Modelling and Measuring Price Discovery in Commodity Markets

by

Isabel Figuerola-Ferretti[A]

and

Jesús Gonzalo[B]

May 2007

ABSTRACT

In this paper we present an equilibrium model of commodity spot (S_t) and future (F_t) prices, with finite elasticity of arbitrage services and convenience yields. By explicitly incorporating and modeling endogenously the convenience yield, our theoretical model is able to capture the existence of backwardation or contango in the long-run spot-future equilibrium relationship, (S_t - $\beta_2 F_t$). When the slope of the cointegrating vector $\beta_2>1$ ($\beta_2<1$) the market is under long run backwardation (contango). It is the first time in which the theoretical possibility of finding a cointegrating vector different from the standard $\beta_2=1$ is formally considered.

Independent of the value of β_2, this paper shows that the equilibrium model admits an Error Correction Representation, where the linear combination of (S_t) and (F_t) characterizing the price discovery process, coincides with the permanent component of the Gonzalo-Granger (1995) Permanent-Transitory decomposition. This linear combination depends on the elasticity of arbitrage services and is determined by the relative liquidity traded in the spot and future markets. Such outcome not only provides a theoretical justification for this Permanent-Transitory decomposition; but it offers a simple way of detecting which of the two prices is dominant in the price discovery process.

All the results are testable, as it can be seen in the application to spot and future non-ferrous metals prices (Al, Cu, Ni, Pb, Zn) traded in the London Metal Exchange (LME). Most markets are in backwardation and future prices are "information dominant" in the most liquid future markets (Al, Cu, Ni, Zn).

JEL classification: C32, C51, G13, G14.

Keywords: Backwardation, Cointegration, Commodity Markets, Contango, Convenience Yield, Future Prices, Permanent-Transitory Decomposition, Price Discovery.

[A] Business Department, Universidad Carlos III de Madrid, Spain
[B] Economics Department, Universidad Carlos III de Madrid, Spain

1. Introduction

Future markets contribute in two important ways to the organization of economic activity: (i) they facilitate price discovery; (ii) they offer means of transferring risk or hedging. In this paper we focus on the first contribution. Price discovery refers to the use of future prices for pricing cash market transactions (Working, 1948; Wiese, 1978; and Lake 1978). In general, price discovery is the process of uncovering an asset's full information or permanent value. The unobservable permanent price reflects the fundamental value of the stock or commodity. It is distinct from the observable price, which can be decomposed into its fundamental value and its transitory effects. The latter consists of price movements due to factors such as bid-ask bounce, temporary order imbalances or inventory adjustments.

Whether the spot or the futures market is the center of price discovery in commodity markets has for a long time been discussed in the literature. Stein (1961) showed that futures and spot prices for a given commodity are determined simultaneously. Garbade and Silver (1983) (GS thereafter) develop a model of simultaneous price dynamics in which they establish that price discovery takes place in the market with highest number of participants. Their empirical application concludes that "about 75 percent of new information is incorporated first in the future prices." More recently, the price discovery research has focused on microstructure models and on methods to measure it. This line of literature applies two methodologies (see Lehman, 2002; special issue of Journal of Financial Markets), the Gonzalo-Granger (1995) Permanent-Transitory decomposition (PT thereafter) and Information Shares of Hasbrouck (1995) (IS thereafter). Our paper suggests a practical econometric approach to characterize and measure the phenomenon of price discovery by demonstrating the existence of a perfect link between an extended GS theoretical model and the PT decomposition.

Extending and building on GS, we develop an equilibrium model of commodity spot and future prices where the elasticity of arbitrage services, contrary to the standard assumption of being infinite, is considered to be finite, and the existence of convenience yields is endogenously modeled. A finite elasticity is a more realistic assumption that reflects the existence of factors such as basis risks, storage costs, convenience yields, etc. A convenience yield is natural for goods, like art or land, that offer exogenous rental or service flows over time. It is observed in commodities, such as agricultural products, industrial metals and energy, which are consumed at a single point in time. Convenience yields and subsequent price backwardations have attracted considerable attention in the literature (see Routledge et al. 2000). A backwardation (contango) exists when prices decline (increase) with time-to-delivery, so that spot prices are greater (lower) than future prices. We explicitly incorporate and model endogenously convenience yields in our framework, in order to capture the existence of backwardation and contango in the long-run equilibrium relationship between spot and future prices. In our model, this is reflected on a cointegrating vector, $(1, -\beta_2)$, different from the standard $\beta_2=1$. When $\beta_2>1$ (<1) the market is under long run backwardation (contango). As a by-product of this modeling we find a theoretical justification for a cointegrating vector between log-variables different from the standard $(1, -1)$. To the best of our knowledge this is the first time this has been formally considered.

Independent of the value of β_2, this paper shows that the proposed equilibrium model implies cointegration and therefore admits an Error Correction Representation (see Engle and Granger, 1987). The permanent component of the PT decomposition coincides with the linear combination of S_t and F_t that, according to GS, characterizes the price discovery process in commodity markets. This linear combination depends on the elasticity of arbitrage services and is determined by the liquidity traded in the spot and in the future market. This result not only offers a theoretical justification for this PT decomposition; but it provides a simple way of detecting which of the two prices is dominant in the price discovery process. Information on price discovery is important because spot and future markets are widely used by firms engaged in the production, marketing and processing of commodities. Consumption and production decisions depend on the price signals from these markets.

All the results produced in the paper can easily be tested as may be seen directly from our application to London Metal Exchange (LME) data. We are interested in these metal markets because they have highly developed future contracts. Applying our model to LME spot and future data we obtain: (i) All markets with the exception of copper are backwarded in equilibrium. This is reflected in a cointegrated slope greater than one, and (ii) The future price is information dominant for all metals with a liquid future markets: Aluminium (Al), Copper (Cu), Nickel (Ni) and Zinc (Zn). The spot price is information dominant for Lead (Pb), the least liquid LME contract.

The paper is organized as follows. Section 2 describes the equilibrium model with finite elasticity of supply of arbitrage services incorporating the dynamics of endogenous convenience yields. It demonstrates that the model admits an Error Correction Representation, and derives the contribution of the spot and future prices to the price discovery process. In addition, it shows that the metric used to measure price discovery, coincides with the linear combination defining the permanent component in the PT decomposition. Section 3 discusses the theoretical background of the two techniques available to measure price discovery, the Hasbrouck´s IS and the PT of Gonzalo-Granger. Section 4 presents empirical estimates of the model developed in section 2 for five LME traded metals, it tests for cointegration and for the presence of long run backwardation ($\beta_2 > 1$) , and estimates the participation of the spot and future prices in the price discovery process, testing the hypothesis of the future price being the sole contributor to price discovery. A by-product of this empirical section is the construction of time series of the unobserved convenience yields of all the commodities. Section 5 concludes. Graphs are collected in the appendix.

2. Theoretical Framework: A Model for Price Discovery in Futures and Spot Markets

The goal of this section is to characterize the dynamics of spot and future commodity prices in an equilibrium non arbitrage model, with finite elasticity of arbitrage services and existence of endogenous convenience yields. Our analysis builds and extends on GS setting up a perfect link with the Gonzalo-Granger PT decomposition. Following GS and for explanatory purposes we distinguish between two cases: (1) infinite and (2) finite elastic supply of arbitrage services.

2.1. Equilibrium Prices with Infinitely Elastic Supply of Arbitrage Services

Let S_t be the natural logarithm of the spot market price of a commodity in period t and let F_t be the natural log of the contemporaneous price of future contract for that commodity after a time interval $T_1 = T-t$. In order to find the non-arbitrage equilibrium condition the following set of standard assumptions apply in this section:

- (a.1) No taxes or transaction costs
- (a.2) No limitations on borrowing
- (a.3) No cost other than financing a (short or long) futures position
- (a.4) No limitations on short sale of the commodity in the spot market
- (a.5) Interest rates are determined by the process $r_t = \overline{r} + I(0)$ where $\overline{r}$ is the mean of r_t and I(0) is an stationary process with mean zero and finite positive variance.[1]
- (a.6) The difference $\Delta S_t = S_t - S_{t-1}$ is $I(0)$.

If r_t is the continuously compounded interest rate applicable to the interval from t to T, by the above assumptions (a.1-a.4), non-arbitrage equilibrium conditions imply

$$F_t = S_t + r_t T_1 . \qquad (1)$$

For simplicity and without loss of generality for the rest of the paper it will be assumed $T_1=1$. From (a.5) and (a.6), equation (1) implies that S_t and F_t are cointegrated with the standard cointegrating relation *(1, -1)*.[2] This constitutes the standard case in the literature.

2.2. Equilibrium Prices with Finitely Elastic Supply of Arbitrage Services Under the Presence of Convenience Yield

There are a number of cases in which the elasticity of arbitrage services is not infinite in the real world. Factors such as the existence of basis risk, convenience yields, storage cost, constraints on warehouse space, and the short run availability of capital, may restrict the supply of arbitrage services by making arbitrage transactions risky. From all these factors,

[1] Note that this assumption is consistent with the interest rate being deterministic. This is a common assumption for pricing vanilla derivatives see Hull (2006). Even when pricing more complicated payoffs in a two factor set up, with stochastic underlying commodity price and interest rates, the parameters are calibrated in such a way that they can match vanilla prices.

