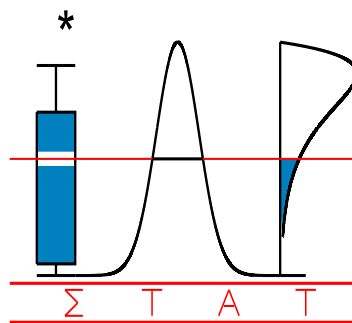


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**DOES THE OPEN LIMIT ORDER BOOK MATTER  
IN EXPLAINING LONG RUN VOLATILITY ?**

PASCUAL R. and D. VEREDAS



I A P S T A T I S T I C S  
N E T W O R K

**INTERUNIVERSITY ATTRACTION POLE**

# Does the Open Limit Order Book Matter in Explaining Long Run Volatility?

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## Abstract

This paper evaluates the informational content of an open limit order book by studying its role in explaining long run volatility. We separate liquidity-driven (transitory) volatility from information-driven (long run) volatility using a dynamic state-space co-integration model for ask and bid quotes. We report that changes in immediacy costs precede posterior fluctuations in long run volatility even after controlling for the incoming order flow. The book is less informative for large-caps than for small-caps. Consistently with previous studies, the book beyond the best quotes adds explanatory power to the best quotes. Finally, the explanatory power of the book decreases with the time resolution of the analysis

Keywords Limit order book, volatility, electronic order-driven markets, state-space models, price formation, market microstructure

JEL classification: G1

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## 1. Introduction

In recent years, several empirical and theoretical studies have examined the informational value of open limit order books (LOBs) in explaining future stock returns and the composition of the incoming order flow.<sup>3</sup> With the notable exceptions of Ahn, Bae, and Chan (2001), and Coppejans, Domowitz, and Madhavan (2004), the empirical relationship between return volatility and the state of the LOB has received a very limited attention. Ahn *et al* (2001) evidence that volatility declines after an increase in book depth. Similarly, Coppejans *et al* (2004) find that positive liquidity shocks, as measured by the unexpected component of book depth, substantially reduce volatility. Yet, these studies do not account for the nature of the observed volatility.

In this paper, we distinguish between transitory and informational volatility. Transitory volatility is triggered by noise or liquidity trading. It may also be explained by a paucity of limit orders on the book, due to temporary liquidity withdrawals either at the bid or at the ask side. On the contrary, long run volatility relates to the underlying efficient price. It is linked to the trading of informed investors, to the disclosure of public information, and to permanent shocks in the fundamentals of the stock price.<sup>4</sup> Bae, Jang, and Park (2003) illustrate the importance of distinguishing between these two sources of volatility. Their aim is to analyze the causal relationship between volatility and limit order submissions.<sup>5</sup> By means of state-space models, they decompose the transaction price into an efficient price and a transitory noise. Then, they compute proxies for the long run and short run volatility components using the returns in each component. They find short run volatility to cause limit order submissions, but no effect is reported for long run volatility.

Our focus is on the role the LOB plays in explaining long run volatility. If the state of the LOB contributes to the price discovery process, we should observe the volatility of the efficient price to vary with the state of the book. How can the LOB be related to informational volatility? It is usually assumed that informed traders always choose to submit market orders, as they are impatient traders endowed with a perishable informational advantage. Limit order traders, however, may also be information-motivated, as theoretically suggested by Seppi

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<sup>3</sup> See Biais, Hillion, and Spatt (1995); Handa and Schwartz (1996); Parlour (1998); Foucault (1999); Corwin and Lipson (2000); Irvine, Benston and Kandel (2000); Franke and Hess (2000); Griffiths et al. (2000); Coppejans and Domowitz (2002); Cao, Hansch, and Wang (2003); Handa, Schwartz, and Tiwari (2003); Rinaldo (2004); Pascual and Veredas (2004), and Foucault, Kadan, and Kandel (2005), among others.

<sup>4</sup> Ahn et al (2001) assume their measure of volatility is liquidity-driven. However, there is no justification for such an assumption, since they do not isolate the volatility component due to information flows.

<sup>5</sup> Theoretically, Handa and Schwartz (1996) predict higher liquidity-motivated volatility to increase limit order submissions. Foucault (1999) predicts a similar relationship for information-motivated volatility.

(1997), Harris (1998), Rindi (2003), and Kaniel and Liu (2006). These papers qualify Copeland and Galai (1983), since periods with high informational volatility might not necessarily be tied to a decrease in limit-order submissions. Recently, Bloomfield, O'Hara, and Saar (2005), and Anand, Chakravarty, and Martell (2005) provide experimental and empirical evidence, respectively, supporting the use of limit orders by informed traders. If limit orders may be information-motivated, then the shape of the LOB may be informative about future information flows and, hence, about long run volatility. Therefore, orders, and not only trades, as it is usually assumed, may have a permanent price impact as a result of private information revelation.

In a recent theoretical effort, Foucault, Moinas, and Theissen (2006) develop a model in which limit order traders possess volatility information. In particular, informed dealers have private information on the occurrence of future information events, such as corporate announcements. These traders adjust their order submission strategies to the level of risk perceived. Uninformed traders learn volatility information from the LOB, and this information is more precise when traders' identity is not concealed. They conclude that the LOB is a channel for volatility information.

We use high-frequency data on a set of 33 stocks listed in the Spanish Stock Exchange (SSE) in 2000. For each stock, we estimate a structural time series co-integration model for ask and bid quotes. We decompose the best quotes into three unobserved components: (a) the common long run component (efficient price); (b) the transitory component of the ask quote, and (c) the transitory component of the bid quote. We allow the short run components of ask and bid quotes to be cross and auto-correlated. In addition, we control for intraday regular patterns in immediacy costs. The efficient price is modeled as a random walk process and, following Hasbrouck (1999), the long run volatility (the volatility of the efficient price) follows an EGARCH process (Nelson, 1991), which accommodates intraday regularities.

Theoretical and empirical research claims for the existence of an adverse selection component in the bid-ask spread.<sup>6</sup> For the particular case of order driven markets, Handa, Schwartz, and Tiwari (2003) theoretically shows that the size of the bid-ask spread is a function of adverse selection and differences in valuation among investors. Consequently, we allow the innovations in the efficient price to be contemporaneously correlated with the

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<sup>6</sup> See O'Hara (1995), Madhavan (2000), Stoll (2000), and Biais, Glosten and Spatt (2005), for a general review on the theoretical and empirical literature on the unobservable components of the bid-ask spread.

innovations in the short term components of ask and bid quotes.<sup>7</sup> This feature of our model leads to a tri-variate volatility model for the transitory and long run components. Following Bollerslev (1990), we model the volatility of the errors of the unobserved components using the Constant Conditional Correlation (CCC) model.

We employ the estimated time series of the long run volatility to evaluate the informational content of different pieces of limit order book information. Using structural vector autoregression (SVAR) models for the long run volatility and the LOB, we show that shocks to long run volatility contemporaneously cause liquidity deterioration by increasing immediacy costs and decreasing quoted depth. More importantly, we report that the LOB does contain information about future long run volatility, even when we control for the succeeding order flow. More precisely, we find that shocks to immediacy costs are followed by an increase in the intensity of information arrival in the short run. Therefore, as predicted by Foucault et al. (2006), variations in immediacy costs measures precede fluctuations in long run volatility. Moreover, we show there is significant information beyond the best quotes, since immediacy costs measures for hypothetical large-sized trades provide more information than the quoted bid-ask spread. We therefore corroborate previous evidence by Cao, Hansch, and Wang (2003) and Pascual and Veredas (2006). Our findings suggest that the book is more informative among small-cap/less frequently traded stocks. Finally, the informativeness of the LOB decreases with time aggregation, that is, the LOB becomes less informative as we sample at lower frequencies.

The rest of the paper is organized as follows. In the next section, we briefly introduce the microstructure of the SSE and the database. In section 3, we present the structural model for ask and bid quotes and describe the estimation technique. In section 4, we summarize the estimation results of the structural model. In section 5, we evaluate the informational content of the LOB. In section 6, we conclude.

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<sup>7</sup> Hasbrouck (1995, 2002), Lehmann (2002), and related papers, which estimate the unobservable efficient price from the quotes by assuming it to be a co-integrated martingale, do not presume the efficient price innovation to be uncorrelated with the microstructural noise. Additionally, the recent literature on realized volatility (e.g., Bandi and Russell, 2005; Ait-Sahalia, Mykland and Zhang, 2006, and Barndorff-Nielsen, Hansen, Lunde and Shepard, 2006) also acknowledges the correlation between the transitory component and the innovations in the efficient price.

## 2. Data

Our database consists of 6 months, from July to December 2000, of high frequency data on a set of SSE-listed stocks.<sup>8</sup> All the stocks in the sample are negotiated in the electronic order-driven platform of the SSE, called SIBE. This electronic venue handles the trading activity of the most frequently traded and liquid SSE-listed stocks. Liquidity is provided by an open LOB (there are no market makers). Traders can observe the five best levels of the book, both at the offer and demand sides. The screens are updated in real time. Three basic types of orders are allowed: market, limit, and market-to-limit orders. Market orders walk up or down the book till they are fully executed. Market-to-limit orders are restricted to the best price on the opposite side of the market. Limit orders which are not executed instantaneously get stored on the LOB until they find counterparty, they are cancelled, or they expire (by default, at the end of the day). A strict price-time priority rule determines the order of execution and storage. Cancellations and modifications are allowed anytime. A trade occurs when an incoming order matches at least one order stored on the opposite side of the LOB. The trading session is continuous from 9:00 a.m. to 5:30 p.m. This period is preceded by a 30-minute opening call auction and followed by a 5-minute closing call auction.

The database includes book and transaction data. We have the five best ask and bid levels of the LOB updated each time the book changes, and time stamped to the nearest hundredth of a second. The book files include the displayed depth and the number of limit orders accumulated at each level.<sup>9</sup> Transaction files are updated each time the first level of the limit order book changes. They provide information about the accumulated traded volume (in shares) at each update. We apply an algorithm originally developed by Pardo and Pascual (2006) to differentiate between trades, limit order submissions, cancellations, modifications, etc. The algorithm is based on the matching of book and transaction files.

The official market index of the SSE is the IBEX-35, which includes the 35 most liquid and active stocks of the SIBE, weighted by market capitalization. Its composition is revised every semester. Our initial sample is formed by the 35 index constituents during the second semester of 2000. We discard two stocks because they experienced splits. Table I provides some daily descriptive statistics on the remaining 33 stocks. We provide cross-sectional statistics of liquidity and activity for the complete sample, but also separated statistics for the

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<sup>8</sup> The 2004 “Annual Report and Statistics” of the World Federation of Exchanges classifies the SSE as the 9<sup>th</sup> world largest stock exchange in terms of capitalization (the 4<sup>th</sup> among European markets), and the 7<sup>th</sup> in terms of total value of share trading (the 4<sup>th</sup> in Europe).

<sup>9</sup> The SIBE allows submitting partially hidden limit orders (see Pardo and Pascual, 2006).

5 largest and the 15 smallest stocks in terms of market capitalization (as measured by the index weight).

[Table I]

Table I shows that we have a quite heterogeneous sample. The 5 largest (15 smallest) stocks account for 70.76% (7.53%) of the market capitalization, 72.94% (8.9%) of the volume traded, 48.91% (18.02%) of the transactions, and 43.55% (21.48%) of the order flow (market, limit, market-to-limit, and cancellations), of the whole sample. Compared with the 15 smallest stocks, the median daily volume (in shares) for the 5 largest stocks is 35.7 times larger; the euro value of the book depth is 8 times larger; the relative spread is 3.45 times narrower, and they collect 6 times more orders (market, limit, market-to-limit, and cancellations).

