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SUSTAINABLE INTERVENTION POLICIES AND EXCHANGE RATE DYNAMICS

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ABSTRACT

Sustainable Intervention Policies and Exchange Rate Dynamics*

Recently developed models of exchange rate dynamics emphasize the expectational effects of infrequent intervention. This paper proposes a stylized probabilistic framework in which such effects can be studied along with realistic concerns about the sustainability of the intervention policy. In this framework, the level of reserves determines the extent to which non-linear intervention affects the level of exchange rates and their sensitivity to movements in fundamentals. We show that all such effects are absent when the possible reserve levels are weighted by their long-run probabilities.

JEL classification: 431, 432
Keywords: exchange rates, target zones, reserves, sustainability of intervention

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NON-TECHNICAL SUMMARY

Exchange rates depend on the level and on the expected behaviour of such 'fundamental' variables as liquidity and activity levels. Realistic models of exchange rate determination should allow these variables to vary over time in a variety of ways: on the one hand, smooth continuous movements (reflecting day-by-day policy decisions and small exogenous innovations) and, on the other hand, relatively rare, possibly sharp movements (reflecting official intervention to defend declared fluctuation bands as well as infrequent realignments of central parities).

A recent study has noted that the mere possibility of the sharp but infrequent movements changes the way in which exchange rates react to small change in fundamentals. For example, if it is believed that a realignment is very likely once the exchange rate reaches the limit of its current fluctuation band, then the exchange rate should react very strongly to relatively minor innovations, as forward-looking agents should bid down the price of a currency that is expected to be depreciated discretely. Conversely, should the exchange rate attempt to move outside the band, expectations of intervention to defend the fluctuation band should be stabilizing, and should reduce the responsiveness of the exchange rate's level to movements in its fundamental determinants. Recent contributions have formalized these arguments, making specific assumptions regarding both the processes followed by fundamentals and the likelihood of devaluations, and have characterized explicitly the non-linear expectational effects of infrequent fundamental movements.

The direction and character of such effects depends on the perceived likelihood of realignment versus defence of a central parity. In turn, this should depend on the size of available reserves: the authorities should be more likely to defend the exchange rate against depreciation when reserves are plentiful, and more likely to validate expectations of devaluation when they are running out of reserves. If this were not the case, the intervention policy would be unsustainable: reserves would rise or fall to arbitrarily large or small levels. Thus, repeated interventions to defend a central parity should be reflected in lower and lower reserves, and in a tendency for the exchange rate to weaken.

In the model we analyse, the (logarithm of) the exchange rate depends on the rate of change of its expected value and on exchange rate 'fundamentals'. We distinguish between two kinds of fundamental determinants, the first kind varying smoothly and continuously over time (as Brownian motion) and the second kind subject to discrete jumps at certain points in time. If the probabilities of these jumps are constant or independent of the exchange rate and the fundamentals, the relationship between fundamentals and the exchange rate remains linear. If, however, the size or the probability of jumps varies over time in a way that is related to the fundamentals or to the exchange rate, we obtain the non-linear relationship between fundamentals and the exchange rate emphasized in the target-zone literature.

The smoothly varying component of the fundamentals can be interpreted as representing money velocity shocks or as monetization of government deficits beyond the control of the monetary authorities. The 'jump' component of the fundamentals can be taken to represent non-sterilized intervention in the foreign exchange markets. As such, it is only plausible to think of the jumps as related to the behaviour of the exchange rate itself in a target zone. The authorities, for example, may intervene when the rate reaches a pre-specified distance f above or below the central parity c. At this point they may either defend the band and bring the rate back to the central parity c or they may realign the central parity and declare a new band adjacent to the existing one.

We note that under this assumption, the jumps themselves behave as a random walk, and since the jumps represent non-sterilized interventions, reserves also follow a random walk and, over time, reach arbitrarily large and arbitrarily small levels with certainty. This raises questions of sustainability of the exchange rate regime. In our analysis we examine sustainability by allowing the probability and/or the size of a jump outside the band to depend on the cumulative interventions to date. We assume that the probability of a realignment at the upper edge of the band is a decreasing function of the size of the cumulative intervention to date: devaluations are more likely when reserves are low.

Under this assumption, we can show that the cumulative interventions are bounded and we can therefore use this framework to analyse exchange rate behaviour in a sustainable target-zone regime. We study the joint behaviour over time of the fundamentals, the central parity and cumulative interventions. In particular, this framework allows us to examine how the short-run relationship between the exchange rate and the fundamentals depends on the level of reserves. If the probability of intervention is a linear function of cumulative intervention, for example, then as reserves fall the function relating the exchange rate to fundamentals moves upward and becomes more convex: intervention is more likely to increase than to decrease reserves as they become scarce, to slow down and eventually stop their fall. Since an increase in reserves entails an upward jump in fundamentals, the expected level of fundamentals in the future is higher than it would be if intervention were never to occur and the exchange rate is, correspondingly, higher (more depreciate) for every level of fundamentals.

We can also study the unconditional relationship between the exchange rate and fundamentals by taking the expectation over all values of cumulative interventions (or reserves). When these values have a well-defined probability distribution, we show that the relationship is linear, as in the case of a freely-floating exchange rate. This implies that when no information on reserves is available, the exchange rate in a target-zone system may be expected to behave as it would in a free float; it also shows that even though, for a given level of reserves, the exchange rate may be a highly non-linear function of fundamentals, these non-linearities cancel each other out in the long run (provided that reserves have a well-defined probability distribution).

In conclusion, we outline ways in which the simple model of this paper can be generalized. In particular, it may be fruitful to relax the assumption that interventions take place only at the boundaries of the bands. The behaviour of EMS rates suggests that from 1979-87 fundamentals were moving as random walks with small drift and low variability, while the probability of large realignments with appreciation of the DM were close to one at the edge of the target zones. If intervention only occurred at the edge of the zone, this would imply that reserves rose in weak currency countries, which would be surprising. It seems more realistic to assume that central banks monitor and control exchange rates in the interior of the zone: this suggests modelling the probability of realignments and interventions as depending on the fundamentals as well as on the behaviour of reserves.

1. Introduction

Recent work on stochastic exchange rate models has focused on the nonlinearities induced by intervention aimed at maintaining exchange rates within target zones and by exchange-rate regime shifts. In this literature, the stochastic process followed by the fundamental determinants of exchange rates is modeled as a combination of continuous developments, assumed exogenous, and infrequent shifts (either infinitesimal, as in Krugman 1990, or of finite size, as in Flood and Garber 1989) occurring on a measure-zero set of time points (or perhaps at one point in time only, as in some models of Froot and Obstfeld, 1989). Exchange rate determination has typically been modeled in terms of money market equilibrium conditions, and this has led to interpreting the infrequent fundamental shocks as (nonsterilized) intervention in the foreign exchange or money market. Since foreign exchange reserves impose obvious limits on the size of cumulative interventions, some attention has been devoted to the sustainability of such intervention schemes (see Delgado and Dumas, 1989).

This paper discusses these aspects and their relationship to each other. In a stylized probabilistic model of exchange rate fundamentals, we find that if the cumulation of infrequent fundamental movements has bounded support (which is necessary for the intervention policy to be sustainable in the long run), then not only is the long-run relationship between fundamentals and exchange rates the same that would be valid under a free-float exchange rate regime, but also the possibly very pronounced within-band nonlinearities in the exchange rate/fundamentals relationship induced by "intervention" cancel each other out when weighed by their long-run probabilities.