[2] Brener and Kroner (1995) consider r_t to be an *I(1)* process (random walk plus transitory component) and therefore they argue against cointegration between S_t and F_t. Under this assumption r_t should be explicitly incorporated into the long-run relationship between S_t and F_t in order to get a cointegrating relationship.

in this paper we focus on the existence of convenience yields by explicitly incorporating them into our model. Users of consumption commodities may feel that ownership of the physical commodity provides benefits that are not obtained by holders of future contracts. This makes them reluctant to sell the commodity and buy future contracts resulting in positive convenience yields and price backwardations. There is a large amount of literature showing that commodity prices are often backwarded. For example Litzenberger and Rabinowitz (1995) document that nine-month future prices are bellow the one-month prices 77 of the time for crude oil. Bessembinder et al. (1995) do not explicitly address the phenomenon of backwardation but show that, when a commodity becomes scarce, there is a proportionally larger increase in the convenience yield, and they associate this finding with the existence of spot price mean reversion.[3]

Convenience yield as defined by Brenan and Schwartz (1985) is "the flow of services that accrues to an owner of the physical commodity but not to an owner of a contract for future delivery of the commodity". Accordingly backwardation is equal to the present value of the marginal convenience yield of the commodity inventory. A futures price that does not exceed the spot price by enough to cover "carrying cost" (interest plus warehousing cost) implies that storers get some other return from inventory. For example a convenience yield can arise when holding inventory of an input lowers unit output cost and replacing inventory involves lumpy cost. Alternatively, time delays, lumpy replenishment cost, or high cost of short term changes in output can lead to a convenience yield on inventory held to meet customer demand for spot delivery.

Unlike Brennan and Schwartz (1985) as well as Gibson and Schwartz (1990) who model convenience yield as an exogenous "dividend", in this paper convenience yield is determined endogenously as a function of S_t and F_t. In particular, following the line of Routledge et al. (2000) and Bessembinder et al. (1995) we model the convenience yield process y_t as a weighted difference between spot and future prices

$$y_t = \gamma_1 S_t - \gamma_2 F_t + I(0), \qquad \gamma_i \in (0,\ 1),\ i = 1,\ 2. \tag{2}$$

Under the presence of convenience yields equilibrium equation (1) becomes

[3] The work of Bessembinder et al. (1995) belongs to the literature (see also Schwartz, 1997) that models spot prices to be mean reverting process (*I(0)* in our notation). In our paper this possibility is ruled out by assumption a.6, which is strongly empirically supported. Instead, our model produces mean reversion towards the long run spot-future equilibrium relationship.

$$F_t = S_t + (r_t - y_t)\,. \tag{3}$$

Substituting (2) into (3) and taking into account (a.5) the following long run equilibrium is obtained

$$S_t = \beta_2 F_t + \beta_3 + I(0)\,, \tag{4}$$

with a cointegrating vector (1, -β_2, -β_3) where

$$\beta_2 = \frac{1-\gamma_2}{1-\gamma_1} \text{ and } \beta_3 = \frac{-\bar{r}}{1-\gamma_1}\,. \tag{5}$$

It is important to notice the different values that β_2 can take and the consequences in each case:

1) $\beta_2>1$ if and only if $\gamma_1>\gamma_2$. In this case we are under long run backwardation ($S_t>F_t$ in the long run).
2) $\beta_2=1$ if an only if $\gamma_1=\gamma_2$. In this case we do not observe neither backwardation nor contango.
3) $\beta_2<1$ if and only if $\gamma_1<\gamma_2$. In this case we are under long run contango ($S_t<F_t$ in the long run).

In addition, the following remarks must be highlighted:

a) The parameters γ_1 and γ_2 are not identified from the equilibrium equation (4) unless $\bar{r}$ is known. In practice, the term $\bar{r}$ will also include storage costs.[4] Once a range of plausible values is assigned to this term, it is straightforward from (5) to obtain a sequence of γ_1 and γ_2 values, and therefore to calculate the convenience yield following (2). This is done in the empirical section 4-D for values of $\bar{r}$ that range from 7% to 10% (15-month rate plus warehousing cost).
b) Convenience yields are stationary when $\beta_2=1$. When $\beta_2 \neq 1$ it contains a small random walk component. The size depends on the difference (β_2 -1).
c) Backwardation (contango) is on average associated with positive (negative) convenience yields.

[4] Note that assumption a.3 states that there is no other cost than financing a (short or long) futures position. When the underlying asset is a storable commodity this takes into account warehousing cost as well as interest cost. Given that storage cost are small for non ferrous metals these are accounted by the parameter $\bar{r}$ in our model.

To the best of our knowledge this is the first instance in which the theoretical possibility of having a cointegrating vector different from *(1, -1)* for a pair of log variables is formally considered. The finding of non unit cointegrating vector has been interpreted empirically in terms of a failure of the unbiasedness hypothesis (see for example Brenner and Kroner, 1995). However it has never been modelled in a theoretical framework that allows for endogenous convenience yields and backwardation relationships.

To describe the interaction between cash and future prices we must first specify the behavior of agents in the marketplace. There are N_S participants in the spot market and N_F participants in futures market. Let $E_{i,t}$ be the endowment of the i^{th} participant immediately prior to period t and R_{it} the reservation price at which that participant is willing to hold the endowment $E_{i,t}$ .Then the demand schedule of the i^{th} participant in the cash market in period t is

$$E_{i,t} - A\left(S_t - R_{i,t}\right) \ , \qquad A > 0, \quad i = 1, \ldots, N_S, \tag{6}$$

where A is the elasticity of demand, assumed to be the same for all participants. Note that due to the dynamic structure to be imposed to the reservation price, R_{it}, the relevant results in our theoretical framework are robust to a more general structure of the elasticity of demand, such as, $A_i = A + a_i$, where a_i is an independent random variable, with $E(a_i)=0$ and $V(a_i)= \sigma^2_i<\infty$.

The aggregate cash market demand schedule of arbitrageurs in period t is

$$H\ \left((\beta_2 F_t + \beta_3) - S_t\right), \qquad H\ > 0, \tag{7}$$

where H is the elasticity of spot market demand by arbitrageurs. As previously discussed, it is finite when the arbitrage transactions of buying in the spot market and selling in the futures market or vice versa are not risk less.

The cash market will clear at the value of S_t that solves

$$\sum_{i=1}^{N_S} E_{i,t} = \sum_{i=1}^{N_S} \left\{E_{i,t} - A(S_t - R_{i,t})\right\} + H\ \left((\beta_2 F_t + \beta_3) - S_t\right). \tag{8}$$

The future market will clear at the value of F_t such that

$$\sum_{j=1}^{N_F} E_{j,t} = \sum_{j=1}^{N_F} \left\{E_{j,t} - A(F_t - R_{j,t})\right\} - H\ \left((\beta_2 F_t + \beta_3) - S_t\right). \tag{9}$$

Solving equations (8) and (9) for S_t and F_t as a function of the mean reservation price of spot market participants $\left(R_t^S = N_S^{-1} \sum_{i=1}^{N_S} R_{i,t} \right)$ and the mean reservation price for future market participants $\left(R_t^F = N_F^{-1} \sum_{j=1}^{N_F} R_{j,t} \right)$, we obtain

$$
\begin{aligned}
S_t &= \frac{(AN_F + H\beta_2)N_S R_t^S + HN_F \beta_2 R_t^F + HN_F \beta_3}{(H + AN_S)N_F + HN_S \beta_2}, \\
F_t &= \frac{HN_S R_t^S + (H + AN_S)N_F R_t^F - HN_S \beta_3}{(H + AN_S)N_F + HN_S \beta_2}.
\end{aligned} \tag{10}
$$

To derive the dynamic price relationships, the model in equation (10) must be characterized with a description of the evolution of reservation prices. We assume that immediately after the market clearing period *t-1* the i^{th} spot market participant was willing to hold amount $E_{i,t}$ at a price S_{t-1}. Following GS, this implies that S_{t-1} was his reservation price after that clearing. We assume that this reservation price changes to $R_{i,t}$ according to the equation

$$
\begin{aligned}
&R_{i,t} = S_{t-1} + v_t + w_{i,t}, \quad i = 1,..., N_S, \\
&R_{j,t} = F_{t-1} + v_t + w_{j,t}, \quad j = 1,..., N_F, \\
&\operatorname{cov}(v_t, w_{i,t}) = 0, \ \forall_i, \\
&\operatorname{cov}(w_{i,t}, w_{e,t}) = 0, \ \forall i \neq e,
\end{aligned} \tag{11}
$$

where the vector $\left(v_t,\ w_{i,t},\ w_{j,t}\right)$ is vector white noise with finite variance.

