Banco Central de Chile
Documentos de Trabajo

Central Bank of Chile
Working Papers

N° 327

Septiembre 2005

PROBABILITY OF INSOLVENCY

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Documento de Trabajo
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Working Paper
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PROBABILITY OF INSOLVENCY

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Resumen
Este trabajo analiza el problema que enfrenta el balance de un agente que invierte en monedas distintas a la moneda base en que se financia. Asumiendo rentabilidad de las inversiones y costo de financiamiento constantes, el agente puede enfrentar episodios de insolvencia ante variaciones del tipo de cambio relevante, el cual es modelado como un movimiento browniano geométrico. Posteriormente, el proceso es generalizado permitiendo la dependencia del coeficiente difusivo respecto del nivel del tipo de cambio, reproduciendo algunas de las propiedades reportadas en estudios empíricos de series de precios de activos financieros. El proceso hiperbólico resultante es calibrado utilizando una función de estimación de martingala, para luego obtener una aproximación de la probabilidad de que el valor de los activos caiga por debajo del valor de los pasivos, en una fecha futura dada. Los resultados obtenidos son consistentes independiente del supuesto de volatilidad del proceso. Finalmente, se proponen algunas practicas para minimizar la probabilidad de tal evento.

Abstract
This paper analyzes the problem of the balance sheet of an agent that invests in currencies different than those she finances. Assuming a constant rate of return and fixed financing costs, the agent can face the event of insolvency due to swings in the relevant exchange rate that is assumed to follow a geometric Brownian motion. Then, the process is generalized to allow dependency of the diffusion coefficient on the level of the exchange rate, reproducing many of the properties encountered in empirical studies of financial asset prices. The resulting hyperbolic process is calibrated via a martingale estimating function, and then we approximate the probability that the value of assets fails to match the value of liabilities at a given future date. The findings are consistent regardless the volatility assumption of the process. Finally, we give some insights to minimize the probability of such event.

We thank Alejandro Corvalán, Héctor Felipe Bravo, Alvaro Rojas, Cristian Salinas and Esteban Jadresic from Central Bank of Chile, Kenneth Wilder and Hae-Kyung Im from The University of Chicago, Jaime Casassus and Rodrigo Cerda from Pontificia Universidad Católica de Chile, and an anonimous referee for their useful comments.
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I. INTRODUCTION

An important part of the literature on asset-liability management is based on the dynamics of the value of assets net of liabilities, which is assumed to be a random quantity. Thus, the problem reduces to the match of incoming flows against the ones that are due at a given time. This condition can be required either on average or at specific times throughout the relevant horizon. In this set up, it seems natural to analyze the problem using a contingent claim approach. The first efforts on these lines were basically intended to price corporate securities subject to some default event defined in a specific manner. Merton [**1**] recognized that it is possible to apply option pricing theory to price corporate debt in general. More recently, Nielsen et al. [**2**] extend the problem when the default event is defined as a random time, and then the default time corresponds to the stopping time of a stochastic process. Longstaff and Schwartz [**3**] define the event of financial distress as the event that the value of assets reaches some constant barrier. On the asset liability side, Janssen [**4**] develops an asset-liability model assuming that such variables follow a geometric Brownian motion, and then finds closed form expressions for the probability of perfect and partial mismatch for a given horizon. Ars and Janssen [**5**] extend the model obtaining duration-like measures, and study applications to hedging. Deelstra and Janssen [**6**] generalize the model to the case of several assets and liabilities, and explore the results in presence of mean reversion in the rate of return of assets.

The models just mentioned assume cash flows denominated in the same currency, and the problem of the agent simplifies to the optimal allocation in the sense of minimizing the probability of mismatch given some negative differential between asset returns and financing costs. This work innovates these models solving the problem when assets are denominated in a currency different than the base currency of liabilities. In this case, the relevant variable is the base currency value of assets net of liabilities at a given point in time. Throughout the time horizon, we assume a constant rate of return on assets and fixed financing costs, and therefore the event of insolvency can be triggered by swings in the relevant exchange rate. This structure allows us to solve the problem as a ruin process in probability theory.

II. THE INSOLVENCY PROCESS

From now on we will assume that the agent's balance sheet is composed by a cero coupon bond (asset) denominated in foreign currency, and one cero coupon bond (liability) issued in domestic currency, both maturing in $T > t$ years from now. Specifically, let

R_t : value of the asset at time t in foreign currency
P_t : value of the liability at time t in local currency
S_t : time t value of the exchange rate in local currency per unit of foreign currency.

