ADVANCES IN
HIGH FREQUENCY STRATEGIES

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to

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A mis hijos.

"Far better an approximate answer to the right question,
which is often vague,
than an exact answer to the wrong question,
which can always be made precise."

John W. Tukey (1915-2000)
The future of data analysis
Annals of Mathematical Statistics, 33 (1), (1962), p.13.

CONTENTS

PREFACE

Motivation

My interest in High Frequency Finance began in early 2006, when I started to trade strategies with shorter holding periods. I quickly realized that many standard Microestructural, Financial and Econometric theories could not be exported into a framework where time and information have a different relationship. I knew the Low Frequency framework well, from my perspective of both a practitioner and an academic. The literature devoted to High Frequency Finance at that time was relatively small, fragmented, and in many cases developed by stretching Low Frequency models, forced to perform in an environment for which they had not been conceived.

Thus began the work on my second doctoral thesis, which covers topics with important practical implications for optimal execution, liquidity provision, market risk, the risk of market failure, … and of course alpha generation by High Frequency strategies. Most of the profits harvested by High Frequency trading nowadays can be attributed to speed. But as our trading speed reaches the limits of Physical feasibility, being fast is no longer enough. Some critics of High Frequency trading argue that a speed limit should be imposed on market participants. We have news for them: That has already been taken care of.

We are witnessing the dawn of a new paradigm in the science of investing. Those who ignore these principles are broadcasting their trading intentions, and become easy prey for predatory algorithms every day. In effect, they are paying a virtual tax for each transaction –enriching their competitors. Not to mention their underestimation of the risks induced by this new market microstructure. Some firms (and academic approaches) will evolve and adapt accordingly, but many will fade and vanish over time.

Acknowledgements

Several models presented here were developed during my term as Visiting Scholar at *Cornell University*. My collaboration with Prof. Dr. David Easley, Chairman of the Economics Department, and Prof. Dr. Maureen O'Hara, former President of the *American Finance Association* (AFA), resulted in the development of the *VPIN Flow Toxicity Metric*, and three patent applications.

INTRODUCTION

High Frequency Strategies

Recent legislative changes in the United States ("Regulation National Market System" of 2005, or "RegNMS") and Europe ("Markets in Financial Instruments Directive" or "MiFID", in force since November 2007), preceded by substantial technological advances in computation and communication, have revolutionized the financial markets.

Europe's MiFID fosters greater competition among *brokers*, with the objective of improving liquidity, cohesion and depth in financial markets. Similarly, U.S. RegNMS encourages competitiveness among *exchanges* by allowing market fragmentation. Cohesion is recovered through a mechanism for the consolidation of individual orders processed via multiple venues (NBBO, or "National Best Bid and Offer"). The result has been an "arms race" for developing the technology and quantitative methods that squeeze the last cent of profitability when serving the demands of market participants.

High frequency strategies are of a very diverse nature. We will follow the general description proposed by Aldridge (2010), defining *high frequency strategies* as those characterized by a brief investment horizon, which may range from a split of a second to several hours. A main advantage comes from placing numerous independent bets every day on the same instrument or portfolio, because as the "Fundamental Law of Active Management" postulates, a tiny predictive power on a sufficiently large number of independent bets yields a high Information Ratio (Grinold (1989)). The goal is to exploit the inefficiencies derived from the market's microstructure, such as rigidities, agents' idiosyncrasy, asymmetric information, etc. As a consequence of this higher frequency, the identification of opportunities, risk control, execution and other investment management activities must be automated. Not all *algorithmic trading* occurs in high frequency, but all high frequency requires algorithmic trading. This in turn has made it possible to interact directly with the exchange's auction mechanism (or "double auction order book").

High frequency traders often operate with proprietary capital, meaning that investors are also investment managers. Their actions are not derived from client orders but for their own benefit. Their servers reside in the proximity of the exchange's matching engine ("co-location"), with the purpose of minimizing the time that passes between the shipping of an order and the arrival of confirmation of reception by the exchange ("latency"). All of the above demands a considerable investment in terms of infrastructure and of course the development of trade secrets in the form of algorithms and quantitative models.

According to Herdershott, Jones and Menkveld (2011), high frequency strategies overall benefit the investment community by lowering trading costs, improving the information in the order book, eliminating arbitrage opportunities across markets, narrowing the bid-ask spread, adding liquidity, etc. Cartea and Penalva (2010) conclude that high frequency strategies increase market impact, with mixed results depending on the type of participant.

Fields of study

The introduction to each chapter presents a detailed analysis of the state of the art regarding the subject discussed. Nevertheless, there exists a set of general and shared themes referred to in multiple occasions across this study that we find convenient to introduce now for the sake of clarity.

Researching high frequency trading models encompasses a wide range of fields, which we could group in the areas of Financial Economics (measurement and management of risks), Statistics (estimation and forecasting of high frequency time series) and Economic Analysis (microstructure of financial markets, price formation and price discovery processes).

a) Statistics

Modern markets require real time pricing of products and risk management. Iati (2009) has estimated that over 70% of the volume of U.S. shares is transacted by high frequency participants. For the year 2010, TABB has estimated that number to be 60% in the U.S., and around 40% in Europa.

The generalization of electronic markets and automation of financial transactions have accelerated the decision-making process to the point of rendering many old standing economic models obsolete. Higher frequency not only means that a large number of actions are taken every day, but also that these actions occur in stochastic time (i.e., with uncertainty regarding the time gap between these decisions). If ten years ago it was difficult to find research based upon tick-by-tick datasets, nowadays it is extraordinary to encounter recently published papers that use daily series.

