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Beneath the Gold Points: European Financial Market Integration, 1844-1870

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Abstract

We measure the degree of financial integration among the top five financial centers of mid-19th-century Europe by applying threshold-regression analysis to a new database of exchange rates and bullion prices. We find that, instead of London, Hamburg, Frankfurt or Amsterdam, it was Paris that played the role of hub of European foreign exchange markets. We also document a high level of financial integration before the gold standard period, with estimated transaction costs far lower than historically-observed "gold" and "silver points" (i.e., the costs to bullion arbitrage). We review the assumptions of the classical gold-point arbitrage model and conclude that TAR-computed thresholds cannot be interpreted as transaction costs in the bullion trade. High integration may be explained not by low transaction costs in bilateral bullion arbitrage, but by the availability of multilateral financial arbitrage techniques.[4]

Keywords: Financial integration, efficiency, exchange rate, gold points, TAR model

JEL classification: F3, G15, N23

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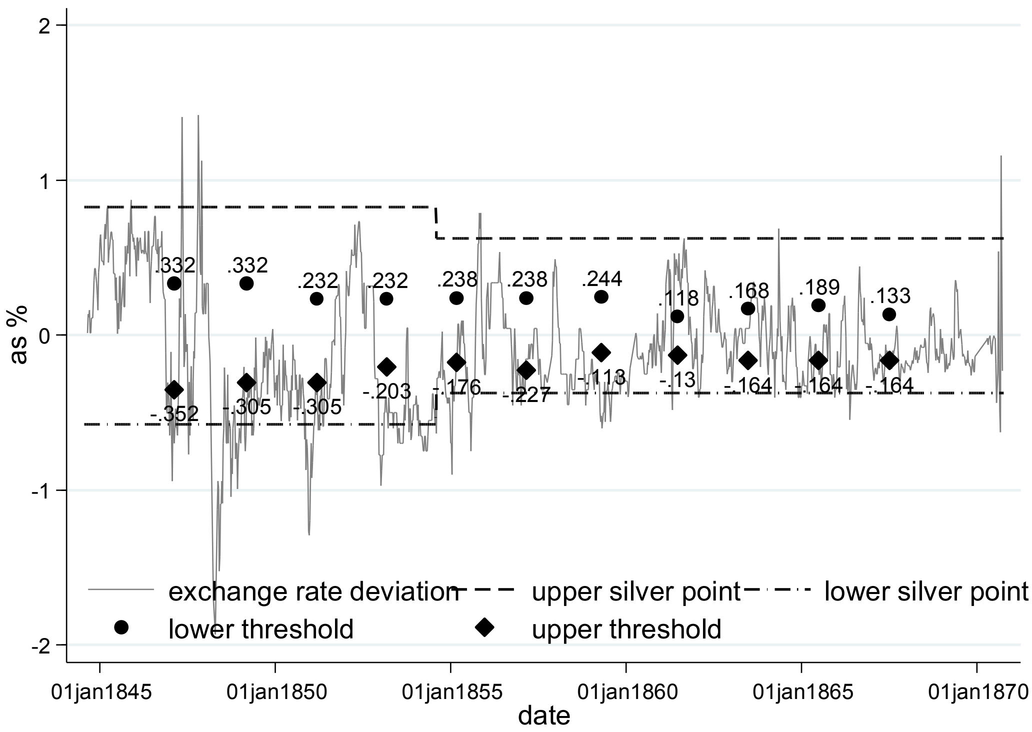
NON-TECHNICAL SUMMARY

How deeply integrated were European financial markets before the advent of the international gold standard in the 1870s? We show a very high level of financial integration among the main European financial centers (Amsterdam, Frankfurt, Hamburg, London, and Paris) in the period from the Bank of England Act of 1844 to the French-Prussian War of 1870.

In order to measure financial integration, we focus on foreign exchange markets. Foreign exchange markets were organized similarly across Europe before 1870. They were based on a similar instrument (the bill of exchange) whose legal features were fairly homogenous across the Continent. Bills of exchange were denominated in different currencies; before 1870, European currencies were convertible into different precious metals. Amsterdam, Frankfurt, and Hamburg were on the silver standard, London was on the gold standard and Paris on the bimetallic standard. Moreover this era coincides with the consolidation of the European national states and their effort to foster national financial integration with the creation of central banks' networks of branches.

We use threshold autoregressive (TAR) models to estimate the degree of integration of the markets for bills of exchanges. Technically, a bill payable at sight was a promise to receive upon presentation a given amount of local currency in a foreign place. The state-of-the-art literature on financial integration maintains that the thresholds estimated with TAR models can be interpreted as "gold" or "silver points" (i.e., the level of the exchange rate beyond which gold or silver would start to be imported or exported). Our paper questions this view both empirically and theoretically.

Figure I: Historically-observed gold and silver points, TAR-estimated transaction costs (thresholds), and exchange rate deviation from the arbitrated metallic par, Paris on London 1844-1870



Source: authors' computations using *Cours de la Bourse de Paris* and *The Economist*.

We document a very high level of integration, as illustrated by the example plotted on Figure 1. For some financial markets, those levels are comparable to the transaction costs found in today's markets. This level of integration was achieved before the harmonization fostered by the advent of the international gold standard. We discuss the traditional interpretation of estimated thresholds, and show that their level is actually too small to be interpreted as representative of transaction costs to bullion arbitrage.

We also document that information technology innovations played some role in fostering market integration: there are non-negligible improvements in the level of integration between the 1840s and the 1860s, as showed by the declining average absolute deviation of direct spot exchange rates from basically all benchmarks throughout the period. Also, our findings do not support the view that actual gold and silver flows were an effective force on arbitrage between currencies.

Our results confirm that there were hierarchies in the international monetary system. Although direct exchange rates stayed systematically closer to some cross-exchange pars with respect to direct metallic pars, this was not the case for all "cross-exchange arbitrage routes". This suggests that because the level of transaction costs varied across markets, not all "cross-exchange arbitrage routes" were actually equally used by arbitrageurs.

The most active route for international adjustment consisted of arbitraging through Paris; in this particular ranking, London only came third after Amsterdam, while Hamburg supplied the less popular route. While this conclusion may appear in contrast with received wisdom (which traditionally considers London as the center of the international monetary system since the early 19th century), it is consistent with the information provided on the structure of the international payments network. Although London was very important, Paris provided international arbitrageurs with a performing infrastructure for implementing international transactions in bills of exchange, as it was the only place to have the maximum number of currencies quoted there, but also because of the maximum number of markets quoting the French franc. One might speculate that this had roots in the geographical position of France or in the peculiarities of its bimetallic standard. The identification of this cause is left for future research.

En dessous des points-or : Intégration financière européenne entre 1844 et 1870

RÉSUMÉ

Nous mesurons le degré d'intégration financière des cinq principales places financières européennes entre 1844 et 1870 par l'estimation de modèles autorégressifs à seuils en utilisant des données originales de taux de change et de prix des lingots d'or et d'argent. Nous trouvons que Paris jouait davantage un rôle de *hub* des marchés financiers Européens que Londres, Amsterdam, Francfort ou Hambourg. Nous documentons un très fort niveau d'intégration financière avant la période d'étalon-or, avec des estimations de coûts de transaction systématiquement inférieures aux « points or », (c'est-à-dire, au niveau observé du coût d'arbitrage des métaux). Nous passons en revue les hypothèses du modèle classique d'arbitrage par points or et montrons que les seuils estimés ne peuvent être interprétés comme des points or. La forte intégration peut en revanche s'expliquer par les techniques d'arbitrage multilatéral.

Mots-clés : Intégration financière, taux de change, points-or, modèle TAR

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1. Introduction

This paper studies financial integration between five core European financial centers in the middle of the 19th century (Amsterdam, Frankfurt, Hamburg, London, and Paris). To measure market integration, we use price series for the main financial asset used in international arbitrage at the time: the bill of exchange which was a promise to pay a given amount of money in a given currency at a pre-specified maturity. In each of the five centers we consider, the local currency was convertible into gold, silver or both metals. We measure market integration by estimating a threshold autoregressive (TAR) model that computes the limits beyond which the price of bills of exchange (i.e. the exchange rate) displayed a mean-reverting behavior.

The paper makes two sets of contributions, one historical and one methodological. The first contribution is methodological. We question the traditional interpretation of TAR-estimated thresholds as transaction costs *in the bullion market*, and we propose to interpret them as transaction costs *in the foreign exchange market* that are not necessarily tied to the costs of bullion. Second, from a historical viewpoint, our results suggest a high level of integration, with estimated thresholds ranging between 0.1% and 1.0% of the relative price of bills. If one interprets these thresholds as transaction costs, this suggests quite a substantial level of integration.

Two main conclusions stand out in terms of historical interpretations. On the one hand, we find that the level of integration is high despite the absence of a common monetary standard uniting these five centers: this suggests that, in contrast to what has been often suggested in the literature,[1] financial markets did not apparently wait for the advent of the Gold Standard to integrate. On the other hand, we find that the role of hub of European foreign exchange markets was played by Paris rather than London or Amsterdam. Among the five markets considered, Paris was the only one to have a complete bilateral spot exchange rate connection with all other markets. Moreover, Paris also is the center whose estimated thresholds are lowest.

The rest of the paper is organized as follows. The next section illustrates the theoretical foundations of the application of threshold-regression analysis to the study of financial integration in commodity-based monetary systems. Section 3 presents our empirical methodology, Section 4 our data, and Section 5 our results. In Section 6 we discuss the question of how to interpret the outcomes of threshold-regression analysis, and suggest a new interpretation which goes beyond the limits of the classical gold-point arbitrage model. Section 7 concludes.

[1] See e.g. Obstfeld and Taylor (2004), who argue that this was the case because of the reduction in the costs to bullion arbitrage fostered by the generalized adoption of the gold standard.

2. Analytical Framework

In this Section we discuss the analytical framework adopted by the literature in order to measure financial market integration under commodity-based monetary systems. First, we present the state of the art, and the questions left often by it. Second, we point out that this framework rests on a number of restrictive assumptions – something that is not generally put forward by its users. Third, we point out that one must be careful in selecting the correct price series for computing arbitrage opportunities: microstructural issues suggest that albeit often exploited by the literature, mint prices are not the right data to use in order to properly assess financial integration.

2.1. Measuring Integration under a Commodity Money Standard

So far, the workhorse model used by economic historians to understand the integration of financial markets under the commodity money standard has been the *classical gold-point arbitrage model*. This model argues that adjustment across foreign markets occurs through bilateral flows of the metal into which domestic currencies are convertible.[2] Bullion (specie) flows are supposed to occur whenever the exchange rate exceeds the thresholds determined by the transaction costs of moving metal – usually known as the gold (or silver) points. In a context of full capital mobility across countries, the width of the band within which the exchange rate can float *without* triggering bullion shipments has therefore been seen as an indicator of the degree of financial integration.

Within this analytical framework, the efficiency of the international monetary system has been judged by its ability to trigger bullion flows whenever the exchange rate reach the gold points (see e.g. Einzig, 1929; Morgenstern, 1959; Officer, 1986, 1996). This definition of efficiency has prompted scholars to estimate gold points in order to check whether financial markets were integrated – i.e., whether bullion flows actually followed depreciation or appreciation of nominal exchange rates.

Two main approaches have been developed to measure the size of the gold points.

The direct approach consists of calculating transaction costs from historical sources (see e.g. Einzig, 1929; Officer, 1996; Flandreau, 1996; Esteves et al., 2007). The results of these investigations have sparked a large debate,[3] notably on one specific historical case: the dollar-sterling market during

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[2] Unlike Hume's (1752) price-specie-flow mechanism model, the classical gold-point arbitrage model is actually a partial equilibrium model – focusing on the international purchasing power parity of gold in terms of *currency*, not on international purchasing power parity of gold in terms of *all traded commodities*. Marcuzzo and Rosselli (1987) explain that the reason is that the international equalization of general price levels is a sufficient, but not a necessary condition for gold arbitrage to stop.

[3] Defining which *specific* transaction cost actually matters in a given period is difficult, and measuring it is tricky: for instance, think of the difficulty in measuring the monetary benefit of speedier transport technologies.

the classical gold standard period (1873-1914). Morgenstern (1959) and Clark (1984) argued that the gold standard was inefficient because gold arbitrage did not take place when the exchange rate lied outside of the band. Officer (1986, 1996) computed new estimates of the transaction costs of moving gold between New York and London to restore the efficiency view of the gold standard.

Other scholars have developed an indirect approach by developing econometric techniques on exchange rate data series to estimate the threshold above/below which exchange rate series displayed a mean-reverting behavior. The intuition for this is as follows: in a deficit country, the price of bills of exchange must stop appreciating when agents start using gold or silver (instead of bills) for their international payments; therefore, mean-reversion occurs for the exchange rate when appreciation stops. Pioneered by Obstfeld and Taylor (1997), the application of TAR models to price data has been considered as an efficient method to measure mean-reverting processes.[4]

Canjels et al. (2004) have extended the application of TAR models to the classical gold-point arbitrage model.[5] In so doing, they have uncovered a puzzle: the thresholds estimated with this technique for the London-New York bilateral exchange relationship were considerably smaller than the transaction costs accurately computed by Officer (1996) on the basis of extensive historical research.[6] Canjels et al. (2004) imputed this remarkable discrepancy to the faults of primary sources, but they failed to establish convincingly that historical evidence was systematically inaccurate. Hence, the puzzle remains unsolved: do indirect strategies for measuring transaction costs always point to a higher degree of financial integration than direct ones? And if so, why is that the case? In order to provide an answer to these questions, the rationale of the application of TAR models to the study of foreign exchange series in a commodity money system needs to be examined in detail.

2.2. The Gold-Point Arbitrage Model

Samuelson's model of price arbitrage is the cornerstone supporting the application of the threshold-regression approach to the measuring of market integration (see Samuelson, 1952). In this model, agents arbitrage price differentials away between two locations, when the price differential

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Another problem consists of finding of the historical documentation and constructing complete time series of the evolution of those transaction costs.

[4] Here we only discuss univariate analyses; for a multivariate regression analysis, see e.g. Bernholz and Kugler (2011). An early example of the indirect approach to measuring transaction costs is Spiller and Wood (1988), who used a probabilistic model and concluded that transaction costs were very volatile under the classical gold standard.

[5] The influential paper by Canjels at al. (2004) has established a new branch of the historical literature. Followers include Volckart and Wolf (2006), Esteves et al. (2007), Chilosi and Volckart (2011), Li (2012), and Nogues and Herranz (2015).

[6] Note that also Esteves et al. (2007) got the very same result for the London-Lisbon bilateral exchange relationship under the gold standard: TAR-estimated thresholds were smaller than the transaction costs computed on the basis of historical sources.

between the two markets is large enough to compensate for the transaction cost of moving goods across locations. Formally this can be written as

$$-C_{G,t}^{B,A} \leq X_{G,t}^{A,B} \leq C_{G,t}^{A,B} \quad (1)$$

where $C_{G,t}^{B,A}$ is the transaction cost associated with physically transferring good G from location B to location A at time *t*, $C_{G,t}^{A,B}$ is the transaction cost associated with physically transferring G from A to B, while $X_{G,t}^{A,B}$ is the nominal price margin between A and B of commodity G, defined as

$$X_{G,t}^{A,B} = P_{G,t}^{B} \frac{P_{MB,t}^{A}}{P_{MB,t}^{B}} - P_{G,t}^{A} \quad (2),$$ [7]

where $P_{G,t}^{A}$ is the price of G in A, $P_{G,t}^{B}$ is the price of G in B, and $P_{MB,t}^{A}/P_{MB,t}^{B}$ is the nominal exchange rate – defined as the ratio of the unitary price in A of the asset MB used as money in B ($P_{MB,t}^{A}$) and the unitary price in B of the asset MB used as money there ($P_{MB,t}^{B} = 1$). $-C_{G,t}^{A,B}$ and $C_{G,t}^{B,A}$ are known as the (respectively) lower and upper commodity points (Obstfeld and Taylor, 1997).