The paper is organized as follows. Section 2 describes, under simplifying assumptions, the general structure of the class of models we study. Section 3 interprets the technical assumptions in terms of exchange rates and fundamentals, and notes that sustainability issues arise when cumulative intervention has no role in determining the behavior of fundamentals. Section 4 addresses those issues by allowing the probability of repeated, stochastic realignments to vary as a function of cumulative intervention; Section 5 characterizes exchange rate behavior under such an intervention scheme; and Section 6 studies the long-run implications of sustainability for the relationship between exchange rates and their fundamental determinants. Section 7 concludes outlining directions for further research.

2. The probability structure of intervention and realignment models

We denote with $\{x_t\}$ the log-exchange rate process, and we assume the familiar asset-pricing relationship

$$x_t = f_t + \frac{\alpha}{dt} E_t \{dx_t\} \tag{1}$$

where $E_t\{.\}$ denotes the conditional expectation formed on the basis of relevant information available at time t, and $\{f_t\}$ denotes the process followed by the *fundamental* determinants of exchange rates, e.g. the variables appearing in the excess money demand function. Ruling out bubbles, we can integrate equation (1) between t and infinity to obtain

$$x_t = \frac{1}{\alpha} \int_t^\infty E_t\{f_\tau\} e^{-(\tau - t)/\alpha} d\tau. \tag{2}$$

Without specifying the economic counterpart of f_t, we simply write $f_t = i_t + z_t$: by assumption, the levels of the $\{i_t\}$ and $\{z_t\}$ processes have identical roles in exchange rate determination, but their dynamic behavior is different. To capture the expectational effects emphasized by the literature on target zones and on intervention, we assume continuous sample paths of infinite variation for the $\{z_t\}$ process, while i_t is constant almost everywhere on the time line and increases or decreases by finite or infinitesimal amounts on a measure-zero set of time points.

We let the dynamics of $\{z_t\}$ be given by

$$dz_t = \sigma \, dW_t \tag{3}$$

and all movements of $\{i_t\}$ have equal absolute size Δf. If j_t denotes the *net* number of jumps up to and including time t (i.e. the number of positive jumps *minus* that of negative jumps), we then have

$$i_t = j_t \Delta f$$

Allowing for non-zero $\{z_t\}$ drift or for jumps of different sizes, while conceptually easy, would considerably complicate the notation and the algebraic derivations.

If $\Delta f = 0$, i.e. if no jumps ever occur in the fundamentals process, then

$$E_t\{f_\tau\} = E_t\{z_\tau\} = z_t = f_t \qquad \forall \tau \geq t$$

which, by equation (2), yields the exchange rate solution $x_t = f_t$ for all t, plotted in Figure 1 as the solid diagonal line.

When $\Delta f > 0$, the likelihood of a jump at every point in time has an essential role in determining the relationship between f_t and x_t. We denote with p_t^u the probability of a positive jump at time t, with p_t^d that of a negative jump, and with $1 - p_t^u - p_t^d \geq 0$ the probability of no jump at time t.

If the jump probabilities are *constant* or, more generally, independent of the exchange rate and fundamental processes, the relationship between fundamentals and exchange rates remains linear.[1] To obtain the nonlinear relationships emphasized in the target zone literature, it is necessary to allow the size and/or the probability of jumps to vary over time *in a way that is related to the position of the fundamentals.*

The simplest of the models proposed in our earlier paper (Bertola and Caballero, 1990), for example, is obtained if the jump probabilities are specified as

$$p_t^u = \begin{cases} p & \text{if } f_t = c_t + \Delta f \\ (1-p) & \text{if } f_t = c_t - \Delta f \\ 0 & \text{otherwise;} \end{cases} \qquad p_t^d = \begin{cases} (1-p) & \text{if } f_t = c_t + \Delta f \\ p & \text{if } f_t = c_t - \Delta f \\ 0 & \text{otherwise,} \end{cases} \tag{4}$$

where the auxiliary "central parity" process $\{c_t\}$ jumps up by $2\Delta f$ when $f_t = c_t + \Delta f$ and i_t jumps upwards, down by $2\Delta f$ when $f_t = c_t - \Delta f$ and i_t jumps downwards. This process has no direct effect on exchange rates, but its level does determine the probability of $\{i_t\}$ jumps.

The horizontal axis in Figure 1 may then be divided into adjoining segments of length $2\,\Delta f$ ("fluctuation bands"), each centered at a value of c. In the interior of every band jumps have probability zero and $\{f_t\}$ has the dynamics of $\{z_t\}$ in equation (3). By (2), the exchange rate can, as a conditional expectation, be written as a function of f_t and c_t processes; and the usual stochastic calculus arguments imply that in the interior of regions where c_t and i_t are constant this function should satisfy the differential equation

$$x(f;c) = f + \frac{\alpha\sigma^2}{2}\, x''(f;c) \tag{5}$$

where $x''(f;c) \equiv \partial^2 x(f;c)/\partial f^2$. It should also be the case that

$$\begin{aligned} p\,x(c+2\,\Delta f; c+2\,\Delta f) + (1-p)\,x(c;c) &= x(c+\,\Delta f;c), \\ p\,x(c-2\,\Delta f; c-2\,\Delta f) + (1-p)\,x(c;c) &= x(c-\,\Delta f;c), \end{aligned} \qquad \forall c, \tag{6}$$

namely that the two possible exchange rates just after a jump be equal, when weighted by their respective probabilities, to the exchange rate prevailing at the instant before the jump. From the economic point of view, these boundary conditions rule out arbitrage opportunities; from the purely technical standpoint, they ensure that equation (1) is satisfied at the instant before a jump: $E_t\{dx_t\}$ would be larger than infinitesimal if (6) did not hold with equality, and no finite exchange rate could satisfy (1), where $E_t\{dx_t\}/dt \to \infty$.

All solutions to the differential equation in (5) have the form

$$x(f;c) = f + A_1(c)\,e^{\lambda f} + A_2(c)\,e^{-\lambda f}, \qquad \lambda \equiv \sqrt{\frac{2}{\alpha\sigma^2}} \tag{7}$$

Using (7) in (6), we obtain

$$A_1(c) = -\frac{(1-2p)\,\Delta f}{e^{\lambda(\,\Delta f+c)} - e^{-\lambda(\,\Delta f-c)}} \qquad\qquad A_2(c) = \frac{(1-2p)\,\Delta f}{e^{\lambda(\,\Delta f-c)} - e^{-\lambda(\,\Delta f+c)}}$$

The two $A(.)$ functions have opposite signs for every c, and in the interior of every zone the relationship between exchange rates and fundamentals takes an S-shaped form like those plotted by dashed lines in Figure 1.

If $p = \frac{1}{2}$, then $E_t\{f_\tau\} = f_t$ for all $\tau \geq t$, and $x(f;c)$ once again lies on the 45^o line.

If $p < \frac{1}{2}$, however, $x(f;c) \lessgtr f$ according to $f \gtrless c$: because the jump in fundamentals at the upper (lower) boundary of a zone is expected to be negative (positive), $E_t\{f_\tau\} < f_t$ if f_t is close to $c + \Delta f$, and $E_t\{f_\tau\} > f_t$ if f_t is close to $c - \Delta f$. Symmetrically, if $p > \frac{1}{2}$ then $x(f;c) \lessgtr f$ according to $f \lessgtr c$.