We also assume for the relevant horizon T, $T > t$, that these variables move according to the following

$$dR_t = R_t r dt \quad (1)$$
$$dP_t = P_t r_P dt \quad (2)$$
$$dS_t = \mu S_t dt + \sigma S_t dW_t \quad (3)$$

where

W_t : standard Brownian motion.
r : constant asset return in foreign currency
r_P : fixed borrowing rate in local currency
μ : exchange rate drift in local currency
σ : exchange rate volatility (standard deviation), $\sigma > 0$.

This corresponds to the problem of an agent that at time $t = 0$ borrows at a rate r_P for a time period T, swaps such flows into foreign currency, and makes a deposit that yields a rate of return r for the same time period. Then at time T, the individual unwinds the strategy buying the local currency back at the time T exchange rate, and honors the liability contracted at time $t = 0$. Since in general $r_P > r$, the strategy can be justified in the context of a speculator with some prior about future exchange rate evolution, or simply because such strategy is part of a global optimization process that enforces the agent to bear such cost.

Due to swings in the exchange rate S_t, the agent can face the event that assets in local currency are not enough to cover the value of liabilities. In such case we will say that the agent experiences the event of insolvency, where cash coming from investments does not cover the amount of debt at a given time t. Since the relevant time is T, where he reverts the strategy, it turns out interesting to estimate at time $t = 0$, the probability of such event, and what determines such measure.

Definition. Let a_t be the natural logarithm of the value at time t of net assets measured in local currency. That is

$$a_t = \ln\left(\frac{A_t}{P_t}\right) \quad (4)$$

where $A_t = R_t S_t$ is the time t value of assets in local currency. By Ito's lemma we have

$$dA_t = A_t(r + \mu)dt + A_t \sigma dW_t \quad (5)$$

Proposition 1. The time t local currency value of net assets, a_t is the solution of the stochastic differential equation

$$da_t = \nu dt + \sigma dW_t \quad (6)$$

with $\nu = (\mu + r) - r_P - \frac{\sigma^2}{2}$.

Proof. See appendix 1.

III. PROBABILITY OF INSOLVENCY

The assumptions made in section II allow us to determine the probability of having the event of insolvency at the final date of the strategy put by the agent. This is equivalent to calculate the probability of a_T is negative. That is

$$\Pr(A_T < P_T) = \Pr(a_T < 0)$$

In order to determine this value we need to know the distribution of a_T. From equation (6) we know that a_t is a markov process, and

$$a_T \sim N(m(T), \sigma(T))$$

noting $z = m(T)/\sigma(T)$, with T fixed, the probability of the event of insolvency is

$$\Pr(A_T < P_T) = \Pr(a_T < 0) = 1 - \Phi(z)$$

where $\Phi(z)$ is the standard normal distribution accumulated in z.

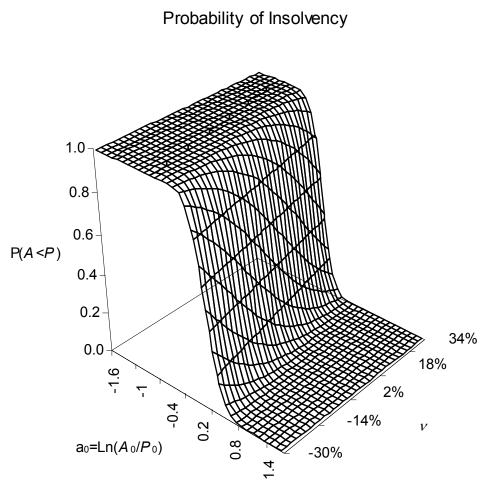
If a_t is the solution of the stochastic differential equation (6), then for a given T

$$z = \frac{a_0 + \nu T}{\sigma\sqrt{T}}.$$

This expression indicates that the measure of insolvency depends on the parameters a_0, σ and ν. So from the agent's point of view, knowing this dependency is important since enables him to do adjustments to control such risk.