In papers measuring commodity market integration, the model described by Equations (1) and (2) is interpreted as saying that for a given level of the nominal exchange rate $P_{MB,t}^{A}/P_{MB,t}^{B}$, fluctuations of the real exchange rate $P_{G,t}^{A}/P_{G,t}^{B}$ are constrained by the commodity points: whenever $P_{G,t}^{A}/P_{G,t}^{B}$ gets too low, a commodity flow from A to B intervenes to restore equilibrium. However, the model can well be read the other way round, viz. as saying that for a given level of the real exchange rate, fluctuations of the nominal exchange rate are constrained by the very same commodity points: whenever $P_{MB,t}^{A}/P_{MB,t}^{B}$ gets too high, a financial flow from B to A intervenes to restore equilibrium. The idea is that every commodity flow from A to B is always matched by an equal and opposite financial flow from B to A, allowing the arbitrageur to repatriate profits and hence to close the operation. The counterpart to the nominal price margin of commodity G between A and B ($X_{G,t}^{A,B}$), therefore, is the real price margin of the monetary asset MB between B and A ($X_{MB,t}^{B,A}$), defined as

$$X_{MB,t}^{B,A} = P_{MB,t}^{A} - P_{MB,t}^{B} \frac{P_{G,t}^{A}}{P_{G,t}^{B}} \quad (3).$$ [8]

The model described by Equations (1) and (3) is the actual analytical framework that has generally been adopted in order to measure financial integration under commodity-based monetary systems (see e.g. Canjels et al., 2004). Under a regime such as the gold standard, gold flows are

[7] Differently said, this is the gross nominal profit of arbitraging good G from A to B (selling price minus buying price) for an agent located in A.

[8] Differently said, this is the gross real profit of arbitraging the monetary asset MB from B to A (selling price minus buying price) for an agent located in A. This is equal to the gross nominal profit of arbitraging commodity G from A to B, divided by the price of the commodity: $X_{MB,t}^{B,A} = X_{G,t}^{A,B}\left(P_{MB,t}^{B}/P_{G,t}^{B}\right)$.

expected to impact not the price of gold, but the nominal exchange rate: by modifying the profitability of gold arbitrage, fluctuations of the exchange rate are hence seen as the determinant of gold flows across locations. Note that as $P_{MB,t}^{B} = 1$, $X_{MB,t}^{B,A}$ is equivalent to the deviation of the nominal exchange rate from the real exchange rate (i.e. from the metallic par). Threshold-regression analysis can thus be applied to this framework: the intuition is that the price margin (the exchange rate deviation from the metallic par) will follow a random walk within the band constrained by the commodity points (the gold points), while it will converge back towards the band once its bounds are violated (Hansen 2011).

It is worth underlining that the arbitrage model presented above only works under three assumptions. The first one is *bilaterality*: only what happens in the two considered locations (A and B) can have an impact on the nominal exchange rate. The second one is *non-substitutability of the arbitraged good*: only flows of the considered commodity (G) can have an impact on the nominal exchange rate – or differently said, the only relevant real exchange rate is the ratio of the prices of G ($P_{G,t}^{A}/P_{G,t}^{B}$).[9] The third one is *strict coincidence between commodity and financial flows*: financial flows can only exist as a simultaneous counterpart to commodity flows – or differently said, the commodity market (where G is exchanged) and the currency market (where MB is exchanged) are but the two sides of the same coin.[10]

Following Canjels et al. (2004), we are also going to use Equations (1) and (3) as the input of our empirical analysis. Before we do that, however, another crucial question needs to be discussed: what is the actual commodity price we should take as P_G in a commodity-based monetary system? As we shall see in Section 2.2, the answer is not as self-evident as it might appear at first sight.

2.3. What Price? Microstructural Issues

In a commodity money system, bullion is special because it is both a commodity valued for its own sake and a currency because of its "moneyness" (or, liquidity). It trades freely on local markets, but it can also be traded with privileged organizations (such as banks of issue, giro banks, or mints) at a regulated price. So far, the dominant view in the literature has been that under monetary regimes such as the gold standard, the price of bullion was set by such organizations, and not by traders on the market.[11] The main rationale that has been put forward is that, abstracting from transaction costs, the trading operated by those organizations was sufficient to make the legal ratio equal to the market price – or differently said, that the bullion market was fully internalized by them.

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[9] This reflects that fact that, as already pointed out, the gold-point arbitrage model is a *partial* equilibrium model.

[10] This is encapsulated by Canjels et al.'s (2004, p. 872) Equation 2, which explicitly sets changes in the stock of foreign currency domestically held as determined by gold flows.

[11] See e.g. Morgenstern (1959), Officer (1986), Spiller and Wood (1988), or Canjels et al. (2004) to quote but a few. An exception is Flandreau (1996).

Historical evidence, however, suggests that bullion markets were *not* fully internalized by official organizations, as external bullion market *did* exist.[12] As a result, understanding the microstructure of bullion markets is crucial in order to select the correct price series to compute price differentials across countries. In this section, we show that in the historical context on which we focus, arbitrageurs had a better deal on local (external) markets than at the privileged organizations, so that the market price of bullion is the relevant price to study arbitrage relations across countries.

Before the 1870s, the currencies of all five European financial centers in our sample were on a gold monometallic, silver monometallic, or bimetallic foot. In Paris, private agents had the right to ask the mint to coin both metals; in London, the level of the legal ratio made it profitable to coin only gold, while only silver was minted in Amsterdam[13] and Frankfurt; Hamburg, which was on the silver standard, did not however have a mint. Except for Hamburg, regulated organizations did not intervene directly and in unlimited quantity on the market to set price. Although they were used to buy and sell bullion, they would generally do so at a cost and with delays.

Some institutional complementarity between markets and organizations followed. Markets allowed traders to secure the benefit of the immediacy, while regulated organizations acted as market-makers offering limit prices (Ugolini, 2013). The transaction cost associated to trading with organizations generated a non-negligible price difference. This varying spread between the legal and the market price proves that arbitrageurs generally resorted to markets for implementing their operations. The rest of this section shows the historical evidence grounding this conclusion.

In a mid-19th-century financial center, three types of regulated organizations could have been operated: 1) a mint, 2) a giro bank, or 3) a bank of issue. 1) Mints were in charge of transforming bullion into the local variety of coins, but they did not sell ingots. This means that the mint price was a bid price, not an ask price. A mint was operated in all five centers in our sample except Hamburg. 2) Giro banks issued bank money against deposit of bullion. As they did not have any obligation to convert bank money into local coins, they could hence change their bid price and an ask price for bullion at their will. The only giro bank still surviving at this date was in Hamburg. 3) Banks of issue issued banknotes against local coins, and were committed to reimburse them in local coins. This means that while their bid and ask prices for bullion could not diverge too much from the mint price, they could anyway change at their will according to market conditions (Ugolini, 2013). Banks of issue were active in all centers in our sample except Hamburg.

[12] We confine the argument to the most developed European financial centers of the time. We concede that the situation might have been different in peripheral countries like e.g. Portugal (Esteves et al., 2007) or Spain (Nogues and Herranz, 2015).

[13] To be precise, until 1847 the Netherlands were *de jure* on a bimetallic standard, but the Utrecht mint was not obliged to buy bullion at a fixed price. On that year, the country switched to silver monometallism and the mint became committed to buy silver at the official mint price (Vrolik, 1853).

Hence, each regulated organization decided the terms of the exchange of coins against metallic bars or any other means of payment such as banknotes or deposits. Only in Hamburg did the local public bank buy and sell silver to its depositors on demand and at a fixed price, thus anchoring the mark banco on this metal (Seyd, 1868, p. 316). In London, the Bank of England was obliged by Peel's Act (1844) to buy unlimited amounts of gold bullion at a legally-fixed price (which was lower than the mint price), but it had no obligation to sell ingots. Elsewhere, neither mints nor banks intervened systematically on local gold or silver markets in order to keep the market price in line with the official parity.

Table 1: Mint prices vs. market prices of bullions in five European centers. 1844-1870

	Amsterdam	Frankfurt	Hamburg	London	Paris	Paris
Metal	**silver**	**silver**	**silver**	**gold**	**gold**	**silver**
Mint price	105.80	105.00	118.67	136.57	3444.44	222.22
Market prices	104.59	104.49	118.69	136.35	3437.17	220.60
Average spread as % of Mint price	1.14%	0.49%	-0.0002%	0.16%	0.21%	0.33%
Median spread as % of Mint price	1.13%	0.40%	-0.0006%	0.16%	0.27%	0.35%
Standard Deviation	0.43%	0.40%	0.0010%	0.01%	0.20%	0.08%
Min spread as % Mint price	-0.90%	-0.25%	-0.0016%	0.00%	0.21%	0.33%
Max	4.06%	1.19%	0.0030%	0.16%	0.74%	0.39%

Notes: Mint prices and market prices correspond to the value in local currency of 1 kilogram of pure metal. The spread is the difference between mint and market price. Mint prices did not change in any of the considered centers throughout the analyzed period.

Source: Authors' computation using data described in Section 4.

Not only were regulated organizations an unviable source for buying bullion (except in Hamburg); most often, they were also an inconvenient outlet for selling it. For the five financial markets in our sample, Table 1 shows average market prices, together with legal prices (i.e. mints' official bid prices) and the spread between them (see Section 4 for details). All prices are for 1 kilogram of pure alloy in terms of local currency. These results look paradoxical at first sight. For instance, in Frankfurt the bid price of a kilogram of silver was 105 guilder at the mint and 104.49 on the market. The same is true for the other cities, except in Hamburg where the spread was nil. The average spread for silver was substantial: 0.4% in Frankfurt, 0.33% in Paris, and 1.14% in Amsterdam. Spreads on gold were lower but substantial too: 0.16% in London and 0.23% in Paris. The comparison is unaffected by the use of the median, suggesting that the difference is an enduring feature of those markets. The reason why market bid prices could stay systematically lower than official ones is that arbitrageurs had to face substantial transaction costs while trying to sell their bullion to them. European mints charged to the buyers fees for the minting of coins. The cheapest mint was the London one, which charged no minting fee *but* asked the buyer to pay the cost of assaying the quality of the metal, as well as to bring in a quantity of bullion worth no less than £20,000. But the highest concern to arbitrageurs was surely the fact that the mint price was not a spot price, but a price for future delivery. In London, bullion purveyors had to wait at least 14 days to obtain the proceeds in coins, thus losing the corresponding interest (Seyd, 1868, p. 158). In Paris, delivery took place 10 days after deposit, and the minting fee was 0.21875%.[14] A more convenient outlet for bullion might have been banks of issue. The Banque de France charged a 0.1% fee for buying gold ingots (Haupt, 1882, p. 410). The Bank of England did not charge any monetary fee, but nonmonetary costs were non-negligible anyway (Seyd, 1868, p. 243).[15]

It is therefore unsurprising that investment manuals advised investors to use the market to buy and sell bullion (e.g. Tate, 1858; Seyd, 1868). We conclude that market prices are the only relevant data series that should be used in order to compute arbitrage opportunities across our five core financial centers.[16] As a result, the price margin that we are going to analyze is the deviation of the nominal exchange rate not from the *official* metallic par (the ratio of mint prices), but from the *arbitrated* metallic par (the ratio of market prices: Tate, 1858).

3. Econometric Specification of the TAR Model

The threshold autoregressive (TAR) model was first proposed by Tong (1978) and further developed by Tong and Lim (1980) and Tong (1983).[17] A special class of TAR, called the Band-TAR model, has been applied to the estimation of the transaction costs that limit price arbitrage across markets. Within the band defined by the transaction costs, agents do not arbitrage. Outside the band, unexploited profit will trigger arbitrage, which triggers a reversion of the price to the interior of the band. A simple version of such Band-TAR model may be written as:

$$\Delta x_t = \begin{cases} \rho^{out1}(x_{t-1} - c^{up}) + \varepsilon_t^{out} & if \quad x_{t-1} > c^{up} \\ \rho^{in} x_{t-1} + \varepsilon_t^{in} & if \quad c^{low} \le x_{t-1} \le c^{up} \\ \rho^{out2}(x_{t-1} - c^{low}) + \varepsilon_t^{out} & if \quad x_{t-1} < c^{low} \end{cases} \tag{4}$$

[14] Haupt (1882, p. 413) wrote that the Paris mint issued a certificate in exchange for gold (the so-called "mint bill") that allowed retrieving coins after a lag, and that could be discounted on the money market. The corresponding loss of interest should therefore to be taken into account to compute the profit from arbitrage when the mint was involved in the operation.

[15] "A stranger unacquainted with the modus operandi comes to the Bank, and offers Gold Bars for sale; he will be told, at the Bullion Office, that these Bars must first be re-melted, by the authorised Bank melters. The addresses of these being given him, he must proceed to one of them, to have the Bars remelted. The Bars are there casts into what is called the *Bank of England shape* (…). They may now be taken back to the Bullion Office. Here they are weighed in the Gold scales, the mark and weight of each Bar being called out for mutual noting. The Porters then cut off the Assay pieces, after which the Bars are trucked into the vaults. If an advance of money be there and then required, the chief of the office, roughly estimating the fineness and value of the Gold from the appearance of the Bars, will authorize a payment on account, to within 5 to 10 per cent. of such estimated value. (…). A day or a couple of days after the Assays come in, and the account is got ready. The calculations are verified, the balance due is settled and paid, and the transaction is closed. The seller pays for the Assays." (Seyd, 1868, p. 243).

[16] For further empirical evidence confirming the irrelevance of mint prices, see Section 6.3.

[17] See Hansen (2011) for a selective review of the application of TAR models in empirical economics.

where x_t is the *percent* exchange rate deviation from the arbitrated metallic par defined in Equation (3) and divided by the metallic par to allow for comparison across city pairs. c^{up} (c^{low}) is the upper (lower) threshold which captures the level of arbitrage cost. The residuals ε_t^{in} (ε_t^{out}) are supposed to be normally distributed with a mean of zero and a variance σ_{in}^2 (σ_{out}^2), and ρ^{out2} (ρ^{in}) is the adjustment speed outside (inside) the thresholds of arbitrage. The speed of adjustment depends on structural elements of the economy and on nonlinear components of arbitrage costs (due e.g. to possible risk-aversion by traders). The threshold and the speed of adjustment are supposed to provide a measure of the degree of integration of two markets: the lower the costs of arbitrage, the less time it took for the adjustment to occur, and the better integrated the two markets are (i.e. ρ^{out1} , ρ^{out2} will be zero in case of no integration, and negative in case of perfect integration).[18]

Theory predicts that within the band formed by thresholds there is no arbitrage, which means no price (i.e. exchange rate) adjustment when the gross profit from arbitrage is smaller than transaction costs. This theoretical property implies that the exchange rate deviation from the metallic par will follow a random walk within the metal points. We impose unit root behavior inside the band by restricting ρ^{in} to zero to increase identification of the parameters. Moreover, we assume the same error terms and conditional variance inside and outside the band. When c^{up} and c^{low} are known, simple least-squares methods can be applied to each subset of the data partitioned by the band (or the two thresholds). In the absence of prior knowledge about the threshold, we can still estimate this model via a grid search of all possible values of the threshold variable (here x_{t-1}),[19] which either minimizes the sum of squared residuals or maximizes the log-likelihood function of the model.[20] We use the Conditional Least Squares developed by Chan and Tsay (1998) estimation to estimate the following equation, a restrictive version of an asymmetric but time-invariant threshold model of equation (4):

$$\Delta x_t = \begin{cases} \rho^{out1}(x_{t-1} - c^{up}) + \varepsilon_t^{out} & if \quad c^{up} < x_{t-1} \\ \varepsilon_t^{in} & if \quad -c^{low} \le x_{t-1} \le c^{up} \\ \rho^{out2}(x_{t-1} + c^{low}) + \varepsilon_t^{out} & if \quad x_{t-1} < -c^{low} \end{cases} \tag{5}$$

which is called a TAR(3,1,1) model with 3 regimes, order 1, and with a delay parameter also of 1.

[18] Jacks (2005) takes market integration as a process with two separate but related developments: namely the articulation of a system of price convergence and adjustment.

[19] Here the delay parameter d is set to 1 for the threshold variable.

[20] It is undesirable for a threshold value to be selected with too few observations into one or the other regime. This possibility can be excluded by restricting the search to values of threshold variable such that a minimal percentage of the observations lie in each regime (Hansen, 1999). Following Rapach and Wohar (2006), we require each regime (outer or inner) to contain at least 15% of the observations for the threshold variable.

For each deviation of the exchange rate from its par, we start with the stationary or unit-root analysis of the exchange deviations using the NP test developed by Ng and Perron (2001) or the KPSS test developed by Kwiatkowski et al. (1992) for different sub-periods. If the series is detected as non-stationary (or unit root is detected), it indicates that the deviations are persistent and there is neither a mean reverting process, nor a process of returning to the edge of the band. Following Obstfeld and Taylor (1997), the exchange rate deviation is demeaned to center the series on zero. As discussed below, the fact that the series are not always centered on the metallic par may be due to other reasons than asymmetric costs to bullion arbitrage (see Section 6.1).

