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Cables, Sharks and Servers: Technology and the Geography of the Foreign Exchange Market

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Abstract

We analyze the impact of technology on production and trade in services, focusing on the foreign exchange market. We identify exogenous technological changes by the connection of countries to submarine fiber-optic cables used for electronic trading, but which were not laid for purposes related to the foreign exchange market. We estimate the impact of cable connections on the share of offshore foreign exchange transactions. Cable connections between local markets and matching servers in the major financial centers lower the fixed costs of trading currencies and increase the share of currency trades occurring onshore. At the same time, however, they attenuate the effect of standard spatial frictions such as distance, local market liquidity, and restrictive regulations that otherwise prevent transactions from moving to the major financial centers. Our estimates suggest that the second effect dominates. Technology dampens the impact of spatial frictions by up to 80 percent and increases, in net terms, the share of offshore trading by 21 percentage points. Technology also has economically important implications for the distribution of foreign exchange transactions across financial centers, boosting the share in global turnover of London, the world's largest trading venue, by as much as one-third.

Key words: Technology, Geography, Foreign Exchange Market, Exogeneity, Submarine Fiber-Optic Cables

JEL classification: F30

Non-technical summary

The impact of technology on services, and specifically on where services are produced and traded, is one of the great unanswered questions of the post-industrial age. One view is that cheap information and communication technology (ICT) significantly attenuates the effect of distance and other trading barriers on the geography of production. Another view is that distance and other trading barriers still matter significantly. In this paper we shed light on this debate using the global foreign exchange market as a case study.

What might be called the "Flat World" hypothesis (after Friedman 2005) is that location, distance and other aspects of geography no longer matter in a ubiquitous 24-7 FX marketplace. In a world of high-speed communication, foreign exchange transactions can take place anywhere and should be observed in a growing number of places, reflecting the availability of relevant inputs.

Alternatively, what might be called the "Flash Boys" hypothesis (after Lewis 2014) suggests that location matters more importantly than ever in a 21st-century foreign exchange market characterized by competition between high-frequency traders for proximity to data-matching servers and in which speed of execution is critical. In this view, foreign exchange transactions will concentrate in a handful of locations – those that possess data-matching servers and high-speed communications with the rest of the world.

We investigate how the geography of the foreign exchange market has been affected by changes in ICT. Has ICT led to greater concentration of transactions in a handful of major financial centers such as London, New York and Tokyo by allowing more market participants to reap the advantages of being close to the matching servers on which trades are executed electronically? Or has it enhanced the competitive position of suppliers of these services in other places, who can impart local knowledge to their customers but also now more easily link to matching servers located in the major financial centers from afar? Has the landscape of the foreign exchange market become "flashier" or "flatter," in other words?

How to investigate these questions is not obvious. Investments in technology can affect the geographical distribution of economic activity, but changes in the geographical distribution of economic activity also provide an incentive for investments in technology. Instances where it is possible to identify the diffusion of technology shocks over economic and geographical space are even fewer and further between.

But in the case of the foreign exchange market, we have just such a source of exogenous change and spatial variability. This is the laying of submarine cables starting in the late 1980s. These cables were not laid for purposes related to electronic foreign exchange trading. Rather, their underwriters foresaw them as efficient and

profitable vehicles for long-distance telegraphic communication, telephone calls, fax and internet transmission. Only over time was their utility for electronic trading of foreign exchange and other financial instruments discovered. Moreover, the shape of the submarine fiber-optical cable network is heavily influenced by geography, in that cables can only connect terrestrial points with direct access to the ocean, among others. Since cables were laid and came into use at different points in time, the network of active submarine cables provides us with a source of exogenous changes that vary over both space and time.

Our identification strategy capitalizes on the special role in electronic foreign exchange trading played by three of the largest financial centers: London, New York and Tokyo. It is in these cities that the matching servers of Electronic Broking Services (EBS) and Thomson Reuters, the leading platforms for electronic broking and trading, have been located since the early 1990s. It follows that a country's connection to the UK (for London), US (for New York) or Japan (for Tokyo) via a submarine fiber-optic cable reduces latency time and increases bandwidth.

We posit that lower latency and greater bandwidth reduce the importance of spatial frictions such as distance, information asymmetries, domestic market liquidity and regulatory frictions like capital controls. These effects are similar to a reduction in transportation costs of buy and sell orders involving counterparties in different locations, which will be attractive to high-frequency traders seeking to exploit tiny, short-lived price discrepancies at the millisecond level, but also to other traders. We also posit that lower latency and larger bandwidth reduce the fixed costs of undertaking transactions electronically, insofar as they reduce the costs of aggregating and matching buy and sell orders, as well as the costs of processing information and data more generally.

If lower latency and greater bandwidth matter, they will affect the geography of foreign exchange trading, such as the shares of transactions in a currency that occur onshore (in the issuing country) and offshore (in the major financial centers). Specifically, the reduction in spatial frictions and transportation costs may encourage onshore transactions to move offshore to the major financial centers, in the manner of the standard "home market effect" (Krugman 1980, 1995) and consistent with the "Flash Boys" hypothesis. The reduction in the fixed costs of trading currencies locally, in contrast, can be expected to increase the attractiveness of transacting through local sales desk and to help them retain or repatriate foreign exchange transactions onshore, in line with the "Flat World" hypothesis.

In the paper we estimate the effect of technological progress on the location of transactions in 55 currencies between 1995 and 2013, utilizing a confidential BIS data set. We use these data to estimate the effect of fiber-optic cable connections on location, operating both directly on the share of offshore transactions and indirectly by altering the relative importance of other standard determinants of location such as distance, domestic market liquidity and regulation.

We find that cable connections between local markets and matching servers in the major financial centers lower the fixed costs of trading currencies and increase the share of currency trades occurring onshore. At the same time, they attenuate standard spatial frictions such as distance, the effect of local market liquidity, and restrictive regulations that otherwise prevent transactions from moving offshore to the major financial centers. Our estimates suggest that the second effect dominates – that the landscape of the foreign exchange market has become "flashier," not "flatter." Technology dampens the impact of spatial frictions by up to 80 percent and increases, in net terms, the share of offshore trading by 21 percentage points. It also has economically important implications for the distribution of foreign exchange transactions across financial centers, boosting the share in global turnover of London, the world's largest trading venue, by as much as one-third.

These findings matter for both markets and policy and contribute, for instance, to shed light on current discussions on competition between financial centers to attract trading in renminbi or in euros.

1. Introduction

The impact of technology on services, and specifically on where services are produced and traded, is one of the great unanswered questions of the post-industrial age. The cost of everything related to information and communication is dropping like a stone due to developments in computation, big data, fiber optics and satellite technology. But the implications for the location of service activities that make intensive use of information and communication technology (ICT) – activities that are likely to be a principal source of employment in the post-industrial age – remain highly uncertain.

One view is that cheap ICT significantly attenuates the effect of distance and other trading barriers on the geography of production.[1] Another view is that distance and other trading barriers still matter significantly.[2]

In this paper we shed light on this debate using the global foreign exchange market as a case study. Our study thus speaks to the heavily-discussed question of whether advances in ICT leading to the advent of electronic trading have increased or reduced the importance of proximity for trading in the foreign exchange market.

What might be called the "Flat World" hypothesis (after Friedman 2005) is that location, distance and other aspects of geography no longer matter in a ubiquitous 24-7 FX marketplace. In a world of high-speed communication, foreign exchange transactions can take place anywhere and should be observed in a growing number of places, reflecting the availability of relevant inputs (information about domestic policies likely to affect the value of the national currency, or information about local customer tastes, for example).

Alternatively, what might be called the "Flash Boys" hypothesis (after Lewis 2014) suggests that location matters more importantly than ever in a 21st-century

[1] Cairncross (1997), Bakos (1997), Shapiro and Varian (1999) and Friedman (2005) all argue that the Internet all but eliminates communication, search, and transportation costs, neutralizing the effect of distance on production decisions for a wide range of activities. Antràs, Garicano and Rossi-Hansberg (2006) consider offshoring in a knowledge economy and propose a framework that allows them to examine the impact of offshoring on wages, occupational choices, and the distribution of firm sizes. For a review of the international trade literature on multinational firms, including offshoring and outsourcing, see Antràs and Yeaple (2014).

[2] As Ed Leamer puts it, the distance effect on international trade is "possibly the only important finding that has fully withstood the scrutiny of time and the onslaught of economic technique" in the literatures of international economics and economic geography (see Leamer 2007, p. 11). Disdier and Head (2008) find that the estimated negative impact of distance on international trade rose around the middle of the century and has remained persistently high since then. Blum and Goldfarb (2006) show that the distance effect holds even in the case of taste-dependent digital goods consumed over the Internet that have no trading costs. The literature on economic geography similarly finds, in a variety of settings (within the United States, for example, as in Bartelme 2015), that distance as a proxy for trade costs retains a robust impact on the location of production and direction of trade.

foreign exchange market characterized by competition between high-frequency traders for proximity to data-matching servers and in which speed of execution is critical.[3] In this view, foreign exchange transactions will concentrate in a handful of locations – those that possess data-matching servers and high-speed communications with the rest of the world. Proximity to the country whose currency is being traded – to the individuals and institutions responsible for policies likely to affect the value of the currency being traded, for example – should no longer matter to the same extent as before.

The global foreign exchange market is an appealing case for several other reasons. First, the foreign exchange market is one of the largest markets in the world as measured by the volume of transactions, with an average daily turnover in excess of $5 trillion. Second, the market is "immaterial" in the sense that what are provided are financial services, as opposed to merchandise, which makes it highly relevant for thinking about the geographical distribution of activity in a post-industrial age. Third, the foreign exchange market has undergone a dramatic transformation since the late 1980s, reflecting the availability of cheap and efficient ICT and the growth of electronic trading.

We investigate how the geography of the foreign exchange market has been affected by changes in ICT. Has ICT led to greater concentration of transactions in a handful of major financial centers such as London, New York and Tokyo by allowing more market participants to reap the advantages of being close to the matching servers on which trades are executed electronically? Or has it enhanced the competitive position of suppliers of these services in other places, who can impart local knowledge to their customers but also now more easily link to matching servers located in the major financial centers from afar? Has the landscape of the foreign exchange market become "flashier" or "flatter," in other words?

How to investigate these questions is not obvious. Investments in technology can affect the geographical distribution of economic activity, but changes in the geographical distribution of economic activity also provide an incentive for investments in technology. Examples of sharp, discontinuous, exogenous changes in information and communication technology would help to pin down the causal effect, but technological progress tends to be continuous rather than discrete, endogenous rather than exogenous. Instances where it is possible to identify the diffusion of technology shocks over economic and geographical space are even fewer and further between.

[3] Courtesy of Michael Lewis' book *Flash Boys* (Lewis 2014). Proximity means purchasing colocation services, i.e. the ability of traders to locate their trading applications in the same data center as the exchange's matching engines and servers (see e.g. Brogaard et al. 2014; Biais, Foucault and Moinas forthcoming). If anything, the growth of algorithmic trading (see e.g. Chaboud et al. 2014) has increased sensitivity to location given the value of proximity to servers for, inter alia, high-frequency trading.

But in the case of the foreign exchange market, we have just such a source of exogenous change and spatial variability. This is the laying of submarine cables starting in the late 1980s. These cables were not laid for purposes related to electronic foreign exchange trading. Rather, their underwriters foresaw them as efficient and profitable vehicles for long-distance telegraphic communication, telephone calls, fax and internet transmission. Only over time was their utility for electronic trading of foreign exchange and other financial instruments discovered. Moreover, the shape of the submarine fiber-optical cable network is heavily influenced by geography, in that cables can only connect terrestrial points with direct access to the ocean.[4] Since cables were laid and came into use at different points in time, the network of active submarine cables provides us with a source of exogenous changes that vary over both space and time. This enables us to identify the causal effects of technology on international financial transactions.[5]

Our identification strategy capitalizes on the special role in electronic foreign exchange trading played by three of the largest financial centers: London, New York and Tokyo. It is in these cities that the matching servers of Electronic Broking Services (EBS) and Thomson Reuters, the leading platforms for electronic broking and trading, have been located since the early 1990s.[6] It follows that a country's connection to the UK (for London), US (for New York) or Japan (for Tokyo) via a submarine fiber-optic cable reduces latency time and increases bandwidth. In a world where data processing needs grow exponentially and high-frequency trading accounts for a rapidly growing share of FX trading, both bandwidth and latency time are critically important. Bandwidth refers to the amount of data that can flow through a cable per unit of time. Latency time refers to the speed in milliseconds at which trading venues acknowledge an order after the order in question was sent.[7]

[4] Landing points are carefully chosen to be in areas with gently sloping, sandy or silty sea-floors and without strong current to minimize risks of damage. This explains why islands or peninsulas like Hong Kong and Singapore are hubs where carrier networks interconnect or why Greenland could only be connected in 2009. The global network of some 350 submarine fiber-optic cables that today make up the backbone of the internet is shown in Figure 1.

[5] This is in the spirit of recent studies that use geographical attributes and related infrastructure as sources of exogenous variation, such as Acemoglu, Johnson and Robinson (2005), who used direct access to the Atlantic Ocean, or Acemoglu, García-Jimeno and Robinson (2015), who used colonial royal roads built in Colombia in the 18th century, as the sources in question.

[6] Electronic trading also takes place on multibank electronic communication networks (such as Currenex, Hotspot FX and FXall). But since these are typically US-based, they do not change the story. They should also have a weaker impact on the location of trading than EBS and Thomson Reuters servers, since in some cases they only provide pricing updates at set intervals. In addition, other inter-dealer venues tend to restrict the number of quotes per second and demand certain fill ratios (i.e. the amount of trades completed relative to quotes submitted).

[7] Latency time is sufficiently important that saving only six milliseconds in transmission time is enough to justify the laying of the first submarine cable in a decade between New York and London, at a cost of more than $300 million. This project, known as "Hibernia," was first tested on 24 September 2015. Further details are at http://www.hibernianetworks.com/hibernia-express/ (accessed on October 2, 2015). The Hibernia project is the only example of which we are aware of a submarine cable laid for the purpose of electronic trading. The first cable built for electronic trading purposes seems to have been Spread Networks' terrestrial cable between Chicago and New Jersey in 2010; see below.

We posit that lower latency and greater bandwidth reduce the importance of spatial frictions such as distance, information asymmetries (as in the analyses of Hau 2001, Bachetta and van Wincoop 2006, Menkhoff and Schmeling 2008, Lyons and Moore 2009 and Moore and Payne 2011), domestic market liquidity (as in Krugman and Venables 1995, 1996 and Gabaix and Maggiori forthcoming), and regulatory frictions like capital controls (as in Friedman 1969). This effect is similar to a reduction in transportation costs of buy and sell orders involving counterparties in different locations; this will be attractive to high-frequency traders seeking to exploit tiny, short-lived price discrepancies at the millisecond level, but also to other traders. We also posit that lower latency and larger bandwidth reduce the fixed costs of undertaking transactions electronically, insofar as they reduce the costs of aggregating and matching buy and sell orders, as well as the costs of processing information and data more generally.

If lower latency and greater bandwidth matter, they will affect the geography of foreign exchange trading, such as the shares of transactions in a currency that occur onshore (in the issuing country) and offshore (in the major financial centers). Specifically, the reduction in spatial frictions and transportation costs may encourage onshore transactions to move offshore to the major financial centers, in the manner of the standard "home market effect" (Krugman 1980, 1995) and consistent with the "Flash Boys" hypothesis. The reduction in the fixed costs of trading currencies locally, in contrast, can be expected to increase the attractiveness of transacting through local sales desk and to help them retain or repatriate foreign exchange transactions onshore, in line with the "Flat World" hypothesis.

As an example of the relevance of submarine fiber-optic cables, consider Figure 2, which shows the evolution of the volume of offshore foreign exchange trading in Switzerland (Zurich) and Singapore.[8] As the figure shows, offshore trading was 60% higher in Singapore as in Zurich in the mid-1990s. But offshore trading is now more than twice as large in Singapore as in Zurich.

Standard determinants in the literature on the location of foreign exchange trading – factors like distance, market liquidity and regulation – are unlikely explanations.[9] A more appealing explanation is that Singapore, which borders the sea, has been a hub for fiber-optic submarine cables since 1999, while Switzerland, which is landlocked, has not. Singapore took off as a center for foreign exchange

[8] "Offshore trading" in these centers refers to trading there of currencies other than their respective national units (the Swiss franc and Singapore dollar, respectively).

[9] Distances between Zurich, Singapore and other markets have not changed. Capital controls in both cases were and are virtually inexistent. That Zurich cracked down on money laundering and tax evasion in recent years, under US pressure, is an unlikely culprit insofar as Singapore faced similar pressure from the G20 (see e.g. OECD, 2009). To be sure, market liquidity – another factor emphasized in the literature – has changed as trading in Singapore has grown much faster than in Zurich, but this fact is not unrelated to the very factor whose behavior we are seeking to explain. In econometric analysis below we exclude trading of the domestic currency from our measure of domestic foreign exchange market liquidity in order to minimize the potential problem of endogeneity that might otherwise flow from this association.

trading in the mid-2000s at the same time as high-frequency trading, while Zurich missed the boat, as it were. That Singapore was directly connected to the internet backbone, while Zurich was not, goes a long way toward explaining this difference.[10]

In the paper we estimate the effect of technological progress on the location of transactions in 55 currencies between 1995 and 2013, utilizing a confidential BIS data set. BIS statisticians identify the location of foreign exchange transactions on the basis of the location of the initiating sales desk. They distinguish transactions between those that are conducted within the borders of the issuing jurisdiction, i.e. onshore, and those outside these borders, i.e. offshore in major financial centers like London, New York and Tokyo or other smaller centers. We use these data to estimate the effect of fiber-optic cable connections on location, operating both directly on the share of offshore transactions and indirectly by altering the relative importance of other standard determinants of location such as distance, domestic market liquidity and regulation.

We find that cable connections between local markets and matching servers in the major financial centers lower the fixed costs of trading currencies and increase the share of currency trades occurring onshore. At the same time, they attenuate standard spatial frictions such as distance, the effect of local market liquidity, and restrictive regulations that otherwise prevent transactions from moving offshore to the major financial centers. Our estimates suggest that the second effect dominates – that the landscape of the foreign exchange market has become "flashier," not "flatter." Technology dampens the impact of spatial frictions by up to 80 percent and increases, in net terms, the share of offshore trading by 21 percentage points. It also has economically important implications for the distribution of foreign exchange transactions across financial centers, boosting the share in global turnover of London, the world's largest trading venue, by as much as one-third.

These issues matter for both markets and policy. They arose following the launch of the euro in 1999, when London (the leading regional financial center) and Frankfurt (where euro area monetary policy was made) competed to attract business in the single currency.[11] They now arise in discussions of whether Shanghai, Tokyo, London or another financial center will attract the lion's share of international transactions in renminbi or whether this business will be spread across them. They could again be important for the British referendum on EU membership, insofar as "Brexit" could lead to the relocation of foreign exchange trading in euros (and

[10] That transactions in Singapore rose strongly over the period rather than simply falling more slowly than in Zurich would appear to support the "Flash Boys" hypothesis over the "Flat World" hypothesis, but it will be important to test these hypotheses more systematically.