Goodhart and O'Hara (1997) describe many peculiarities characteristic of high frequency time series, finding that some of them are incompatible with the assumptions generally made by traditional statistical and econometric models (e.g., Hamilton (1994)). As we shall see in Chapter I, high frequency returns time series are serially conditioned (Bollerslev and Domowitz (1993)), are subject to stochastic volatility (Andersen and Bollerslev (1996)), are irregularly spaced, and follow non-Gaussian distributions with elevated kurtosis and asymmetry.

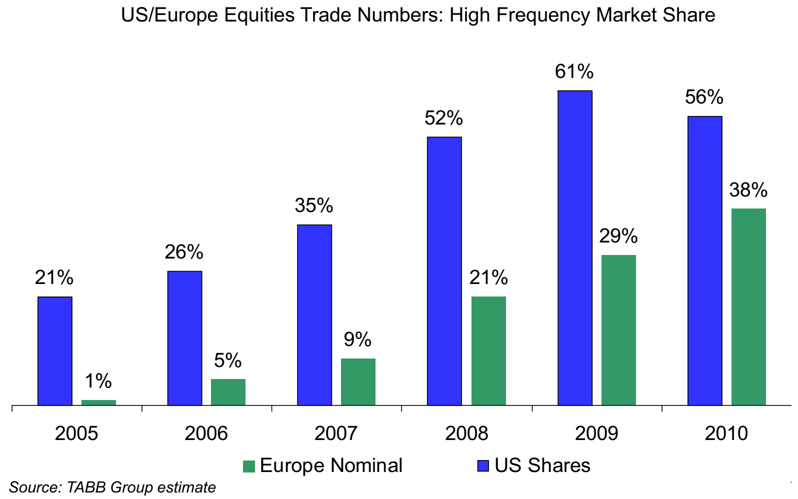

Figure 1 – Volume contributed by High Frequency Traders

Some of these problems can be partially dealt with through complex specifications, such as the ACD models proposed by Engle and Russell (1996), Engle and Russell (2005), or variants discussed by Bauwens and Giot (1998), Dufour and Engle (2000) among others. Refenes et al. (1996) and Bolland et al. (1998) apply Neural Networks. The complexity inherent to many of these models makes them prone to numerical instability. Furthermore, most of them lack any theoretical foundation, becoming purely empirical exercises whose conclusions can hardly be rationalized.

A different approach, consistent with microstructure theory, has attempted to model the impact that information arrival has on prices and bid-ask spreads. Some examples are Almeida et al. (1997), Goodhart et al. (1991), Low and Muthuswamy (1996). Most of this research has focused on FX, and its presence has decayed over the years. A possible explanation is that they relied on daily time series, and the aforementioned problems associated with the modeling of tick data prevented their evolution into the high frequency domain.

Ané and Geman (2000) re-discovered an idea of Clark (1973) that allows for a partial recovery of the properties assumed by most traditional statistical models on high frequency datasets. Instead of sampling by regular time intervals (chronological clock), the authors adopt a sampling subordinated to their measurement of stochastic volatility: The higher the volatility, the more samples are drawn per unit of time. The resulting high frequency time series are closer to normal. Unfortunately, the procedure requires the estimation of instantaneous volatility, which is inaccurate and not directly observable in real time.

Chapter I will address the same problem as Ané and Geman (2000). We present a simple sampling procedure that delivers high frequency time series nearly normal, plus it allows for a reduction of serial correlation and heteroskedasticity.

b) Economic Analysis

O'Hara (1995) describes the purpose of market microstructure theory and explains its motivation:

> *"The study of the process and outcomes of exchanging assets under a specific set of rules. While much of economics abstracts from the mechanics of trading, microstructure theory focuses on how specific trading mechanisms affect the price formation process."*

It is a relatively new area of research that combines elements of economic analysis (agents, expectations, utility maximization) and financial economics (valuation, risks, asset management).

As for this study, we begin with the basic model of sequential trading devised by Glosten and Milgrom (1985). Easley, Kiefer, O'Hara and Paperman (1996) much improved that model by recognizing the existence of participants with asymmetric information under event uncertainty. The outcome was the celebrated PIN ("Probability of Informed Trading") model, which allows market makers to monitor information asymmetry and thus avoid adverse selection. Although a few PIN estimation procedures exist for low frequency data (Easley, Engle, O'Hara and Wu (2008), Easley, Kiefer, O'Hara and Paperman (1996)), there was no possibility of measuring PIN in the high frequency domain because of the intractability of those datasets.

Chapter I is dedicated to solving the problem of estimating VPIN for high frequency data.

c) Financial Economics

The statistical and microstructure models developed in this book address a number of issues treated in the Financial Economics literature. In particular, our contributions aim to further the understanding of the following research topics:

- Models for valuation and risk measurement in the context of high frequency.
- Forecasting of toxicity-induced volatility, as derived from the high frequency series of transactions.
- Development of new financial instruments which may provide a hedge to the risks inherent in high frequency trading.
- A benchmark to assess brokers' performance on behalf of their clients.
- Dealing with *spreads* and computation of optimal hedges based on time series, in the high as well as the low frequency domain.

We believe that this study is pioneering in the aforementioned subjects. Chapter II provides evidence that volatility forecasting can be improved through microstructural models. Those models analyze the behavior of market makers operating under asymmetric information, and explain how their response to order flow toxicity is a source of volatility. Most volatility forecasting models do not incorporate in their specification a theory that explains the origin of volatility, thus they tend to treat volatility as an exogenous, generally univariate, filtered process. We are left with tools that attempt to forecast "something" without an understanding of why and how that "thing" comes to be. But how is an econometric model unsupported by a theory any better than a high-tech horoscope? Under these circumstances, we should consider the possibility that a large part of the results reported in the volatility forecasting literature are in fact spurious, numerically driven, and unrelated to any existing structure. Conversely, Chapter II presents a bivariate, dynamic equilibrium model that studies the interaction between toxicity (signal) and realized volatility (response). Out-of-sample results are superior to those derived from univariate specifications, especially in the context of forecasting beyond the immediate horizon. Empowered with this new analytical tool, Chapter III throws light upon the events of May 6th 2010 ('flash crash'). Chapter IV defines a futures contract that provides a hedge to market makers against the risk of order flow toxicity or adverse selection. Chapter V offers a new benchmark to assess the costs of trading under conditions of asymmetric information.

