_b(1)$ |
| 0 | 4.49 | 5.41 | 4.48 | 5.38 | 5.10 | 5.23 |
| 0.5 | 8.57 | 6.23 | 6.96 | 5.69 | 6.39 | 5.36 |
| 0.7 | 11.55 | 7.09 | 9.32 | 5.95 | 8.65 | 5.79 |
| 0.8 | 16.50 | 8.91 | 12.95 | 6.35 | 11.53 | 5.84 |
| 0.9 | 26.59 | 21.43 | 26.00 | 7.42 | 22.88 | 6.36 |
| 0.95 | 37.27 | 37.95 | 48.03 | 17.90 | 46.24 | 8.87 |
| 0.98 | 46.37 | 49.69 | 71.37 | 46.34 | 77.94 | 32.09 |
| 0.99 | 48.49 | 51.90 | 78.62 | 57.92 | 88.59 | 54.33 |

Notes*:* Based on 20,000 Monte Carlo trials and data generating process $y_t = r\, y_{t-1} + z_t$ with NID(0,1) innovations. $l = \text{int}[\,12\,(T\,/\,100)^{1/4}\,]$ where *int* denotes the integer part. The asymptotic critical values are from Kwiatkowski et al. (1992).

It is of some practical interest to compare the performance of the LMC and the KPSS test. For the model without trend, the KPSS test tends to be uniformly more accurate than the LMC test for $T$ = 100, for $T$ = 300 the LMC test is more accurate, except for the most persistent processes, and for $T$ = 600 the LMC test is uniformly more accurate. The size of both tests improves with larger sample size, but only very slowly. Consistent with the theoretical results about the rate of convergence of the two tests, the size of the LMC test converges much more rapidly to its nominal level than that of the KPSS test. However, for the relevant range of $r$, severe size distortions persist even for $T$ = 600. For the model with trend in Table 1b, the size distortions of the LMC test are considerably smaller than in Table 1a. The LMC test almost always is more accurate than the KPSS test, often by a wide margin. The differences are most pronounced for larger sample sizes. However, even the LMC test has rejection rates of up to 58 percent for $r$ = 0.99 and $T$ = 300.

Table 1 also shows that for highly persistent stationary processes, the convergence of the size to its nominal level may be non-monotonic. As the sample size increases from $T$ = 100 to $T$ = 300, the effective size actually worsens in some cases. For $T$ = 600, the effective size improves relative to $T$ = 300, but may still be higher than for $T$ = 100. The degree of non-monotonicity is more pronounced for the KPSS test than for the LMC test.

We conclude that both tests have a strong tendency to spuriously reject the null hypothesis of stationarity for realistic values of $r$ and $T$. The existence of such severe size distortions has not been previously recognized in the literature. In applied work, rejections of the stationarity hypothesis have often been welcomed as strong evidence in favor of a unit root (and as a formal justification for pursuing cointegration tests for linear combinations of I(1) variables). Our results suggest that many of these findings are likely to have been spurious. One might conjecture that these size distortions could be overcome easily by the use of appropriately adjusted finite sample critical values. Indeed, that strategy has been pursued in recent papers by Cheung and Chinn (1997) and by Kuo and Mikkola (1999). However, as the next section will illustrate, such corrections are not feasible in the context of tests of the I(0) null hypothesis [7]

## 4 The Impossibility of Constructing Conventional Finite-Sample Corrections for Tests of Stationarity

It is well-known that size distortions of tests of the unit root null hypothesis may be overcome by the use of approximate finite-sample (or bootstrap) critical values. The basic principle is best understood in a simple example. Let $y_t$ denote the real exchange rate. Then the model of interest is:

$$y_t = a + r\, y_{t-1} + z_t ,$$

where $z_t$ in general will be serially correlated and $a$ denotes the intercept. The slope parameter $r$ is the (dominant) root of the autoregressive lag order polynomial. To a first approximation, $r$ measures the speed of mean reversion of the process. In testing the unit root null hypothesis we postulate the simple null hypothesis: $H_0$: $r = 1$. We test $H_0$ against the composite alternative hypothesis $H_1$: $r < 1$. Finite sample critical values may be generated under the null hypothesis after fitting an approximating model subject to the constraint $r = 1$. For example, the conventional textbook DF finite-sample critical values assume $z_t$ = 0. Alternatively, one could model $z_t$ parametrically and bootstrap the approximating ADF regression subject to the constraint $r = 1$.