[11] That trading in the euro occurred heavily offshore, in London, and not in Frankfurt where euro area monetary policy would again appear to support the "Flash Boys" hypothesis.

perhaps other currencies) away from the City of London to a financial center on the continent or elsewhere.[12]

Section 2 provides a primer on electronic trading of foreign exchange and submarine fiber-optic cables. Section 3 then describes the data, after which Section 4 presents some stylized facts, while Section 5 presents our identification strategy. Section 6 discusses our empirical framework and hypotheses. Section 7 reviews the empirical results. Section 8 reports robustness checks, after which Section 9 gauges the distributional effects of cable connections across the world's financial centers. Section 10 concludes.

2. Electronic Foreign Exchange Trading and Submarine Cables

The foreign exchange market has been transformed since the late 1980s by the advent of electronic broking and trading, reflecting the availability of less expensive and more efficient information and communications technology. Electronic trading dominates today's foreign exchange market, with a share above 50% for all customer segments and availability for instruments and investors across the globe.[13]

Electronic brokers were introduced in the inter-dealer foreign exchange market as early as in 1992. Two platforms, EBS and Thomson Reuters, dominated this market segment. They reduced transaction costs relative to traditional means of dealing, like voice trading. In voice trading, a dealer would contact other dealers to obtain information on prices available in the market and, presumably, complete the deal at the best price offered. With the advent of electronic brokers, dealers could immediately learn via a computer terminal the best available price and complete the transaction then and there.

In contrast to the inter-dealer market, which rapidly migrated to electronic platforms, as late as 2000 the main trading channel for market participants other than dealers remained direct contacts with dealers over the phone. As a result, the turn-of-the-century foreign exchange market was still segmented between the inter-dealer market (which was heavily electronic) and the retail-dealer market (which was not). This segmentation was then reduced in the course of the subsequent decade. A multi-bank trading system providing customers with competing quotes from different dealers on a single page (Currenex) was launched in 1999. As other multi-bank platforms such as FXall and Hotspot followed, transparency rose and transactions costs fell further. Between 2001 and 2006 large dealers launched proprietary single-bank trading systems for their customers; examples of such systems include Barclays'

[12] On the euro see e.g. HM Treasury (2003) and Cantillon and Pai-Ling (2008); on the renminbi see e.g. He et al. (2015); on the risks associated with a Brexit for the City of London see e.g. Faulconbridge (2015).

[13] See Rime and Schrimpf (2013), p. 34. Earlier, in 2001, market sources suggest, half of turnover in the major currencies was conducted through electronic brokers, up from 40% in 1998 and roughly 10% in 1995 (see Galati 2001, p. 39 and BIS 2001), although the share of turnover in other currencies was far less.

BARX, Deutsche Bank's Autobahn and Citigroup's Velocity. And starting around 2005, EBS and Thomson Reuters, which previously offered brokerage services to dealers only, opened up to hedge funds and other traders. Their platforms consequently evolved into leading venues for high-frequency trading firms.

A key factor underlying the rise of electronic trading in the foreign exchange market was the internet and its backbone, i.e. the network of some 350 submarine fiber-optic cables that connect computers around the world. An important feature of this network, highly relevant to our analysis, is that it was not laid for purposes related to electronic foreign exchange trading. Establishing this fact requires us to review some of the relevant history.[14]

The first submarine cables were laid to carry telegraph signals. Samuel Morse (of Morse Code fame) submerged a copper cable covered by tarred hemp and rubber in New York Harbor in 1842 and demonstrated the feasibility of transmitting telegraphic signals. Cables covered with gutta-percha (gum from gutta-percha trees) connecting Great Britain with the European continent were then laid starting in the 1850s. A successful transatlantic cable followed, after eight years of failed attempts, in 1866. Other copper cables (more precisely, cables of copper wire surrounded by rubber or gutta-percha, in turn surrounded by an outer layer of iron or steel wire) subsequently connected a growing range of locations.

Early submarine cables were subject to problems of reliability and capacity. In the absence of repeater amplifiers, high voltages were required to transmit signals over long distances, creating distortion, limiting carrying capacity and heightening the risk of short-circuiting. Thick, costly copper wires were required to slow signal loss. The physical cables were often weakened or disrupted by storms and damaged by currents and fishing trawlers.

Only in the 1890s did the science of transmitting higher frequencies, essential for data and voice, begin to be established. Another breakthrough essential for long-distance telephonic communication was development of a practical vacuum-tube-based repeater amplifier in the opening years of the 20th century. Commercialization was then delayed by the two world wars and the Great Depression. The first modern submarine cable, TAT-1 (Transatlantic No. 1), a coaxial cable insulated using polyethylene (rather than gutta-percha) and utilizing vacuum tubes as repeaters, was finally laid starting in 1955. TAT-1 connected Oban, Scotland with Clarenville, Newfoundland. It was underwritten by AT&T, the Canadian Overseas Telecommunications Corporation, and the UK General Post Office. When inaugurated on September 25, 1956, it had 36 separate channels, enabling it to carry 35 simultaneous telephone calls along with 22 telegraph lines on the 36th channel. The 1960s saw the development of coaxial cables of somewhat greater reliability and

[14] A detailed account of the early history of submarine cables is Wenzlhuemer (2013).

carrying capacity that operated with narrower bandwidths and utilized transistors rather than vacuum tubes as repeaters.[15]

Coaxial cables were superseded in the 1980s by fiber-optic cables.[16] Fiber-optic cables transfer data at a speed of 180,000-200,000 kilometers per second (i.e. the speed of light in glass), resulting in latency per kilometer of 5 to 5.5 microseconds (a 10 to 11 millisecond delay for a roundtrip of 1,000 kilometers); latency time will be important to our subsequent story. Fiber optic cable connections also increase bandwidth (i.e. the amount of data that can be put through per unit of time) significantly relative to coaxial cables. They reduce losses in signal transmission over long distances. The first submarine fiber-optic cable, TAT-8, entered service in December 1988. Financed by a consortium led by AT&T, France Télécom (now Orange) and British Telecom, TAT-8 had a branching unit underwater, off the coast of Great Britain, enabling it to connect to both the US and France. It had a capacity of 40,000 circuits, allowing it to carry as many as 40,000 simultaneous telephone calls or similar communications, a tenfold increase relative to coaxial cables.

Initially, this cable, not unlike its 1850s predecessor, had reliability problems. The absence of electrical interference shielding caused electrical current it carried to attract sharks, which attacked the cable. (Sharks are subject to electroreception, the biological ability to perceive electric current, which sets off feeding frenzies.) Subsequent cables, starting with PTAT-1 in 1989, were fitted with shark shielding, enhancing reliability. This is the point in time that we would date the initial availability of the information and communication technology needed to support long-distance electronic foreign exchange trading.

PTAT-1 was also the first fiber optic submarine cable to be financed entirely privately. It was underwritten by a US company, TelOptik, and by Cable and Wireless plc in the U.K, which built it – importantly – to carry telephonic traffic in competition with AT&T and British Telecom.

The submarine cables laid between 1989 and the early 2000s were overwhelmingly financed by telecommunication companies to accommodate general telecommunication needs, namely long-distance telegraphic communication, telephone calls, fax and internet transmission. They were not underwritten to facilitate electronic trading (see below and Table A1 for information on the owners of the cables connected with London, New York and Tokyo in 2002).[17] 2010 was a turning point, when Spread Networks unveiled an 827 miles terrestrial cable running

[15] In coaxial cables, the copper or copper-plated steel wire is surrounded by an insulating layer which is in turn enclosed by a metallic shield.

[16] Fiber-optic cables are made by stretching glass (or silica) to roughly the diameter of a human hair.

[17] Hibernia Atlantic, which was placed in receivership in 2001, was financed by Tyco Submarine Systems for 360networks (a telecommunication company) in 2000 for $962 million and only later purchased by Hibernia (i.e. the same company which more recently has financed the laying of Hibernia Express between New York and London).

through mountains and under rivers from Chicago (home to the Chicago Mercantile Exchange where derivatives are traded) to New Jersey (home of the Nasdaq data center). This cable reduced latency time from 17 to 13 milliseconds (see Lewis, 2014); it is the first example of which we are aware of a terrestrial cable laid for the sole purpose of electronic trading. Hibernia Express, which was tested in September 2015, is the first submarine cable laid for the express purpose of electronic trading. The existence of these recent cables does not affect our identification strategy, however. As we explain in more detail below, we only use for identification submarine cables laid between 1989 and 2002 (i.e. the year by when all countries in our sample were connected to either London, New York or Tokyo), i.e. almost a decade before investors sought to lay them with electronic trading in mind.[18]

By 2006, 99 per cent of international communications traffic was carried by submarine cables, the remainder carried by satellite. Fiber-optic cables remain the principal conduit for data transmission for the internet in general and electronic trading of foreign exchange in particular, because submarine fiber-optic cables still have much lower latency, larger bandwidth and reliability performance than satellite transmission.

Might earlier telephonic cables, before the advent of fiber optics, have had a similar effect on the location of foreign exchange trades? We doubt this. Electronic trading developed because market participants gained access to high-speed internet connections, which are important to high-frequency trading. Such high-frequency trading was not possible with earlier telephonic cables, which transmitted data and orders less quickly and reliably. Electronic trading also developed because market infrastructure (EBS and Thomson Reuters servers) was now able to handle large numbers of simultaneous orders at high frequency. Such infrastructure was not feasible (it was non-existent) before the 1990s because it requires large data storage capacity and fast computing, which were beyond technical capabilities in the earlier period.

3. Data

We take our data on the network of submarine fiber-optic cables from TeleGeography's interactive Submarine Cable Map.[19] These data were collected by Global Bandwidth Research, a consultancy specializing in data and analysis of long-distance networks and the submarine cable market. They provide information on 368 submarine cables starting in 1989. The information reported includes the cable's profile, name, year when it was ready for service, length, owners, and geographical coordinates of its landing points.

[18] In technical terms, this means that the existence of a cable link can be regarded as econometrically exogenous with respect to the share of foreign exchange trading occurring offshore. Still more recent cables, backed by Google, connecting Florida with Brazil, Southeast Asia with Japan, and Japan with California, are similarly being built with the Internet in mind and not high speed trading.

[19] TeleGeography has made the source code behind the interactive Submarine Cable Map available for download at https://github.com/telegeography/www.submarinecablemap.com.

For data on the location of foreign exchange trading, we obtained confidential estimates of onshore, offshore and global foreign exchange turnover by currency from the Bank for International Settlements (BIS). We have data for 55 currencies (including 12 euro legacy currencies) in seven years (1995, 1998, 2001, 2004, 2007, 2010 and 2013). The data were collected in the context of the BIS's triennial central bank surveys of foreign exchange and derivatives market activity.[20]

BIS statisticians define foreign exchange turnover as the daily average of the notional amount (in US dollar equivalents) of all transactions struck in April of the year of the triennial survey.[21] They produce data in "net-net" terms. In other words, they adjust for local double-counting – i.e. for transactions between reporting dealers located in the same country – as well as for cross-border double-counting.[22]

Foreign exchange turnover is allocated across countries according to where the transaction is arranged. Since 2004, BIS statisticians have specified that they mean the location of the initiating sales desk (which may not coincide with the location of the trading desk).[23] For example, when an employee of a savings bank in Berlin asks his or her foreign exchange dealer at Deutsche Bank Frankfurt to buy Y50 million against euros, this transaction will be recorded as having taken place in Germany, because the sales desk is in Germany. Actual trading could take place elsewhere, for example by traders at Deutsche Bank London.[24] BIS statisticians use the trading desk to determine the location of a deal when no sales desk is involved.[25] Discussions with

[20] These surveys offer the most comprehensive and internationally consistent information on the size and structure of the foreign exchange market although, as King and Mallo (2010, p. 71) observe, "the underlying data remain largely unexplored." An exception is e.g. He et al. (2015), who do not however focus on the impact of technology on the location of FX transactions, as here.

[21] A broad array of foreign exchange instruments are covered, including spot transactions, outright forwards, foreign exchange swaps, currency swaps, currency options and other foreign exchange products, including nondeliverable forwards. Dealers report their transactions in these instruments with other reporting dealers, other financial institutions and non-financial customers. Each transaction is recorded once, and offsetting contracts are not netted. There is no distinction between sales and purchases. Direct cross-currency transactions (e.g. pound sterling for Swiss francs) are counted as single transactions. Transactions that use a vehicle currency (e.g. the US dollar) are counted as two separate transactions. See King and Mallo (2010) for further details. The data include transactions in dark pools such as MidFX and BGC.

[22] For instance, local inter-dealer transactions in Germany are halved to obtain the correct turnover for Germany. As another example, transactions between a reporting dealer located in the United Kingdom and a reporting dealer located in France are halved to obtain the correct estimate of global turnover.

[23] The nationality of the reporting dealer is not relevant in this context. For example, when UBS Frankfurt reports trades to the Bundesbank, these transactions are allocated to Germany.

[24] In reality the dealer will not execute every single trade individually because transaction costs would be excessive and he/she would take credit risk for each transaction. Dealers will instead add additional trading orders to their dealing books, net FX positions internally (via Autobahn, BARX or Velocity, for example) and trade the residual either on exchange platforms (EBS, Reuters, etc.) or via OTC transactions. From a BIS perspective, what matters is the location where the FX book is aggregated and netted (i.e. at the back-office).

[25] Given the growing use of electronic execution methods, moreover, it can be expected that in the next BIS Triennial Survey (which is to be conducted in April 2016) the sales contact of the electronic

foreign exchange dealers suggest that banks net and aggregate their positions in the same location (in the back-office) where they trade (in the front-office). In other words, there are no major differences between sales and trading desks in most cases.[26] The distinction might still be more important in the case of smaller financial centers where the sales desk might remain local but the trading desk might be in a larger center, such as London, New York or Tokyo. But readers should note that when a bank decides to relocate its trading desk to a major financial center, it may move its sales team there, too.

4. Stylized Facts

Figure 3 shows that in the course of the last two decades transactions in foreign exchange have increasingly taken place offshore, in locations other than the country issuing one of the currencies involved in the trade. The figure shows the evolution between 1995 and 2013 of the weighted and unweighted global averages of foreign exchange trading occurring offshore (weighted in the left-hand-side panel, unweighted at the right).[27] The global weighted average rose over this period by five percentage points, to about 78% in 2013. Insofar as this estimate is considerably higher than the theoretical lower bound of 50% (one of the two currencies involved in a foreign exchange trade undertaken in a particular national market is the currency of a foreign country, meaning that it is necessarily traded offshore), this confirms that a substantial fraction of transactions occur in third markets.

From 1995 to 2013 the global unweighted average of the individual currency shares of foreign exchange trading occurring offshore essentially tripled, from 20 to 60 per cent. (Note that the unweighted arithmetic average, which weights every unit equally, is not subject to the 50% lower bound.) This suggests that internationalization (trading in third markets) affected not only major currencies like the US dollar but also other units.

Not only does a substantial fraction of offshore transactions occur in markets such as London, New York or Tokyo, but that share is increasing. This is evident from Figure 4, which shows the evolution between 1995 and 2013 of scaled and unscaled Herfindahl indices of concentration of global foreign exchange transactions occurring offshore in these three financial centers (left-hand-side panel), as well as the combined share of global transactions they account for (right-hand side panel). Both charts show a clear upward trend, testifying to the importance of London, New York and Tokyo in the global market for offshore foreign exchange transactions.

platform who services the client, or the trading desk or the electronic matching engine, will be used to determine the location of a deal when no sales desk is involved (see BIS 2015).

[26] This is consistent with the observation that there were no major breaks in the data when the BIS changed its definition of trading location in 2004 from the trading desk to the sales desk.

[27] The weighted average is the sum of foreign exchange trading occurring offshore in all currencies scaled by the sum of total (onshore and offshore) foreign exchange trading in all currencies. The unweighted average is the arithmetic average of the individual currency shares traded offshore.

That internationalization (trading in third markets) involved not just major currencies but also smaller units is again evident from Figure 5, which shows the evolution between 1995 and 2013 of the share of foreign exchange trading occurring offshore for each of the 55 currencies in our sample between 1995 and 2013.[28] The figure is a heat map, whose shades darken over time in line with the growing importance of trading occurring offshore for all units.

In addition to these changes over time, there is heterogeneity among currencies in the extent of foreign exchange trading offshore. Note in Figure 6, which focuses on a selection of units, the relatively high shares of the US dollar and also the euro and Japanese yen, compared to the relatively low shares of several emerging market currencies, like the Korean won and Indian rupee, while still other emerging market units have high shares (for example the Polish zloty). In total, only 9 of the 55 units had an offshore share of less than 50%. In other words, most currencies actively trade offshore.

5. Identification

Our identification strategy capitalizes on the special role of the UK, the US and Japan in electronic foreign exchange trading. It is in these countries that matching servers of EBS and/or Thomson Reuters – the leading platforms for electronic broking and trading – are located. EBS servers have been located in the UK, US and Japan since 1990. Thomson Reuters has servers in both the United Kingdom and the United States.[29]

Our identification assumption is that a direct or indirect connection to the UK, US or Japan via a submarine fiber-optic cable reduces latency time and losses in signal transmission while increasing bandwidth for a large range of internet-based applications. It therefore enhances the attraction of transacting in the location that now possesses a high-speed connection to an electronic platform. It reduces the costs of undertaking transactions electronically through EBS and/or Thomson Reuters, rather than other means or in other venues. The reduction in latency is especially attractive to high-frequency traders seeking to exploit tiny, short-lived price discrepancies at the millisecond level and to an extent also for other traders.[30] And lower latency together with larger bandwidth reduce the costs of aggregating and

[28] Darker shades of grey indicate higher shares of trading occurring offshore (actual shares are not reported for confidentiality reasons). The color white indicates that the data are unavailable or simply not reported.

[29] EBS is predominantly used for transactions involving the US dollar, euro, yen and Swiss franc, while Thomson Reuters is predominantly used for transactions involving the pound sterling, the Australian, Canadian and New Zealand dollars, and emerging market units.

[30] It has been estimated that 30 to 35% of foreign exchange trading on EBS is HFT-driven. See Rime and Schrimpf (2013), p. 40. The reduction in signal loss transmission and the increase in bandwidth enable traders to aggregate large amounts in real time of buy and sell orders in spot, forward and other derivative markets. This helps to ease price discovery and matching, which is convenient for all market participants, not only high-frequency traders. This is also why sales desk, which remain crucial to non-HFT, non-dealer market participants, are important to determine the location of trading.

matching large numbers of buys and sells orders, which is also attractive to other market participants.[31]

If these gains are sufficiently large, they will affect the geography of trading and the relative importance of standard spatial frictions, i.e. distance, domestic market liquidity and other frictions like capital controls (more on this below). That cable connections attenuate the effect of the frictions in question, which otherwise prevent transactions from moving offshore to the major financial centers, is not unlike the standard "home market effect" (Krugman 1980, 1995). Production of the varieties of a differentiated good or service (here exchange rate transactions) moves to the larger market (here major financial centers like London, New York or Tokyo) under monopolistic competition (here the restricted number of electronic platforms like EBS or Thomson Reuters that dominate the electronic foreign exchange market or the restricted number of dealers, like Citi, Barclays, Deutsche or UBS, that dominate the OTC foreign exchange market) and increasing returns (here e.g. in the self-reinforcing effect of greater market liquidity; in the concentration of suppliers of intermediate goods or specialized services, such as legal, IT and accounting services; or in the availability of skilled and talented staff), when transportation costs are lowered (here latency is lowered and bandwidth increased through cable connections) and exported to the rest of the world from the market in question.[32]

But the effect could go in the opposite direction, to the extent that cable connections between local markets and matching servers in the major financial centers lower the fixed costs of trading currencies locally by easing access to financial information and increasing bandwidth, they enhance the competitiveness of local sales desks and help them keep or repatriate foreign exchange transactions domestically. (To continue with the analogy with Krugman's model discussed above, production of the varieties of the differentiated good or service in question becomes more domestic when their fixed costs of production are reduced.) In other words, the services provided by the sales desk in Frankfurt discussed above could become more appealing to the customer in Berlin, since the sales desk can now have access to a more timely and broader set of quotes and other financial information. It can now communicate more quickly with a matching server in London, providing the Berlin-based customer with a better price while also conveying (in German) useful Frankfurt-based information about relevant monetary (and other policy) initiatives. And more generally it can match a larger number of transactions and process a larger amount of information and data.

