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Latency Arbitrage When Markets Become Faster*

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Abstract

We measure the incidence of latency arbitrage for cross-listed stocks around the time of an exogenous shock that made the markets faster. Our sample is from NASDAQ Nordic and consists of Nordic blue chip firms listed and traded in multiple markets. We document a sharp decline in the incidence of cross-market arbitrage opportunities across the Nordic markets for cross-listed stocks from 2009 to 2010 and later. Over the five year sample period 77% of the observed cross-market arbitrage opportunities occurred in 2009 and 13% in 2010 and the remaining 10% spread over the last three years. The inside spread declines by, on average, 14.5 basis points or 53% from 2009 to 2013. Our results point to significant improvements in market efficiency and market quality as a result of the switch to a faster trading system.

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1. Introduction

The absence of arbitrage is a basic starting point for many questions in financial economics. When an arbitrage opportunity arises we expect arbitrageurs to quickly compete to take advantage of the opportunity and the absence of arbitrage is restored as a result of their activities. The length of time it takes for the arbitrage process to play out is primarily driven by attention costs and technological constraints. We expect these opportunities to be fewer and last for shorter periods of time as markets and the market participants invest massively in faster trading technology. As market makers invest in faster trading technology that allows them to reduce the option value of the quotes they place in the market (**?**) fewer arbitrage opportunities will arise in the first place.

The INET trading system was introduced on February 8th 2010 on the NASDAQ Nordic exchanges (Copenhagen, Stockholm, and Helsinki) for all equity markets. Hans-Ole Jochumsen, President NASDAQ OMX Nordic said,

> "This trading system shift is one of the biggest infrastructural changes in the history of the Nordic equities markets. With INET in place we can offer investors access to the world's fastest and most scalable trading system. This will allow us to grow volumes and liquidity, which benefits all investors and ultimately the regional economies. It will enable us as an exchange and the Nordic regions to better compete in Europe's increasingly competitive trading environment."[1]

We study the incidence of arbitrage opportunities for cross-listed securities on NASDAQ Nordic exchanges (Copenhagen, Stockholm, and Helsinki) for a sample period that begins more than a year before the switch to the INET trading platform and ends more than 3 years later. The three markets, Copenhagen, Helsinki, and Stockholm, are well integrated and the main trading friction is that they all use a different currency. Finland is the only Nordic country that adopted the Euro (EUR), Sweden and Denmark, also EU members, voted not to adopt the common currency, continuing to use Swedish Kronor (SEK) and Danish Kroner (DKK). For several large listed firms there exists investor clienteles in the respective markets and that makes local markets in these securities viable. The existence of large local investor clienteles is a result, in many but not all cases, of cross-border mergers.

Take for instance Stora Enso, a large global wood and paper company, which was the

[1]Source: Press release "NASDAQ OMX LAUNCHES INET TRADING SYSTEM ACROSS ITS SEVEN MARKETS IN THE NORDICS AND BALTICS' accessed at `http://ir.nasdaq.com/releasedetail.cfm?releaseid=443390`

results of a merger of the Finnish company Enso with the Swedish company Stora in 1998 (fifth largest paper and woodproducts company in the world by sales). Both companies have very long histories and naturally a large base of shareholders in the two respective countries as well as elsewhere. Hence for Stora Enso it was a natural decision in this case to continue to be listed in both countries after the merger. The Stora Enso shares in traded in Helsinki (EUR) and Stockholm (SEK) represent claims to future dividends paid that ought to be equivalent once converted to the same currency. What this means from a financial market perspective is that there is a segmentation of the order flow with a local investor clientele in both markets. There is also a significant group of sophisticated market participants who either make markets or act as arbitrageurs when prices appear to be out of line for these securities. We expect the sophisticated market participants to do so more quickly when the new faster trading system is implemented.

It is important to note that the exchange servers for Copenhagen, Stockholm, and Helsinki are all located in one place in Stockholm. In other words, there are no real information propagation delays for a participant whose computers are located in Stockholm, see for example **?** who discuss these issue in the context of markets in New York City and Chicago. As a result we would expect that the exchange members who will engage in either market making or latency arbitrage, or both activities, to have computers located close to the servers in Stockholm. Nasdaq Nordic offers a full range of colocation services.

Our results document a significant increase in the correlations of the mid-quotes for the cross-listed firms suggesting greater informational efficiency over this period. The rate of increase varies with the time interval and the over the years but on average the correlation between mid-quotes of the same security increase by between 61% and 89%. The frequency of cross-market arbitrage opportunities also falls dramatically from 2009 to the later years. For the following group of four stocks: Nokia, Nordea, Stora Enso, and Telia, over the five year sample period 77% of the observed cross-market arbitrage opportunities occurred in 2009. In 2010 the number corresponded to 13% leaving 10% spread across 2011-2013 implying that the cross-market arbitrage opportunities dried up over this period. Note that we do not make any assumptions about costs and minimum size for opportunities so we may be including opportunities that were not viable arbitrage opportunities. Be that as it may the quotes for the cross-listed securities are much more aligned in the later part of our sample period.

One may of course wonder if this is a result of widening spreads because in principle, everything else equal, a wider spread implies fewer arbitrage opportunities. That is not what we find. The inside spread gets tighter over the sample period with the inside depth not

displaying a significant change. In this light the disappearance of the cross market arbitrage opportunities is more remarkable when one considers the strong tightening of bid-ask spreads. The tick size was reduced in what was called the *tick size harmonization* across European markets which occurred in October 2009 and January 2010 for the markets we study. The tick size harmonization clearly was also a factor in the tightening of bid-ask spreads. Overall our results suggests the Nasdaq Nordic market displays an improvement in informational efficiency and an improvement or no change in market liquidity over a period when the markets becomes faster. A big component of this improvement is that limit orders are managed in a radically different way for many market participants in this new regime for equity trading in the Nordic region.

The studies most closely related to ours are **?** and **?**. The **?** study focuses on the arbitrage between the two largest financial instruments that track the S&P 500 index, the SPDR S&P 500 exchange traded fund and the S&P 500 E-mini futures contract. For the 2005 – 2011 they document the prevalence of high-frequency arbitrage opportunities that have not decreased in size despite the more intense competition over the sample period. They argue that the results are symptoms of a fundamental flaw with continuous trading and argue for a frequent batch auction as an alternative market design. Foucault, Kozham, and Tham (2017) present a theoretical model and their empirical analysis focuses on triangular arbitrage opportunities between USD/EUR, USD/GBP and EUR/GBP for the period 2003 to 2004. They model cross-market arbitrage and focus on the difference between toxic arbitrage opportunities–those due to asynchronous price adjustments to news—as opposed to non-toxic arbitrage opportunities—those due to liquidity shocks. We also study cross-market arbitrage and in that sense we are closely related to these two studies albeit we study a different market and sample period. The bigger difference is that our main finding is a decline in the incidence of latency arbitrage opportunities. We believe that vis-a-vis the **?** an important difference is that despite being different markets, for example, for Nokia shares traded in EUR or SEK the exchange server is located in a single place.[2]

The rest of our paper is organized as follows. Related literature is discussed in the next section. We then present some institutional background, our sample, and our empirical approach. The next section details our results. A section on the interpretation follows and then we conclude.

[2] **?** documents the prevalence and profitability of latency arbitrage opportunities on US Stock exchanges.

2. Related Literature

? makes the following point "The arrival of new capital to an investment opportunity can be delayed by fractions of a second in some markets, for example, an electronic limit-order-book market for equities or by months in other markets...[...]" We examine changes in the time it takes for either quote setting parties to update their quote *or* arbitrage capital to arrive over a period that experience a major technological shock to the trading system making it a lot faster. Our study contributes to the growing literature on high-frequency trading reviewed by **?**, **?**, and **?** and others. **?** review equity trading in the 21st century and documents a continued improvement in market quality.