It would seem natural to expect a similar approach to work for stationarity tests. However, there are fundamental differences between stationarity tests and unit root tests. Stationarity tests evaluate the composite null hypothesis $H_0$: $r < 1$ against the simple alternative hypothesis $H_1$: $r = 1$. In order to generate finite sample critical

[7] Sephton (1995) calculates finite-sample critical values for the KPSS test using the same technique as Kwiatkowski et al. (1992). He does not make any allowance for serial correlation, however, and his

values for stationarity tests we would have to restrict $H_0$ to a simple null hypothesis $H_0$: $r = r_0 < 1$. The resulting test would involve both a simple null hypothesis and a simple alternative hypothesis. Thus, the test would be qualitatively different from the original test. Moreover, such a test would only be meaningful economically if it could be shown that $H_0$ and $H_1$ jointly comprise all states of the world. However, in practice, no economist would feel comfortable ruling out stationary processes with half-lives longer than 3 years in testing the null hypothesis of 3 years. Finally, even if we agreed on the alternative $H_1$: $r = 1$, a rejection of the null hypothesis of 3 years using actual data would be consistent with the true half-life being lower or somewhat higher than 3. It would be difficult to interpret the result of that test.

This example shows that it is not possible to construct conventional finite-sample corrections for tests of the null hypothesis of stationarity. As a result, tests of the null hypothesis of stationarity cannot be recommended unless the sample size is very large. While the further theoretical development of such tests continues at a rapid pace, their usefulness for applied work is questionable. We will illustrate the practical importance of this point in the next section.

## 5 Example: Testing for Long-Run PPP in the Post-Bretton Woods Era

### 5.1 Motivation

More than twenty years after the breakdown of the Bretton Woods exchange rate system there still is considerable disagreement over the question of whether real exchange rates are mean-reverting (see Froot and Rogoff (1995), Rogoff (1996)). While most economists find some version of long-run purchasing power parity plausible and indeed well nigh indispensable in the construction of theoretical international macroeconomic models, statistical tests for the absence of mean reversion to date have yielded at best conflicting results. This makes it appealing to

critical values for the sample sizes typically of interest in applied work are virtually identical to those reported in Kwiatkowski et al.

test directly the null hypothesis that real exchange rates are mean-reverting. A failure to reject this null hypothesis would not suffice to convince a skeptic of the existence of long-run PPP, but a rejection would be compelling evidence against long-run PPP. Such PPP tests have been conducted for example by Baillie and Pecchenino (1991) to assess the validity of the building blocks of the monetary model of exchange rate determination for the U.K. and the U.S. Kuo and Mikkola (1999) conduct a similar analysis for long-run US-UK real exchange rates. However, their analysis has no direct implications for the post-Bretton Woods period. In work more closely related to ours, Culver and Papell (1997) observe that the failure to reject the null of stationarity for real exchange rates, together with evidence against the null of stationarity for nominal exchange rates for the same sample period, would constitute strong evidence of long-run PPP.

Culver and Papell investigate the null hypothesis of stationary real exchange rates in the post-Bretton Woods era using the KPSS test. For quarterly real exchange rate data, they conclude that the evidence against long-run PPP is mixed, with the KPSS test at the 5 percent critical value not rejecting the null of stationarity in most cases. While the KPSS test has the advantage of being consistent for a broader class of models, including models with innovations that exhibit autoregressive conditional heteroskedasticity (ARCH), ARCH is not a concern for the monthly and quarterly real exchange rate data used in this paper. Thus, there is no a priori reason for favoring the KPSS test at the expense of the LMC test, and we will employ both tests.

What makes the application of stationarity tests to real exchange rates problematic is the fact that the mean-reversion in real exchange rates is slow. Slow mean reversion does not contradict the view that long-run PPP holds. It is well known that theoretical models with intertemporal smoothing of consumption goods (see Rogoff, 1992) or cross-country wealth redistribution effects (see Obstfeld and Rogoff, 1995) imply highly persistent but transitory deviations from PPP. Thus, the relevant comparison involves a highly persistent stationary null and a unit root alternative, consistent with our claim in section 3. One would expect that the accuracy of the test depends on the value of the dominant root under the null hypothesis. Since the extent of the size distortions increases with the persistence of the process under the null hypothesis, it is essential to obtain a sense of the degree of mean reversion under the null in order to assess the potential size distortions in applied work. It is useful to reparameterize this problem in terms of the half-life of the response of the real exchange rate to a shock.