[31] That bandwidth is crucial for financial trading is also evident from the fact that Singapore's bandwidth consumption was three times larger than Korea's in 2012, although its population is ten times smaller, according to data by TeleGeography.

[32] One difference with Krugman (1980)'s model is that he considered two types of goods of different varieties whereas we focus here on one type of services, i.e. foreign exchange transactions in different units.

The direction of the effect and how the impact of other factors like time-zone differences is altered are what we will seek to uncover.

Our analysis takes advantage of heterogeneity across countries and over time in when different countries were connected to the network of submarine fiber-optic cables, either directly or indirectly. Here "directly" means that there is a point-to-point submarine fiber-optic cable connecting country x to the UK, US or Japan. "Indirectly" means that country x is connected to country y and country y is in turn connected to the UK, US or Japan. In practice we take into account indirect connections up to the ninth order.

Figure 7 shows the year of first direct or indirect connection to the UK, US or Japan. France and the Netherlands were connected to the UK in 1989.[33] South Africa, to take a contrasting example, was connected much later, in 2002 (as were other African countries).[34]

Figures 8 and 9 illustrate the growing density of the submarine cable network. They show the network of countries directly or indirectly connected to the UK in 1998 and 2013, respectively.[35] Countries in time zones corresponding to Asian trading hours are shown as light grey nodes, against grey nodes for those located in time zones corresponding to European trading hours and dark grey nodes for US trading hours. Solid lines indicate countries with highly liquid units – those that are in the top third by FX turnover – while dashed lines are units in the middle third, and dotted lines are illiquid units in the bottom third. The contrast between the two figures is pronounced. That the network of connections to the UK has grown markedly over time, and improved access to the matching servers of EBS and Thomson Reuters for electronic trading is readily apparent.

6. Empirical Framework and Hypotheses

We estimate the determinants of foreign exchange trading offshore, building on the literature emphasizing spatial frictions such as distance, domestic market liquidity, and regulations such as capital controls. We account for the possibility of unobservable currency and time effects by estimating the following specification:

$$y_{i,t} = \beta_1 Information\ Asymmetries + \beta_2 Domestic\ Market\ Liquidity + \beta_3 Capital\ Controls + \boldsymbol{\beta}'_4\, \mathbf{X} + \alpha_i + \lambda_t + \varepsilon_{i,t} \quad (1)$$

[33] France and the UK were connected through a cable called UK-France 3 (owned by B.T., Orange and Vodafone); the Netherlands and the UK were connected through a cable called Farland North (owned by B.T.).

[34] Through a cable connecting a large part of Africa's western shore called SAT-3/WASC owned by some 30 telecom companies from advanced and emerging market economies.

[35] We report here only the countries in our sample.

where i and t denote currency and time; y is the share of trading occurring offshore for the unit issued by country i in year t; α_i are currency-level effects and λ_t are time fixed effects. We estimate Eq. (1) using a panel tobit estimator and a panel generalized linear model with a logit link (both with random effects). Tobit is appropriate insofar as a number of observations of the dependent variable are censored from below.[36] We also report results using linear panel and pooled OLS estimators, reporting standard errors robust to heteroskedasticity and clustered by trading zone, although these estimates do not take into account the boundedness of the dependent variable.[37]

The first friction we consider is information asymmetries across participants in the foreign exchange market, which are key to exchange rate determination in the analysis of Bachetta and van Wincoop (2006) and to the vehicle role of a particular unit in the model of Lyons and Moore (2009).[38] We assume, other things being equal, that transactions will tend to take place where information about the currency or currencies being traded is most easily obtained.

The precise nature of these information asymmetries matters importantly. The "local information" hypothesis posits that traders outside the country of issuance of a particular unit face an information disadvantage and trade less profitably because of culture, language and distance (Hau 2001). Foreign exchange traders further distant, in the relevant economic sense, from policy-decision-making centers are more reluctant to trade than market participants located closer to these centers because they are further from institutions that generate or interpret public information, such as central banks, ministries or national statistical institutes. They are also further from customer order flows, including those from the central banks in question when they intervene in the foreign exchange market (Menkhoff and Schmeling 2008). The local information hypothesis thus suggests that traders located in the country of issuance possess more and better information, implying that the share of trades in a currency that occur offshore should decline with distance to London, New York and Tokyo.

In contrast, the "financial center" hypothesis suggests that traders in large financial centers enjoy an information advantage over traders in smaller centers (see the discussion in Hau 2001 in relation to the equity market). Traders in large financial

[36] In some cases data submitted to the BIS does not distinguish clearly between negligible and zero trading activity. For discussion of why panel GLM might be especially relevant in our context see below.

[37] Specifically we distinguish the three time zones corresponding to Asian trading hours, European trading hours and US trading hours. We effectively assume that observations within time zones are correlated in some unknown way but that observations across time zones are not correlated. This allows us to take into account variations in liquidity over the trading day and across time zones, as discussed e.g. in Bollersev and Domowitz (1993) and Huang and Masulis (1999).

[38] In the model of Lyons and Moore, for instance, information is dispersed across market participants who differ e.g. in their ability to observe order-flow conveying price-relevant information. In this model, the vehicle role of a particular unit depends on the ease of execution of informed trade, i.e. on the ability to hide informed trades. The vehicle role of a currency is determined by its price-impact: the lower the latter is, the more the currency will be used as a vehicle. Vehicleness is hence greater in currencies with deeper markets (Lyons and Moore 2009, p. 220).

centers may have access to proprietary data bases or in-house research which can result in significant economies of scale and scope. They may benefit from a larger customer base and better access to private information about order flows, which may also help them forecast and exploit the future trading interests of smaller traders (Moore and Payne 2011).[39] Since information about currencies is generated mainly in London, New York and Tokyo according to this hypothesis, distance from there to the country issuing a currency should have a zero or insignificant effect on share traded offshore or may even have a positive effect, since traders in a local market further removed from these global financial centers will be at an even greater informational disadvantage.

Our measure of information asymmetries is the shortest distance in time zones between the country issuing currency *i* and London, New York or Tokyo.[40] We prefer hour distance over physical distance since traders in adjoining time zones will receive news more or less simultaneously (when traders in very different time zones may be sleeping). Focusing on hour distance also allows us to take into account differences in liquidity arising from non-overlapping trading hours, which matter for computer-run algorithmic or automated trading strategies seeking to transact with sleeping agents, this factor being emphasized in studies of the microstructure of the foreign exchange market such as in e.g. Bollersev and Domowitz (1993) and Huang and Masulis (1999). This choice of "information distance" is consequential: Johannesburg, for example, is more than 13,000 kilometers away from London but only one time zone ahead. For this reason we also consider physical distance in robustness checks below.[41] We would expect that $\beta_1 \geq 0$ if the "large financial center/institutions" hypothesis is true; in contrast we would expect that $\beta_1 < 0$ if the "local information" hypothesis is correct.

The second spatial friction we consider is domestic market liquidity. More liquid markets allow transactions to be undertaken at lower cost. Bid-ask spreads are narrower, and traders can buy and sell larger blocks without moving prices. Where local markets are small and illiquid, the appeal of offshore markets like London known for their depth and liquidity will be particularly strong; conversely, where local markets are liquid, they are likely to capture a larger share of trades of the local

[39] Moore and Payne (2011) find evidence that foreign exchange traders on large floors tend to have larger aggressive (initiated trade) impact than those on smaller floors, in line with the hypothesis that the size of an institution matters for its information advantage. As they put it, larger institutions are likely to observe a larger share of customer order flows and to have access to better research. We are aware that we have invoked information based on order flows in connection with both the financial center hypothesis and the local information hypothesis (both in this paragraph and its predecessor).

[40] We take hour distance between London and Frankfurt for the euro.

[41] Hau (2001) calculated physical distance relative to Frankfurt, which he posited to be the largest financial center for trading of German equities. Similarly, Menkhoff and Schmeling (2008), in their study of the Russian foreign exchange market, calculated distances between Moscow or St Petersburg and centers in other Russian regions.

currency.[42] Our measure of domestic market liquidity is the volume of transactions in foreign currencies in country *i* (in USD trillion).[43] In the baseline model we exclude transactions in the domestic currency in order to avoid endogeneity with the dependent variable. We anticipate that $\beta_2 < 0$; transactions in units issued by countries with relatively deep and liquid domestic financial markets tend to be undertaken onshore. In robustness checks, we also consider the logarithm of this variable, as well as the volume of transactions in all currencies (both foreign and domestic).

The third set of frictions is restrictions on capital flows. Friedman (1969) argued in a classic article that taxing financial transactions onshore provides incentives for business to migrate offshore (where capital controls are equivalent in this context to a tax on purchases and sales of a foreign currency).[44] That controls are instrumental to the development of offshore currency markets is widely argued by market participants (see e.g. HSBC 2011 and Credit Suisse 2013).[45] In some cases these offshore markets have developed through trading in non-deliverable forward contracts which enable investors there to actively trade claims indexed to a currency despite controls maintained by the issuing country that limit their access to the underlying currency itself (McCauley, Shu and Ma 2014).[46]

As a measure of restrictions on capital flows, we use the time-varying indices of de jure capital account openness constructed by Fernandez et al. (2015). These capture the overall importance of capital controls in country *i* and in year *t*.[47] We anticipate that $\beta_3 > 0$; transactions in units issued by countries with closed capital

[42] This can also be rationalized by referring to models in which concentration of an activity in a particular location has positive feedbacks on the advantages of further concentrating that activity in that location. See the models and arguments of Krugman and Venables (1995, 1996).

[43] We take the total volume of transactions in euro area members for the euro.

[44] His example illustrating the power of this hypothesis was the development of the Eurodollar market in London as a response to the adoption by the US of Regulation Q in the 1960s. "The most important regulation that has stimulated the development of the Euro-dollar market [i.e. of markets in dollars outside the US] has been Regulation Q, under which the Federal Reserve has fixed maximum interest rates that member banks could pay on time deposits. Whenever these ceilings became effective, Euro-dollar deposits, paying a higher interest rate, became more attractive than U.S. deposits, and the Euro-dollar market expanded." (Friedman 1969, p. 4).

[45] For instance, entities that are not registered in China are not allowed to participate in onshore foreign exchange transactions of renminbi (also known as "CNY"), which must be executed via designated foreign exchange banks. Offshore entities can receive and pay renminbis to settle trade in goods transactions under certain conditions, however. This has contributed to the development of an offshore market of renminbis in Hong Kong (also known as "CNH") in the 2000s in which the renminbi can be freely transferred between accounts and across banks (although transfers to/from the mainland remain tightly regulated).

[46] Non-deliverable forwards are forward exchange agreements settled with a single US dollar payment. They hence allow market participants to obtain exposure to the underlying local unit without having to deliver it (unlike deliverable forwards). Transactions in non-deliverable forwards are included in the BIS data.

[47] The index runs from zero (no controls) to one (full controls). For the euro we take the average of the index for the euro area members.

accounts have an incentive to migrate offshore. In robustness checks we also separate controls on inflows and outflows.

In additional sensitivity tests, we control for other variables (denoted **X** in eq. 1 above) cited in previous literature as bearing on the geography of the foreign exchange market, and whose omission from the baseline specification could conceivably bias the results. Such variables include trade openness (measured as exports plus imports scaled by GDP, constructed from IMF data); financial openness (measured by net external financial assets scaled by GDP, using updated data from Lane and Milesi-Ferretti 2007); a dummy variable for exchange rate flexibility, which equals one if a country has a managed exchange rate or a float, and zero otherwise, using the updated classification of Ilzetzki, Reinhart and Rogoff (2004); and a metric of dollar-funded carry trades, namely the difference between the short-term local-currency interest rate in country *i* and in year *t* and the corresponding US interest rate.[48]

We estimate the effect of technology on the geography of the foreign exchange market as follows:

$$\begin{aligned} y_{i,t} = {} & \beta_1 Information\ Asymmetries + \beta_2 Domestic\ Market\ Liquidity \\ & + \beta_3 Capital\ Controls + \beta_4 Cables \\ & + \boldsymbol{\beta}'_5 \left[(Information\ Asymmetries \right. \\ & + Domestic\ Market\ Liquidity + Capital\ Controls) \\ & \left. \times Cables \right] + \boldsymbol{\beta}'_6 \mathbf{X} + \alpha_i + \lambda_t + \varepsilon_{i,t} \end{aligned} \tag{2}$$

with $\boldsymbol{\beta}_5 = [\beta_5^{inf}, \beta_5^{liq}, \beta_5^{cap}]$ and we consider the following null hypothesis:

$$H_0: \beta_4 = 0 \text{ or } \forall\, j \in \{inf, liq, cap\}, \beta_5^j = 0.$$

Our baseline measure of technology is a dummy variable that equals one if country *i* is connected directly or indirectly by a fiber-optic submarine cable to the UK, US or Japan (the three countries where matching servers of EBS and Thomson Reuters are located) and zero otherwise. In robustness checks, we also consider point-to-point connections only, as well as the number of separate cable connections.

[48] We used money market rates (and Treasury bill rates when they are not available). In robustness checks we also obtained estimates using proxies of yen-funded carry trades, which gave similar results. Discussions with market participants suggested that yen-short/long kiwi (or aussie) dollar carry trade strategies have been popular in Tokyo in recent years, for instance. The long leg of the transaction was often broken in two segments, i.e. a US dollar-yen onshore transaction and a US dollar-kiwi dollar offshore transaction. This contributed to increase offshore transactions in Japan, regardless of cable connections.

Rejecting the null hypothesis suggests that technology has an impact on the geography of the foreign exchange market that can be direct, as captured by the coefficient β_4, or indirect, i.e. via the interacted determinants of foreign exchange trading occurring offshore, as captured by the vector of coefficients $\boldsymbol{\beta_5}$. The signs of β_4 and of the $\boldsymbol{\beta_5}$ coefficients indicate whether the cable connection increases or decreases trading occurring offshore through its effect on the fixed costs of trading and whether it amplifies or reduces the impact of frictions such as information asymmetries, domestic market liquidity and capital controls on the location of foreign exchange trading. The net effect from the different coefficients indicate whether cable connections lower the costs of trading locally, in line with the "Flat World" hypothesis, or whether they cause trading to move offshore to major financial centers, in contrast, in line with the "Flash Boys" hypothesis and the "home market" effect discussed above.

7. Empirical Results

Table 1 reports estimates of equation 1. Panel tobit estimates with random effects are reported in columns 1 and 2; panel GLM estimates are in columns 3 and 4; linear panel estimates with random effects are in columns 5 and 6; and pooled OLS estimates with country fixed effects are in column 7. Standard errors in columns 3 to 7 are robust to heteroskedasticity and those in columns 5 to 7 are clustered by time zone. Time fixed effects are included in all columns.

The estimated effect of information asymmetries on the share of trading offshore is negative and statistically significant, consistent with the "local information" hypothesis. The coefficient in column 1 suggests that each hour difference in time zone relative to the US, the UK or Japan lowers the share of offshore trading of the currency issued by the country located in the time zone in question by 12 percentage points.

The estimated effect of domestic market liquidity on offshore trading is also negative, as anticipated, and significant. The coefficient estimate in column 1 implies that the share of offshore trading of a currency issued by a country where the volume of local FX transactions is USD 250 billion larger (a large amount by today's standards) is about 10 percentage points lower.[49]

The effects of capital controls are more varied. The panel tobit estimates in columns 1 and 2 suggest that their effect is insignificant, as do the panel GLM and

[49] Recall that domestic market liquidity is expressed in $trillion. $250 billion is not too far off the volume of offshore FX trading in Singapore or Zurich as of 2013. Readers will remember that we exclude here transactions in domestic currencies from the metric of domestic market liquidity to avoid spurious correlations. This result may possibly reflect agglomeration effects arising in a self-perpetrating way, as in Krugman and Venables (1995, 1996). It is also consistent with models emphasizing financial frictions, such as the limited risk-bearing capacity of financiers or international imbalances in the demand for financial assets, as in Gabaix and Maggiori (forthcoming).

pooled OLS estimates of columns 3, 4 and 7.[50] The linear random-effects estimates in columns 5 and 6, in contrast, suggest that the impact of controls is negative and significant – that the tighter are controls the less a currency is traded offshore. This is at variance with Friedman's hypothesis that capital controls (since they are equivalent to a tax) encourage foreign exchange transactions to migrate offshore. However, it may be that this result reflects omitted variable bias, in particular the effect of technology, as we show below.

Estimates controlling for trade integration, financial integration, the exchange rate regime and carry trades are similar (see column 2 of Table 1). So are the panel GLM and linear panel random-effects estimates (in columns 3 to 6 of Table 1). The coefficient on exchange rate flexibility is positive and significant, which is consistent with our findings on the effect of capital controls insofar as exchange rate flexibility and capital openness typically go hand-in-hand. The coefficient on carry trades is negative and also significant, which suggests that high local interest rates relative to the US encourage market participants to invest in local money markets and exchange funding in dollars, yen (or another low-interest rate unit) against local currency onshore to that end.

Table 2 turns to the impact of technology, reporting estimates of equation 2 where the share of foreign exchange trading taking place offshore is regressed on the standard determinants of the geography of foreign exchange trading as well as the direct and interacted effect of a submarine fiber-optic cable connection to the UK, the US or Japan. Both point-to-point connections and connections via third countries, recall, are considered here.[51]

Consider again the panel tobit estimates in columns 1 and 2. The main findings of Table 1 for the determinants of the geography of foreign exchange trading remain broadly unchanged, with the estimated coefficients now being if anything larger in economic magnitude.[52] In addition, the effect of connection to a submarine fiber-optic cable is negative and typically statistically significant. This implies that a cable connection makes it more likely that a country will be able to retain (or repatriate) trading in its currency at home, other things being equal, presumably because the costs of trading locally is lower i.e. local sales desks can now more quickly and efficiently communicate with the matching servers in offshore financial centers and are hence more competitive through a reduction in their fixed costs of trading.

[50] He et al. (2015) analyze a smaller cross-section of currencies and a different specification, but they too find no significant impact of capital controls.