Chapter VI reviews and improves some of the most used methods for hedging portfolios, plus it introduces two new methods with superior characteristics. These methods are applicable in a High Frequency space, but also in Low Frequency. Chapter VII reviews the scientific literature on Sharpe ratio, offers its projection on the probabilistic space (*Probabilistic Sharpe ratio*), and develops a new methodology which determines the minimum track record length required to evidence investment skill at a preset confidence level. High Frequency returns are non-Gaussian, so a new *Sharpe Ratio Efficient Frontier* is needed to address this feature. Chapter VIII introduces the EF3M algorithm, with important applications in the modeling of financial data. This new estimation procedure is particularly useful in Financial applications, and satisfies the high frequency computational requirements established in Chapter VII.

Objectives

Cahan et al. (2010) argue that a large portion of the financial literature has devoted itself to measuring low frequency risks, to some extent ignoring the specific risks associated with high frequency trading. In particular, those authors call for research that may uncover the relationships between risks in both domains.

A first objective of the present study is to put forth a procedure for transforming high frequency data in order to comply with the assumptions of traditional econometric models. Once we are able to deal with high frequency series with relative simplicity, we address the second objective, namely to provide a measurement of the risk of toxicity in the high frequency order flow (our VPIN model). In particular, we present abundant empirical evidence of the bidirectional relationship between order flow toxicity and future volatility.

A third objective consists in answering the challenge formulated by Cahan et al. (2010). Consequently, we show how high frequency risks *spill over* into the low frequency domain and vice versa. We believe that this study is the first to propose such unified framework, in an attempt to explain the transmission of risk between both domains. A paradigmatic case of how high frequency risks unleash low frequency risks is evidenced by the *'flash crash'* of May 6th 2010, an episode studied in detail in Chapter III.

The fourth objective is to characterize market makers as sellers of an option to be adversely selected, at a premium determined by the range at which they are willing to provide liquidity. We will show that exchanges currently lack a mechanism or tool to protect market makers against the risk of adverse selection. As a solution, we propose a futures contract with VPIN as underlying, which could allow liquidity providers to dynamically manage toxicity risk, avoiding future repetitions of the *'flash crash'*.

The fifth objective is to propose a new benchmark for measuring brokers' efficiency when executing the clients' orders. We argue that VWAP does not incorporate all available information in connection to the level of flow toxicity, thus being an incomplete benchmark.

The sixth objective is to study the optimality of some of the most popular portfolio hedging methods. Solving the problem of portfolio hedging has critical applications in high frequency, not only for risk management but also in trading strategies. This study presents two new methodologies that overcome some of the caveats found in previous methods: DFO and MMSC.

The seventh objective is to analyze the characteristics of returns distributions which are responsible for "inflating" the Sharpe ratio. Such characteristics happen to be intrinsic to high frequency series, from which we can expect a certain upwards bias on the Sharpe ratios derived from high frequency strategies. The conclusions reached allow us to develop an alternative performance measure, named *Probabilistic Sharpe ratio*, which corrects the referred "inflation", and translates Sharpe ratio readings into probabilities of skillful investing. One application of this model is to answer the key question of *"how long should a track record be in order to have statistical confidence that its Sharpe ratio is above a given threshold?"* The empirical evidence we present indicates that, despite the high Sharpe ratios publicized for several hedge fund styles, in many cases they may not be high enough to indicate statistically significant investment skill beyond a moderate annual Sharpe ratio of 0.5 for the analyzed period, confidence level and track record length. This in turn leads to the concept of Sharpe Ratio Efficient Frontier. As we would like to model distributions matching the empirically observed first four moments, we develop the EF3M methodology for the exact fit of a mixture of two Gaussian distributions.

The analysis and management of investments in high frequency is an emerging field that will gradually attract the attention of more researchers. The present study confronts some of the most urgent questions on this subject, such as the measurement and control of high frequency risks, its contagion to the low frequency domain and the computation of hedges. Being a new field of research, the list of pending questions not addressed by this work, and for which (presently) no answer exists, is endless. In particular, we will not participate in the polemic regarding the social benefit or cost derived from high frequency trading. This is an extremely complex debate which would require a monographic book.

Methodology

We will employ an assortment of techniques drawn from mathematical and statistical analysis to answer questions derived from this confluence of areas (Finance, Statistics, Economic Analysis). In particular:

- Probability and econometric methods for time series
    - Chapter II estimates VAR and Granger-causality models in order to analyze VPIN's predictive power on volatility.
    - Chapter II estimates conditional distribution probabilities, correlation surfaces and threshold correlations.
    - Chapter VI makes use of cointegration and error correction models to estimate the optimal hedging vectors on spreads.
    - Chapter VII employs a mixture of Normal distributions to illustrate the inflationary effect that skewed and fat-tailed returns distributions have on Sharpe ratio.