3. Intervention, reserves, and sustainability

Other specifications for the probability and size of i_t jumps may be recast in terms of Section 2 's notation along similar lines. The full-credibility model in Krugman (1990) lets the jump component be infinitesimally small (and therefore unrelated to the width of the fundamental fluctuation band, $\bar{f}$), and assumes

$$p_t^u = \begin{cases} 1 & \text{if } f_t = c_t - \bar{f} \\ 0 & \text{otherwise;} \end{cases} \qquad p_t^d = \begin{cases} 1 & \text{if } f_t = c_t + \bar{f} \\ 0 & \text{otherwise,} \end{cases}$$

while Flood and Garber (1989) make similar assumptions on the probabilities and let jumps have finite size. Svensson (1989) considers both infinitesimal and discrete movements in the $\{i_t\}$ component of fundamentals, making assumptions similar to Krugman's on the former and letting the latter have constant probability and size, and Bertola and Svensson (1990) extend the model to allow for stochastic fluctuations in the probability and size of $\{i_t\}$ jumps.

Following these and other authors, this probabilistic framework can be interpreted as a stylized model of (adjustable) exchange rate bands. The Brownian motion component of fundamentals $\{z_t\}$ may be viewed as a money velocity shock, or perhaps as monetization of government deficits beyond the control of the monetary authorities, and the jump component $\{i_t\}$ may be taken to represent nonsterilized intervention in the foreign exchange market.

Intervention, of course, entails a variation in foreign exchange reserves; and if only the infrequent $\{i_t\}$ component is associated to interventions, then the variation of reserves corresponds to the variation in $\{i_t\}$. To illustrate this point and introduce sustainability issues, consider the simple probabilistic assumptions of equation (4), where the size Δf of the $\{i_t\}$ jumps coincides with a half-width of the fundamental fluctuation band, $\bar{f}$. These assumptions correspond to the economic framework of our earlier paper, where authorities *intervene* at prespecified, common knowledge points $c_t - \bar{f}$, $c_t + \bar{f}$: *either* defending the band and bringing f and x back to the center of the current band (c_i), *or* realigning the central parity and declaring a new fluctuation band, adjoining the current one, with center

$c_{t+} \equiv c_t + 2\bar{f}$ and unchanged width. By a normalization, set $z_0 = i_0 = 0$ and let reserves be equal to zero at time zero. Starting at zero, z_t takes a random, finite time to reach one of the boundaries and to trigger the first jump. Either boundary can be reached with probability $\frac{1}{2}$ since $\{f_t\}$ follows a driftless Brownian motion. Denoting with $\tau > 0$ the time at which the first jump occurs, we have:

$i_\tau = -\bar{f}$ if $\{z_t\}$ has drifted upwards to $\bar{f}$ and the band has been defended *or* if $\{z_t\}$ has drifted downwards to $-\bar{f}$ and a realignment has taken place: the combined probability of these events is $\frac{1}{2}(1-p)+\frac{1}{2}p = \frac{1}{2}$;

$i_\tau = +\bar{f}$ if $\{z_t\}$ has drifted downwards to $-\bar{f}$ the band has been defended *or* if $\{z_t\}$ has drifted upwards to $\bar{f}$ and a realignment has taken place: the combined probability of these events is, again, $\frac{1}{2}p+\frac{1}{2}(1-p) = \frac{1}{2}$.

The derivation in Karatzas and Schreve (1988, especially pp. 99-100) can be adapted to show that the time interval between jumps is finite with probability one and has expectation $(\bar{f}/\sigma)^2$; its distribution is independent of the past history of the stochastic processes under study, which enjoy the strong Markov property. Thus, *regardless of the realignment probabilities*, $\{i_t\}$ follows a generalized random walk with variable time steps, constant state steps, and constant transition probabilities under our stylized assumptions; this is true, in particular, when the fluctuation band is fully credible ($p = 0$).[2]

Reserves therefore follow a random walk on a redefined time scale and, over an infinite time horizon, reach arbitrarily large and arbitrarily small levels with probability one, raising obvious issues of *sustainability* of the exchange rate regime.[3] To obtain a (stochastically) bounded reserve process when *intervention* is taken to occur only at the boundaries and is interpreted in terms of purchases/sales of foreign exchange, the probability and size of upwards and downwards jumps should be allowed to depend on reserve levels or, equivalently, on cumulative intervention up to date. For example, the probability structure of interventions might be assumed to be independent of reserves until these reach some prespecified boundary, and to change abruptly at that point, adapting to the problem at hand the assumptions of the literature on exchange rate regime collapses (Krugman 1979, Flood and Garber 1984). Delgado and Dumas (1989) analyze the case of infinitesimal interventions at the margin of fluctuation zones along these lines, supposing that exchange rates revert to a one-sided or two-sided float when reserves reach a nonrandom, prespecified limit.

Collapse models, however, have several shortcomings. On the one hand, there is no clear-cut upper or lower limit to cumulative exchange rate intervention in reality, since foreign exchange can in principle be borrowed in any amount (provided, of course, that principal and interest are surely repaid over the relevant, possibly infinite time horizon).[4] On the other hand, the assumption of *permanent* reversion to free float when the reserves limits (however specified) are reached is both unrealistic and formally questionable: no central bank ever operates without exchange rate reserves, thus exchange rates are never truly freely floating; and allowing for the free-float regime to be absorbing prevents any study of the long-run properties of the model. Historically, exchange rate crises have most often resulted in a realignment of central parities or in a redefinition of the exchange rate regime. While these points are not essential to the stylized models of Krugman (1979) and Flood and Garber (1984), the discrete time structure of the empirically oriented model of Blanco and Garber (1986) produces stochastic, recurring balance-of-payments crises.

4. A sustainable probability structure

In what follows, we address sustainability issues in the context of a stylized model of repeated, stochastic realignments (of the type studied in Miller and Weller, 1989 and in our earlier paper). To this end, we allow the probability and/or the size of upward and downward fundamental jumps to depend on accumulated interventions or, equivalently, on the net number j_t of interventions. When reserves are plentiful, downward jumps should be more likely (or larger) than upward ones if reserves are to display a tendency to return to normal levels; symmetrically, when reserves move towards minus infinity upward jumps must become more likely (or larger) than downward ones.

As above, let all jumps have absolute size $\bar{f}$, let jumps only occur when f_t is at the edges of a $(c_t - \bar{f}, c_t + \bar{f})$ band, and let a jump that takes f_t beyond the limits of the current fluctuation band be accompanied by a jump in $\{c_t\}$ of the same sign and twice the absolute size: after every jump, the f_t process is always in the middle of its current fluctuation band. Still assuming jump to have nonzero probability only when fundamentals are at the boundary of a band, we let the probability of an upwards j jump be decreasing in the size of cumulative intervention to date, capturing the qualitatively realistic idea that devaluations are more likely when reserves are low and, for simplicity, we let the probability of upward or downward jumps be the same at both boundaries of the band:

$$p_t^u = \begin{cases} p(j_t) & \text{if } f_t = c_t + \bar{f} \text{ or } c_t - \bar{f} \\ 0 & \text{otherwise;} \end{cases} \qquad p_t^d = \begin{cases} 1 - p(j_t) & \text{if } f_t = c_t + \bar{f} \text{ or } c_t - \bar{f} \\ 0 & \text{otherwise;} \end{cases} \tag{8a}$$

where

$$\begin{gathered} 0 < p(j) < 1 \text{ for } \underline{j} < j < \bar{j} \\ p(j) = 1 \text{ for } j \leq \underline{j} \\ p(j) = 0 \text{ for } j \geq \bar{j} \end{gathered} \tag{8b}$$