[51] Again, panel tobit estimates with random effects are reported in columns 1 and 2; panel GLM estimates are in columns (3) and (4); linear panel estimates with random effects are in columns 5 and 6; and pooled OLS estimates with currency fixed effects are in column 7.

[52] As a result the negative effect of capital controls is also statistically significant at the 20% level of confidence.

But other things are not all equal in practice. The interacted effects of submarine fiber-optic connections, which operate through information asymmetries, domestic market liquidity and capital controls, are also statistically significant.[53] They go in the opposite direction from the direct effect of fiber optic connections (they enter with a sign opposite to the sign of the connections variable when it is not interacted with the other determinants). The results are similar with a panel GLM estimator (see columns 3 and 4). Overall, they suggest that the negative effect on the share of a currency traded offshore of information asymmetries is smaller (in absolute value) in the presence of cable links. The negative effect of a relatively liquid local market is smaller (in absolute value) in the presence of cables. The negative effect of capital controls is again smaller (in absolute value). Thus, where the direct effect of a cable link to one of the three major centers is to enable a country to retain more transactions in its currency onshore, the indirect effect is to weaken other factors (distance, local market liquidity, capital controls) that previously segmented markets and gave it a locational advantage.

Figure 10 shows the predicted share of offshore FX trading conditional on the extent of information asymmetries (time-zone differences) when other spatial frictions are set to zero, both with cable connections (the solid line) and without (the dashed line).[54] The figure on the left-hand side is based on the tobit estimates reported in column 1 of Table 2; the figure on the right-hand side is based on the panel GLM estimates reported in column 3 of Table 2.

Consider the tobit estimates first. That a cable connection attenuates the effect of distance and local information is evident from the fact that the solid line (with cable) is flatter than the dashed line (without cable). For a country close to one of the financial centers, the main impact of the cable connection is direct; it allows the country to retain a larger share of trading in its currency (toward the left-hand side of the figure the solid line is below the dashed line, indicating that a smaller share of transactions occur offshore in the presence of a cable). An example is the case of Korea, which is in the same time zone as Japan, where the Korean won is among the least traded offshore. Conversely, for a country far from one of the financial centers, the main impact of the cable connection is indirect; it works to erode the advantages of distance, causing the country to lose a larger share of trading in its currency to offshore markets (toward the right-hand side of the figure, the solid line is above the dashed line, indicating that a larger share of transactions occur offshore). This is the case of New Zealand, for example, which is three hours ahead of Japan and whose unit is heavily traded offshore.

At a distance of three hours, our tobit estimates suggest that the share of foreign exchange occurring offshore should be negative. The reason is that our dependent variable is bounded between zero and one, which implies that quasi-linear

[53] At the 20% level of confidence for capital controls.

[54] The time effects – which range from zero in 1998 and 70% in 2013 – are also set to zero.

estimates such as those obtained with tobit only approximate the true effects of the predictors around the dependent variable mean. Fitting the response variable with large predictor values may hence result in predicting expected shares outside the [0,1] domain, as it is the case here. This problem is familiar from other applications, such as in medical science and epidemiology, which has encouraged scholars to obtain panel generalized linear model (GLM) estimates with a logistic link function and a binomial distribution, as we do here (see Localio, Margolis and Berlin 2007 and Diaz-Quijano 2012).[55] This approach allows the logistic transformation of the fitted response to vary linearly with the predictors while keeping the predicted share between zero and one. Consider now the figure on the right-hand side of Figure 10. That a cable connection attenuates the effect of distance and local information over the relevant range is again evident from the fact that the solid curve (with cables) is flatter than the dashed curve (no cable).

The crossover point is at roughly one hour. For countries in the same time zone as one of the three big financial centers, a cable connection is a positive for the market share of local sales desks. For countries two or more time zones away, the net effect on the local sales desk is negative.

How large is the effect on average? Taking the ratio in percentage terms of the slopes of the two lines obtained from the tobit estimates suggests that the effect of hour distance on the share of foreign exchange trading occurring offshore is 78% lower on average in countries connected to a submarine fiber-optic cable relative to countries that are equally distant from a major financial center but not connected.[56]

Figure 11 illustrates the extent to which the attractions of deep and liquid domestic markets are lessened by cable connections, constructing predicted shares in the same manner. Again, the solid line is flatter than the dashed line, below it on the left and above it on the right. For a country whose domestic market is relatively illiquid, the direct impact of the cable, in leading to the retention or repatriation of business onshore, is the main effect. But a cable connection also attenuates the advantages of a highly liquid domestic market. Countries that previously saw a relatively high share of transactions in their currency occurring onshore due to domestic market liquidity may see a decline in that share with a cable connection. An example is Australia, which was connected in 2001 and saw the share of its currency trading offshore jump by seven percentage points in the three subsequent years, despite the fact that domestic market liquidity increased by 28% over the same period.

Again, how large is the effect on average? Taking the ratio in percentage terms of the slopes of the two lines obtained from the tobit estimates suggests that the effect of domestic market liquidity on the share of foreign exchange trading occurring offshore is 80% lower on average in countries connected to a submarine fiber-optic

[55] We also obtained very similar results with a probit link function in robustness checks.

[56] For the panel GLM estimates cable connection also reduces considerably the economic importance of distance, although the reduction rate is now nonlinear and varies with distance itself.

cable than in countries with equally liquid domestic markets but not possessing a cable connection.

Figure 12 depicts the extent to which technology neutralizes the effect of capital controls.[57] Again the solid line is flatter than the dashed line, indicating that a cable connection attenuates the effect of controls.[58] A cable connection reduces the share of trading in a currency that occurs offshore through its direct effect; tighter controls would be expected to bottle up more of this business, but their impact is weakened by a cable connection, this being the cable's indirect effect. This time, however, the solid line is below the dashed line over the entire range due to the cable's direct effect.[59] But the effect of capital controls on the share of foreign exchange trading occurring offshore is still 83% lower on average in countries connected to a submarine fiber-optic cable relative to countries equally open financially but not connected in this manner.

8. Robustness

Table 3 reports estimates when the share of foreign exchange trading offshore is regressed on the standard determinants of the geography of foreign exchange trading as well as the direct and interacted effect of exclusively point-to-point submarine fiber-optic cable connections to the UK, US and Japan (as opposed to including also cable connections to the UK, US and Japan via third countries).[60] Our main results remain broadly unchanged in terms of sign, statistical significance and economic magnitude, which suggests that they are not sensitive to a specific definition of technology.[61]

Table 4 reports the estimates when we use the number of connections to submarine fiber-optic cables as our measure of technology. Again our main results are broadly unchanged.[62]

Table 5 reports an array of additional sensitivity checks, namely where we use a time trend in lieu of time fixed effects (column 1); cable connections interacted with

[57] We do not report the panel GLM estimates here because the interaction between cable connection and capital controls was not statistically significant.

[58] Intuitively one might interpret this as cable communication opening up additional channels for evasion.

[59] This is evident from Table 2, where the coefficient on capital controls interacted with cables is always smaller than the coefficient on controls, and the controls measure varies between zero and one.

[60] Convergence of the panel GLM estimates were here obtained with a probit (rather than logit) link function.

[61] The exception is the effect on capital controls, which loses statistical significance.

[62] The exception is again the effect on capital controls, which loses statistical significance. Note also that the estimated coefficients on the interacted effects are smaller in economic magnitude, which is due the fact that our measure of technology is a continuous variable rather than a binary dummy as in Tables 2 and 3. Convergence of the panel GLM estimates with the additional controls was not obtained.

a time trend (column 2)[63]; geographical distance instead of the time difference to the UK, US or Japan (column 3); the log of FX turnover rather than its level (column 4); total FX turnover rather than FX turnover net of domestic currency turnover (column 5); restrictions on capital inflows rather than restrictions on all flows (column 6); and restrictions on capital outflows (column 7). Our findings remain robust to these checks, again indicating that they do not depend on particular definitions of the determinants of the geography of the foreign exchange market.

One finding in Table 5 is that there is no effect of technology on physical distance in column 3, unlike hour distance, which suggests that it is the latter that matters for the impact of technology on influence of information asymmetries in the foreign exchange market. Another finding is in column 7, where it appears that the effect of technology on capital controls mainly goes through restrictions on outflows rather than inflows.[64]

9. Distributional Effects

Finally we inquire into the impact of cable connections on the location of foreign exchange trading among the world's financial centers. Who are the winners and losers? How large are the effects?

We proceed in two steps. First, we estimate the net impact of cable connections on the share of offshore foreign exchange transactions using the panel GLM estimated coefficients in column 3 of Table 2. We also predict shares under a counterfactual where issuing countries are not cable-connected (i.e. by setting the coefficient β_4 and those in vector $\boldsymbol{\beta}_5$ to zero). The difference between the predicted and estimated counterfactual shares is the net effect of cable connections in percentage points by currency. The net effect is converted into transaction volumes using actual turnover figures for each currency.

The results are shown in Figure 13 based on 2013 data. The dampening effect of cable connections on spatial frictions generally dominates the reduction in the costs of trading currencies locally in net terms; the share of offshore trading is higher for most units. The cross-currency average suggests that cable connections increase, in net terms, the share of offshore trading by about 21 percentage points. This is consistent with the "Flash Boys" hypothesis. The landscape of the foreign exchange market, in other words, has become "flashier" not "flatter".

One exception is the Canadian dollar, whose offshore share declines by 10 percentage points. This is intuitive in that Toronto is in the same time zone as New

[63] We therefore control for the fact that our cable connection variable could just be picking up other global changes insofar as cable connectivity is positively correlated with time.

[64] We also examined bilateral data published by the BIS where we could look directly at offshore trading in London, Tokyo and New York for a small number of advanced economy units. However, their countries of issuance were almost all connected to the internet backbone simultaneously, implying that was hardly any variation to exploit for identification.

York, the Canadian forex market of Canada is relatively thin, and Canada is financially open. In this case there are few spatial frictions to attenuate, in other words, so only the reduction in the costs of trading locally remains. A similar story emerges for the Korean won.

The New Zealand dollar and Indian rupee are contrary cases: their offshore shares both increase by about 50 percentage points. This is also intuitive: these units are issued by the two countries most remote from the major financial centers. Hence the dampening effect of cable connections on distance is substantial.[65]

The shares of the US dollar, the euro and sterling also increase substantially, which similarly reflects the mitigating effects of cable connections on distance and on the attractions of their large and liquid local foreign exchange markets. The shares of the Swiss franc and Hungarian forint, in contrast, do not change, which is again intuitive: Switzerland and Hungary are landlocked and have no submarine fiber-optic cable connections.[66]

In the second step, we allocate net gains and losses in the volume of offshore trading by currency between financial centers. We have total net volume estimates by currency. (Unfortunately, we are not able to split these estimates by both currency and financial center. In other words, we know by how much trading volumes move offshore, but we do not know exactly to where.) We therefore allocate the counterfactual offshore trading volumes across financial centers proportionately to their actual shares in global foreign exchange turnover in 2013. Thus, if London (more precisely the UK) accounts for 42% of global foreign exchange turnover, it receives 42% of the counterfactual net gains in the volume of offshore trading by currency.[67]

The results are depicted in Figure 14, which shows the net percentage points change in the share of global foreign exchange turnover by country. The main losers from cable connectivity are the euro area (i.e. Frankfurt and other euro area financial centers) as well as, perhaps surprisingly, the US (i.e. New York), with losses of seven and five percentage points of global foreign exchange turnover, respectively. The intuition here is that cable connections not only lead large shares of transactions in the dollar and the euro to move offshore, i.e. away from New York and Frankfurt, but in addition they lead to the geographical redistribution of a relatively large *volume* of foreign exchange transactions, insofar as the dollar and the euro are two of the principal currencies traded in foreign exchange markets. The volume of transactions

[65] New Zealand is three hours ahead of Tokyo while India is four hours behind.

[66] No connections within our sample period, that is; see also the conclusion below.

[67] Onshore trading volumes in the currency in question are reduced accordingly so that global turnover remains unchanged. A more extreme assumption would be to allocate net gains only to London, New York and Tokyo (i.e. to consider only point-to-point connections rather than also indirect connections). But that would only magnify the sizeable boost to the global market share of London and Tokyo which we document below.

in other currencies that move *to* Frankfurt and New York from other financial centers, in contrast, is much smaller.

The main winner overall is the UK (London), with a gain of 10 percentage points of global foreign exchange turnover due to cable connectivity. Other centers affected positively include Japan (Tokyo) and Singapore, with gains of about one percentage point each. While London, Tokyo and Singapore are all major financial centers for foreign exchange trading, their own currencies are not traded as heavily as the euro and the dollar. Thus, what London, Tokyo and Singapore lose when trading in their respective units moves offshore is more than compensated for by the trading in other units that cables allow them to take away from other financial centers.[68] That the winners are islands (or a peninsula in the case of Singapore) is a reminder that the advantages afforded by cable connections have deep geographical roots, which underscores their exogeneity.

These changes are economically important. For instance, the increase of 10 percentage points of the share of London in global foreign exchange turnover is equivalent to a one-third increase relative to the counterfactual when it has no cable connections. In contrast, Switzerland's share stays constant since it has no submarine cable connection.

10. Conclusion

This paper has assessed the impact of technology on the location of production and trade in services using the rise of electronic trading in the foreign exchange market as a case study. Employing data on the location of trading of 55 currencies between 1995 and 2013 and the inauguration of submarine fiber-optic cables as a source of exogenous technological change, we estimate the impact of cable connections on the share of offshore foreign exchange transactions. We find that the dampening effect of cable connections on spatial frictions dominates the reduction in the fixed costs of trading currencies locally in net terms, hence making the world "flashier" not "flatter". Cable connections tend to lead to an increase in the share of offshore trading for most units. Our estimates suggest that technology dampens the impact of spatial frictions by up to 80 percent and increases, in net terms, the share of offshore trading by an average 21 percentage points. Technology also has economically important implications for the distribution of foreign exchange transactions across financial centers, boosting e.g. the share in global turnover of London, the world's largest trading venue, by an estimated one-third.

Submarine fiber-optic cables have formed the backbone of the internet for almost three decades. They have given a competitive advantage to financial centers bordered by the sea, like Singapore, over centers located in landlocked countries, like Zurich. Very recently terrestrial cables have been laid to connect financial centers in

[68] An additional explanation in the case of the yen is that the net effect of cable connection is to increase the share of onshore trading.

a scramble for low latency. The first such cable was Spread Networks' cable between Chicago, home to the Chicago Mercantile Exchange's data center, and New Jersey, home to the Nasdaq data center, unveiled in 2010. euNetworks' fiber network route, which opened in 2015 between Frankfurt and Zurich, is another example.[69] But digging trenches, tunneling through natural obstacles and obtaining transit rights from property owners are costly and difficult (as colorfully recounted by Lewis 2014) – more costly and difficult than laying cables on the seabed.

Since these terrestrial cables connecting two data centers come later, they are far fewer. And since they are recent, they fall outside our sample period and do not affect our results. But they suggest a future in which it is not only whether a financial center has access to the sea but also other attributes – like having a history as and commitment to being a financial center (like Zurich), and deep pockets (like Zurich) – that will influence the geography of the foreign exchange market, global finance, and trade in services more generally. Landlocked or not, there may be hope for Zurich after all.

[69] This cable then connects up with Germany's existing fiber-optic connections to the UK and hence to the EBS and Thomson Reuters servers there. The euNetworks cable link thus also allows London financial services firms to directly access Zurich-Equinix ZH4, the platform where SIX Swiss Exchange (the leading Swiss stock exchange) shares are traded. But that is a different market.

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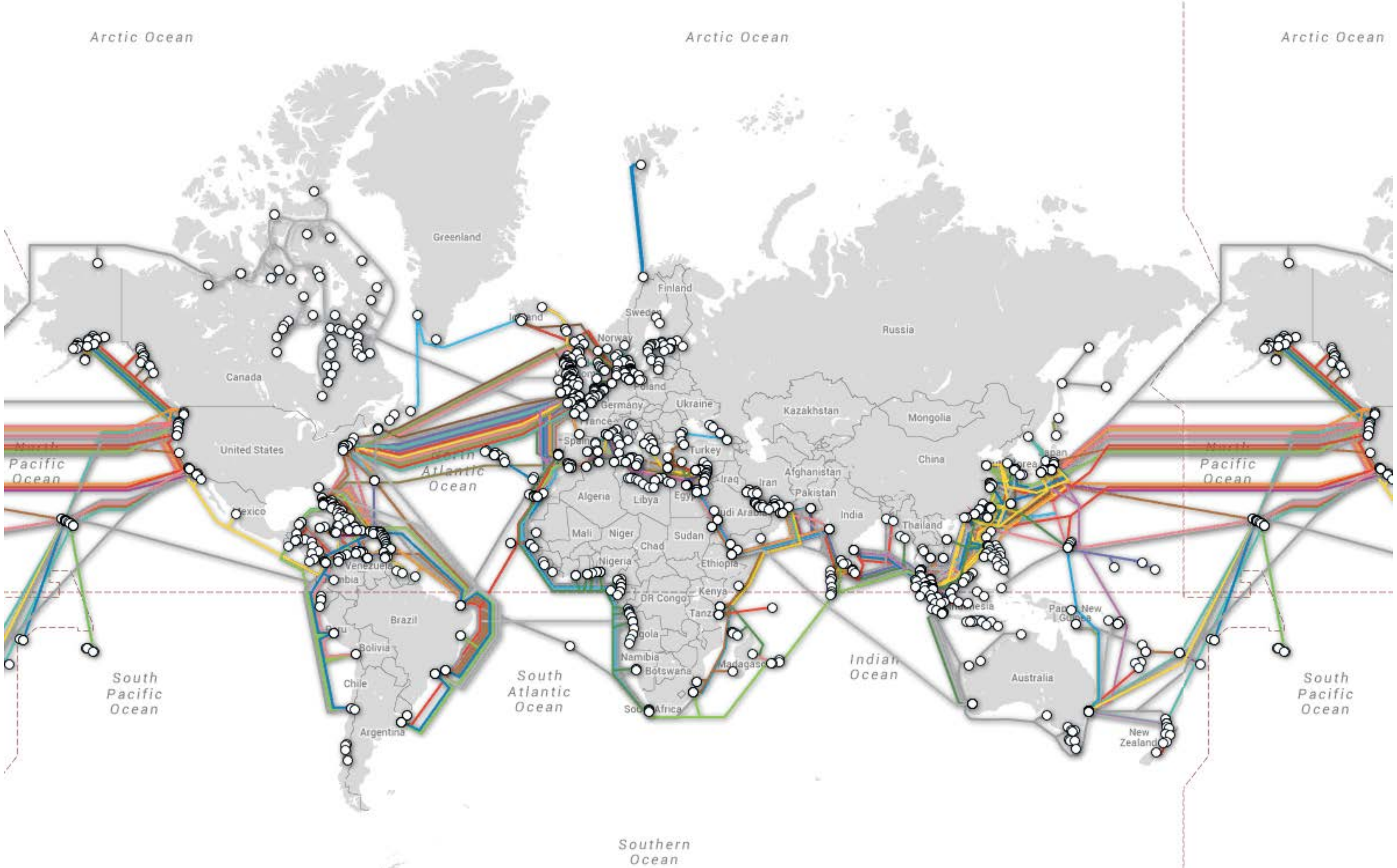
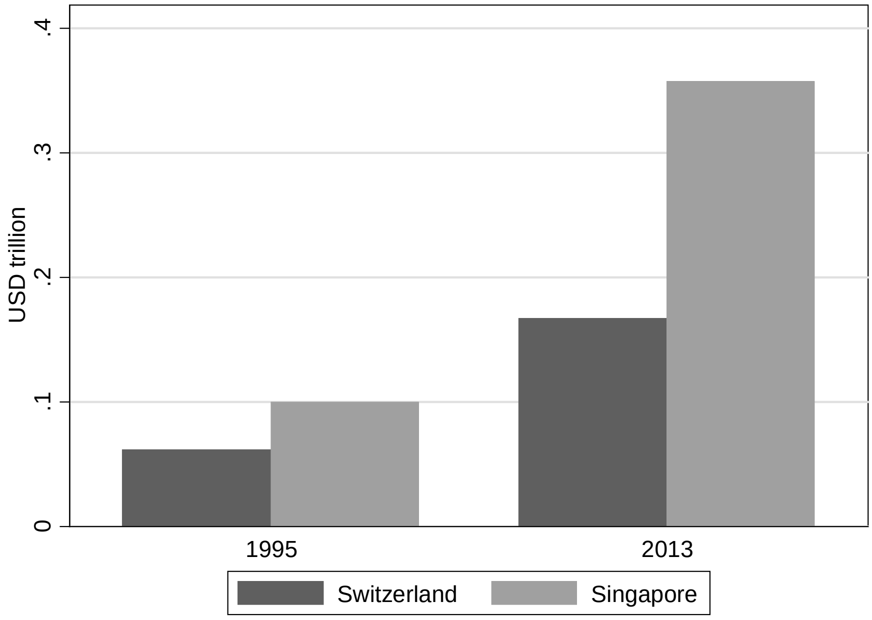
Figure 1: The Internet Backbone – The Global Network of Submarine Fiber-Optic Cables