Our results complement the empirical results of **?** which motivates their market design proposal; both studies focus on markets that in theory should be perfectly correlated, the difference is that there is a physical distance in the **?** study, New York to Chicago, whereas in ours there is no physical distance as the exchange matching engines for all Nordic markets are located in Stockholm.[3] We believe a similar trend towards faster trading systems and connections to market centers prevails for the markets and the time period we study. The difference is that the big shocks are changes introduced by the exchange itself (market technology) and therefore changes that affect all participants in the same fashion. For all participants with the right technology it is a form of democratized access to faster trading. Specifically we are finding that the frequency of arbitrage opportunities decline over our sample period and also that the size of the arbitrage opportunities shrink. This contrasts with the results of **?**.

In theory speed improvements may be good or bad for liquidity depending on whether the speed improvements enable the market makers to updated their quotes more quickly or enable fast traders to pick up stale quote raising the adverse selection risk. **?** and **?** provide different theoretical models that analyze the equilibrium effects of faster trading. Both point out the possible over-investment in fast trading technology that may not be beneficial for market liquidity.

? use the introduction of automated quote dissemination on the NYSE in 2003 as an exogenous instrument to study the impact of algorithmic trading on liquidity. Their results indicate that algorithmic trading improves liquidity and enhances informativeness of quotes. Our results also document significant improvements in liquidity in parallel with the market becoming more efficient.

[3] **?** examine execution quality of geographically dispersed stock traders throughout the United States documenting an increase in time to execution as the distance from the trader's location to NYC grows.

? study the impact of an optional co-location upgrade at Nasdaq OMX Stockholm. The upgrade that is studied take place in September 2012. Their results show improved liquidity in the markets for all entities including those that did not choose to take advantage of the colocation upgrade. Our sample overlaps with theirs and our results reinforce each other.

Our study does not address the question of whether high frequency trading is good or bad which has received considerable attention. Instead we focus on a metric of how well the markets are working—high frequency correlations between mid-quotes for securities that should be perfectly correlated and the absence of cross-market arbitrage opportunities—over a period in which the market becomes faster presumably for all participants.[4] In the setting we study we cannot say if the improvements we observe are due to more nimble behavior by those who post quotes or quicker reactions by those who pick off quotes or a combination of both.[5]

Our study is also related to the existing literature on dual-class shares and arbitrage albeit the focus here is on higher frequency phenomenon, see, for example, **?** or **?**.

Arbitrage plays a fundamental role in finance theory and practice. Cross-market arbitrage can in principle be beneficial or harmful for liquidity, see the analysis and discussion in **?**. Among policy makers the discussion of the social-value of high-speed arbitrage and specifically whether arbitrage strategies "benefit or harm the interests of long-term investors and market quality in general. [...]" (U.S. Securities and Exchange Commission (2010), Section B, page 52 point to some of the issues. Our study does not directly address the types of arbitrage across markets, but by reporting evidence for a period over which trading became faster and arbitrage opportunities declined while the bid-ask spread shrunk is encouraging and point to benefits to market quality of faster trading technology.

[4]We are aware that the introduction of INET was a massive technological shock for some member firms and as a consequence they may not have been prepared to take advantage or even survive under this new regime. Nonetheless this was a shock that involved an investment in *market technology* that made the market faster for all rather than an investments in *trading technology* that would make some participants faster. Of course, such investments may also have taken place but we focus on the changes in market dynamics and performance around the market wide shocks.

[5]Analysis is in progress to document the frequencies of arbitrage episodes concluding in a quote change, a trade, or an FX quote change.

3. Institutional Background and Sample

3.1. Institutional Background

NASDAQ as the exchange operator in the Nordic and Baltic region started with the merger of NASDAQ with the OMX group in 2007. In 2010 the equity markets in the Nordic and Baltic countries introduced the INET trading system which replaced the SAXESS (OMX) trading system. We will focus on the institutional setting that pertains to Denmark, Sweden and Finland that have a few large cross-listed firms whose trading we focus on. All three markets operate their continuous-time limit order books which quotes prices in their respective currencies, DKK, SEK and EUR. The major exchange member firms tend to be members of all three of these markets.[6] Naturally as markets operated by one exchange operator the exchange rules are for the most part harmonized and hence we have an ideal situation with strongly integrated markets with a few frictions.

Our sample period includes a few major shocks to the Nordic equity markets. Arguably the biggest shock was the aforementioned introduction of the INET trading system. Two other shocks were the two-step introduction of the harmonized tick sizes. The harmonized tick sizes were implemented in Stockholm on October 26th, 2009, and on January 4th, 2010, for Copenhagen and Helsinki. The new tick size rules were to decrease the tick sizes by about 47% across index constituent stocks across the three markets. All stocks in our sample were affected in one or both markets.

The European harmonized tick sizes was implemented for the most liquid stocks on the Stockholm, Helsinki and Copenhagen exchanges. The new tick size regime was implemented on October 26th for Stockholm, followed by the Helsinki and Copenhagen equity markets on January 4th, 2010. A harmonized tick size reduced one friction that could cause the quotes in two markets to be misaligned. With a smaller tick size that became less likely.

3.2. Data and Sample Period

Our sample consists of order book and trade data for a selection of cross-listed stocks trading on the Nasdaq Nordic. Nasdaq Nordic refers to Nasdaq-operated exchanges in Helsinki, Copenhagen, Stockholm, Iceland (Reykjavik) , Riga, Tallinn and Vilnius. We identify six cross-listed securities, each of which are listed on the Stockholm and Helsinki exchanges. Nordea

[6] As an illustration of this point the top twenty exchange member firms had a combined market share over 70% in June 2009 and June 2010 and of those twenty member firms only two were not members of all three exchanges, Helsinki, Stockholm, and Copenhagen. Those firms were members of the Helsinki and Stockholm exchanges but not Copenhagen. Sorce: `http://www.nasdaqomx.com/transactions/markets/nordic/statistics`

Group is the lone security in our sample that is listed on three exchanges, the third being Copenhagen. Our trade and quote data, with microsecond granularity, was acquired from Thomson Reuters.[7]

In selecting our sample, we eliminated one stock, Ericsson, due to low relative volume. Ericsson shares traded in EUR has a very small volume and underscores that the working liquid cross-listings happens because a firm has an active local investor clientele in two or more markets, not the other way around. (See Table **??**) Initially we restrict our analysis to Nordea in Helsinki and Stockholm only in order to avoid the additional complexity of a third currency at this stage. In subsequent versions we plan to include SAS and Nordea (Copenhagen), SAS is cross-listed on Stockholm and Copenhagen exchanges.[8] The remaining stocks are Nokia, Nordea Group, Stora Enso, Tieto, and Telia Sonera.

Nokia is the well known telecommunications company headquartered in the Helsinki metropolitan area. Nordea Group is a Swedish bank that has grown through a number of mergers with Danish, Finnish, Norwegian and Swedish banks, which accounts for its cross listing on three exchanges. Stora Enso is a paper company headquartered in Helsinki. The company is a result of a merger the Swedish company Stora and the Finnish company Enso, explaining the cross-listing. Telia Sonera, a telecommunications company resulting from the merger of Swedish company Telia and Finnish company Sonera. Scandinavian Airlines (SAS) is one of the flagship airlines in Scandinavia and it was formed with investors from Denmark, Sweden, and Norway in the 50s.

The trading hours are adjusted so that there are identical for Helsinki, Stockholm, and Copenhagen. Effectively Helsinki trading hours are shifted by one hour to account for the different time zone that Finland is in. GMT is used in our analysis.

Table 1 reports the volume share of each market within the NASDAQ Nordic market. In the case of each stock, there is a dominant market in terms of volume. Helsinki is the dominant market with the majority of volume for Nokia, Stora Enso and Tieto. Stockholm is the dominant market for Nordea Group and Telia Sonera.

Prices and quotes in Swedish Kronor (SEK) are converted to euros (EUR) using exchange rate data acquired from *Olsen Financial Technologies*[9]. The foreign exchange data is provided

[7] As the data is not direct feed data from the exchange one may worry about whether the Thomson Reuters time stamps accurately reflect the Nasdaq Nordic time stamps. We believe that is less of a concern here as all data originates with Nasdaq Nordic in Stockholm and therefore should not bias our data in any particular way.