By these assumptions and the arguments above, $\{j(t)\}$ follows a random walk with variable transition probabilities and random time steps over the $(\underline{j}, \bar{j})$ region; $\underline{j}$ and $\bar{j}$ may be, respectively, minus and plus infinity, in which case we require

$$\lim_{j \to -\infty} p(j) = 1, \qquad \lim_{j \to \infty} p(j) = 0$$

Since $0 < p(j) < 1$ in this range, all $\underline{j} \leq j \leq \bar{j}$ can be reached from each other with positive probability, and the corresponding states of the Markov chain are recurrent.[5] The unconditional distribution of the $\{j_t\}$ process, denoted $\phi(.)$, is non-degenerate under our assumptions and can be computed by the invariance relationship

$$\phi(j) = p(j-1)\,\phi(j-1) + (1 - p(j+1))\,\phi(j+1) \tag{9a}$$

and the summing-up constraint

$$\sum_{j=\underline{j}}^{\bar{j}} \phi(j) = 1 \tag{9b}$$

The $\phi(j)$ probability distribution has a simple analytic form for simple $p(.)$ functions, and can be computed numerically for any $p(.)$. Our assumptions guarantee that the probability of the absolute value of j ever exceeding arbitrarily large amounts over an infinite time horizon is zero, or vanishingly small. If the jump component of fundamentals is associated to official intervention in exchange rate markets and j_t corresponds to the cumulative variation of reserves, we can thus proceed to model exchange rate behavior in a "sustainable" exchange rate regime

5. Exchange rate dynamics under sustainable intervention

The $\{f_t, c_t, j_t\}$ processes are jointly Markov under the assumptions in (8): the distribution of f_τ at all future times depends only on their current levels. The exchange rate is then, by equation (2), a function of the three driving processes, and this function must once again satisfy

$$x(f; c, j) = f + \frac{\alpha\sigma^2}{2} x''(f; c, j) \tag{10}$$

when jumps are ruled out (i.e. in the interior of a fluctuation zone), as well as the no-expected-jump conditions

$$\begin{aligned} x(c+\bar{f}; c, j) &= p(j)\, x(c+2\bar{f}; c+2\bar{f}, j+1) + (1-p(j))\, x(c; c, j-1) \\ x(c-\bar{f}; c, j) &= (1-p(j))\, x(c-2\bar{f}; c-2\bar{f}, j-1) + p(j)\, x(c; c, j+1) \end{aligned} \qquad \forall c, \forall j$$

at the boundaries between fluctuation zones.

It is notationally convenient to define the transformed variables

$$\tilde{x}_t \equiv \frac{x_t - c_t}{\bar{f}} \qquad \tilde{f}_t \equiv \frac{f_t - c_t}{\bar{f}} \tag{11}$$

The assumptions of our simple model guarantee that $-1 \leq \tilde{f} \leq 1$, and that $\tilde{f}$ jumps to zero with probability one whenever it reaches one or minus one.

In terms of these normalized processes, (10) can be written

$$\tilde{x}(\tilde{f};j) = \tilde{f} + \frac{\alpha}{2}\tilde{x}''(\tilde{f};j)(\sigma/\bar{f})^2 \tag{12}$$

and the no-expected-jump conditions are satisfied if

$$\begin{aligned}\tilde{x}(1;j) &= p(j)\Big(\tilde{x}(0;j+1)+2\Big) + \Big(1-p(j)\Big)\tilde{x}(0;j-1) \\ \tilde{x}(-1;j) &= (1-p(j))\Big(\tilde{x}(0;j-1)-2\Big) + p(j)\tilde{x}(0;j+1)\end{aligned} \qquad \forall j \tag{13}$$

Subtraction of one condition from the other immediately yields $\tilde{x}(1;j) = \tilde{x}(-1;j) + 2$, for all j. Thus, the difference between the extremes of exchange rate fluctuation bands is independent of reserves, and the general solution of (10) can be written

$$\tilde{x}(\tilde{f};j) = \tilde{f} + A(j)\left(e^{\tilde{\lambda}\tilde{f}} + e^{-\tilde{\lambda}\tilde{f}}\right), \qquad \tilde{\lambda} \equiv \frac{\bar{f}}{\sigma}\sqrt{2/\alpha} \tag{14}$$

Using (14) in (13), we obtain a second-order, variable-coefficients difference equation in $A(.)$:

$$\big(1-p(j)\big)A(j-1) - \delta A(j) + p(j)A(j+1) = \left(\tfrac{1}{2} - p(j)\right), \qquad \delta \equiv \frac{e^{-\tilde{\lambda}} + e^{\tilde{\lambda}}}{2} \tag{15}$$

At the upper and lower boundaries of the allowable range of reserves, the no-expected-jump conditions and (15) imply that

$$\begin{aligned}\delta A(\underline{j}) - A(\underline{j}+1) &= \tfrac{1}{2} \\ \delta A(\bar{j}) - A(\bar{j}-1) &= -\tfrac{1}{2}\end{aligned} \tag{16}$$

The difference equation (15) and boundary conditions (16) form a system of linear equations, which is easily solved for any $p(j)$ function; simple analytical solutions are available for some $p(.)$ functional forms.

Several $p(j)$ functions, the corresponding $A(j)$ and $\phi(j)$ sequences, and the $\tilde{x}(\tilde{f};j)$ they imply for a selection of j values are plotted in Figures 2-4. All the $p(j)$ functions considered in the Figures satisfy the assumptions in (8b) and, in all cases, the probability of reserves ever reaching unbounded levels in either direction is zero or vanishingly small. Thus, the exchange rate regime is "sustainable." In the Figures, we set $\tilde{\lambda} = \sqrt{2}$, consistently with, for example, $\alpha = 1$ (unitary semi-elasticity of the exchange rate to its own expected rate of change over a time unit) and $\sigma = \bar{f}$ (fluctuations bands and fundamental volatility are such that the expected time to hit either boundary is one time unit).

In Figures 2, 3, and 4 the assumed jump probability function is symmetric around zero (in the sense that $p(j) = 1 - p(-j)$), with $p(0) = \frac{1}{2}$. Then, $A(0)$=0: when intervention is as likely to be positive as it is to be negative over all forecast horizons the relationship between the (normalized) exchange rate and the (normalized) fundamentals is linear, since $E_t\{f_\tau\} = f_t$ for $\tau > t$. The $p(j)$ function considered in Figure 2, which is constant throughout and moves sharply to zero or one when reserves reach their absolute limit, models a reversible collapse model. The $p(j)$ function in Figure 5 is asymmetric, in the sense that the probability of upward jumps increases faster as $j \rightarrow \underline{j}$ than it decreases as $j \rightarrow \bar{j}$: this may be taken to represent greater concern for unusually low levels of reserves than for unusually high ones, as might be appropriate for a small country, and yields a skewed long-run distribution of reserves.

The relationship between exchange rates, fundamentals, central parities and reserves can be recovered from the change-of-variable in equation (11). Figure 6 plots all possible $x(f; c, j)$ relationships in a three dimensional box, and Figure 7 plots the $x(f; c, j)$ relationships implied by the probability function of Figure 4 in the neighborhood of $c = 0, j = 0$. When $c = 0$ and $j = 0$, exchange rates and fundamentals are driven by z_t fluctuations along the solid 45^o line in Figure 7. If the upper boundary of the $(-\bar{f}, \bar{f})$ region is reached at point T^u, a jump is triggered in the fundamental process, in the reserves process, and (possibly) in the central parities process. The relevant $x(f; c, j)$ function is then one of those plotted by long dashes in the Figure. With probability $\frac{1}{2}$, an upward jump in fundamentals and central parities occurs, accompanied by an upward jump in reserves: the exchange rate jumps to B, and starts fluctuating along the (concave) ABC line. With probability $\frac{1}{2}$, fundamentals and reserves jump down, while c remains constant at zero: the exchange rate then jumps to point B' and starts fluctuation along the (convex) A'B'C' line. If the lower boundary of $(-\bar{f}, \bar{f})$ is reached first (at point T^l), the exchange rate symmetrically shifts to points on the lines plotted by short dashes.