We estimate a TAR model when the series are stationary and run a threshold test as a test of specification to check the adequacy of the TAR alternative relative to the AR null. If the AR null is rejected, the estimated threshold is interpreted as the cost of arbitrage between the two locations. If the AR null cannot be rejected, this means that the deviation returns to its mean immediately, something that we interpret as the absence of cost to arbitrage. [21]

We check the robustness of our estimates with three exercises. First, to ease the comparison with previous papers, we re-estimate a symmetric TAR model over three sub-periods corresponding to three decades (1844-1850, 1851-1860, and 1861-1870). Second, we relax the hypothesis of symmetricity of thresholds and estimate an asymmetric TAR model for the whole period 1844-1870. We choose the delay parameter according to Tsay's suggestion to maximize the F-stat (Tsay, 2010).[22] Third, we construct a series of rolling thresholds by estimating the asymmetric TAR model over a window of 5 years (261 weeks) that is each time moved by 2 years.

4. Data

We use a hand-collected database of spot exchange rates and bullion prices. The starting date is July 20, 1844. The start date corresponds to the adoption of the Bank Act of 1844, which implied important modifications in the Bank of England's discount and bullion policy. The last available quote is October 1, 1870, but in most markets quotations are discontinued several weeks before this date because of the interruption of trade triggered by the Franco-Prussian war. Following 19th-century practice, the spot exchange rate $P^A_{MB,t}$ is defined as the price of a bill of exchange in city A for a payment to be delivered at sight in city B in local currency. Sight bills were typically issued by private banks and were payable upon presentation to the accepting bank in the foreign city. Bills were

[21] A half-life is the time taken for a given series to return to half of its initial value. It is calculated by inputting the autoregressive coefficient ρ^{out1} (ρ^{out2}) in ln(0.5)/ln(1+ ρ^{out1}). We interpret a low (high) half-life as a high (low) speed of the correction toward the mean (in the AR case) or towards the threshold (TAR case).

[22] Tsay's suggestion implies a delay parameter equal to 1 in most cases, and to 2 for the rest of the pairs, see the results of the nonlinearity test output in Appendix Table 4 using this rule.

denominated in the currency of the city on which they were drawn: for instance, bills on London sold in Amsterdam were payable in sterling upon presentation to the London address specified on the bill.

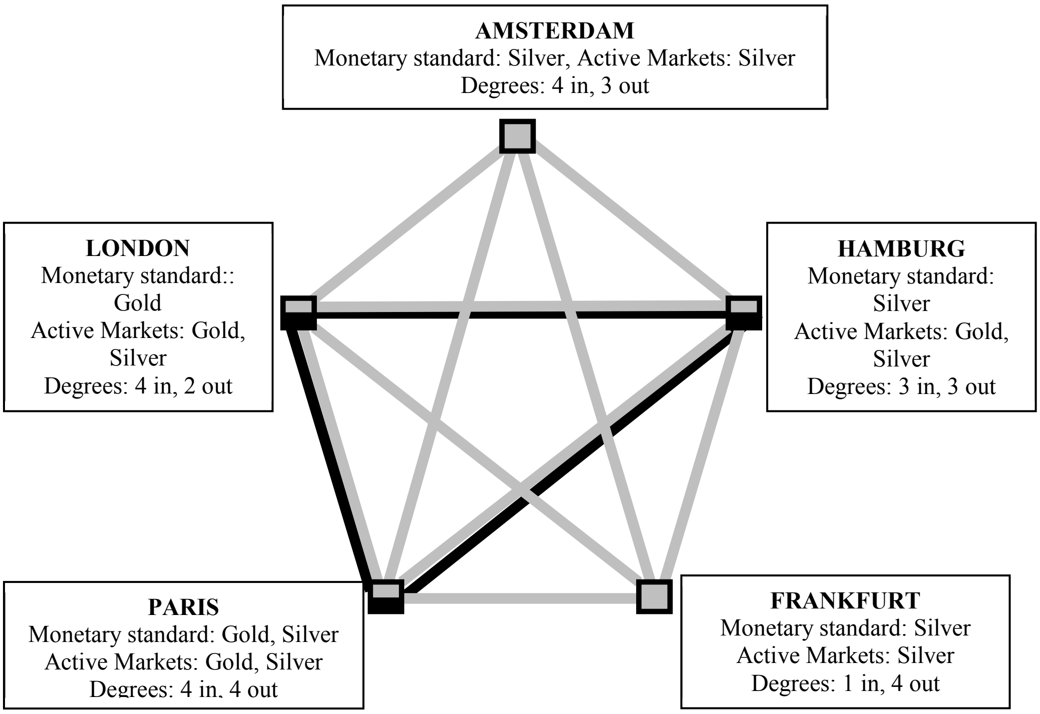
While all European currencies were quoted at long maturity (typically, sixty or ninety days), only core currencies were also quoted spot. To avoid corrections for the interest-rate component included in each long maturity,[23] we only collect data on currencies with an active spot exchange rates market. Between 1844 and 1870, there were only five such currencies: the pound sterling (London), the French franc (Paris), the mark Banco (Hamburg), the Dutch guilder (Amsterdam), and the South-German guilder (Frankfurt).[24]

Bill prices are collected from stock exchange bulletins (Amsterdam, Frankfurt, Paris) or their reprinting in the financial press (London, Hamburg). Among the twenty possible bilateral exchange rate relationships between our five financial centers, four series are missing as not all core currencies were quoted spot everywhere. The most extreme cases are London on the one hand (whose currency was quoted spot everywhere else, but which only quoted spot two foreign currencies – viz. the French franc and the Dutch guilder) and Frankfurt on the other hand (which quoted spot all other currencies, but was only quoted spot in Paris).[25] Interestingly, Paris was the only place to both quote and be quoted by all other centers (more on this in Section 6.3).

Gold and silver prices in each city were collected from the same sources as bill prices. Figure 1 summarizes the information on the available price quotes. It shows that market prices of both gold and silver ingots are available only in London, Paris and Hamburg, while Amsterdam and Frankfurt only quoted silver. We compute silver arbitrated pars for all available bilateral exchange relationships between our five centers. For the sake of robustness, we compute exchange rate deviations from both arbitrated pars (gold and silver) whenever gold was quoted on local financial market. To sum up, our database includes sixteen bilateral exchange rate relationships of which five can be checked against two different metallic benchmarks. This makes a total of twenty-one series of exchange rate deviations from an arbitrated metallic par.

Figure 1: Metallic standards, bullion markets, "in-degrees" (spot exchange rate on the given place quoted abroad) and "out-degrees" (spot exchange rate on a foreign place quoted in the given place) for Europe's top five financial centers, 1844-1870. Source: authors' database.
Note: G = gold (in black), S = silver (in grey).

[23] The pricing of long exchange rate included both the spot exchange rate and the offshore interest rate (De Roover, 1953) and there is no proper method to disentangle those dimensions.
[24] It is interesting to notice that before German unification, the Prussian thaler (i.e. Berlin's currency) was not quoted spot in any major international financial center.
[25] Seyd (1868, p. 443) explains the small number of foreign currencies quoted spot in London by the fact that the English banker "is under no necessity of seeking investment for his funds in Foreign securities of this kind", given the "so vast an amount of enterprise [that] continually extends the boundaries of commerce [in England]". By contrast, non-English bankers "do not so readily find convenient investment for large sums of money, and are therefore driven to deal in a variety of bills".



Following Officer (1996) and Canjels et al. (2004), we average bid and ask prices when both are available. We collect data at the weekly frequency to ensure consistency of our comparison of the threshold across the various pairs of markets. Actually, bills of exchanges were not quoted daily on all markets: for instance, Hamburg prices of sight bills are available only twice a week. Moreover, as Baillie and Bollerslev (2002) have shown, reducing the frequency (e.g. from daily to weekly) of exchange rate data decreases time-dependent heteroscedasticity, which is a source of inefficient estimates and suboptimal statistical inferences. Therefore, to avoid biasing the comparison, and because all markets quoted sight bills at least at the weekly frequency, we collect and use in the analysis all available end-of-week prices.

For some cities, no price is available for some sub-periods. As noted by Neal (1990), a missing price can indicate the inability to set a price, as was sometimes the case during period of financial tensions such as during the revolutions of 1848. In the case of Frankfurt, our source was discontinued after June 23, 1866 perhaps in connection with its annexation by Prussia. Table 2 summarizes the main statistics for all series. The maximum number of weeks in the sample is equal to 1363 for the Hamburg-London pair. The minimum is 869 in the case of the London-Frankfurt pair. Except for bilateral exchanges rate with Frankfurt, most bilateral exchange series contain about 1,300 observations.

Table 2: Descriptive statistics of exchange rate deviation from arbitrated pars. 1844-1870 (in percentage)

Exchange rate deviations							
Market of origin	**Market of destination**	**Metallic Par**	**Obs.**	**Mean**	**Std. Dev.**	**Min.**	**Max.**
Amsterdam	**London**	**Silver**	1062	0.035	0.594	-3.420	2.326

Amsterdam	**Hamburg**	**Silver**	1343	0.326	0.543	-1.141	2.097
Amsterdam	**Paris**	**Silver**	1236	-0.157	0.513	-1.667	1.555
Hamburg	**London**	**Gold**	1354	-0.354	0.577	-3.130	1.933
Hamburg	**London**	**Silver**	1363	-0.792	0.580	-3.570	0.824
Hamburg	**Amsterdam**	**Silver**	1345	-1.111	0.702	-4.230	1.742
Hamburg	**Paris**	**Gold**	1322	-0.231	0.678	-2.557	8.717
Hamburg	**Paris**	**Silver**	1363	-0.947	0.654	-2.836	0.737
Frankfurt	**London**	**Silver**	819	0.169	0.649	-3.075	2.683
Frankfurt	**Hamburg**	**Silver**	1106	0.303	0.476	-1.902	1.507
Frankfurt	**Amsterdam**	**Silver**	1097	-0.081	0.566	-2.045	1.416
Frankfurt	**Paris**	**Silver**	1019	-0.252	0.530	-3.868	1.305
London	**Amsterdam**	**Silver**	1053	-0.217	0.614	-2.127	3.541
London	**Paris**	**Silver**	1334	-0.215	0.538	-3.158	2.578
London	**Paris**	**Gold**	1287	0.080	0.453	-1.050	6.238
Paris	**Frankfurt**	**Silver**	1018	0.086	0.512	-1.190	1.894
Paris	**London**	**Gold**	1317	-0.118	0.440	-5.808	1.422
Paris	**London**	**Silver**	1359	0.170	0.544	-2.654	3.521
Paris	**Hamburg**	**Gold**	1300	-0.322	0.467	-2.480	1.173
Paris	**Hamburg**	**Silver**	1337	0.389	0.568	-1.009	2.475
Paris	**Amsterdam**	**Silver**	1225	0.077	0.492	-1.505	1.696

Source: authors' computations

5. Results

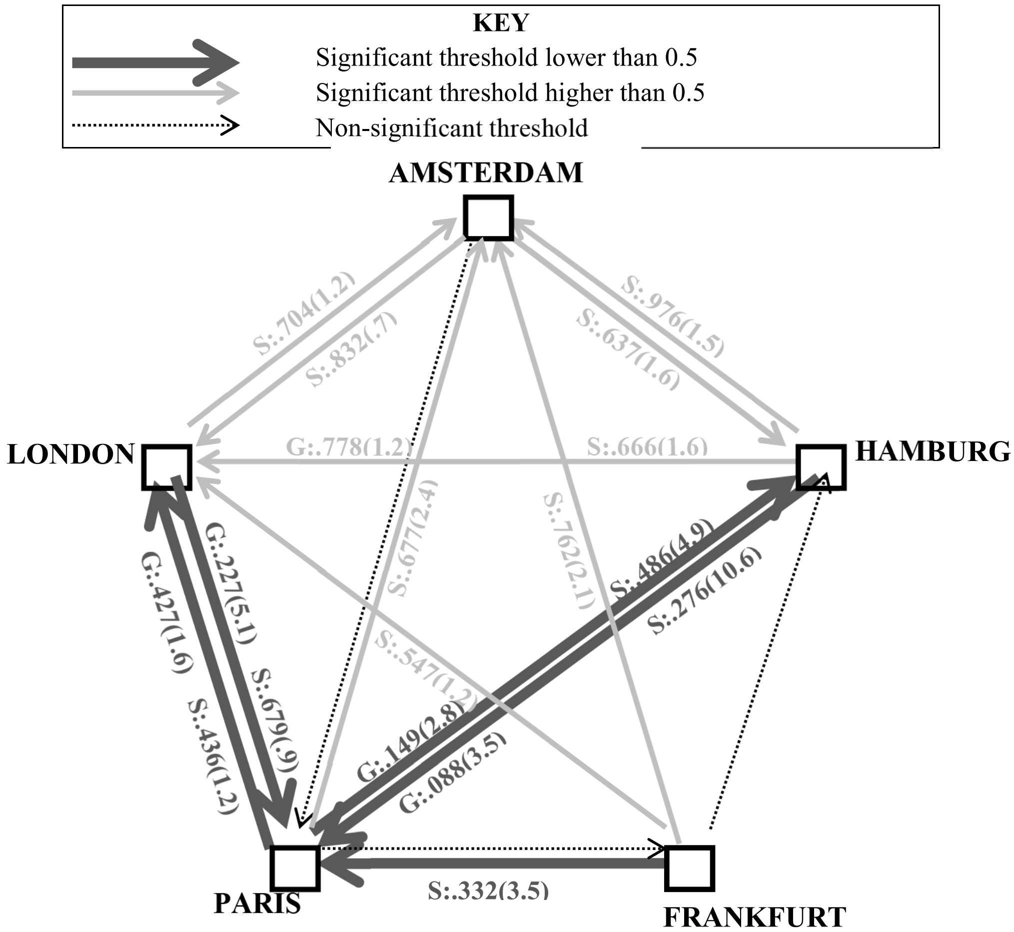
The preliminary step of our empirical analysis consists of establishing whether all bilateral exchange rate series display a mean-reverting behavior for the whole period. The results of the NP and/or KPSS unit root confirm this to be the case for all series (see Appendix table 1). The results indicate that, in the long run, any deviation of the price of sight bills (i.e. the spot exchange rate) from the metallic arbitrated par was followed by a return towards the par itself. Once these series are stationary (mean-reverting), we can estimate the thresholds beyond which the exchange rate deviation returns toward the par.

On the basis of this preliminary result, we estimate symmetric thresholds throughout the period 1844-1870. Figure 2 plots the estimated thresholds. The unit of the thresholds is the percentage deviation from the arbitrated par, and the unit of the half-life is in number of weeks. We also report the half-life of each threshold in parenthesis. Detailed results are reported in Appendix Table 2.

In all series but three, the estimated threshold is positive and significant, which points to the existence of some positive transaction cost before the deviation of the exchange rate returned to its mean. In three instances, the threshold is not significant, which might be interpreted as a negligible level of transaction cost to arbitrage. On the whole, the symmetric thresholds shown in Figure 2 point to a high level of integration, in particular between Paris on the one hand and the other European financial centers on the other hand.

Figure 2: TAR-estimated symmetric thresholds for the period 1844-1870. Source: Appendix Table 2.

Note: Information provided close to each arrow includes 1) the benchmark metallic par (G = gold, S=silver); 2) the size of the estimated threshold; and 3) the half-life (in parentheses).



We then proceed to perform three robustness checks. The first one consists of estimating symmetric thresholds by decades. Results of unit root tests and of TAR estimations are displayed in Appendix Tables 3 and 5. The results confirm that integration was strong, and suggest that it was generally increasing over time. In particular, the level of integration between Paris and the other financial centers is seen to be improving steadily over the decades.As a second robustness check, we relax the hypothesis of symmetricity of thresholds. Table 3 presents the result of the estimations obtained through an asymmetric TAR model for the whole period 1844-1870, and compares it with data on actual transaction costs to bullion arbitrage drawn from historical sources. Overall, the upper thresholds vary between a minimum 0.057% for Hamburg-on-Paris (silver) and a maximum 0.902% for Amsterdam-on-Hamburg. The half-lives for these two pairs are at about 0.6 for Hamburg on Paris and 2.6 for Amsterdam on Hamburg: this means that it took less than four days for the Hamburg-on-Paris exchange rate to return to half of its initial value when it deviated outside the band, but two weeks and a half for the Amsterdam-on-Hamburg pair. All this appears to confirm a strong degree of integration (especially around Paris), which confirms the findings illustrated in Figure 2. A further inspection of the results of Table 3 reveals three other findings.

