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### Just how fast?

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Around half of all buying and selling on many of the world's most crucial financial markets is now automated high-frequency trading. HFT is, famously, ultrafast, and whenever I speak to someone who might know and be prepared to tell me, I ask them just how fast that currently is: in other words, what's the minimum time interval between the arrival of a 'signal' – a pattern of market data that informs how an HFT algorithm trades – and an HFT system responding to the signal by sending in an order to buy or sell, or perhaps cancelling an existing order? When I first asked, in 2011, the answer was five microseconds: five millionths of a second. At the time, that seemed extraordinarily fast, but now it seems leisurely. The most recent answer I received – backed up by data released in September by Eurex, Europe's leading futures exchange – is 84 nanoseconds (billionths of a second), which is 60 times faster than the speed in 2011.

In a nanosecond, the fastest possible signal – light in free space – travels only 30 cm, or roughly a foot. That's the fundamental physical limit that is now shaping what one might call the infrastructure of financial capitalism. HFT's closeness to that limit creates an exquisite sensitivity to the technology used to transmit signals and above all to where exactly – *very* exactly – the technical devices involved are located. The most prominent recent addition to finance's infrastructure is a tower – essentially a large pylon – in the grounds of the Chicago Mercantile Exchange's computer datacentre, which is in the city's outer suburbs. At just over 100 metres, the tower isn't especially tall, but when viewed close up it's quite striking, looming over the low-rise buildings of the datacentre. It's designed to carry microwave dishes, although they weren't yet in place when I gazed up at the tower in October. Those dishes are going to be the fastest form of communication between the tens of thousands of computer systems packed into the CME's datacentre and the outside world.

The CME is the world's most important financial exchange, with no real rival in that role, either in the US or internationally. It trades 'futures', which originally were standardised contracts between two participants essentially equivalent to one agreeing to buy, and the other to sell, a set quantity of a commodity such as grain on a given future date, at a price agreed today. Although you might think that the price of a futures contract on grain would track the price of the underlying physical commodity, it's actually the other way about: the concentration of buying and selling interest in futures markets means that the price of commodities is often in effect set in those markets rather than in the direct buying and selling of the underlying commodity.

That's also largely the case with the financial futures that the CME began to trade from the 1970s onwards. Their prices often move a fraction of a second before the prices of the underlying shares, bonds or currencies. In addition, price movements in the US – especially in the CME's share-index futures and government-bond futures – frequently lead those in Europe, Asia and Latin America. That makes the speed at which price data from the CME are received hugely important to the world's automated trading systems.

Fast transmission of price data used to mean fibre-optic cable, but the material of which the strands of such a cable are made (which is usually a specialised form of glass) slows light down to around two-thirds of its speed in free space. In contrast, microwave and other

wireless signals travel through the atmosphere at almost that free-space speed.<sup>1</sup> From 2010 onwards, therefore, no fewer than 17 competing microwave links were built to connect the CME's datacentre in suburban Chicago to the datacentres in northern New Jersey in which shares, US Treasury bonds and currencies are traded. Fierce competition in speed has, however, winnowed out the slower links, and now only three firms remain in the race. (At the time of writing, a fourth competitor seems about to emerge: a new network seems to be being built by Scientel, a specialist telecommunications firm with its origins in the nuclear power sector. Most likely Scientel is doing this for an undisclosed HFT client, but I haven't been able to discover whether that's actually the case or who that might be.)

Chicago's outer suburbs are not a tourist destination. There are logistics depots, light industrial plants, and scrubby vegetation; the landscape is flat and often dominated by power lines and freeways. If you're involved in the microwave speed race, though, you've had to get to know intimately the patch of that landscape immediately surrounding the CME datacentre. The CME hasn't allowed the three competing firms to install their microwave dishes directly on the roof of the datacentre, so their dishes are on towers several hundred metres away. Until quite recently, this meant that the crucial signals from the CME's trading – and, although they tend to be not quite as important, the market data that flow from other exchanges to the CME – were slowed, perhaps by as much as a microsecond, by having to get from the datacentre to one of these towers (or vice versa) via a fibre-optic cable. A considerable stir was thus caused in May 2017 when the financial news service

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<sup>1</sup> Donald MacKenzie first wrote about finance's microwave links in the *LRB* of 11 September 2014.

Bloomberg published a photograph of a diesel generator in a field beside the road that runs along the north side of the CME datacentre. Connected to the generator was a short pole carrying two small antennas. That each of the antennas was facing slightly upwards gave the game away: it was an 'uplink', which could transmit microwave signals to, and receive signals from, a nearby microwave tower. Bloomberg revealed that a company affiliated to Jump Trading (a leading HFT firm) had paid \$14 million for the field. Having an uplink just across the road from the datacentre means that the length of fibre-optic cable through which a signal needs to run is reduced from hundreds to tens of metres, thus saving that crucial microsecond. The other two competitors in the race for speed have also now constructed similar up-links close to the datacentre: they had no alternative, because that microsecond is the difference between success and failure.

I'm told that Jump intended to recoup much of the field's purchase price by reselling all but the small portion of it needed for the uplink. I hope it has done so, because the new tower – which, as I've said, is inside the grounds of the datacentre, and so at least 30 metres closer to it than any of the uplinks – will have considerably reduced the value of the surrounding land. Each of the firms that compete to have the fastest Chicago-New Jersey link will again have no real choice but to install microwave dishes on the tower. I'm told they have been promised that the cables from their dish into the datacentre will be of the same length wherever their dish is on the tower. I haven't been able, though, to discover the prices they're going to be charged – the tower belongs not to the CME but to the datacentre owner – but it's already clear they're going to have to pay them.