We use the above mentioned book files to compute summary measures that characterize the state of the LOB at each point in time. In particular, in the following sections we consider the following variables:

- (a) The relative bid-ask spread ( $S_t$ ).
- (b) The displayed depth at the best ask ( $D_t^a$ ) and bid ( $D_t^b$ ) quotes.
- (c) The quoted depth beyond the best quotes, defined as the accumulated depth at up to  $k$  ticks from the quote midpoint. We distinguish between depth at the ask side ( $BD_t^a(k)$ ) and at the bid side ( $BD_t^b(k)$ ). This measure is the minimum volume needed to move the price by  $k$  ticks, a natural measure of liquidity.
- (d) Order imbalances in the limit order book are computed as  $AsD_t = |D_t^a - D_t^b|$  for the best quotes, and  $AsBD_t(k) = |BD_t^a(k) - BD_t^b(k)|$  for the book beyond the best quotes.
- (e) We follow Irvine *et al* (2000) in defining our bi-dimensional liquidity measure as,

$$BLM_t(s) = \frac{PI_t^a(s) - PI_t^b(s)}{Q_t}, \quad [1]$$

where  $PI_t^a(s)$  ( $PI_t^b(s)$ ) is the price impact of a fictitious buyer-initiated (seller-initiated) trade with size  $s$  times the normal market size (NMS). NMS is computed as the median trade size per stock and month. Finally,  $Q_t$  represents the quote midpoint. The measure in [1] could be understood as the immediacy costs of a round-trip for a medium-sized order.

### 3. The dynamic state-space model for ask and bid quotes

In this section, we introduce a microstructure structural model for the bid and ask quotes that features short run and long run volatility effects. The model shares some similarities with that proposed by Hasbrouck (1999), but there are remarkable disparities. Most notably, we do not explicitly model price discreteness, as Hasbrouck did, so as to preserve the linearity of the model.<sup>10</sup>

The model builds on the traditional microstructure price decomposition that splits the quoted prices into a “true” long run efficient price and a transitory non-informative component (e.g. Hasbrouck, 1996). In our particular case, the ask and bid quotes are given by

$$\begin{pmatrix} a_t \\ b_t \end{pmatrix} = \beta \begin{pmatrix} 1 \\ -1 \end{pmatrix} + \begin{pmatrix} 1 & 0 & 1 \\ 0 & 1 & 1 \end{pmatrix} \begin{pmatrix} S_{at} \\ S_{bt} \\ m_t \end{pmatrix}, \quad [2]$$

where  $a_t$  and  $b_t$  stand for the best ask and the best bid quotes, respectively. The observed quoted prices are a function of three unobservable factors,  $S_{at}$  and  $S_{bt}$ , which are the transitory components of ask and bid quotes that move the quoted prices away from the efficient price ( $m_t$ ). These transitory components are due to microstructure frictions, including the tick size. Quoted prices are co-integrated, with theoretical co-integration vector  $(1, -1)$  (e.g., Engle and Patton, 2004). The  $\beta$  coefficient captures the average distance between the two quoted prices, which must be always positive. Hence, we expect  $\beta$  to be positive and close to half the average bid-ask spread.

The dynamics of the unobservable components of ask and bid quotes and the efficient price are modeled as

$$\begin{pmatrix} S_{a,t} \\ S_{b,t} \\ m_t \end{pmatrix} = \begin{pmatrix} \phi_a & \phi_{ab} & 0 \\ \phi_{ba} & \phi_b & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} S_{a,t-1} \\ S_{b,t-1} \\ m_{t-1} \end{pmatrix} + \begin{pmatrix} g_t \\ -g_t \\ 0 \end{pmatrix} + \begin{pmatrix} \varepsilon_{a,t} \\ \varepsilon_{b,t} \\ \varepsilon_{m,t} \end{pmatrix}. \quad [3]$$

As it is usually assumed in microstructure structural models of price formation, the efficient price  $m_t$  follows a random walk process (e.g., Hasbrouck, 2002). In contrast, the transitory components are stationary, and follow a bi-variate first order autoregressive process. We

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<sup>10</sup> Hasbrouck (1999) models discreteness using an asymmetric rounding of ask and bid quotes around the efficient price. Although quotes are discrete in nature, we believe that the progressive conversion into decimals in markets around the world has significantly reduced the importance of the practical implications of ignoring discreteness. In the SSE, the minimum tick is 0.01€ for stocks with prices below 50€, which is the case of all the stocks in our sample.



allow for lagged causality between the transitory components. Thus, a shock in  $S_{b,t}$  ( $S_{a,t}$ ) may affect  $S_{a,t}$  ( $S_{b,t}$ ) the next period if  $\phi_{ab}$  ( $\phi_{ba}$ ) is different from zero. The function  $g_t$  is linear in a set of  $J$  dummy variables  $D_{t,j}$  for the time intervals,<sup>11</sup> which take value 1 if  $t$  falls in interval  $j$  and 0 otherwise. They are meant to capture the deterministic intraday pattern in the bid-ask spread

$$g_t = \sum_{j=1}^J \varphi_j D_{t,j}. \quad [4]$$

The vector of innovations in [3] is assumed to be jointly normally distributed,

$$\begin{pmatrix} \varepsilon_{a,t} \\ \varepsilon_{b,t} \\ \varepsilon_{m,t} \end{pmatrix} \sim \mathcal{N} \left( \begin{pmatrix} 0 \\ 0 \\ 0 \end{pmatrix}, \Sigma_t \right). \quad [5]$$

Admittedly, normality is a less than ideal assumption. In our setting, however, normality allows us to estimate the factors ( $m_t$ ,  $S_{a,t}$ , and  $S_{b,t}$ ) using the Kalman filter, and the parameters using the error prediction decomposition of the Kalman filter (see Harvey, 1992). Moreover, using Pseudo-Maximum Likelihood (PML) arguments in a Quadratic Exponential Family setting (the Gaussian distribution belongs to this family), the estimates are consistent, albeit not efficient, under distributional misspecification as far as the conditional means and variances are correctly specified. More specifically, if the parameters of interest are in the conditional mean and the conditional variance, consistency is guaranteed as far as the assumed density belongs to the Quadratic Exponential Family, as it is in our case (see Gouriéroux, Monfort, and Trognon, 1984).

Microstructure theory has shown that the size of the bid-ask spread is partially determined by the risk of information asymmetries. Copeland and Galai (1983), Glosten and Milgrom (1985), and Easley and O'Hara (1987) for price-driven markets, and more recently Glosten (1994), Foucault (1999), and Handa et al. (2003) for order-driven markets, emphasize the role of adverse selection in price discovery. Glosten and Harris (1988), Stoll (1989), George, Kaul, and Nimalendran (1991), Easley, Kiefer, and O'Hara (1997), and Madhavan, Richardson, and

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<sup>11</sup> In particular, we split the SSE trading session into 9 ( $=J+1$ ) time intervals: [9:00am, 9:30am), [9:30am, 10:00am), [10:00, 1:00pm), [1:00pm, 3:00pm), [3:00pm, 3:30pm), [3:30pm, 4:00pm), [4:00pm, 4:30pm), [4:30pm, 5:00pm), [5:00pm, 5:30pm]. The control interval is [10:00, 1:00pm). With this particular splitting, we attempt to capture the widely evidenced particularities of the initial and final intervals of the trading session in financial markets, but also the effects associated with the opening of the US markets at 3:30pm (Spanish time). So as to get a more parsimonious model, we impose the same intraday deterministic pattern for the transitory components of ask and bid quotes. Preliminary estimations using a more parameterized model suggest this restriction is a weak one.

Roomans (1997), among others, propose models for decomposing the bid-ask spread into its theoretical components, including the one due to adverse selection. This literature therefore suggests that the transitory components of ask and bid quotes may be correlated with the efficient price innovations in the presence of adverse selection. Common factor models of price discovery (see Hasbrouck, 1995, 2002, and Lehmann, 2002), and the literature on realized volatility (e.g., Bandi and Russell, 2005, and Barndorff-Nielsen et al. 2006), also admit this correlation. Accordingly, we do not restrict the correlation between the innovations to the transitory components  $(\varepsilon_{a,t}, \varepsilon_{b,t})$  and the innovations to the efficient price  $(\varepsilon_{m,t})$ . However, we do restrict the contemporaneous correlation between the transitory components. Assuming that shocks are either buyer initiated or seller initiated, a non-informational shock in one side of the market is expected to cause a lagged, rather than a contemporaneous, effect on the other side of the market, as captured by the autoregressive structure in [3].

Therefore, the variance-covariance matrix  $\Sigma_t$  in [5] becomes,

$$\Sigma_t = \begin{pmatrix} \sigma_{a,t}^2 & 0 & \sigma_{am,t} \\ 0 & \sigma_{b,t}^2 & \sigma_{bm,t} \\ \sigma_{am,t} & \sigma_{bm,t} & \sigma_{m,t}^2 \end{pmatrix}. \quad [6]$$

With matrix [6], our specification becomes a tri-variate volatility model. We adopt the Bollerslev's (1990) approach of modeling the covariance terms in [6] using a Constant Conditional Correlation (CCC) model,

$$\Sigma_t = \begin{pmatrix} \sigma_{a,t}^2 & 0 & \rho_{am} \sigma_{a,t} \sigma_{m,t} \\ 0 & \sigma_{b,t}^2 & \rho_{bm} \sigma_{b,t} \sigma_{m,t} \\ \rho_{am} \sigma_{a,t} \sigma_{m,t} & \rho_{bm} \sigma_{b,t} \sigma_{m,t} & \sigma_{m,t}^2 \end{pmatrix}. \quad [7]$$

This model permits a time-varying covariance with only two extra parameters to be estimated: the constant correlations.

Rather than imposing homoskedasticity, as Hasbrouck (1999) does, we assume that the variances of the short run components,  $\sigma_{a,t}^2$  and  $\sigma_{b,t}^2$ , are time-varying according to deterministic intraday regular patterns,

$$\sigma_{i,t}^2 = \exp\left(\sigma_i^2 + \sum_{j=1}^J \phi_j D_{t,j}\right), \quad i = \{a, b\}. \quad [8]$$

The exponential form in [8] is used for convenience, so as to guarantee the non-negativity of the conditional variance (since some  $\phi_j$  could be negative).<sup>12</sup>

In contrast, long run volatility ( $\sigma_{m,t}^2$ ) is allowed to have deterministic and dynamic components, which are captured, following Hasbrouck (1999), by an EGARCH model,

$$\sigma_{m,t}^2 = \exp \left( \alpha_0 + \alpha_1 \ln(\sigma_{m,t-1}^2) + \alpha_2 \xi_{m,t-1} + \alpha_3 \left[ |\xi_{m,t-1}| - \sqrt{2/\pi} \right] + \sum_{j=1}^J \phi_j^m D_{t,j} \right), \quad [9]$$

where  $\xi_{m,t} = \varepsilon_{m,t} / \sigma_{m,t}$  is the standardized shock. Model [9] includes an intercept ( $\alpha_0$ ), a persistence parameter ( $\alpha_1$ ), a sign or leverage parameter ( $\alpha_2$ ), which captures the asymmetric effects of good and bad news of prior shocks, and a magnitude parameter ( $\alpha_3$ ), which measures the effect of the size of these same shocks. Finally, we account for the deterministic intraday patterns in long run using the set of dummy variables previously defined.<sup>13</sup> The exponential form in [9] guarantees the non-negativity of the conditional variance, as some of the  $\phi_j^m$  may take negative values.