Table 3: Estimation result of asymmetric lower and upper thresholds for the period 1844-1870, compared with actual gold and silver points from historical sources (when available)

Market of origin	Market of destination	Metallic Par	Import point: Lower threshold	Export points: Upper threshold	Lower gold or silver point (when known)	Upper gold or silver point (when known)
London	**Paris**	**Silver**	-0.397	0.357	-0.865 / -0.625 (F)	0.667 / 0.428 (F)
Paris	**London**	**Silver**	-0.363	0.501	-0.667 / -0.428 (F)	0.865 / 0.625 (F)
London	**Paris**	**Gold**	-0.182	0.125	-0.825 / -0.625 (F)	0.575 / 0.375 (F)
Paris	**London**	**Gold**	-0.193	0.187	-0.575 / -0.375 (F)	0.825 / 0.625 (F)
Hamburg	**Paris**	**Gold**	-0.230	0.243		
Hamburg	**Paris**	**Silver**	-0.759	0.057		
Hamburg	**London**	**Gold**	-0.402	0.252	-0.600 (T)	0.600 (T)
Hamburg	**London**	**Silver**	NA	NA	-1.160 (S)	0.696 (S)
Paris	**Hamburg**	**Silver**	-0.347	0.303		
Paris	**Hamburg**	**Gold**	-0.347	0.326		
Paris	**Frankfurt**	**Silver**	-0.210	0.281		
Frankfurt	**Paris**	**Silver**	-0.598	0.376		
Amsterdam	**Paris**	**Silver**	-0.358	0.387		
Paris	**Amsterdam**	**Silver**	-0.323[d]	0.461[d]		
Amsterdam	**Hamburg**	**Silver**	-0.307[d]	0.902[d]		
Hamburg	**Amsterdam**	**Silver**	NA	NA		
Frankfurt	**Hamburg**	**Silver**	-0.277[d]	0.373[d]		
Frankfurt	**London**	**Silver**	-0.433	0.401	-0.700 (S)	0.700 (S)
London	**Amsterdam**	**Silver**	-0.434	0.416	-0.725 (T)	0.725 (T)
Amsterdam	**London**	**Silver**	-0.355	0.473	-0.833 (S)	0.417 (S)
Frankfurt	**Amsterdam**	**Silver**	-0.474[d]	0.486[d]		

Notes: d denotes that the delay parameter d of TAR model is 2 according to the nonlinearity test of Tsay. For other series, d can be set to 1 (see Appendix Table 4 for more details).
Sources: Estimations based on authors' computations (see Appendix Table 6). Historical data: (F) = Flandreau (1996. p. 424) (note: before 1854 / after 1854); (S) = Seyd (1868. p. 424); (T) = Tate (1858. p. 251).

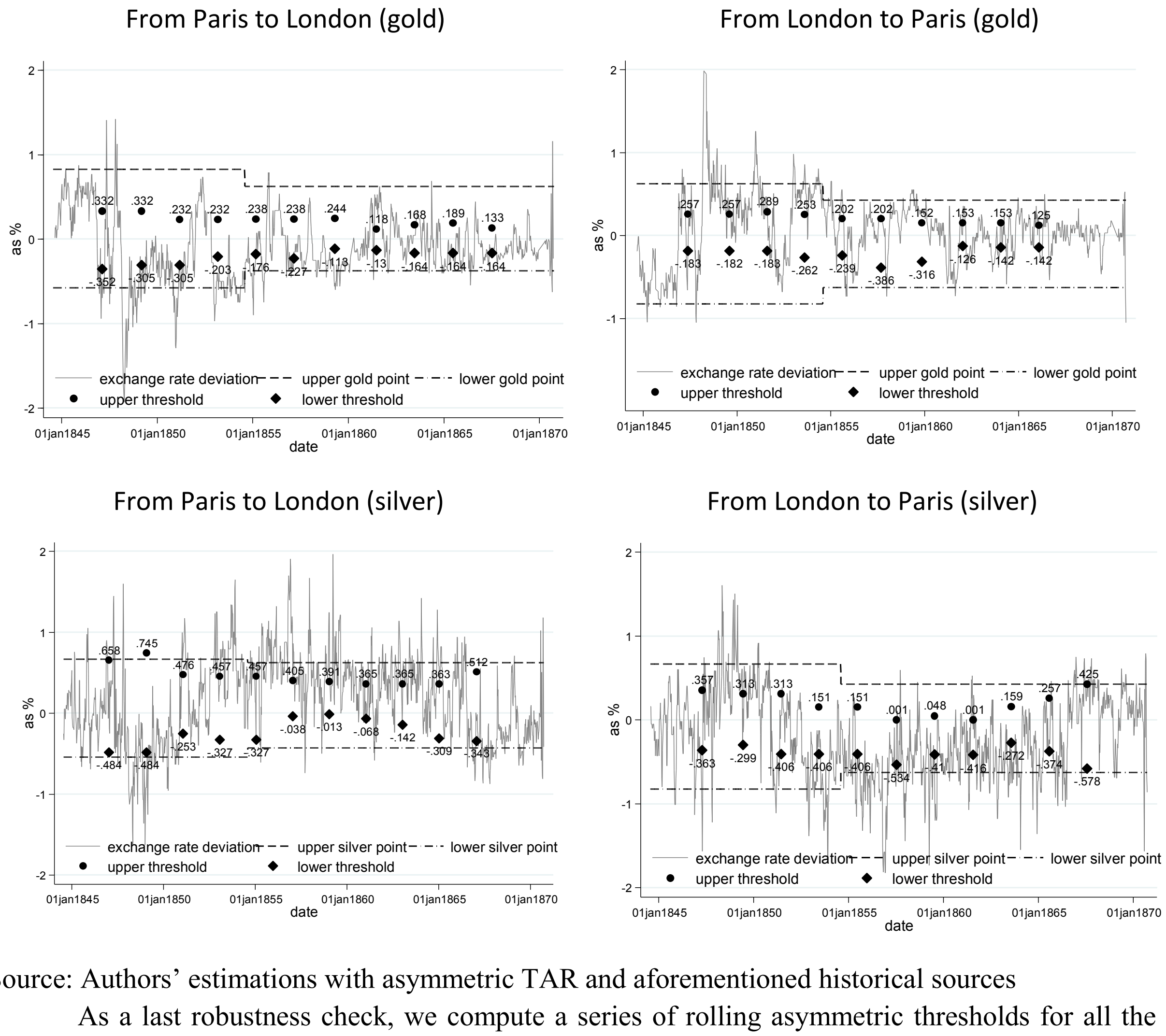
First, our results confirm (with new data and new financial markets) the intuitive conclusion that the exchange rate deviation from the gold arbitrated par (when available) was lower than the one from the silver arbitrated par. For instance, for the Paris-on-London arbitrage relationship, the exchange rate is found to display a mean-reverting behavior as soon as it deviated more than 0.187% from the gold arbitrated par, while it is found to display such a behavior when it deviated more than 0.501% from the silver arbitrated par. This can be seen as consistent with the historical literature that has documented higher transportation costs for silver than for gold.

Second, relaxing the hypothesis of symmetricity of thresholds allows showing that there actually was a non-negligible asymmetry between the lower bound and the upper bound of the exchange rate fluctuation around the par. This is consistent with Flandreau's (1996) finding that arbitrage was directional, and that the specificities of each market mattered in determining the level of transaction costs. It follows that the width of the fluctuation band of the exchange rate is asymmetric in the sense that transaction costs were lower on some routes than on others.

Third, we confirm the puzzle found in the literature (see Section 2.1): when actual transaction costs to bullion arbitrage are known from contemporary sources, they are systematically higher than the thresholds estimated through TAR models. As shown in Table 3, the estimated threshold for Paris-on-London (when parity is computed with gold) is at 0.187% and that the half-life is about 3 days (or 0.4 week). This has to be compared with Flandreau's (1996, p. 424) estimates of the direct cost of gold arbitrage, that are 0.825% before 1854 and 0.625% afterwards. A great connoisseur of the bullion markets of the time, Ernest Seyd, reported that in the late 1860s gold points were 0.5% around the metallic par for the Paris-on-London relationship (Seyd 1868, p. 394). For the London-on-Paris pair, Flandreau's (1996, p. 424) upper estimates are 0.540% for silver and 0.375% for gold. This has to be compared respectively to our 0.357% estimated threshold for silver and 0.125% for gold.

Figure 3: Historical gold and silver points vs. estimated asymmetric thresholds: Paris and London

Reading: the graph plots the gold and silver points between Paris and London as computed from historical sources, together with the asymmetric thresholds estimated using a TAR model of the exchange rate deviation from the gold and silver arbitrated par.



Source: Authors' estimations with asymmetric TAR and aforementioned historical sources

As a last robustness check, we compute a series of rolling asymmetric thresholds for all the bilateral exchange relationships in our sample. Complete results are plotted in Appendix Figure 1. Here, Figure 3 plots the moving-thresholds involving London and Paris, including series of exchange rate deviations from both gold and silver arbitrated pars. The threshold varies quite always within the band defined by the gold and silver points reported in Flandreau (1996) or Seyd (1868). This is consistent with our claim that except in some very specific circumstances, the TAR-estimated thresholds are in general lower than historically-observed bullion points.

When comparing our general results, two points are noteworthy. First, all available direct evidence on gold points for this and for later periods (e.g. Seyd, 1868; Tate, 1858; Einzig, 1929; Morgenstern, 1959; Flandreau, 1996) suggest that our estimates are substantially smaller than one would expect. On this regard, our analysis systematically replicates the puzzle first raised by Canjels et al. (2004) – i.e., that TAR-computed thresholds are much lower than bullion points reconstructed from historical sources. Our estimates are in fact much closer to the level of the financial transaction cost estimated for late-20th-century fiat-money regimes (see e.g. Coakley and Fuertes 2001). Given that the sample period was characterized by the absence of capital controls, this suggests that there were cheaper arbitrage vehicles available to traders than moving gold or silver across countries (more on this in Section 6.2).

Second, our estimations reveal obvious discrepancies between the long-run and moving-windowed or decadal estimates of the thresholds. One potential explanation may lie in the swings exhibited in the medium-run by the series. This may be linked to the qualitative properties of the exchange rate deviation for each decade, as reported in Appendix Table 1. It was not uncommon in the 1840s that the deviation from metallic par of some market pairs was non-stationary. This was the case for Amsterdam-on-London, Amsterdam-on-Paris, London-on-Amsterdam, Hamburg-on-London, and Frankfurt-on-Paris. We check that this non-stationarity is not caused by the presence of structural breaks in the series.[26] This may be related to the fact that this decade was an epoch of dramatic shocks in Europe. A period of intense speculation linked to the Railway Mania (1844-1847) was followed first by huge financial and political shocks (1847-1849), then by a time of an unusual volatility of bullion prices following the Gold Rush (1849-1850). This suggests that financial events of specific decades had an impact on the cost of arbitrage between markets.

To sum up, our empirical analysis points to two noteworthy (and robust) findings. The first one is that the level of financial integration in Europe before the advent of the Gold Standard was substantial, and that Paris stood up as the financial center which was more strongly integrated with all other core centers of Europe. The second finding is that transaction costs estimated with a TAR model are systematically lower than actual gold or silver points reported by historical sources. This is consistent with the literature, and suggests that this cannot be imputed to the quality of the estimates or of the data. We have also found that TAR-estimated thresholds are sensitive both to the direction of

[26] As the TAR model is estimated only on stationary series, we checked whether the unit root on non-stationary series is caused by the existence of time break(s) using the multiple breakpoint tests of Bai and Perron (2003) for 6 pairs whose observations are characterized by the Unit-root, see table A1 in appendix. The results show no breakpoint, except the pair Hamburg-on-Paris. See Appendix Table 3 for the result of the stationarity tests.

the arbitrage and to the way time series are sampled. This suggests that TAR-computed thresholds can hardly be interpreted as reflecting the costs of bullion arbitrage: instead of the extra-gold-point mean-reverting pattern predicted by the classical gold-point arbitrage model, TAR estimates may actually happen to detect an *intra-gold-point* mean-reverting process. This suggests that the international arbitrage that allows for a re-equilibration of exchange rates in commodity-based monetary systems may have been of another nature than the bullion arbitrage envisaged by the classical model. The next section discusses potential reasons.

6. Discussion

6.1: The Limits to the Classical Gold-Point Arbitrage Model

As explained in Section 2.1, the classical gold-point arbitrage model rests on three fairly restrictive assumptions: 1) bilaterality, 2) non-substitutability of the arbitraged good, and 3) strict coincidence between bullion and currency flows. The three of them can actually be criticized.

Criticism of the most basic assumption of the classical gold-point arbitrage model – i.e., *bilaterality* – is put forward by Coleman (2007) When arbitrage between two locations is feasible at non-prohibitive costs through a third place – he argues – then *trilateral* arbitrage may occur even though the price margin does not exceed *bilateral* transaction costs. Focusing on the same historical example as Canjels et al. (2004), he shows that gold happened to be shipped from New York to London through Paris although the sterling/dollar exchange rate did not exceed the bilateral gold point. As such shipments prevented the exchange rate from reaching the bilateral gold point, the implication is that TAR-estimated thresholds will necessarily be lower than the actual bilateral cost of arbitraging gold or silver bullion. Coleman's (2007) conclusion is very relevant. However, as trilateral bullion shipments tended to be quite cumbersome and costly, the number of occasions in which trilateral gold/silver arbitrage was cheaper than bilateral one must have been limited. On the whole, this explanation does not seem to be sufficient to account for the remarkable narrowness of TAR-estimated non-bullion-arbitrage bands.

A second source of criticality can be drawn from Flandreau (1996), who targets another important assumption of the classical gold-point arbitrage model – i.e., *non-substitutability* of the arbitraged good. When more than one kind of monetary assets is available to settle international payments – he argues – then arbitrage in *one* monetary instrument may occur even though the price margin does not exceed the transaction costs implied by arbitrage in *another* monetary instrument. Focusing on the London-Paris bilateral relationship in the same period as ours (when Britain was on gold and France on bimetallism), he shows that silver shipments happened to occur between London and Paris although the sterling/franc exchange rate remained within the bilateral gold points (and vice-versa). As such shipments prevented the exchange rate from reaching the bilateral gold point, the implication is that TAR-estimated thresholds for gold are necessarily lower than the actual gold or silver points. No doubt, Flandreau's (1996) conclusion is very relevant. However, only five out of twenty-one bilateral exchange relationships in our sample actually had competing metallic instruments at the time. Moreover, this argument does not apply to the monometallic systems considered by the literature (Canjels et al., 2004; Esteves et al., 2007) – whose analysis leads, nonetheless, to the same results as ours.

A third source of criticality can be traced down to another crucial hypothesis of the classical gold-point arbitrage model – i.e., the *strict coincidence between bullion and currency flows*. This assumption is a very binding one: gold and money are thought to amount to the very same thing, and money/credit creation never occurs. This condition is fundamental from a theoretical viewpoint, as it ensures the applicability of threshold-regression analysis to exchange rate series: in fact, in case foreign currency could be created at will by the banking system (instead of being imported in the form of gold), there would be no reason for the exchange rate to display a mean-reverting behavior only after hitting the gold points. Unfortunately, the assumption of strict coincidence between bullion and currency flows seems to be too restrictive to correspond to the actual workings of historical monetary systems (Esteves et al. 2007, p. 12). Foreign currency (in the form of drawing rights granted by foreign banks to local ones – which is what bills of exchange actually amounted to) could indeed be created without necessarily implying physical gold shipments. One important application of this critique comes from the extension of target-zone models to the classical gold standard (Bordo and MacDonald 2005; Flandreau and Komlos 2006). According to this literature, because the gold standard was a credible target zone, mean-reverting speculation systematically drove exchange rates back to the metallic par without any need for gold shipments to occur. This means that when the exchange rate rose, the banking system *did* create foreign currency and sold it against local one – at least, as long as it expected the price of local money to return to its real value (the metallic par). As such credit creation prevented the exchange rate from reaching the bilateral gold point, the implication is that TAR-estimated thresholds for gold will necessarily be lower than the actual gold or silver points. The conclusions of the target-zone literature are – again – very relevant. However, their direct applicability to our analysis is unclear. As we have computed our thresholds by using the exchange rate deviation from the *arbitrated* (and not from the *mint*) metallic par, our non-arbitrage bands are dynamic – and not static as in the classical gold-standard analysis. The metallic par was hence volatile, and in some cases it moved rather considerably (as e.g. for the London-Paris bilateral relationship, where the gold par varied as much as 5.82% between April 8, 1848 and February 1, 1851). This means that it might have been difficult for arbitrageurs to have converging expectations leading to mean-reverting foreign exchange speculation. As such, even this explanation does not seem to be sufficient to account for our results.