In this regard, neither the volatility σ, nor the *drift* μ of the process (3) can be adjusted by the agent, so he is only left with the parameters a_0 y $(r\text{-}r_P)$, the latter implicit in the drift ν. Also it is interesting to verify that $\partial z/\partial a_0 = 1/(\sigma T^{1/2}) > 0$ and $\partial z/\partial \nu = T^{1/2}/\sigma > 0$. Then with T fixed, the probability of insolvency decreases for greater values of a_0 and ν. Intuitively, this result supports the notion that the individual must implement policies oriented to increase the rate of return on assets relative to borrowing costs, and maintain an adequate level of assets relative to the size of the liabilities. Figure 1 shows the joint probability of insolvency for different values of asset-liability ratio, and *drift* of the net assets process, for $T = 1$ and $\sigma = 0.2$.

Figure 1



We can see from figure 1 that for a given value of ν, the probability of insolvency increases when the size of assets relative to liabilities decreases. On the other hand, for a given value of a_0, the probability of insolvency increases for smaller values of the *drift* ν.

Moreover, by inspecting the derivatives of z with respect to a_0 and ν, yields an idea about the efficiency when managing the insolvency risk using one variable or the other. Indeed, depending on the time horizon, it is possible to know which effect dominates the other. Specifically, for $T > 1$ the effect of ν is greater than the one of a_0, and consequently if the agent is given both instruments, it is more efficient to utilize ν. Conversely, if $T < 1$, then the agent must manage the insolvency risk by modifying the initial condition a_0. Finally, a particular case is when $T = 1$, where both effects are equivalent.

This result has a natural interpretation for a dynamic equation like (6). That is, for relatively short term horizons, the initial condition will weight more on the net assets process and the resulting probability, whereas if we allow the process to evolve for a greater period of time, the initial condition lose relevance and what matters is the *drift* of the process.

IV. GENERALIZATION OF THE EXCHANGE RATE PROCESS

In this section we introduce a generalization of the exchange rate process S_t, allowing dependency of the diffusion coefficient on the level of the parity. There exist several studies reporting that ex post financial assets returns are far from being normally distributed. In particular, the tails of the empirical distributions tend to be log linear. Eberlein and Keller [**7**] utilize Levy processes based on hyperbolic distributions to describe stock prices. Stegenborg and Sørensen [**8**] use a Jacobi process to model the dynamics of exchange rates under target bands. Bibby and Sørensen [**9**] shows a hyperbolic process capable to describe many of the regularities encountered in financial asset prices. That is, the logarithm of the price has increments that are uncorrelated but not independent. This idea, suggests the utilization of a process of the form

$$S_t = \exp(\mu t + X_t) \tag{7}$$

$$X_t = X_0 + \int_0^t v(X_s) dW_s \tag{8}$$

Given (7) and (8), it is possible to show that S_t is the solution of the following process,

$$dS_t = S_t[\mu + \frac{1}{2}v^2(\log S_t - \mu t)]dt + S_t v(\log S_t - \mu t)dW_t \tag{9}$$

Equation (9) corresponds to a generalization of the process (3). Indeed, if we assume v constant, S_t follows a geometric Brownian motion. Bibby and Sørensen [**9**] show that depending of the choice of the function $v(x)$, it is possible to obtain several models with different distributions that account for the desired empirical regularities. In general, $v(x)$ must be chosen such that

$$\int_{-\infty}^{+\infty} v^{-2}(x)dx < \infty$$

This ensures that the process (8) is ergodic with invariant mean, and that X_t converges in law to a probability measure proportional to $v(x)^{-2}$. Moreover, if X_0 has that distribution, then X_t will be stationary with density proportional to $v(x)^{-2}$ at all times. Following the authors we will utilize

$$v^2(x) = \sigma^2 \exp[\alpha\sqrt{\delta^2 + (x-\mu)^2} - \beta(x-\mu)] \tag{10}$$

Using a function like (10) implies that the logarithm of the exchange rate will be distributed approximately hyperbolic after a sufficiently long period of time. The same is true with the increments of the logarithm of the exchange rate, since they correspond to the difference of two hyperbolic random variables approximately independent. Note that equation (10) implies that the volatility of the process (9) increases exponentially whenever the exchange rate departs from its drift.

Given these assumptions, we can formulate the following proposition for the general net assets process.

Proposition 2. The time t value of the general net assets process, a_t is the solution of the stochastic differential equation

$$da_t = \eta dt + v(\log S_t - \mu t)dW_t \tag{11}$$

with $\eta = \mu + r - r_P$.

Proof. See appendix 2.