The price change $R_{i,t}$-S_{t-1} reflects the arrival of new information between period *t-1* and period *t* which changes the price at which the i^{th} participant is willing to hold the quantity $E_{i,t}$ of the commodity. This price change has a component common to all participants (v_t) and a component idiosyncratic to the i^{th} participant ($w_{i,t}$), The equations in (11) imply that the mean reservation price in each market in period *t* will be

$$
\begin{aligned}
&R^S{}_t = S_{t-1} + v_t + w^F{}_t, \quad i = 1,..., N_S, \\
&R^F{}_t = F_{t-1} + v_t + w^S{}_t, \quad j = 1,..., N_F,
\end{aligned} \tag{12}
$$

where, $w_t^S = \frac{\sum_{i=1}^{N_S} w_{i,t}^S}{N_S}$, $w_t^F = \frac{\sum_{j=1}^{N_F} w_{j,t}^F}{N_F}$.

Substituting expressions (12) into (10) yields the following vector model

$$\begin{pmatrix} S_t \\ F_t \end{pmatrix} = \frac{H\beta_3}{d}\begin{pmatrix} N_F \\ -N_S \end{pmatrix} + (M)\begin{pmatrix} S_{t-1} \\ F_{t-1} \end{pmatrix} + \begin{pmatrix} u_t^S \\ u_t^F \end{pmatrix}, \tag{13}$$

where

$$\begin{pmatrix} u_t^S \\ u_t^F \end{pmatrix} = M\begin{pmatrix} v_t + w_t^S \\ v_t + w_t^F \end{pmatrix}, \tag{14}$$

$$M = \frac{1}{d}\begin{pmatrix} N_S(\beta_2 H + AN_F) & \beta_2 HN_F \\ HN_S & (H + AN_S)N_F \end{pmatrix}, \tag{15}$$

and

$$d = (H + AN_S)N_F + \beta_2 HN_S \ . \tag{16}$$

GS perform their analysis of price discovery in an expression equivalent to (13). When $\beta_2=1$, GS conclude that the price discovery function depends on the number of participants in each market. In particular from (13) they propose the ratio

$$\frac{N_F}{N_S + N_F}, \tag{17}$$

as a measure of the importance of the future market relative to the spot market in the price discovery process. Price discovery is therefore a function of the size of a market. Our analysis is taken further. Model (13) is written as a Vector Error Correction Model (VECM) by subtracting $(S_{t-1}, F_{t-1})'$ from both sides,

$$\begin{pmatrix} \Delta S_t \\ \Delta F_t \end{pmatrix} = \frac{H\beta_3}{d}\begin{pmatrix} N_F \\ -N_S \end{pmatrix} + (M - I)\begin{pmatrix} S_{t-1} \\ F_{t-1} \end{pmatrix} + \begin{pmatrix} u_t^S \\ u_t^F \end{pmatrix}, \tag{18}$$

with

$$M - I = \frac{1}{d}\begin{pmatrix} -HN_F & HN_F\beta_2 \\ HN_S & -HN_S\beta_2 \end{pmatrix}. \tag{19}$$

Rearranging terms

$$\begin{pmatrix} \Delta S_t \\ \Delta F_t \end{pmatrix} = \frac{H}{d}\begin{pmatrix} -N_F \\ N_S \end{pmatrix}\begin{pmatrix} 1 & -\beta_2 & -\beta_3 \end{pmatrix}\begin{pmatrix} S_{t-1} \\ F_{t-1} \\ 1 \end{pmatrix} + \begin{pmatrix} u_t^S \\ u_t^F \end{pmatrix}. \tag{20}$$

Applying the PT decomposition (described in the next section) in this VECM, the permanent component will be the linear combination of S_t and F_t formed by the orthogonal vector (properly scaled) of the adjustment matrix $(-N_F, N_S)$. In other words the permanent component is

$$\frac{N_S}{N_S + N_F} S_t + \frac{N_F}{N_S + N_F} F_t. \tag{21}$$

This is our price discovery metric, which coincides with the one proposed by GS. Note that our measure does not depend neither on β_2 (and thus on the existence of backwardation or contango) nor on the finite value of the elasticities A and H (>0). These elasticities do not affect the long-run equilibrium relationship, only the adjustment process and the error structure. For modelling purposes is important to notice that the long run equilibrium is determined by expressions (2) and (3), and it is the rest of the VECM (adjustment processes and error structure) that is affected by the different market assumptions on elasticities, participants, etc.

Two extreme cases with respect H are worthwhile discussing (at least mathematically):

i) $H = 0$. In this case there is no cointegration and thus no VECM representation. Spot and future prices will follow independent random walks, futures contracts will be poor substitutes of spot market positions and prices in one market will have no implications for prices in the other market. This eliminates both the risk transfer and the price discovery functions of future markets.

ii) $H = \infty$. It can be shown that in this case the matrix M in expression (13) has reduced rank and is such that $(1, -\beta_2)M = 0$. Therefore the long run equilibrium relationship (4), $S_t = \beta_2 F_t + \beta_3$, becomes an exact relationship. Future contracts are in this situation perfect substitutes for spot market positions and prices will be “discovered” in both markets simultaneously. In a sense, it can be said that this analytical model is not prepared for $H = \infty$ because it produces a VECM with an error term with non-full rank covariance matrix.

3. Two different Metrics for Price Discovery: the IS of Hasbrouck and the PT of Gonzalo and Granger

Currently there are two popular common factor metrics that are used to investigate the mechanics of price discovery: the IS of Hasbrouck (1995) and the PT of Gonzalo and Granger (1995) (see Lehman, 2002; special issue on price discovery by the Journal of Financial Markets). Both approaches start from the estimation of the following VECM:

$$\Delta X_t = \alpha\beta' X_{t-1} + \sum_{i=1}^{k} \Gamma_i \Delta X_{t-i} + u_t, \tag{22}$$

with $X_t = (S_t, F_t)'$ and u_t a vector white noise with $E(u_t) = 0, Var(u_t) = \Omega > 0$. To keep the exposition simple we do not introduce deterministic components in model (22).

The IS measure is a calculation that attributes the source of variation in the random walk component to the innovations in the various markets. To do that, Hasbrouck transforms equation (22) into a vector moving average (VMA)

$$\Delta X_t = \Psi(L) u_t, \tag{23}$$

and its integrated form

$$X_t = \Psi(1) \sum_{i=1}^{t} u_i + \Psi^*(L) u_t, \tag{24}$$

where $\Psi(L)$ and $\Psi^*(L)$ are matrix polynomials in the lag operator L. By assuming that $\beta = (1, -1)$, it is implied that all the rows of $\Psi(1)$ are identical and the long-run impact of a disturbance on each of the prices are the same. Letting Ψ denote the common row vector in $\Psi(1)$ and l be a column unit vector, the price levels may be written as

$$X_t = \Psi\left(\sum_{i=1}^{t} u_i\right) l + \Psi^*(L) u_t. \tag{25}$$

The last step on the calculation of the IS consists on eliminating the contemporaneous correlation in u_t. This is achieved by constructing a new set of errors

$$u_t = Qe_t, \tag{26}$$

with Q the lower triangular matrix such that $\Omega = QQ'$.

The market-share of the innovation variance attributable to e_j is computed as

$$IS_j = \frac{\left([\Psi Q]_j\right)^2}{\Psi\Omega\Psi'}, \qquad j=1, 2 \ , \tag{27}$$

where $[\Psi\, Q\,]_j$ is the j^{th} element of the row matrix ΨQ.

Some limitations of the IS approach should be noted. First, it lacks of uniqueness. There is not a unique way of eliminating the contemporaneous correlation of the error u_t (there are many square roots of the covariance matrix Ω). Even if the Cholesky square root is chosen, there are two possibilities that produce different information share results. Hasbrouck (1995) bounds this indeterminacy for a given market j information share by calculating an upper bound (placing that market´s price first in the VECM) and a lower bound (placing that market last). These bounds can be very far apart from each other (see Huang, 2002). Second, it depends on the cointegrating vector structure. It is not clear how to proceed in (27) when $\beta=(1, -\beta_2)$ with β_2 different from one. Third, the IS methodology presents difficulties for testing. As Hasbrouck (1995) comments, asymptotic standard errors for the information shares are not easy to calculate. Fourth, it remains unclear whether there exists an economic theory behind the concept of IS.

Harris (1997) and Harris et al. (2002) were the first ones to use the PT measure of Gonzalo-Granger for price discovery purposes. This PT decomposition imposes the permanent component (W_t) to be a linear combination of the original variables, X_t. This implies that the transitory component has to be formed also by a linear combination of X_t (in fact by the cointegrating relationship, $Z_t = \beta' X_t$). The linear combination assumption together with the definition of a PT decomposition fully identify the permanent component as

$$W_t = \alpha_\perp X_t, \tag{28}$$

and the PT decomposition of X_t becomes

$$X_t = A_1 \alpha_\perp' X_t + A_2 \beta' X_t, \tag{29}$$

where

$$\begin{aligned} A_1 &= \beta_\perp(\alpha_\perp'\beta_\perp)^{-1}, \\ A_2 &= \alpha(\beta'\alpha)^{-1}, \end{aligned} \tag{30}$$

$$\text{with} \qquad \begin{aligned} \alpha_\perp{}'\alpha &= 0, \\ \beta_\perp{}'\beta &= 0. \end{aligned} \tag{31}$$

This permanent component is the driving factor in the long run of X_t. The information that does not affect W_t will not have a permanent effect on X_t. It is in this sense that W_t has been considered, in one part of the literature, as the linear combination that determines the importance of each of the markets (spot and futures) in the price discovery process. For these purposes the PT approach may have several advantages over the IS approach. First, the linear combination defining W_t is unique (up to a scalar multiplication) and it is easily estimated by Least Squares from the VECM. Secondly, hypothesis testing of a given market contribution in the price discovery is simple and follows a chi-square distribution. And third, the simple economic model developed in section 2 provides a solid theoretical ground for the use of this PT permanent component as a measure of how determinant is each price in the price discovery process. There are situations in which thee IS and PT approaches provide the same or similar results. This is discussed by Ballie et. al (2002). A comparison of both approaches can also be found in Yan and Zivot (2007). There are two minor drawbacks of this PT decomposition that are worthwhile noting. First, in order for (29) to exist we need to guarantee the existence of the inverse matrices involved in (30) (see proposition 3 in Gonzalo and Granger, 1995). And second, the permanent component W_t may not be a random walk. It will be a random walk when the VECM (22) does not contain any lags of ΔX_t or in general when $\alpha_\perp{}'\Gamma_i = 0$ $(i = 1,..., k)$.