The properties of our model are consistent with the evidence in the realized variance literature. Hansen and Lunde (2006) describe some empirical facts about the transitory component in quotes, which in this literature is called noise. First, the transitory component is time dependent, as in equation [3]. Second, the transitory components are quite small, a fact that we will corroborate with our data. Third, the properties of the transitory component change over time. Our model permits conditional changes in the transitory component both at the mean and at the variance level. Finally, the transitory component is correlated with the efficient price, and the covariance between the efficient return and the transitory component is time varying, as in equations [6] and [7].

Equations [2] to [9] form a linear state space model. The standard Kalman filter, however, cannot be applied to estimate the model's factors and parameters because of the EGARCH assumption in [9]. Since the efficient price is unobserved, the volatility model in [9] is a function of the squares of past unobserved shocks, and the standard Kalman filter is

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<sup>12</sup> Note that the seasonal coefficients are the same for  $\sigma_{a,t}^2$  and  $\sigma_{b,t}^2$ . Alternative model specifications that allow for different seasonal coefficients for ask and bid quotes show no remarkable improvements. Results are available under request.

<sup>13</sup> We allow both transitory and informational volatility to show intraday regular patterns. While deterministic components in long run volatility would reveal concentration in information revelation at particular intervals of the trading session, regular patterns in short run volatility are not information-driven.

unfeasible. To circumvent this problem, we rely on Harvey, Ruiz, and Sentana (1992), who propose to augment the state space and treat the error term of the efficient price as another state variable to be estimated jointly with  $S_{a,t}$ ,  $S_{b,t}$  and  $m_t$ . Once the state space vector has been augmented, the estimation of the factors with the Kalman filter, and of the parameters with the error prediction decomposition, is attainable. We refer to the Appendix for a brief explanation of the augmented state space model.

#### 4. Estimation of the state-space model

We proceed next to summarize the estimation results of the state space model in [2]-[9] for each of the 33 Spanish stocks in our sample. The time series of ask and bid quotes are computed in 5-minute intervals using the last best quotes in each interval. Table II provides cross-sectional statistics on the estimated parameters in equations [2]-[3] and [7]-[9]. Panel A in Table II provides average statistics for the whole sample, as well as for the 5 largest and 15 smallest stocks by market capitalization.<sup>14</sup> Panel B provides correlations between the estimated parameters and some daily statistics about liquidity and trading activity (previously defined in Table I).

[Table II]

Panel A in Table II shows that the median estimated spread ( $2\beta$  in [2]) is around 4 ticks (0.0412€), and it is 3 times narrower for the 5 largest stocks (1.6 ticks) than for the 15 smallest stocks (4.6 ticks). Panel B in Table II also evidences that  $2\hat{\beta}$  decreases with the average liquidity of the stock, as measured by the relative bid-ask spread and the book depth.<sup>15</sup> Moreover,  $\hat{\beta}$  is smaller among frequently traded stocks, with an intense order flow. The cross-sectional correlation between  $2\hat{\beta}$  and the true median bid-ask spread is 0.99.

We also report a high degree of persistence in the short-term components of prices. The cross-sectional median  $\hat{\phi}_a$  ( $\hat{\phi}_b$ ) in [3] is 0.763 (0.612). Persistency decreases with market capitalization, with a median  $\hat{\phi}_a$  ( $\hat{\phi}_b$ ) of 0.607 (0.475) for the large-caps and 0.817 (0.677) for small-caps. Panel B in Table II shows persistency is also strongly negatively correlated with liquidity and trading activity. This implies that the largest, most liquid and active stocks, also

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<sup>14</sup> In general, the individual-security estimated coefficients of the state-space model are statistically significant at the 1% level. Exceptionally, for some stocks we obtain non-significant coefficients for the seasonal intraday dummies in equations [4], [8], and [9], implying that these periods do not differ from the benchmark time [13:00 to 15:00).

<sup>15</sup> This is consistent with the negative correlation between both dimensions of liquidity, immediacy costs and depth, analyzed by Lee, Mucklow, and Ready (1993), and Pascual, Escribano, and Tapia (2004), among others.

exhibit the desirable property of being the most resilient.<sup>16</sup> Since the costs of submitting limit orders increase with the expected time to execution (see Lo, MacKinlay, and Zhang, 2002), uninformative shocks should be reversed earlier when the stock is highly active and, therefore, the average time to execution is shorter. We also find  $S_{a,t}$  and  $S_{b,t}$  to cause each other in the short run, with  $\hat{\phi}_{ab}$  ( $\hat{\phi}_{ba}$ ) in [3] being positive. Hence, transitory components of ask and bid quotes move together, though not necessarily in a symmetric manner.

Figure 1 represents the estimated intraday regular patterns in the transitory components of ask and bid quotes. We report the cross-sectional median of  $2\hat{\phi}_j$  in [4] and the realized cross-sectional median level of the bid-ask spread for each time interval. The estimated pattern fits reasonably well the observed bid-ask spread regularities. The spread achieves its maximum level at the beginning of the session and sharply decays in one and a half hours. Minimum levels of the spread are observed toward the end of the day, with a slight increase right after the opening of the US markets (15:30 Spanish time).

[Figure 1]

Panel A in Table II provides the cross-sectional median level of transitory volatility ( $\sigma_a^2$  and  $\sigma_b^2$  in [7]) during the control interval (1:00pm to 3:00pm). Results are similar for ask and bid quotes: transitory volatility decreases with market capitalization. This finding should not be surprising since transitory volatility is associated with illiquidity shocks. Indeed, Panel B in Table II shows that both  $\sigma_a^2$  and  $\sigma_b^2$  decrease with the average liquidity and trading activity of the stock.

As for the long run volatility in [9], the persistence parameter ( $\alpha_l$ ) is larger among the 5 largest ( $\alpha_l = 0.9759$ ) than among the 15 smallest ( $\alpha_l = 0.8972$ ) stocks. Panel B in Table II reinforces this finding. Since information comes in clusters, informational volatility also progresses in clusters of high and low levels. Our findings point toward information flow intensity being more stable among the largest stocks in the sample, since volatility clusters last longer for these stocks. We also obtain that the estimated magnitude parameter ( $\alpha_3$ ) is lesser among the large caps ( $\alpha_3 = 0.1578$ ) than among the small caps ( $\alpha_3 = 0.3625$ ), meaning that the formers tend to be less responsive to an informative shock of any given size. Consistent findings are reported in Panel B of Table II. These findings are in line with the very well known fact that smaller, less liquid, and less active stocks suffer from higher

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<sup>16</sup> Resiliency refers to the speed with which prices recover from a random, uninformative shock. Kyle (1985) considers resiliency as a dimension of liquidity, together with immediacy costs and depth.

information asymmetry risk (e.g., Stoll, 2000). Finally, the leverage parameter in [9] ( $\alpha_2$ ) is smaller in magnitude than the other parameters in the EGARCH model, but still statistically significant. Table II shows that  $\alpha_2$  tends to be negative for large, active, and liquid stocks. As usually documented, negative shocks cause larger fluctuations in the variance than positive shocks. For the smaller, less liquid and less active stocks, however,  $\alpha_2$  tends to be positive, implying that, unexpectedly, good news induce a larger variance than bad news.

Figure 2 represents the cross-sectional median of the intraday regular patterns in transitory and informational volatility, as given by the estimated  $\phi_j$  parameters in [8] and the  $\phi_j^m$  parameters in [9], respectively. We report the deviation of the estimated parameters with respect to the control interval (1:00pm to 3:00pm). Transitory volatility regularly reaches its maximum level at the initial intervals of the session. This initial peak in short run volatility coincides with the least liquid trading period. Both volatility components increase towards the end of the day, right before the opening of the US markets. Indeed, informational volatility achieves its regular maximum in the last half-hour of the trading session.<sup>17</sup> This highly active two-hour closing period therefore appears as the most contributive to price discovery.

[Figure 2]

Table II shows that the estimated average correlation between the long-run innovations and the short-run innovations to ask (bid) quotes is -0.277 (-0.259), with this correlation decreasing in absolute terms with market capitalization, trading activity, and liquidity. These negative correlations suggest lagged and asymmetric adjustments of ask and bid quotes to new information.<sup>18</sup> In periods of positive (negative) innovations to the efficient price, the transitory component of ask quotes decreases (increases) whereas the transitory component of bid quotes increases (decreases), which is symptomatic of both quotes adjusting to a slower pace than the efficient price. Gradual adjustments in ask quotes may be explained by limit order traders that do not continuously monitor the market. Gradual adjustments in bid quotes may reflect that, as they become more aggressive, buyers cancel limit orders and/or choose to submit market orders (e.g., Rinaldo, 2004). The fact that correlations are minor among large-caps indicates that quotes respond faster (i.e., symmetries are less prominent) among frequently traded and liquid stocks.

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<sup>17</sup> Recently, Pascual, Pascual-Fuster, and Climent (2006) have shown that the NYSE contribution to the price discovery process of the Spanish cross-listed stocks during the two-hour overlapping interval is negligible. Nonetheless, the opening of the US market is regularly followed by a sharp increase in the SSE trading activity and order flow (see Pardo and Pascual, 2006).

<sup>18</sup> Jang and Venkatesh (1991), Engle and Patton (2004), and Escribano and Pascual (2006) provide evidence of asymmetric dynamics in ask and bid quotes for NYSE-listed and SSE-listed stocks.

Finally, Panel C in Table II provides cross-sectional correlations between liquidity and activity measures and the average estimated  $S_{a,t}$  and  $S_{b,t}$  in [2],  $\sigma_{a,t}^2$  and  $\sigma_{b,t}^2$  in [8], and  $\sigma_{m,t}^2$  in [9]. Panel C reinforces the results in previous findings. Short run components of ask and bid quotes are larger and more volatile among the smallest, less liquid, and less active stocks in our sample. That market frictions are negatively related to measures of trading activity, such as volume or number of trades, are empirical regularities (e.g., Stoll, 2000). More interesting is the finding that  $\sigma_{m,t}^2$  is positively related with trading activity, as measured by the number of trades and the intensity of the order flow. A fundamental notion in market microstructure research is that trades convey new information about the long run value of the stock.<sup>19</sup> Therefore, trades move prices and cause long run variance. For the 5 most frequently traded stocks, in terms of number of trades, the median  $1000\sigma_{m,t}^2$  is 0.75, while it is 0.33 for the 15 less frequently traded stocks.

## 5. The informativeness of the limit order book

In this section, we use the time series of the informational volatility estimated through the state space model described in previous sections to evaluate the informational content of the LOB.<sup>20</sup> Namely, we use multivariate time series models to check whether different pieces of LOB information explain posterior variations in informational volatility. Admittedly, it could be argued that the LOB should have been introduced in equation [8] as part of the EGARCH specification. However, doing so raises several problems. The first one, rather conceptual, is that volatilities are never observed and hence they have to be estimated based on some relevant information set. In particular, long-run volatility should be estimated conditional on that information that causes permanent changes in prices. Since variations in the LOB might induce both permanent and transitory price impacts, by adding the LOB directly in the EGARCH specification we would introduce microstructure noise in the estimated long-run variance. Second, in this paper we are not interested in how the LOB information influences the estimation of the informational variance, but in how the LOB affects the unobserved informational variance. Therefore, even if we could isolate the non-informative component from the informative component of the LOB, a one-step estimation procedure would impair our empirical analysis. Finally, we could be facing endogeneity problems. Instead, we use

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<sup>19</sup> Models for the estimation of adverse selection costs using structural models of price formation are based on this basic principle (e.g., Huang and Stoll, 1997).

