High-Frequency Cross-Market Trading:
Model Free Measurement and Applications

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†The views in this paper are solely those of the authors and should not be interpreted as reflecting the views of the Federal Reserve Board of Governors or AQR Capital Management, LLC.
Connection Speeds Globally at Millisecond Precision

As Currently Advertised on Heathrow Express Trains:
Heathrow to Hong Kong in 0.239 Seconds
Microwave Tower Transmission Across Different Trading Venues Now Commonplace

100 km
Maximum distance between towers to avoid transmission problems

130+
Number of microwave licenses Jump holds in the U.S.

The Houtem tower
Sold for €5 million according to the mayor of Veurne
Cross-market trading activity has always been popular

- Reaction to news
- Cross-market arbitrage
- Market-making across related markets

What is (relatively) new?

- HFT/low-latency technology arms race towards speed of light
- Cross-market connectivity at latencies given by laws of physics
  
  *Implies concentration of co-activity at known leads/lags*

What makes this important?

- Market efficiency: nearly perfectly synchronized cross-market prices
- Market liquidity: harder to quantify aggregate liquidity across venues
- Market interconnectedness: new risks from increased concentration
Motivating Example

U.S. Commodity Futures Trading Commission (CFTC)
January 19, 2017 Enforcement Press Release (pr7516-17)

Five traders (who worked on either U.S. Treasury or U.S. Swaps desks) engaged in spoofing in various Chicago Mercantile Exchange (CME) U.S. Treasury futures products.

The traders’ spoofing strategy involved placing bids or offers of 1,000 lots or more with the intent to cancel those orders before execution.

Spoofing orders were placed in the Treasury futures markets after another smaller bid or offer was placed on the opposite side of the same or a correlated futures or cash market.

- HFT known to use new technology to speed up existing trading strategies
- Makes non-HFT examples of trading strategies relevant to consider
- Compliance of high-speed activity across markets poses surveillance challenges
- Data collected by a single trading venue or SRO need not cover all relevant markets
Introduce our model-free measure of cross-market activity

- Main purpose: uncover profile of cross-market activity of any kind
- Key features: peak offset location, dispersion and magnitude
- Nice complement to existing return-based approaches based on correlation measures and price impact regressions or VARs

Exploit ability to uncover dominant lead-lag relationships

- Study closely-linked markets such as cash versus futures
- Document differentiation by participant type, activity type, etc.

Shed new light on cross-market liquidity provision

- Prudent market-making across related markets?
- Directional trading ahead of others?

Study testable implications

- Improved price impact regressions on cross-market order flow
- Stronger link to volatility than single-market activity measures
The Cross-Market Need for Speed: A Brief Overview

Microwave Towers: Fastest 4-5 Millisecond Link between New Jersey and Chicago

- High-speed traders transmit data across markets approaching the speed of light
- Economics perspective: benefits vs costs of alleged changes in market functioning
- Econometric task: detection and measurement of high speed cross-market activity
### The Cross-Market Need for Speed: Our Key Insight

<table>
<thead>
<tr>
<th>Latencies of Live Circuits – One Way (ms)</th>
<th>Illinois Destinations</th>
<th>New Jersey Destinations</th>
<th>London Destinations</th>
<th>Marseille Destination</th>
<th>Madrid Destination</th>
<th>Frankfurt Destination</th>
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Latencies as of May 13, 2016. Source: Quincy Data - Microwave Market Data

### Can the Timing of Activity as Recorded in Time-Stamps Reveal Its Cross-Market Nature?

- Fastest active traders subject to nearly pre-determined timing offsets
- Implies concentration of the prevailing cross-market activity response times
- Can be captured by a simple model-free timing-based measure of co-activity
Capturing dominant lead-lag relationships between activity in two markets

- Activity in two markets, $A$ and $B$, observed over $N$ time buckets, $i = 1, \ldots, N$
- Raw measure $\mathcal{X}_t^{\text{raw}}$ counts how many times both markets are active at any offset $t$
  - Example: $\mathcal{X}_0^{\text{raw}} = 2$ at offset $0$, $\mathcal{X}_1^{\text{raw}} = 5$ at offset $1$
- Relative measure $\mathcal{X}_0^{\text{rel}}$ scales by the total activity count in the less active market
  - Example: $\mathcal{X}_0^{\text{rel}} = \frac{2}{6}$ at offset $t = 0$, $\mathcal{X}_1^{\text{rel}} = \frac{5}{6}$ at offset $t = 1$
- Excess measure $\mathcal{X}_t$ subtracts expected level of coincidental cross-market activity
  - Example: $\mathcal{X}_0 = \frac{2}{6} - \frac{1}{3} = 0$ at offset $t = 0$, $\mathcal{X}_1 = \frac{5}{6} - \frac{1}{3} = \frac{1}{2}$ at offset $t = 1$
Capturing dominant lead-lag relationships between activity in two markets