[8] SAS is actually also listed in three markets, Stockholm, Copenhagen, and Oslo but the Oslo Exchange is not operated by Nasdaq introducing several frictions like differences in exchanges rules, geographical distance to exchange server etc.

[9] $http://www.olsendata.com$

at microsecond granularity. We use the mid-quote at time t to convert the bid and ask in stocks on NASDAQ OMX Stockholm to euro ignoring the bid-ask spread in the FX market.

3.3. Empirical Methodology

In this section we present our empirical approach. First, we explain how we measure high-frequency mid-quote correlations for pairs of markets. Second, we present the definition of cross-market arbitrage that we apply.

3.3.1. Mid-Quote Correlations

Let the two markets for the same security be denoted market 1 and market 2 on day d. Define returns based on the mid-quotes in market i in native currency over the time interval t to $t + \Delta t$ on day d as

$$r^{i,d}_{t,t+\Delta t} = \frac{mq^{i,d}_{t+\Delta t} - mq^{i,d}_{t}}{mq^{i,d}_{t}},$$

where typical Δt is 16 milliseconds or 10 milliseconds. For a trading day d the returns for markets i and j for the same security form two series $r^{i,d} = \{r^{i,d}_{t,t+\Delta t}, r^{i,d}_{t+\Delta t,t+2\Delta t}, r^{i,d}_{t+2\Delta t,t+3\Delta t}, ...\}$ and $r^{j,d} = \{r^{j,d}_{t,t+\Delta t}, r^{j,d}_{t+\Delta t,t+2\Delta t}, r^{j,d}_{t+2\Delta t,t+3\Delta t}, , ...\}$. The mid-quote correlations for this security and day d is then computed as

$$correlation(i, j, d) = Corr(r^{i,d}, r^{j,d}),$$

so the correlation in computed based on rates of returns in the native currency and as such ignored the foreign exchange conversion. We believe this approach gets a cleaner estimate of the correlation by filtering out exchange rate induced noise. We have computed correlations both ways and believe that over the time intervals that we are working with omitting FX noise gives a cleaner correlation estimate.

3.3.2. Cross-Market Arbitrage

Let the two markets for the same security be denoted market 1 and market 2 on day d. Define the bid and ask quotes for a security on day d and time t as follows

$$\{bid^{1,d}_t, ask^{1,d}_t\}$$

for market 1 and for market 2 the parallel quotes are denoted

$$\{bid^{2,d}_t, ask^{2,d}_t\}.$$

These quotes are in native currency. We use the mid-quote for the EUR/SEK exchange rate to convert the mid-quotes to the same currency (euro) and denote the converted quote with a $\widehat{\ }$ as $\{\widehat{bid}_t^{1,d}, \widehat{ask}_t^{1,d}\}$ and $\{bid_t^{2,d}, ask_t^{2,d}\}$. The exchange rate quote are matched on time stamps without any adjustment, i.e., we are assuming that the equity markets and the FX markets data set are synchronized and we are abstracting from any information transmission delays. We believe this is a reasonable starting point in this case but we realize that this likely ignores a little slippage that FX frictions introduce.

A cross-market arbitrage opportunity arises when one of the following inequalities hold

$$\widehat{bid}_t^{1,d} > ask_t^{2,d} + 0.005 \text{ euro},$$

or

$$bid_t^{2,d} > \widehat{ask}_t^{1,d} + 0.005 \text{ euro},$$

where the 0.005 euro indicates the tolerance imposed. The arbitrage opportunity must exceed a half euro cent for at least a 1 millisecond period of time to register as an arbitrage opportunity. Since neither costs of placing the required trades nor slippage from the foreign exchange transactions are included we are clearly marking small price deviations arbitrage opportunities that in practice would not present viable opportunities to make arbitrage profits. Nonetheless we believe including too many rather than too few price violations is preferable in this situation as it is hard to accurately pinpoint the right applicable costs and it is changes in this metric that our analysis will focus on.

4. Results

The results section is organized as follows. First, we examine the correlations between mid-quotes for the same security quoted in SEK and EUR. Are these correlation changing over this period? If so, how and when are they changing? Second, we examine the incidence of cross-market arbitrage opportunities across these markets. Third, we examine whether these changes are associated with any changes in market quality.

4.1. Correlations

Budish, Cramton and Shim (2015) begin their analysis by illustrating how the continuous limit order book does not actually work in continuous time. The frictionless market benchmark

is that the correlations between mid-quotes for one and the other market would be one for identical securities. We expect the actual correlations to be less than one for a host of reasons. What we are particularly interested in is changes in the correlations over our sample period. We illustrate the breakdown in the mid-quote correlation structure for Nordea Group using the midpoints in Stockholm and Helsinki respectively and by converting the quotes in Stockholm to euros using a high frequency time matched foreign exchange mid-quote. The first plot shows the midpoint series for a *day* in our sample, the second plot shows the two quote series for *an hour* in our sample, and the third for *a minute* in our sample. it is clear in the first plot that the two series are close to perfectly correlated over the trading day as we would expect as the represent effectively perfect substitutes for a global investor. The correlation is also fairly strong in the second plot, but, in the third plot we observe the breakdown in the correlation. The correlation breakdown is a high frequency version of the well known 'Epps-effect' after **?**. The consequences of the breakdown is the possibility of cross-market arbitrage opportunities.

Figure **??** shows the range of the mean correlations for mid-quote returns on an annual basis across the four cross listed securities. Correlations are calculated on a daily basis at a number of different resampling rates and averaged over the year. There is a clear upward shift with correlations increasing clearly from 2009 to 2013. Based on the upward shift in correlations depicted in Figure **??** we would expect there to be fewer cross-market arbitrage opportunities in the later part of the sample period. Note, however, that while correlations are getting stronger they are still far below one.

Figure **??** shows the increase in correlations at 16 milliseconds resampling interval. Here the correlations are computed for Nordea, Nokia, Stora Enso, and Telia for Helsinki and Stockholm with the Δt being 16 milliseconds. There is a shift upwards for all series in the beginning of 2010. This shift is mostly likely an effect related to improvements in technological infrastructure of the exchange, such as the introduction of INET. There appear to be two regimes, a low correlation regime and a high correlation regime starting at the beginning of 2010. Overall, a higher cross-correlation for the two mid-quote series indicate an increase in the level of informational market efficiency.

Table **??** reports the estimation results for fixed effects regression with the correlation between the mid-quote returns computed for the two markets computed over various high-frequency time intervals. Table **??** reports the results for 10 milliseconds to 50 milliseconds. The right-hand side variables used are the high-low range computed as a ratio for each day and stock[10] In addition we include year effects for 2010, 2011, 2012, and 2013 to capture any secular

[10]We plan to check robustness using other proxies for volatility.

trends in the correlations over our sample period. Robust standard errors and corresponding t-statistics are reported in the table. The regression results confirm the general trend toward stronger correlations between the markets over our sample period (the coefficients for 2013 are not significantly different from zero). Note that while correlations are overall stronger they are still only in the range of 0.1-0.2 for high-frequency intervals. It is important to note that is a necessary but not sufficient condition for cross-market arbitrage opportunities.[11] The results for correlations point towards the market becoming more efficient while there is still room for cross-market arbitrage because the markets do not move in lock-step.

4.2. Arbitrage opportunities

In this section we focus on the cross-market arbitrage opportunities that arise when the bid quote in one market exceeds the ask quote in the other market.

4.2.1. The Incidence of Arbitrage Opportunities

An arbitrage opportunity is defined as any situation where for at least 1 microsecond the bid quote exceeds the ask quote in the other market by at least 0.005 euros. The quotes in the aforementioned comparison have been converted to euros. We believe our definition will capture all actual actionable arbitrage opportunities as well as many deviations that would not be viable arbitrage opportunities. We do not a priori exclude arbitrage opportunities because of their size. We abstract from pinpointing any costs of engaging in arbitrage trades. We believe these simplifying assumptions are justified given the main purpose of our analysis.