A. Empirical Price Discovery in Non-Ferrous Metal Markets

The data include daily observations from the London Metal Exchange (LME) on spot and 15-month forward prices for Al, Cu, Pb, Ni, and Zn. Prices are available from January 1989 to October 2006. The data source is Ecowin. Quotations are denominated in dollars and reflect spot ask settlement prices and 15-month forward ask prices. The LME is not only a forward market but also the centre for physical spot trade in metals. The LME data has the advantage that there are simultaneous spot and forward prices, for fixed forward maturities, every business day. We look at quoted forward prices with time to maturity fixed to 15 months. These are reference future prices for delivery in the third Wednesday available within fifteen months delivery. Although the three month contract is the most liquid, reports from traders suggest that there are currently few factors which play differently between 3 months and spot.[5] Figures 1-5 the appendix, depict spot settlement ask prices, 15-month forward ask prices, and spot-15-month backwardation for the five metals considered. A common feature of the graphs shows that the degree of backwardation is highly correlated with prices, suggesting that high demand periods lead to backwardation structures. The data is thus consistent with the work of Routledge et al. (2000) which shows that forward curves are upward sloping in the low demand state and slope downward in the high demand state.

Our empirical analysis is based on the VECM (20) of section 2.2. Lags of the vector $(\Delta S_t, \quad \Delta F_t)'$ are added until the error term is a vector white noise. Econometric details of the estimation and inference of (20) can be found in Johansen (1996), and Juselius (2006), and the procedure to estimate $\alpha_{\perp}$ and to test hypotheses on it are in Gonzalo and Granger (1995). Results are presented in Tables 1-4, following a sequential number of steps corresponding to those that we propose for the empirical analysis and measuring of price discovery.

A. Univariate Unit Root Test

None of the Log-prices reject the null of a unit root. The results are available upon request.

B. Determination of the Rank of Cointegration

Before testing the rank of cointegration in the VECM specified in (20) two decisions are to be taken: (i) selecting the number of lags of $(\Delta S_t, \quad \Delta F_t)'$necessary to obtain white noise errors and, (ii) deciding how to model the deterministic elements in the VECM. For the former we use an information criteria (the AIC), and for the latter we restrict the constant term to be inside the cointegrating relationship, as the economic model in (20) suggests. Results on the Trace test are presented in Table 1. Critical values are taken from Juselius (2006). As it is predicted by our model, in all markets apart from copper, S_t and F_t are clearly cointegrated. In the case of copper, we fail to reject cointegration at the 80% confidence level.

[5] Spot and three month future price graphs can be provided upon request. They demonstrate that the two are effectively identical for all metals.

Table 1: Trace Cointegration Rank Test					
	Al	**Cu**	**Ni**	**Pb**	**Zn**
Trace test					
r ≤1 vs r=2 *(95% c.v=9.14)*	1.02	1.85	0.57	0.84	5.23
r = 0 vs r=2 *(95% c.v=20.16)*	27.73	15.64*	42.48	43.59	23.51

* Significant at the 20% significance level (80*% c.v=15.56).*

C. Estimation of the VECM

Results from estimating the reduced rank VECM model specified in (20) are reported in Table 2. The following two characteristics are displayed: (i) all the cointegrating relationships tend to have a slope greater than one, suggesting that there is long-run backwardation. This is formally tested in the next step D; (ii) with the exception of lead, in all equations future prices do not react significatively to the equilibrium error, suggesting that future prices are the main contributors to price discovery. This hypothesis is investigated in greater detail in step E.

Table 2: Estimation of the VECM (20)

Aluminium (Al)

$$\begin{bmatrix} \Delta S_t \\ \Delta F_t \end{bmatrix} = \begin{bmatrix} -0.010 \\ \mathit{(-2.438)} \\ 0.001 \\ \mathit{(0.312)} \end{bmatrix} \left[\hat{z}_{t-1}\right] + k\ lags\ of\ \begin{bmatrix} \Delta S_{t-1} \\ \Delta F_{t-1} \end{bmatrix} + \begin{bmatrix} \hat{u}_t^S \\ \hat{u}_t^F \end{bmatrix}$$

with $\hat{z}_t = S_t - 1.20F_t + 1.48$, and $\boldsymbol{k}$(AIC)=17.

Copper (Cu)

$$\begin{bmatrix} \Delta S_t \\ \Delta F_t \end{bmatrix} = \begin{bmatrix} -0.002 \\ \mathit{(-0.871)} \\ 0.003 \\ \mathit{(1.541)} \end{bmatrix} \left[\hat{z}_{t-1}\right] + k\ lags\ of\ \begin{bmatrix} \Delta S_{t-1} \\ \Delta F_{t-1} \end{bmatrix} + \begin{bmatrix} \hat{u}_t^S \\ \hat{u}_t^F \end{bmatrix}$$

with $\hat{z}_t = S_t - 1.01F_t + 0.06$, and $\boldsymbol{k}$(AIC)=14.

Nickel (Ni)

$$\begin{bmatrix} \Delta S_t \\ \Delta F_t \end{bmatrix} = \begin{bmatrix} -0.009 \\ \mathit{(-2.211)} \\ 0.005 \\ \mathit{(1.267)} \end{bmatrix} \left[\hat{z}_{t-1}\right] + k\ lags\ of\ \begin{bmatrix} \Delta S_{t-1} \\ \Delta F_{t-1} \end{bmatrix} + \begin{bmatrix} \hat{u}_t^S \\ \hat{u}_t^F \end{bmatrix}$$

with $\hat{z}_t = S_t - 1.19F_t + 1.69$, and $\boldsymbol{k}$(AIC)=18.

Lead (Pb)

$$\begin{bmatrix}\Delta S_t \\ \Delta F_t\end{bmatrix} = \begin{bmatrix} -0.001 \\ (-0.206) \\ 0.013 \\ (3.793) \end{bmatrix} [\hat{z}_{t-1}] + k \text{ lags of } \begin{bmatrix}\Delta S_{t-1} \\ \Delta F_{t-1}\end{bmatrix} + \begin{bmatrix}\hat{u}_t^S \\ \hat{u}_t^F\end{bmatrix}$$

$\hat{z}_t = S_t - 1.19F_t + 1.25$, and $\boldsymbol{k}$(AIC)=15.

Zinc (Zn)

$$\begin{bmatrix}\Delta S_t \\ \Delta F_t\end{bmatrix} = \begin{bmatrix} -0.009 \\ (-2.709) \\ 0.001 \\ (0.319) \end{bmatrix} [\hat{z}_{t-1}] + k \text{ lags of } \begin{bmatrix}\Delta S_{t-1} \\ \Delta F_{t-1}\end{bmatrix} + \begin{bmatrix}\hat{u}_t^S \\ \hat{u}_t^F\end{bmatrix}$$

with $\hat{z}_t = S_t - 1.25F_t + 1.78$, and $\boldsymbol{k}$(AIC)=16.

Note: t- statistics are given in parenthesis.

D. Hypothesis Testing on Beta

Results reported in Table 3 show that the standard cointegrating vector (*1, -1*) is rejected in all metal markets apart from copper in favour of a cointegrating slope greater than one. This shows that there is long run backwardation implying that spot prices have, on average, exceeded 15-month prices over our sample period.

Table 3: Hypothesis Testing on the Cointegrating Vector and Long Run Backwardation

	Al	**Cu**	**Ni**	**Pb**	**Zn**
Coint. Vector *(β_1, -β_2,-β_3)*					
β_1	1.00	1.00	1.00	1.00	1.00
β_2	1.20	1.01	1.19	1.19	1.25
SE (β_2)	(*0.06*)	(*0.12*)	(*0.04*)	(*0.05*)	(*0.07*)
β_3 *(constant term)*	-1.48	-0.06	-1.69	-1.25	-1.78
SE (β_3)	(*0.47*)	(*0.89*)	(*0.34*)	(*0.30*)	(*0.50*)
Hypothesis testing					
H_0:β_2=1 vs H_1:β_2>1 *(p-value)*	(0.001)	(0.468)	(0.000)	(0.000)	(0.000)
Long Run Backwardation	yes	no	yes	yes	yes

Fama and French (1988) show that metal production does not adjust quickly to positive demand shocks around business cycle peaks. As a consequence, inventories fall and forward prices are bellow spot prices. We contend that in these situations price backwardations and convenience yields arise due to the high costs of short term changes in output.