6.2: An Alternative View: Cross-Exchange Arbitrage

While none of the three explanations examined in Section 6.1 can alone account for the puzzle we observed, any of them contains a crucial element of truth: three of the most basic assumptions of the classical gold-point arbitrage model (bilaterality, uniqueness of the payments instrument, impossibility of currency creation) may not hold in the context of historical monetary systems. Analyzing the theoretical implications of relaxing all of the three assumptions at the time is way beyond the scope of this paper, and we leave this task to future research. In what follows, we will bind ourselves to proposing a strategy for rationalizing our puzzle that is consistent with both historical evidence and the underlined limits of the gold-point arbitrage model. This strategy consists of focusing on the role played by *cross-exchange arbitrage*.

In the context of historical monetary systems, many options were available to an arbitrageur willing to settle a payment from location A to location B. First, he could buy foreign currency (bills of exchange on B) directly in A. Second, he could physically ship gold or silver directly from A to B. Third, he could – as suggested by Coleman (2007) – ship bullion to B through a third location C. But a fourth option was also available: he could buy foreign currency (bills of exchange on B) in a third location C. Cross-exchange arbitrage of this sort was very common in the 19th century, and archival sources from private banks abound with evidence of such practices (see e.g. Gille 1961-3). The existence of this form of arbitrage is, *per se*, proof of extensive violation of the three above-mentioned assumptions of the classical gold-point arbitrage model: 1) by definition, it was non-bilateral but trilateral; 2) it provided an additional, viable alternative to bullion shipments; and 3) it was based on payments instruments (bills of exchange) which could be created by the banking system without necessarily entailing bullion shipments.

We are not the first ones to underline the importance of cross-exchange arbitrage in the workings of commodity-based monetary systems. Morgenstern (1959) has been the first to take the exchange rate deviation from cross-exchange pars as an indicator of market integration under the classical gold standard. His intuition has been applied by Schubert (1989) to the 18th-century international monetary system. De Roover (1949) and then Li (2012) have provided extensive evidence of cross-exchange arbitrage already in the late-medieval and early-modern periods.

When this form of arbitrage is allowed to exist between two locations, it is possible to compute one cross-exchange par for any third location available as a trading partner. The cross-exchange par between A and B through C ($P_{C,t}^{par}$) will be equal to

$$P_{C,t}^{par} = \frac{P_{MC,t}^{A}}{P_{MC,t}^{C}} \cdot \frac{P_{MB,t}^{C}}{P_{MB,t}^{B}}$$

where $P^{A}_{MC,t}/P^{C}_{MC,t}$ is the direct exchange rate between A and C, and $P^{C}_{MB,t}/P^{B}_{MB,t}$ is the direct exchange rate between C and B. Following Morgenstern (1959), the direct exchange rate deviation from the cross-exchange par x^{C}_{t}, defined as

$$x^{C}_{t} = \frac{P^{A,B}_{t} - P^{par}_{C,t}}{P^{par}_{C,t}},$$

can then be taken as an indicator of financial integration. By comparing the deviations of the direct exchange rate from cross-exchange pars with its deviations from metallic pars (gold/silver mint and arbitrated pars), it is possible to have a sense of the role played by cross-exchange arbitrage in reducing the volatility of direct exchange rates. In case direct exchange rates are closer to cross-exchange pars than to metallic pars, it is possible to conclude that it was the activation of cross-exchange arbitrage (instead of bilateral bullion arbitrage) which kept exchange rates far from the actual bullion points.

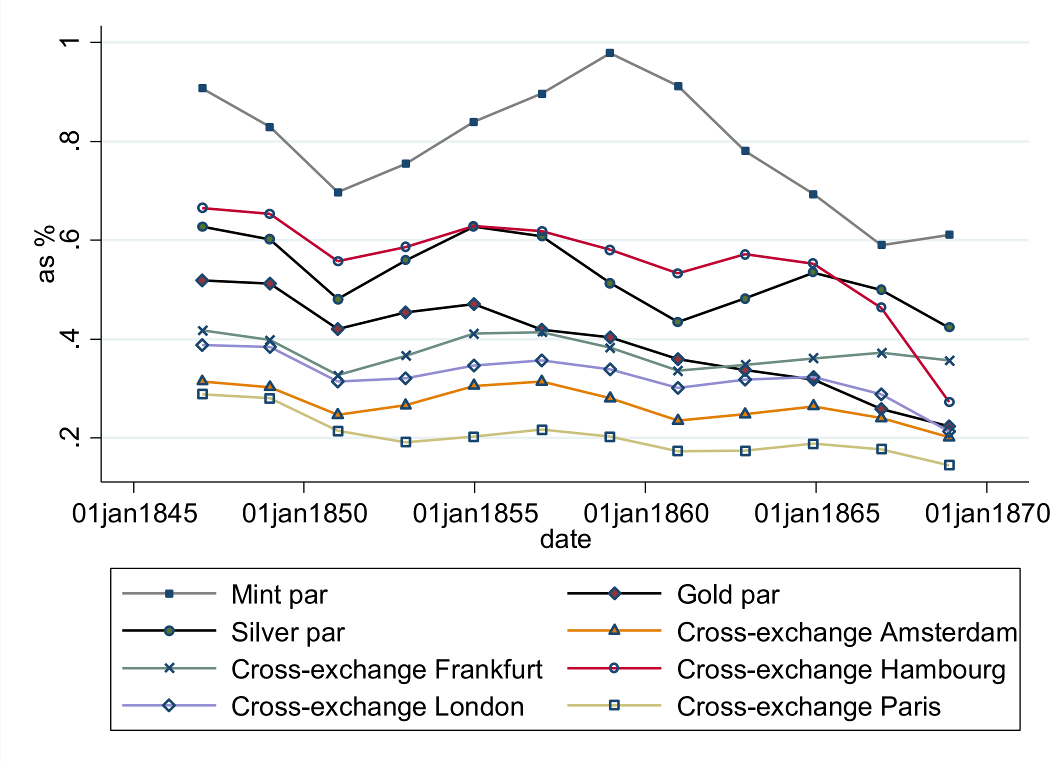
6.3: Cross-Exchange Arbitrage: Evidence

In order to measure financial market integration along the lines proposed by Morgenstern (1959) and Schubert (1989), for each of our twenty-one bilateral pairs we compare the mean absolute deviation of the direct exchange rates from a number of benchmarks (mint pars, gold arbitrated pars, silver arbitrated pars, and cross-exchange pars through all third cities included in our sample). [27] Appendix Figure 2 presents the results for every pair per decade. The figures can be read as a sort of "horse race" among the different payments strategies (or "arbitrage routes") available to arbitrageurs, allowing to see which one is more likely to have exerted an influence on direct exchange rates by its proximity (and hence, by the activation of mean-reverting arbitrage of the kind). To provide a broader view, we aggregate information from bilateral pairs in order to get general statistics for every "arbitrage route".[28] Aggregate values on mean absolute deviations are visualized in Figure 4.

[27] As discussed in Section 4, information on spot exchange rates on all other four cities is not available in all five centers (also see Figure 1). This means that in some cases, the cross-exchange par cannot be computed properly. However, we do not think that lack of price information means lack of trading: after all, even though the price of sight bills of exchange was not officially quoted, the price of ninety-day bills was – meaning that trading was active between the two cities. As a result, to compute cross-exchange pars between A and B through C when the price in C of sight bills on B ($P^{C}_{MB,t}$) is unavailable, we substitute the missing rate $P^{C}_{MB,t}/P^{B}_{MB,t}$ with the inverse of the spot exchange rate on B in C ($P^{C}_{MC,t}/P^{B}_{MC,t}$).

[28] Note that statistics in Figure 4 are for all observations in the decade regardless of their belonging to the one or the other pair. This means that each observation contributes equally, but each pair contributes unequally to the computation of the aggregated value.

Figure 4: Rolling average exchange rate deviation from various benchmarks.
Source: Data underlying the figures of Appendix Figure 2.



The results are telling: in most cases, direct exchange rates used to be much closer to cross-exchange pars than to any bilateral metallic par. They always stayed furthest from mint pars, but also rather far from arbitrated pars – although a considerable improvement is recorded in the "performance" of gold arbitrated pars, probably reflecting broader utilization of this monetary metal after the Gold Rush of the early 1850s. By contrast, direct exchange rates tended to stay remarkably closer to cross-exchange pars. This seems to suggest that the mean-reverting processes detected by threshold-regression analysis had nothing to do with violations of the bullion points: in fact, the random walk of the exchange rate was constrained not by the occurrence of bilateral bullion arbitrage, but by the occurrence of cross-exchange arbitrage.[29] As cross-exchange arbitrage took place whenever the closest of the many available "cross-exchange points" were hit, the economic meaning of TAR-estimated thresholds is impossible to interpret in a clear-cut way.

[29] Of course, there might be a possibility that the direct exchange rate deviation from cross-exchange pars is meaningless: transaction costs on cross-exchange arbitrage might have been prohibitive, so that the series happens to stay close to each other for purely fortuitous reasons. However, we think this to be very unlikely – at least, in the light of the above-mentioned historical evidence of extensive cross-exchange arbitrage (see Section 6.2). For instance, Tate's (1858, p. 150) bestselling textbook on foreign exchanges writes explicitly that cross-exchange arbitrage was vastly performed within branches of the same bank or joint banking ventures, which reduced its cost to the mere loss of interest. In view of this, we think it much more likely that the direct exchange rate often hit the one or the other "cross-exchange point": whenever that occurred, cross-exchange arbitrage took place and prevented the direct exchange rate from moving further in the same direction.

Figure 4 also provides a number of insights on European financial integration in the mid-19th century.

On the one hand, it suggests that information technology innovations played some role in fostering market integration: Figure 4 points to a non-negligible improvement between the 1840s and the 1860s, as the average absolute deviation of direct spot exchange rates from basically all benchmarks declined throughout the period.

On the other hand, our results confirm that there were hierarchies in the international monetary system. Direct exchange rates stayed systematically closer to some cross-exchange pars with respect to others: this suggests that because of unequal transaction costs, not all "cross-exchange arbitrage routes" were actually equally used by arbitrageurs.

Figure 4 shows that the most active route for international adjustment consisted of cross-exchange arbitrage through Paris; in this particular ranking, London only came third after Amsterdam, while Hamburg supplied the less popular route.[30] While this conclusion may appear in contrast with received wisdom (traditionally considering London as the center of the international monetary system since the early 19th century), it is well consistent with the information provided by Figure 1 on the structure of the international payments network. Although London was a very important financial center, Paris appears to have provided international arbitrageurs with a more performing infrastructure for implementing international transactions in bills of exchange, as it was the only place to have the maximum number of currencies quoted there, but also the maximum number of markets quoting the French franc (see Figure 1). One might speculate that this vantage situation had its roots in the peculiarities of France's bimetallic standard. However, a non-negligible role might also have been played by the different evolutionary path followed by England with respect to the Continent for what concerns the use and legal status of the bill of exchange (De Roover, 1953).

7. Conclusions

With the aim of measuring the evolution of financial market integration in Europe before the advent of the Gold Standard, we apply threshold-regression analysis to twenty-one series of weekly bilateral exchange rate deviation from an arbitrated metallic par between five core financial centers of the time. We provide two contributions. First, we find robust evidence of strong integration, and (contrary to received wisdom) of a pivotal role played by Paris as the European hub of foreign

[30] The case of Hamburg is special. As it is apparent from Appendix Figure 2, cross-exchange pars through the Hanse town tend to be far from direct exchange rates when they are computed using Hamburg prices (in roman), while they are much closer when they are computed using inverse exchange rate on Hamburg (in italics). This suggests that unobserved transaction costs (not included in official quotations) may have existed for accessing the Hamburg bill market, thus reducing its efficiency. These may have been tied to the restrictions in force at the local giro bank (Seyd 1868).

exchange markets. This suggests that while the advent of the Gold Standard in the 1870s cannot be imputed of having removed obstacles to financial integration, it can well be imputed of having fostered the emergence of London as the pre-eminent hub of international finance. Second, we point out that there are good reasons why TAR-computed thresholds cannot be interpreted as transaction costs in the bullion trade (the gold or silver points). In fact, the hypotheses underlying the classical gold-point arbitrage model appear to be too restrictive to correspond to the historical reality of commodity-based monetary systems. Building on a number of contributions, we suggest that multilateral currency arbitrage played a more crucial role than bilateral bullion arbitrage in capping exchange rate volatility. Looking at the deviation of the bilateral exchange rate from cross-exchange pars, we find that financial integration did actually increase substantially between 1844 and 1870. We conclude that the application of the TAR model to the estimates of gold or silver points of credible exchange rate is misleading. "Beneath the gold points" more complex arbitrage strategies were adopted by arbitrageurs thanks to the high sophistication of payments techniques at the time. Such strategies contributed much more substantially than "primitive" bullion arbitrage to the remarkable stability of the international monetary system.

Data Sources

London: *The Economist* (1844-1870).
Paris: *Cours général de la bourse de Paris publié par Jacques Bresson* (1844-1861); *Cours de la banque et de la bourse, anciens cours De Choisy et Bresson réunis* (1862-1870).
Hamburg: *Börsen-Halle: Hamburgische Abendzeitung für Handel, Schiffart und Politik* (1844-1860; 1862-1870); *Hamburger Geld- und Wechsel-Cours* (1860-1862).
Amsterdam: *Amsterdamsch Effectenblad* (1844-1870).
Frankfurt: *Börsen-Kursblatt von A. Sulzbach* (1844-1866).

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Appendix Tables and Figures

Appendix Table 1: Qualitative propriety of exchange rate deviation (results of the Ng-Perron/KPSS stationarity test and LLR linearity test).

	Market of origin	Market of destination				
		Amsterdam	**Frankfurt**	**Hamburg**	**London**	**Paris**
	Amsterdam	-	NA	**TAR**	**TAR**	AR
	Frankfurt	**TAR**	-	AR	**TAR**	**TAR**
1844-1870	**Hamburg**	**TAR**	NA	-	**TAR**	**TAR**
	London	**TAR**	NA	NA	-	**TAR**
	Paris	**TAR**	**TAR**	**TAR**	**TAR**	-
Sub-period 1	**Amsterdam**	-	NA	**TAR**	UR	UR
1844-1850	**Frankfurt**	**TAR**	-	**TAR**	UR	AR
	Hamburg	**TAR**	NA	-	**TAR**	UR
	London	UR	NA	NA	-	**TAR**
	Paris	**TAR**	**TAR**	**TAR**	**TAR**	-
	Amsterdam	-	NA	AR	**TAR**	AR
Sub-period 2	**Frankfurt**	**TAR**	-	AR	**TAR**	**TAR**
1851-1860	**Hamburg**	**TAR**	NA	-	**TAR**	UR
	London	**TAR**	NA	NA	-	AR
	Paris	**TAR**	**TAR**	**TAR**	**TAR**	-
	Amsterdam	-	NA	**TAR**	AR	TAR
Sub-period 3	**Frankfurt**	**TAR**	-	AR	AR	**TAR**
1861-1870	**Hamburg**	**TAR**	NA	-	**TAR**	**TAR**
	London	**TAR**	NA	NA	-	AR
	Paris	**TAR**	**TAR**	**TAR**	**TAR**	-

Notes: NA = Data non available; AR = Autoregressive process; TAR = Threshold autoregressive process; UR = Unit root.
The multiple breakpoint tests of Bai and Perron (2003) is used to identify whether the unit root is not wrongly identified because of existence(s) of time break(s). The results (unreported) does not detect a breakpoint is detected, except for the pair of Hamburg-Paris. However, for the whole sample period, no unit-root have been identified neither for the pair of Hamburg-Paris nor for other pairs no matter.
Source: Appendix Tables 2, Table 3 and Table 5.

Appendix Table 2: Estimation of the symmetric TAR model (1844-1870).