There is a consensus view in the PPP literature about the half-life of the response of the real exchange rate to a shock. For example, Abuaf and Jorion (1990, p. 173) suggest a half-life of 3-5 years for the post-Bretton Woods era. Rogoff (1996, pp. 657-658) conjectures that deviations from PPP dampen out at the rate of about 15 percent per year. Froot and Rogoff (1995), p. 1645) consider a half-life of 3-5 years quite plausible. In what follows, we will exploit the close link between the half-life and the value of the dominant root of the autoregressive process, $r$. Thus, we may obtain a benchmark for plausible values of $r$ under the null hypothesis based on the consensus view in the literature. The half-life of the response of the process to a shock is defined as $h$ = i/$f$ where $f$ denotes the sampling frequency of the data (1/year for years; 4/year for quarters; 12/year for months, etc.) and $i$ is defined by $r^i = 0.5$. Ignoring higher order lags, the model under $H_0$ can be written as:

$$y_t = a + b\,t + r\,y_{t-1} + z_t\,, \qquad (5)$$

where the value of $r$ is a function of the half-life. Since the coefficient $r$ in (5) may be viewed as the leading term of an ADF regression, $r$ can be interpreted as the dominant root of the autoregressive process. For example, if the half-life of an innovation is 5 years under $H_0$ and the data frequency is monthly, we obtain $r = 0.5^{(1/60)} = 0.9885$. For quarterly data, under the same assumptions, $r = 0.5^{(1/20)} = 0.9659$, and for annual data $r = 0.5^{(1/5)} = 0.8704$. For the null hypothesis of a half-life of three years, the corresponding values are $r = 0.5^{(1/36)} = 0.9809$ for monthly data, $r = 0.5^{(1/12)} = 0.9439$ for quarterly data, and $r = 0.5^{(1/3)} = 0.7937$ for annual data.

These considerations together with the simulation results in Table 1a suggest that for the LMC test we should expect rejection rates of about 70 percent for monthly and about 55 percent for quarterly data, if real exchange rates indeed are stationary with half-lives of about 3-5 years. For the KPSS test the corresponding rejection rates are about 65 percent for the monthly data and 35 percent for the quarterly data. Hence, the test results will be all but impossible to interpret. We will illustrate this point in the next section.

### 5.2 Empirical Analysis

The real exchange rate data are constructed from the IMF's *International Financial Statistics* data base on CD-ROM. They are based on the end-of-period nominal U.S. dollar spot exchange rates and the U.S. and foreign consumer price indices. The first data set comprises monthly data for 1973.1-1997.4 (292) observations for 17 countries including Austria, Belgium, Canada, Denmark, Finland, France, Germany, Greece, Italy, Japan, The Netherlands, Norway, Portugal, Spain, Sweden, Switzerland, and the United Kingdom. The second data set includes quarterly data for 1973.I-1997.II (98 observations) for the same 17 countries plus Australia, Ireland, and New Zealand.

We begin the analysis with the LMC test of the null hypothesis of stationarity. The lag orders for the ARIMA($p$,1,1) model were selected using the Akaike Information Criterion (AIC). Our results are robust to alternative assumptions about the lag order. Table 2 provides strong evidence against the null hypothesis of PPP for all countries at the monthly frequency and for all countries but Australia, New Zealand and Switzerland at the quarterly frequency. The apparent finding of a unit root in all 17 monthly and 17 of 20 quarterly series is striking in that no other test to date has produced such strong results. If correct, these results would imply that most, if not all, real exchange rate processes contain important permanent components, implying a sharp reversal of the evidence in the literature and a direct rejection of long-run PPP.