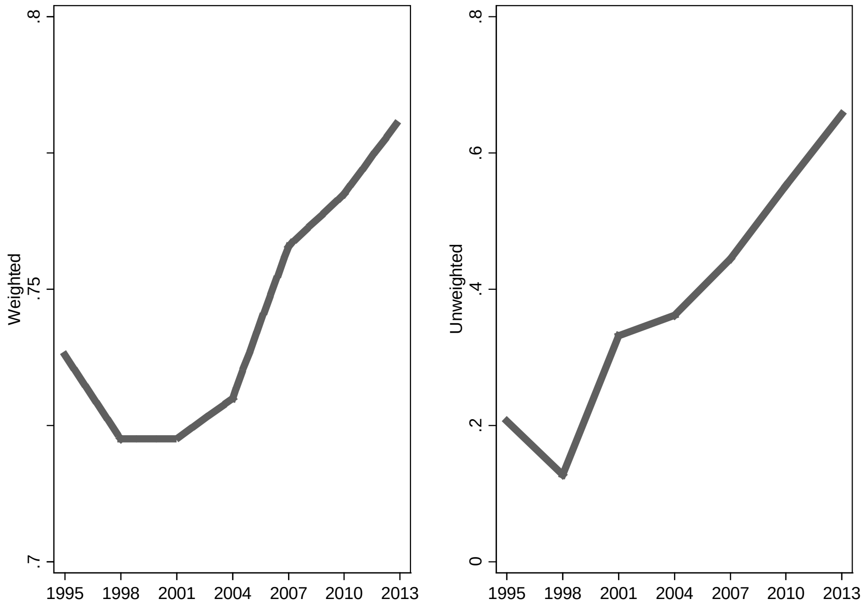
Notes: This figure reproduces the global network of submarine fiber-optic cables using the same data and codes made available by TeleGeography at the following url: https://github.com/telegeography/www.submarinecablemap.com.

Figure 2: Offshore Foreign Exchange Trading in Two Major Financial Centers – *Zurich vs. Singapore*



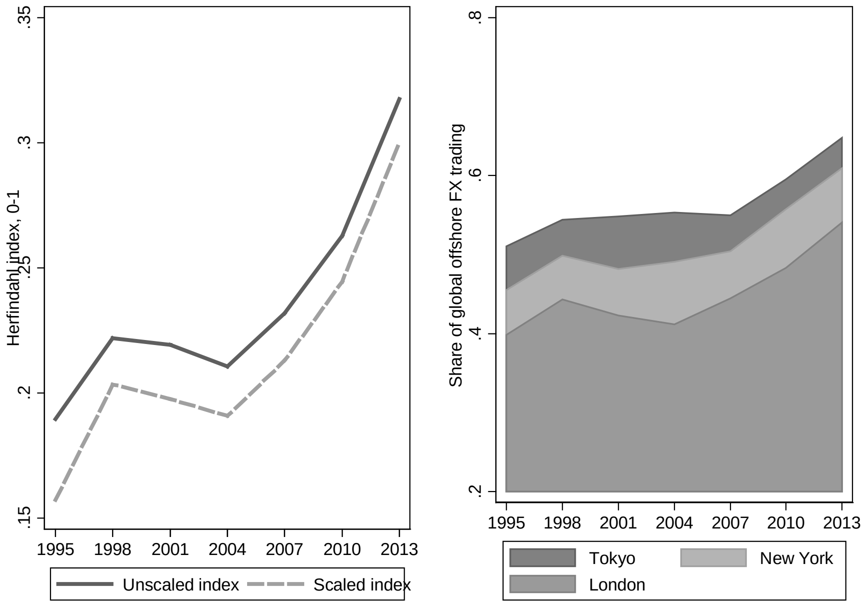
Notes: This figure shows the evolution between 1995 and 2013 of the volume of foreign exchange trading occurring offshore in Switzerland and Singapore, i.e. of trading in currencies other than the respective domestic units (the Swiss franc and the Singapore dollar).

Figure 3: Offshore Foreign Exchange Trading – *Weighted vs. Un-weighted Global Averages*



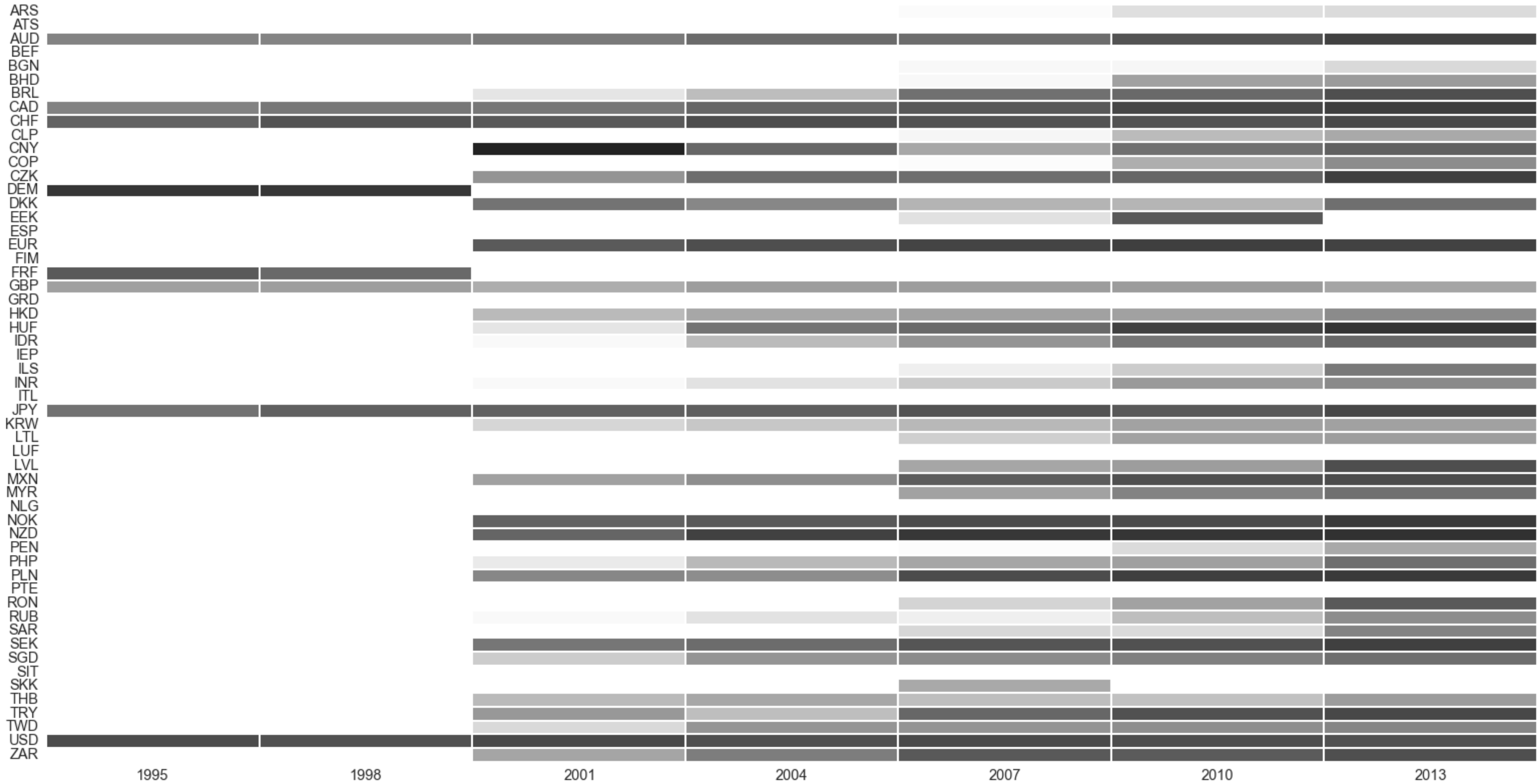
Notes: This figure shows the evolution between 1995 and 2013 of the weighted (left-hand side panel) and un-weighted (right-hand side panel) global averages of foreign exchange trading occurring offshore. The weighted average, which is subject to a theoretical 50%-lower bound, is the sum of foreign exchange trading occurring offshore in all currencies scaled by the sum of total (onshore and offshore) foreign exchange trading in all currencies. The unweighted average is the arithmetic average of the individual currency shares.

Figure 4: Importance of London, New York and Tokyo for Offshore FX trading



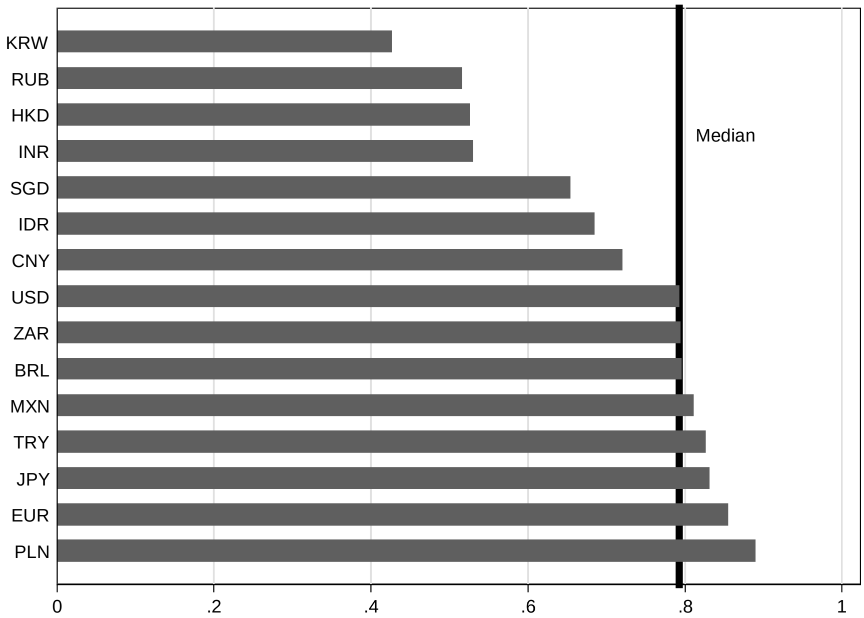
Notes: This figure shows the evolution between 1995 and 2013 of the scaled and unscaled Herfindahl indices of concentration of global foreign exchange trading occurring offshore for London (U.K.), New York (U.S) and Tokyo (Japan) in the left-hand-side panel, as well as the cumulated share of global foreign exchange trading accounted for by these three financial centers in the right-hand side panel.

Figure 5: Offshore Foreign Exchange Trading between 1995 and 2013 – Breakdown by Currency



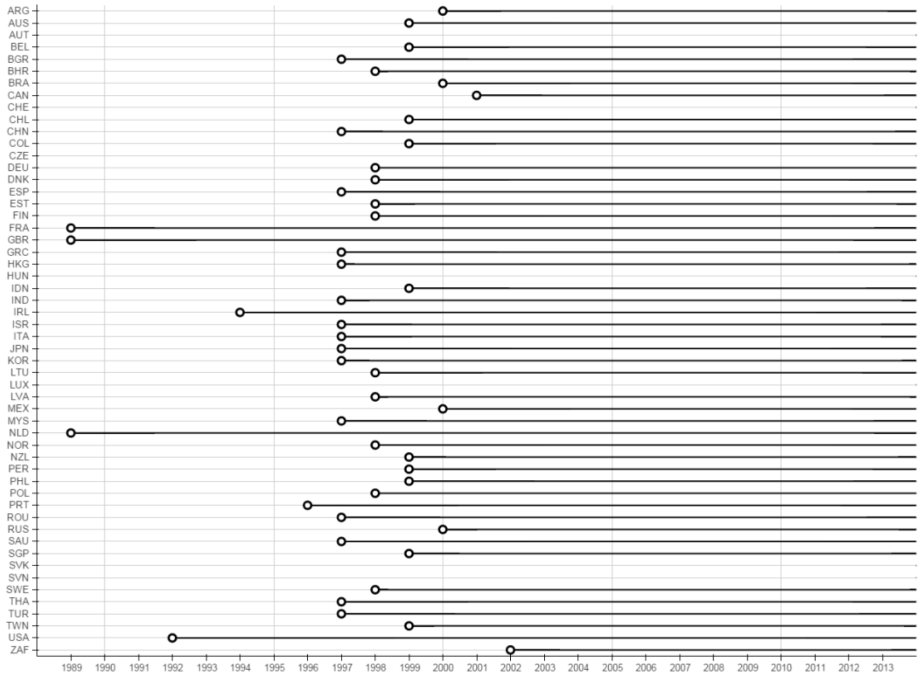
Notes: This figure shows the evolution between 1995 and 2013 of the share of foreign exchange trading occurring offshore for our sample's 55 units between 1995 and 2013. Darker shades of grey indicate higher shares of trading occurring offshore (actual shares are not reported for confidentiality reasons). White cells indicate that the data are unavailable or not reported.

Figure 6: Offshore Foreign Exchange Trading in 2013 – *Breakdown for Selected Currencies*



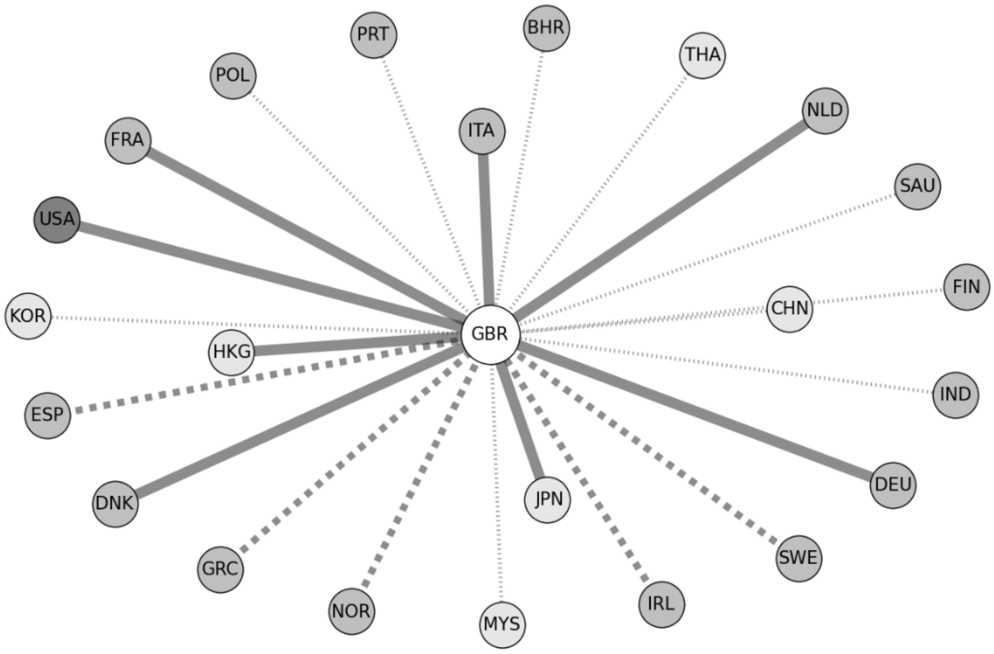
Notes: This figure shows the shares of foreign exchange trading occurring offshore for the same units as in McCauley and Scatigna (2011) and Ehlers and Packer (2013). The thick black line is the (unweighted) median of all individual currency shares (including those not reported in the figure).

Figure 7: Year of First Connection to the UK, US or Japan via a Submarine Fiber-Optic Cable



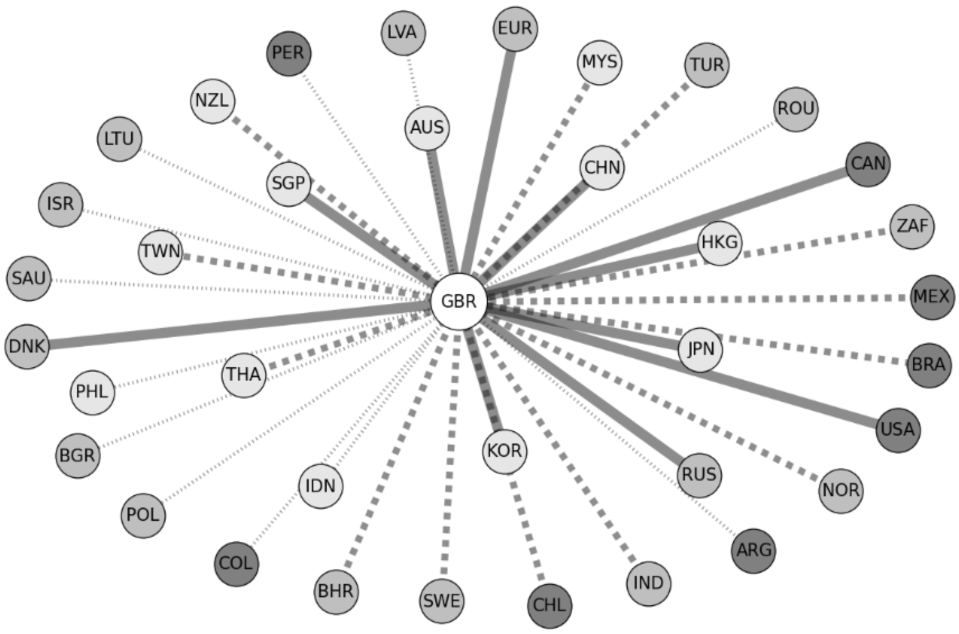
Notes: This figure shows the year when the countries issuing the 55 currencies of our sample were first connected (point-to-point or via third countries) via a submarine fiber-optic cable to the U.K., the U.S. or Japan (i.e. the three countries where the matching servers of EBS/Reuters for electronic foreign exchange trading are located).