6. Short-run nonlinearities and the long-run

In all the cases considered, $p(j)$ is monotonic and $A(j)$ is decreasing in j; when $p(j)$ is linear (Figure 3), so is $A(j)$. As j moves downwards, therefore, the $\tilde{x}(\tilde{f})$ function drifts upwards and becomes increasingly convex: intervention becomes more likely to increase than to decrease reserves as they become scarce, to slow down and eventually stop their fall. Since an increase in reserves entails an upward jump in fundamentals, the expected level of f_τ at all future time is *higher* than it would be if intervention were never to occur, and the exchange rate is, correspondingly, higher (more depreciated) for every level of fundamentals.

It is apparent from the Figures that the relationship between exchange rates and fundamentals depends on the level of reserves, $j\bar{f}$. Not all values of j are equally likely, of course: in particular, our assumptions in (8b) ensure that very large or very small values of j are seldom or never observed.

Taking an expectation over all possible j values, we then obtain the *unconditional* relationship between exchange rates and fundamentals,

$$E\{\tilde{x}(\tilde{f};j)\,|\,\tilde{f}\} = \sum_{j=\underline{j}}^{\bar{j}} \phi(j)\,\tilde{x}(\tilde{f};j) = \tilde{f} + \left(e^{\tilde{\lambda}\tilde{f}} + e^{-\tilde{\lambda}\tilde{f}}\right) \sum_{j=\underline{j}}^{\bar{j}} \phi(j)A(j), \tag{17}$$

The $\phi(j)$ probability distribution can be computed by (9), and is plotted in the third panel of Figure 2-4 for the cases we consider.

The Appendix shows that if the $p(j)$ function satisfies the assumptions in (8a), then

$$\sum_{j=\underline{j}}^{\bar{j}} \phi(j)A(j) = 0, \tag{18}$$

to imply that when no information as to the level of reserves is available exchange rates should be expected to respond *linearly* to movements in fundamentals, as in the case of flexible exchange rates.

Thus, even though for particular reserve levels exchange rates may be a very nonlinear function of "fundamentals" (reflecting the changing expectations of intervention in either direction), these nonlinearities cancel each other out in the long run if reserves have a well-defined probability distribution.

7. Directions for further research

The tendency of nonlinearities to cancel each other out in the long run (or when no information about "reserves" is available) is more general than the specific simple model proposed above.[6] At the cost of notational and analytical complications, the simple model outlined above could be extended in several realistic directions, still assuming the only intervention to occur at the edges of prespecified fluctuation bands. The z_t process driving within-band fluctuations could be allowed to have non-zero drift, or to display mean reversion; and the probabilities and size of jumps in fundamentals and reserves could be modified so as to allow an interpretation of intervention as a "defense" or "realignment" of a given target zone.

For "infrequent" intervention to be sustainable, the probability and size of jumps in either direction should still be allowed to depend on cumulative intervention, so as to obtain stationarity of the reserves process. If exchange rate bands are more likely to be defended than to be realigned, realignments will generally need to be large to keep cumulative intervention bounded; since these two elements interact in determining the shape of the relationship between exchange rates and "fundamentals" (see our earlier paper), the concavity or convexity effects of infrequent intervention schemes would still be ambiguous in such an extended model, and would still tend to offset each other out as longer and longer periods of time are considered.

It may be more fruitful, however, to relax the assumption that interventions occur only at the boundaries of fluctuation bands. The behavior of EMS exchange rates suggests that in 1979-1987 fundamentals followed within-band processes with small drifts and low variability, and that the probability of large realignments in the direction of a Deutsche

Mark appreciation were very close to one at the boundary of the target zone (see our earlier paper). If intervention were indeed occurring only at the boundaries of exchange rate bands, these facts would unrealistically imply a tendency of reserves to *increase* in "weak" currency countries. In fact, *sustainability* of intervention need not be related to its *infrequency*, a purely technical device. Central banks may well monitor and control exchange rates in the interior of target zones, expending reserves, and reconstitute reserves by infrequent realignments: to model this realistic feature in a probabilistic framework similar to that outlined above, the probability of realignments and interventions should be allowed to depend on $\{z_t\}$ as well as on $\{i_t\}$.

Appendix [7]

The recursions in (9a-b) and in (15-16) can be written in matrix form as

$$(I-T)\vec{\phi}=\vec{0} \quad \Rightarrow \quad \vec{\phi}=T\vec{\phi}$$

$$\vec{\phi}'\ell=1$$

$$(T'-\delta I)\vec{A}=\tfrac{1}{2}\ell-\vec{p} \quad \Rightarrow \quad T'\vec{A}=\delta A+\tfrac{1}{2}\ell-\vec{p}$$

where $\delta=(e^{-\bar{\lambda}}+e^{\bar{\lambda}})/2>1$, ℓ is a vector of ones, I is an identity matrix, and

$$T=\begin{pmatrix} 0 & 1-p(\underline{j}+1) & 0 & \dots & 0 & 0\\ 1 & 0 & 1-p(\underline{j}+2) & \dots & 0 & 0\\ 0 & p(\underline{j}+1) & 0 & \dots & 0 & 0\\ \vdots & 0 & \ddots & & \vdots & \vdots\\ 0 & \vdots & \dots & & 1-p(\bar{j}-1) & 0\\ 0 & 0 & \dots & & 0 & 1\\ 0 & 0 & \dots & & p(\bar{j}-1) & 0 \end{pmatrix}$$

$$\vec{p}=\begin{pmatrix}1\\ p(\underline{j}+1)\\ \vdots\\ p(\bar{j}-1)\\ 0\end{pmatrix} \qquad \vec{A}=\begin{pmatrix}A(\underline{j})\\ A(\underline{j}+1)\\ \vdots\\ A(\bar{j}-1)\\ A(\bar{j})\end{pmatrix} \qquad \vec{\phi}=\begin{pmatrix}\phi(\underline{j})\\ \phi(\underline{j}+1)\\ \vdots\\ \phi(\bar{j}-1)\\ \phi(\bar{j})\end{pmatrix}$$

Thus,

$$\sum_{j=\underline{j}}^{\bar{j}}\phi(j)A(j)=\vec{\phi}'\vec{A}=\mathrm{tr}\left(\left(T\vec{\phi}\right)'\vec{A}\right)=\mathrm{tr}\left(\vec{\phi}'\left(T'\vec{A}\right)\right)=\vec{\phi}'(\delta\vec{A}+\tfrac{1}{2}\ell-\vec{p})=\delta\vec{\phi}'\vec{A}+\vec{\phi}'(\tfrac{1}{2}\ell-\vec{p})$$

to imply that

$$(1-\delta)\vec{\phi}'\vec{A}=\vec{\phi}'(\tfrac{1}{2}\ell-\vec{p})$$

Then (noting that $\vec{\phi}\ell=1$)

$$\sum_{j=\underline{j}}^{\bar{j}}\phi(j)A(j)=0 \quad \Leftrightarrow \quad \vec{\phi}'\vec{p}=\tfrac{1}{2}$$

We can prove that, in fact, $\vec{\phi}'\vec{p}=\frac{1}{2}$. Rearranging (9a),

$$p(j+1)\phi(j+1)+\phi(j)=p(j-1)\phi(j-1)+\phi(j+1)$$

Summing the two sides of this relationship up from $j = \underline{j}$, we obtain

$$\sum_{k=\underline{j}}^{j} p(k+1)\phi(k+1) + \sum_{k=\underline{j}}^{j} \phi(k) = \sum_{k=\underline{j}}^{j} p(k-1)\phi(k-1) + \sum_{k=\underline{j}}^{j} \phi(k+1)$$

or

$$\sum_{k=\underline{j}}^{j} p(k+1)\phi(k+1) - \sum_{k=\underline{j}}^{j} p(k-1)\phi(k-1) = \sum_{k=\underline{j}}^{j} \phi(k+1) - \sum_{k=\underline{j}}^{j} \phi(k)$$

which simplifies to

$$p(j+1)\phi(j+1) + p(j)\phi(j) - \phi(\underline{j}) = \phi(j+1) - \phi(\underline{j}).$$

Summing over j on each side, and noting that $\phi(j) = 0$ for $j < \underline{j}$ and $j > \bar{j}$, we obtain

$$2\sum_{j=\underline{j}}^{\bar{j}} p(j)\phi(j) - \phi(\underline{j}) = \sum_{j=\underline{j}+1}^{\bar{j}} \phi(j) = 1,$$

to imply that $\vec{\phi}'\vec{p} = \frac{1}{2}$ as was to be shown.