## Table 2: Testing for Long-Run Purchasing Power Parity in the Post-Bretton Woods Era

### (a) Monthly Data

| Country | LMC | | KPSS | DF-GLS |
|---|---|---|---|---|
| | $\hat{p}$ | $\hat{s}_a(\hat{p})$ | $\hat{d}_a(l)$ | $\hat{t}_{f_0}(p)$ |
| Austria | 1 | 6.026 ** | 0.505 ** | -1.199 |
| Belgium | 7 | 2.045 ** | 0.248 | -1.966 * |
| Canada | 1 | 9.591 ** | 0.707 ** | -0.581 |
| Denmark | 3 | 4.212 ** | 0.300 | -1.534 |
| Finland | 1 | 0.550 ** | 0.186 | -1.432 |
| France | 1 | 1.663 ** | 0.223 | -1.903 * |
| Germany | 3 | 3.959 ** | 0.278 | -2.021 ** |
| Greece | 2 | 5.032 ** | 0.350 * | -1.850 * |
| Italy | 3 | 6.320 ** | 0.454 * | -2.321 ** |
| Japan | 1 | 17.313 ** | 1.397 ** | -0.866 |
| Netherlands | 3 | 3.238 ** | 0.225 | -1.843 * |
| Norway | 4 | 2.759 ** | 0.198 | -1.277 |
| Portugal | 7 | 4.681 ** | 0.487 ** | -1.441 |
| Spain | 1 | 1.229 ** | 0.489 ** | -1.332 |
| Sweden | 1 | 4.227 ** | 0.298 | -1.952 * |
| Switzerland | 1 | 8.906 ** | 0.687 ** | -0.978 |
| United Kingdom | 1 | 4.054 ** | 0.323 | -1.637 |

Notes: All real exchange rates are constructed from IFS CD-ROM data on consumer price and end-of-period U.S.$ exchange rates. Monthly data are for 1973.1-1997.4 (292 observations). $\hat{p}$ refers to the Akaike Information Criterion (AIC) lag order estimate of the ARIMA($p$,1,1) model. Lag orders are constrained to lie between 0 and 8. $l = \text{int}[12(T/100)^{1/4}]$ where *int* denotes the integer part. For the DF-GLS test we follow the convention of setting $p$ = 12. At the 5 (10) percent significance level, the asymptotic critical value for the LMC and the KPSS test is 0.463 (0.347). The finite-sample critical values for the DF-GLS test are -2.020 (-1.703). ** (*) denotes a rejection at the 5 (10) percent level.

## (b) Quarterly Data

| Country | LMC | | KPSS | DF-GLS |
|---|---|---|---|---|
| | $\hat{p}$ | $\hat{s}_a(\hat{p})$ | $\hat{d}_a(l)$ | $\hat{t}_{f_0}(p)$ |
| Australia | 1 | 0.134 | 0.545 ** | -1.451 |
| Austria | 1 | 2.324 ** | 0.268 | -1.919 * |
| Belgium | 3 | 0.981 ** | 0.134 | -2.525 ** |
| Canada | 3 | 2.673 ** | 0.423 * | -1.309 |
| Denmark | 3 | 1.305 ** | 0.166 | -2.355 ** |
| Finland | 3 | 0.539 ** | 0.102 | -2.082 * |
| France | 2 | 1.100 ** | 0.127 | -2.598 ** |
| Germany | 1 | 1.355 ** | 0.154 | -2.351 ** |
| Greece | 1 | 1.751 ** | 0.191 | -1.721 |
| Ireland | 2 | 3.697 ** | 0.475 ** | -1.975 * |
| Italy | 1 | 2.114 ** | 0.252 | -2.216 ** |
| Japan | 1 | 6.383 ** | 0.771 ** | -0.663 |
| Netherlands | 3 | 0.898 ** | 0.126 | -2.432 ** |
| Norway | 2 | 0.989 ** | 0.199 | -2.730 ** |
| New Zealand | 1 | 0.165 | 0.110 | -2.887 ** |
| Portugal | 1 | 2.540 ** | 0.261 | -2.079 * |
| Spain | 1 | 1.304 ** | 0.266 | -2.319 ** |
| Sweden | 3 | 1.203 ** | 0.170 | -2.741 ** |
| Switzerland | 1 | 0.081 | 0.378 * | -1.257 |
| United Kingdom | 1 | 1.536 ** | 0.216 | -2.643 ** |

Notes: All real exchange rates are constructed from IFS CD-ROM data on consumer price and end-of-period U.S.$ exchange rates. Quarterly data are for 1973.I-1997.II (98 observations). $\hat{p}$ refers to the Akaike Information Criterion (AIC) lag order estimate of the ARIMA($p$,1,1) model. Lag orders are constrained to lie between 0 and 3 for the quarterly data. $l = \text{int}[12(T/100)^{1/4}]$ where *int* denotes the integer part. For the DF-GLS test we follow the convention of setting $p = 8$. At the 5 (10) percent significance level, the asymptotic critical value for the LMC and the KPSS test is 0.463 (0.347). The finite-sample critical values for the DF-GLS test are -2.148 (-1.841). ** (*) denotes a rejection at the 5 (10) percent level.