Figure 8: Submarine Fiber-Optic Cable Connections to the UK – *1998*



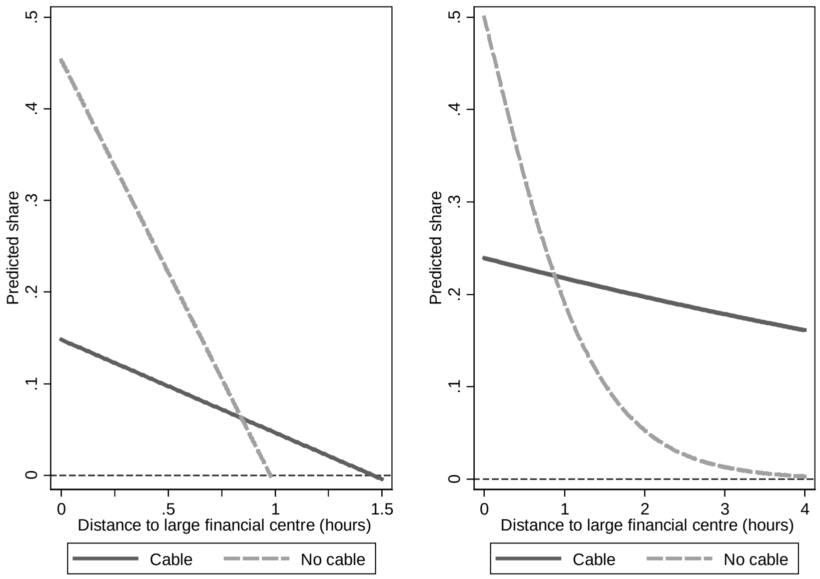
Notes: This figure shows the network of countries connected (point-to-point or via third countries) to the UK (one of the three countries where the matching servers of EBS/Reuters for electronic foreign exchange trading are located) via a submarine fiber-optic cable in 1998. Countries located in the time zone corresponding to Asian trading hours are shown as light grey nodes, against grey nodes for those located in the time zone corresponding to European trading hours and dark grey nodes for US trading hours. Solid lines indicate countries whose currencies ranked in the top third by FX turnover; dashed line those in the middle third, and dotted lines those in the bottom third.

Figure 9: Submarine Fiber-Optic Cable Connections to the UK – *2013*



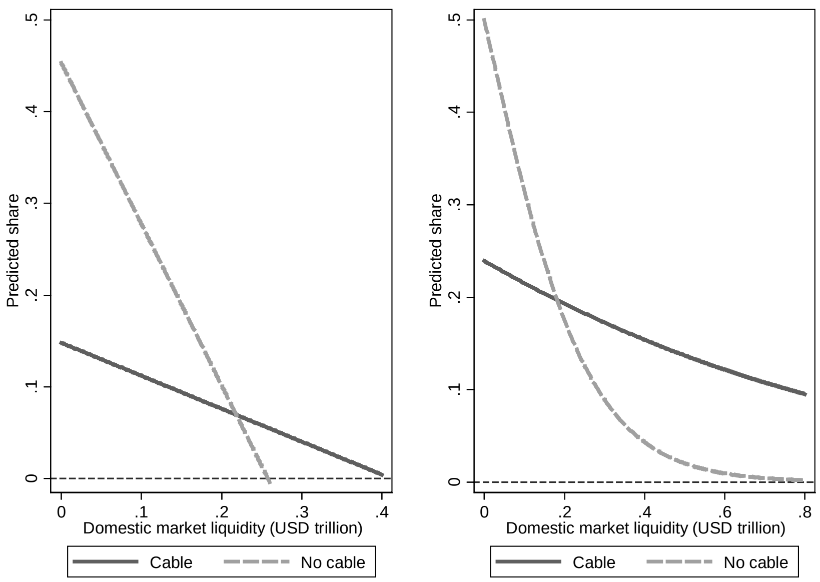
Notes: This figure shows the network of countries connected (point-to-point or via third countries) to the UK (one of the three countries where the matching servers of EBS/Reuters for electronic foreign exchange trading are located) via a submarine fiber-optic cable in 2013.

Figure 10: Impact of Submarine Fiber-Optic Cable Connection
– Information Asymmetries



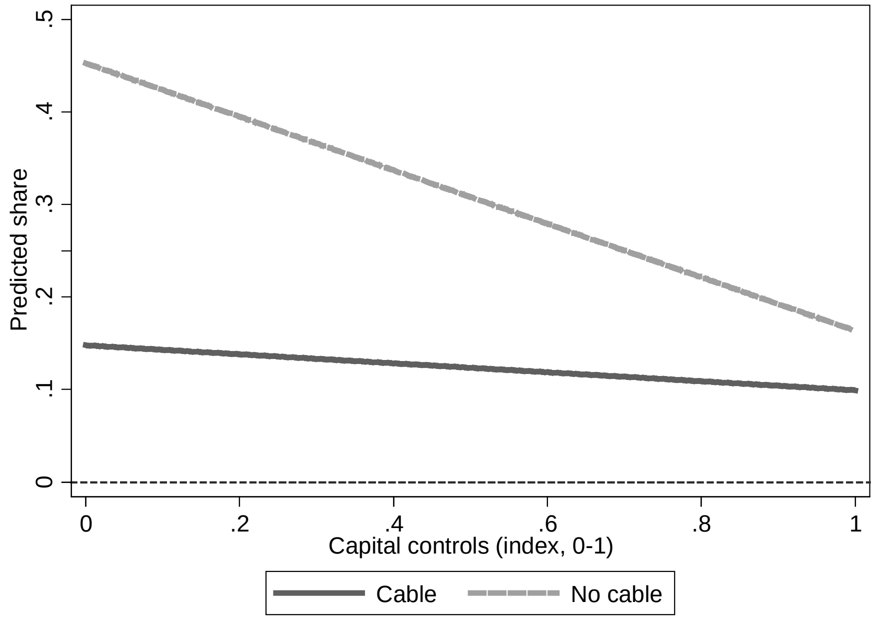
Notes: This figure shows the predicted share of offshore FX trading conditional on the extent of information asymmetries, while other spatial frictions are set to zero with (solid line) and without (dashed line) cable connection. The left-hand side figure is based on the tobit estimates reported in column 1 of Table 2; the right-hand side figure is based on the panel GLM estimates reported in column 3 of Table 2.

Figure 11: Impact of Submarine Fiber-Optic Cable Connection
– Domestic Market Liquidity



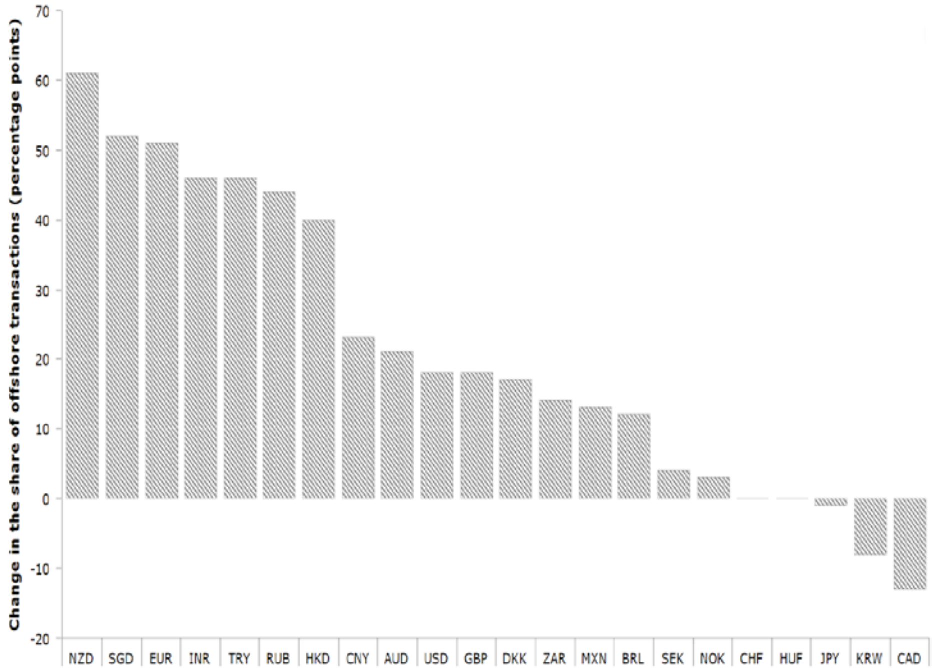
Notes: This figure shows the predicted share of offshore FX trading conditional on the extent of domestic market liquidity, while other spatial frictions are set to zero, with (solid line) and without (dashed line) cable connection. The left-hand side figure is based on the tobit estimates reported in column 1 of Table 2; the right-hand side figure is based on the panel GLM estimates reported in column 3 of Table 2.

Figure 12: Impact of Submarine Fiber-Optic Cable Connection – *Capital Controls*



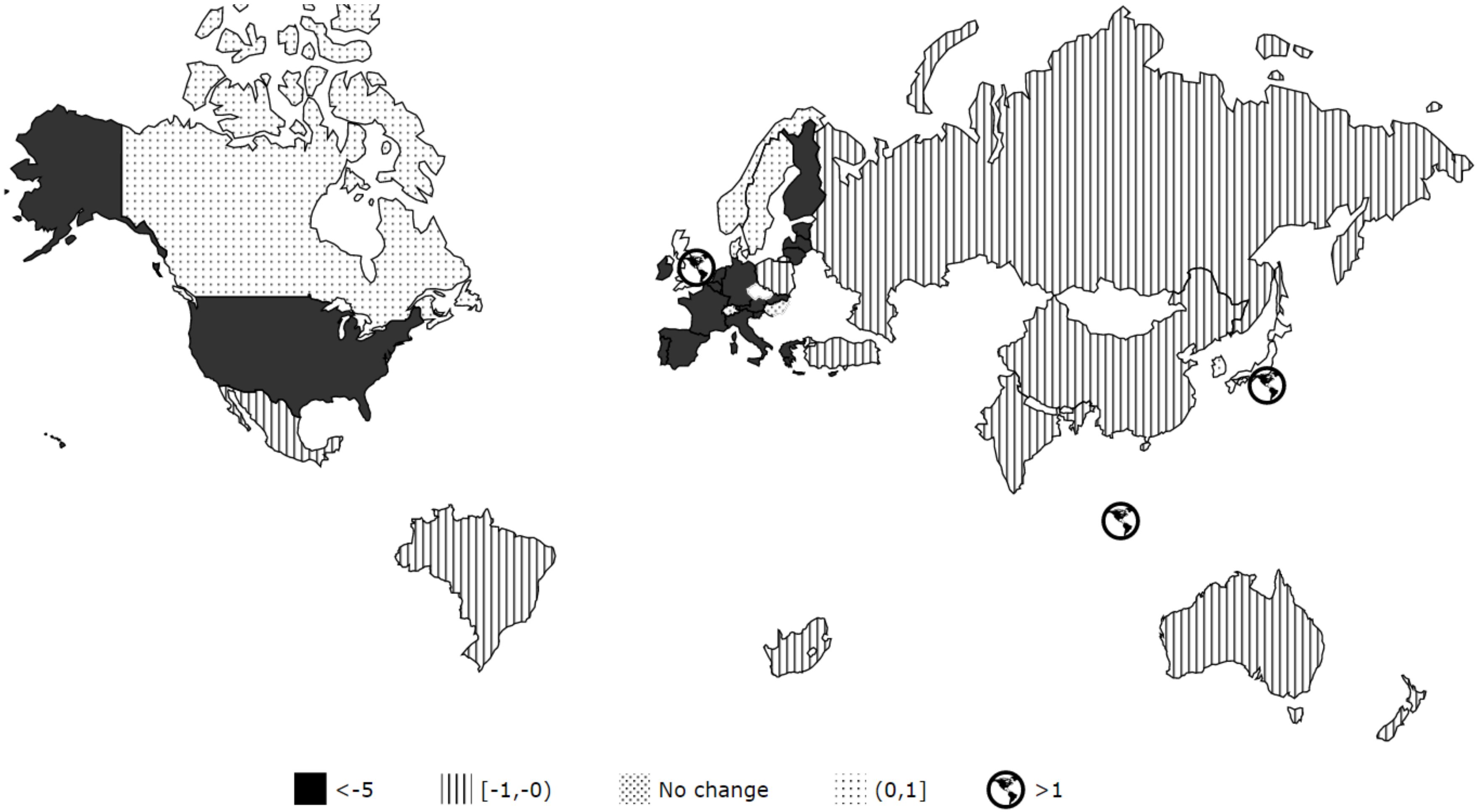
Notes: This figure shows the predicted share of offshore FX trading conditional on the extent of capital controls, while other spatial frictions are set to zero, with (solid line) and without (dashed line) cable connection. The figure is based on the tobit estimates reported in column 1 of Table 2.

Figure 13: Net Effect of Cable Connections on Offshore FX trading



Notes: This figure shows the change (in percentage points) in the share of foreign exchange transactions occurring offshore by currency if countries which issue the currencies in question are connected to a submarine fiber-optic cable relative to a counterfactual situation when they are not. These estimates are based on data for 2013 and the GLM results reported in column 3 of Table 2.

Figure 14: Distributional Effects of Cable Connections on Financial Centers – Winners and Losers



Notes: This map shows the change in percentage points in the share of global foreign exchange transactions undertaken in the countries of our sample if they are connected to a submarine fiber-optic cable relative to a counterfactual in which they are not. The estimates are based on data for 2013 and the panel GLM results reported in column 3 of Table 2. They are based on the assumption that net gains in offshore trading (i.e. the balance between the direct and indirect effects of cable connections) are allocated across connected countries proportionately to their actual share of global foreign exchange transactions in 2013.

Table 1: Estimates with Standard Determinants of the Location of FX trading

	(1) Panel tobit	(2) Panel tobit	(3) Panel GLM	(4) Panel GLM	(5) Random effects	(6) Random effects	(7) Pooled OLS
Time zone distance	-0.120*	-0.085+	-0.257	-0.384+	-0.104***	-0.083*	-0.005
	(0.064)	(0.060)	(0.263)	(0.271)	(0.036)	(0.049)	(0.027)
Domestic market liquidity	-0.383***	-0.388***	-1.384***	-1.342***	-0.299***	-0.303***	-0.345**
	(0.093)	(0.095)	(0.391)	(0.201)	(0.015)	(0.016)	(0.038)
Capital controls	-0.109	-0.100	-0.502	-0.525	-0.111**	-0.145***	-0.094
	(0.107)	(0.106)	(0.466)	(0.476)	(0.045)	(0.054)	(0.123)
Trade integration		-0.091		-0.249		-0.067+	
		(0.071)		(0.299)		(0.048)	
Financial integration		0.094+		0.240		0.044	
		(0.060)		(0.281)		(0.045)	
Flexible exchange rate regime		0.145**		0.765**		0.094***	
		(0.056)		(0.341)		(0.033)	
Carry trades		-0.005**		-0.032		-0.002	
		(0.002)		(0.045)		(0.002)	
Constant	0.119	0.124	-1.331**	-1.150**	0.262***	0.275***	0.002
	(0.100)	(0.110)	(0.547)	(0.568)	(0.047)	(0.005)	(0.005)
Currency effects	YES	YES	YES	YES	YES	YES	YES
Time effects	YES	YES	YES	YES	YES	YES	YES
Observations	252	238	252	238	252	238	252
R^2					0.343	0.393	0.841
ρ	0.783	0.740			0.744	0.686	

Note: The table reports estimates of model equation (1) where the share of foreign exchange trading occurring offshore is regressed on the standard determinants of the geography of foreign exchange trading. Panel tobit estimates with random effects are reported in columns (1) and (2); panel GLM estimates are reported in columns (3) and (4); linear panel estimates with random effects are reported in columns (5) and (6); and pooled OLS estimates with country fixed effects are reported in column (7). The standard errors reported in parentheses in columns (3) to (7) are robust to heteroskedasticity and those in columns (5) to (7) are clustered by time zone (i.e. Asian, European, and US trading sessions); *** p<0.01, ** p<0.05, * p<0.1, $^{+}$ p<0.2.

Table 2: Basic Estimates – Impact of Submarine Cable Connections

	(1) Panel tobit	(2) Panel tobit	(3) Panel GLM	(4) Panel GLM	(5) Random effects	(6) Random effects	(7) Pooled OLS
Time zone distance	-0.463***	-0.430***	-1.443***	-1.586***	-0.221***	-0.195***	-0.147
	(0.127)	(0.126)	(0.478)	(0.508)	(0.067)	(0.045)	(0.140)
Domestic market liquidity	-1.757**	-1.784**	-7.746***	-7.047***	-1.270***	-1.104***	-1.761**
	(0.818)	(0.831)	(2.115)	(1.827)	(0.131)	(0.066)	(0.222)
Capital controls	-0.289+	-0.288+	-1.358+	-1.650**	-0.119**	-0.197**	-0.102
	(0.186)	(0.190)	(0.845)	(0.794)	(0.060)	(0.090)	(0.094)
Cables	-0.305***	-0.332***	-1.157**	-1.315***	-0.129	-0.141	-0.160
	(0.114)	(0.115)	(0.518)	(0.483)	(0.120)	(0.120)	(0.148)
Cables × time zone distance	0.362***	0.361***	1.320***	1.294**	0.132	0.123	0.141
	(0.112)	(0.113)	(0.486)	(0.510)	(0.114)	(0.108)	(0.126)
Cables × domestic market liquidity	1.398*	1.415*	6.380***	5.677***	0.986***	0.814***	1.431**
	(0.814)	(0.827)	(2.104)	(1.807)	(0.117)	(0.061)	(0.212)
Cables × capital controls	0.241+	0.243+	0.833	1.152+	0.014	0.060	0.033+
	(0.189)	(0.192)	(0.892)	(0.858)	(0.034)	(0.052)	(0.014)
Trade integration		-0.079		-0.142		-0.064*	
		(0.073)		(0.317)		(0.037)	
Financial integration		0.095+		0.155		0.043+	
		(0.062)		(0.303)		(0.029)	
Flexible exchange rate regime		0.128**		0.737**		0.092***	
		(0.054)		(0.346)		(0.035)	
Carry trades		-0.004*		-0.026		-0.001	
		(0.002)		(0.034)		(0.001)	
Constant	0.453***	0.463***	-0.159	0.016	0.405***	0.412***	0.165
	(0.133)	(0.142)	(0.431)	(0.565)	(0.090)	(0.094)	(0.145)
Currency effects	YES	YES	YES	YES	YES	YES	YES
Time effects	YES	YES	YES	YES	YES	YES	YES
Observations	252	238	252	238	252	238	252
R^2					0.324	0.380	0.853
ρ	0.830	0.799			0.759	0.684	

Note: The table reports estimates of model equation (2) where the share of foreign exchange trading occurring offshore is regressed on the standard determinants of the geography of foreign exchange trading as well as the direct and interacted effect of both point-to-point and via third countries submarine fiber-optic cable connections to the U.K., U.S. or Japan (i.e. the three countries where the matching servers of EBS/Reuters for electronic trading are located). Panel tobit estimates with random effects are reported in columns (1) and (2); panel GLM estimates are reported in columns (3) and (4); linear panel estimates with random effects are reported in columns (5) and (6); and pooled OLS estimates with currency fixed effects are reported in column (7). The standard errors reported in parentheses in columns (3) to (7) are robust to heteroskedasticity and those in columns (5) to (7) are clustered by time zone (i.e. Asian, European, and US trading hours); *** p<0.01, ** p<0.05, * p<0.1, $^{+}$ p≤0.2.