    - Chapter VII develops a projection of Sharpe ratio in the probabilistic domain (PSR).
    - Chapter VIII develops the EF3M algorithm for the exact fit of a Mixture of two Gaussian distributions.
- Monte Carlo methods
    - Chapter I evaluates how accurately VPIN estimates PIN.
    - Chapter V simulates the impact that a variety of serial price correlation scenarios have on VPIN.
    - Chapter V simulates the performance of the VPINC execution algorithm in comparison to VWAP.
    - Chapter VIII applies a Monte Carlo to evaluate the Probability of Departure of an investment strategy.
- Linear algebra
    - Chapter II computes an analytical spectral decomposition of the VAR coefficients matrix.
    - Chapter VI develops a generalized PCA hedging procedure, not bounded by number of instruments or asset class.
- Differential calculus
    - Chapters I, II, V and VI apply optimization methods to identify the global maxima or minima on a variety of problems.
    - Chapter VI solves the analytical derivatives of the objective functions for the MMSC and DFO methods.
    - Chapter VI presents a customized algorithm for the optimization of the MMSC objective function.
    - Chapter VII computes the gradient of the "minimum track record length" due to sampling frequency.
- Differential equations and equations in differences
    - Chapter II develops a dynamic equilibrium model for the determination of the state of the VPIN-Volatility system, in discrete and continuous time.
- Historical simulations
    - Chapters I, II, V and VI estimate the historical performance of multiple variables based upon high frequency time series.
    - Chapter VII determines the minimum backtest size required in order to evidence skill subject to a predefined confidence level.

Organization and format

This study is organized in eight interrelated papers. Four have been peer-reviewed and accepted for publication at scientific journals (the first three co-authored with Profs. Easley and O'Hara):

- Chapter I is the basis for a paper accepted for publication in the *Review of Financial Studies* (forthcoming, 2012).
- Chapter III is the basis for a paper accepted for publication in the *Journal of Portfolio Management* (Winter 2011). http://www.iijournals.com/doi/abs/10.3905/jpm.2011.37.2.118
- Chapter IV is the basis for a paper accepted for publication in the *Journal of Trading* (Spring 2011). http://www.iijournals.com/doi/abs/10.3905/jot.2011.6.2.008
- Chapter VI is the basis for a paper accepted for publication in the *Journal of Investment Strategies* (Risk Journals, forthcoming, 2012).

According to *"The Social Science Research Network"* (SSRN), these papers have been downloaded by up to 35,000 social scientists members of this network (http://ssrn.com/author=434076). Some of the papers derived from this study have been included in the top 10 ranking for the most read papers in the history of SSRN, in the areas of Finance, Economic models and Econometrics:

- http://papers.ssrn.com/sol3/topten/topTenResults.cfm?groupingId=1152425&netorjrnl=jrnl
- http://papers.ssrn.com/sol3/topten/topTenResults.cfm?groupingId=1153655&netorjrnl=jrnl
- http://papers.ssrn.com/sol3/topten/topTenResults.cfm?groupingId=1153629&netorjrnl=jrnl

Compliant with Complutense University's regulations, we include an extensive summary of the findings and conclusions, written in Spanish.[1]

Seminars

A number of the models included in this work have been presented in international seminars:

1. Opening Keynote Speech at *"Best Execution USA 2010"* conference:
    a. Title: *"Flash Crash: Dissecting what happened and preventing it from happening again"*.
    b. Location: New York City
    c. Date: October 6th 2010.
    d. Host: Risk Magazine.
    e. Link: http://ev153.eventive.incisivecms.co.uk/static/day11
2. Seminar offered to CFTC Commissioners and Researchers:
    a. Title: *"The Microstructure of the Flash Crash"*.

[1] Art. 4.3 of UCM's Directive of 12/02/2010, developing the Royal Decree 1393/2007 of October 29th (B.O.E. 30/10/2007).

Carlin, Sousa Lobo and Viswanathan (2007) developed a model of how predatory trading can lead to episodic liquidity crises and contagion. We have found that, over the last three years, hundreds of extreme price actions can be associated with failures in the liquidity provision process. It is not our goal to demonstrate that predatory algorithms are to blame. We are content with making the case that: i) liquidity crises are becoming more recurrent and ii) that this is happening despite the extraordinary degree of sophistication achieved by high-frequency market makers. We believe that a plausible explanation to this apparent contradiction is that predatory algorithms are taking advantage of the commitment of high-frequency market makers, just as macro traders would not let pass an opportunity like U.K.'s ERM episode.

Brunnermeier and Pedersen (2005) theorized that predatory trading could amplify contagion and price impact in related markets. This amplification would not be driven by a correlation in economic fundamentals or by information spillovers, but rather by the composition of the holdings of large traders who must significantly reduce their positions.

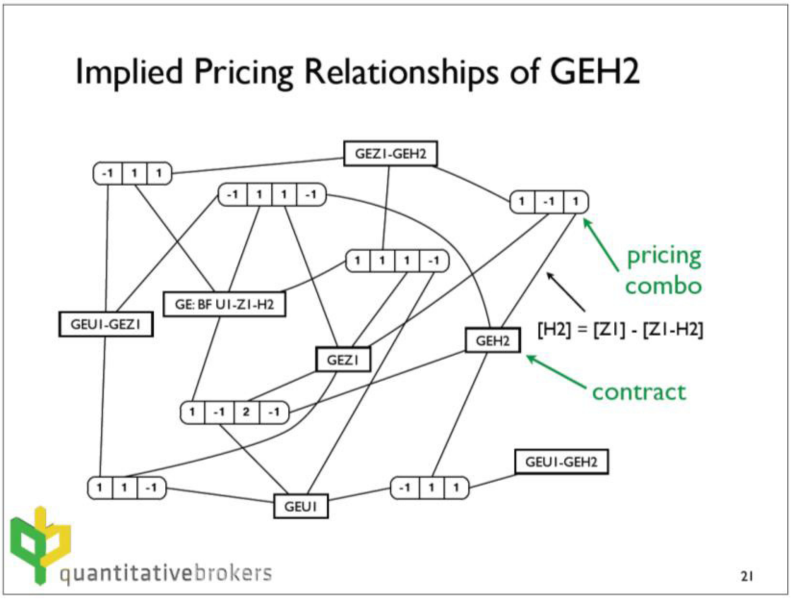

Figure 32 – Discovering hidden liquidity in the GEH2 contract

The dynamics of the order books are interrelated across multiple products. Figure 32 illustrates how, in order to decide at what level to place a client's order on Eurodollar short futures, Quantitative Brokers' algorithms analyze 6 different relationships in real time, searching for *hidden liquidity* (liquidity that, although is not displayed in that particular book, is implied by the liquidity present in the related books). Consequently, in order to operate on