Table **??** reports the total number of arbitrage opportunities for four of our sample stocks for the sample period. One way to illustrate the dramatic shift is to consider that the total number of cross-market arbitrage opportunities for the years 2010 to 2013 (four year) is approximately 30% of the total number of arbitrage opportunities during the year of 2009. The shift hold true for the number of arbitrage opportunities as well as for the aggregate value of the arbitrage opportunities as Figure-**??** illustrates.

Table **??** reports the estimation results for four fixed effects regression designed to summarize the changes in the incidence of cross-market arbitrage opportunities. The first fixed-effects regression uses year effects for 2010 to 2013 and a constant to capture the variation over the sample period. The natural logarithm of one plus the daily number of cross-market arbitrage opportunities is used as the dependent variable. The regression results confirm what the graphs illustrated above, that significant decease in the number of arbitrage opportunities for 2010, 2011, 2012, and 2013. The estimates imply that on average the incidence of cross-market

[11] Note that there are five stocks rather than four as in some of the analysis because Tieto is included.

arbitrage opportunities fell by between 61% and 75% in the four years following 2009. We also estimated the same regressions using the date, February 8th 2010, for the INET introduction, the date, October 26thg 2009, for the first step in the tick size harmonization, and the second date, January 4th 2010, for the second step in the tick size harmonization as right hand side variables. We realize that these events occur relatively close to each other in terms of time and therefore we do not think of these regression as more than descriptions of the data. With the caveat in mind the coefficients for the three event dates are naturally also negative and the size of the coefficients underscore the dramatic shift in the market dynamics over this period.

4.2.2. The Value of the Arbitrage Opportunities

The previous section documented the dramatic drop in the incidence of cross-market arbitrage opportunities over the sample period. It is also of interest to understand what happens to the value of the arbitrage opportunities as this change unfolds. At this stage we focus on the value of the arbitrage opportunities for one sample stock, NORDEA.[12] The time around the open and close of the market introduces different challenges that may be unrelated to the asynchronous quote updates or dislocations due liquidity shocks that is our primary interest. We therefore trim our sample so that any observations from the first and last 10 minutes of trading are dropped. Figure **??** show how the mean, median, 95th percentile and 99th percentile of the values of the arbitrage opportunities developed from Jan 2009 to Dec 2010.

Figure **??** plots the monthly number of arbitrage opportunities from January 2009 to December 2013 for NORDEA. The series exhibits what seems like a structural shift around March 2010. Both graphs above underscore the large change around February to March 2010.

4.2.3. Duration of the Arbitrage Opportunities

Figure **??** illustrates what happens to the duration and the frequency of arbitrage opportunities for one stock in our sample, Nordea. In Figure **??** what is plotted is the monthly aggregate time spent in a state of quotes that violate no-arbitrage. Each month the number of arbitrage opportunities is multiplied by the average duration of the arbitrage opportunities. The curve flattens out both as the number of arbitrage opportunities dwindle and/or if the duration shrinks. The challenge when the number of opportunities shrinks is that there are few observations making it harder and harder to get a reliable estimate of the average duration.

[12]We are in the process of carrying out the analysis for the whole sample.

4.3. Market Quality

The results reported so far provides a picture of a market for the cross-listed securities that is becoming more efficient in an information sense displaying fewer cross-market arbitrage opportunities. The cross-correlation, while still far below the theoretical boundary of unity, s getting stronger. At the same time there is a dramatic drop in the incidence of cross-market arbitrage opportunities and the value of arbitrage opportunities when they do occur also shifts down. This all would seem like good news for all (most) market participants. But that assumes there is not corresponding adverse change in the bid-ask spread or the market depth provided in the order book. In this section we provide results that show that the bid-ask spread declines and the depth is largely unchanged implying that the market quality is improving over the sample period.

Table **??** illustrates the development of the bid-ask spread for five stocks (Nordea, Nokia, Stora Enso, Tieto and Telia) over the sample period. Overall, the inside bid-ask spread drops by 13 basis points (Helsinki) and 15 basis points (Stockholm) for the sample stocks over the 2009 to 2013 period. The drop corresponds to a change of -49% (Helsinki) and -56% (Stockholm). The significant drop in the spread makes the drop in arbitrage opportunities even more remarkable as two securities, with unchanged price dynamics, would need to have more or the same number of arbitrage opportunities. We interpret this as evidence that part of the change is that those who make markets are monitoring and updating their quotes in a high frequency fashion. We are not saying that fast traders picking off stale quote does not occur anymore but that activity has dried up at the same time as the spreads have dramatically narrowed.

It is also the case that the drop in the bid-ask spread is sharper for the dominant markets. Comparing Tables **??** and **??** makes it clear that the spread decline more sharply for the dominant markets Helsinki for Nokia, Stora Enso, and Tieto, and Stockholm for Nordea and Telia.

Table **??** reports the estimation results for fixed effects regressions estimated for the bid-ask spread and the market depth for the four stocks in the plots above[13]. The regressions for the bid-ask spread shows a an average spread of between 25 and 30 basis in 2009 and a shift down to around 15-20 basis points for 2010 through 2013. For the depth there is no significant coefficient estimates (robust standard errors) indicating that the market depth is not changing. Overall our results indicate that the market quality based on conventional measures has improved also significantly over the sample period.

[13]Here we use data for Nokia, Nordea, Stora Enso, and Telia Sonera.

5. Conclusion

We examine the incidence, magnitude and duration of cross-market arbitrage for cross-listed securities over a sample period in which the market was exposed to a major shock that increased the speed of trading dramatically and other shocks that lower the minimum price increment (tick size). Altogether our results show that the markets are becoming significantly more efficient in an informational sense. Mid-quote correlation at high frequency time intervals of 10 - 50 milliseconds display a significant increase towards the benchmark of unity albeit standing still far below that benchmark. The correlations are still below unity so the question of whether the markets will exhibit violations of no-arbitrage is not clear. Our results from examining the cross-market no-arbitrage violations show a dramatic decrease in the violations. Market quality also shows strong improvements or no change based on conventional metrics such as inside spread and depth. Altogether our results provide evidence of the gains from faster trading.

What makes the markets we study different from the case studied in **?** is that while nominally the markets represent three geographically distinct locations; Stockholm, Helsinki, and Copenhagen. But in terms of the exchange technology or the location of the exchange servers to be precise all trading takes place in Stockholm. This may be a reason for the big improvements we document. Effectively these markets may not as fragmented as the market studied in **?**. Of course, one underlying difference that matters when interpreting our results is that all markets are sub-markets within one exchange company, Nasdaq, removing a lot of the coordination difficulties that would make this much harder for competing exchanges.

	Ericsson		Nokia		Nordea			Stora Enso		Telia Sonera		Tieto	
Year	HE	ST	HE	ST	HE	ST	CO	HE	ST	HE	ST	HE	ST
2009	0.00	1.00	0.95	0.05	0.11	0.77	0.12	0.82	0.18	0.11	0.89	0.89	0.11
2010	0.00	1.00	0.92	0.08	0.11	0.82	0.07	0.78	0.22	0.10	0.90	0.89	0.11
2011	0.00	1.00	0.94	0.06	0.08	0.88	0.04	0.81	0.19	0.10	0.90	0.89	0.11
2012	0.00	1.00	0.82	0.18	0.10	0.83	0.07	0.77	0.23	0.10	0.90	0.89	0.11
2013	0.00	1.00	0.76	0.24	0.09	0.83	0.08	0.73	0.27	0.08	0.92	0.95	0.05

Table 1: Annual Volume Share Volume share by stock in each currency within NASDAQ Nordic where HE denotes NASDAQ Helsinki, ST denotes NASDAQ Stockholm and CO denotes NASDAQ Copenhagen. Ericsson volume in Helsinki (HE) is approximately 10^{-5} percent. Future versions will include data for SAS as well.