Market of origin	Market of destination	Metallic Par	parameters	estimate	t-stat.	C.I.	HL
Amsterdam	**London**	**Silver**	**rho**	-0.620	**-5.805**	0.21	0.7
			threshold	0.832	**11.381**	0.15	
			Obs_out (Obs_in)	154(847)			
Amsterdam	**Paris**	**Silver**	**rho**	-0.157	**-6.160**	0.05	4.0
			threshold	0.127	**2.304**	0.11	
			Obs_out (Obs_in)	996(239)			
Amsterdam	**Hamburg**	**Silver**	**rho**	-0.361	**-6.927**	0.10	1.5
			threshold	0.643	**11.236**	0.11	
			Obs_out (Obs_in)	800(562)			
Hamburg	**London**	**Silver**	**rho**	-0.451	**-6.640**	0.14	1.2
			threshold	0.778	**12.535**	0.12	
			Obs_out (Obs_in)	206(1156)			
Hamburg	**London**	**Gold**	**rho**	-0.345	**-6.809**	0.10	1.6
			threshold	0.666	**11.172**	0.12	
			Obs_out (Obs_in)	295(1058)			
Hamburg	**Amsterdam**	**Silver**	**rho**	-0.370	**-5.068**	0.15	1.5
			threshold	0.976	**11.058**	0.18	
			Obs_out (Obs_in)	208(1134)			
Hamburg	**Paris**	**Silver**	**rho**	-0.073	**-3.734**	0.04	9.1
			threshold	0.294	**3.084**	0.19	
			Obs_out (Obs_in)	113(207)			
Hamburg	**Paris**	**Gold**	**rho**	-0.189	**-10.561**	0.04	3.3
			threshold	0.092	**3.731**	0.05	
			Obs_out (Obs_in)	1123(198)			
Frankfurt	**London**	**Silver**	**rho**	-0.429	**-5.202**	0.16	1.2
			threshold	0.547	**6.745**	0.16	
			Obs_out (Obs_in)	298(452)			
Frankfurt	**Hamburg**	**Silver**	**rho**	-0.095	**-4.252**	0.04	6.9
			threshold	0.081	1.247	0.13	
			Obs_out (Obs_in)	892(205)			
Frankfurt	**Amsterdam**	**Silver**	**rho**	-0.284	**-4.200**	0.14	2.1
			threshold	0.762	**8.221**	0.19	
			Obs_out (Obs_in)	170(918)			
Frankfurt	**Paris**	**Silver**	**rho**	-0.224	**-6.047**	0.07	2.7
			threshold	0.309	**6.146**	0.10	
			Obs_out (Obs_in)	543 (475)			
London	**Amsterdam**	**Silver**	**rho**	-0.445	**-5.946**	0.15	1.2
			threshold	0.692	**9.966**	0.14	
			Obs_out (Obs_in)	263(789)			
London	**Paris**	**Silver**	**rho**	-0.562	**-8.548**	0.13	0.8
			threshold	0.674	**15.795**	0.09	
			Obs_out (Obs_in)	222(1111)			
London	**Paris**	**Gold**	**rho**	-0.327	**-6.605**	0.10	1.7
			threshold	0.563	**12.877**	0.09	
			Obs_out (Obs_in)	194(1092)			
Paris	**Frankfurt**	**Silver**	**rho**	-0.097	**-3.697**	0.05	6.8
			threshold	0.144	**1.957**	0.15	
			Obs_out (Obs_in)	751(192)			
Paris	**London**	**Gold**	**rho**	-0.346	**-4.709**	0.15	1.6
			threshold	0.427	**8.856**	0.10	
			Obs_out (Obs_in)	265(879)			
Paris	**London**	**Silver**	**rho**	-0.427	**-6.439**	0.13	1.2
			threshold	0.436	**7.535**	0.12	
			Obs_out (Obs_in)	418(746)			
Paris	**Hamburg**	**Gold**	**rho**	-0.219	**-7.352**	0.06	2.8
			threshold	0.149	**2.847**	0.10	
			Obs_out (Obs_in)	911(373)			
Paris	**Hamburg**	**Silver**	**rho**	-0.133	**-4.444**	0.06	4.9
			threshold	0.486	**5.820**	0.17	
			Obs_out (Obs_in)	434(866)			
Paris	**Amsterdam**	**Silver**	**rho**	-0.254	**-4.469**	0.11	2.4
			threshold	0.677	**8.699**	0.16	
			Obs_out (Obs_in)	176(967)			

Notes: This table presents the results of the model of eq. (5) assuming $c^{up} = c^{low}$ =c and $\rho^{out1} = \rho^{out2} = \rho^{out}$ implying symmetric transaction costs and mean reverting speed.T-stat. in bold denotes statistical significance at least at 10%. HL denotes the Half-Life in terms of weeks. Obs_out (Obs_in) denotes the number of observations outside (inside) the threshold. T-stat. is calculated based on the bootstrapped standard errors. C.I. denotes the confidence interval of the threshold estimate. *Source*: authors' estimations.

Appendix Table 3: Ng-Perron/KPSS unit root test for exchange rate deviations from arbitrated pars for the 1844-1870 and sub-periods.
This table shows the results of two unit root tests based on which we decide if we can estimate a TAR model.

Exchange rate deviation			1844-1850				1851-1860				1861-1870				1844-1870			
Market of origin	**Market of destination**	**Metallic Par**	MZa	MZt	**Lag**	**Obs.**	**MZa**	**MZt**	**Lag**	**Obs.**	**MZa**	**MZt**	**Lag**	**Obs.**	**MZa**	**MZt**	**Lag**	**Obs.**
Amsterdam	**London**	**Silver**	**1.719k**			158	**-16.038**	**-2.763**	1	324	**-13.491**	**-2.569**	7	486	**-18.913**	**-3.073**	1	905
Amsterdam	**Hamburg**	**Silver**	**-28.790**	**-3.712**	1	298	0.336k			522	**-25.731**	**-3.454**	2	503	**-94.388**	**-6.777**	1	1323
Amsterdam	**Paris**	**Silver**	-13.751t	-2.315t	1	160	**-35.450**	**-4.206**	2	510	**-8.515**	**-2.053**	6	476	**-28.178**	**-3.740**	2	1211
Hamburg	**London**	**Gold**	**-8.801**	**-2.080**	3	332	**-8.821**	**-2.041**	3	511	**-14.684**	**-2.514**	8	507	**-12.377**	**-2.410**	4	1351
Hamburg	**London**	**Silver**	**-7.894**	**-1.984**	4	332	**-28.735**	**-3.778**	10	520	**-16.312**	**-2.844**	14	509	**-35.652**	**-4.065**	3	1340
Hamburg	**Amsterdam**	**Silver**	**-19.226**	**-3.050**	2	300	**-12.187**	**-2.427**	2	520	**-8.551**	**-1.862**	0	507	**-47.992**	**-4.757**	1	1320
Hamburg	**Paris**	**SilverGold**	-10.083t	-2.053t	0	327	**-16.986**	**-2.902**	1	520	-4.070	-1.177	4	467	**-8.827**	**-2.085**	4	1361
Hamburg	**Paris**	**SilverGold**	-3.137	-0.994	3	321	-1.663	-0.754	10	511	**-10.616**	**-2.242**	7	453	**-24.115**	**-3.438**	2	1308
Frankfurt	**London**	**Silver**	**0.480k**			104	**-21.304**	**-3.256**	1	496	**-22.776**	**-3.373**	0	261	**-20.506**	**-3.202**	0	663
Frankfurt	**Hamburg**	**Silver**	**-18.055**	**-2.982**	0	330	**-21.736**	**-3.294**	2	496	**-23.464**	**-3.276**	0	268	**-63.583**	**-5.321**	0	1085
Frankfurt	**Amsterdam**	**Silver**	**-26.230**	**-3.563**	2	307	**-10.832**	**-2.287**	2	496	**-11.798**	**-2.419**	1	272	**-59.933**	**-5.247**	0	1069
Frankfurt	**Paris**	**Silver**	**-6.514**	-1.441	0	188	**-10.773**	**-2.287**	2	478	**-19.936**	**-3.132**	2	268	**-30.716**	**-3.913**	2	1006
London	**Amsterdam**	**Silver**	**1.610k**			149	**-23.111**	**-3.341**	0	321	**-15.997**	**-2.772**	7	490	**-21.396**	**-3.270**	0	898
London	**Paris**	**Gold**	**-13.190**	**-2.537**	0	156	**-9.501**	**-2.138**	0	480	**-49.316**	**-4.957**	0	451	**-84.971**	**-6.468**	0	1249
London	**Paris**	**Silver**	**-47.115**	**-4.750**	2	156	**-19.995**	**-3.085**	6	502	**-15.748**	**-2.792**	8	463	**-31.312**	**-3.882**	8	1309
Paris	**Frankfurt**	**Silver**	**-12.571**	**-2.412**	0	188	**-11.985**	**-2.407**	4	476	**-20.629**	**-3.188**	0	268	**-42.445**	**-4.587**	0	996
Paris	**London**	**Gold**	**-12.401**	**-2.477**	2	183	**-9.466**	**-2.146**	0	496	**-53.267**	**-5.159**	0	455	**-142.213**	**-8.428**	0	1292
Paris	**London**	**Silver**	**-31.461**	**-3.841**	8	183	**-30.454**	**-3.826**	6	518	**-16.235**	**-2.844**	8	461	**-71.031**	**-5.958**	2	1344
Paris	**Hamburg**	**Gold**	**-20.519t**	**-3.035t**	3	337	**-13.265**	**-2.516**	0	502	**-10.945**	**-2.312**	7	453	**-28.139**	**-3.666**	0	1274
Paris	**Hamburg**	**Silver**	**-11.556**	**-2.397**	0	321	-5.614	-1.613	4	511	**-5.752**	-1.489	5	461	**-17.724**	**-2.902**	3	1320
Paris	**Amsterdam**	**Silver**	**-21.158t**	**-2.922t**	0	160	**-22.912**	**-3.381**	5	505	**-22.408**	**-3.346**	0	455	**-35.295**	**-4.200**	0	1194

Notes: Only constant is included; t indicates the inclusion of linear trend and constant (following Canjels et al.. 2004, we introduce a linear trend as well to see if the process is trend-stationary); the optimal number of lags is chosen by minimizing the Modified SIC; T-stat. in bold denotes statistical significance at least at 10% for rejecting the unit root null hypothesis. MZa and MZt denote efficient versions of the PP tests based on GLS detrending procedure (Ng and Perron. 2001. table 1). k means that the KPSS test (Kwiatkowski et al.. 1992), which has a stationary null. is applied and that the LM test statistics are reported.
Source: authors' computations.

Appendix Table 4: Test of non-linearity (Tsay. 1989)

This allows to test the null hypothesis of linearity and at the mean time to determine the delay parameter d which defines the threshold autoregressive model. The delay d giving the largest F statistic is chosen as optimal.

Market of origin	Market of destination	Metallic Par	d=1		d=2	
			F-stat	P-val	F-stat	P-val
Amsterdam	**London**	Silver	16.688	**0.000**	5.939	**0.001**
Amsterdam	**Hamburg**	Silver	0.824	0.481	2.312	**0.075**
Amsterdam	**Paris**	Silver	4.985	**0.002**	2.170	**0.090**
Hamburg	**London**	Gold	4.565	**0.004**	7.671	**0.000**
Hamburg	**London**	Silver	17.664	**0.000**	2.931	**0.033**
Hamburg	**Amsterdam**	Silver	24.753	**0.000**	20.071	**0.000**
Hamburg	**Paris**	Gold	7.607	**0.000**	2.569	**0.053**
Hamburg	**Paris**	Silver	3.595	**0.013**	3.162	**0.024**
Frankfurt	**London**	Silver	18.335	**0.000**	6.095	**0.000**
Frankfurt	**Hamburg**	Silver	0.286	0.835	2.590	**0.052**
Frankfurt	**Amsterdam**	Silver	1.114	0.343	2.362	**0.067**
Frankfurt	**Paris**	Silver	15.274	**0.000**	4.942	**0.002**
London	**Amsterdam**	Silver	5.378	**0.001**	5.416	**0.001**
London	**Paris**	Silver	18.888	**0.000**	26.288	**0.000**
London	**Paris**	Gold	19.265	**0.000**	4.244	**0.005**
Paris	**Frankfurt**	Silver	4.688	**0.003**	2.410	**0.066**
Paris	**London**	Gold	34.548	**0.000**	29.431	**0.000**
Paris	**London**	Silver	10.990	**0.000**	19.988	**0.000**
Paris	**Hamburg**	Gold	2.898	**0.034**	4.699	**0.003**
Paris	**Hamburg**	Silver	0.733	0.532	0.190	0.904
Paris	**Amsterdam**	Silver	2.151	**0.092**	4.632	**0.003**

Source: authors' computation. Null Hypothesis: no threshold nonlinearity. The maximal lag d is set at 2 as a high order AR model may actually approximate non-liner dynamics relatively well (Tsay. 2010. p. 664). P-val. in bold denotes the statistical significance at least at 10%.

Appendix Table 5: Estimation results of the threshold autoregressive model for the three sub-periods.

This table shows the results of symmetric threshold model presented by eq. A1 in which we assume that $c^{up} = c^{low} = c$. $\rho^{out1} = \rho^{out2} = \rho^{out}$ implying symmetric transaction costs and mean reverting speed.

Market of origin	Market of destination	Metallic Par	parameters	estimate	t-stat.	C.I.	HL	estimate	t-stat.	C.I.	HL	estimate	t-stat.	C.I.	HL
				1844-1850				1851-1860				1861-1870			
Amsterdam	**London**	**Silver**	**rho**	UR				-0.244	-4.000	0.12	2.5	-0.166	-3.074	0.11	3.8
			threshold					0.167	1.942	0.17		0.178	1.369	0.26	
			Obs_out (Obs_in)					304(102)				421(75)			
Amsterdam	**Paris**	**Silver**	**rho**	UR				-0.199	-3.431	0.12	3.1	-0.243	-2.700	0.18	2.5
			threshold					0.149	1.693	0.18		0.370	2.913	0.25	
			Obs_out (Obs_in)					356(156)				226 (257)			
Amsterdam	**Hamburg**	**Silver**	**rho**	-0.628	-4.272	0.29	0.7	-0.161	-2.729	0.12	3.9	-0.230	-3.594	0.13	2.7
			threshold	0.601	7.24	0.17		0.106	1.104	0.19		0.482	5.021	0.19	
			Obs_out (Obs_in)	53(261)				415(106)				126(379)			
Hamburg	**London**	**Gold**	**rho**	-0.180	-2.022	0.18	3.5	-0.325	-4.221	0.15	1.8	-0.655	-5.157	0.25	0.7
			threshold	0.364	2.737	0.27		0.393	4.367	0.18		0.669	10.967	0.12	
			Obs_out (Obs_in)	137(195)				259(253)				77(430)			
Hamburg	**London**	**Silver**	**rho**	-0.404	-3.848	0.21	1.3	-0.293	-4.726	0.12	2.0	-0.86	-5.119	0.34	0.4
			threshold	0.494	5.200	0.19		0.172	2.389	0.14		0.603	8.868	0.14	
			Obs_out (Obs_in)	125(207)				402(118)				86(422)			
Hamburg	**Amsterdam**	**Silver**	**rho**	-0.252	-3.452	0.15	2.4	-0.171	-3.420	0.10	3.7	-0.062	-1.127	0.11	10.8
			threshold	0.205	1.990	0.21		0.406	3.593	0.23		0.658	2.730	0.48	
			Obs_out (Obs_in)	245(70)				289(229)				126(381)			
Hamburg	**Paris**	**Silver**	**rho**	UR				-0.318	-3.180	0.20	1.8	UR			
			threshold					0.566	5.241	0.22					
			Obs_out (Obs_in)					110(410)							
Hamburg	**Paris**	**Gold**	**rho**	UR				UR				-0.230	-3.898	0.12	2.7
			threshold									0.272	3.831	0.14	
			Obs_out (Obs_in)									247(212)			
Frankfurt	**London**	**Silver**	**rho**	UR				-0.435	-3.718	0.23	1.2	-0.259	-3.548	0.15	2.3
			threshold					0.559	4.545	0.25		0.101	1.312	0.15	
			Obs_out (Obs_in)					139(238)				227(41)			
Frankfurt	**Hamburg**	**Silver**	**rho**	-0.113	-1.413	0.16	5.8	-0.130	-2.600	0.10	5.0	-0.116	-1.105	0.21	5.6
			threshold	0.723	3.286	0.44		0.084	0.923	0.18		0.066	0.702	0.19	
			Obs_out (Obs_in)	53(278)				389(103)				228(44)			
Frankfurt	**Amsterdam**	**Silver**	**rho**	-0.209	-2.297	0.18	3.0	-0.121	-2.017	0.12	5.4	-0.335	-2.577	0.26	1.7
			threshold	0.405	3.894	0.21		0.341	2.258	0.30		0.612	5.368	0.23	
			Obs_out (Obs_in)	113(207)				268(224)				58(216)			
Frankfurt	**Paris**	**Silver**	**rho**	-0.063	-0.460	0.27	10.7	-0.341	-3.187	0.21	1.7	-0.235	-2.901	0.16	2.6
			threshold	0.197	0.995	0.40		0.589	5.557	0.21		0.126	1.826	0.14	
			Obs_out (Obs_in)	124(63)				106(377)				219(53)			
London	**Amsterdam**	**Silver**	**rho**	UR				-0.454	-3.266	0.28	1.1	-0.149	-2.980	0.10	4.3
			threshold					0.665	5.155	0.26		0.250	2.033	0.25	
			Obs_out (Obs_in)					98(306)				383(115)			
London	**Paris**	**Silver**	**rho**	-0.397	-3.336	0.24	1.4	-0.234	-4.034	0.12	2.6	-0.342	-3.600	0.19	1.7
			threshold	0.103	1.226	0.17		0.073	1.177	0.12		0.282	3.169	0.18	
			Obs_out (Obs_in)	125(42)				421(88)				281(183)			
London	**Paris**	**Gold**	**rho**	-0.248	-2.084	0.24	2.4	-0.093	-1.755	0.11	7.1	-0.157	-2.211	0.14	4.1
			threshold	0.341	2.623	0.26		0.085	1.076	0.16		0.059	1.157	0.10	
			Obs_out (Obs_in)	72(95)				388(104)				339(119)			