Notes

1 To see this, consider the simple case of constant, symmetric jump probabilities $p_t^u = p_t^d = p$, for all t. The $\{i_t\}$ process then has no moments unless either p or $\bar{f}$ are infinitesimally small; we consider these two possibilities in turn. If $\bar{f}$ is larger than infinitesimal, let one downwards (or one upwards) jump have probability $p \approx 1 - e^{-\gamma \Delta t}$ over a Δt time increment. In the continuous time limit, $\{i_t\}$ is the sum of two Poisson process with equal probability intensity γ and increments of equal absolute size and opposite sign. Alternatively, we may let the jump probabilities remain finite and normalize the size of jumps. If we let $\bar{f} = \gamma\sqrt{\Delta t}$, as $\Delta t \to 0$ the $\{i_t\}$ process converges to Brownian motion with variance γ^2 per unit time. In both cases, $E_t\{f_\tau\} = f_t$ for all $\tau \geq t$, and $x_t = f_t$. More general cases can be analyzed along similar lines.

2 If its drift were positive, the $\{z_t\}$ process would be more likely to hit $\bar{f}$ first rather than $-\bar{f}$; the probability that a Brownian motion process with drift ϑ and standard deviation σ hits $\bar{f}$ before $-\bar{f}$, starting at zero, is

$$q(\vartheta, \sigma) = (1 - e^{-\frac{2\vartheta \bar{f}}{\sigma^2}})/(e^{\frac{2\vartheta \bar{f}}{\sigma^2}} - e^{-\frac{2\vartheta \bar{f}}{\sigma^2}})$$

if $\vartheta \neq 0$. The $\{i_t\}$ "reserves" process would then follow a random walk with drift. These and other equally straightforward extensions are omitted for simplicity.

3 The model we propose, although phrased in terms of a single exchange rate and a single set of fundamentals, can easily be interpreted in a two-country framework. If the sum of the two countries' reserves is constant, which might be appropriate in a model of the gold standard, then unboundedly positive levels of j are just as unsustainable as unboundedly negative ones. Even more stringently, reserves should sum up to zero in a model of fiat money creation, where one central bank's assets must be offset by another's liabilities. Delgado and Dumas (1989) somewhat unconvincingly assume instead that reserves consist of assets in infinitely elastic supply.

4 The assumption of hard limits on reserve decumulation is particularly unrealistic in the context of the exchange rate mechanism of the European Monetary System: cen-

tral banks often intervene to prevent excessive *appreciation* of their currency, thus accumulating reserves, and when intervening to prevent excessive depreciation they have statutory access to —in principle— unbounded credit from the issuer of the appreciating currency.

[5] Once again, we might want to allow for a drift in the process driving the within-band fluctuations. The transition probabilities of the $\{j_t\}$ process would then have to be modified by the $q(\vartheta, \sigma)$ function of footnote 2.

[6] Nonlinearities cancel in the long run of collapse models as well: the expectational effects emphasized by these models disappear in the long run if their assumption of reversion to perpetual float is to be taken literally.

[7] We are very much indebted to Hyeng Keun Koo for decisive help on this proof.

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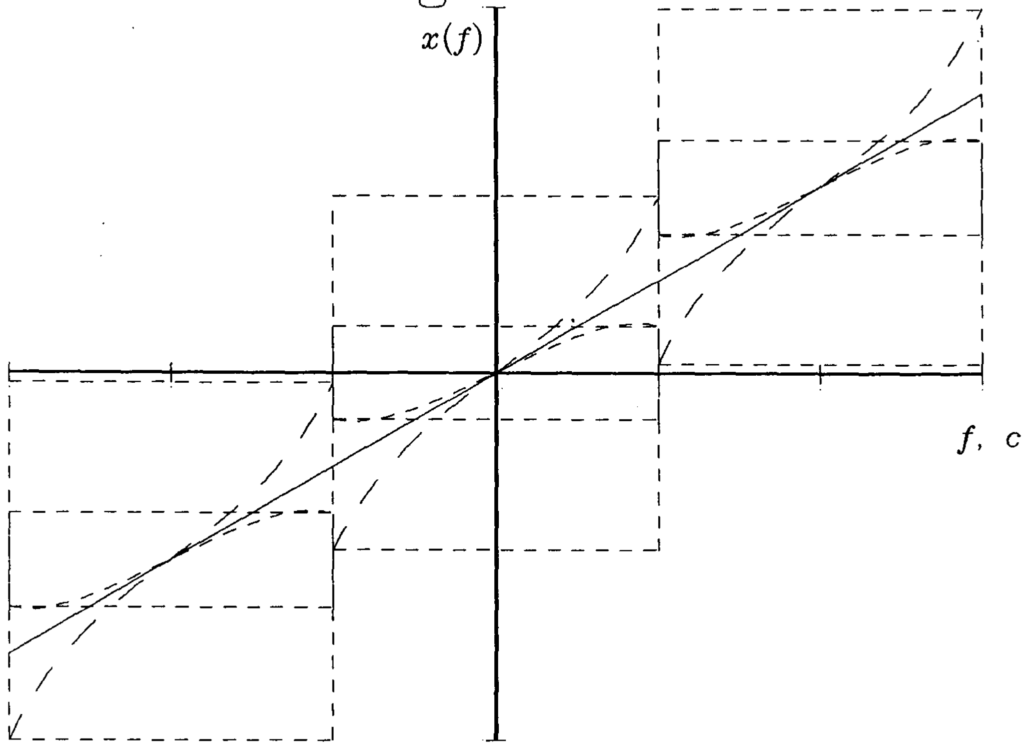
Figure 1