Inventory decisions are crucial for commodities because they influence the current and future scarcity of the good, linking its current (consumption) and expected future (asset values). However, this link is imperfect because inventory is physically constrained to be *nonnegative.* Inventory can always be added to keep current spot prices from being too low relative to expected future spot prices. Increased storage raises the good´s valuation since it reduces the amount available for immediate use. If spot prices are expected to rise by more that "carrying cost", additional inventory is purchased. This increases current (and lower future) spot prices. Conversely if prices are expected to fall (or rise by less than carrying cost) then inventory will be sold. This decreases the good's current valuation by increasing the amount available for immediate consumption. However once inventory is driven to zero, its spot price is tied solely to the good's "immediate consumption value". This situation, usually referred to as "stock out", breaks the link between the current consumption and expected future asset values of a good resulting in backwardations and positive convenience yields.

The economic intuition behind the non existence of long-run backwardation in the copper market may be explained by the high use of recycling in the industry. Copper is a valuable metal and like gold and silver it is rarely thrown away. In 1997, 37% of copper consumption came from recycled copper. We contend that recycling provides a second source of supply in the industry and may be responsible for smoothing the convenience yield effect.

D.1. *Construction of Convenience Yields*

One of the advantages of our model is the possibility of calculate a range of convenience yields. From expression (5),

$$\gamma_1 = 1 + \frac{\bar{r}}{\beta_3} \text{ and } \gamma_2 = 1 - \beta_2 \ (1- \gamma_1)\,, \tag{32}$$

given $\beta_3 \neq 0$. The only unknown in (32) is $\bar{r}$. In practice this parameter is the average of the interest rates and storage costs. For the analyzed sample period the average LIBOR yearly dollar rate is 4.9% which makes the 15 month rate 6.13%. Non ferrous metal storage costs are provided by the LME (see www. lme.com). These are usually very low and in the order of 1% to 2%. In response to these figures we have calculated convenience yields for values between 6-8% of interest cost and 1-2% of storage cost. Therefore we have considered a range of $\bar{r}$ going from 7% to 10% and calculated the corresponding sequence of values of γ_1 and γ_2. With these values the long-run convenience yield $y_t = \gamma_1 S_t - \gamma_2 F_t$ is obtained, converted into annual rates and plotted in Figures 6-10. The only exception is Copper because (32) can not be applied (β_3 is not significantly different from zero). In this case the only useful information we have is that $\beta_2 = 1$, and therefore $\gamma_1 = \gamma_2$. To calculate the corresponding range of convenience yields we have given values to these parameters that go from .9 to 1.0. Figure 7 plots the graphical result. Figures 6-10 show two common features that are worth noting: i) Convenience yields are positively related to backwardation price relationships, and ii) convenience yields are remarkably high in times of excess demand and subsequent "stockouts", notably the 1989-1990 and the 2003-2006 sample sub-periods both leading to a metal price boom.

E. *Estimation of* $\alpha_\perp$ *and Hypothesis Testing*

Table 4 shows the contribution of spot and future prices to the price discovery function. For all metals with the exception of lead, future prices are the determinant factor in the price discovery process. This conclusion is statistically obtained by the non-rejection of the null hypothesis $\alpha_\perp' = (0, 1)$. In the case of lead, the spot price is the determinant factor of price discovery (the hypothesis $\alpha_\perp' = (1, 0)$ is not rejected). We justify this result by stating that lead is the least important LME traded future contract in terms of volumes traded (see Figure 11 in the graphical appendix). [6] While for all commodities only one of the hypotheses (*0, 1*) or (*1, 0*) is non rejected, this is not the case for copper. In the copper market both the spot and future prices contribute with equal weight to the price discovery process. As a result the hypothesis $\alpha_\perp' = (1, 1)$ cannot be rejected (*p-value = 0.79*). We are unable to offer a formal explanation for this result. We can only state that cointegration between spot and 15-month prices is clearly weaker for copper and that this may be responsible for non rejection of the tested hypotheses on $\alpha_\perp$.

[6] Note that an appropriate comparison would require us to provide data on spot volumes traded so that an estimate of the ratio in (17) could be calculated. We have been unable to get spot volume data, which implies that Figure 11 only provides some guidance on relative volumes traded. Data source in Figure 11 are LME for the Jan1990- Dec 2003 sample and Ecowin for the Sep2004-Dec2006 sample.

Table 4: Proportion of Spot and Future Prices in the Price Discovery Function ($\alpha_\perp$)

Estimation	**Al**	**Cu**	**Ni**	**Pb**	**Zn**
$\alpha_{1\perp}$	0.09	0.58	0.35	0.94	0.09
$\alpha_{2\perp}$	0.91	0.42	0.65	0.06	0.91
Hypothesis testing *(p-values)*					
H_0: $\alpha_\perp{'}=(0,1)$	(*0.755*)	(*0.123*)	(*0.205*)	(*0.000*)	(*0.749*)
H_0: $\alpha_\perp{'}=(1,0)$	(*0.015*)	(*0.384*)	(*0.027*)	(*0.837*)	(*0.007*)

Note: $\alpha_\perp$is the vector orthogonal to the adjustment vector α: $\alpha_\perp`\alpha=0$. For estimation of $\alpha_\perp$ and inference on it, see Gonzalo-Granger (1995).

The finding that future markets on average are more important than spot prices is consistent with the literature on commodity markets. GS suggest that "the cash markets in wheat, corn, and orange juice are largely satellites of the futures markets for those commodities, with about 75% of new information incorporated first in future prices and then flowing into cash prices". Yang et al. (2001) use VECM estimates to provide strong evidence in support of the theory that storable future commodity prices are at least equally important as informational sources as the spot prices. Schroeder and Goodwin (1991) apply the methodology developed by GS to examine the short run price discovery role of the live hog cash and futures markets to conclude that price discovery generally originates in the futures market with an average of roughly 65% of new information being passed from the futures to the cash prices. Oellerman et al. (1989) determine the price leadership relationship among cash and futures prices for feeder cattle and live cattle using the Granger causality model and the GS model. They conclude that the cattle futures markets serve as the center of price discovery for feeder cattle. Figuerola-Ferretti and Gilbert (2005) use an extended version of the Beveridge-Nelson (1981) decomposition and a latent variable approach to examine the noise content, and therefore the informativeness, of four aluminium prices. They find that the start of aluminium futures trading in 1978 resulted in greater price transparency in the sense that the information content of transactions prices increased. Although the literature on price discovery has to some extent quantified the price discovery effects of futures trading, non of the cited studies on commodity price discovery has formally tested whether the future price is the sole contributor to price discovery. This is easily done with our approach.

F. Construction of the Corresponding PT Decomposition

The proposed PT decomposition constitutes a natural way (see Table 5) of summarizing the empirical results.

Table 5: Gonzalo-Granger Permanent-Transitory Decomposition

Aluminium (Al)

$$\begin{bmatrix} S_t \\ F_t \end{bmatrix} = \begin{bmatrix} 1.177 \\ 0.983 \end{bmatrix} W_t + \begin{bmatrix} 0.901 \\ -0.083 \end{bmatrix} Z_t$$

with

$$W_t = 0.088 S_t + 0.912 F_t$$
$$Z_t = S_t - 1.197 F_t.$$

Copper (Cu)

$$\begin{bmatrix} S_t \\ F_t \end{bmatrix} = \begin{bmatrix} 1.004 \\ 0.995 \end{bmatrix} W_t + \begin{bmatrix} 0.409 \\ -0.585 \end{bmatrix} Z_t$$

with

$$W_t = 0.582 S_t + 0.418 F_t$$
$$Z_t = S_t - 1.010 F_t.$$

Nickel (Ni)

$$\begin{bmatrix} S_t \\ F_t \end{bmatrix} = \begin{bmatrix} 1.117 \\ 0.938 \end{bmatrix} W_t + \begin{bmatrix} 0.613 \\ -0.325 \end{bmatrix} Z_t$$

with

$$W_t = 0.345 S_t + 0.654 F_t$$
$$Z_t = S_t - 1.191 F_t.$$

Lead (Pb)

$$\begin{bmatrix} S_t \\ F_t \end{bmatrix} = \begin{bmatrix} 1.010 \\ 0.849 \end{bmatrix} W_t + \begin{bmatrix} 0.055 \\ -0.794 \end{bmatrix} Z_t$$

with

$$W_t = 0.937 S_t + 0.062 F_t$$
$$Z_t = S_t - 1.190 F_t.$$

Zinc (Zn)

$$\begin{bmatrix} S_t \\ F_t \end{bmatrix} = \begin{bmatrix} 1.223 \\ 0.978 \end{bmatrix} W_t + \begin{bmatrix} 0.893 \\ -0.086 \end{bmatrix} Z_t$$

with

$$W_t = 0.089 S_t + 0.911 F_t$$
$$Z_t = S_t - 1.251 F_t.$$

Note: See last part of Section 3 for a brief summary of how to construct this P-T decomposition and its interpretation.