Table 3: Robustness – Only Point-to-Point Submarine Cable Connections

	(1) Panel tobit	(2) Panel tobit	(3) Panel GLM	(4) Panel GLM	(5) Random effects	(6) Random effects	(7) Pooled OLS
Time zone distance	-0.324***	-0.302***	-0.802***	-0.842***	-0.228***	-0.208***	-0.205+
	(0.083)	(0.080)	(0.189)	(0.195)	(0.025)	(0.004)	(0.075)
Domestic market liquidity	-1.741**	-1.817**	-4.286**	-4.129***	-1.056***	-0.913***	-1.670**
	(0.824)	(0.838)	(1.699)	(1.516)	(0.109)	(0.136)	(0.182)
Capital controls	-0.084	-0.074	-0.231	-0.385	-0.062**	-0.112**	-0.043
	(0.138)	(0.141)	(0.332)	(0.307)	(0.025)	(0.051)	(0.060)
Cables	-0.259***	-0.297***	-0.681**	-0.783**	-0.149**	-0.159**	-0.207+
	(0.100)	(0.103)	(0.343)	(0.323)	(0.073)	(0.079)	(0.086)
Cables × time zone distance	0.276***	0.289***	0.845***	0.854***	0.189***	0.184***	0.198*
	(0.070)	(0.071)	(0.210)	(0.197)	(0.040)	(0.028)	(0.053)
Cables × domestic market liquidity	1.377*	1.444*	3.444**	3.289**	0.773***	0.627***	1.339**
	(0.818)	(0.833)	(1.711)	(1.533)	(0.090)	(0.139)	(0.186)
Cables × capital controls	-0.027	-0.040	-0.446	-0.232	-0.105+	-0.084	-0.024
	(0.159)	(0.164)	(0.439)	(0.432)	(0.077)	(0.112)	(0.079)
Trade integration		-0.086		-0.132		-0.050	
		(0.071)		(0.175)		(0.043)	
Financial integration		0.088+		0.096		0.023	
		(0.062)		(0.171)		(0.042)	
Flexible exchange rate regime		0.137**		0.412**		0.092**	
		(0.054)		(0.182)		(0.046)	
Carry trades		-0.005**		-0.015		-0.001	
		(0.002)		(0.016)		(0.002)	
Constant	0.354***	0.375***	-0.099	-0.060	0.409***	0.408***	0.210+
	(0.115)	(0.124)	(0.282)	(0.350)	(0.043)	(0.064)	(0.081)
Currency effects	YES	YES	YES	YES	YES	YES	YES
Time effects	YES	YES	YES	YES	YES	YES	YES
Observations	252	238	252	238	252	238	252
R^2					0.377	0.429	0.858
ρ	0.802	0.762			0.748	0.671	

Note: The table reports estimates of model equation (2) where the share of foreign exchange trading occurring offshore is regressed on the standard determinants of the geography of foreign exchange trading as well as the direct and interacted effect of point-to-point submarine fiber-optic cable connections to the U.K., U.S. or Japan (i.e. the three countries where the matching servers of EBS/Reuters for electronic trading are located). Panel tobit estimates with random effects are reported in columns (1) and (2); panel GLM estimates are reported in columns (3) and (4); linear panel estimates with random effects are reported in columns (5) and (6); and pooled OLS estimates with currency fixed effects are reported in column (7). The standard errors reported in parentheses in columns (3) to (7) are robust to heteroskedasticity and those in columns (5) to (7) are clustered by time zone (i.e. Asian, European, and US trading hours); *** p<0.01, ** p<0.05, * p<0.1, $^+$ p<0.2.

Table 4: Robustness – Number of Submarine Cable Connections

	(1) Panel tobit	(2) Panel tobit	(3) Panel GLM	(4) Random effects	(5) Random effects	(6) Pooled OLS
Time zone distance	-0.239***	-0.284***	-0.505**	-0.161***	-0.193***	-0.064
	(0.076)	(0.077)	(0.257)	(0.032)	(0.050)	(0.050)
Domestic market liquidity	-0.866*	-0.982**	-1.065	-0.342***	-0.201+	-1.210**
	(0.449)	(0.499)	(1.992)	(0.083)	(0.151)	(0.240)
Capital controls	-0.171+	-0.137	-0.576+	-0.122***	-0.192***	-0.094
	(0.120)	(0.121)	(0.358)	(0.022)	(0.010)	(0.075)
Cables	-0.018***	-0.017***	-0.035***	-0.009***	-0.010***	-0.014**
	(0.004)	(0.004)	(0.009)	(0.003)	(0.003)	(0.002)
Cables × time zone distance	0.014***	0.024***	0.043***	0.010***	0.016***	0.011+
	(0.004)	(0.005)	(0.012)	(0.003)	(0.002)	(0.005)
Cables × domestic market liquidity	0.014*	0.016*	0.015	0.004+	0.001	0.020**
	(0.009)	(0.009)	(0.036)	(0.002)	(0.004)	(0.004)
Cables × capital controls	0.011	0.007	0.016	-0.002	0.004	-0.003
	(0.015)	(0.015)	(0.039)	(0.012)	(0.008)	(0.008)
Trade integration		-0.021			-0.044	
		(0.076)			(0.036)	
Financial integration		0.014			-0.002	
		(0.063)			(0.034)	
Flexible exchange rate regime		0.146***			0.109**	
		(0.056)			(0.047)	
Carry trades		-0.004*			-0.001	
		(0.002)			(0.002)	
Constant	0.227**	0.227*	-0.456	0.317***	0.341***	0.005
	(0.112)	(0.121)	(0.356)	(0.030)	(0.042)	(0.003)
Currency effects	YES	YES	YES	YES	YES	YES
Time effects	YES	YES	YES	YES	YES	YES
Observations	252	238	252	252	238	252
R^2				0.309	0.371	0.862
ρ	0.860	0.842		0.742	0.681	

Note: The table reports estimates of model equation (2) where the share of foreign exchange trading occurring offshore is regressed on the standard determinants of the geography of foreign exchange trading as well as the direct and interacted effect of the number of submarine fiber-optic cable connections of the currency issuing country. Panel tobit estimates with random effects are reported in columns (1) and (2); panel GLM estimates are reported in columns (3); linear panel estimates with random effects are reported in columns (4) and (5); and pooled OLS estimates with currency fixed effects are reported in column (6). The standard errors reported in parentheses in columns (3) to (6) are robust to heteroskedasticity and those in columns (4) to (6) are clustered by time zone (i.e. Asian, European, and US trading hours); *** p<0.01, ** p<0.05, * p<0.1, $^+$ p<0.2.

Table 5: Other Robustness Checks

	(1) Time trend	(2) Cables × time trend	(3) Geo distance	(4) Log turnover	(5) Total turnover	(6) Capital inflows	(7) Capital outflows
Time zone distance	-0.405***	-0.401***	-0.058**	-0.450***	-0.476***	-0.453***	-0.432***
	(0.110)	(0.109)	(0.023)	(0.129)	(0.132)	(0.132)	(0.122)
Domestic market liquidity	-1.727**	-2.603***	-1.639*	-2.193**	-1.273**	-1.902**	-1.711**
	(0.834)	(0.972)	(0.868)	(0.907)	(0.622)	(0.845)	(0.832)
Capital controls	-0.469***	-0.577***	-0.265+	-0.280+	-0.289+	-0.232	-0.208+
	(0.180)	(0.201)	(0.206)	(0.187)	(0.187)	(0.275)	(0.128)
Cables	-0.332***	-0.282***	-0.064	-0.331***	-0.374***	-0.326***	-0.327***
	(0.101)	(0.103)	(0.094)	(0.115)	(0.123)	(0.120)	(0.113)
Cables × time zone distance	0.333***	0.342***	0.020	0.366***	0.392***	0.390***	0.358***
	(0.093)	(0.093)	(0.017)	(0.114)	(0.119)	(0.119)	(0.108)
Cables × domestic market liquidity	1.357+	2.257**	1.265+	1.353+	0.911+	1.538*	1.339+
	(0.829)	(0.974)	(0.864)	(0.894)	(0.616)	(0.840)	(0.828)
Cables × capital controls	0.454**	0.561***	0.229	0.230	0.247+	0.164	0.195+
	(0.179)	(0.198)	(0.210)	(0.190)	(0.190)	(0.277)	(0.133)
Trade integration	-0.054	-0.103+	-0.116+	-0.071	-0.078	-0.085	-0.074
	(0.074)	(0.077)	(0.072)	(0.073)	(0.073)	(0.073)	(0.072)
Financial integration	0.085+	0.125*	0.115*	0.098+	0.081+	0.099+	0.090+
	(0.063)	(0.067)	(0.060)	(0.062)	(0.062)	(0.063)	(0.062)
Flexible exchange rate regime	0.112**	0.119**	0.161***	0.121**	0.125**	0.126**	0.129**
	(0.054)	(0.055)	(0.058)	(0.054)	(0.053)	(0.055)	(0.054)
Carry trades	-0.003+	-0.004+	-0.004*	-0.004*	-0.004*	-0.004*	-0.004*
	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)
Constant	0.283**	0.274**	0.210*	0.479***	0.506***	0.477***	0.447***
	(0.137)	(0.135)	(0.111)	(0.145)	(0.150)	(0.145)	(0.141)
Currency effects	YES	YES	YES	YES	YES	YES	YES
Time effects	NO	NO	YES	YES	YES	YES	YES
Observations	238	238	238	238	238	238	238
ρ	0.792	0.782	0.739	0.822	0.821	0.799	0.802

Note: The table reports estimates of model equation (2) where the share of foreign exchange trading occurring offshore is regressed on the standard determinants of the geography of foreign exchange trading as well as the direct and interacted effect of both point-to-point and via third countries submarine fiber-optic cable connections to the U.K., U.S. or Japan (i.e. the three countries where the matching servers of EBS/Reuters for electronic trading are located) and a time trend in lieu of time fixed effects (in column 1); cable connections interacted with a time trend (in column 2); geographical distance in lieu of the time difference to the U.K., U.S. or Japan (in column 3); the log of FX turnover rather than its level (in column 4); total FX turnover rather than FX turnover net of domestic currency turnover (in column 5); restrictions on capital inflows rather than restrictions on all flows (in column 6); restrictions on capital outflows (in column 7). *** p<0.01, ** p<0.05, * p<0.1, $^{+}$ p<0.2.

Online Appendix

Table A1: Ownership of the Submarine Fiber-Optic Cables Laid Between 1989 and 2002

a. Point-to-Point Connections to the U.K. (London)

Cable name	*Year*	*Length (km)*	*id*	*Owners*
	1989	35	1387	BT
UK-France 3	1989	155	1314	BT, Orange, Vodafone
Farland North	1989	150	1819	BT
BT-MT-1	1990	80	1752	BT, Manx Telecom
Lanis-2	1992	67	1751	Vodafone
Lanis-1	1992	113	1616	Vodafone
Lanis-3	1992	122	1834	Vodafone
Swansea-Brean	1993	97	1835	Vodafone
Scotland-Northern Ireland 2	1993	82	1614	BT
Swansea-Brean	1993	97	1835	Vodafone
Celtic	1994	275	1054	BT, eircom, Orange
UK-Netherlands 14	1996	208	1365	BT, KPN, Vodafone
Ulysses	1997	250	1343	Verizon
FLAG Europe-Asia (FEA)	1997	28000	1027	Global Cloud Xchange
Ulysses	1997	250	1343	Verizon
Atlantic Crossing-1 (AC-1)	1998	14301	1143	Level 3
SeaMeWe-3	1999	39000	1031	Orange, BT, KDDI, SingTel, Telecom Italia Sparkle, Telekom Malaysia, OTEGLOBE, AT&T, Belgacom, Communications Authority of Thailand, China Telecom, Deutsche Telekom, Etisalat, Telecom Egypt, CTM, PT Indonesia Satellite Corp., Jabatan Telecom Brunei, KT, Portugal Telecom, Maroc Telecom, PLDT, Saudi Telecom, Sri Lanka Telecom, Turk Telekom, Tata Communications, Chunghwa Telecom, Verizon, KPN, Telekom Austria, SingTel Optus, Telstra, Vietnam Telecom International, Omantel, PCCW, Pakistan Telecommunications Company Ltd., Cyta, eircom, LG Uplus, Softbank Telecom, Telkom South Africa, Rostelecom, Orange Polska, SingTel Optus, Telecom Argentina, Myanmar Post and Telecommunication, Sprint, Vocus Communications, Djibouti Telecom, Embratel, Vodafone
Sirius North	1999	147	1754	Virgin Media Business
Solas	1999	232	1205	eircom, Vodafone
Concerto	1999	550	1538	Interoute
Pan European Crossing (UK-Belgium)	1999	117	1539	Level 3
Tampnet Offshore FOC Network	1999	1751	1203	Tampnet
Sirius South	1999	219	1092	Virgin Media Business
Circe South	1999	115	1323	VTLWavenet, euNetworks
Sirius North	1999	147	1754	Virgin Media Business
Circe North	1999	203	1137	VTLWavenet, euNetworks
ESAT-1	1999	261	1223	Esat BT
Pan European Crossing (UK-Ireland)	2000	495	1547	Level 3
Tangerine	2000	112	1324	Level 3
ESAT-2	2000	245	1224	Esat BT
Yellow	2000	7001	1081	Level 3
Hibernia Atlantic	2001	12200	1080	Hibernia Networks
Tata TGN-Atlantic	2001	13000	1149	Tata Communications
FLAG Atlantic-1 (FA-1)	2001	14500	1028	Global Cloud Xchange
TAT-14	2001	15295	1043	BT, Verizon, Deutsche Telekom, Orange, Sprint, TeliaSonera, Level 3, KPN, Telenor, Etisalat, OTEGLOBE, SingTel, KDDI, Softbank Telecom, Zayo Group, Portugal Telecom, Slovak Telekom, TDC, Telus, Tata Communications, Telefonica, AT&T, Belgacom, Elisa Corporation, Cyta, Rostelecom, Vodafone
Hibernia Atlantic	2001	12200	1080	Hibernia Networks
Tata TGN-Western Europe	2002	3578	1173	Tata Communications

b. Point-to-Point Connections to the U.S. (New York)

Cable name	*Year*	*Length (km)*	*id*	*Owners*
Taino-Carib	1992	186	1229	AT&T, Embratel, Telecom Argentina, Orange, CANTV, Columbus Networks, Telecom Italia Sparkle
HICS (Hawaii Inter-Island Cable System)	1994	479.081	1455	Hawaiian Telcom
Columbus-II b	1994	2068	1643	n.a.
HIFN (Hawaii Island Fibre Network)	1997	529	1456	TW Telecom, Hawaiian Telcom
Antillas 1	1997	650	1227	AT&T, Verizon, Sprint, Tata Communications, Orange, Columbus Networks, Telecom Italia Sparkle, Embratel
HIFN (Hawaii Island Fibre Network)	1997	529	1456	TW Telecom, Hawaiian Telcom
Bahamas 2	1997	470	1069	AT&T, Telefonica, Verizon
Atlantic Crossing-1 (AC-1)	1998	14301	1143	Level 3
Pacific Crossing-1 (PC-1)	1999	20900	1007	NTT
NorthStar	1999	3229	1166	Alaska Communications Systems Group
Pacific Crossing-1 (PC-1)	1999	20900	1007	NTT
Pan American (PAN-AM)	1999	7050	1073	AT&T, Telefonica del Peru, Softbank Telecom, Telecom Italia Sparkle, Sprint, CANTV, Tata Communications, TelefÃ³nica de Argentina (Speedy), Telstra, Verizon, Entel Chile, Telecom Argentina, Telconet, Cable & Wireless Communications, Corporacion Nacional de Telecommunicaciones, Columbus Networks, Embratel
Alaska United East	1999	3751	1168	GCI
Columbus-III	1999	9833	1046	Telecom Italia Sparkle, AT&T, Verizon, Telefonica, Portugal Telecom, CANTV, Tata Communications, Ukrtelecom, Telkom South Africa, Telecom Argentina, Cable & Wireless Communications, Embratel
GlobeNet	2000	23500	1076	BTG Pactual
South American Crossing (SAC)/Latin American Nautilus (LAN)	2000	20000	1084	Level 3, Telecom Italia Sparkle
Southern Cross Cable Network (SCCN)	2000	30500	1009	Spark New Zealand, SingTel Optus, Verizon
GlobeNet	2000	23500	1076	BTG Pactual
Maya-1	2000	4400	1071	Cable & Wireless Communications, Verizon, Tata Communications, AT&T, Sprint, Hondutel, CANTV, Telefonica, BT, Orbitel, Telecom Italia Sparkle, Columbus Networks, Entel Chile, Telmex, Embratel, ETB, Alestra
Mid-Atlantic Crossing (MAC)	2000	7500	1070	Level 3
China-U.S. Cable Network (CHUS)	2000	30476	1146	Verizon, AT&T, KDDI, Tata Communications, China Telecom, Chunghwa Telecom, KT, NTT, Level 3, SingTel, Sprint, Telekom Malaysia, Spark New Zealand, Telstra, PCCW, LG Uplus, Softbank Telecom, Rostelecom, SingTel Optus, Orange, PLDT
Yellow	2000	7001	1081	Level 3
name	2000	10000	1072	Level 3
Southern Cross Cable Network (SCCN)	2000	30500	1009	Spark New Zealand, SingTel Optus, Verizon
Americas-II	2000	8373	1148	Embratel, AT&T, Verizon, Sprint, CANTV, Tata Communications, Level 3, Centennial of Puerto Rico, Corporacion Nacional de Telecommunicaciones, Telecom Argentina, Orange, Portugal Telecom, Columbus Networks, Telecom Italia Sparkle, Entel Chile
Southern Cross Cable Network (SCCN)	2000	30500	1009	Spark New Zealand, SingTel Optus, Verizon
Mid-Atlantic Crossing (MAC)	2000	7500	1070	Level 3
Japan-U.S. Cable Network (JUS)	2001	22682	1010	Verizon, AT&T, BT, Sprint, CenturyLink, KDDI, NTT, Chunghwa Telecom, Tata Communications, SingTel, Telekom Malaysia, Softbank Telecom, Orange, Level 3, SK Broadband, KT, China Telecom, China Unicom, LG Uplus, New World Telecom, Starhub, PCCW, Telstra, Vodafone, PLDT
FLAG Atlantic-1 (FA-1)	2001	14500	1028	Global Cloud Xchange
Hibernia Atlantic	2001	12200	1080	Hibernia Networks
Bahamas Internet Cable System (BICS)	2001	1100	1232	Caribbean Crossings
TAT-14	2001	15295	1043	BT, Verizon, Deutsche Telekom, Orange, Sprint, TeliaSonera, Level 3, KPN, Telenor, Etisalat, OTEGLOBE, SingTel, KDDI, Softbank Telecom, Zayo Group, Portugal Telecom, Slovak Telekom, TDC, Telus, Tata Communications, Telefonica, AT&T, Belgacom, Elisa Corporation, Cyta, Rostelecom, Vodafone
South America-1 (SAm-1)	2001	25000	1083	Telefonica
Japan-U.S. Cable Network (JUS)	2001	22682	1010	Verizon, AT&T, BT, Sprint, CenturyLink, KDDI, NTT, Chunghwa Telecom, Tata Communications, SingTel, Telekom Malaysia, Softbank Telecom, Orange, Level 3, SK Broadband, KT, China Telecom, China Unicom, LG Uplus, New World Telecom, Starhub, PCCW, Telstra, Vodafone, PLDT
ARCOS	2001	8600	1078	Columbus Networks, Axtel, CANTV, Codetel, Hondutel, Belize Telemedia, Enitel, AT&T, Alestra, Verizon, RACSA, United Telecommunication Services (UTS), Telecarrier, Tricom USA, Telecomunicaciones Ultramarinas de Puerto Rico, Internexa, Orbinet Overseas, Telepuerto San Isidro, Bahamas Telecommunications Company
Tata TGN-Atlantic	2001	13000	1149	Tata Communications
TAT-14	2001	15295	1043	BT, Verizon, Deutsche Telekom, Orange, Sprint, TeliaSonera, Level 3, KPN, Telenor, Etisalat, OTEGLOBE, SingTel, KDDI, Softbank Telecom, Zayo Group, Portugal Telecom, Slovak Telekom, TDC, Telus, Tata Communications, Telefonica, AT&T, Belgacom, Elisa Corporation, Cyta, Rostelecom, Vodafone
South America-1 (SAm-1)	2001	25000	1083	Telefonica
Tata TGN-Pacific	2002	22300	1155	Tata Communications

a. Point-to-Point Connections to Japan (Tokyo)