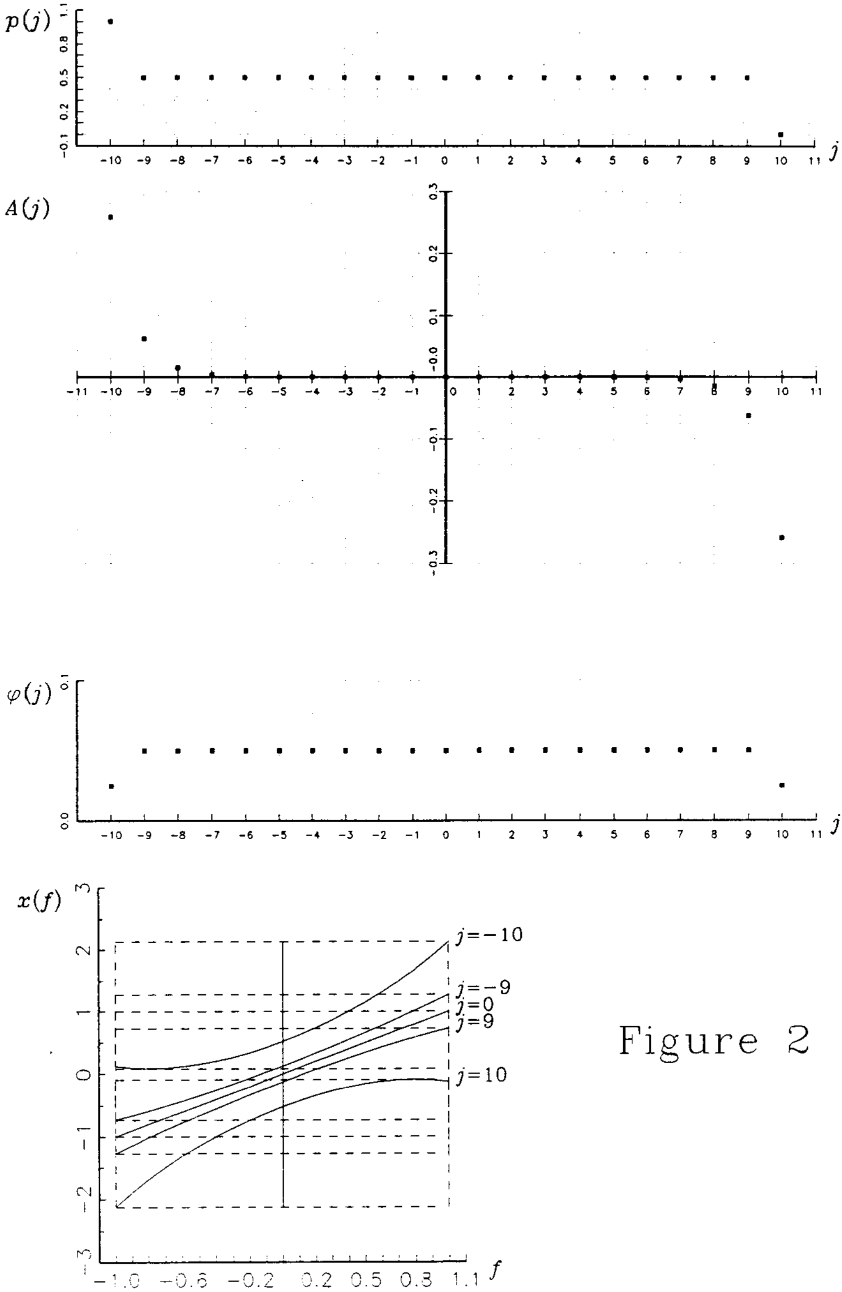


Figure 2

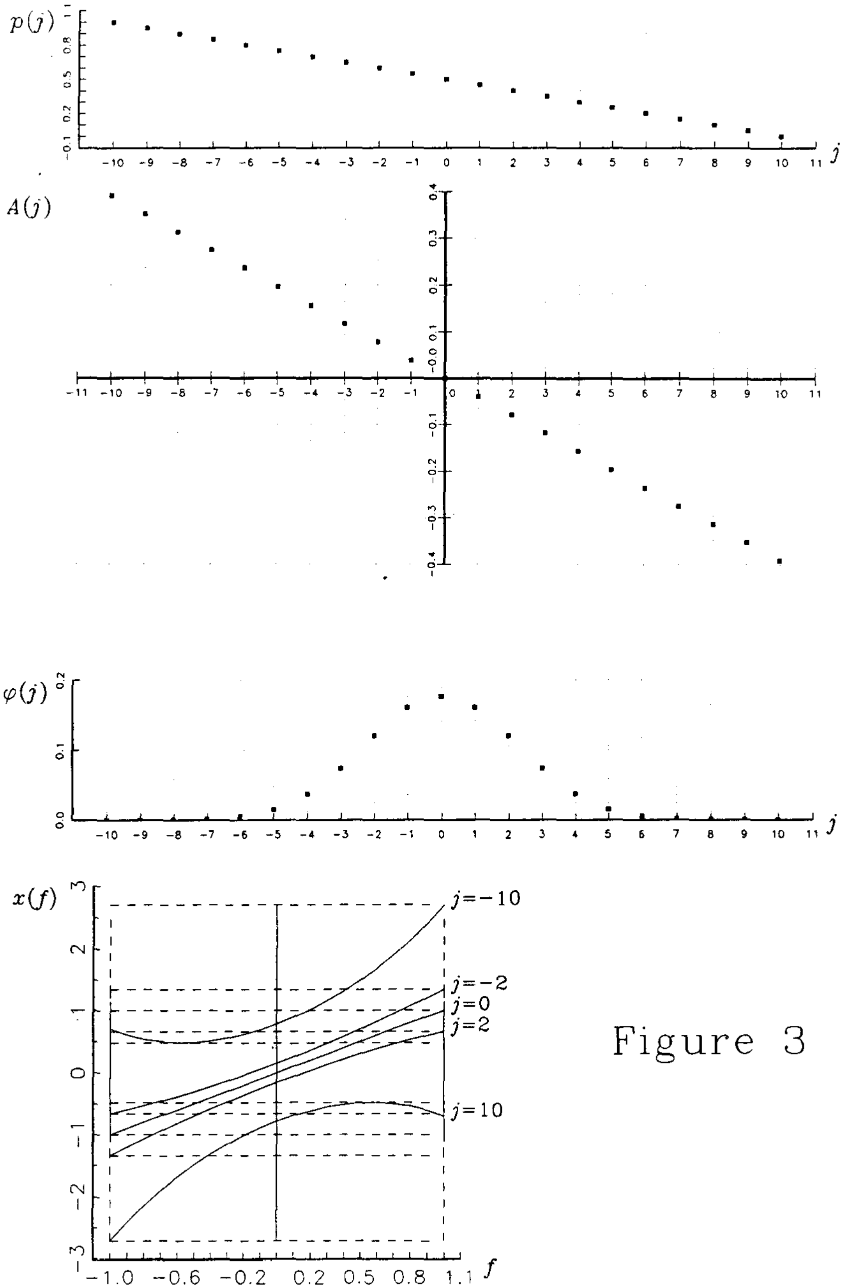


Figure 3

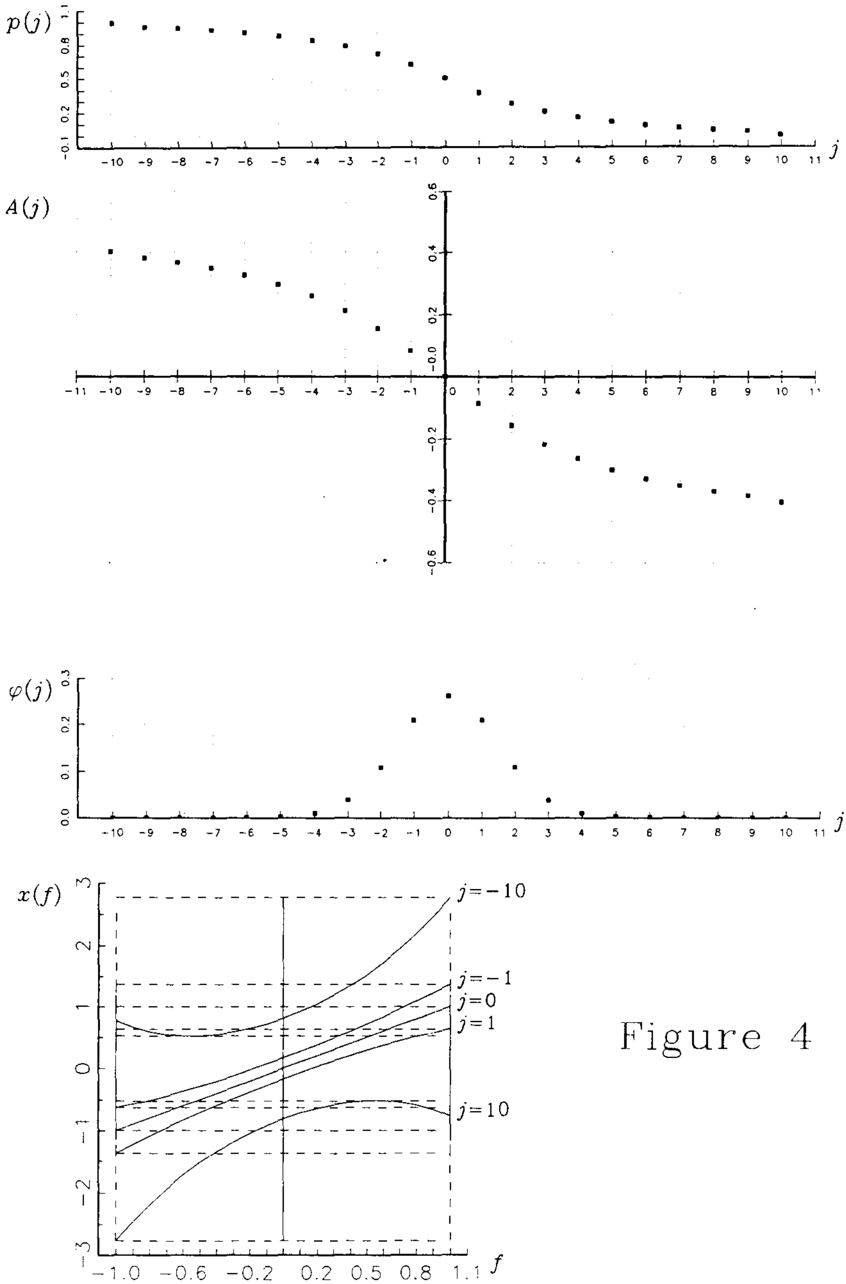


Figure 4

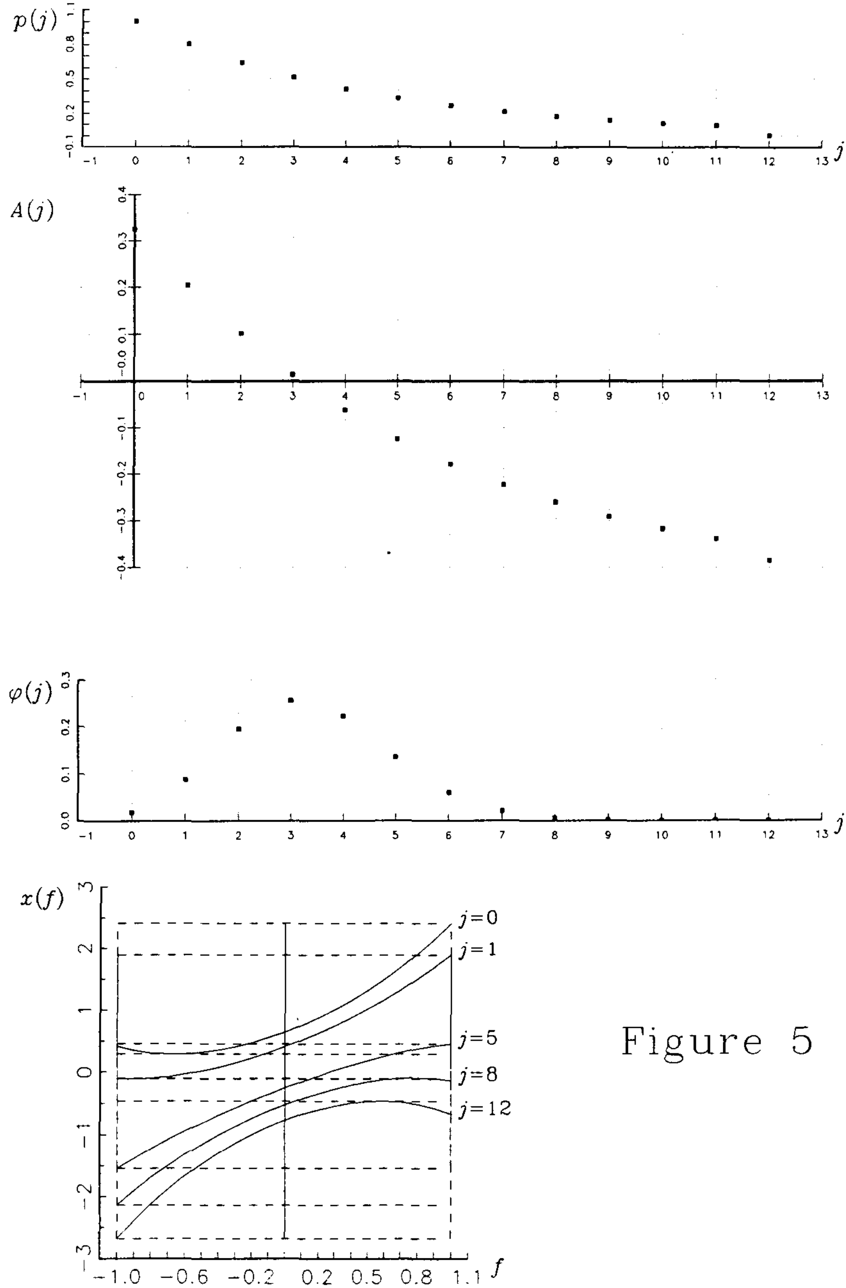