This decomposition is an "observable" factor model with two components: i) the permanent component W_t is the driving factor in the long-run of X_t and is formed by the linear combination of S_t and F_t that characterizes the price discovery process; and ii) the transitory component Z_t formed by the stationary linear combination of S_t and F_t that captures the price movements due to the bid-ask bounces. The information that does not affect W_t will not have a permanent effect on X_t. In this way we can define a transitory shock as a shock to S_t or F_t that keeps W_t constant.

5. Conclusions, Implications and Extensions

The process of price discovery is crucial for all participants in commodity markets. The present paper models and measures this process by extending the work of GS to consider the existence of convenience yields in spot-future price equilibrium relationships. Our modeling of convenience yields with I(1) prices is able to capture the presence of backwardation or contango long-run structures, in such a way that it becomes reflected on the cointegrating vector $(1, -\beta_2)$ with $\beta_2 \neq 1$.When $\beta_2 > 1$ (<1) the market is under long-run backwardation (contango). This is the first important contribution in this paper. As a by-product, we find a theoretical justification for a cointegrating vector between log-variables different from the standard $(1, -1)$. To the best of our knowledge this is the first time this has been formally considered. Secondly, we are able to obtain time series of the unobserved convenience yield. This becomes crucial when the goal of the research is a detail causal analysis of this variable. Thirdly, we show that under very general conditions, including finite elasticity of supply of arbitrage, the model admits an Error Correction Representation. Under this framework, the linear combination of S_t and F_t characterizing the price discovery process coincides with the permanent component of the Gonzalo-Granger PT decomposition. And fourthly, we propose empirical strategy based on five simple steps to test for long-run backwardation, and estimate and test the importance of each price (spot and future) in the price discovery process. Applied to LME spot and future prices for five metals (Al, Cu, Ni, Pb, Zn), our technique suggests that, with the exception of Cu, all markets are in long-run backwardation. More importantly, in most instances, for those markets with highly liquid futures trading, the preponderance of price discovery takes place in the futures market. Our result is consistent with the literature on commodity price discovery and has the following implications:

- The advent of centralized futures trading has been responsible for the creation of a publicly known, uniform reference price reflecting the true underlying value of the commodity.
- Future prices are used by market participants to make production, storage and processing decisions thus helping to rationalize optimal allocation of productive resources (Stein 1985, Peck 1985).

Extensions to consider different regimes according to whether the market is in backwardation or in contango and their impact into the VECM and PT decomposition, following the econometrics approach of Gonzalo and Pitarakis (2006) are under current investigation by the authors.

REFERENCES

Baillie R., G. Goffrey, Y. Tse, and T. Zabobina (2002). “Price discovery and common factor models.” *Journal of Financial Markets*, 5, 309-325.

Bessembinder H., J.F. Coughenour, P.J. Seguin, and M.M. Smoller (1995). “Mean reversion in equilibrium asset prices: Evidence from the futures term structure.” *The Journal of Finance*, 50, 361-375.

Beveridge, S. and C.R. Nelson (1981). “A new approach to decomposition of economic time series into permanent and transitory components with particular attention to measurement of the Business Cycle.” *Journal of Monetary Economics*, 7, 151-174.

Brennan, M.J. and E. Schwartz (1985). “Evaluing natural resource investments.” *Journal of Business* 58,135-157.

Brenner, R.J. and K. Kroner (1995). “Arbitrage, cointegration, and testing the unbiasedness hypothesis in financial markets.” *Journal of Finance and Quantitative Analysis*, 30, 23-42.

Engle, R.F. and C.W.J. Granger (1987). “Cointegration and error correction: Representation, estimation, and testing.” *Econometrica*, 55, 251-276.

Fama E. and K.R. French (1988). “Business cycles and the behaviour of metals prices”. *The Journal of Finance*, XLIII, 1075-1093.

Figuerola-Ferretti I. and C.L. Gilbert (2005). “Price discovery in the aluminium market.” *Journal of Futures Markets*, 25, 967-988.

Garbade, K.D. and W.L. Silber (1983). “Price movements and price discovery in futures and cash markets.” *Review of Economics and Statistics*, 65, 289-297.

Gibson, R. and E. Schwartz (1990). “Stochastic convenience yield and the pricing of oil contingent claims.” *Journal of Finance*, 45, 959-956.

Gonzalo, J. and C.W.J. Granger (1995). “Estimation of common long-memory components in cointegrated systems.” *Journal of Business and Economic Statistics*, 13, 27-36.

Gonzalo, J. and J. Pitarakis (2006). “Threshold effects in multivariate error correction models.” Palgrave Handbook of Econometrics, vol I, Chapter 15.

Harris F.H., T.H. McInish, and R.A. Wood (1997).”Common long-memory components of intraday stock prices: A measure of price discovery.” *Wake Forest University Working Paper.*

Harris F. H., T.H. McInish, and R.A. Wood (2002). “Security price adjustment across exchanges: an investigation of common factor components for Dow stocks.” *Journal of Financial Markets*, 5, 277-308.

Hasbrouck, J. (1995). “One security, many markets: Determining the contributions to price discovery.” *Journal of Finance*, 50, 1175-1199.

Huang, R.D. (2002). “The Quality of ECN and Nasdaq market maker quotes.” *The Journal of Finance*, 57, 1285-1319.

Hull, J. C. (2006). *Options, Futures and Other Derivatives (sixth edition)*. Prentice Hall. New Jersey.

Johansen, S. (1996). *Likelihood-based Inference in Cointegrated Vector Autoregressive Models (2nd edition)*. Oxford University Press. Oxford.

Juselius, K. (2006). *The Cointegrated VAR Model: Methodology and Applications*. Oxford University Press. Oxford.

Lehman B. N. (2002). Special issue of *Journal of Financial Markets*, Volume 5, 3.

Lake, F. (1978). “The Miller´s se of commodity exchange”. In A. Peck (ed). *Views from the trade* (Chicago: Board of Trade of the City of Chicago, 1978).

Litzenberger, R. and N. Rabinowitz (1995). “Backwardation in oil futures markets: Theory and empirical evidence.” *The Journal of Finance*, 50, 1517-1545.

Oellermann, C.M., B. W. Brorsen., and P. L. Farris (1989). “Price discovery for feeder cattle.” *The Journal of Futures Markets*, 9, 113-121.

Peck, A.E. (1985). “The economic role of traditional commodity futures markets.” In *A. E. Peck (Ed.) Futures markets: Their Economic Roles*. Washington DC: American Enterprise Institute for Public Policy Research, 1-81.

Routledge B.R., D.J. Seppi, and C.S. Spatt (1995). “Equilibrium forward curves for commodities.” *The Journal of Finance*, LV, 1297-1337.

Schoroeder T. and B.K. Goodwin (1991). “Price discovery and cointegration for live hogs.” *The Journal of Futures Markets*, 11, 685-696.

Stein, J.L. (1961). “The simultaneous determination of spot and future prices.” *The American Economic Review*, 51,1012-1025.

Stein, J.L. (1985). “Futures markets, speculation and welfare”, *Department of Economics, Brown University, Working Paper* 85-12.

Schwartz E. (1997). “The Stochastic behaviour of commodity prices: Implications for valuation and hedging.” *The Journal of Finance*, 52, 923-973.

Wiese, V. (1978). “Use of commodity exchanges by local grain marketing organizations”. In A. Peck (ed). *Views from the trade* (Chicago: Board of Trade of the City of Chicago, 1978).

Working, H. (1948). “Theory of the inverse carrying charge in futures markets.” *Journal of Farm Economics*, 30, 1-28.

Yang J., D. Bessler, and D.J. Leatham (2001). “Asset storability and price discovery in commodity futures markets: a new look.” *Journal of Futures Markets*, 21, 279-300.

Yan, B. and E. Zivot (2007). “The dynamics of price discovery.” *Department of Economics, University of Washington, Working Paper*.