	Time Interval				
Variable	10ms	20ms	30ms	40ms	50ms
High-Low (%)					
coeff.	-0.2088	-0.2649	-0.3032	-0.3199	-0.3215
s.e.	(0.0547)	(0.0825)	(0.0671)	(0.0879)	(0.0778)
t-statistic	-3.82	-3.21	-4.52	-3.64	-4.13
Year-2010	0.0469	0.0494	0.0460	0.0370	0.0308
	(0.0084)	(0.0102)	(0.0118)	(0.0137)	(0.0139)
	5.61	4.83	3.91	2.70	2.70
Year-2011	0.0442	0.0606	0.0663	0.0664	0.0671
	(0.0123)	(0.0157)	(0.0171)	(0.0183)	(0.0181)
	3.59	3.86	3.87	3.64	3.72
Year-2012	0.0457	0.0619	0.0667	0.0627	0.0618
	(0.0172)	(0.0248)	(0.0273)	(0.0291)	(0.0280)
	2.65	2.50	2.44	2.15	2.21
Year-2013	0.0348	0.0455	0.0452	0.0399	0.0385
	(0.0251)	(0.034)	(0.0374)	(0.0340)	(0.0415)
	1.39	1.34	1.21	1.00	0.93
Constant	0.0398	0.0555	0.0693	0.084	0.0940
	(0.0137)	(0.0185)	(0.0196)	(0.0213)	(0.0207)
	2.92	3.00	3.54	3.96	4.53

Table 2: Mid-Quote Correlations Regression results for fixed effects regressions with the correlation between mid-quote returns over intervals of different length on the high-low range for each stock and year dummies. The time intervals range from 10 milliseconds to 50 milliseconds. There are 5 stocks and 1253 observation per stock. Coefficients with robust standard errors in parenthesis and with t-statistics are reported.

Year	Nokia	Nordea	Stora	Telia
2009	18086	7729	3676	857
2010	1877	2103	896	243
2011	187	910	1428	122
2012	45	126	134	24
2013	110	330	463	155

Table 3: Arbitrage Opportunitites Annual number of arbitrage opportunities based on 0.005 euro and 1 microsecond threshold.

	Regression			
Variable	I	II	III	IV
Year-2010	-0.8855			
	0.2235			
	-3.96			
Year-2011	-0.9687			
	0.3072			
	-3.15			
Year-2012	-0.9532			
	0.3741			
	-2.55			
Year-2013	-1.297			
	0.3367			
	-3.85			
Constant	3.4666	3.4692	3.4833	3.4676
	0.2313	0.2210	0.2526	0.2313
	14.99	15.70	13.80	14.99
INET-Intro		-1.0550		
		0.2835		
		-3.72		
Tick Size			-1.0014	
Harmon. I			0.3020	
			-3.32	
Tick Size				-1.0278
Harmon. II				0.2895
				-3.55

Table 4: Number of Arbitrage Opportunities Regression results for fixed effects regressions with the natural logarithm of one plus the number of arbitrage opportunities per stock and day as the dependent variable. Robust standard errors are reported below the coefficient estimates followed by the t-statistics. There are five stocks and 1,253 observations per stock. Model I uses only year dummies; Model II uses only a dummy which is one for all days after the introduction of the INET trading system (Feb 8th 2010) and zero before, Model II includes only a dummy for the first tick size harmonization change which occurred on October 26th, 2009; and finally Model IV includes a dummy which is one and zero before the second tick size harmonization.

	Bid-Ask Spread		Depth	
Variable	Helsinki	Stockholm	Helsinki	Stockholm
Year-2010	-0.0015	-0.0014	-19.3663	-33.7831
	0.0002	0.00021	15.1666	28.5706
	-6.21	-6.73	-1.28	-1.18
Year-2011	-0.0011	-0.0015	-15.7533	-41.4966
	0.0004	0.0004	18.2057	31.0331
	-3.12	-4.16	-0.87	-1.34
Year-2012	-0.0011	-0.0014	-9.6186	-46.3565
	0.0004	0.0004	19.0926	35.6431
	-2.79	-3.48	-0.50	-1.30
Year-2013	-0.0013	-0.0011	-11.0114	-41.0909
	0.0003	0.0007	15.0322	33.0345
	-3.86	-1.67	-0.73	-1.24
Constant	0.0025	0.0030	58.9148	76.2297
	0.0003	0.0003	13.3469	25.5032
	9.69	10.47	4.41	2.99

Table 5: Bid-Ask Spread and Depth Regression results for fixed effects regressions with the bid-ask spread and the depth (scaled by / 1000), respectively, in Helsinki or Stockholm as the dependent variables. Robust standard errors are reported below the coefficient estimates followed by the t-statistics. There are five stocks and 1,253 observations per stock.

		Helsinki			Stockholm		
Stock	Year	Average	(s.e.)	Median	Average	(s.e.)	Median
Nordea	2009	28.53	(0.76)	26.75	18.04	(1.14)	15.68
	2010	15.43	(0.41)	15.33	9.23	(0.58)	7.67
	2011	15.91	(0.39)	15.25	9.04	(0.57)	8.00
	2012	12.44	(0.66)	14.26	9.89	(0.63)	8.38
	2013	9.12	(0.19)	8.94	7.31	(0.46)	6.51
Nokia	2009	11.61	(0.24)	10.46	16.57	(1.05)	15.42
	2010	7.43	(0.43)	6.91	11.64	(0.74)	11.81
	2011	7.43	(0.31)	7.31	10.31	(0.65)	9.55
	2012	10.18	(0.28)	9.13	10.24	(0.65)	10.35
	2013	8.53	(0.17)	7.06	9.18	(0.58)	8.70
Stora Enso	2009	27.91	(0.64)	23.56	41.72	(2.64)	36.06
	2010	11.13	(0.43)	9.89	25.25	(1.60)	23.76
	2011	9.14	(0.26)	7.88	15.00	(0.95)	14.75
	2012	11.28	(0.29)	10.72	13.36	(0.84)	13.51
	2013	11.82	(0.25)	11.13	12.63	(0.80)	13.17
Tieto	2009	23.60	(0.79)	21.45	48.08	(3.04)	46.08
	2010	16.59	(0.53)	15.47	33.84	(2.14)	33.41
	2011	21.58	(0.63)	20.19	33.18	(2.10)	32.75
	2012	22.32	(0.59)	21.25	35.54	(2.25)	35.02
	2013	16.29	(0.47)	15.24	34.97	(2.21)	30.17
Telia	2009	32.18	(0.74)	25.64	22.46	(1.42)	21.67
	2010	14.81	(0.41)	15.61	8.92	(0.56)	8.53
	2011	11.97	(0.29)	10.22	6.15	(0.39)	5.78
	2012	12.19	(0.29)	10.30	4.17	(0.26)	4.24
	2013	12.39	(0.27)	9.82	4.87	(0.31)	4.93

Table 6: Bid-Ask Spreads The table reports the average daily spread (average of the daily averages for each year) with standard errors in parenthesis and then the median spread (median of the daily median spreads). The mean and medians are reported by stock and year. The left three columns report the spreads for Helsinki and the right three for Stockholm. Relative spreads reported in basis points.