<sup>20</sup> The fitting of the state space model is generally worse for the first observations in the time series due to the initialization of the filter. We therefore discard the first 15 days in our sample period.

structural vector autoregressive models (SVAR hereafter) to study the dynamics between the book and the informational volatility.

So as to describe the state of the LOB, we use the variables defined in section 2: the relative bid-ask spread ( $S_t$ ); the displayed depth in euros at the best ask ( $D_t^a$ ) and bid ( $D_t^b$ ) quotes; the accumulated depth in euros at up to four ticks from the quote midpoint ( $BD_t^a(4)$ ,  $BD_t^b(4)$ ); the order imbalance on the first level of the LOB ( $AsD_t$ ); the order imbalance beyond the best quotes ( $AsBD_t(4)$ ), and the bi-dimensional liquidity measure in [1] for a trade of size equal to 2 times the NMS ( $BLM_t(2)$ ).<sup>21</sup> We are only interested in the informative component of these variables. Therefore, we remove their deterministic, and therefore predictable, component by regressing them against the set of dummy variables in equation [4].<sup>22</sup> Moreover, we intend each of these pieces of LOB information to be additive, in the sense of not providing redundant information. We identify the dynamics of each variable not responding to other LOB variables by estimating following VAR model,<sup>23</sup>

$$y_t = \gamma_0 + \sum_{j=1}^3 \gamma_j' y_{t-j} + w_t, \quad [10]$$

where  $y_t$  is the vector of non-deterministic components of the LOB variables. In [10], we stack together the time series of the 33 stocks in the sample. We do not allow any lag to reach back to the previous day, implying that we drop the first three observations of each day. Table III summarizes the estimation of model [10] by least squares for time series in a 5-minute periodicity. Panel A provides the estimated coefficients. For each equation and variable, we sum the coefficients at all lags whenever they are statistically significant (at least) at the 5% level. Panel B reports the residual correlation matrix.

[Table III]

We find a negative relationship between immediacy cost and quoted depth. An increase in either  $D_t^i$  or  $BD_t^i(4)$  causes posterior decreases in  $S_t$  and  $BLM_t(2)$ , and vice versa. The negative relationship between both liquidity dimensions was originally reported by Lee, Mucklow, and Ready (1993). Moreover, imbalances between bid and offer depth cause posterior increases in immediacy costs. This finding is at odds with Handa, Schwartz, and

<sup>21</sup> Our main conclusions do not vary if we consider larger values for  $k$  and  $s$  to compute  $BD_t^i(k)$  and  $BLM_t(s)$ .

<sup>22</sup> Results are not reported because of space limitations, but they are available upon request from the authors.

<sup>23</sup> We truncate the VAR model at lag 3. Additional lags are not statistically significant for almost all the dependent variables.



Tiwari (2004), who predict the bid-ask spread in order-driven markets to achieve its maximum when the imbalance between buyers and sellers is zero. Panel B in Table III shows that some of the  $w_t$  residuals are strongly contemporaneously correlated, most notably  $BLM_t(2)$  and  $S_t$ .

From now on, we consider the residuals  $w_t$  in [10] as the LOB variables. Since they have been filtered by deterministic intraday components and expected components given the past values of the LOB, these residuals can be interpreted as the unpredictable component of the LOB. In a similar way as structural models of price formation with asymmetric information assume that trade-related information exists in the unexpected component of trades (e.g., Hasbrouck, 1991a, and Huang and Stoll, 1997), we presume that any relevant LOB-related information should reside in  $w_t$ . The dynamic response of the information-driven volatility to an innovation in the LOB is measured by the coefficients of the following VAR model,

$$z_t = \begin{pmatrix} \tilde{\sigma}_{m,t} \\ w_t \end{pmatrix} = B_0 + \sum_{j=1}^p B_j' z_{t-j} + C' x_t + \varepsilon_t, \quad [11]$$

with  $E(\varepsilon_t) = 0$ ,  $E(\varepsilon_t \varepsilon_t') = \Sigma$ ,  $E(\varepsilon_t \varepsilon_s') = 0 \forall s \neq t$ , and  $x_t$  being a vector of exogenous variables we will make explicit latter. The first component of  $z_t$ ,  $\tilde{\sigma}_{m,t}$ , is the non-deterministic component of the estimated long run standard deviation. From [9],

$$\tilde{\sigma}_{m,t} = \sqrt{\frac{\hat{\sigma}_{m,t}^2}{\exp\left(\sum_{j=1}^J \hat{\phi}_j^m D_{t,j}\right)}}. \quad [12]$$

A problem with VAR analysis is that the variance-covariance matrix of the innovations ( $\Sigma$ ) is not restricted to be a diagonal matrix. Therefore, a shock to one variable provides information about the innovations to other variables. This implies that causal interpretations of, for example, simple impulse response functions are not possible. Nonetheless, the VAR in [11] could be considered as the reduced form of a more general structural VAR (SVAR). Let  $P$  be a matrix such that  $\Omega = PP'$ . Then,  $e_t = P^{-1}\varepsilon_t$  are orthogonal unit-variance disturbances ( $E(e_t e_t') = I_k$ ). Pre-multiplying both sides of the VAR model [11] by a square matrix  $A$ , with  $AP = V$ , we can represent the VAR model in [10] as,

$$Az_t = A_0 + \sum_{j=1}^p A_j z_{t-j} + F' x_t + v_t, \quad [13]$$

where  $A_j = AB_j$ ,  $F = AC'$ , and  $v_t = Ve_t = A\varepsilon_t$ , with  $E(v_t v_t') = VV'$ .

By imposing the convenient restrictions in matrix  $A$  and  $V$ , we can isolate the shocks to the LOB from the shocks to the long run volatility. In our particular application, we follow Coppejans, Domowitz, and Madhavan (2004) in setting the identification restrictions. These authors do not allow liquidity to contemporaneously affect returns. They argue that liquidity is a function of bid and offers, which naturally precede transactions, and therefore returns. Ranaldo (2004) evidenced that the state of the LOB determines posterior order flow composition, that is, the state of the LOB naturally precedes cancellations, and market and limit order submissions. Since the market infers about the true value of the stock from the order flow composition, the LOB should affect long run volatility in the next period. In contrast, our specification permits long run volatility to contemporaneously cause the LOB, since long run volatility is associated with the arrival of new information, and liquidity is inversely related to adverse selection costs (e.g., Lee et al., 1993). Moreover, informational volatility influences the choice between market and limit orders (Foucault, 1999), and therefore the shape of the LOB. According to these arguments, the matrix  $A$  for an hypothetical model with 4 variables,  $\tilde{\sigma}_{m,t}$  and three LOB measures, would be of the form,

$$A = \begin{bmatrix} 1 & 0 & 0 & 0 \\ a_{21} & 1 & 0 & 0 \\ a_{31} & 0 & 1 & 0 \\ a_{41} & 0 & 0 & 1 \end{bmatrix}, \quad [14]$$

with  $a_{ij}$  being unrestricted parameters.

Additionally, a shock to either LOB variable is likely derived from the same source of information than contemporaneous shocks to other LOB variables. Therefore, our identification restrictions allow the shocks in different LOB variables to be contemporaneously correlated. Thus the matrix  $V$  for the hypothetical 4-variable model would be of the form,

$$V = \begin{bmatrix} v_{11} & 0 & 0 & 0 \\ 0 & v_{22} & 0 & 0 \\ 0 & v_{32} & v_{33} & 0 \\ 0 & v_{42} & v_{43} & v_{44} \end{bmatrix}, \quad [15]$$

with  $v_{ij}$  being unrestricted parameters.

The reduced (VAR) form [10] is a seemingly unrelated regression model. Since the model has the same explanatory variables in each equation, estimating the coefficients equation by equation by least squares generates the maximum likelihood estimates (e.g., Greene, 2003). The residuals of the VAR model [11] can then be used to estimate the variance-covariance matrix of  $\varepsilon_t$  ( $\Omega$ ). With the restrictions [14]-[15], model [13] is exactly identified. Therefore, the coefficients of the structural model [13] can be recovered from the coefficients of the reduced form [11].

As previously discussed, the LOB influences the incoming order flow composition, and the market could learn from the particular mix between market orders and limit orders. However, this would not necessarily mean that the book is informative, since the market would be learning from the order flow, but not from the LOB. To account for the order flow between  $t-1$  and  $t$ , the vector  $x_t$  of control variables in [11] and [13] includes the number of trades completed ( $T_t$ ) and the total number of orders submitted ( $O_t$ ) in each time interval. The second variable includes limit orders, market orders, market-to-limit orders, and cancellations. We exclude order modifications. By including these control variables, we intend to evaluate whether the LOB is informative per se. As with the LOB variables, we remove the deterministic components of  $T_t$  and  $O_t$  using the intraday dummy variables in [4].

In the next subsections, we report our main findings under alternative model specifications. First, we summarize the estimation of models [11] and [13] with time series aggregated in 5-minute intervals. Then we check the robustness of our findings to time aggregation and market capitalization.

### *5.1. SVAR estimates with five-minute time series*

Table IV summarizes the estimation of the SVAR model [13] with a 5-minute periodicity. The time series of all the stocks are pooled together into a single estimation. To scale the series, we divide each time series by its average value per stock. Then, we stack together the time series of the 33 stocks in the sample. In this manner, we can evaluate the informativeness of the LOB by directly checking the significance of the pooled regression coefficients. We consider three alternative definitions of the vector  $z_t$  of dependent variables. The “best quotes” model includes liquidity measures based on the best ask and bid quotes, that is,

$z'_t = (\tilde{\sigma}_{m,t}, S_t, D_t^a, D_t^b, AsD_t)$ .<sup>24</sup> The “book” model considers liquidity measures based on the five best book levels of ask and bid quotes,  $z'_t = (\tilde{\sigma}_{m,t}, BLM_t(2), BD_t^a(4), BD_t^b(4), AsBD(2))$ . Finally, the “best + book” model includes all the LOB variables in the former models. All models are truncated at lag one.<sup>25</sup>

[Table IV]

Panel A in Table IV reports the estimated coefficients of the matrix of contemporaneous relationships  $A$  in [13] for each of the three models considered. We find that an increase in long run volatility causes a contemporaneous decrease in the liquidity supply by the LOB. A positive shock to long run volatility increases immediacy costs ( $S_t$  and  $BLM_t$ ), and decreases the accumulated book depth ( $BD_t^a$  and  $BD_t^b$ ). We also find that increases in informational volatility contemporaneously enhance the imbalance between the ask side and the bid side of the book. These findings are in harmony with the adverse selection costs models, such as Handa, Schwartz, and Tiwari (2003), and the empirical evidence in Lee *et al* (1993), among others. In periods of intense information flow, liquidity providers manage the increased risk of information asymmetries by both demanding greater compensations for immediacy (wider spreads) and reducing their exposure risk (lower depth).

Panel B in Table IV reports the estimated coefficients in the  $\tilde{\sigma}_{m,t}$  equation of the reduced form model [11].<sup>26</sup> We also provide the Granger causality test for each piece of LOB information and for the whole LOB. The best quotes model shows that wider bid-ask spreads tend to head periods of greater informational volatility. More remarkable, the information content of the bid-ask spread persists even when we control for the incoming order flow, implying that investors grasp additional information from the state of the LOB. Changes in quoted depth at the best ask and bid quotes, however, are not found to signal changes in the intensity of information arrival. Indeed, the Granger causality tests for this model clearly indicate that only the quoted bid-ask spread has some explanatory power on posterior long run volatility. The book-based model points to similar conclusions than the best-quotes model. The bi-dimensional liquidity measure in [1] is highly statistically significant, positively

<sup>24</sup> Here, we purposely abuse of the notation since the LOB variables in  $z_t$  are the residuals  $w_t$  in [10], not the book variables themselves. For the ease of exposition, however, we keep using the LOB notation.