Europe's equivalent of the Chicago-New Jersey route is the microwave links between Frankfurt – where Eurex is based, along with most of the trading of German shares – and Greater London, where most of the rest of Europe's share trading and nearly all its foreign-exchange trading takes place. (The electronic trading of Eurozone sovereign bonds that currently takes place in London is going to move to a datacentre in Milan, at least if Brexit goes ahead.) There's a similar competition in speed on the London-Frankfurt route as on the route from Chicago to New Jersey, and indeed it's the same three firms as in the US that are the competitors. (The race has been documented in remarkable detail by the researcher Alexandre Laumonier in a blog that's been a huge success in the world of high-frequency trading.) Europe's different geography, though, has made microwave's chief limitation salient: it is a 'line-of-sight' technology. There needs to be an uninterrupted straight line between each successive dish in a microwave link and the dishes before it and after it. The curvature of the earth therefore limits the possible distance between microwave towers.

That's a real problem when it comes to the sea crossing from southern England to the Continent. The shortest path (the 'geodesic') between London and Frankfurt crosses the east coast of Kent near Richborough, at a point at which the crossing is too long to be achievable with standard microwave towers. (Lake Michigan is also a challenge, but a lesser one, for the Chicago-New Jersey links.) In 2016, two HFT-owned microwave companies applied for planning permission to build giant 300 metre masts – three times as tall as the CME tower, and as high as the Shard or Eiffel Tower – on the Kent coast near Richborough so as to establish a line of sight that would make a geodesic-hugging link to the Continent feasible. Unsurprisingly, in 2017 Dover District Council turned down their applications, so the three competing microwave links still have to deviate from the geodesic and cross the

Channel further south, closer to the narrow Dover Straits, at a cost in speed of around 10 microseconds.

If the English Channel is an obstacle to microwave, the world's oceans are a currently insuperable barrier: there have been proposals to suspend microwave dishes from balloons, or have them carried by ships, helicopters or drones, but none have so far been adopted.

The crucial signals from the US datacentres to Europe therefore still travel by fibre-optic cables on the bed of the Atlantic. In the context of Brexit, that's perhaps fortunate. Hibernia Atlantic's cable, which is the fastest, makes landfall near Brean on the Bristol Channel, which means that the signals from the CME reach London a thousandth of a second or so before they get to Frankfurt and the other financial centres on the Continent. That just might give London a continuing slender advantage as a centre of trading.

A competitor to submarine cables, though, is starting to emerge. Over the last couple of years, one of the contributors to Laumonier's blog has been an engineer, Bob Van Valzah, who is a keen cyclist and lives in the Chicago suburbs. On his outings, he started to notice the appearance of new shortwave radio antennas. Like microwave, shortwave is an old technology: that's how Radio Moscow used to broadcast, and the Voice of America and BBC World Service still rely on it in some parts of the world. The point of shortwave is that at least a small portion of a radio signal in that frequency band will often bounce back to the earth's surface from the ionosphere, the layer high in the atmosphere in which electrons can be stripped from the atmosphere's molecules by the sun's rays or cosmic radiation. Shortwave signals are therefore not restricted to a line of sight: they can travel over the

horizon, sometimes for thousands of kilometres – potentially across the Atlantic, for example.

The new antennas spotted by Van Valzah are almost certainly experiments to find out if shortwave can be used in transoceanic HFT. Shortwave's bandwidth is very limited, but the critical signals for trading are often extremely simple: you don't need many binary digits to convey the fact that the price of a futures contract on the CME has ticked up or ticked down. A deeper problem, though, is that shortwave is a fickle technology, affected by conditions in the upper atmosphere, by solar flares, and simply by whether it is daytime or night. If in your youth you listened to shortwave radio stations in distant countries, you will have experienced that fickleness: a station you could hear clearly one night could be entirely inaudible the following night.

With skilled planning and powerful enough transmitters, though, shortwave signals can most likely reach London and Frankfurt from Chicago, at least much of the time. What, though, about Mumbai, Singapore, Hong Kong, Shanghai or Tokyo? Shortwave is unlikely ever to make direct transmission over those distances feasible. This potentially brings satellites into the picture. The cost of launching them is coming down sharply, and satellites could become a faster alternative to transoceanic cables. When I first heard discussion of this, I was deeply sceptical, because a whole constellation of satellites would be necessary: you can't simply use a single geostationary satellite, since that has to be over 30,000 km above the surface of the earth, and that would make a signal transmitted by satellite slower than one travelling in a direct undersea cable.



What's changed my mind about likelihood of the use of satellites in HFT has been talking to two people in the industry whom I know not simply to be dreamers but to be serious people who actually build things. One led the construction of the earliest Chicago-New Jersey microwave link; the other has built several impressively fast links. Both have been doing in-depth research on both the geometry of the problem (the low-earth-orbit satellites that are needed constantly change position with respect to the earth) and its economics. Both think that a global network of a hundred or more satellites, constantly passing financial signals among themselves, is feasible technologically and potentially within the budget of the world's HFT firms. It still might not happen, but there were sceptics about microwave transmission and these two people proved them wrong. I therefore wouldn't be entirely surprised if a world-girdling satellite network becomes part of finance's infrastructure. It's quite a thought.

Donald MacKenzie