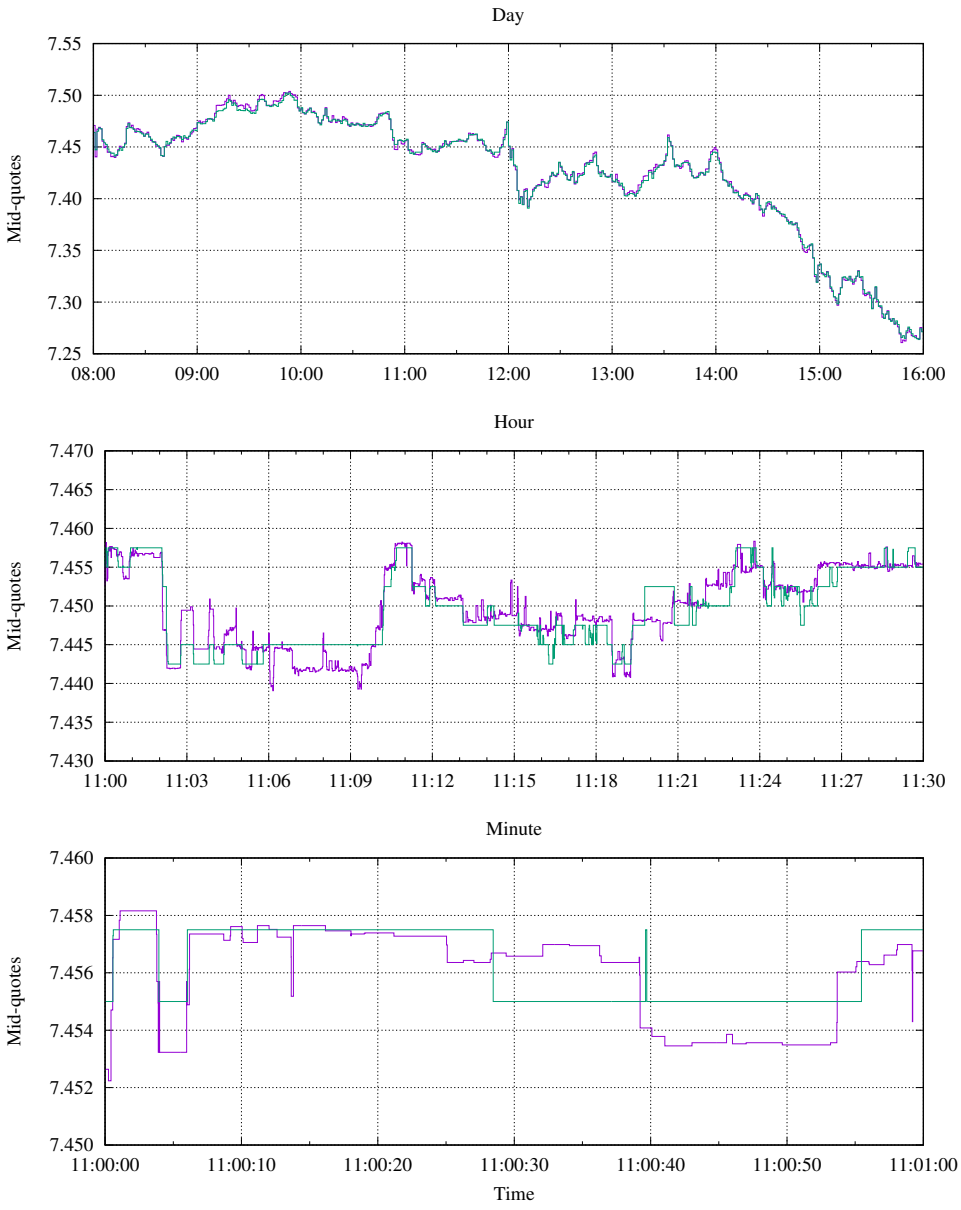

Figure 1: Nordea Group mid-quotes over different time intervals. In this figure, mid-quotes are shown in a common currency, the euro. Quotes in SEK are converted to euros using the mid-quote of the spot exchange rate. The mid-quotes are shown over a day (top), one hour (middle) and one minute (bottom) panel**.**

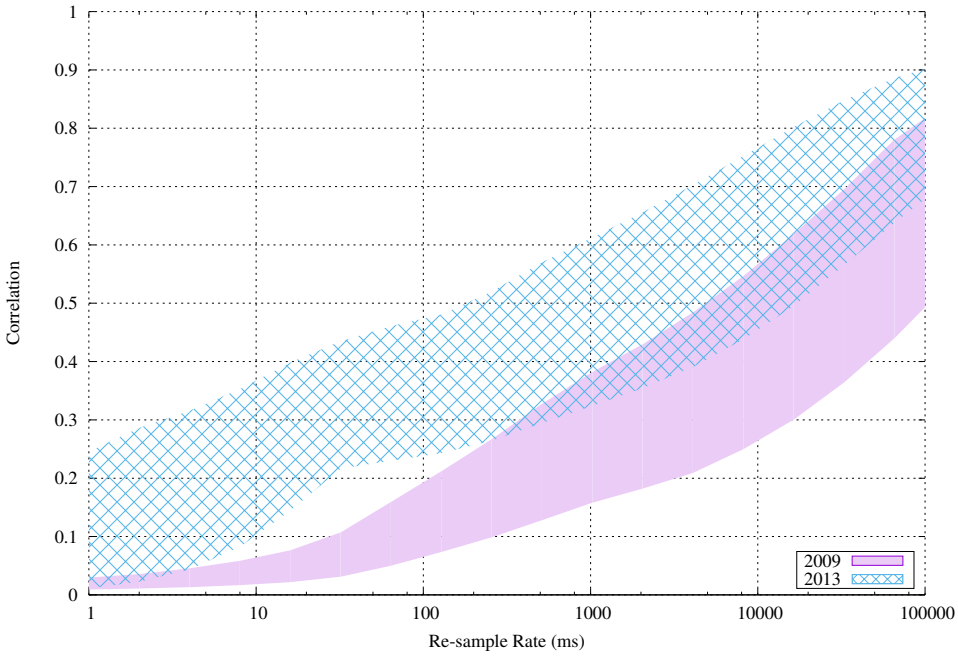

Figure 2: Correlation range for miq-quote returns. This figure is based on the average daily correlation for Nokia, Nordea Group, Stora Enso and Telia. For each stock, the daily correlation of the mid-quote returns are computed. The average correlations for each year, 2009 through 2013 is then calculated. The filled curves show the range of those averages across the four stocks for 2009 and 2013. These calculations are done without any FX conversion as the mid-quote returns rather than mid-quotes are used.