- Computational simplicity enables large-scale deployment and automated surveillance

- Raw measure $X_{t}^{\text{raw}} = \sum_{i=-|t|}^{N-|t|} \mathbb{1}\{\text{market A active in period } i\} \cap \{\text{market B active in period } i+t\}$
  - Interpretation: raw count of coincidental activity at a given offset $t$

- Relative measure $X_{t}^{\text{rel}} = \frac{X_{t}^{\text{raw}}}{\min\left[\sum_{i=-|t|}^{N-|t|} \mathbb{1}\{\text{market A active in period } i\}, \sum_{i=-|t|}^{N-|t|} \mathbb{1}\{\text{market B active in period } i+t\}\right]}$
  - Interpretation: view as proportion of activity in the less active market of the two

- Excess measure $X_{t} = X_{t}^{\text{rel}} - X_{\infty}^{\text{rel}}, \quad X_{\infty}^{\text{rel}} = \frac{1}{2(T_{2}-T_{1})} \sum_{|t|=T_{1}+1}^{T_{2}} X_{t}^{\text{rel}} \quad \text{for large } T_{2} > T_{1}$
  - Interpretation: adjust for coincidental activity implied under independence
Simplicity: Intuitive and straightforward to compute measures of cross-activity

- Raw measure $\mathcal{X}_t^{\text{raw}}$ counts cross-active time buckets at offset $t$
- Relative measure $\mathcal{X}_t^{\text{rel}}$ scales to proportion between 0 and 1
- Excess measure $\mathcal{X}_t$ adjusts for cross-activity implied under independence

Generality: Activity can be any point-in-time quantity with granular time-stamps

- Trade executions
- Order book depth changes
- Quote modifications or cancellations
- Buy-side or sell-side aggressive order placement
- ...
- Can look at the market as a whole or at participant-level data
Key Feature 1/3: Location

Cross-Market Trading in the 10-Year and 5-Year Treasury Cash Markets

- Location of the peak at zero: trading on the same platform
- Sharpness of the spike: Brokertec platform latency is small
Cross-Market Trading in the 10-Year and 5-Year Treasury Futures Markets

- Much more diffuse spike: spreads over a wider range of offsets
- A wider range of connectivity options, larger variability of CME platform latency
Evolution of Zero-Offset Cross-Trading in the 10-Year and 5-Year Treasury Cash Markets

- Historical levels of cross-market trading at zero millisecond offset
- Correspond to BrocerTec platform upgrades, indicative of rise in HFT
Cross-Market Trading in the S&P 500 Cash and Futures Markets

- High-speed traders see the two markets 5 msec apart by microwave tower speed
- Pronounced asymmetry of cross-market activity peaking exactly at +5 msec
- Consistent with the well-known lead role of S&P futures in price discovery
Cross-Market Trading in the 10-Year Treasury Cash and Futures Markets

- Peaks at +/-5 msec also match microwave tower transmission times
- Futures leads cash (+5 msec) or cash leads futures (-5 msec)
- Possible explanation: DC-originating news announcements closer to New Jersey
A Note on Data Quality: Time Stamps

Time-Stamps of at Least Millisecond or Higher Precision Required for Correct Inference

- Compare 10Y T-Note Activity on BrokerTec vs CME based on two different feeds
- Time-stamps in Data #2 delayed with respect to the accurate ones in Data #1
- Data #2 displays wrong cross-market activity pattern between BrokerTec and CME
- Data #1 displays the correct pattern with spikes at the +/-5 millisecond offset
So far: Empirical validation that our measure can identify dominant cross-activity patterns for the market as a whole.

Another real-world test: activity differentiation by participant type.


- Compares cross-market activity patterns for two participant types:
  - Banks/Dealers: client-oriented trading, mix of low and high frequency.
  - Principal Trading Firms (PTF): prop-oriented trading, low latency key element for a number of prominent firms.