2.4.1. Specification of the spill over mechanism

A system of equations in differences suits our problem, since we can only estimate VPIN in discrete (volume) time, i.e. updated every time a new volume bucket is completed.

The system is composed of two equations. The first one forecasts the absolute return over the next volume bucket as a function of the last absolute return and reading of log VPIN. The second equation forecasts the log VPIN as a function of the same variables as in the first equation. Evidently, the second equation is redundant for a unit forecasting horizon *k*, but as *k>1* the second equation allows us to incorporate in the first one the feedback mechanism.

Consider the system

$$p_1(t+1) = \beta_{1,1} p_1(t) + \beta_{1,2} p_2(t)$$
$$p_2(t+1) = \beta_{2,1} p_1(t) + \beta_{2,2} p_2(t)$$

with initial conditions $p_1(0)$, $p_2(0)$, where $p_1(t) = \left| \frac{P_t}{P_{t-1}} - 1 \right|$ and $p_2(t) = Ln(VPIN_t)$.[39]

Its matrix representation is $p(t+1) = \beta\ p(t)$, where $p(t+1) = \begin{bmatrix} p_1(t+1) \\ p_2(t+1) \end{bmatrix}$, $\beta = \begin{bmatrix} \beta_{1,1} & \beta_{1,2} \\ \beta_{2,1} & \beta_{2,2} \end{bmatrix}$.

The key role played by the second equation can be illustrated with an example. Suppose that market makers are being impacted by excessive flow toxicity. As they widen their trading ranges, volatility increases. Those market makers who were ‘slow’ in adjusting will suffer losses and vanish, which will force the ‘fast’ market makers to re-adjust. Some of those ‘fast’ market makers may miss this re-adjustment, being driven away in a second wave of losses, and so on. At some point, the chain of events may be broken (e.g., by new market makers making their appearance, attracted by wide spreads), or lead to an ‘explosive’ state. The feedback dynamics do not affect volatility over the next bucket, but it adds information over the long run, explaining the mechanism by which high frequency risks *spill over* the low frequency domain. A univariate or single-equation specification fails to provide an explanation for such spillover.

[39] Centering these variables introduces an intercept, if so desired.

2.4.2. Eigenvalues of the characteristic matrix

We know that $\beta W = W\Lambda$, which leads to the eigenvalue equation $|\beta - I\Lambda| = 0$, where W is the matrix of eigenvectors and Λ is the matrix of eigenvalues.

$\begin{vmatrix} \beta_{1,1} - \lambda & \beta_{1,2} \\ \beta_{2,1} & \beta_{2,2} - \lambda \end{vmatrix} = 0 \Rightarrow (\beta_{1,1} - \lambda)(\beta_{2,2} - \lambda) - \beta_{1,2}\beta_{2,1} = 0$, a second degree equation with roots in $\lambda_1 = \dfrac{Tr(\beta) + \sqrt{Tr(\beta)^2 - 4|\beta|}}{2}$; $\lambda_2 = \dfrac{Tr(\beta) - \sqrt{Tr(\beta)^2 - 4|\beta|}}{2}$, where $Tr(\beta)$ is the trace of β and $|\beta|$ its determinant. Thus, $\Lambda = \begin{bmatrix} \lambda_1 & 0 \\ 0 & \lambda_2 \end{bmatrix}$.

2.4.3. Eigenvectors of the characteristic matrix

Λ has been found to make the matrix $\beta - I\Lambda$ singular. Let's compute β's eigenvectors by finding $\beta - I\Lambda$'s kernel.

For λ_1, we establish a system $\begin{bmatrix} \beta_{1,1} - \lambda_1 & \beta_{1,2} \\ \beta_{2,1} & \beta_{2,2} - \lambda_1 \end{bmatrix}\begin{bmatrix} w_{1,1} \\ w_{2,1} \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix}$. Elemental row operations will yield $\begin{bmatrix} 1 & \dfrac{\beta_{1,2}}{\beta_{1,1} - \lambda_1} \\ 0 & 1 \end{bmatrix}$, and so we reduce the system to:

$$w_{1,1} + w_{2,1}\frac{\beta_{1,2}}{\beta_{1,1} - \lambda_1} = 0$$

$$w_{2,1} = 1$$

Applying the especial solutions on the kernel allow us to conclude that $W = \begin{bmatrix} \dfrac{-\beta_{1,2}}{\beta_{1,1} - \lambda_1} & \dfrac{-\beta_{1,2}}{\beta_{1,1} - \lambda_2} \\ 1 & 1 \end{bmatrix}$.

Let's write $p(0) = Wc$, where c is, like before, the column vector that solves W for the initial conditions $p(0)$. Assuming that β has all independent eigenvectors, we know that β is diagonalizable and $\beta = W\Lambda W^{-1}$. Then, $p(1) = \beta p(0) = W\Lambda W^{-1}Wc = W\Lambda c$. Multiplying k times by β will yield $p(k) = \beta^k p(0) = W\Lambda^k c$, or what is the same, $p(k) = \begin{bmatrix} p_1(k) \\ p_2(k) \end{bmatrix} = c_1\lambda_1^k \begin{bmatrix} w_{1,1} \\ w_{2,1} \end{bmatrix} + c_2\lambda_2^k \begin{bmatrix} w_{1,2} \\ w_{2,2} \end{bmatrix}$.