It would be tempting to rationalize this result by appealing to theoretical explanations such as permanent changes in the relative productivity of the tradables and nontradables sector (see Baumol and Bowen, 1966), permanent changes in the level of government spending (see Froot and Rogoff (1991), Alesina and Perotti

(1995)), and systematic bias in CPI measurement (see Shapiro and Wilcox, 1996). However, Table 1 shows that the effective size of the LMC test is questionable. We know a priori that such strong rejections are extremely likely, even if the null hypothesis is true. For example, for the consensus view that shocks to real exchange rates have half-lives of 3-5 years, Table 1 predicts a rejection probability of about 55-75 percent. Thus, the results of the LMC test simply are not informative. It is all but impossible to determine whether the test correctly rejects the null in favor of a unit root or whether the rejection is simply due to size distortions. Moreover, this problem is unlikely to be overcome by waiting for more data to accumulate. The size results in Table 1a suggest that even doubling the sample size for the monthly real exchange rate to about 600 observations would do little to improve the accuracy of the test.

The fact that our rejections of the null of stationarity for the quarterly data are considerably stronger than those reported in Culver and Papell (1997b) is qualitatively consistent with the relative size distortions of the KPSS test and of the LMC test in Table 1a for highly persistent stationary processes. The second column of Table 2 shows the corresponding results for the KPSS test. We find that the KPSS test is far less prone to reject the I(0) null for this data set than the LMC test. For our choice of $l$, Culver and Papell rejected the null of stationarity at the quarterly frequency for Australia, Ireland, and Japan.[8] Using our updated sample, we obtained the same rejections plus Canada and Switzerland. However, at the monthly frequency, for the same time period, the KPSS test rejects the null of stationarity for 8 of 17 countries. This finding is consistent with our evidence in Table 1a of increasing size distortions, as $r$ and $T$ are increased. Similarly, the increase in the rejection rates of the LMC test, as we move from quarterly to monthly data in Table 2, is consistent with the evidence in Table 1a. As in the case of the LMC test, the observed rejections of the stationarity null are not informative, given the size distortions of the KPSS test.

However, there are other indications that many of the rejections of the null hypothesis of stationarity in Table 2 are actually spurious. That evidence comes from results for the asymptotically efficient DF-GLS test of the unit root hypothesis. The power of this test compares favorably to standard ADF tests (see Cheung and Lai (1998), Elliott et al. (1996)). The DF-GLS test for the case of unknown mean is based on the following regression:

$$(1-L)y_t^m = f_0 y_{t-1}^m + \sum_{j=1}^{p} f_j (1-L) y_{t-j}^m + z_t$$

where $y_t^m$ , the locally demeaned process under the local alternative of $\bar{r} = 1 + \bar{c}/T$, where $\bar{c} < 0,$ is given by

$$y_t^m = y_t - z_t b,$$

with $z_t = 1$ and $b$ being the least-squares regression coefficient of $\tilde{y}_t$ on $\tilde{z}_t$ , the latter being defined by

$\tilde{y}_t = [y_1, (1-\bar{r}L)y_2, \ldots, (1-\bar{r}L)y_T]'$ and

$\tilde{z}_t = [z_1, (1-\bar{r}L)z_2, \ldots, (1-\bar{r}L)z_T]'$ .

The DF-GLS test statistic is given by the *t*-ratio for testing $H_0\!: f_0 = 0$ against the one-sided alternative $H_0\!: f_0 < 0.$ Implementation of the test requires the choice of the parameter $\bar{c}$. We follow Elliott et al.’s recommendation and set *c* = -7.

Rather than using the asymptotic critical values for the DF-GLS test we rely on approximate finite-sample critical values. The use of these critical values protects against spurious rejections of the null hypothesis. Appropriate finite-sample critical values under the unit root null hypothesis may be obtained by simulation as described in Elliott et al. (1996). We depart from that procedure in that we allow for some serial correlation under the null hypothesis. We postulate an ARIMA(0,1,1) model, consistent with assumptions of the LMC and KPSS tests, with $q$ = 0.25. This

[8] Using smaller values of *l*, they reject the null of stationarity for 10 of their 17 countries. This result is consistent with evidence in Kwiatkowski et al. (1992) and Lee (1996) that small values of *l* tend to

specification accounts for the presence of a small nonzero MA(1) component in the growth rates of many economic time series, including real exchange rates (see Engel and Kim (1998), Canzoneri et al. (1999), Froot and Rogoff (1996), Lothian and Taylor (1996)). In fitting the ADF model and in calculating the finite sample critical values, we use 8 autoregressive lags in the quarterly case and 12 lags in the monthly case.[9]