Figure 5

Figure 6

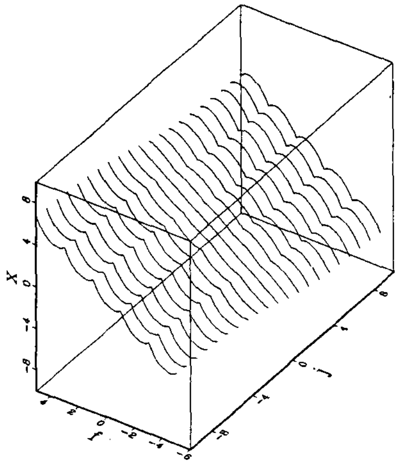
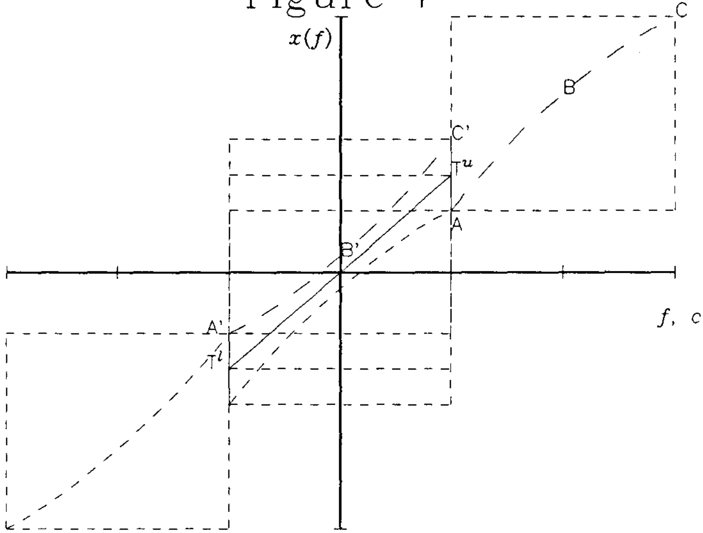


Figure 7



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