At the initial conditions, $p(0) = c_1 \begin{bmatrix} w_{1,1} \\ w_{2,1} \end{bmatrix} + c_2 \begin{bmatrix} w_{1,2} \\ w_{2,2} \end{bmatrix}$, which is a system we already solved: $c_1 = p_2(0) - c_2$, $c_2 = \dfrac{p_1(0) - p_2(0)w_{1,1}}{w_{1,2} - w_{1,1}}$.

2.4.4. The solution

$$\begin{bmatrix} \left|\dfrac{P_{t+k}}{P_{t+k-1}} - 1\right| \\ Ln\left(VPIN_{t+k}\right) \end{bmatrix} = c_1\lambda_1^k \begin{bmatrix} w_{1,1} \\ w_{2,1} \end{bmatrix} + c_2\lambda_2^k \begin{bmatrix} w_{1,2} \\ w_{2,2} \end{bmatrix}$$, where:

- $\begin{bmatrix} w_{1,1} & w_{1,2} \\ w_{2,1} & w_{2,2} \end{bmatrix} = \begin{bmatrix} \dfrac{-\beta_{1,2}}{\beta_{1,1} - \lambda_1} & \dfrac{-\beta_{1,2}}{\beta_{1,1} - \lambda_2} \\ 1 & 1 \end{bmatrix}$.
- $\lambda_1 = \dfrac{Tr(\beta) + \sqrt{Tr(\beta)^2 - 4|\beta|}}{2}$; $\lambda_2 = \dfrac{Tr(\beta) - \sqrt{Tr(\beta)^2 - 4|\beta|}}{2}$, where $Tr(\beta)$ is the trace of β and $|\beta|$ its determinant.
- $c_1 = Ln\left(VPIN_0\right) - c_2$; $c_2 = \dfrac{\left|\dfrac{P_1}{P_0} - 1\right| - Ln\left(VPIN_0\right)w_{1,1}}{w_{1,2} - w_{1,1}}$.

Our solution is analytical and the forecast can be estimated in a single calculation for any horizon (no sequential estimation is needed). This is an important advantage for the purpose of integrating our equations in optimization exercises.

2.4.5. Stability conditions

Now that we know how to estimate our dynamic system, we would like to understand what causes a crash from a mathematical standpoint. Later on, we will offer an interpretation from a market microstructure perspective.

The previous analysis is powerful in the sense of establishing the conditions for the system to be *stable*, *steady* or *explosive* in discrete time:

- *Stable state*: $|\lambda_i| < 1; i = 1,2$. Both eigenvalues must be smaller than one in absolute value. If imaginary eigenvalues exist, their real part must be smaller than one in absolute value.
- *Steady state*: $\exists i, j \| \lambda_i| = 1, |\lambda_j| < 1$. The absolute value of one eigenvalue is equal to one, and the other is not greater than one in absolute value (or their real part, being imaginary).
- *Explosive state*: $\exists i \| \lambda_i| > 1$. The absolute value of any eigenvalue is greater than one (or their real part, being imaginary).

2.5. The continuous time model

2.5.1. Model specification

Consider two variables with levels $p_1(t), p_2(t)$, mutually related by a system of differential equations:

$$\begin{aligned}\frac{dp_1(t)}{dt} &= \beta_{1,1}p_1(t) + \beta_{1,2}p_2(t)\\ \frac{dp_2(t)}{dt} &= \beta_{2,1}p_1(t) + \beta_{2,2}p_2(t)\end{aligned}$$

, with initial conditions $p_1(0)$, $p_2(0)$ where $p_1(t) = \left|\frac{P_t}{P_{t-1}} - 1\right|$ and $p_2(t) = Ln(VPIN_t)$.

Its matrix representation is $\frac{dp(t)}{dt} = \beta\ p(t)$, where $\frac{dp(t)}{dt} = \begin{bmatrix}\frac{dp_1(t)}{dt}\\ \frac{dp_2(t)}{dt}\end{bmatrix}$,

$\beta = \begin{bmatrix}\beta_{1,1} & \beta_{1,2}\\ \beta_{2,1} & \beta_{2,2}\end{bmatrix}$, $p(t) = \begin{bmatrix}p_1(t)\\ p_2(t)\end{bmatrix}$.

Let's assume that β is diagonalizable[40], i.e. it has linearly independent eigenvectors. Under this assumption, we will solve this system and, furthermore, study its dynamics, stability conditions and possible equilibrium.

[40] A non-necessary but sufficient condition is having all different eigenvalues.

We have already derived $\Lambda = \begin{bmatrix} \lambda_1 & 0 \\ 0 & \lambda_2 \end{bmatrix}$, with $\lambda_1 = \frac{Tr(\beta) + \sqrt{Tr(\beta)^2 - 4|\beta|}}{2}$ and $\lambda_2 = \frac{Tr(\beta) - \sqrt{Tr(\beta)^2 - 4|\beta|}}{2}$, as well as $W = \begin{bmatrix} \frac{-\beta_{1,2}}{\beta_{1,1} - \lambda_1} & \frac{-\beta_{1,2}}{\beta_{1,1} - \lambda_2} \\ 1 & 1 \end{bmatrix}$.