For the same data set, for which the LMC test (and to a lesser extent the KPSS test) find strong evidence against stationarity, Table 2 shows that the 5 (10) percent DF-GLS test rejects the unit root null hypothesis for (2) 7 of the 17 countries for which monthly data are available and for 11 (15) of the 20 countries for which quarterly data are available. In fact, for several countries the test results for the DF-GLS test directly contradict those for the stationarity tests. For example, for Greece and Italy both the KPSS and the LMC test reject stationarity at the monthly frequency, yet the DF-GLS test rejects the unit root null hypothesis. The same is true for Ireland at the quarterly frequency. Given the fact that the DF-GLS test is based on accurate finite-sample critical values and the LMC and KPSS tests are not, a strong case can be made that the DF-GLS test results are far more credible. While the DF-GLS test may have low power against some stationary alternatives, the fact that we *are* able to reject the unit root null hypothesis, despite the small sample size, is unequivocal evidence against the unit root hypothesis. This finding further corroborates the interpretation that the strong rejection of stationarity using the LMC and the partial rejection of stationarity by the KPSS test is spurious, and accounts for the apparent contradiction in the test results for several countries.

Since the results of the DF-GLS test may be sensitive to the lag order choice, we chose to deliberately overfit the model by allowing for up to 12 (8) lags for monthly (quarterly) data. The choice of these bounds is conventional in the literature. We

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result in spurious rejections of the null hypothesis.

[9] Since some of the results are sensitive to the choice of lag order we follow the convention of using a large number of lags by default. This convention is conservative in that the power of the test declines as more lags are included.

adjusted the critical values to account for the extra lags. While adding extra lags may lower the power of the test (and hence the probability of a rejection of the unit root null hypothesis if the true model is stationary), it cannot spuriously generate rejections of the unit root. Thus, we feel confident about the result that real exchange rates indeed are mean-reverting. Our results are also of independent interest for the PPP debate in that we provide considerably stronger evidence against the unit root null hypothesis than previous research.[10]

Our example of the defects of stationarity tests is not an isolated case. The apparent tendency of the KPSS and LMC tests to reject the null hypothesis of stationarity in empirical work has been noted by other researchers. For example, Cheung and Chinn (1997, p. 71) reported rejections of the null hypothesis of trend stationarity for quarterly U.S. GNP at the 1 percent level based on asymptotic critical values. Several other researchers remarked on the decisive nature of their evidence against stationarity. Our evidence that the LMC and KPSS tests suffer from severe size distortions provides a plausible explanation of the source of these “strong” rejections of stationarity.

## 6 Conclusion

It is common in applied econometrics to test a highly persistent process under the null hypothesis against the alternative of a unit root process. We showed that the use of conventional asymptotic critical values for stationarity tests may cause extreme size distortions, if the model under the null hypothesis is highly persistent. This finding is important because the case of highly persistent processes under the null hypothesis is the rule rather than the exception in econometric applications. Given our simulation evidence, one would expect stationarity tests to reject the null

[10] Cheung and Lai (1998) analyze 3 of the 17 monthly real exchange rates used in our study using the same DF-GLS test. They are able to reject the unit root hypothesis for the U.K., France, and Germany. We obtain similar results for France and Germany, but not for the U.K. Our results are based on a longer sample period and more conservative critical values and lag order choices. The difference in the results is driven by the sample period.

hypothesis of stationarity far too often, even if the true model is stationary. We illustrated the practical importance of this point for the example of testing for long-run purchasing power parity (PPP) under the recent float. The results of stationarity tests based on asymptotic critical values were shown to be potentially very misleading and difficult to interpret in practice. Moreover, we showed that it is not possible to improve the finite-sample accuracy of stationarity tests by using conventional finite-sample corrections. We concluded that tests of the null hypothesis of stationarity (and by extension tests of the null hypothesis of cointegration) cannot be recommended unless the sample size is very large. Such suitably large samples are typically not available in applied econometrics. Moreover, the common practice of viewing tests of the null hypothesis of stationarity as complementary to tests of the unit root null must be regarded as highly questionable. Our size evidence suggests that this practice will frequently result in contradictions or in spurious acceptances of the unit root hypothesis.

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