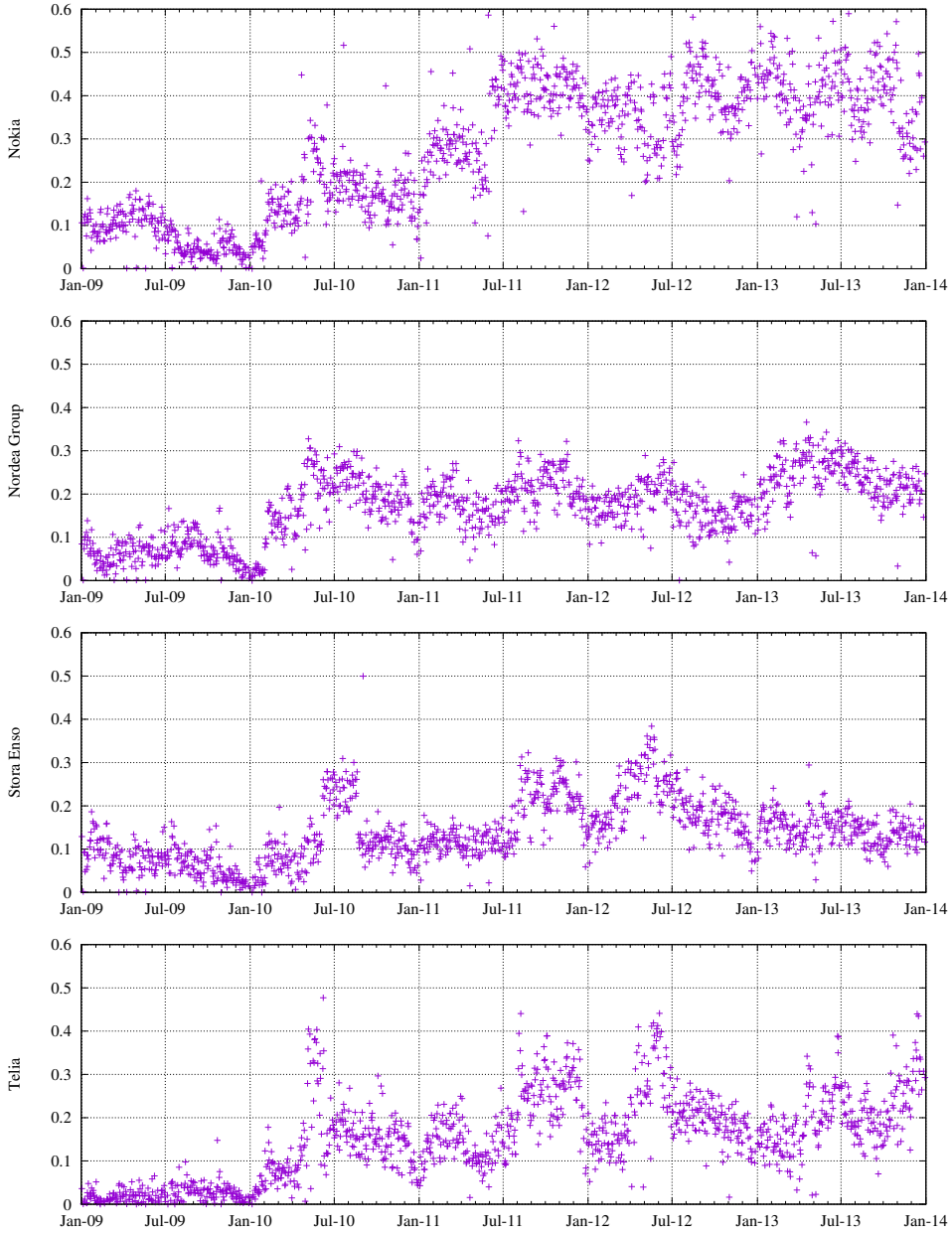

Figure 3: Daily mid-quote correlations based on 16 millisecond sampling The panels show the mid-quote correlations, Stockholm and Helsinki for Nokia (top), Nordea (second from top), Stora Enso (third from top), and Telia Sonera (bottom panel) for 16 millisecond sampling intervals over our sample period, 2009 – 2013.

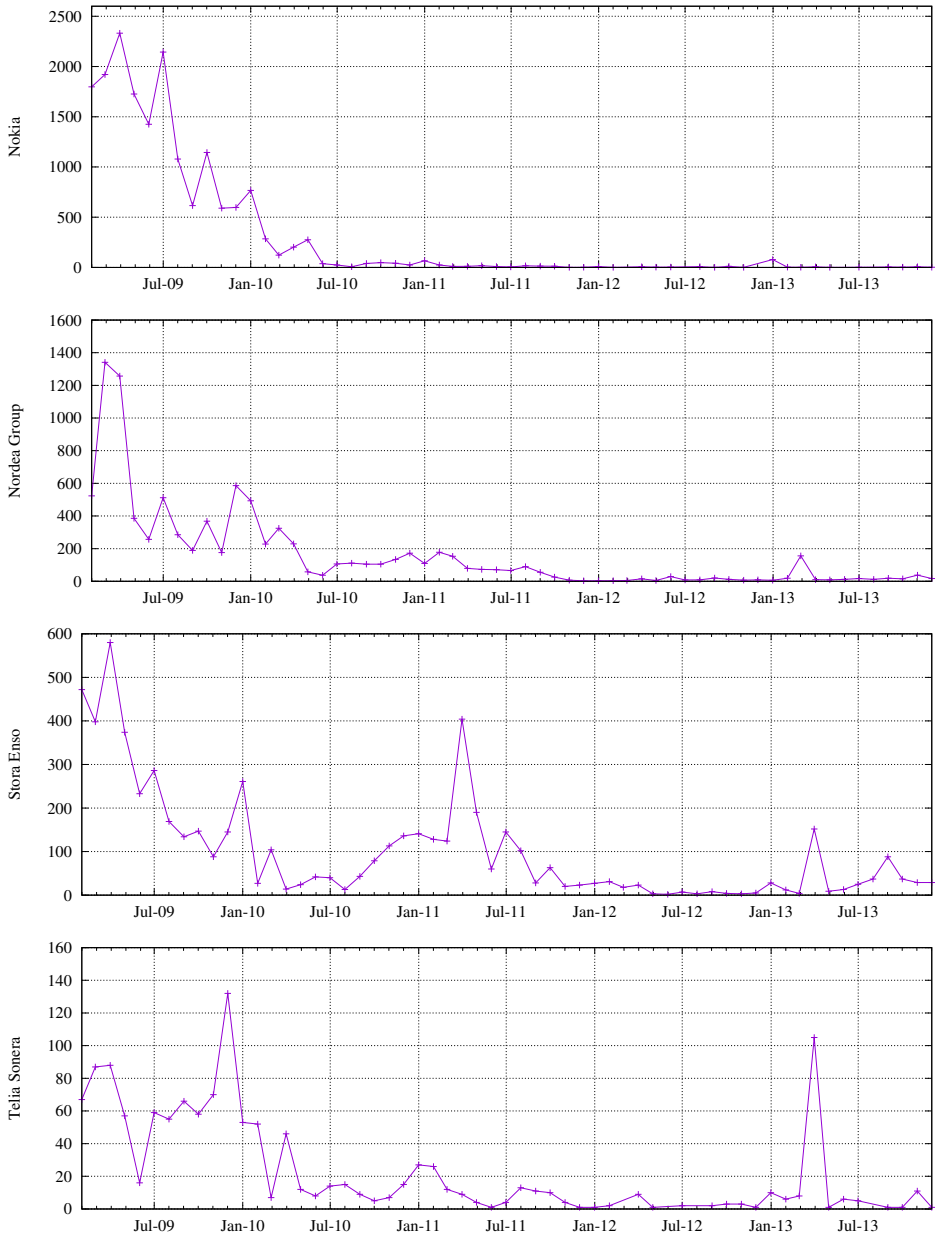

Figure 4: Number of arbitrage opportunities per stock The number of arbitrage opportunities per stock and month is plotted for Nokia (top panel), Nordea Group (second panel), Stora Enso (third panel), Telia Sonera (bottom panel). An arbitrage opportunity is defined as a situation in which the bid in one market exceeds the ask quote in the other market. Quotes are converted to euros to make this comparison. FX data from Olsen and Associates is used to convert quotes to euros. An arbitrage opportunity exists when the bid in one market exceeds the ask quote in the other market for a minimum of one microsecond and has a value of at least 0.005 euro per share.

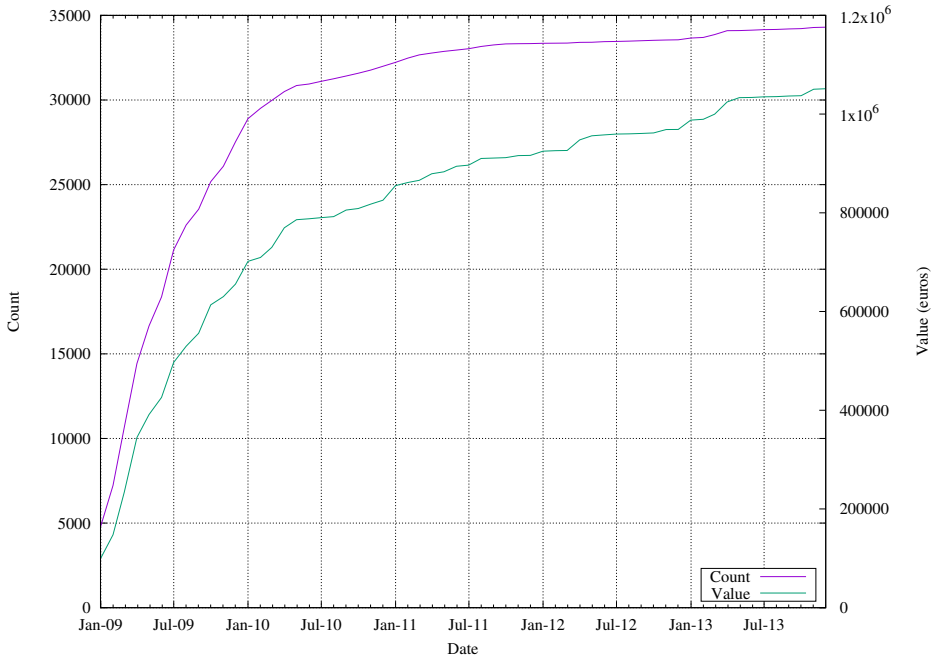

Figure 5: Cumulative number of arbitrage opportunities. This figure presents the cumulative number of arbitrage opportunities using the 0.005 euro threshold. The calculation aggregates the number of arbitrage opportunities in Nokia, Nordea Group, Stora Enso and Telia Sonera over the 5 year sample period. The aggregated count of opportunities is plotted as well as the aggregated value of the opportunities.