Cable name	*Year*	*Length (km)*	*id*	*Owners*
FLAG Europe-Asia (FEA)	1997	28000	1027	Global Cloud Xchange
Pacific Crossing-1 (PC-1)	1999	20900	1007	NTT
SeaMeWe-3	1999	39000	1031	Orange, BT, KDDI, SingTel, Telecom Italia Sparkle, Telekom Malaysia, OTEGLOBE, AT&T, Belgacom, Communications Authority of Thailand, China Telecom, Deutsche Telekom, Etisalat, Telecom Egypt, CTM, PT Indonesia Satellite Corp., Jabatan Telecom Brunei, KT, Portugal Telecom, Maroc Telecom, PLDT, Saudi Telecom, Sri Lanka Telecom, Turk Telekom, Tata Communications, Chunghwa Telecom, Verizon, KPN, Telekom Austria, SingTel Optus, Telstra, Vietnam Telecom International, Omantel, PCCW, Pakistan Telecommunications Company Ltd., Cyta, eircom, LG Uplus, Softbank Telecom, Telkom South Africa, Rostelecom, Orange Polska, SingTel Optus, Telecom Argentina, Myanmar Post and Telecommunication, Sprint, Vocus Communications, Djibouti Telecom, Embratel, Vodafone
Pacific Crossing-1 (PC-1)	1999	20900	1007	NTT
China-U.S. Cable Network (CHUS)	2000	30476	1146	Verizon, AT&T, KDDI, Tata Communications, China Telecom, Chunghwa Telecom, KT, NTT, Level 3, SingTel, Sprint, Telekom Malaysia, Spark New Zealand, Telstra, PCCW, LG Uplus, Softbank Telecom, Rostelecom, SingTel Optus, Orange, PLDT
Australia-Japan Cable (AJC)	2001	12700	1102	Softbank Telecom, NTT, Telstra, Verizon, AT&T
APCN-2	2001	19000	1049	SingTel, Verizon, KDDI, Chunghwa Telecom, AT&T, BT, Orange, Softbank Telecom, NTT, Tata Communications, Telekom Malaysia, Starhub, PLDT, China Unicom, KT, SingTel Optus, Telstra, PCCW, China Telecom, LG Uplus, New World Telecom, Vodafone
Japan-U.S. Cable Network (JUS)	2001	22682	1010	Verizon, AT&T, BT, Sprint, CenturyLink, KDDI, NTT, Chunghwa Telecom, Tata Communications, SingTel, Telekom Malaysia, Softbank Telecom, Orange, Level 3, SK Broadband, KT, China Telecom, China Unicom, LG Uplus, New World Telecom, Starhub, PCCW, Telstra, Vodafone, PLDT
FLAG North Asia Loop/REACH North Asia Loop	2001	9504	1150	Global Cloud Xchange, PCCW, Telstra
Japan-U.S. Cable Network (JUS)	2001	22682	1010	Verizon, AT&T, BT, Sprint, CenturyLink, KDDI, NTT, Chunghwa Telecom, Tata Communications, SingTel, Telekom Malaysia, Softbank Telecom, Orange, Level 3, SK Broadband, KT, China Telecom, China Unicom, LG Uplus, New World Telecom, Starhub, PCCW, Telstra, Vodafone, PLDT
APCN-2	2001	19000	1049	SingTel, Verizon, KDDI, Chunghwa Telecom, AT&T, BT, Orange, Softbank Telecom, NTT, Tata Communications, Telekom Malaysia, Starhub, PLDT, China Unicom, KT, SingTel Optus, Telstra, PCCW, China Telecom, LG Uplus, New World Telecom, Vodafone
EAC-C2C	2002	36500	1592	Pacnet
Korea-Japan Cable Network (KJCN)	2002	500	1231	QTNet, KT, Softbank Telecom, NTT
Tata TGN-Pacific	2002	22300	1155	Tata Communications

Sources: Authors' compilation based on the data made available by TeleGeography at the following url: https://github.com/telegeography/www.submarinecablemap.com.

Online Appendix

Table A1: Ownership of the Submarine Fiber-Optic Cables Laid Between 1989 and 2002

a. Point-to-Point Connections to the U.K. (London)

Cable name	*Year*	*Length (km)*	*id*	*Owners*
	1989	35	1387	BT
UK-France 3	1989	155	1314	BT, Orange, Vodafone
Farland North	1989	150	1819	BT
BT-MT-1	1990	80	1752	BT, Manx Telecom
Lanis-2	1992	67	1751	Vodafone
Lanis-1	1992	113	1616	Vodafone
Lanis-3	1992	122	1834	Vodafone
Swansea-Brean	1993	97	1835	Vodafone
Scotland-Northern Ireland 2	1993	82	1614	BT
Swansea-Brean	1993	97	1835	Vodafone
Celtic	1994	275	1054	BT, eircom, Orange
UK-Netherlands 14	1996	208	1365	BT, KPN, Vodafone
Ulysses	1997	250	1343	Verizon
FLAG Europe-Asia (FEA)	1997	28000	1027	Global Cloud Xchange
Ulysses	1997	250	1343	Verizon
Atlantic Crossing-1 (AC-1)	1998	14301	1143	Level 3
SeaMeWe-3	1999	39000	1031	Orange, BT, KDDI, SingTel, Telecom Italia Sparkle, Telekom Malaysia, OTEGLOBE, AT&T, Belgacom, Communications Authority of Thailand, China Telecom, Deutsche Telekom, Etisalat, Telecom Egypt, CTM, PT Indonesia Satellite Corp., Jabatan Telecom Brunei, KT, Portugal Telecom, Maroc Telecom, PLDT, Saudi Telecom, Sri Lanka Telecom, Turk Telekom, Tata Communications, Chunghwa Telecom, Verizon, KPN, Telekom Austria, SingTel Optus, Telstra, Vietnam Telecom International, Omantel, PCCW, Pakistan Telecommunications Company Ltd., Cyta, eircom, LG Uplus, Softbank Telecom, Telkom South Africa, Rostelecom, Orange Polska, SingTel Optus, Telecom Argentina, Myanmar Post and Telecommunication, Sprint, Vocus Communications, Djibouti Telecom, Embratel, Vodafone
Sirius North	1999	147	1754	Virgin Media Business
Solas	1999	232	1205	eircom, Vodafone
Concerto	1999	550	1538	Interoute
Pan European Crossing (UK-Belgium)	1999	117	1539	Level 3
Tampnet Offshore FOC Network	1999	1751	1203	Tampnet
Sirius South	1999	219	1092	Virgin Media Business
Circe South	1999	115	1323	VTLWavenet, euNetworks
Sirius North	1999	147	1754	Virgin Media Business
Circe North	1999	203	1137	VTLWavenet, euNetworks
ESAT-1	1999	261	1223	Esat BT
Pan European Crossing (UK-Ireland)	2000	495	1547	Level 3
Tangerine	2000	112	1324	Level 3
ESAT-2	2000	245	1224	Esat BT
Yellow	2000	7001	1081	Level 3
Hibernia Atlantic	2001	12200	1080	Hibernia Networks
Tata TGN-Atlantic	2001	13000	1149	Tata Communications
FLAG Atlantic-1 (FA-1)	2001	14500	1028	Global Cloud Xchange
TAT-14	2001	15295	1043	BT, Verizon, Deutsche Telekom, Orange, Sprint, TeliaSonera, Level 3, KPN, Telenor, Etisalat, OTEGLOBE, SingTel, KDDI, Softbank Telecom, Zayo Group, Portugal Telecom, Slovak Telekom, TDC, Telus, Tata Communications, Telefonica, AT&T, Belgacom, Elisa Corporation, Cyta, Rostelecom, Vodafone
Hibernia Atlantic	2001	12200	1080	Hibernia Networks
Tata TGN-Western Europe	2002	3578	1173	Tata Communications

b. Point-to-Point Connections to the U.S. (New York)

Cable name	*Year*	*Length (km)*	*id*	*Owners*
Taino-Carib	1992	186	1229	AT&T, Embratel, Telecom Argentina, Orange, CANTV, Columbus Networks, Telecom Italia Sparkle
HICS (Hawaii Inter-Island Cable System)	1994	479.081	1455	Hawaiian Telcom
Columbus-II b	1994	2068	1643	n.a.
HIFN (Hawaii Island Fibre Network)	1997	529	1456	TW Telecom, Hawaiian Telcom
Antillas 1	1997	650	1227	AT&T, Verizon, Sprint, Tata Communications, Orange, Columbus Networks, Telecom Italia Sparkle, Embratel
HIFN (Hawaii Island Fibre Network)	1997	529	1456	TW Telecom, Hawaiian Telcom
Bahamas 2	1997	470	1069	AT&T, Telefonica, Verizon
Atlantic Crossing-1 (AC-1)	1998	14301	1143	Level 3
Pacific Crossing-1 (PC-1)	1999	20900	1007	NTT
NorthStar	1999	3229	1166	Alaska Communications Systems Group
Pacific Crossing-1 (PC-1)	1999	20900	1007	NTT
Pan American (PAN-AM)	1999	7050	1073	AT&T, Telefonica del Peru, Softbank Telecom, Telecom Italia Sparkle, Sprint, CANTV, Tata Communications, TelefÃ³nica de Argentina (Speedy), Telstra, Verizon, Entel Chile, Telecom Argentina, Telconet, Cable & Wireless Communications, Corporacion Nacional de Telecommunicaciones, Columbus Networks, Embratel
Alaska United East	1999	3751	1168	GCI
Columbus-III	1999	9833	1046	Telecom Italia Sparkle, AT&T, Verizon, Telefonica, Portugal Telecom, CANTV, Tata Communications, Ukrtelecom, Telkom South Africa, Telecom Argentina, Cable & Wireless Communications, Embratel
GlobeNet	2000	23500	1076	BTG Pactual
South American Crossing (SAC)/Latin American Nautilus (LAN)	2000	20000	1084	Level 3, Telecom Italia Sparkle
Southern Cross Cable Network (SCCN)	2000	30500	1009	Spark New Zealand, SingTel Optus, Verizon
GlobeNet	2000	23500	1076	BTG Pactual
Maya-1	2000	4400	1071	Cable & Wireless Communications, Verizon, Tata Communications, AT&T, Sprint, Hondutel, CANTV, Telefonica, BT, Orbitel, Telecom Italia Sparkle, Columbus Networks, Entel Chile, Telmex, Embratel, ETB, Alestra
Mid-Atlantic Crossing (MAC)	2000	7500	1070	Level 3
China-U.S. Cable Network (CHUS)	2000	30476	1146	Verizon, AT&T, KDDI, Tata Communications, China Telecom, Chunghwa Telecom, KT, NTT, Level 3, SingTel, Sprint, Telekom Malaysia, Spark New Zealand, Telstra, PCCW, LG Uplus, Softbank Telecom, Rostelecom, SingTel Optus, Orange, PLDT
Yellow	2000	7001	1081	Level 3
name	2000	10000	1072	Level 3
Southern Cross Cable Network (SCCN)	2000	30500	1009	Spark New Zealand, SingTel Optus, Verizon
Americas-II	2000	8373	1148	Embratel, AT&T, Verizon, Sprint, CANTV, Tata Communications, Level 3, Centennial of Puerto Rico, Corporacion Nacional de Telecommunicaciones, Telecom Argentina, Orange, Portugal Telecom, Columbus Networks, Telecom Italia Sparkle, Entel Chile
Southern Cross Cable Network (SCCN)	2000	30500	1009	Spark New Zealand, SingTel Optus, Verizon
Mid-Atlantic Crossing (MAC)	2000	7500	1070	Level 3
Japan-U.S. Cable Network (JUS)	2001	22682	1010	Verizon, AT&T, BT, Sprint, CenturyLink, KDDI, NTT, Chunghwa Telecom, Tata Communications, SingTel, Telekom Malaysia, Softbank Telecom, Orange, Level 3, SK Broadband, KT, China Telecom, China Unicom, LG Uplus, New World Telecom, Starhub, PCCW, Telstra, Vodafone, PLDT
FLAG Atlantic-1 (FA-1)	2001	14500	1028	Global Cloud Xchange
Hibernia Atlantic	2001	12200	1080	Hibernia Networks
Bahamas Internet Cable System (BICS)	2001	1100	1232	Caribbean Crossings
TAT-14	2001	15295	1043	BT, Verizon, Deutsche Telekom, Orange, Sprint, TeliaSonera, Level 3, KPN, Telenor, Etisalat, OTEGLOBE, SingTel, KDDI, Softbank Telecom, Zayo Group, Portugal Telecom, Slovak Telekom, TDC, Telus, Tata Communications, Telefonica, AT&T, Belgacom, Elisa Corporation, Cyta, Rostelecom, Vodafone
South America-1 (SAm-1)	2001	25000	1083	Telefonica
Japan-U.S. Cable Network (JUS)	2001	22682	1010	Verizon, AT&T, BT, Sprint, CenturyLink, KDDI, NTT, Chunghwa Telecom, Tata Communications, SingTel, Telekom Malaysia, Softbank Telecom, Orange, Level 3, SK Broadband, KT, China Telecom, China Unicom, LG Uplus, New World Telecom, Starhub, PCCW, Telstra, Vodafone, PLDT
ARCOS	2001	8600	1078	Columbus Networks, Axtel, CANTV, Codetel, Hondutel, Belize Telemedia, Enitel, AT&T, Alestra, Verizon, RACSA, United Telecommunication Services (UTS), Telecarrier, Tricom USA, Telecomunicaciones Ultramarinas de Puerto Rico, Internexa, Orbinet Overseas, Telepuerto San Isidro, Bahamas Telecommunications Company
Tata TGN-Atlantic	2001	13000	1149	Tata Communications
TAT-14	2001	15295	1043	BT, Verizon, Deutsche Telekom, Orange, Sprint, TeliaSonera, Level 3, KPN, Telenor, Etisalat, OTEGLOBE, SingTel, KDDI, Softbank Telecom, Zayo Group, Portugal Telecom, Slovak Telekom, TDC, Telus, Tata Communications, Telefonica, AT&T, Belgacom, Elisa Corporation, Cyta, Rostelecom, Vodafone
South America-1 (SAm-1)	2001	25000	1083	Telefonica
Tata TGN-Pacific	2002	22300	1155	Tata Communications

a. Point-to-Point Connections to Japan (Tokyo)

Cable name	*Year*	*Length (km)*	*id*	*Owners*
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Pacific Crossing-1 (PC-1)	1999	20900	1007	NTT
SeaMeWe-3	1999	39000	1031	Orange, BT, KDDI, SingTel, Telecom Italia Sparkle, Telekom Malaysia, OTEGLOBE, AT&T, Belgacom, Communications Authority of Thailand, China Telecom, Deutsche Telekom, Etisalat, Telecom Egypt, CTM, PT Indonesia Satellite Corp., Jabatan Telecom Brunei, KT, Portugal Telecom, Maroc Telecom, PLDT, Saudi Telecom, Sri Lanka Telecom, Turk Telekom, Tata Communications, Chunghwa Telecom, Verizon, KPN, Telekom Austria, SingTel Optus, Telstra, Vietnam Telecom International, Omantel, PCCW, Pakistan Telecommunications Company Ltd., Cyta, eircom, LG Uplus, Softbank Telecom, Telkom South Africa, Rostelecom, Orange Polska, SingTel Optus, Telecom Argentina, Myanmar Post and Telecommunication, Sprint, Vocus Communications, Djibouti Telecom, Embratel, Vodafone
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Australia-Japan Cable (AJC)	2001	12700	1102	Softbank Telecom, NTT, Telstra, Verizon, AT&T
APCN-2	2001	19000	1049	SingTel, Verizon, KDDI, Chunghwa Telecom, AT&T, BT, Orange, Softbank Telecom, NTT, Tata Communications, Telekom Malaysia, Starhub, PLDT, China Unicom, KT, SingTel Optus, Telstra, PCCW, China Telecom, LG Uplus, New World Telecom, Vodafone
Japan-U.S. Cable Network (JUS)	2001	22682	1010	Verizon, AT&T, BT, Sprint, CenturyLink, KDDI, NTT, Chunghwa Telecom, Tata Communications, SingTel, Telekom Malaysia, Softbank Telecom, Orange, Level 3, SK Broadband, KT, China Telecom, China Unicom, LG Uplus, New World Telecom, Starhub, PCCW, Telstra, Vodafone, PLDT
FLAG North Asia Loop/REACH North Asia Loop	2001	9504	1150	Global Cloud Xchange, PCCW, Telstra
Japan-U.S. Cable Network (JUS)	2001	22682	1010	Verizon, AT&T, BT, Sprint, CenturyLink, KDDI, NTT, Chunghwa Telecom, Tata Communications, SingTel, Telekom Malaysia, Softbank Telecom, Orange, Level 3, SK Broadband, KT, China Telecom, China Unicom, LG Uplus, New World Telecom, Starhub, PCCW, Telstra, Vodafone, PLDT
APCN-2	2001	19000	1049	SingTel, Verizon, KDDI, Chunghwa Telecom, AT&T, BT, Orange, Softbank Telecom, NTT, Tata Communications, Telekom Malaysia, Starhub, PLDT, China Unicom, KT, SingTel Optus, Telstra, PCCW, China Telecom, LG Uplus, New World Telecom, Vodafone
EAC-C2C	2002	36500	1592	Pacnet
Korea-Japan Cable Network (KJCN)	2002	500	1231	QTNet, KT, Softbank Telecom, NTT
Tata TGN-Pacific	2002	22300	1155	Tata Communications

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