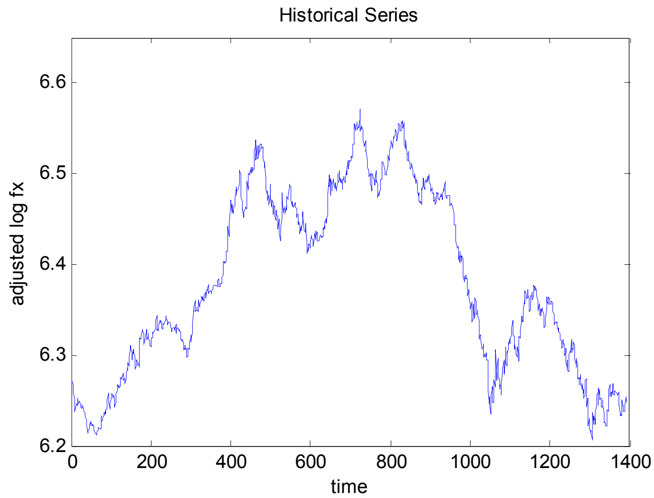
V. CALIBRATION OF THE EXCHANGE RATE PROCESS

In this section we show the results for the calibration of process (9) to daily closing prices of the Chilean exchange rate for the period December 31 of 1999 to April 29 of 2005. Specifically, if we denote the observations S_t on times t_1, t_2,...,t_n (days when there was a transaction) as $S_{t_1}, S_{t_2}, ..., S_{t_n}$, then the drift adjusted exchange rate is given by

$$X_{t_i} = \log S_{t_i} - \mu t_i, \qquad i = 1,...,n.$$

Using the sample, the ordinary least squares estimate of μ corresponds to 6.152×10^{-5}. Figure 2 depicts the drift adjusted time series of the logarithm of the Chilean exchange rate.

Figure 2



On the other hand, when estimating the parameters of model (9) and (10), Bibby and Sørensen [**9**] emphasize that, even though the distribution of process is known in steady state, this is not the case for the transition density, and thus it is not possible to make inference about the parameters. In order to account for this problem, the authors propose the use of a martingale estimating function that results from compensating the score function, such that it becomes a martingale. That is, a function of the form

$$K_n(\theta) = \sum_{i=1}^{n} [g_i(X_{t_{i-1}};\theta)(X_{t_i} - F_i(X_{t_{i-1}};\theta)) + h_i(X_{t_{i-1}};\theta)(((X_{t_{i-1}};\theta) - F(X_{t_{i-1}};\theta))^2 - \phi_i(X_{t_{i-1}};\theta)]$$

where F_i is the conditional mean, and ϕ_i is the conditional variance of X_{t_i} given $X_{t_{i-1}}$, and θ the parameter vector. The authors show that under regularity conditions on the functions g_i and h_i, and a large number of observations, there exists a θ such that $K_n(\theta) = 0$ which is asymptotically normal. Moreover, since X_t is a local martingale, it is possible to substitute F_i y ϕ_i for their respective conditional counterparts, $X_{t_{i-1}}$ and $(X_{t_i} - X_{t_{i-1}})^2$.

Thus, for a small $\Delta_i = t_i - t_{i-1}$, we will use the following discrete approximation for the martingale estimating function

$$\widetilde{K}_n(\theta) = \sum_{i=1}^{n} \frac{\dot{v}(X_{t_i};\theta)}{(t_i - t_{i-1})v(X_{t_{i-1}};\theta)^3}((X_{t_i} - X_{t_{i-1}})^2 - \widetilde{\phi}_i(X_{t_{i-1}};\theta)) \tag{11}$$

where $\dot{v}$ is the gradient of v with respect to the vector $\theta = (\alpha,\beta,\delta,\mu,\sigma)^{T}$.