GRAPHICAL APPENDIX

Figure1: Aluminium spot ask settlement prices, 15-month ask forward prices and backwardation

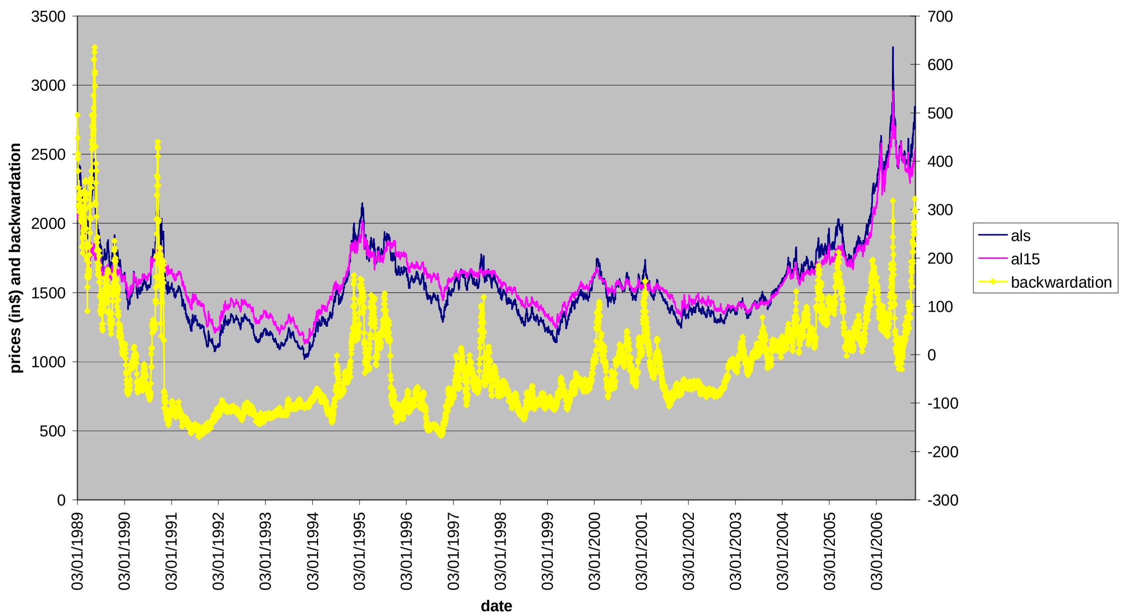

Figure 2: Copper spot ask settlement prices, 15 month forward ask prices and backwardation

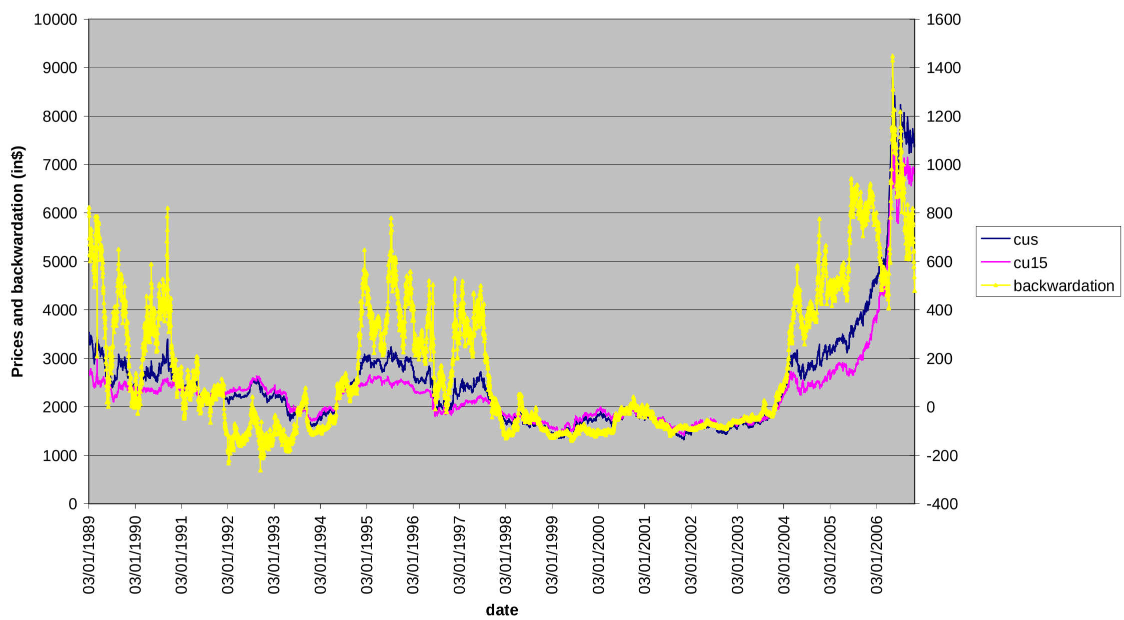

Figure 3: Nickel spot ask settlement prices, 15-month ask forward prices and backwardation

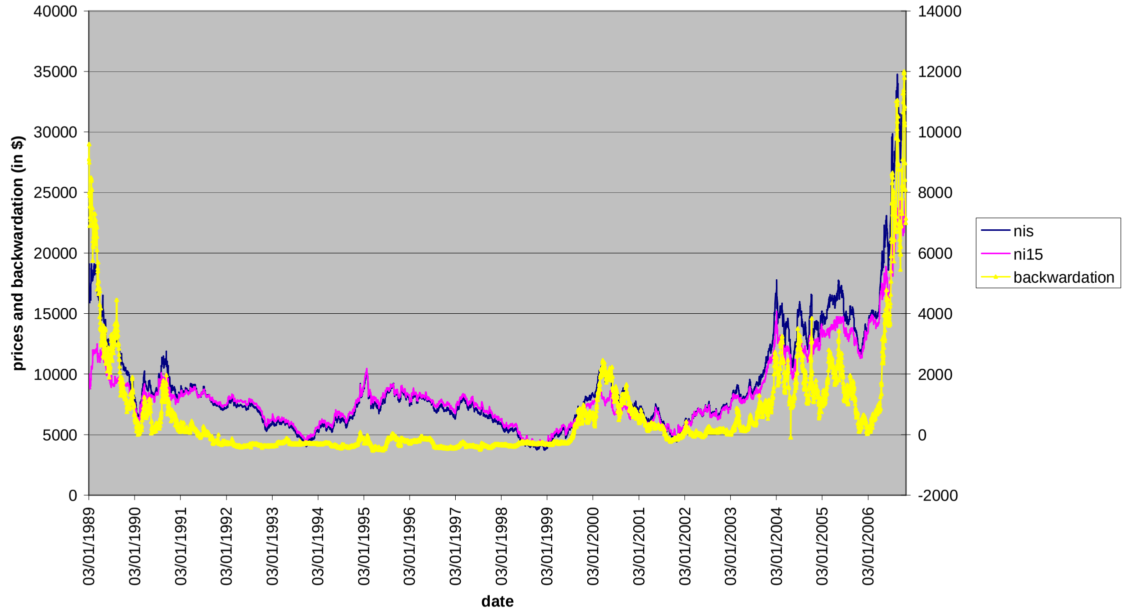

Figure 4: Lead spot ask settlement prices, 15-month forward prices and backwardation

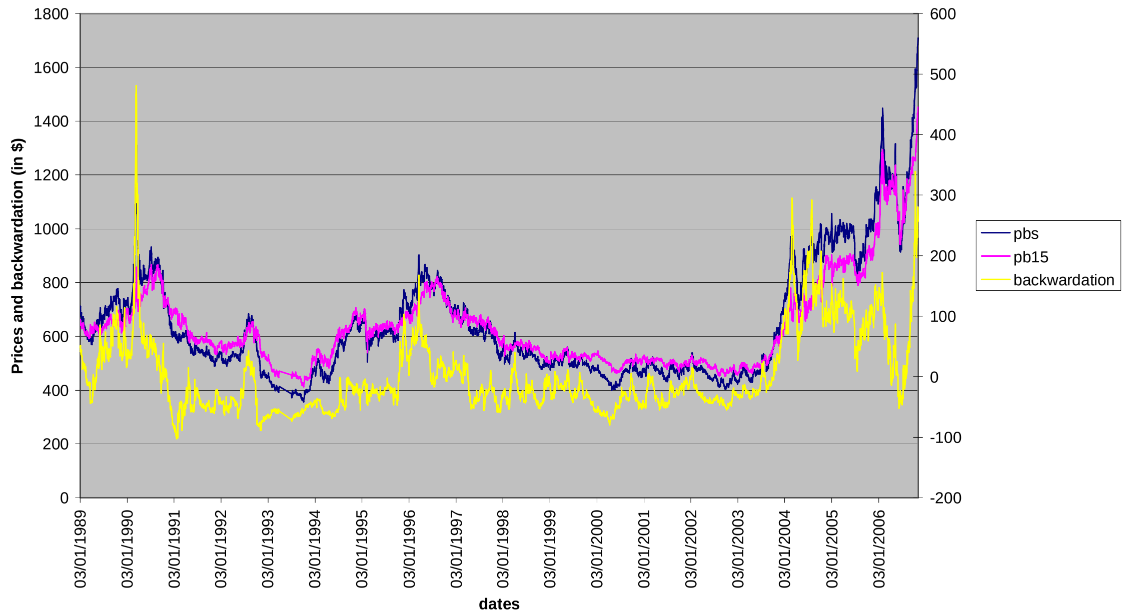

Figure 5: Zinc spot ask settlement Prices, 15-month forward pirces and backwardation