2.5.2. The solution

The general solution of this system has the form[41] $p(t) = c_1 e^{\lambda_1 t} \begin{bmatrix} w_{1,1} \\ w_{2,1} \end{bmatrix} + c_2 e^{\lambda_2 t} \begin{bmatrix} w_{1,2} \\ w_{2,2} \end{bmatrix}$, all of which has been previously derived except for the $\begin{bmatrix} c_1 \\ c_2 \end{bmatrix}$. This we can compute thanks to the initial conditions of the system ($p(0)$). At *t=0*, we know that

$$\begin{bmatrix} \frac{-\beta_{1,2}}{\beta_{1,1} - \lambda_1} & \frac{-\beta_{1,2}}{\beta_{1,1} - \lambda_2} \\ 1 & 1 \end{bmatrix} \begin{bmatrix} c_1 \\ c_2 \end{bmatrix} = \begin{bmatrix} p_1(0) \\ p_2(0) \end{bmatrix}.$$

Finally, $c_1 = p_2(0) - c_2$, $c_2 = \frac{p_1(0) - p_2(0) w_{1,1}}{w_{1,2} - w_{1,1}}$.

Note how similar the solution to the system in differences is to the solution of the system of differential equations. However, this similarity is only in structure, because *β* (and therefore also *Λ*, *W* and *c*) will have different values.

[41] For a simple proof, see that $\frac{dp(t)}{dt} = \beta\ p(t)$ can be rewritten in terms of its pure solutions. For example, $\frac{dp(t)}{dt} = \lambda_1 e^{\lambda_1 t} \begin{bmatrix} w_{1,1} \\ w_{2,1} \end{bmatrix}$ and $\beta\ p(t) = \beta e^{\lambda_1 t} \begin{bmatrix} w_{1,1} \\ w_{2,1} \end{bmatrix}$, which are one and the same since we know that $\lambda_1 \begin{bmatrix} w_{1,1} \\ w_{2,1} \end{bmatrix} = \beta \begin{bmatrix} w_{1,1} \\ w_{2,1} \end{bmatrix}$ from linear algebra.

2.5.3. Stability conditions of the differential specification

Looking at the general form of the solution, $p(t) = c_1 e^{\lambda_1 t} \begin{bmatrix} w_{1,1} \\ w_{2,1} \end{bmatrix} + c_2 e^{\lambda_2 t} \begin{bmatrix} w_{1,2} \\ w_{2,2} \end{bmatrix}$, we ought to distinguish among three alternative outcomes in continuous time:

- *Stable state*: Both eigenvalues are negative. If imaginary eigenvalues exist, their real part must be negative.
- *Steady state*: If at least one eigenvalue is null and the other is negative (or their real part, if imaginary).
- *Explosive state*: If any eigenvalue is positive (or their real part, being imaginary).

2.6. Empirical results

Chapter I showed that a VAR model on log VPIN and Absolute Returns had more predictive power *over the next observation in-sample* than an AR model on Absolute Returns. We would like to test how much more predictive our dynamic system is in a *multi-horizon out-of-sample forecast*.

After computing VPINs on our standard *(V,n)=(50,250)* combination, we have fitted our dynamic system every 50 buckets (equivalent to a day on average) starting January 1st 2008 on samples of 250 buckets (encompassing 1 week worth on data on average). After every fit, we have computed out-of-sample forecasts 1, 2, …, 50 buckets forward (equivalent to 1 day ahead on average). We have compared each k-horizon forecast with the realized absolute return, which gives us the out-of-sample forecasting error.

Let's denote τ the bucket at which a fit has occurred. As discussed, we can compute the *k=1,…,50* forecasting errors that follow our fit at bucket τ as:

$$e_\tau(k) = \left|\frac{P_{\tau+k}}{P_{\tau+k-1}} - 1\right| - E_\tau\left[\left|\frac{P_{\tau+k}}{P_{\tau+k-1}} - 1\right|\right]$$

Table 3 and 4 compare the standard deviation of the out-of-sample forecasting errors of the autoregressive univariate specification with those of the dynamic system.

Two important aspects can be extracted from these results:

1. VPIN improves the single horizon forecast of volatility (*k=1*). The univariate forecast (20% StDev) is more unreliable than the bivariate forecast that includes VPIN (17%). We knew this from Section 2.3.
2. As forecasts are produced beyond the immediate horizon (*k>1*), our dynamic system's confidence does not significantly decay, while the confidence of the univariate forecast persistently deteriorates.

$$\frac{\partial^2 \sigma_{\Delta S}^2}{\partial {\omega_i}^2} = 2\sigma_{\Delta \mathrm{P}_i}^2 \tag{39}$$

$$\frac{\partial^2 \sigma_{L(S)}}{\partial {\omega_i}^2} = -\frac{1}{8}\left[\sigma_{L(S)}^2\right]^{-2} \left(\frac{\partial \sigma_{L(S)}^2}{\partial \omega_i}\right)^2 \frac{\partial^2 \sigma_{L(S)}^2}{\partial {\omega_i}^2} \tag{40}$$

$$\frac{\partial^2 \sigma_{L(S)}^2}{\partial {\omega_i}^2} = 2\sigma_{L(\mathrm{P}_i)}^2 \tag{41}$$

$$\begin{aligned}\frac{\partial^2 \rho_{\Delta S,L(S)}}{\partial {\omega_i}^2} = \left(\sigma_{\Delta S}\sigma_{L(S)}\right)^{-4} \Bigg[\Bigg(&\frac{\partial\left[\sigma_{\Delta S}\sigma_{L(S)}\right]}{\partial \omega_i}\frac{\partial \sigma_{\Delta S,L(S)}}{\partial \omega_i} \\ &- \frac{\partial^2\left[\sigma_{\Delta S}\sigma_{L(S)}\right]}{\partial {\omega_i}^2}\rho_{\Delta S,L(S)} \\ &- \frac{\partial \rho_{\Delta S,L(S)}}{\partial \omega_i}\frac{\partial\left[\sigma_{\Delta S}\sigma_{L(S)}\right]}{\partial \omega_i}\Bigg)\sigma_{\Delta S}^2\sigma_{L(S)}^2 \\ &- \frac{\partial\left[\sigma_{\Delta S}^2\sigma_{L(S)}^2\right]}{\partial \omega_i}\Bigg(\frac{\partial \sigma_{\Delta S,L(S)}}{\partial \omega_i}\sigma_{\Delta S}\sigma_{L(S)} \\ &- \frac{\partial\left[\sigma_{\Delta S}\sigma_{L(S)}\right]}{\partial \omega_i}\rho_{\Delta S,L(S)}\Bigg)\Bigg]\end{aligned} \tag{42}$$