<sup>25</sup> Formal lag-selection criteria are not very conclusive regarding the optimal lag length. We have considered specifications up to three lags and our main conclusions are the same. Therefore, we opt for the most parsimonious specification.

<sup>26</sup> Results from the other equations of each model are omitted because of the limited space, but they are available upon request from the authors.

causing the intensity of information arrival. Although in this model depth measures are found to be statistically significant ( $BD_t^a, BD_t^b$ ), causality tests indicate that their contribution in explaining posterior informational volatility is negligible.

Finally, the estimates of the best-plus-book model, in the last column in Panel B, suggest that the market gleans additional information from the secondary steps of the book. In all models, causality tests reject the null that the LOB variables do not cause informational volatility, but this rejection is stronger for models that include book-based proxies of liquidity. Our findings are in line with Cao *et al*'s (2003) findings, who report the book beyond the best quotes to account for a remarkable part of the information share of the complete LOB. Consistently, among all the liquidity measures considered,  $BLM_t$  happens to be the most important in explaining long run volatility. Regarding the sign of the relationship between the LOB and the long run volatility, our findings are not conclusive. While the book-based measures indicate that larger immediacy costs, lower depth, and higher imbalances on the book anticipate periods of more intense information arrival, the coefficients of the best-quotes-based variables suggest just the opposite. Nonetheless, as previously remarked, book-based liquidity measures dominate. It should be also noted that results for the best-plus-book model could be distorted by the high correlation between the spread and BLM formerly reported in Table III.

The LOB is updated constantly due to the permanent flow of orders. Consequently, its shape at a particular point in time could be informative only about the very short run. If this were the case, time aggregation could bias our analysis towards the conclusion that the book is less informative than it really is. This line of argument could be particularly appropriate for the case of the largest stocks, which usually are the most frequently traded too. As a matter of robustness, in the next sections we repeat our former study, first, for the 5-largest and 15 smallest stocks in our sample, and, then, with time series computed over 1-minute intervals.

## 5.2. SVAR estimates conditional on market capitalization

Table V summarizes the estimation of the SVAR model [13] for the 5 largest stocks and the 15 smallest stocks in the sample with a 5-minute resolution. As in Table IV, we provide the estimated free parameters of the matrix of contemporaneous relationships in Panel A, and the estimated coefficients of the reduced form [11] for three different model specifications in Panel B.

[Table V]

Table V reinforces the findings reported in Table IV for the complete sample. Panel A shows greater long run volatility contemporaneously causing increases in illiquidity, both among the largest and among the smallest stocks, and most notably when the book-based liquidity measures are considered. In addition, Panel B in Table V shows that the lagged causality running from liquidity to informational volatility is robust across subsamples. For both the small-caps and the large-caps, an increase in  $BLM_t(2)$  precede an increase in the intensity of information arrival. Causality tests in Table V strengthen the idea that  $BLM_t(s)$  could be a good summary measure of the informational content of the LOB, especially among the smallest stocks. The incidence of depth-based measures is again imprecise, since the level of significance and the direction of the relationship vary with the model specification.

Granger causality tests reject, for all model specifications and for the two subsamples, the null that the shape of the book does not provide relevant information about posterior informational volatility, but with more strength for the least frequently traded stocks. Franke and Hess (2000) conclude the book is informative only during periods of low information intensity. Likewise, our findings in Table V suggest that, once we control for the incoming order flow, the LOB is more informative among the least frequently traded stocks, probably because the book is steadier.

### 5.3. SVAR estimates with one-minute time series

Table VI reports the results of estimating the SVAR model [13] with a 1-minute resolution. As in previous tables, we provide the pooled contemporaneous coefficients of the SVAR model in Panel A, and the pooled regression coefficients of the reduced form [11] in Panel B.

[Table VI]

Regarding the contemporaneous coefficients of the SVAR model in [13], Panel A reports similar findings to those shown in former model specifications. Higher informational volatility contemporaneously causes liquidity by increasing immediacy costs and, to a lesser degree, by decreasing quoted depth. Moreover, Panel B in Table VI reports significant lagged causality running from the LOB variables to the long run volatility. In the “best quotes” model and the “book” model specifications, increases in immediacy costs precede periods of higher information volatility, consistently with the theoretical predictions in Foucault et al. (2006). Granger causality test reject the null that the LOB information does not contain volatility information, particularly for “book” model, suggesting there is some additional information contained in the secondary levels of the LOB. Finally, the “best + book” model

shows that the piece of LOB information with higher explanatory power is the bi-dimensional measure in equation [1].

Table VI confirms our findings are robust to time aggregation. Indeed, the rejection of the null of no causality is more dramatic in Table VI than in Table IV, which suggests the dynamics between the LOB and the long run volatility being better captured with shorter time resolutions. We have also estimated model [13] with a 1-minute resolution for the 5 largest and 15 smallest stocks separately. Our findings do not remarkably differ from those reported in Tables V and VI.<sup>27</sup> Knowing the state of the LOB at a given point in time is more informative about the intensity of information arrival for the least frequently traded stocks.

## 6. Conclusions

In this paper, we use data on a set of 33 Spanish stocks to evaluate whether open limit order books (LOBs) contain relevant information for price discovery. In particular, we examine the dynamic relationship between the state of the LOB and the long run (informational) volatility of the stock, that is, the volatility of the efficient price.

We estimate informational volatility using a dynamic co-integration state-space model for ask and bid quotes. In this model, ask and bid quotes are decomposed into three unobservable factors: the efficient price, and the transitory component of each quote. The short run components are modeled as a stationary bivariate first order autoregressive process. The efficient price is modeled as a heteroskedastic random walk process, common to both ask and bid quotes. The variance of the innovations in the efficient price is stochastic, and follows an Exponential GARCH (EGARCH) model. We estimate the unobserved components of ask and bid quotes by the Kalman filter, and the model parameters by Pseudo Maximum Likelihood. Finally, we use multivariate time series models to study the dynamic relationship between different pieces of LOB information and the estimated long run volatility.

Our main conclusion is that the state of the LOB explains posterior fluctuations in the intensity of the information flow, as recently suggested in a theoretical paper by Foucault et al. (2006). We find that immediacy costs measures computed for imaginary trades of different sizes are positively related with higher levels of informational volatility in the very short run. The shape of the LOB is informative even when the incoming order flow and trading activity are taken into account. Although our conclusions are robust to time aggregation, a comparison between models with 1-minute and 5-minute resolution suggests that the dynamics between

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<sup>27</sup> We do not provide these findings because of space limitations, but they are available upon request from the authors.

liquidity and long run volatility are better captured at very short time frequencies. We also show the LOB is informative for both the most frequently traded and the least frequently traded stocks in our sample, even though causality is accepted with more strength for the latter. This finding is consistent with more unsteady LOB books being less informative. Finally, book-based liquidity measures have higher explanatory power than best-quotes-based liquidity measures in explaining informational volatility. This finding is in line with Cao et al's (2003) conclusions: the information derived from the secondary steps of the book adds explanatory power to the information contained in the best quotes.

This paper complements previous empirical studies addressing the issue of whether the LOB is informative (e.g., Rinaldo, 2004; Harris and Panchapagesan, 2005, and Cao et al., 2003). This is, however, the first empirical paper that focuses on the relationship between the long run component of volatility and the shape of the LOB. Moreover, our findings are in harmony with recent empirical studies (see Bloomfield et al, 2005, and Anand et al, 2005) showing that limit order traders may be information-motivated. In particular, as theoretically suggested by Foucault et al. (2006), limit order traders may possess volatility information, that is, they may have advanced information about the occurrence of future informative events, such as corporate announcements.

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**TABLE I**  
**Sample statistics**

This table provides daily statistics on the 33 Spanish stocks in the sample. We use the weight of each stock in the IBEX-35 index as the proxy for market capitalization. We compute the median of the following daily statistics for each stock: the relative spread is the average ratio of the quoted bid-ask spread over the quote midpoint, weighted by time; depth is measured as the € value of the accumulated volume offered at the 5 best ask and bid quotes, weighted by time; volume traded is measured as the number of shares transacted; finally, order flow is the total number of orders submitted (market, limit, market-to-limit, and cancellations). We compute daily medians for each stock, and we provide cross-sectional statistics of those medians: median, percentiles (25% and 75%) maximum and minimum. We include separated statistics for the 5 largest and the 15 smallest stocks in terms of market capitalization.

Sample	Capitalization (index weight)	Relative Spread	Depth (€)	Volume (shares)	Trades	Order flow
Median	0.75	0.0034	124322.02	347205	365.00	833.50
pctl.(75%)	1.94	0.0039	195705.07	1093215	669.50	1374.50
pctl.(25%)	0.59	0.0024	102173.16	161382	226.50	584.00
Max.	24.68	0.0066	1264221.90	22195189	5675.50	10357.50
Min.	0.18	0.0007	72380.74	95755	86.50	243.50
<u>5 largest stocks</u>						
Median	16.28	0.0011	880163.79	7108202.5	1904.50	3470.00
Over the sample	70.76%			72.94%	48.91%	43.55%
<u>15 smallest stocks</u>						
Median	0.52	0.0038	102173.16	198705	241.00	586.00
Over the sample	7.53%			8.90%	18.02%	21.48%

**TABLE II**  
**Estimated co-integration state space model for ask and bid quotes**

This table summarizes the estimation of the co-integration state space model for ask and bid quotes in equations [2] to [9] in the paper with 5-minute periodicity. The parameters  $\beta$ ,  $\phi_a$ ,  $\phi_b$  correspond to half the average bid-ask spread, and the persistency of the transitory components of the best ask and bid quotes, as shown in [T1], where  $S_{a,t}$  and  $S_{b,t}$  are the transitory component of ask and bid quotes, and  $m_t$  is the efficient price.

$$\begin{pmatrix} a_t \\ b_t \end{pmatrix} = \beta \begin{pmatrix} 1 \\ -1 \end{pmatrix} + \begin{pmatrix} 1 & 0 & 1 \\ 0 & 1 & 1 \end{pmatrix} \begin{pmatrix} S_{a,t} \\ S_{b,t} \\ m_t \end{pmatrix}, \quad \begin{pmatrix} S_{a,t} \\ S_{b,t} \\ m_t \end{pmatrix} = \begin{pmatrix} \phi_a & \phi_{ab} & 0 \\ \phi_{ba} & \phi_b & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} S_{a,t-1} \\ S_{b,t-1} \\ m_{t-1} \end{pmatrix} + \begin{pmatrix} g_t \\ -g_t \\ 0 \end{pmatrix} + \begin{pmatrix} \varepsilon_{a,t} \\ \varepsilon_{b,t} \\ \varepsilon_{m,t} \end{pmatrix}, \quad [T1]$$

The parameters  $\sigma_a^2$  and  $\sigma_b^2$  correspond to the average transitory volatility of ask and bid quotes, represented in equation [T3], and  $\alpha_0$ ,  $\alpha_1$ ,  $\alpha_2$ , and  $\alpha_3$  are the parameters of the EGARCH model in [T4] that represents the volatility of the efficient price.

$$\sigma_{i,t}^2 = \exp \left( \sigma_i^2 + \sum_{j=1}^J \phi_j D_{i,j} \right), \quad i = \{a, b\} \quad [T2]$$

$$\sigma_{m,t}^2 = \exp \left( \alpha_0 + \alpha_1 \ln(\sigma_{m,t-1}^2) + \alpha_2 \varepsilon_{m,t-1} + \alpha_3 \left[ |\varepsilon_{m,t-1}| - \sqrt{2/\pi} \right] + \sum_{j=1}^J \phi_j^m D_{i,j} \right) \quad [T3]$$

The parameters are the constant correlations in the variance-covariance matrix [T4] of the innovations.

$$\Sigma_t = \begin{pmatrix} \sigma_{a,t}^2 & 0 & \rho_{am} \sigma_{a,t} \sigma_{m,t} \\ 0 & \sigma_{b,t}^2 & \rho_{bm} \sigma_{b,t} \sigma_{m,t} \\ \rho_{am} \sigma_{a,t} \sigma_{m,t} & \rho_{bm} \sigma_{b,t} \sigma_{m,t} & \sigma_{m,t}^2 \end{pmatrix} \quad [T4]$$

The model is estimated with the Kalman filter. Panel A provides cross-sectional medians on the estimated parameters for the 33 Spanish stocks in our sample. Panel B provides cross-sectional correlations among the parameters and the following statistics: the relative spread is the average ratio of the quoted bid-ask spread over the quote midpoint, weighted by time; depth is measured as the € value of the accumulated volume offered at the 5 best ask and bid quotes, weighted by time; volume traded is measured as the number of shares transacted; finally, order flow is the total number of orders submitted (market, limit, market-to-limit, and cancellations). Panel C provides cross-sectional correlations between the same statistics than in Panel B with the estimated short-term component of ask and bid quotes in [T1] and with the transitory and long run volatilities in [T2] and [T3].