In practice, it is necessary to estimate the conditional expectation of ϕ via simulations. Then we will substitute, $\widetilde{\phi}_i(X_{t_{i-1}};\theta)$ by

$$\frac{1}{N}\sum_{i=1}^{N}(X_{t_i}^{(j)} - X_{t_i})^2 \ ; i = 1,2,...,n.$$

where $X_{t_i}^{(j)}$ corresponds to the *j-th* realization of X_{t_i} obtained using a strong Taylor scheme of order 1.5. Following Kloeden and Platen [**10**], the scheme is of the form

$$\begin{aligned} X_{t_{i-1}+\frac{\Delta_i k}{m}} &= X_{t_{i-1}+\frac{\Delta_i(k-1)}{m}} + v_{k-1}\Delta W + \frac{1}{2}v_{k-1}v'_{k-1}\{(\Delta W)^2 - \frac{1}{m}\} \\ &+ \frac{1}{2}v_{k-1}^2 v''_{k-1}\{\Delta W\frac{1}{m} - \Delta Z\} \\ &+ \frac{1}{2}v_{k-1}(v_{k-1}v''_{k-1} + (v'_{k-1})^2)\{\frac{1}{3}(\Delta W)^2 - \frac{1}{m}\}\Delta W \end{aligned}$$

where

$$v_{k-1} = v(X_{t_{i-1}+\frac{\Delta_i(k-1)}{m}};\theta), \ k = 1, 2, ..., m$$

and v' denotes differentiation with respect to x.

Also,

$$\sqrt{m}\Delta W = U_1$$
$$2m^{3/2}\Delta Z = (U_1 + U_2/\sqrt{3})$$

U_1 and U_2 are independent random variables distributed $N(0,1)$.

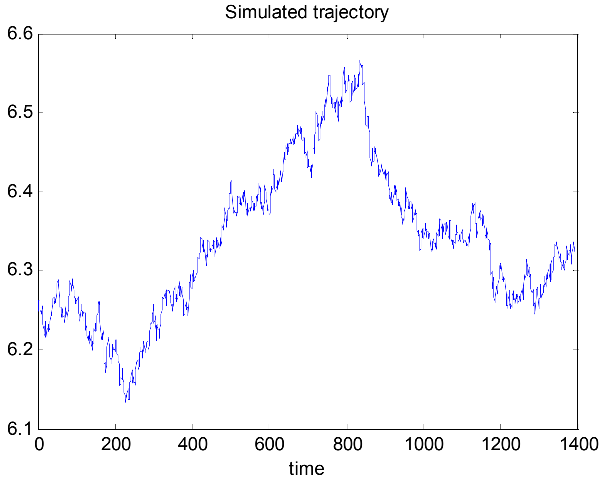
Table 1 shows the results of the estimation code programmed in MATLAB, using $N = 50$ realizations, and a time resolution set to $m = 50$ points between consecutive times.

Table 1

	α	β	δ	μ	σ
Hyperbolic Process	4.2182	1.8626	1.0270	5.7708	0.0010

Figure 3 depicts one realization of the simulated series from the calibrated process (9).

Figure 3



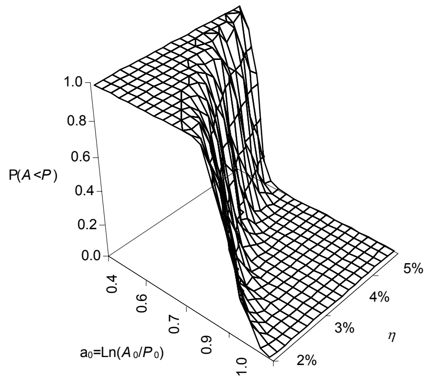
It is important to note that the convergence to the solution of the system (11) is relatively slow. Blaesild [**11**] points the importance of the choice of initial parameters to ensure the convergence of the algorithm to the solution. The author finds limiting approximations for the third and fourth moments of the bi-variate hyperbolic distribution, and then forms a system of equations that equates the first four moments with their sample counterparts, which solution corresponds to the initial parameters for the algorithm.

In our work we opted for an alternative strategy. First, we set a grid of reasonable vectors of initial parameters, and stop the algorithm after a hundred function evaluations. Among the solutions we selected the ones with the least norm of (11), and then rerun the algorithm with those solutions as the initial parameters. Then we stopped iterating after the solution reached a reasonable tolerance. In our estimation we used a tolerance level of order 10^{-2}.

Figure 4 shows the probability of insolvency calculated numerically for the calibrated hyperbolic process, for different combinations of a_0 y η.

Figure 4

Probability of Insolvency



As shown in figure 4, the insolvency risk measure is consistent regardless the volatility assumption for the exchange rate. That is, the probability of insolvency increases for higher values of a_0 and η.

VI. SOME APPLICATIONS AND EXTENSIONS OF THE MODEL

The problem described in this paper might correspond, in general, to the one that several agents bear regarding exchange rate exposure, such as, banks, pension funds opened to international financial markets, and companies that operate in different countries. In this regard, the probability of insolvency gives them an additional risk measure to account for, which can be calibrated depending on their ability to modify borrowing costs, rates of return, and the asset to liability ratio.