$$\begin{aligned}&\frac{\partial^2 \widehat{DF}}{\partial {\omega_i}^2} \\ &= \frac{\partial^2 \rho_{\Delta S,L(S)}}{\partial {\omega_i}^2}\Bigg(\left(\frac{1-\rho_{\Delta S,L(S)}^2}{T-2}\right)^{-\frac{1}{2}} \\ &+ \frac{1}{(T-2)}\left(\frac{1-\rho_{\Delta S,L(S)}^2}{T-2}\right)^{-\frac{3}{2}}\rho_{\Delta S,L(S)}^2\Bigg) \\ &+ \frac{\partial \rho_{\Delta S,L(S)}}{\partial \omega_i}\Bigg(\left(\frac{1-\rho_{\Delta S,L(S)}^2}{T-2}\right)^{-\frac{3}{2}}\rho_{\Delta S,L(S)}\frac{\partial \rho_{\Delta S,L(S)}}{\partial \omega_i} \\ &+ \left(\frac{3}{(T-2)}\left(\frac{1-\rho_{\Delta S,L(S)}^2}{T-2}\right)^{-\frac{5}{2}}2\rho_{\Delta S,L(S)}\frac{\partial \rho_{\Delta S,L(S)}}{\partial \omega_i}\right)\rho_{\Delta S,L(S)}^2 \\ &+ \frac{2}{T-2}\rho_{\Delta S,L(S)}\frac{\partial \rho_{\Delta S,L(S)}}{\partial \omega_i}\left(\frac{1-\rho_{\Delta S,L(S)}^2}{T-2}\right)^{-\frac{3}{2}}\Bigg)\end{aligned} \tag{43}$$

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Tudor Investment Corporation has been ranked among the top-3 most profitable hedge funds in history.[113] Tudor's funds manage in excess of 12 billion dollars, of which about 1/3 is allocated to Systems Trading. Tudor's High Frequency group is comprised by leading researchers and developers coming from the fields of Physics, Mathematics, Engineering, Computer Science and Economics.

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[112] Official doctoral record: https://educacion.gob.es/teseo/mostrarRef.do?ref=295773

[113] *"Hedge fund report card"*, Absolute Return Magazine, September 2009.

ABOUT COMPLUTENSE

Founded on May 20th, 1293 by Royal Charter of King Sancho IV of Castile, **Complutense University** (*"Universitas Complutensis"*) is one of the oldest universities in continuous operation. In the course of over 7 centuries of history, Complutense has made some of the most enduring contributions to Western civilization.

While at Complutense, Antonio de Nebrija published the first grammar of a modern language (1492), and the first dictionaries Latin-Spanish (1492) and Spanish-Latin (1495). He was also the first erudite to make claims of intellectual property.

By the year 1509 it already had five major Colleges: Medicine, Philology, Arts and Philosophy, Theology and Canon Law. One of its alumni, Cardinal Cisneros, attracted many of the world's foremost linguists and biblical scholars. The Complutensian Polyglot Bible (1514), one of the greatest academic works of the Renaissance, was the result of 15 years of interdisciplinary research. For instance, the Greek typefaces devised for this 6 volume *tractatus* constituted the template for the Greek fonts used nowadays (*Otter Greek*, *GFS Complutensian Greek*). This publication predates Erasmus' *Textus Receptus* (1516), which later became the basis for Oxford University's King James version (1611).

Other former pupils include renowned philosophers (Ortega y Gasset, Marías, de Soto), writers (Lope de Vega, Quevedo, Lorca), scientists (Ramón y Cajal, Ochoa, Cabrera, Terradas, Marañón), historians (Mariana, Menéndez y Pelayo, Menéndez Pidal), military leaders (Don John of Austria, Farnese) and international officials (Solana, Rato, Borrell, Oreja). Between 1857 and 1954, only Complutense had the authority to grant Doctor degrees in the Kingdom of Spain (Moyano act). Complutense was the first European University from which Albert Einstein accepted a Doctor of Science degree *"Honoris Causa"* (February 28th, 1923). In April 1933, Dr. Einstein also accepted a Faculty position at one of its Research Institutes.

In recent years, the roster of alumni comprises winners of the Prince of Asturias Prize (18), Miguel de Cervantes Prize (7), Nobel Prize (7), Solvay Conference, European Union Commissioners, Presidents of the EU Parliament, European Council Secretary General, ECB Executive Board members, NATO Secretary General, UNESCO Director General, IMF Managing Director, Heads of State, Prime Ministers, etc.

The **Real Colegio Complutense at Harvard University** (RCC) was founded as a joint cooperative institution to foster intellectual and scientific interaction between Harvard University and Complutense. It follows the tradition of the Royal Spanish College, founded in 1364 (and in operation ever since) to host Spanish Visiting Scholars at the University of Bologna. The RCC accord is the only one of its sort ever to have been approved by Harvard. The institution is directed jointly by the President of Harvard and the Rector of Complutense, with an academic council formed by 5 Harvard professors and 5 Complutense professors.

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