Panel A: Estimated coefficients

Sample	Parameter												
	$\beta$	$\phi_a$	$\phi_b$	$\phi_{ab}$	$\phi_{ba}$	$\sigma_a$	$\sigma_b$	$\alpha_0$	$\alpha_1$	$\alpha_2$	$\alpha_3$	$\rho_{am}$	$\rho_{bm}$
Median	0.0206	0.7629	0.6119	0.3191	0.2278	0.0002	0.0001	-0.3825	0.9316	0.0114	0.2283	-0.2774	-0.2595
pctl.(75%)	0.0356	0.7983	0.6425	0.3988	0.3024	0.0006	0.0004	-0.2812	0.9577	0.0328	0.2651	-0.2264	-0.1936
pctl.(25%)	0.0128	0.6662	0.5479	0.2789	0.1880	0.0001	0.0001	-0.6038	0.9093	-0.0053	0.1967	-0.3140	-0.3013
Max.	0.0731	0.8678	0.8255	0.5203	0.5713	0.0018	0.0017	-0.0788	0.9805	0.0614	0.3608	-0.0813	-0.0486
Min.	0.0063	0.4160	0.3478	0.1455	0.0931	0.0000	0.0000	-1.2135	0.8348	-0.0279	0.1039	-0.4759	-0.4678
<b>5 largest stocks</b>													
Median	0.0080	0.6069	0.4756	0.3782	0.4218	0.0000	0.0001	-0.1425	0.9759	-0.0145	0.1578	-0.1750	-0.1881
<b>15 smallest stocks</b>													
Median	0.0233	0.8174	0.6773	0.2105	0.2032	0.0002	0.0002	-0.5626	0.8972	0.0381	0.3625	-0.2895	-0.2697

Panel B: Correlations with estimated parameters

Statistic	$\beta$	$\phi_a$	$\phi_b$	$\phi_{ab}$	$\phi_{ba}$	$\sigma_a$	$\sigma_b$	$\alpha_0$	$\alpha_1$	$\alpha_2$	$\alpha_3$	$\rho_{am}$	$\rho_{bm}$
Capitalization	-0.4102	-0.4542	-0.6627	0.5505	0.7525	-0.3110	-0.2893	0.4384	0.4816	-0.4188	-0.5775	0.2757	0.3477
Relative spread	0.6686	0.7314	0.7765	-0.8445	-0.8437	0.4332	0.4285	-0.4507	-0.5475	0.6576	0.7149	-0.6096	-0.5111
Depth (€)	-0.4574	-0.4936	-0.6945	0.6026	0.7652	-0.3569	-0.3313	0.4818	0.5388	-0.4876	-0.6388	0.3437	0.3988
Volume	-0.3949	-0.3991	-0.6517	0.4586	0.7436	-0.3029	-0.2795	0.3829	0.4274	-0.3747	-0.5312	0.2498	0.3178
Trades	-0.3852	-0.5761	-0.6565	0.6184	0.8385	-0.2530	-0.2384	0.4576	0.4981	-0.4041	-0.5882	0.3997	0.4529
Order flow	-0.3498	-0.5795	-0.6299	0.6145	0.8258	-0.2127	-0.2028	0.4632	0.4936	-0.3931	-0.5714	0.3973	0.4480

Panel C: Correlations with estimated factors and volatilities

Statistic	$\sigma_a^2$	$\sigma_b^2$	$\sigma_m^2$	$S_a$	$S_b$
Capitalization	-0.3143	-0.2851	-0.0023	-0.2482	-0.3954
Relative spread	0.4980	0.3811	-0.2127	0.3745	0.5392
Depth (€)	-0.3538	-0.3222	-0.0269	-0.2801	-0.4399
Volume	-0.3014	-0.2768	0.0259	-0.2304	-0.3872
Trades	-0.2901	-0.2596	0.4110	-0.2771	-0.2772
Order flow	-0.2588	-0.2294	0.4856	-0.2666	-0.2272

**TABLE III**  
**VAR model for limit order book variables**

Panel A summarizes the estimation of the following VAR model by OLS,

$$y_t = \gamma_0 + \sum_{j=1}^3 \gamma_j y_{t-j} + w_t \quad [T5]$$

where  $y_t$  is the vector LOB variables. This vector includes: the relative bid-ask spread ( $S_t$ ); the displayed depth at the best ask ( $D_t^a$ ) and bid ( $D_t^b$ ) quotes; the accumulated depth at up to four ticks from the quote midpoint ( $BD_t^a(4)$ ,  $BD_t^b(4)$ ); the order imbalance on the first level of the LOB ( $AsD_t$ ); the order imbalance beyond the best quotes ( $AsBD_t(4)$ ), and the bi-dimensional liquidity measure in [1] for a trade of size equal to 2 times the NMS ( $BLM_t(2)$ ). For each explanatory variable we provide the sum of the lagged coefficients that are statistically significant (at least) at the 5% level. Panel B provides the residual cross-equation correlations, computed from the estimated  $w_t$  in [T5]. All time series are computed over 5-minute intervals.

Panel A: Coefficients

	Dependent variable							
	$S$	$D^a$	$D^b$	$AsD$	$BLM(2)$	$BD^a(4)$	$BD^b(4)$	$AsDB(4)$
$S$	0.6678	-0.0407	-0.0302	-0.0338	-0.0469	-0.0165	-0.0207	_____
$D^a$	-0.0013	0.6891	0.0469	0.0993	0.0058	0.0051	-0.0063	-0.0198
$D^b$	-0.0017	0.0229	0.6368	0.0596	0.0070	0.0025	0.0161	-0.0033
$AsD$	0.0024	-0.0051	-0.0047	0.5477	-0.0077	0.0073	0.0164	0.0227
$BLM(2)$	0.1462	0.0297	0.0411	-0.0032	0.8555	-0.0721	-0.0395	-0.0896
$BD^a(4)$	-0.0135	0.0616	0.0004	_____	-0.0145	0.8169	0.0648	0.0937
$BD^b(4)$	-0.0154	0.0120	0.0748	0.0178	-0.0143	0.0672	0.7950	0.0673
$AsDB(4)$	0.0128	-0.0193	-0.0041	0.0444	0.0120	-0.0658	-0.0668	0.6248
$R^2$	0.6249	0.4959	0.4119	0.3922	0.6536	0.6166	0.5659	0.4974
Obs.	366920							

Panel B: Correlation matrix of residuals

	$S$	$D^a$	$D^b$	$AsD$	$BLM(2)$	$BD^a(4)$	$BD^b(4)$	$AsDB(4)$
$S$	1.0000							
$D^a$	0.0738	1.0000						
$D^b$	0.0787	0.0287	1.0000					
$AsD$	-0.0005	0.5851	0.5693	1.0000				
$BLM(2)$	0.8314	-0.0101	0.0052	-0.0231	1.0000			
$BD^a(4)$	-0.1354	0.3410	0.0051	0.1728	-0.1412	1.0000		
$BD^b(4)$	-0.1359	0.0092	0.3585	0.1859	-0.1329	0.1066	1.0000	
$AsDB(4)$	-0.1504	0.1526	0.1735	0.2850	-0.1194	0.5973	0.6141	1.0000

**TABLE IV**  
**Estimation of the SVAR model: 5-minute periodicity**

This table summarizes the estimation of the following structural VAR (SVAR) model for the 33 stocks in our sample,

$$Az_t = A_0 + \sum_{j=1}^p A_j z_{t-j} + F'x_t + v_t. \quad [T6]$$

The “Best quotes” model combines a long run volatility proxy with the relative bid-ask spread ( $S$ ), the displayed depth at the best ask ( $D^a$ ) and bid ( $D^b$ ) quotes, and the order imbalance on the first level of the LOB ( $AsD$ ). The “Book” model combines the informational volatility measure with the accumulated depth at up to four ticks from the quote midpoint ( $BD^a$ ,  $BD^b$ ); the order imbalance beyond the best quotes ( $AsDB$ ), and the bi-dimensional liquidity measure in equation [1] in the paper ( $BLM$ ), for a trade of size equal to 2 times the NMS. Finally, the “Best + book” includes all the variables in the two previous models. All time series are computed over 5-minute intervals, and averaged weighting by time. The vector of control variables ( $x_t$ ) includes the number of trades and the orders submitted (market, limit, market-to-limit orders, and cancellations). The deterministic intraday component of each time series has been removed in a previous step. The lag length of the model is fixed at one. The matrix of contemporaneous relationships ( $A$ ) allows contemporaneous causality running from volatility to the LOB variables, but no causality running from the LOB variables to long run volatility. Moreover, the variance-covariance matrix of ( $v_t$ ) allows for contemporaneous correlation among the innovation of the LOB variables, but imposes no correlation between the innovations in long run volatility and the innovations in the LOB. With these restrictions the model is exactly identified. Panel A shows the free parameters of matrix  $A$ . Panel B provides the estimated coefficients of the reduced form of model [T6], a VAR model. Only the results for the equation of the long run volatility are reported. We also report Granger causality tests for each of the LOB variables. Finally, “\*\*\*”, “\*\*”, and “\*” means statistically significant at the 1%, 5% and 10% level, respectively.