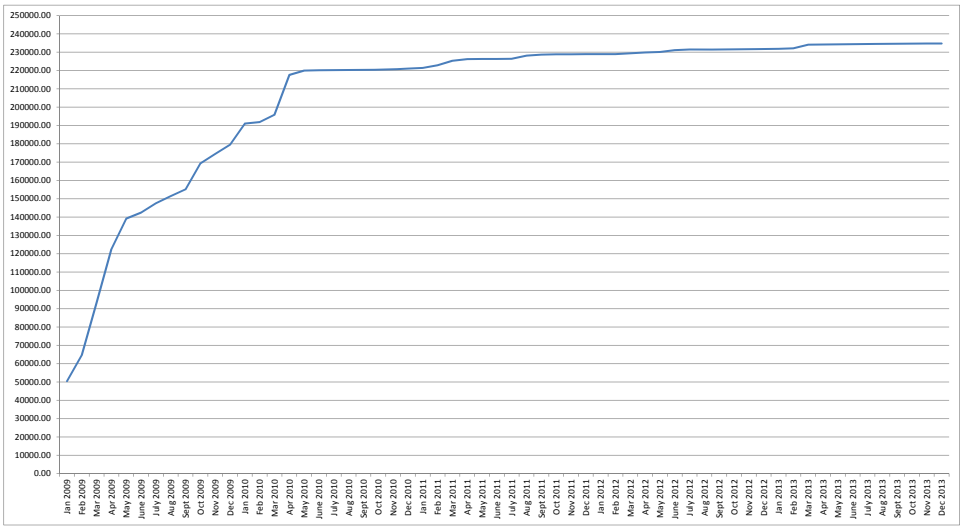

Figure 6: Cumulative Time in Arbitrage 2009 – 2013. This figure presents the cumulative time in seconds that one stock, Nordea, offers an arbitrage opportunity using the 0.005 euro threshold. Each month we multiply the number of opportunities by the average duration of the opportunities and this is summed from the current month from the start of the sample, January 2009.

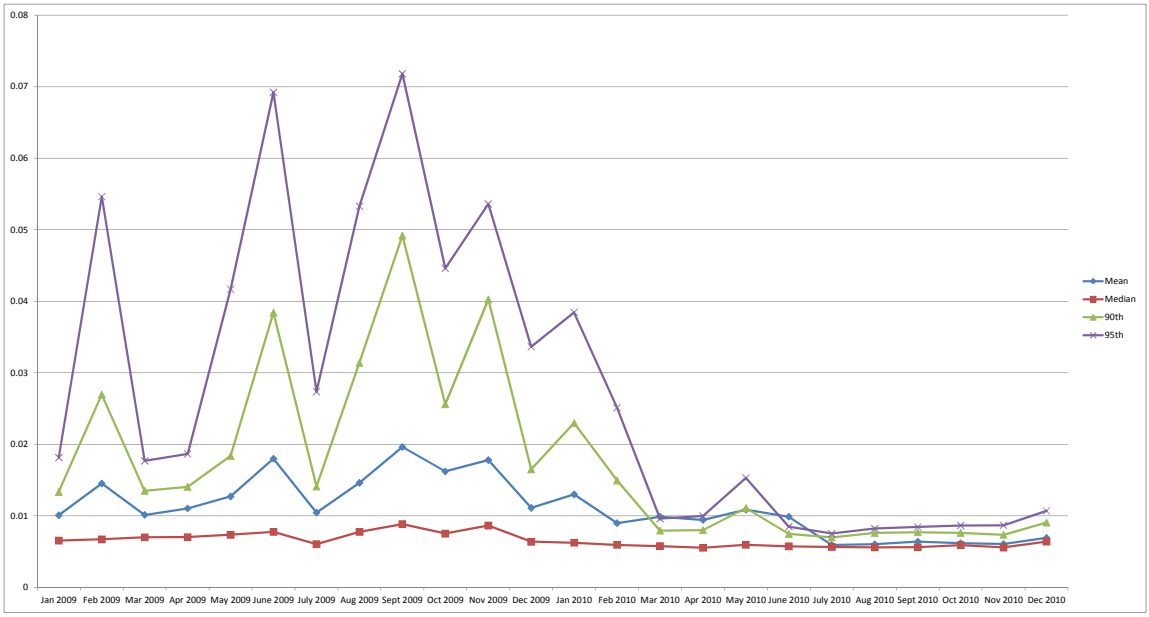

Figure 7: Value of Arbitrage Opportunities (Nokia) 2009-2010 The monthly mean, median, 95th and 99th percentiles for the values of the arbitrage opportunities for Nokia are plotted. An arbitrage opportunity here is defined as any arbitrage deviation exceeding 0.005 euro for one microsecond or longer that occurs in the time interval that starts after 10 minutes of the market open and 10 minutes before the market close. The period goes from January 2009 to December 2010.

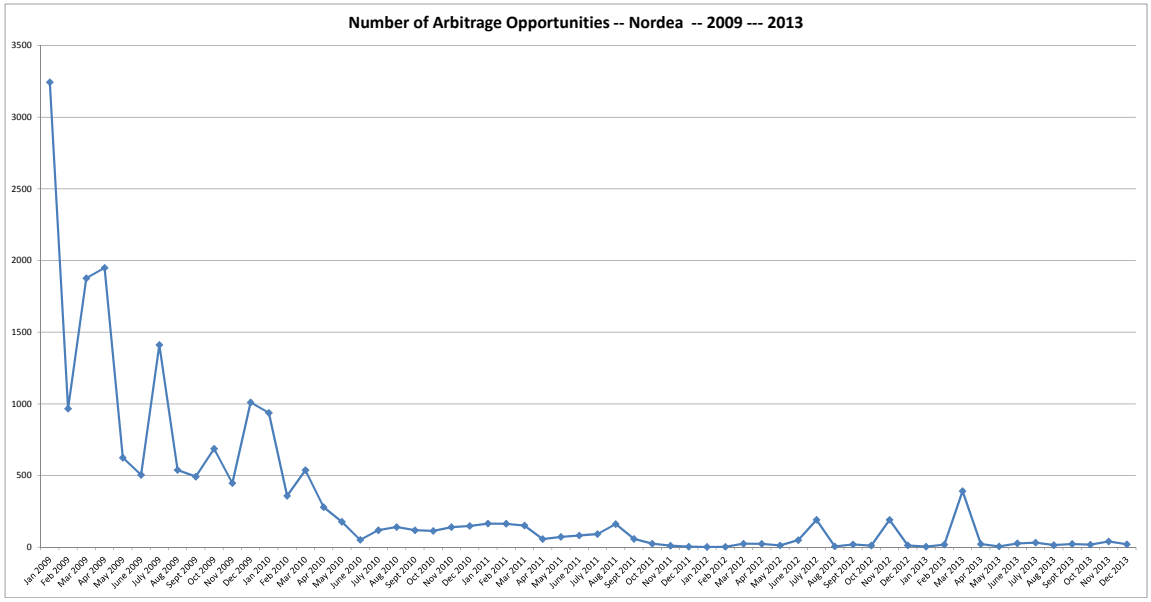

Figure 8: Monthly number of cross-market arbitrage opportunities (Nokia) An arbitrage opportunity here is defined as any arbitrage deviation exceeding 0.005 euro for 10 milliseconds or longer that occurs in the time interval that starts after ten minutes of the market open and ten minutes before the market close.

6. Appendix

Figure 9: EUR to SEK Exchange Rate Euro to Swedish Kronor exchange rate over the sample period 2009 to 2013.

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