Paris	**Frankfurt**	**Silver**	**rho**	-0.124	-0.816	0.30	5.2	-0.549	**-3.866**	0.28	0.9	-0.452	**-2.598**	0.35	1.2
			threshold	0.539	**2.274**	0.47		0.573	**7.253**	0.16		0.489	**4.990**	0.20	
			Obs_out (Obs_in)	48(139)				74(408)				46(226)			
Paris	**London**	**Gold**	**rho**	-0.389	**-2.037**	0.38	1.4	-0.102	-1.619	0.13	6.4	-0.165	**-2.619**	0.13	3.8
			threshold	0.385	**4.010**	0.19		0.176	**1.978**	0.18		0.063	1.537	0.08	
			Obs_out (Obs_in)	58 (124)				276(224)				364(96)			
Paris	**London**	**Silver**	**rho**	-0.418	**-4.309**	0.19	1.3	-0.299	**-5.537**	0.11	2.0	-0.253	**-3.514**	0.14	2.4
			threshold	0.124	1.57	0.16		0.162	**2.893**	0.11		0.229	**2.759**	0.17	
			Obs_out (Obs_in)	134(48)				289(228)				331(132)			
Paris	**Hamburg**	**Gold**	**rho**	-0.284	**-3.595**	0.16	2.1	-0.31	**-4.697**	0.13	1.9	-0.229	**-4.018**	0.11	2.7
			threshold	0.191	**2.011**	0.19		0.257	**3.894**	0.13		0.207	**3.339**	0.12	
			Obs_out (Obs_in)	228(88)				246(261)				253(206)			
Paris	**Hamburg**	**Silver**	**rho**	-0.083	-1.277	0.13	8.0	-0.302	**-3.432**	0.18	1.9	-0.167	**-3.212**	0.10	3.8
			threshold	0.194	1.016	0.38		0.374	**4.110**	0.18		0.161	**2.403**	0.13	
			Obs_out (Obs_in)	236(85)				212(302)				289(174)			
Paris	**Amsterdam**	**Silver**	**rho**	-0.101	-0.828	0.24	6.5	-0.198	**-2.712**	0.15	3.1	-0.099	**-1.800**	0.11	6.6
			threshold	0.084	0.414	0.41		0.547	**5.160**	0.21		0.229	**1.941**	0.24	
			Obs_out (Obs_in)	141(31)				81(428)				286(174)			

Notes: T-stat. in bold denotes statistical significance at least at 10%. NS denotes that the data are non-stationary for the relevant period. HL denotes the Half-Life in terms of weeks. Obs_out (Obs_in) denotes the number of observations outside (inside) the threshold. T-stat. is calculated based on the bootstrapped standard errors. C.I. denotes the confidence interval of the threshold estimate.

Source: authors' computations.

Appendix Table 6: Estimation results of the asymmetric threshold autoregressive model.

This table shows the results of asymmetric threshold model by eq. (5).

Market of origin	Market of destination	Metallic Par	d	Threshold	t-stat.	rho-out2	t-stat.	HL	obs_l	Threshold	t-stat.	rho-out1	t-stat.	HL	obs_h
				Lower regime						Upper regime					
Amsterdam	**London**	**Silver**	1	-0.355	**-1.916**	-0.453	**4.747**	1.1	304	0.473	1.208	-0.728	**3.208**	0.5	239
Amsterdam	**Paris**	**Silver**	1	-0.358	-1.591	-0.260	**3.947**	2.3	471	0.387	0.861	-0.812	**4.387**	0.4	188
Amsterdam	**Hamburg**	**Silver**	2	-0.307	-0.937	-0.453	**2.755**	1.1	103	0.902	**3.511**	-0.233	0.125	2.6	233
Hamburg	**London**	**Gold**	1	-0.402	-0.918	-0.161	**2.920**	4.0	622	0.252	0.498	-0.824	**4.098**	0.4	196
Hamburg	**London**	**Silver**	1	NA											
Hamburg	**Amsterdam**	**Silver**	1	NA											
Hamburg	**Paris**	**Silver**	1	-0.759	-0.724	-0.054	**2.314**	12.5	905	0.057	0.233	-0.668	**2.548**	0.6	103
Hamburg	**Paris**	**Gold**	1	-0.230	-0.433	-0.149	**1.686**	4.3	697	0.243	0.203	-1.073	**10.801**	NM	221
Frankfurt	**London**	**Silver**	1	-0.433	**-2.189**	-0.556	**5.833**	0.9	137	0.401	0.999	-0.799	**5.135**	0.4	309
Frankfurt	**Hamburg**	**Silver**	2	-0.277	-1.041	-0.290	**3.022**	2.0	105	0.373	1.358	-0.797	**6.281**	0.4	541
Frankfurt	**Amsterdam**	**Silver**	2	-0.474	-1.094	-0.195	**3.039**	3.2	248	0.486	**2.026**	-0.571	**1.945**	0.8	187
Frankfurt	**Paris**	**Silver**	1	-0.598	**-2.078**	-0.262	**5.456**	2.3	247	0.376	**2.033**	-0.527	**2.105**	0.9	126
London	**Amsterdam**	**Silver**	1	-0.434	-0.775	-0.152	**2.500**	4.2	350	0.416	**2.992**	-0.225	0.759	2.7	157
London	**Paris**	**Silver**	1	-0.397	-1.358	-0.308	**3.615**	1.9	533	0.357	1.355	-0.598	**2.509**	0.8	182
London	**Paris**	**Gold**	1	-0.182	-0.306	-0.103	0.952	6.4	297	0.125	0.399	-0.912	**17.007**	0.3	580
Paris	**Frankfurt**	**Silver**	1	-0.210	-0.799	-0.136	**2.516**	4.7	298	0.281	0.853	-0.894	**12.540**	0.3	371
Paris	**London**	**Gold**	1	-0.193	-1.451	-0.259	**5.312**	2.3	584	0.187	0.450	-0.835	**4.676**	0.4	279
Paris	**London**	**Silver**	1	-0.363	-1.600	-0.520	**3.957**	0.9	221	0.501	**1.869**	-0.574	**2.052**	0.8	383
Paris	**Hamburg**	**Gold**	1	-0.347	-1.259	-0.194	**3.589**	3.2	627	0.326	**1.772**	-0.436	1.626	1.2	105
Paris	**Hamburg**	**Silver**	1	-0.347	-0.872	-0.242	**1.830**	2.5	130	0.303	0.461	-0.945	**16.285**	0.2	718
Paris	**Amsterdam**	**Silver**	2	-0.323	-1.057	-0.231	**3.118**	2.6	242	0.461	**3.612**	-0.344	1.347	1.6	293

Notes: NA denotes that the estimation results are not available because of the characteristics of the time series. NM denotes non-mean-reverting. HL denotes the Half-Life in terms of weeks. Obs_l (Obs_h) denotes the number of observations in the lower (higher) regime defined by the lower (higher) threshold. T-stat. in bold denotes statistical significance at least at 10%. *d* denotes the delay parameter of the threshold variable.

Source: authors' computations.

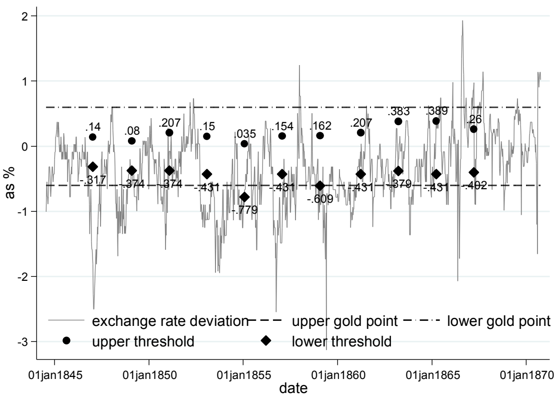
Appendix Table 6: Estimation results of the asymmetric threshold autoregressive model.

Market of origin	Market of destination	Metallic Par	d	Threshold	t-stat.	rho-out2	t-stat.	HL	obs_l	Threshold	t-stat.	rho-out1	t-stat.	HL	obs_h
				Lower regime						**Upper regime**					
Amsterdam	London	Silver	1	-0.355	**-1.916**	-0.453	**4.747**	1.1	304	0.473	1.208	-0.728	**3.208**	0.5	239
Amsterdam	Paris	Silver	1	-0.358	-1.591	-0.260	**3.947**	2.3	471	0.387	0.861	-0.812	**4.387**	0.4	188
Amsterdam	Hamburg	Silver	2	-0.307	-0.937	-0.453	**2.755**	1.1	103	0.902	**3.511**	-0.233	0.125	2.6	233
Hamburg	London	Gold	1	-0.402	-0.918	-0.161	**2.920**	4.0	622	0.252	0.498	-0.824	**4.098**	0.4	196
Hamburg	London	Silver	1	NA											
Hamburg	Amsterdam	Silver	1	NA											
Hamburg	Paris	Silver	1	-0.759	-0.724	-0.054	**2.314**	12.5	905	0.057	0.233	-0.668	**2.548**	0.6	103
Hamburg	Paris	Gold	1	-0.230	-0.433	-0.149	**1.686**	4.3	697	0.243	0.203	-1.073	**10.801**	NM	221
Frankfurt	London	Silver	1	-0.433	**-2.189**	-0.556	**5.833**	0.9	137	0.401	0.999	-0.799	**5.135**	0.4	309
Frankfurt	Hamburg	Silver	2	-0.277	-1.041	-0.290	**3.022**	2.0	105	0.373	1.358	-0.797	**6.281**	0.4	541
Frankfurt	Amsterdam	Silver	2	-0.474	-1.094	-0.195	**3.039**	3.2	248	0.486	**2.026**	-0.571	**1.945**	0.8	187
Frankfurt	Paris	Silver	1	-0.598	**-2.078**	-0.262	**5.456**	2.3	247	0.376	**2.033**	-0.527	**2.105**	0.9	126
London	Amsterdam	Silver	1	-0.434	-0.775	-0.152	**2.500**	4.2	350	0.416	**2.992**	-0.225	0.759	2.7	157
London	Paris	Silver	1	-0.397	-1.358	-0.308	**3.615**	1.9	533	0.357	1.355	-0.598	**2.509**	0.8	182
London	Paris	Gold	1	-0.182	-0.306	-0.103	0.952	6.4	297	0.125	0.399	-0.912	**17.007**	0.3	580
Paris	Frankfurt	Silver	1	-0.210	-0.799	-0.136	**2.516**	4.7	298	0.281	0.853	-0.894	**12.540**	0.3	371
Paris	London	Gold	1	-0.193	-1.451	-0.259	**5.312**	2.3	584	0.187	0.450	-0.835	**4.676**	0.4	279
Paris	London	Silver	1	-0.363	-1.600	-0.520	**3.957**	0.9	221	0.501	**1.869**	-0.574	**2.052**	0.8	383
Paris	Hamburg	Gold	1	-0.347	-1.259	-0.194	**3.589**	3.2	627	0.326	**1.772**	-0.436	1.626	1.2	105
Paris	Hamburg	Silver	1	-0.347	-0.872	-0.242	**1.830**	2.5	130	0.303	0.461	-0.945	**16.285**	0.2	718
Paris	Amsterdam	Silver	2	-0.323	-1.057	-0.231	**3.118**	2.6	242	0.461	**3.612**	-0.344	1.347	1.6	293

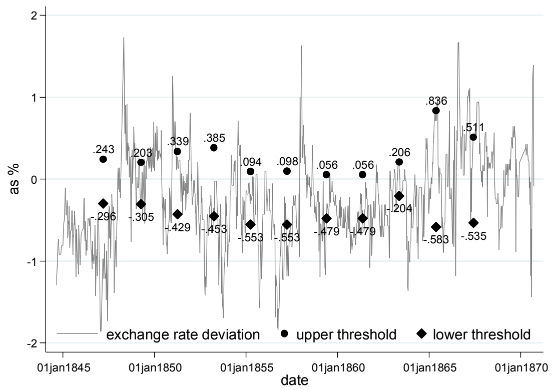
Notes: This table shows the results of asymmetric threshold model by eq. (5). NA denotes that the estimation results are not available because of the characteristics of the time series. NM denotes non-mean-reverting. HL denotes the Half-Life in terms of weeks. Obs_l (Obs_h) denotes the number of observations in the lower (higher) regime defined by the lower (higher) threshold. T-stat. in bold denotes statistical significance at least at 10%. d denotes the delay parameter of the threshold variable.
Source: authors' computations.

Appendix Figure 1: **Rolling asymmetric thresholds for all bilateral exchange rate relationships.**

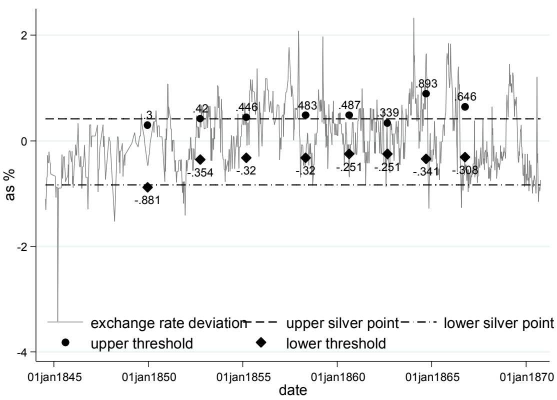
From Hamburg to London (gold)



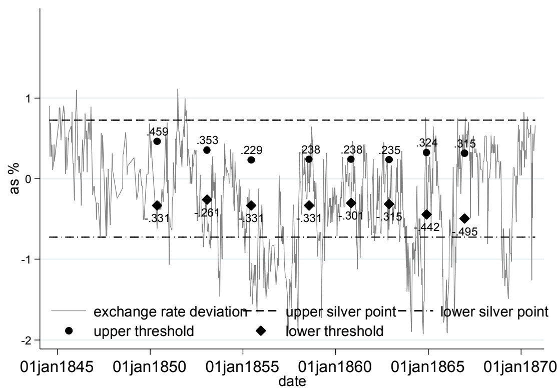
From Hamburg to Paris (gold)



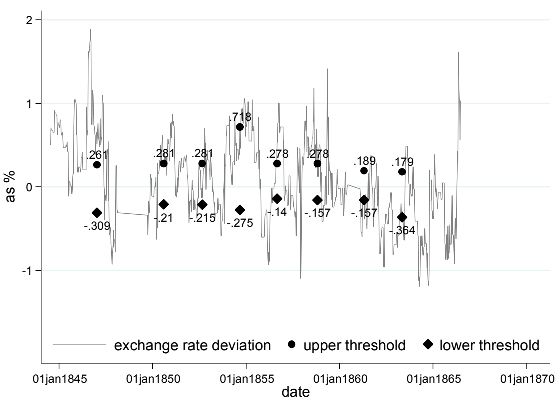
From Amsterdam to London (silver)



From London to Amsterdam (silver)



From Paris to Frankfurt (silver)



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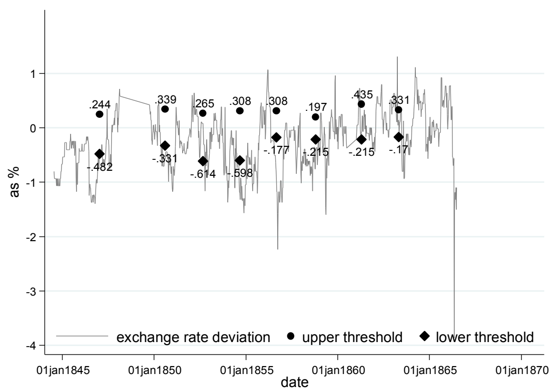