- Documents strong cross-market activity spikes between CME and BrokerTec at the 5-millisecond microwave timing offset, as expected.
  - Only for the trading activity of PTFs.
  - Only for products with near-arbitrage relationship such as Treasuries.
Cross-Market Trading in the 10-Year Treasury Cash and Futures by Participant Type

- As expected, intense cross-market activity among PTFs but not Banks/Dealers
- The peaks are at the +/- 5ms microwave offset, as technologically determined
Cross-Market Trading in the 10-Year Treasuries and S&P 500 Futures by Participant Type

- No intense cross-market activity at millisecond lags by either participant type
- Expected for non-directly related products such as Treasuries vs S&P 500 futures
Millisecond Analysis of Cross-Market Liquidity Impact

- Thus far: Measure validated in cases when we know what to expect
- Justifies looking for “unknown” cross-market activity patterns
- Our goal: Shed new light on cross-market liquidity provision
  - Redefine activity to denote changes in available liquidity
  - Uncover millisecond level cross-market liquidity impact
    - Prudent market-making across related markets?
    - Directional trading ahead of others?
- Can shed light on so-called “liquidity mirage” phenomena
  - Allegations often made by non-PTF firms
  - Picked up by popular press, e.g. “Flash Boys”
  - Speaks to the debate whether static liquidity measures are relevant
Redefine activity as trades for CME and depth reductions for BrokerTec
Positive offset means CME trade precedes BrokerTec depth reduction
Consistent with prudent market making
Large CME Trades versus BrokerTec Depth Reductions: 10-Year Treasury

- Redefine activity as CME trades of size above 50 vs BrokerTec depth reductions
- Much stronger impact for large CME trades (50 is much larger than the median)
- Could explain perception for elusive total liquidity available to a large investor
Millisecond Analysis of Cross-Market Liquidity Impact

CME Trades versus BrokerTec Trades on the Same Side: 10-Year Treasury

- Redefine activity as CME and BrokerTec trades in the same direction
- Little evidence for high-speed directional trading on the same side
- For large trades the evidence is even weaker, unlike for prudent market making
Imbalance $\Delta v_t$ between buyer-initiated and seller-initiated trading volume tends to explain contemporaneous returns $r_t$.

Explanatory power captured by popular price-impact regression:

$$r_t = \alpha + \lambda \Delta v_t + \varepsilon_t$$

Our cross-market activity findings would further suggest possible:
- Strong cross-market price impact for closely linked markets
- Lack of symmetry as one market may dominate price discovery

Implies the following cross-market price-impact regression for returns and volume imbalance in the cash and futures markets:

$$r_t = \alpha + \lambda^{\text{Fut}} \Delta v_t^{\text{Fut}} + \lambda^{\text{Cash}} \Delta v_t^{\text{Cash}} + \varepsilon_t$$

We study the extra explanatory power of cross-market versus single-market price impact for US Treasury, S&P 500 and EUR/USD.
We run daily regressions of 5-sec returns on cash and futures market order flows for each market. Partial $R^2$ is produced for bivariate versus univariate specification. There is a large increase in the explanatory power of futures market order flows after 2007.
Evolution of Extra Explanatory Power Relative to Single-Market Price Impact Regression

- We run daily regressions of 5-sec returns on cash and futures market order flows.
- For each market partial $R^2$ is produced for bivariate versus univariate specification.
- Tangible extra explanatory power of cash market order flows from 2008 onwards.
We run daily regressions of 5-sec returns on cash and futures market order flows for each market. Partial $R^2$ is produced for bivariate versus univariate specification.

Symmetry pre 2009 and divergence post 2011 EBS decimalization.
## Testable Implications for Cross-Market Price Impact

### 10-Year US Treasuries: 2014 (5-min frequency)

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<tr>
<th></th>
<th>$r^{BTEC}$</th>
<th>$\Delta v^{BTEC}$</th>
<th>$\Delta v^{CME}$</th>
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<table>
<thead>
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<th>$r^{CME}$</th>
<th>$\Delta v^{CME}$</th>
<th>$\Delta v^{BTEC}$</th>
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<td>Adj $R^2$</td>
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<td>[0.835]</td>
<td>[70.687]</td>
<td>[66.201]</td>
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</table>

### Results:

- Huge increase in explanatory power based on CME order flows
- Loading on volume imbalance for both markets is highly significant
- CME volume more informative than BrokerTec volume
- Consistent with two-sided lead-lag patterns for CME vs BrokerTec
- **Key insight:** Treasury cash market flows less informative than futures
## Testable Implications for Cross-Market Price Impact