Panel A: Contemporaneous coefficients of the SVAR model			
Explanatory variable	Model		
	Best quotes	Book	Best+Book
$S$	-27.2774 ***		-28.2788 ***
$D^a$	4.8156 *		4.3894
$D^b$	1.8513		1.1206
$AsD$	-14.6514 ***		-21.2577 ***
$BLM(2)$		-26.1284 ***	-26.1910 ***
$BD^a(4)$		29.0610 ***	28.8908 ***
$BD^b(4)$		31.9487 ***	31.7740 ***
$AsDB(4)$		-14.5243 ***	-14.5669 ***

Panel B: Coefficients of the reduced form VAR (x10000 except $\sigma_m$ )			
Explanatory variable	Model		
	Best quotes	Book	Best+Book
$\sigma_m$	0.9413 ***	0.9414 ***	0.9413 ***
$S$	0.5970 ***		-0.5570 ***
$D^a$	-0.0161		0.2140 ***
$D^b$	0.0053		0.2180 ***
$AsD$	0.0061		-0.2550 ***
$BLM(2)$		0.9830 ***	1.4680 ***
$BD^a(4)$		0.0267 **	-0.0460 ***
$BD^b(4)$		0.0321 ***	-0.0461 ***
$AsDB(4)$		-0.0192	0.0590 ***
$T$	0.0364 ***	0.0387 ***	0.0285 ***
$O$	0.5980 ***	0.5760 ***	0.5750 ***
$R^2$	0.9337	0.9342	0.9342
No. of obs.	374131	373854	373865
Causality test:			
$S$	839.040 ***		216.670 ***
$D^a$	2.915		212.140 ***
$D^b$	0.305		231.600 ***
$AsD$	0.682		318.730 ***
$BLM(2)$		1814.800 ***	1247.400 ***
$BD^a(4)$		5.026 **	12.383 ***
$BD^b(4)$		7.296 ***	12.531 ***
$AsDB(4)$		2.472	19.979 ***
$ALL$	865.100 ***	1839.900 ***	2290.700 ***



**TABLE V**  
**Estimation of the SVAR model: Market capitalization**

This table summarizes the estimation of the following structural VAR (SVAR) model for the 5 largest and 15 smallest stocks in our sample by market capitalization, with time series computed over 5-minute intervals,

$$Az_t = A_0 + \sum_{j=1}^p A_j z_{t-j} + F'x_t + v_t. \quad [T7]$$

The “Best quotes” model, the “Book” model, and the “Best + book” model are as described in Table IV. The variables are: a proxy for the long run volatility, estimated using co-integration state-space model for ask and bid quotes, the relative bid-ask spread ( $S$ ), the displayed depth at the best ask ( $D^a$ ) and bid ( $D^b$ ) quotes, the order imbalance on the first level of the LOB ( $AsD$ ), the accumulated depth at up to four ticks from the quote midpoint ( $BD^a$ ,  $BD^b$ ), the order imbalance beyond the best quotes ( $AsDB$ ), and the bi-dimensional liquidity measure in equation [1] in the paper ( $BLM$ ), for a trade of size equal to 2 times the NMS. All LOB variables are averaged weighting by time. The control variables in  $x_t$  are the number of trades and the number of orders submitted. The deterministic intraday component of each time series has been previously removed. The lag length is fixed at one. The matrix of contemporaneous relationships ( $A$ ) allows causality running from volatility to the LOB variables, but not the other way around. The variance-covariance matrix of ( $v_t$ ) allows for contemporaneous correlation among the innovation of the LOB variables, but imposes no correlation between the innovations in long run volatility and the innovations in the LOB. The model is exactly identified. Panel A reports the estimated free parameters of matrix  $A$ . Panel B provides the estimated coefficients of the reduced form (VAR) model. Only the results for the equation of the long run volatility are reported. Granger causality tests for each of the LOB variables are also reported. Finally, “\*\*\*”, “\*\*”, and “\*” means statistically significant at the 1%, 5% and 10% level, respectively.

Panel A: Contemporaneous coefficients of the SVAR model						
Explanatory variable	5 largest stocks			15 smallest stocks		
	Model			Model		
	Best quotes	Book	Best+Book	Best quotes	Book	Best+Book
$S$	-6.9129 ***		-7.6022 ***	-30.1621 ***		-30.8687 ***
$D^a$	10.1605		10.1285	-2.5712		-3.0289
$D^b$	7.5044		7.4141	-7.0201		-7.5474
$AsD$	0.5991		-2.8512	-14.4934 **		-29.7451 ***
$BLM(2)$		-10.3284 ***	-10.4442 ***		-25.8092 ***	-25.8508 ***
$BD^a(4)$		28.4337 ***	28.3287 ***		18.6926 ***	18.4849 ***
$BD^b(4)$		20.0839 ***	19.9144 ***		29.7383 ***	29.5356 ***
$AsDB(4)$		1.1082	1.0863		-14.2947 **	-14.3714 **

Panel B: Coefficients of the reduced form VAR (x10000 except $\sigma_m$ )						
Explanatory variable	5 largest stocks			15 smallest stocks		
	Model			Model		
	Best quotes	Book	Best+Book	Best quotes	Book	Best+Book
$\sigma_m$	0.9413 ***	0.9086 ***	0.9087 ***	0.9413 ***	0.9434 ***	0.9433 ***
$S$	0.7000 ***		-0.5100 ***	0.7400 ***		-0.5810 ***
$D^a$	-0.0434		0.2180 ***	-0.0118		0.2210 ***
$D^b$	0.0317		0.2810 ***	-0.0017		0.2010 ***
$AsD$	-0.0187		-0.2600 ***	0.0085		-0.2640 ***
$BLM(2)$		0.9360 ***	1.3610 ***		1.2340 ***	1.7470 ***
$BD^a(4)$		-0.1880 ***	-0.2680 ***		0.0762 ***	0.0015
$BD^b(4)$		-0.1180 ***	-0.2270 ***		0.0952 ***	0.0228
$AsDB(4)$		0.1370 ***	0.2250 ***		-0.0744 ***	0.0066
$T$	0.2190 ***	0.2470 ***	0.2310 ***	0.0285 **	0.0305 **	0.0197
$O$	0.7670 ***	0.7360 ***	0.7300 ***	0.6150 ***	0.5890 ***	0.5890 ***
$R^2$	0.8677	0.8678	0.8679	0.9447	0.9449	0.9450
No. of obs.	56679	56639	56639	170133	169989	169989
Causality test:						
$S$	91.107 ***		12.310 ***	512.860 ***		95.543 ***
$D^a$	2.248		18.991 ***	0.607		92.849 ***
$D^b$	0.865		30.674 ***	0.014		86.807 ***
$AsD$	0.390		26.732 ***	0.661		146.930 ***
$BLM(2)$		145.720 ***	81.352 ***		1090.700 ***	686.920 ***
$BD^a(4)$		16.624 ***	28.868 ***		18.341 ***	0.005
$BD^b(4)$		6.797 ***	20.825 ***		29.168 ***	1.390
$AsDB(4)$		8.368 ***	19.718 ***		16.659 ***	0.113
$ALL$	99.376 ***	182.000 ***	220.150 ***	523.730 ***	1099.000 ***	1305.300 ***

**TABLE VI**  
**Estimation of the SVAR model: 1-minute periodicity**

This table summarizes the estimation of the structural VAR (SVAR) model [T8] for the 33 stocks in our sample with time series computed over 1-minute intervals,

$$Az_t = A_0 + \sum_{j=1}^p A_j z_{t-j} + F'x_t + v_t. \quad [T8]$$

The “Best quotes” model, the “Book” model, and the “Best + book” model are as described in Tables IV and V. The variables in the model are a proxy for the long run volatility, estimated using a co-integration state-space model for ask and bid quotes; the relative bid-ask spread ( $S$ ); the displayed depth at the best ask ( $D^a$ ) and bid ( $D^b$ ) quotes; the order imbalance on the first level of the LOB ( $AsD$ ); the accumulated depth at up to four ticks from the quote midpoint ( $BD^a$ ,  $BD^b$ ); the order imbalance beyond the best quotes ( $AsDB$ ), and the bi-dimensional liquidity measure in equation [1] in the paper ( $BLM$ ), for a trade of size equal to 2 times the NMS. All the LOB time series are averaged weighting by time. The vector of control variables ( $x_t$ ) includes the number of trades and the number of orders submitted. The deterministic intraday component of each time series has been previously removed. The lag length of the model is fixed at one. The matrix of contemporaneous relationships ( $A$ ) allows causality running from volatility to the LOB variables, but not the other way around. The variance-covariance matrix of ( $v_t$ ) allows for contemporaneous correlation among the innovation of the LOB variables, but imposes no correlation between the innovations in long run volatility and the innovations in the LOB. The model is exactly identified. Panel A reports the estimated pooled free parameters of matrix  $A$ . Panel B provides the estimated pooled coefficients of the reduced form (VAR) model. Only the results for the equation of the long run volatility are reported. Granger causality tests for each of the LOB variables are also reported. Finally, “\*\*\*”, “\*\*”, and “\*” means statistically significant at the 1%, 5% and 10% level, respectively.

Panel A: Contemporaneous coefficients of the SVAR model

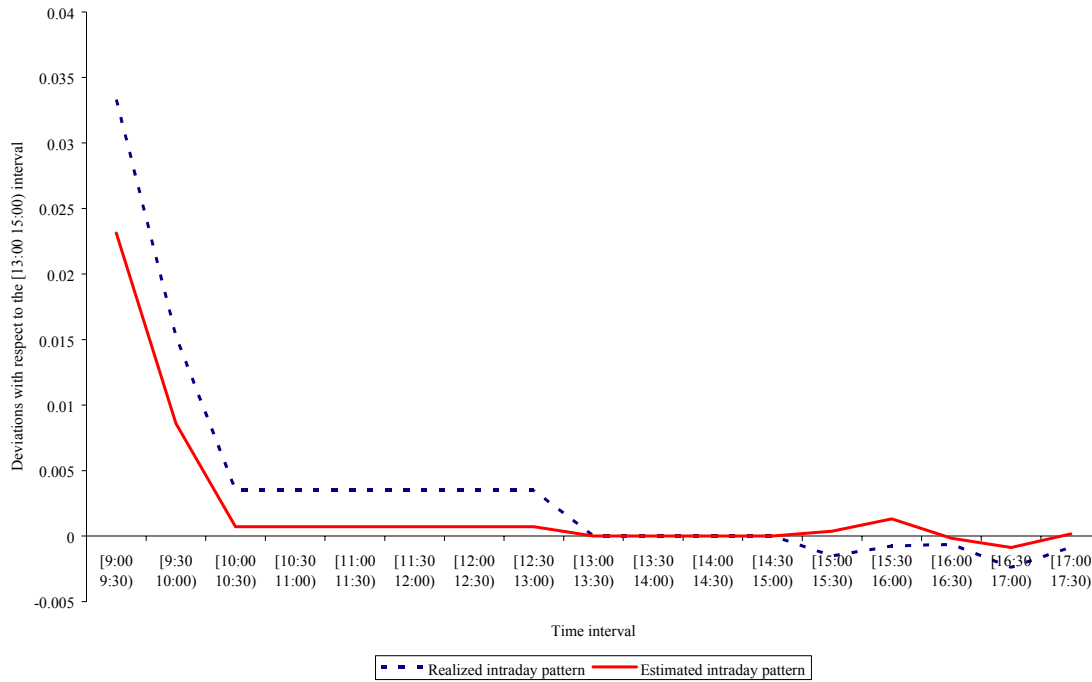
Explanatory variable	Model		
	Best quotes	Book	Best+Book
$S$	-24.0934 ***		-24.1677 ***
$D^a$	2.0479 **		1.9184 *
$D^b$	8.2719 ***		8.1579 ***
$AsD$	-2.3084 *		1.6370
$BLM(2)$		-20.4372 ***	-20.4505 ***
$BD^a(4)$		8.1462 ***	8.1556 ***
$BD^b(4)$		7.8460 ***	7.8392 ***
$AsDB(4)$		-2.3334 *	-2.3039 *

Panel B: Coefficients of the reduced form VAR (x10000 except  $\sigma_m$ )