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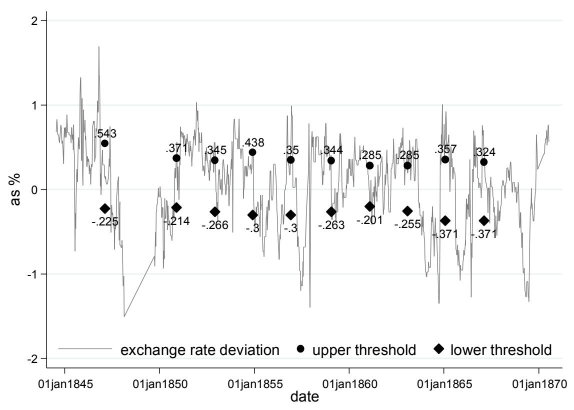

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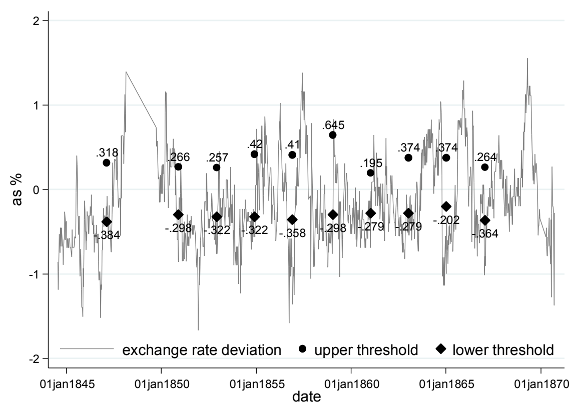

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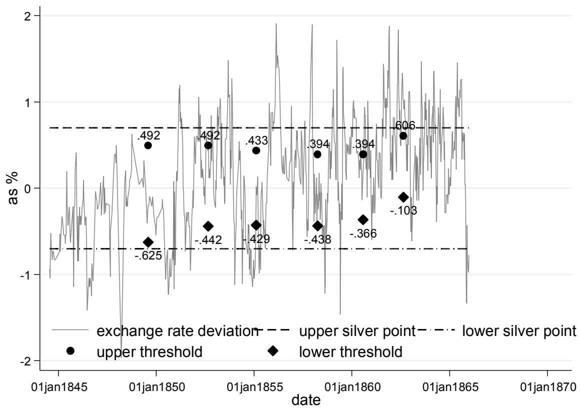

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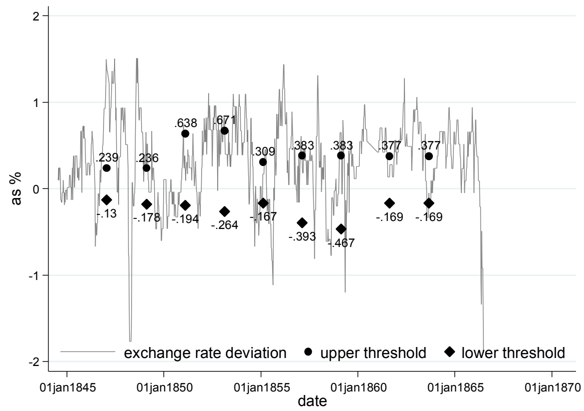

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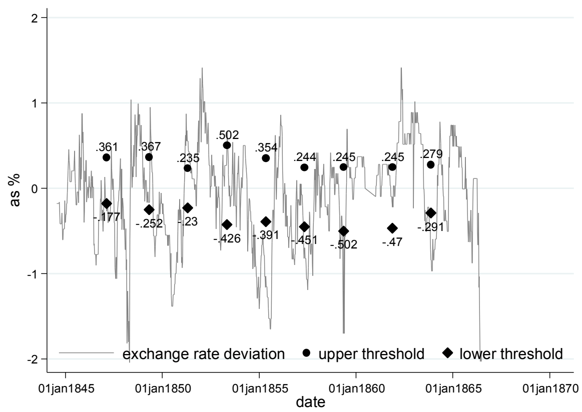

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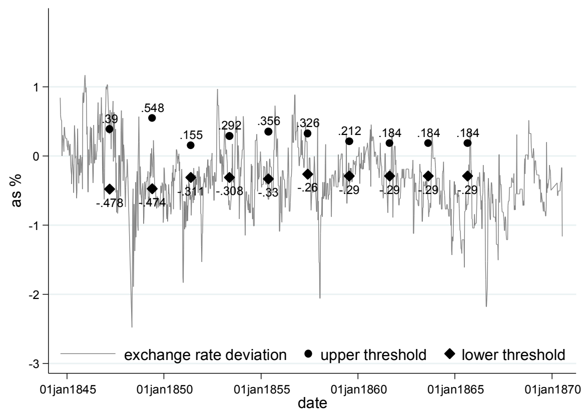
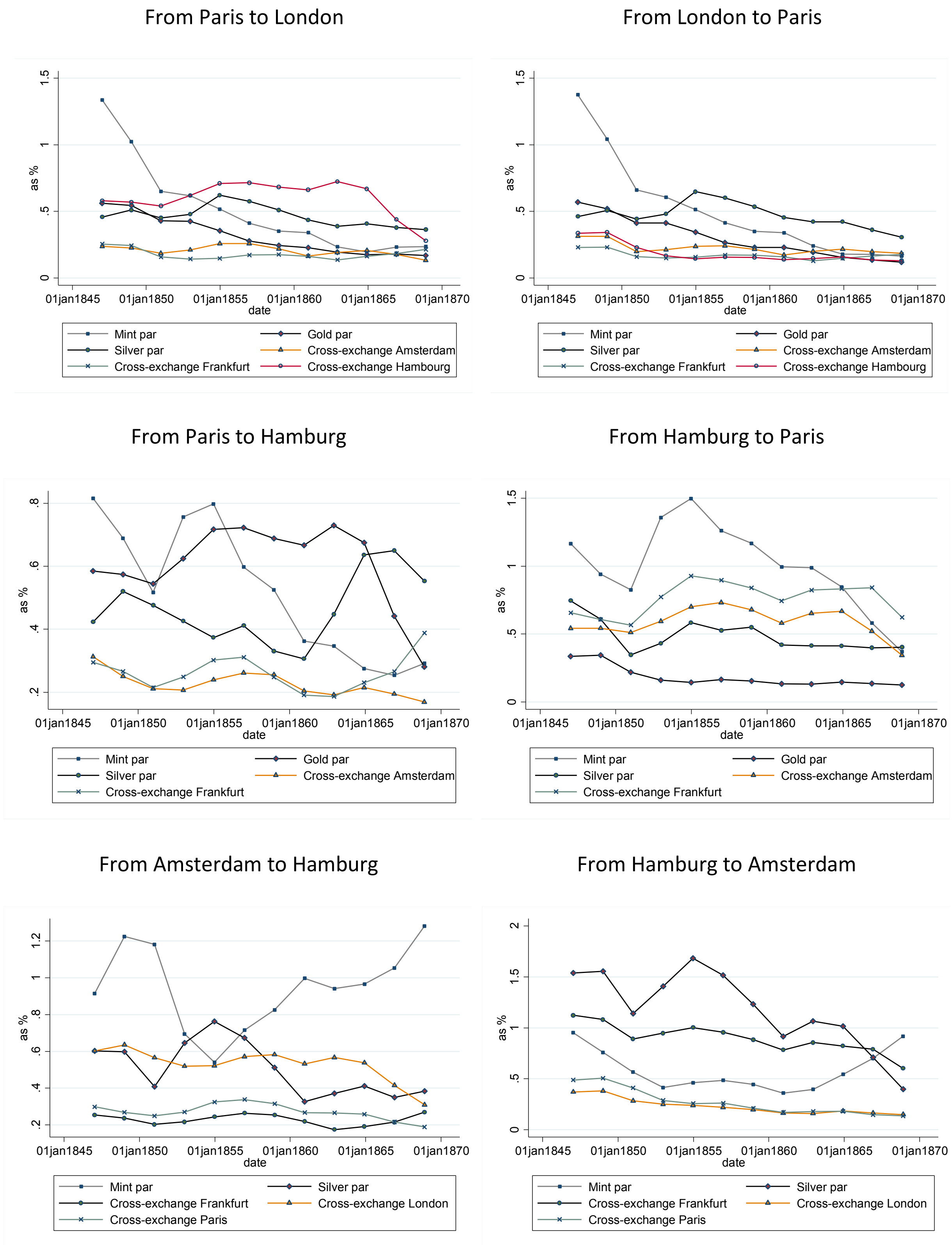


Appendix Figure 2: **Rolling average exchange rate deviation for all available city-paris from a number of different benchmarks**



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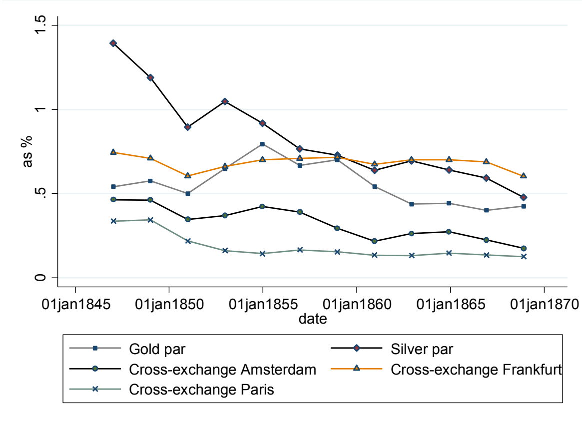

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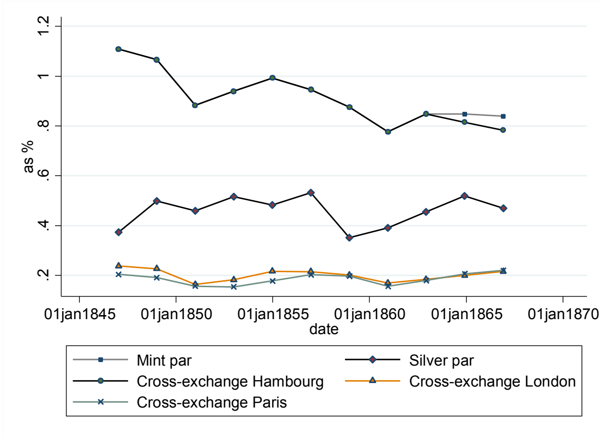
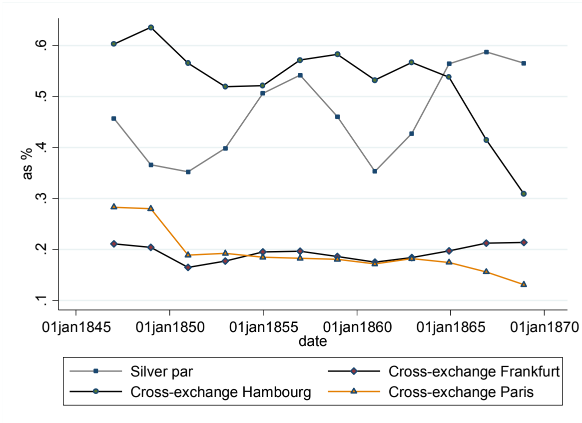
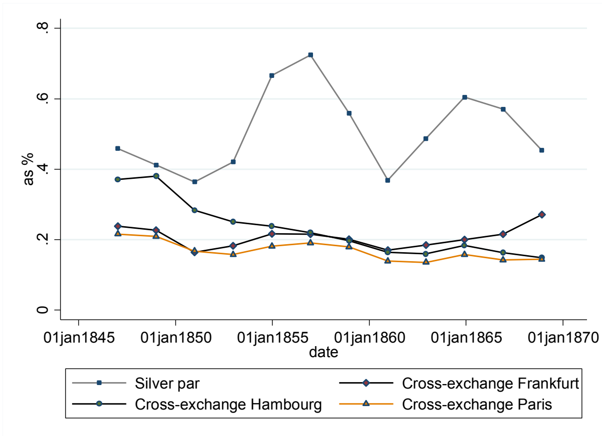


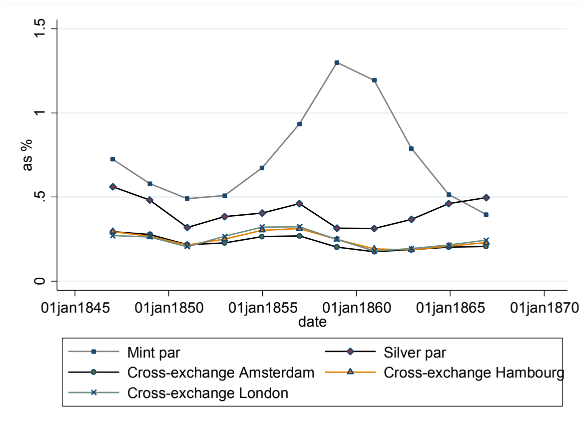
From Amsterdam to London (silver)



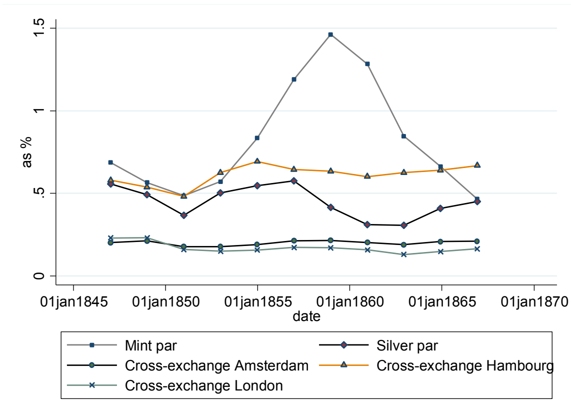
From London to Amsterdam



From Paris to Frankfurt



From Frankfurt to Paris



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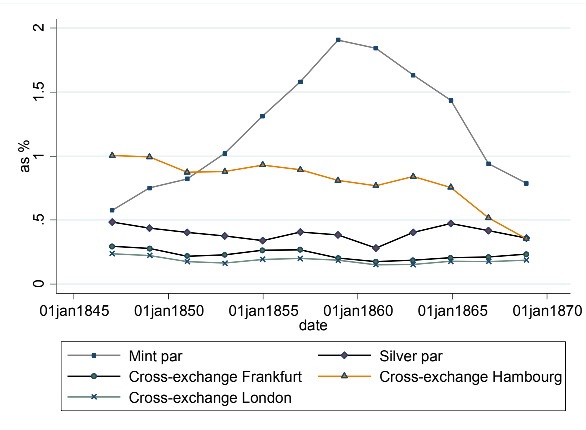

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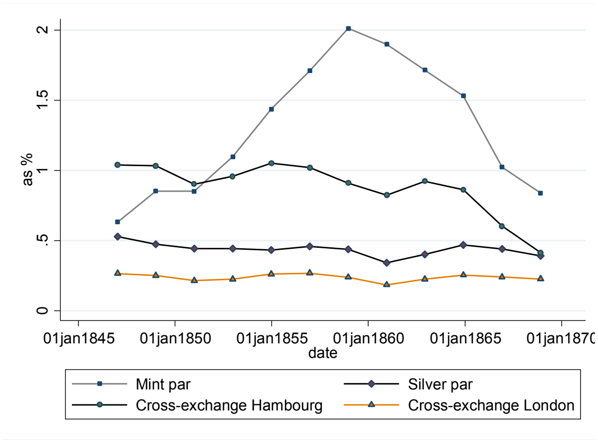
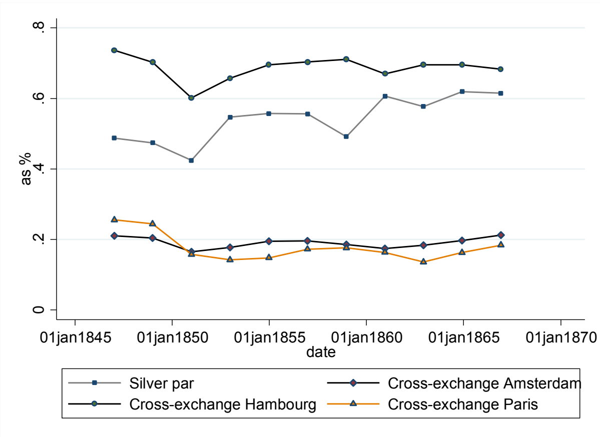


From Frankfurt to London



From Frankfurt to Hamburg