### S&P 500: 2014 (5-min frequency)

<table>
<thead>
<tr>
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<th>( r^{\text{NYSE}} )</th>
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<th>( r^{\text{CME}} )</th>
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<td>[117.21]</td>
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<tr>
<td>( \Delta v^{\text{NYSE}} )</td>
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<td>7.22E-09</td>
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<td>[17.692]</td>
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<tr>
<td>Adj R²</td>
<td>0.54</td>
<td>0.17</td>
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\[
\text{Adj R}^2 = 0.54, 0.17, 0.55
\]

- Nearly dominant explanatory power based on CME order flows
- Loading on volume imbalance for both markets is highly significant
- CME volume much more informative than NYSE volume
- Consistent with one-sided lead-lag patterns for CME vs NYSE
- Key insight: S&P500 cash market flow content subsumed by futures

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30 Dobrislav Dobrev and Ernst Schaumburg “Cross-Market HFT” Alan Turing Institute · March 1, 2017
Stronger Link to Volatility than Single-Market Activity

- Long-standing interest in studying the link between trading activity and market volatility:
  - New information spurs trading
  - Trading induces price changes
  - Price changes convey information

- Two main theories:
  1. Trading activity drives volatility
     “Business time clock”: Clark ’73; Ané & Geman, 00; ...
  2. Trading activity and volatility driven by common latent factor
     “Mixture of distributions hypothesis”: Tauchen & Pitts ’83; Andersen ’96; ...

- Our focus is on the reverse direction: how volatility can ignite trading
  - Portfolio rebalancing and dynamic hedging
  - Cross-market arbitrage trading

- We find stronger cross-market link to volatility than single-market activity measures such as trading volume and number of trades
### Regression of Volatility on Cash and Futures Market Trading Activity Measures

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\[
\Delta r v_t = \text{const} + \beta [n_1] \cdot \Delta n_{1,t} + \beta [n_2] \cdot \Delta n_{2,t} + \beta [v_1] \cdot \Delta v_{1,t} + \beta [v_2] \cdot \Delta v_{2,t} + \beta [x_{12}] \cdot \Delta x_{12,t} + \epsilon_t
\]

---

Does Combining Individual Activities Span the Extra Content in Cross-Market Activity?

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Dobrislav Dobrev and Ernst Schaumburg "Cross-Market HFT"  Alan Turing Institute · March 1, 2017
Regression of Volatility on Cash and Futures Market Trading Activity Measures

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<th>Year</th>
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Does Combining Individual Activities Span the Extra Content in Cross-Market Activity?

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Summary: Empirical Contributions

- Prevalence and nature of high-speed cross-market trading activity:
  - A significant fraction of trading in closely linked US cash and futures markets is accounted for by high-speed cross-market trading.
  - The evidence suggests that much of this high-frequency activity is consistent with “prudent” market making and not “predatory” trading.

- Implications for price discovery:
  - In US Treasury markets price discovery primarily takes place in futures with a minor role played by cash post 2007.
  - In EUR/USD FX markets price discovery was balanced between futures and cash pre 2009 but dominated by futures post 2011.
  - In US Equity index markets price discovery almost entirely occurs in futures consistent with findings in the existing literature.

- Extending the link between trading activity and volatility:
  - Cross market activity appears to be more closely linked to volatility than other activity measures such as volume and number of trades.
Summary: Econometric Contributions

- Simple yet powerful model-free measure of cross-market activity
  - Uncovers profile of cross-market activity
  - Can sharply detect dominant lead-lag relationships
  - Complements existing return-based approaches
  - Can shed light on any cross-market strategies by suitably defining activity, e.g. new insights on cross-market liquidity provision
  - Suitable for large-scale deployment and automated surveillance

- Pros: Model-free, identifies leads/lags, dispersion and magnitude

- Cons: Requires accurate time stamps and clock synchronicity
Closely-linked markets should *not* be studied in isolation of each other!
Just a 5 msec Fast

Thank You!
Our Contribution at A Glance

Evolution of Cross-Market HF Activity between 10-Year and 5-Year Treasuries on BrokerTec

A Model-Free Timing-Based Measure of Cross-Market Activity

- Defined as the proportion of coincident activity at a given offset in excess of what is implied by independence across markets, where activity is anything time-stamped
- Identifies the offset at which co-activity peaks, as well as its magnitude & dispersion