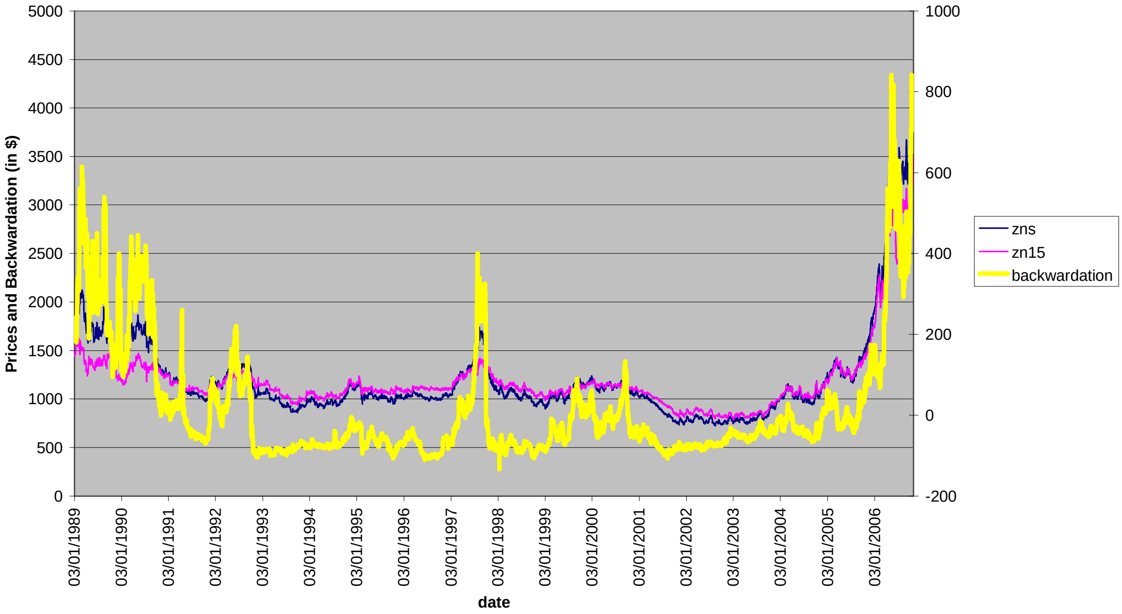

Figure 6: Range of annual Aluminum convenience yields in %

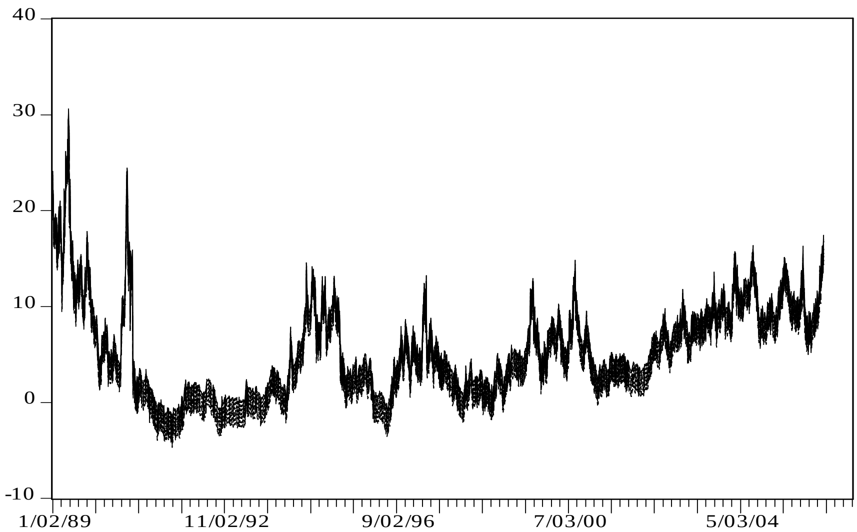

Figure 7: Range of annual Copper convenience yields in %

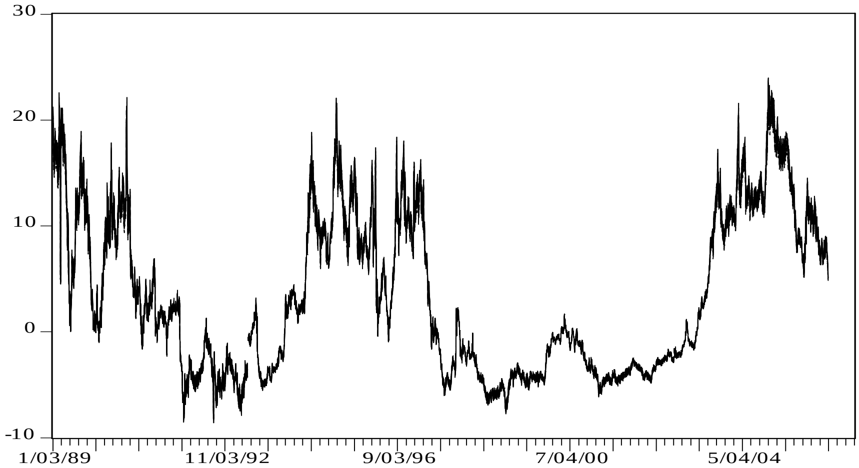

Figure 6: Range of annual Nickel convenience yields in %

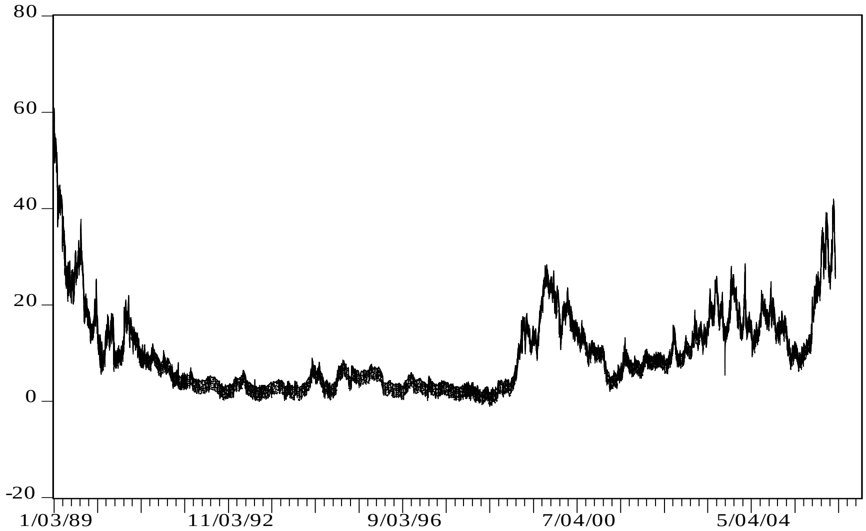

Figure 9: Range of annual Lead convenience yields in %

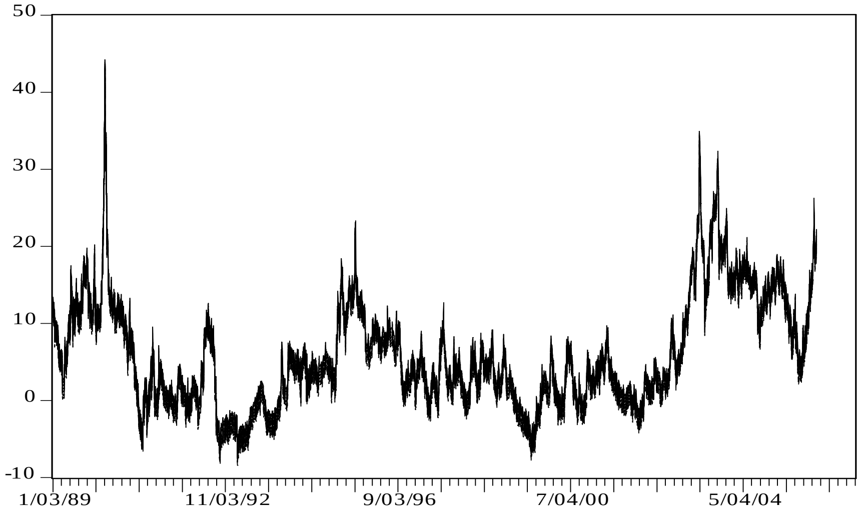

Figure 10: Range of annual Zinc convenience yields in %

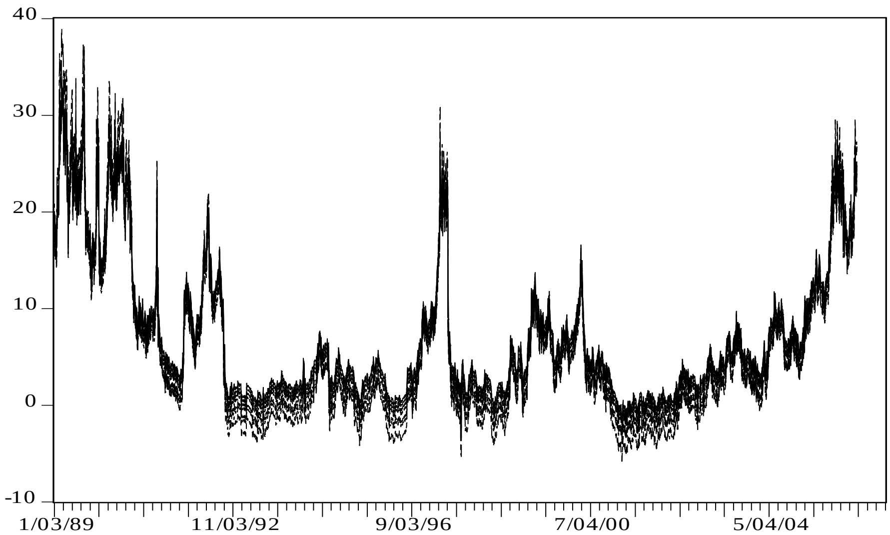

Figure 11: Average yearly LME Futures Trading Volumes-Non Ferrous Metals
January 1990- December 2006