Explanatory variable	Model		
	Best quotes	Book	Best+Book
$\sigma_m$	0.8739 ***	0.8740 ***	0.8740 ***
$S$	0.5690 ***		-0.2370 ***
$D^a$	0.0057		0.1520 ***
$D^b$	0.0450 ***		0.1970 ***
$AsD$	-0.0313 ***		-0.1610 ***
$BLM(2)$		0.9370 ***	1.1430 ***
$BD^a(4)$		0.0674 ***	0.0159 *
$BD^b(4)$		0.0589 ***	-0.0147 *
$AsDB(4)$		-0.0817 ***	-0.0280 ***
$T$	0.0452 ***	0.0457 ***	0.0436 ***
$O$	0.2090 ***	0.2030 ***	0.2030 ***
$R^2$	0.7731	0.7732	0.7733
No. of obs.	1905913	1905527	1905527
Causality test:			
$S$	1945.700 ***		131.090 ***
$D^a$	1.179		344.540 ***
$D^b$	89.951 ***		615.930 ***
$AsD$	48.534 ***		427.640 ***
$BLM(2)$		4042.400 ***	2424.200 ***
$BD^a(4)$		67.935 ***	3.326 *
$BD^b(4)$		52.492 ***	2.862 *
$AsDB(4)$		102.510 ***	10.860 ***
$ALL$	2251.000 ***	4167.500 ***	4835.600 ***

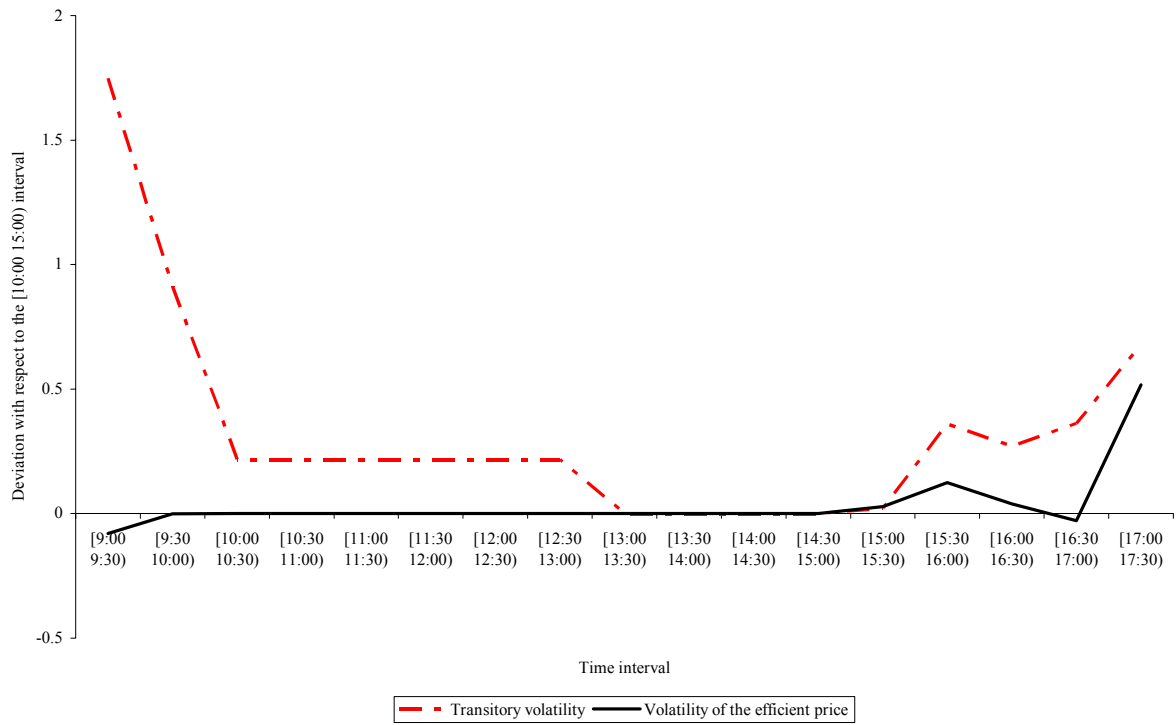
**FIGURE 1**  
**Estimated intraday regularities in the bid-ask spread**

This figure shows the cross-sectional median of the estimated intraday regular patterns of the transitory components of ask and bid quotes for a sample of 33 stocks listed in the electronic platform of the SSE. Transitory components of quotes are characterized in equations [2] and [3] of the co-integration state-space model given by equations [2] to [8] in the paper. The unobserved components of ask and bid quotes are estimated using the Kalman filter. The regular patterns in the transitory components of ask and bid quotes are given by the parameters  $\varphi_j$  in equation [4]. We compare the estimated regularities ( $2\hat{\varphi}_j$ ) with the observed cross-sectional median level of the bid-ask spread during the same time intervals. We split the trading session of the SSE in the following intervals: [9:00, 9:30), [9:30, 10:00), [10:00, 13:00), [13:00, 15:00), [15:00, 15:30), [15:30, 16:00), [16:00, 16:30), [16:30, 17:00), [17:00, 17:30]. The figure reports the deviation of each coefficient or median with respect to the control interval [13:00, 15:00).



**FIGURE 2**  
**Estimated intraday regularities in volatility**

This figure reports the estimated intraday deterministic patterns in the transitory and informational components of the volatility of ask and bid quotes for the 33 Spanish stocks in our sample. Volatility is decomposed in its theoretical components using the co-integration state-space model given by equations [2] to [9] in the paper. Transitory volatility is described by the deterministic process in equation [8]. Informational volatility is modeled as the EGARCH model in equation [9]. The estimated deterministic patterns are given by the parameters  $\phi_j$  in [8] for the transitory volatility, and  $\phi_j^m$  in [9] for the informational volatility. We split the trading session of the SSE in the following intervals: [9:00, 9:30), [9:30, 10:00), [10:00, 13:00), [13:00, 15:00), [15:00, 15:30), [15:30, 16:00), [16:00, 16:30), [16:30, 17:00), [17:00, 17:30]. The table reports the cross-sectional median of the each parameter, but expressed in deviations with respect to the control interval [13:00, 15:00).



## Appendix

In this appendix, we provide some details about how we adjust the state space model in [2]-[9] so as to apply the Kalman filter. We rely on Harvey, Ruiz, and Sentana (1992) and Kim and Nelson (1999, chapter 6). First, notice that [2] and [3] are the so-called measurement and transition equations of the state space model. The EGARCH model in [9] is defined on the innovation of the efficient price in the transition equation, which can be rewritten as

$$\begin{pmatrix} S_{a,t} \\ S_{b,t} \\ m_t \end{pmatrix} = \begin{pmatrix} \phi_a & \phi_{ba} & 0 \\ \phi_{ab} & \phi_b & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} S_{a,t-1} \\ S_{b,t-1} \\ m_{t-1} \end{pmatrix} + \begin{pmatrix} g_t \\ -g_t \\ 0 \end{pmatrix} + \begin{pmatrix} \varepsilon_{a,t} \\ \varepsilon_{b,t} \\ \varepsilon_{m,t} \end{pmatrix} + \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix} \odot \begin{pmatrix} \varepsilon_{a,t}^* \\ \varepsilon_{b,t}^* \\ \varepsilon_{m,t}^* \end{pmatrix}, \quad [3']$$

where

$$\begin{pmatrix} \varepsilon_{a,t} \\ \varepsilon_{b,t} \\ \varepsilon_{m,t} \end{pmatrix} + \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix} \odot \begin{pmatrix} \varepsilon_{a,t}^* \\ \varepsilon_{b,t}^* \\ \varepsilon_{m,t}^* \end{pmatrix} \sim \mathcal{N} \left( \begin{pmatrix} 0 \\ 0 \\ 0 \end{pmatrix}, \Omega_t \right), \quad [5']$$

and

$$\Omega_t = \begin{pmatrix} \sigma_{a,t}^2 & 0 & \sigma_{am,t} \\ 0 & \sigma_{b,t}^2 & \sigma_{bm,t} \\ \sigma_{am,t} & \sigma_{bm,t} & 0 \end{pmatrix} + \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & \sigma_{m,t}^{*2} \end{pmatrix}, \quad [6']$$

with  $\sigma_{m,t}^{*2}$  following the EGARCH model [9]. This model cannot be estimated by the standard Kalman filter since we would need to know  $\sigma_{m,t}^{*2}$ , which would appear in the prediction equations of the filter. The issue is that the EGARCH model depends on past unobserved shocks, and even the knowledge of past factors does not imply the knowledge of past unobserved shocks. The problem is solved by replacing past shocks and past absolute values of the shocks in [9] by their conditional expectations,

$$\ln \sigma_{m,t}^{*2} = \alpha_0 + \alpha_1 \ln(\sigma_{m,t-1}^{*2}) + \alpha_2 E[\xi_{m,t-1}^*] + \alpha_3 \left[ E\left[ \left| \xi_{m,t-1}^* \right| \right] - \sqrt{2/\pi} \right] + \sum_{j=1}^J \phi_j^m D_{t,j}, \quad [9*]$$

where  $\xi_{m,t}^* = \varepsilon_{m,t}^* / \sigma_{m,t}^*$  is the standardized shock.

Therefore, [9\*] represents an approximation to the real process [9] and, hence, the quasi-optimal term proposed by Harvey *et al* (1992) applies. To obtain the conditional expectations the state is augmented yielding new measurement and transition equations,

$$\begin{pmatrix} a_t \\ b_t \end{pmatrix} = \beta \begin{pmatrix} 1 \\ -1 \end{pmatrix} + \begin{pmatrix} 1 & 0 & 1 & 0 \\ 0 & 1 & 1 & 0 \end{pmatrix} \begin{pmatrix} S_{a,t} \\ S_{b,t} \\ m_t \\ \varepsilon_{m,t}^* \end{pmatrix} \quad [2^*]$$

and

$$\begin{pmatrix} S_{a,t} \\ S_{b,t} \\ m_t \\ \varepsilon_{m,t}^* \end{pmatrix} = \begin{pmatrix} \phi_a & \phi_{ba} & 0 & 0 \\ \phi_{ab} & \phi_b & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} S_{a,t-1} \\ S_{b,t-1} \\ m_{t-1} \\ \varepsilon_{m,t-1}^* \end{pmatrix} + \begin{pmatrix} g_t \\ -g_t \\ 0 \\ 0 \end{pmatrix} + \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 1 \end{pmatrix} \begin{pmatrix} \varepsilon_{a,t} \\ \varepsilon_{b,t} \\ \varepsilon_{m,t} \\ \varepsilon_{m,t}^* \end{pmatrix}, \quad [3^*]$$

where

$$\begin{pmatrix} \varepsilon_{a,t} \\ \varepsilon_{b,t} \\ \varepsilon_{m,t} \\ \varepsilon_{m,t}^* \end{pmatrix} \sim \mathcal{N} \left( \begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \end{pmatrix}, \Omega_t \right) \quad [5^*]$$

and

$$\Omega_t = \begin{pmatrix} \sigma_{a,t}^2 & 0 & 0 & \sigma_{am,t} \\ 0 & \sigma_{b,t}^2 & 0 & \sigma_{bm,t} \\ 0 & 0 & 0 & 0 \\ \sigma_{am,t} & \sigma_{bm,t} & 0 & \sigma_{m,t}^{*2} \end{pmatrix}. \quad [6^*]$$

The restriction  $\sigma_{m,t}^2 = 0$  in the diagonal of  $\Omega_t$  is necessary to identify  $\sigma_{m,t}^{*2}$  and  $\alpha_0$ . The model given by equations [2\*]-[3\*]-[4]-[5\*]-[6\*]-[8]-[9\*], with the CCC structure in [7], can be estimated using the standard Kalman filter.