An interesting case is the problem confronted by central banks of economies with floating exchange rates where, as expected, assets are invested in foreign investment grade assets, and issue debt mostly in domestic currency at a higher rate. In such situation, in addition to bear a loss by investing at a rate that is normally lower than the borrowing rate, the order of magnitude of exchange rate swings can severely affect its domestic net assets value. In this sense, the recommendation implicit in the probability measure is consistent with the minimization of the cost of holding reserves, since it is inversely proportional to the drift of the net assets process.

The measure of insolvency risk is also an additional criterion for the management of the balance sheet composition, and decisions such as adequate level of assets. That is, decisions concerning the appropriate level of reserves should consider the level of liabilities. This can also be useful for prepayment decisions, i.e., the idea of selling part of the assets to prepay debt, can be evaluated in the context of the probability of insolvency such that this measure does not exceed a certain reasonable level. Moreover, the probability gives a notion about the efficiency when using either drift based policies or based on asset to liability ratios. In general, policies oriented to the short run ($T < 1$) should be carried over via initial condition a_0, whereas for the long run, interest rate differentials weight more on the risk measure.

VII. FINAL REMARKS

This work extends the problem of asset liability management to a context of an agent that invests in currencies different than those in which he obtains financing. Assuming a one period strategy, the measure depends on the initial ratio of assets to liabilities, and the rate of return of assets relative to borrowing costs. The inspection of the probability of insolvency yields useful information concerning the way the agent can control the risk of such event. In short, for T fixed, there exists a *trade-off* between a_0 and ν that the agent must consider to bound the insolvency measure within a certain limit. In terms of risk management, policies oriented to the short run will have a higher impact using the initial condition, while those oriented to the long run should be carry over through the *drift* of the process.

When the exchange rate process is generalized to account for stochastic volatility, the results are consistent. Even though it is not possible to find a closed form for the probability of insolvency, further study could explore the way to find an expression for the cumulative density function of the general net assets process, which can then be integrated numerically.

APPENDIX 1

Let $f = \ln(A/P)$. By Ito's lemma we have [**12**]

$$df = f_A dA + f_P dP + \frac{1}{2} f_{AA} dA^2 + \frac{1}{2} f_{PP} dP^2 + f_{AP} dAdP$$

since $f_A = A^{-1}$; $f_P = -P^{-1}$; $f_{AA} = -A^{-2}$ f_{AA} = -A^{-2} ; $d < W, W >_t = dt$ and $dtdt = dtdW = 0$, then

$$da_t = vdt + \sigma dW_t$$

with $v = \mu + r - r_P - \frac{1}{2}\sigma^2$.

□

APPENDIX 2

Let $h = R \cdot S$, where R and S are given by (1) and (9), respectively. Using Ito's lemma, the approximation of the stochastic differential equation that follows the function h is given by

$$dh = h_R dR + \frac{1}{2} h_{RR} d < R, R >_t + h_S dS + \frac{1}{2} h_{SS} d < S, S >_t + h_{SR} d < S, R >_t + o(2)$$

since
$d < R, R >_t = d < S, R >_t = 0$, $d < S, S >_t = S_t^2 v^2 (\log S_t - \mu t) dt$, $h_R = S$, $h_S = R$ and $h_{SS} = 0$, then

$$dA_t = A_t[\mu + r + \frac{1}{2} v^2 (\log S_t - \mu t)] dt + A_t v(\log S_t - \mu t) dW_t.$$

Finally, for the general net assets process $a = \ln(A/P)$

$$da = a_A dA + \frac{1}{2} a_{AA} d < A, A >_t + a_P dP + \frac{1}{2} a_{PP} d < P, P >_t + a_{AP} d < A, P >_t + o(2)$$

since only the quadratic co-variation of A_t holds, that is

$d < P, P >_t = d < A, P >_t = 0$, $d < A, A >_t = A_t^2 v^2 (\log S_t - \mu t) dt$, $a_A = A^{-1}, a_P = -P^{-1}$ and $a_{AA} = -A^{-2}$, then

$$da_t = \eta dt + v(\log S_t - \mu t) dW_t$$

with $\eta = r + \mu - r_P$.

□

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